BEYOND REGULATED ENERGY: DELIVERING LONG-TERM BUILDING PERFORMANCE

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ACKNOWLEDGEMENTS

The research journey that formed the basis for the contents of this submission began when I took up my first academic position at the University of Greenwich in 2010. The journey from there to here has been challenging, occasionally frustrating, but ultimately rewarding and transformative.

There are many people to thank for the support, guidance and wisdom I have benefited from on this journey. Firstly I would like to thank my research mentor Professor Keith Jones for starting me on this path and giving me the confidence to believe I could achieve my ultimate goal. Professor Jones has consistently gone above and beyond the call of duty to support me and for that I will be forever grateful.

I would also like to thank my supervisory team of Doctor Spyridon Stravoravdis and Professor David Isaac for their insights and efforts in guiding me through this ‘unusual’ path to a PhD. Their valuable feedback and supportive words are greatly appreciated.

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Finally, a heartfelt thank you to Yulia for accepting the lost evenings, weekends and holidays and Yulia (again), Pat, Cora and Lorna for supporting me throughout.

ABSTRACT

This submission contains eight peer-reviewed publications exploring issues related to the delivery of sustainable built environments and long-term building performance. It is argued that in the context of the drive to deliver sustainable built environments, the current focus on near-term regulated energy and climate change mitigation may not deliver long-term building performance and could ultimately result in premature building obsolescence.

The work examines the role of occupant behaviour and demonstrates that behaviour change campaigns as ‘operational enablers’ have the potential to reduce energy use and may have the potential to improve occupant satisfaction and wellbeing. The work also demonstrates that climate change may have a significant impact on long-term building performance with knock-on impacts on energy use, health, wellbeing and satisfaction. It is demonstrated that the current approach to dealing with climate change risk in the regulatory framework may not be fit-for-purpose. It is noted that in order to deliver long-term performance there is a need for resilience and adaptive capacity. Alternative risk-based approaches, for implementation at the design stage or the operational phase, which account for the potential impacts of climate change are suggested. It is further suggested that occupant behaviour change tools and techniques may have the potential to contribute to climate change adaptation by providing additional adaptive capacity.

The work included utilised a mixed method research approach including case studies, participatory action research and future studies. These approaches were used to explore current practice, the role of occupant behaviour and how such behaviour could be altered. They were also used to explore probable/possible (forecast) future scenarios requiring potential adaptation, which were considered in terms of preferred/desired (backcast) performance.

The research presents an explanatory model considering the potential for occupant behaviour and climate change to contribute to a growing building-performance gap over time and suggests measures to minimise this gap.

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GLOSSARY OF TERMS

BCO	British Council for Offices
BREEAM	Building Research Establishment Environmental Assessment Method
CIAT	Chartered Institute of Architectural Technologists
CIB	International Council for Building
CIOB	Chartered Institute of Building
CO_2	Carbon Dioxide
DCLG	Department for Communities and Local Government
IAQ	Indoor Air Quality
ICT	Information and Communications Technologies
IPCC	Intergovernmental Panel on Climate Change
LEED	Leadership in Energy and Environmental Design
LCC	Life Cycle Costing
POE	Post Occupancy Evaluation
SAP	Standard Assessment Procedure
SBERG	Sustainable Built Environment Research Group
TSB	Technology Strategy Board
UCL	University College London
UHI	Urban Heat Island
WBC	World Building Congress
WHO	World Health Organization

STRUCTURE OF SUBMISSION

This submission is divided into five parts including the main body of the document and four supporting appendices.

The first part of the work which makes up the main body of the text (Chapters One to Six) contains an exposition and literature review. This sets out a framework for the rationale, contribution and impact of the work along with a literature review that places the submitted work within the context of the wider field of research.

Within this, Chapter One introduces the submission and provides a reflection on the author's research journey leading up to the submission. This chapter also includes a discussion about the research theme and rationale, aims, objectives and research questions, impacts and contributions and a consideration of the theoretical underpinning that supports the research. Chapter Two provides a brief summary overview of the published works included in the submission (the publications themselves are included in Appendix A). Chapter Three provides a review of the literature, considering the work submitted within the wider research discussion. Chapter Four provides a discussion considering the impact, contribution and implications of the work. Chapter Five provides concluding statements, notes how the aims and objectives of the research have been met and considers areas for future research.

Appendix A contains the submitted publications including listings of each paper's impact statistics and citations (where available).

Appendix B contains an assessment of the candidate's contribution to each multi-authored paper. A separate supporting document containing verification of the stated contributions from co-authors along with relevant contact details is provided for examiners.

Appendix C lists a number of publications by the author that were not included in this submission.

Appendix D provides a brief curriculum vitae from the candidate considering relevant scholarly activities.

EXPOSITION AND LITERATURE REVIEW

1 INTRODUCTION

Having taken up my first academic post in 2010 following several years working in architectural practice and consultancy roles, I began to – building upon my previous industry-based research activities and academic studies – refine my research interests. From this I observed that although the delivery of sustainable built environments is widely discussed, this tended to focus largely, although not exclusively, on a narrow band of technical matters (although the scope has expanded in more recent years (Schweber and Leiringer, 2012)). As a result there remained a number of challenges to be overcome (such as those suggested by Häkkinen and Belloni, 2011; Rohracher, 2001; Schweber and Leiringer, 2012; Summerfield and Lowe, 2012) in order for sustainable built environments that consider social, economic and environmental matters and ultimately long-term building performance, to be realised.

Following on from this observation I began to explore what other, less explored, factors may have an impact on sustainability in the built environment. Given that some measures focused on reducing regulated energy to mitigate climate change had resulted in unintended consequences, such as overheating and poor Indoor Air Quality [IAQ],(Al-Homoud, 2005; Dengel and Swainson, 2012), this led to thinking about building performance and how this may change over time. This in turn linked to the potential impacts of climate change. Furthermore, at this time, the 'building performance gap' was increasingly being considered in research with the role of occupant behaviour emerging as a contributory factor (Menezes et al., 2012b).

Building upon this, the first of the publications included in this submission (Paper One) explored the role of occupant behaviour in the commercial office environment. The second paper included (Paper Two) explored the potential impact of climate change on long-term building performance. These two initial papers, both published in 2013 (although associated research began in 2011 and 2012), formed a starting point for the wider body of research included in this submission.

This submission includes eight selected peer-reviewed publications representing a coherent body of work focusing on the delivery of long-term (beyond the first 25-30 years of the building lifecycle) building performance. Within this, two key themes are considered, namely the role of occupant behaviour and how it can be harnessed and the potential impacts of climate change and how this can be taken into account in regulation, design and building management.

Reflecting the journey made in developing the research that forms the basis for this submission the papers submitted are listed in chronological order in Figure 1 below, with the two key themes previously mentioned being explored in parallel. As previously noted Papers One and Two presented the starting point for the exploration of occupant behaviour and the potential impact of climate change themes respectively. Paper Three, focused on climate change impacts, then developed the process identified in Paper Two into a theoretical framework. Although Paper Five was published later than Paper Four the research took place earlier and further developed the behavioural theme in the work. The research for Paper Four then took place and was closely followed by Paper Six which built upon Paper Four and focused on the climate change impacts theme. Paper Seven as a follow up to Paper One then completed the behavioural based research before Paper Eight tied the two themes together and highlighted their overlaps and interrelationships.

From this and the discussions that follow, my research journey can be observed as I developed my research focus and explored research ideas independently, turning them into publications, making an original contribution to knowledge and generating impact.

P1. Mulville, M., Jones, K. and Huebner, G. (2013). The potential for energy reduction in UK commercial offices through effective management and behaviour change.

P2. Jones, K., Mulville, M. and Brookes, A. (2013). FM, risk and climate change adaptation.

P3. Jones, K., Desai, A., Mulville, M. and Jones, A. (2015). Asset management using a hybrid backcasting/forecasting approach.

P4. Mulville, M. and Stravoravdis, S. (2016). The impact of regulations on overheating risk in dwellings.

P5. Mulville, M., Callaghan, N and Isaac, D. (2016). The impact of the ambient environment and building configuration on occupant productivity in open-plan commercial offices.

P6. Mulville, M. and Stravoravdis, S. (2016). Regulating for climate change related overheating risk in dwellings.

P7. Mulville, M., Jones, K., Huebner, G. and Powell-Greig, J. (2016). Energy saving occupant behaviours in offices: change strategies.

P8. Mulville, M. and Stravoravdis, S. (2016). Delivering long-term building performance: a user-centred approach.

Figure 1. Timeline of Publications (See Figure 2 for mapping of research themes)

1.1 Key Terms

For completeness some of the key terms used in this submission are considered here to clarify how they are used in the context of this work. Outside individual components, it is perhaps difficult to gauge timeframes in the built environment beyond specific buildings. Jones, Mulville and Brookes (2013) note that buildings are developed on the basis of 60-year-plus design life while in reality the actual service life may be much longer. Building upon this Kellenberger and Althaus (2009) note that many studies assume a lifespan of 75-80 years. Different elements of the building will have differing adaptive capacities and longevity. Duffy as quoted by Brand (1997) notes these as ‘layers of longevity’ and, building on Duffy’s ‘four S’s, Brand (1997) identifies six S’s (Site, Structure, Skin, Services, Space Plan and Stuff) or layers. Brand (1997) suggests that the structure should have a life of 30-300 years and these elements should last at least the lifetime of the building (BS 7543:2015). The ‘Skin’ is noted to have a service life in the region of 20 years with de Wilde, Tian and Augenbroe (2011) suggesting a service life of at least 25 years. Arguably individual elements of the skin or envelope, depending on the construction method, should have a significantly longer service life with shorter timeframes relating to aesthetic alterations, technology integrated or energy upgrades. This is supported by BS7543:2015 which suggests many elements of the building skin should deliver a service life in the region of 40-60 years. Wilkinson and Reed (2006) suggest that non-domestic buildings require major refurbishments every 20-25, depending on the specific building and maintenance regime this could be extended to 30 years.. More minor interventions and refurbishments may correspond to the end of the service life of specific components (Services in the six S’s) and can be as little as 7-10 years (Brand, 1997; Schoen and Fellow, 2010). Over time the impact of minor interventions may compound contributing to the requirement for major refurbishment. The terms near-term and long-term are used throughout this work. In the context of the above discussion near-term refers to the first 20-30 years of the service life of the building, while long-term refers to the first major retrofit and beyond (30-100 years and beyond).

Resilience and adaptation are also key terms used in this work, both are considered in the context of building performance and the potential impacts of climate change. Cox, Nielsen and Rode (2015) note that a building’s resilience is a measure of how well it continues to function after an event and adaptability is a factor of this. Addis and Schouten (2004) define adaptability in buildings as a building that has “been designed with thought of how it might be easily altered to prolong its life”. In the context of this work those definitions are broadly adopted.

The work also makes the distinction between regulated and un-regulated energy. Regulated energy refers to energy use covered by the building regulations such as embedded heating, cooling, ventilation and lighting. Un-regulated energy refers to small power and plug-in equipment such as desktop computers, televisions, lamps and desk fans.

1.2 Research Theme and Rationale

It is widely accepted that the built environment is responsible for a significant proportion of overall energy use and associated emissions (Department for Communities and Local Government, 2015). It is also widely acknowledged that the potential climate change implications of this may be significant (Intergovernmental Panel on Climate Change, 2014). As a result there has in recent years been a growing focus on sustainability in the built environment, particularly in relation to environmental impacts. This is being driven by increasingly stringent regulations focused on reducing heating, cooling and lighting loads (regulated energy) (Mulville and Stravoravdis, 2016c) and increasingly ambitious environmental and energy standards such as Passive House, the Building Research Establishment Environmental Assessment Method [BREEAM] and Leadership in Energy and Environmental Design [LEED] (Cotterell and Dadeby, 2012; Lee, 2013). This, it can be argued, focuses largely, although not exclusively, on the mitigation of climate change and near-term regulated energy performance (Meacham, 2016; Mulville and Stravoravdis, 2016a). Furthermore, although consideration of sustainability in the built environment has intensified in recent years, there remains a focus on short-term thinking and ‘getting the job done’ (Duffy, 1990) particularly within industry.

Despite the increasingly stringent regulations and ambitious environmental standards, it has been widely recognised that a significant building performance gap exists (for a review see van Dronkelaar et al., 2016). To date much of the research around this gap has focused on regulated energy (Menezes et al., 2012a; Sunikka-Blank and Galvin, 2012; de Wilde, 2014), but the role of occupant behaviour has been recognised as a significant contributory factor to the gap with impacts beyond energy use (van Dronkelaar et al., 2016; Karjalainen, 2016). Although increasing in recent years, research in this area (relating to occupant behaviour) remains limited (Al-Homoud, 2005; Dantsiou and Sunikka-Blank, 2015). Furthermore, it has been argued that the increasing drive towards energy efficiency (through higher levels of insulation and air tightness) has resulted in a number of unintended consequences. This could in some cases have negative impacts for occupants (Al-Homoud, 2005; Smith and Pitt, 2011) which could lead to significant performance-related issues that may be exacerbated by the impacts of climate change (Jones, Mulville and Brookes, 2013).

The potential impact of climate change on buildings has been explored in relation to a range of building types (although the focus is largely on domestic buildings) exploring a range of issues (for instance see Sanders and Phillipson (2010)), with many studies focusing on overheating risk (Jenkins et al., 2014b; McLeod, Hopfe and Kwan, 2013). However, a limited amount of research has been carried out in relation to how to first regulate for such impacts (Eisenberg, 2016; Meacham, 2016; Visscher, Laubscher and Chan, 2016) and secondly how to integrate climate change adaptation strategies into long-term built asset management planning (Desai and Jones, 2010).

Where such issues exist (i.e. energy and the wider building performance gap, unintended consequences of energy reduction measures and uncertainty around the role of occupant behaviour) and the potential impacts of climate change present further uncertainty, there is an increased risk of premature building obsolescence (Jones, Mulville and Brookes, 2013). This presents a significant challenge in the face of the current drive for the delivery of sustainable built environments.

1.3 Aims, Objectives and Research Questions

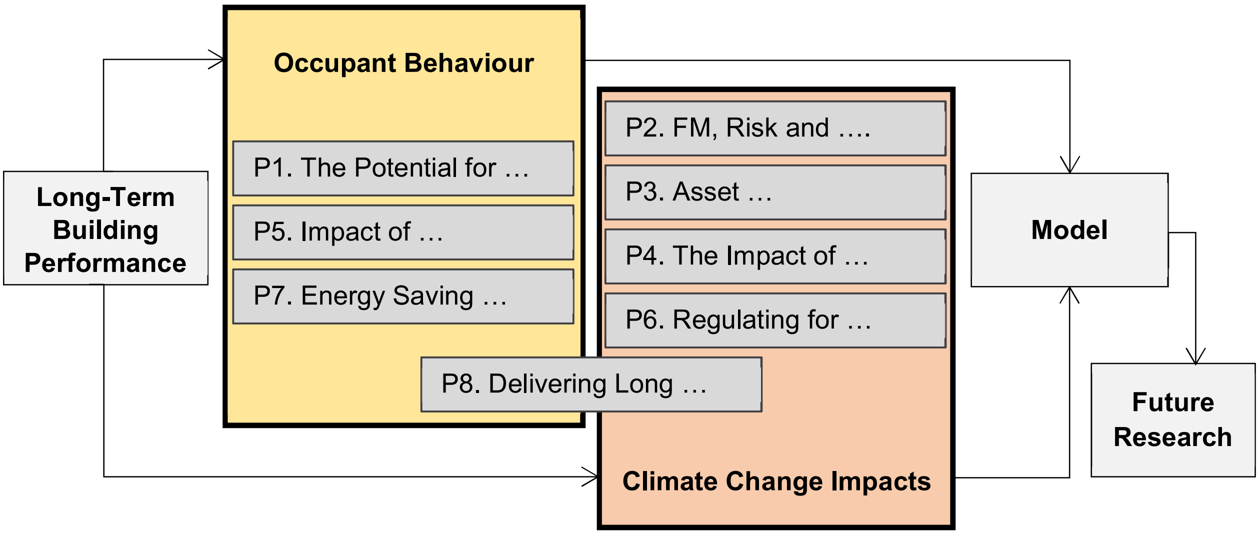


Figure 2. Research Mapping (see Figure 1 for full paper titles)

Framed around the theory of building obsolescence, the aim of the research included in this submission was to examine the role of occupant behaviour and the potential impacts of climate change on long-term building performance (see Figure 2 for mapping of these issues against the papers included in this submission).

This aim led to the development of the following objectives:

1. To investigate, through a critical review of the literature, the potential impacts of climate change on, and the role of occupant behaviour in, building performance (across all papers);
2. To develop tools and techniques that can harness occupant behaviour in order to improve building performance (Papers One, Five, Seven and Eight);
3. To develop regulatory mechanisms and approaches to facilities/built asset management in relation to the potential impacts of climate change that can be used to improve resilience and increase adaptive capacity in buildings (Papers Two, Three, Four, Six and Eight) and;
4. To develop a model that explains the role of occupant behaviour and the potential impacts of climate change on long-term building performance (Paper Eight).

The body of work focuses on the core idea that although consideration of near-term regulated energy use to reduce environmental impacts is not without merit, this may not deliver a truly sustainable built environment and could result in premature building obsolescence. In order to avoid such premature building obsolescence, a focus on long-term building performance (over near-term regulated energy use alone) that delivers resilience and adaptive capacity while harnessing occupant behaviour is required. Within this, and related to the objectives noted above, some key questions emerge which the papers included in the submission seek to address (see Figure 2):

- What is the role of occupant behaviour and how can occupant behaviour be harnessed to deliver better building performance both in energy and non-energy terms?

  Papers One (Mulville, Jones and Huebner, 2013) and Seven (Mulville et al., 2016) explored how occupant behaviour change strategies can be used to alter occupant behaviour, demonstrating what mechanisms are of benefit. Paper Five (Mulville, Callaghan and Isaac, 2016) built upon these by exploring the role of occupant behaviour in occupant wellbeing and productivity. The paper suggests that similar behaviour change techniques, to those applied in Papers One and Seven, may be of benefit in addressing these factors. It is further suggested that harnessing occupant behaviour may help add resilience and adaptive capacity in relation to the potential impacts of climate change.

- What steps can be taken to address the potential impacts of climate change on the building environment?

  Papers Two (Jones, Mulville and Brookes, 2013) and Three (Jones et al., 2015) explored how the potential impacts of climate change can be accounted for during the design and construction phase of the building and managed during the operational phase. The papers suggest a hybrid backcasting/forecasting approach to built asset adaptation planning. Building upon this Papers Four (Mulville and Stravoravdis, 2016c) and Six (Mulville and Stravoravdis, 2016b) explore the potential impacts of climate change on overheating risk in domestic dwellings. These papers demonstrate that the current approach may not be fit for purpose. A risk-based regulatory approach, again utilising adaptation planning, is suggested.

- How can the above issues be addressed in order to deliver long-term building performance?

  Each paper included in the submission considers how such issues can be addressed in relation to the delivery of long-term building performance. Paper Eight (Mulville and Stravoravdis, 2016a) combines the preceding research (in Papers One to Seven) to demonstrate how occupant behaviour and the potential impacts of climate change could impact upon long-term performance and what steps can be taken to minimise the risk.

1.4 Summary of Impacts and Contributions

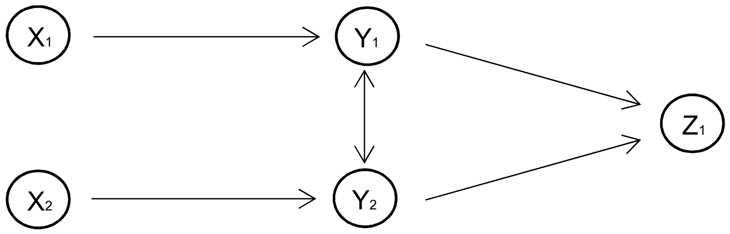
Overall the body of work is about developing an approach to the delivery of sustainability in the built environment that goes beyond near-term regulated energy with a focus on long-term building performance. Within this, the work suggests that there is a need for building designs that take account of the potential impacts of climate change and enable and support preferred user behaviours to deliver resilience and building performance. The work considers how behaviour change techniques (within building management) can be used to benefit near-term and long-term building performance and how the potential impacts of climate change can be accounted for at both the design stage and during the operational phase.

The research makes an original contribution to knowledge by addressing the research gap around the role of occupant behaviour and providing tools and techniques based on information, education and feedback to harness behaviour for better building performance. For instance, Paper One demonstrates that bi-weekly feedback provided electronically combined with information on the performance of others (targeting social norms) and whether or not their behaviour is generally accepted or not (using an injunctive norm) can reduce desk level energy consumption by up to 20%. The research demonstrates that behaviour change techniques used in the domestic sector (which are more developed) may not be readily transferable to the non-domestic sector where workplace culture may take precedence over the importance of underlying environmental attitudes.

Furthermore, the research makes an original contribution to knowledge by providing regulatory mechanisms and approaches to facilities/built asset management that can be used to increase the resilience and adaptive capacity of buildings in the face of predicted climate change. The research suggests that these tools and techniques should be incorporated into the regulatory framework and/or included in facilities and built asset management planning. This presents a shift in thinking for the regulatory framework from backwards looking (Eisenberg, 2016) to a risk-based forecasting role (in relation to the impacts of climate change).

The regulatory mechanism focusing on overheating risk in dwellings (See Papers Four and Six) is original in that it combines the power and capability of complex dynamic building simulation with an approach that is industry focused and minimises the resource and technical knowledge required. This is achieved by basing risk assessments on common dwelling typologies. The research provides a new hybrid backcasting/forecasting approach to climate change adaptation planning (See Papers Two and Three) for facilities and built asset managers aimed at maintaining resilience during the operational phase of the building life cycle. This is achieved through the use of participatory backcasting combined with forecasting to develop a climate change adaptation plan, including enabling works for future adaptations where necessary, which embeds resilience in the initial design. For example, enabling works for the case study building used in this research included the provision of larger duct risers during initial construction to allow for the installation of additional cooling capacity when needed in the future.

Building upon this, and bringing the ideas of climate change impacts and the role of occupant behaviour together, the work suggests there is a need for an active approach to building management utilising behaviour change techniques to optimise building performance and to provide greater adaptive capacity. Overall the work presents a model of long-term building performance including occupant behaviour and behaviour change techniques and climate change planning and adaptation techniques that can minimise the long-term building performance gap and reduce the risk of premature building obsolescence.



Independent Variables	Mediating Variables	Dependent Variable
X_1 Occupant Behaviour	Y_1 Building Management	Z_1 Building Performance
X_2 Climate Change	Y_2 Design & Regulation	

Figure 3. Mapping of Variables

Figure 3 suggests how the factors discussed above may interact with each other to influence long-term building performance. The figure highlights the potential importance of building management (including behaviour change techniques) and the role of design and regulations as potential mediating factors influencing long-term building performance.

The impact of the work is demonstrated in its inclusion in peer-reviewed publications, invited presentations, awards, citations and the discussions and interests it has raised in both the research community and in industry circles. More details regarding the overall impact of the work can be found in Chapter Four of this document and in the impact statistics and details of citations provided in Appendix A alongside the submitted papers.

1.5 Methodological Approach

A range of methodologies were applied to the research included in this submission. The details of the specific methods applied and their associated justifications are provided in the papers themselves. This section of the submission provides a summary of the theoretical underpinning that supports the choice of research methodologies across the body of work submitted.

In broad terms, epistemological philosophies are dominated by positivism or constructivism (Krauss, 2005). The positivistic approach, which is common in the natural sciences, focuses on measurement and experimentation using numerical data and calculation (or quantitative data) (Creswell, 2009) to test how well theory fits against measured data. The constructivist approach, common in the social sciences, seeks to embed the researcher in the phenomenon being explored (such as the culture or organisation) using verbal or written data (qualitative) (Creswell, 2009) to seek understanding and often to generate theory to explain the observations. Mixed or multi-methods approaches aim to utilise a combination of approaches using, for instance, quantitative methods to test existing theory and qualitative methods to gain deeper insight and generate new theory.

Dainty (2008) (although focusing largely on construction management), notes that the positivistic approach remains dominant in built environment research. This is supported by Schweber and Leiringer (2012) who found that three-quarters of construction research and business and social science publications concerning buildings adopted a positivist approach. It has been argued that a positivistic approach in isolation may not be appropriate in a real world area of inquiry and an approach utilising methodological pluralism (or mixed methods) may allow for deeper insights to be gained (Dainty, 2008). This is supported by Robson (2011) who argues that, despite some criticisms, a mixed method approach to real world/applied research may be more reflective of reality and allow quantitative data to be supported by qualitative measures and vice versa. In this context, the research included in this submission takes an approach grounded in pragmatism utilising mixed methods and using both quantitative and qualitative approaches. Although the individual papers included within this submission are dominated by either quantitative or qualitative methods, and quantitative methods dominate overall, the methods adopted have been chosen as best fit for the particular studies. The inclusion of qualitative methods to supplement the quantitative adds depth to the overall body of work. Figure 4 sets out, in notional terms, where the research methods used in the various papers sit against the broad epistemological philosophies.

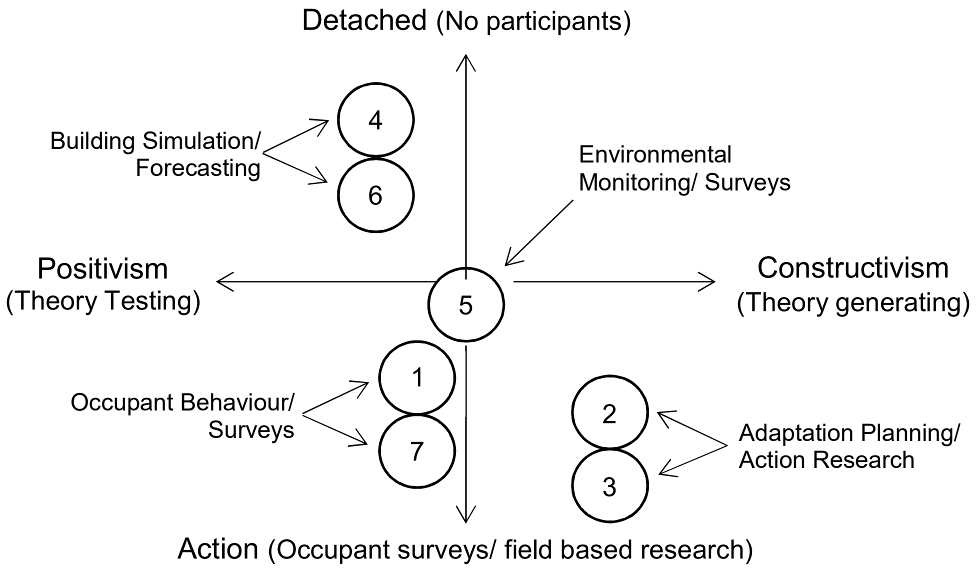


Figure 4. Notional Mapping of Research Papers. Adapted from Kelly (2004)

It has been argued that built environment research occupies an applied field of inquiry (Knight and Turnbull, 2008), the papers that are included in this submission largely follow that tradition. As noted, in broad terms the papers take a mixed methods approach, using quantitative methods to establish empirical data and qualitative methods to establish deeper underlying meaning (and to generate theory) alongside the existing literature.

Proverbs and Gameson (2008) argue that case studies are highly relevant in a project-driven industry and it can be argued that such approaches provide real-world scenarios for an applied field of inquiry. Furthermore, case studies are well suited to exploring processes and behaviours and offer benefits in building theory (Amaratunga et al., 2002) while providing for in-depth investigation and analysis (Wedawatta, Ingirige and Amaratunga, 2011). Papers One (Mulville, Jones and Huebner, 2013) and Seven (Mulville et al., 2016) are based on a case study approach, where occupant surveys are combined with the provision of information, education and feedback along with measured energy data with the researchers engaging in detached observation (Proverbs and Gameson, 2008). This research is conducted in a comparative before and after scenario to explore the impact of the interventions made on occupant behaviour. Similarly Paper Five (Mulville, Callaghan and Isaac, 2016) used occupant surveys combined with measured data of ambient environmental conditions (although that study was not a comparative before and after survey) to assess occupant satisfaction and the role of ambient conditions. These mixed methods (or multi-strategy approaches (Robson, 2011)) allowed for correlations between conditions and the impact on occupants to be considered against existing theories and used to inform the generation of new thinking.

Papers Two (Jones, Mulville and Brookes, 2013) and Three (Jones et al., 2015) (again based on case studies) focused more on qualitative methods (although informed by quantitative measures) in a participatory action research project (using forecasting and backcasting principles). As noted by Robson (2011) participatory action research can work well with a flexible design and with case studies. This qualitative approach allowed for greater depth understanding to be gained and theory developed to align with those observations. For these papers the researchers, due to the nature of the study, were more directly involved in the process and themselves participants, whereas in the preceding papers the researchers were more detached. The direct involvement by the researcher has risks in terms of their influence and bias. However, as argued in the papers, efforts were made to ensure that the researchers did not overly influence the proceedings, taking an observational role as far as was practicable and a reflective approach when conducting analysis.

Papers Two (Jones, Mulville and Brookes, 2013) and Three (Jones et al., 2015) along with Four (Mulville and Stravoravdis, 2016c) and Six (Mulville and Stravoravdis, 2016b) can be classified as scenario-based futures studies. Ratcliffe (2008), noting that all our knowledge is about the past while decisions are about the future, suggests that professions concerned with the built environment need a more informed and structured approach to the study of the future. It is suggested that more traditional approaches may be limited, and foresight, as a vision building process, and scenario learning to describe a future state, may be of benefit. Although such predictions involve uncertainty, given the long-lived nature of the built environment (Eisenberg, 2016) such a forecasting approach is necessary in order to consider the impacts of predicted change. Such ‘future studies’ have been used for policy planning in setting organisational strategies (Jones et al., 2015) and provide policy makers with views and alternatives for the future in order to inform decision making in the present (Ratcliffe, 2008).

Papers Four (Mulville and Stravoravdis, 2016c) and Six (Mulville and Stravoravdis, 2016b) use forecasting to consider probable/possible predictions which are then supplemented by adaptation planning which can be seen as backcasting (to deliver the desired/preferred outcome). To an extent the approach in these papers is similar to, and informed by, parts of the methods applied to Papers Two (Jones, Mulville and Brookes, 2013) and Three (Jones et al., 2015) . However, they differ in that they did not involve participants, thus removing the risk of bias due to the presence of the researcher. The approach taken used probabilistic modelling to predict the potential impact of climate change with the ultimate goal of informing the regulatory framework.

Paper Eight (Mulville and Stravoravdis, 2016a) is a literature-based study collating and building upon the work of the preceding papers included in this submission.

2 OVERVIEW OF PAPERS

For the purpose of clarity, a brief summary (provided in bullet point) for each of the eight papers included in the submission is provided below. The full papers are included in Appendix A along with impact statistics, a summary discussion regarding the impacts and contributions of the papers included in section 4.2.

2.1 Paper One

Mulville, M., Jones, K. and Huebner, G. (2013). The potential for energy reduction in UK commercial offices through effective management and behaviour change. *Architectural Engineering and Design Management,* Vol. 10, 1-2, pp. 79-90.

- Utilised monitoring of energy use along with a behaviour change campaign utilising feedback, education/information and goal setting;
- Demonstrated that up to 23% of energy use occurs outside of productive working hours;
- Demonstrated that savings of up to 20% are possible;
- Established that behaviour change offers significant potential for energy savings;
- Suggested the use of automated mechanisms for measuring energy use and encouraging preferred/desired occupant behaviour;
- Suggested that continuous monitoring and feedback are required in order to ensure that behavioural alterations become habitual and to encourage continuous improvement;
- Among the first papers to consider such behaviour change campaigns in the non-domestic sector.

2.2 Paper Two

Jones, K., Mulville, M. and Brookes, A. (2013). FM, risk and climate change adaptation. In: *FM for a Sustainable Future, 12th EuroFM Research Symposium, Prague, Czech Republic, 22-24 May 2013. International Journal of Facilities Management, pp. 120-128.* ISBN: 978-94-90694-02-9.

- Explored the potential impacts of climate change on the life-time performance of a new £75m educational building;
- Developed as a participatory action research project;
- Highlighted that climate change risk assessments at the design stage are largely absent;
- Considered the potential impacts of climate change on building performance and presents a climate change adaptation framework (combining risk assessment and future climate change scenarios – supported by forecasting and backcasting);
- Suggested, depending on the level of risk, the use of adaptations that are implemented during the design stage, the use of preparatory/enabling works for future adaptations or consideration of future operational changes;
- Provided a more realistic assessment of resilience and mechanisms to provide greater resilience through the delivery of greater adaptive capacity;
- Presented a change to the traditional forecasting role of asset managers and suggested that the presence of facilities managers during the design stage may be key.

2.3 Paper Three

Jones, K., Desai, A., Mulville, M. and Jones, A. (2015). Asset management using a hybrid backcasting/forecasting approach. *Facilities,* Vol. 33, 11-12, pp. 701-715.

- Built upon the work of Paper Two (as a participatory action research project) by explaining the supporting theory behind the findings of that earlier paper;

- Provided a framework for formulating long-term facilities and asset management plans for adaptation to climate change utilising a hybrid backcasting/forecasting approach;
- Suggested a need to concentrate on preferred/desired (backcast) as opposed to possible/probable (forecast) scenarios to set performance criteria and end goals against which alternative adaptation solutions can be developed;
- Frames the approach used as ‘participatory backcasting’ supported by forecasting;
- Highlighted the need for life-cycle analysis tools to support backcasting (which to an extent is addressed in Papers Four and Six);
- The paper was developed on the back of an associated paper (see Appendix A and C) that has been cited by a number of authors and received a ‘best paper’ award.

2.4 Paper Four

Mulville, M. and Stravoravdis, S. (2016). The impact of regulations on overheating risk in dwellings. *Journal of Building Research and Information,* Vol. 44, 5-6, pp. 520-553.

- Examined the potential for current regulatory approaches to reducing energy use to result in increased overheating risk related to climate change;
- Took a future studies approach utilising dynamic building simulation and detailed probabilistic predictions to assess the potential impacts of climate change on overheating risk;
- Demonstrated that the current approach to overheating risk assessment may not be fit for purpose with unrealistic adaptations and the use of historic climate data;
- Demonstrated that buildings in cool climates may in the future suffer from significant overheating and this could have implications for health, wellbeing and energy use;
- Suggested that the current drive to optimise buildings in cool climates for heat retention may be a significant contributory factor;

- Suggested that such issues could result in a shift to summer-time fuel poverty;
- Suggested an alternative risk-based approach to overheating risk assessment embedded in the building regulations.

2.5 Paper Five

Mulville, M., Callaghan, N. and Isaac, D. (2016). The impact of the ambient environment and building configuration on occupancy productivity in open-plan commercial offices. *Journal of Corporate Real Estate,* Vol. 18, 3, pp. 180-193.

- Examined how both building configuration and ambient environmental conditions along with occupant behaviour can impact on health, wellbeing and productivity;
- Utilised the monitoring of ambient environmental conditions along with occupant surveys;
- Demonstrated that occupant behaviour can have a significant impact on occupant satisfaction;
- Suggested that there may be a hierarchy of importance in terms of ambient environmental conditions in relation to occupant satisfaction;
- Demonstrated that there can be significant differences in health, wellbeing and productivity within individual buildings and that this may not always be linked to ambient environmental conditions;
- Suggested the need for an active approach to building management including continuous monitoring, feedback and behaviour change campaigns;
- Suggested that such approaches could be used both to improve occupant satisfaction (and health, wellbeing and productivity) and to reduce energy use.

Since the initial publication of this paper there have been a number of developments in the use and application of wearable technologies. This includes increased miniaturisation and non-invasive monitoring with reducing costs (McCaul, Glennon and Diamond, 2017), increased use of clothing integration, developments in health monitoring and developments in the interpretation and interrogation of wearable sensor data output (King et al., 2017). Such developments could be a significant benefit to similar studies to this one, carried out in the future. This may allow for greater understanding of the impact of the ambient environment on occupants, the role of occupant behaviour in environmental satisfaction and occupants' interactions with building controls to be developed. Furthermore, greater use of Post Occupancy Evaluation [POE] incorporating the methods used in this study and utilising wearable technologies may further benefit asset and facilities managers in maximising building performance.

2.6 Paper Six

Mulville, M. and Stravoravdis, S. (2016). Regulating for climate change related overheating risk in dwellings. In: *Proceedings of the CIB World Building Congress 2016: Creating Built Environments of New Opportunities Conference 30 May - 2 June 2016, Tampere, Finland*. ISBN: 978-952-15-3741-7

- Built upon the work in Paper Four and suggests that the current focus on the point of handover could lead to premature building obsolescence due to climate change;
- Developed an alternative, industry-focused, approach to considering overheating risk. This incorporated adaptation planning (linked to the backcasting/forecasting approach considered in Papers Three and Four), utilising the greater accuracy of dynamic simulation without requiring significant resources;
- The adaptation planning approach suggested could ensure a pathway for the delivery of long-term performance (linked to backcasting);
- The approach suggested aims to ensure that near-term efficiency does not result in an unacceptably high future overheating risk and that developers/designers take a low risk approach;
- Highlighted that temperatures in bedrooms overnight are problematic and that the benefits of high thermal mass may need to be revisited along with greater consideration of the most appropriate overheating metrics;

- Arguably shifts regulations from a point of handover approach to a forecasting role.

2.7 Paper Seven

Mulville, M., Jones K., Huebner G. and Powell, J. (2016). Energy-saving occupant behaviours in offices: change strategies. *Building Research and Information.* http://dx.doi.org/10.1080/09613218.2016.1212299

- Built upon the research in Paper One and demonstrates that a change in habit can be achieved without changes to pro-environmental attitude and perceived social norms;
- Suggested that management campaigns and workplace culture and practice may be of importance and can be viewed as ‘facilitating conditions’ for behaviour change;
- Demonstrated that the length of the baseline and monitoring period is of importance in order to ensure observed savings are realistic;
- Demonstrated that in terms of the effectiveness of behaviour change, the commercial sector may be less elastic that the domestic;
- Presented an altered version of the theory of planned behaviour;
- Suggested that there is a need for a less passive approach to behaviour change and calls for an active approach to building management;
- Suggested that such active management combined with efforts to improve health, wellbeing and productivity could help to reduce the building performance gap.

2.8 Paper Eight

Mulville, M. and Stravoravdis, S. (2016). Delivering long-term building performance: a user-centred approach. In: Gorse, C. and Dastbaz, M. (Eds), *International SEEDS Conference, 14-15 September 2016, Leeds Beckett University, UK, Sustainable Ecological Engineering Design for Society*. ISBN: 978-0-9955690-1-0

- This paper tied together the research included in the preceding papers;
- Suggested that the current focus on climate change mitigation through energy efficiency risks ignoring the influence of occupants and climate change and could result in a building performance gap and premature obsolescence;
- Argued that if sustainable built environments are to be delivered there is a need for a focus on long-term building performance (beyond the point of handover);
- Presented a theoretical model of long-term building performance, addressing issues associated with occupant behaviour and climate change impacts;
- Suggested a need for a user-focused approach to building design to support preferred/desired behaviour and risk-based adaptation planning to consider the potential impacts of climate change;
- Also suggested the need for an active approach to building management incorporating feedback, information and goal-setting to reinforce the design intention.

3 LITERATURE REVIEW

The term ‘obsolescence’ as referring to the process of becoming ‘obsolete’ is generally well understood. However, as noted by Thomsen and van der Flier (2011) although the terminology is clear in practical and even conceptual terms, obsolescence is not well understood or commonly used (Butt et al., 2015) within the built environment. In broad terms obsolescence is widely accepted to be related to the loss of building performance over time, although it should be noted that this relates to change and not necessarily age (Butt et al., 2015). This change can result in the beginning of the ‘end of service life’ phase of a building (Thomsen and van der Flier, 2011). In turn this can be related to issues associated with the building performance gap. Historically, obsolescence in the built environment referred largely to economic factors related to depreciation. However, more recently this has expanded to include a range of internal and external factors including technical, functional, social, locational issues and, within the context of the sustainability debate, environmental factors which can either be physical or behavioural in nature (Baum, 1991; Ross et al., 2016; Rodi et al., 2015; Thomsen and van der Flier, 2011). Butt et al. (2015) argue that climate change should be added to this list as a new element and additional driver of obsolescence with both direct (overheating, flooding, materials degradation) and indirect (regulation linked to climate change mitigation) consequences which could serve to accelerate obsolescence (see Figure 5). Arguably, a lack of focus on long-term building performance may result in premature building obsolescence.

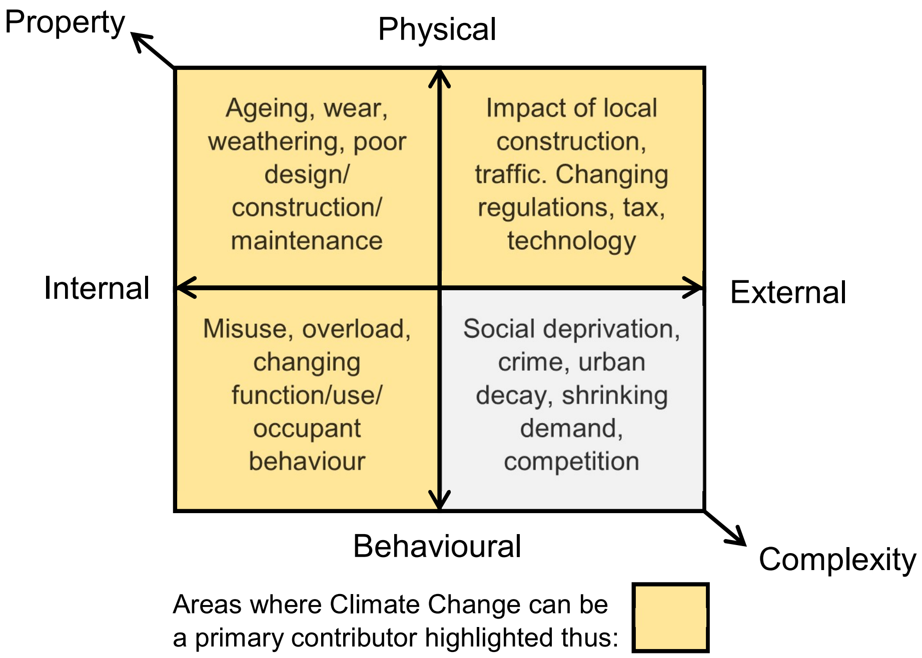


Figure 5. Conceptual Model of Obsolescence.
Adapted from Thomsen and van der Flier (2011)

Many of these factors are interrelated and overlap and, as argued by Thomsen and van der Flier (2011), although many of the factors remain physical in nature they are largely a function of human action or disregard (behaviour). In turn these interrelationships create a level of complexity that can be related back to the lack of practical and conceptual understanding of obsolescence in the built environment.

The current drive for sustainable built environments is largely focused on technical/physical factors associated with near-term performance, regulated energy and climate change mitigation (Mulville and Stravoravdis, 2016a, 2016c). In turn, the regulatory framework, it can be argued, largely focuses on these aspects. However, it is widely recognised that a key aspect of obsolescence is change over time. Therefore a focus on near-term regulated energy alone could result in a number of unintended consequences particularly given the long-lived nature of the built environment (Eisenberg, 2016) and the potential impacts of climate change (Gething and Puckett, 2013; Jones, Mulville and Brookes, 2013; Mulville and Stravoravdis, 2016c, 2016b; Waddicor et al., 2016). Furthermore, the potential for behavioural factors to have wider (beyond regulated energy) performance-based impacts has been increasingly recognised (van Dronkelaar et al., 2016; Ouf, Issa and Merkel, 2016; Mulville, Callaghan and Isaac, 2016).

Both issues (physical and behavioural) have the potential to impact on long-term building performance and sustainability and thus building obsolescence, but research in this area remains limited. In addition, few studies set out what long-term building performance may look like in the context of sustainable built environments. Therefore, the review that follows focuses on physical factors related to the potential impacts of climate change on long-term performance and behavioural factors related to efficiency and user satisfaction. It is argued that, in order to deliver long-term performance, the role of occupant behaviour and the potential impacts of climate change should be considered (in addition to near-term, regulated energy efficiency). It is suggested that a user-centred approach that considers the potential impacts of climate change and an active approach to building management to ensure building performance is maintained and occupant behaviour optimised are required. Such approaches may help to deliver long-term building performance and to reduce the risk of premature building obsolescence.

3.1 Sustainability in the Built Environment

Holistic sustainability often points to social, economic and environmental factors over time. However, it has been argued (Cox, Nielsen and Rode, 2015) that sustainability in the built environment largely refers to reducing the environmental impact of buildings. This is reflected in the focus of the regulatory environment on reducing energy use and in the emergence and growing influence of environmental assessment methods (such as BREEAM, LEED and Passive House). This is not without merit and is linked to the significant proportion of greenhouse gas emissions directly or indirectly associated with the built environment (United Nations Environment Programme, 2009) which in turn have been linked to climate change (Solomon et al., 2007).

Douglas (1996) argues that buildings have been traditionally designed and described ‘synchronically’, as it exists in a single point in time. This is supported by Duffy (1990) highlighting that the focus is on ‘getting the job done’, i.e. the point of handover.

Although this point was made more than two decades ago, it can be argued that there remains a focus on the point of handover and near-term performance (Mulville and Stravoravdis, 2016a, 2016b, 2016c). In support of this, Cox, Nielsen and Rode (2015) note that most maintenance and operational strategies do not yet deal with sustainability and climate change holistically. Instead the majority remain focused on simple energy savings linked to cost reduction, reductions in environmental impacts compared to a baseline and compliance with minimum regulations (Cox, Nielsen and Rode, 2015). However, there have been a number of developments linked to sustainable buildings in recent years demonstrating return on investment beyond simple energy. Miller et al. (2009) for instance found productivity gains of 4.88% in LEED and Energy Star rated buildings, while The World Green Building Council (2014) highlight a body of research demonstrating 8-11% productivity gains from better IAQ. Furthermore, Kok and Jennen (2012) found that office buildings with a green energy label achieved a 6.5% higher rent than non-green buildings (based on 1100 rental transactions) while Eichholtz, Kok and Quigley (2012) found that, across a large data set, the rent and asset value gain from energy efficient commercial buildings was significant. Although there have been improvements, short-term thinking still dominates in industry. It has been argued that such short-term thinking risks ignoring long-term building performance (Mulville and Stravoravdis, 2016a, 2016b) and may ultimately not deliver the levels of energy efficiency now targeted. (The European Union has targeted a 27% improvement in energy efficiency by 2030.)[1]

A number of potential unintended consequences associated with measures aimed at reducing near-term regulated energy linked to occupant health and wellbeing have been highlighted as have issues related to the potential impacts of climate change on such buildings (Al-Homoud, 2005; Dengel and Swainson, 2012; Jones et al., 2015; Jones, Mulville and Brookes, 2013; Mulville and Stravoravdis, 2016b; Toledo, Cropper and Wright, 2016). Building upon this Visscher, Laubscher and Chan (2016) suggest the need for an alternative approach to building regulations in the face of such potential climate change impacts. It has also been argued that as regulated energy is increasingly tightened, the proportional importance of unregulated energy will increase (Mulville, Jones and Huebner, 2013; Mulville et al., 2016) and a focus on regulated energy alone may not deliver the levels of efficiency required. In turn unregulated

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[1] https://ec.europa.eu/energy/en/topics/energy-strategy/2030-energy-strategy

energy has been heavily linked to the impact of occupant behaviour which, in itself, is increasingly recognised as a significant contributory factor in the building performance gap (van Dronkelaar et al., 2016; Mulville, Jones and Huebner, 2013; Mulville et al., 2016).

Ackerly and Brager (2013) in a study considering the design of buildings for thermal comfort, identified three levels of climate change impact:

- First, climate change mitigation goals create a drive to reduce the carbon impact of buildings (which can be observed in the current regulatory framework);
- Second, a need for adaptation and resilience emerges so that buildings can respond to the impacts of climate change along with an ability to deliver performance in relation to more frequent Extreme Weather Events (EWEs) (as considered in Jones, Mulville and Brookes (2013), Jones et al. (2015) and others);
- Third, in the face of rising indoor temperatures, occupants need to be active in their interaction with the environment and may need to tolerate a wider range of comfort temperatures.

Accepting a wider range of comfort temperatures however presents a dilemma in building performance as it has been demonstrated that warmer temperatures reduce occupant productivity (Seppanen, Fisk and Lei, 2006). At the same time occupants must be given sufficient personal control to enable them to adapt (linking to the role of occupant behaviour as discussed in Mulville, Jones and Huebner (2013), Mulville, Callaghan and Isaac (2016), Mulville et al. (2016) and Mulville and Stravoravdis (2016a)). In this context, in addition to an initial energy-efficient design, a building needs to offer resilience and adaptive capacity and to support user interaction if long-term building performance and sustainability is to be delivered.

3.2 Resilience & Adaptation

Butt et al. (2015) note there is growing pressure to counter climate change related obsolescence risk through both mitigation and adaptation. However, the current debate around sustainability in the built environment remains largely focused on mitigation (Mulville and Stravoravdis, 2016a, 2016b). Adaptation planning has been considered in terms of infrastructure (such as water supply (Kingsborough, Borgomeo and Hall, 2016)), at an urban scale (related to heat (Kingsborough, Jenkins and Hall, 2017)), in relation to communities (Stevenson, Baborska-Narozny and Chatterton, 2016) and in relation to flood risk (Wedawatta and Ingirige, 2012). However, adaptation planning remains underdeveloped (Roders, 2015) including at the individual building scale. Butt et al. (2015) argue that in the context of climate change, there is a need for both mitigation and adaptation planning not only at a strategic level but also incorporated into the maintenance and refurbishment cycle of built assets. Arguably, the work of the author (Jones, Mulville and Brookes, 2013; Jones et al., 2015; Mulville and Stravoravdis, 2016c, 2016b) begins to address the need for such approaches by providing risk-based tools and mechanisms.

As noted by Cox, Nielsen and Rode (2015) the merging of sustainability as a mitigation option, and resilience as an adaptation option has been suggested and there is a growing focus on this area. This in turn begins to shift the debate towards long-term building performance with Cox, Nielsen and Rode (2015) reframing sustainability in the built environment by considering it within a risk framework. This builds on the work of Jones, Mulville and Brookes (2013) and Jones et al. (2015) who called for tools to support facilities managers in considering the impacts of climate change. Those studies attempted to quantify resilience using a risk framework and sought to develop adaptation strategies where a lack of resilience was identified. Cox, Nielsen and Rode (2015) citing Jones, Mulville and Brookes (2013) note that climate change is no longer just a political issue and is an emerging issue for facilities management, demonstrating that this is an area of growing importance.

Cox, Nielsen and Rode (2015) note that a building’s resilience is a measure of how well it continues to function after an event (and as noted by Mulville and Stravoravdis (2016a) arguably during the event). In relation to this Bosher (2014) in a review of previous research concerning the concept of resilience, identifies four categories:

1. Resistance, robustness and aspirations;
2. Recovery “bouncing back”;
3. Planning, preparing and protecting and;
4. Adaptive capacity.

In this context, as noted in Mulville and Stravoravdis (2016a), adaptation becomes a key aspect of sustainability and long-term building performance in the face of climate change, with more adaptive capacity delivering greater resilience.

Addis and Schouten (2004) define adaptability in buildings as a building that has “been designed with thought of how it might be easily altered to prolong its life”. As noted by Ross et al. (2016) there is value in adaptability as it is inherently difficult to predict the changes that result in the need for the given adaptation. Gosling et al. (2013) suggest the idea of ‘enablers’ for adaptability to improve resilience and reduce the risk of obsolescence, characterising them as design-based or process-based. Focusing on design-based enablers Ross et al. (2016) note accuracy of information, reserve capacity (such as for additional structural loading), separation of building systems based on rate of replacement and the creation of adjustable spaces as key factors. In process-based terms Gosling et al. (2013) identify three process-based enablers, namely flexibility in planning and in project processes, supply chain integration and supply chain flexibility (see Figure 6).

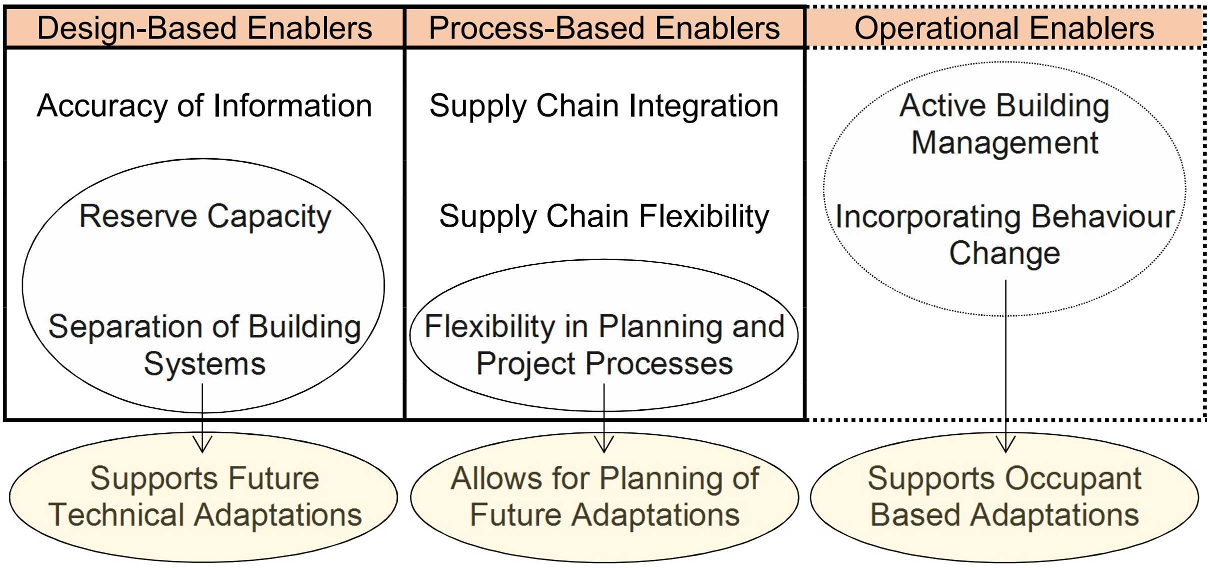

Figure 6. Enablers for Adaptation, building on Gosling et al. (2013)

The identified enablers to an extent fit well with the suggestions of this author (Jones, Mulville and Brookes, 2013; Jones et al., 2015; Mulville and Stravoravdis, 2016b). In particular, the identified enablers reflect both the need to include climate change adaptation planning at the design stage and the need for flexible project planning that could further aid future adaptation. However, within these categories there is little recognition of the role of the building user which has been highlighted as an important factor (Mulville, Callaghan and Isaac, 2016; Mulville, Jones and Huebner, 2013; Mulville et al., 2016). This author would argue that in addition to the previously identified design-based and process-based enablers, *'operational enablers'* may improve flexibility and thus improve resilience and adaptive capacity. Figure 6 which builds on the work of Gosling et al. (2013) highlights how 'operational enablers' could sit alongside design-based and process-based enablers. The operational enablers would focus on occupant behaviour change through an active approach to building management (as suggested in Mulville, Callaghan and Isaac (2016), Mulville et al. (2016) and Mulville and Stravoravdis (2016a)). Such operational enablers could maintain and/or improve energy efficiency (Mulville et al., 2016) and potentially occupant satisfaction and productivity overtime (Mulville, Callaghan and Isaac, 2016), thus having the potential to lengthen the operational life of the building and reduce the obsolescence risk (see Figure 6). As such, combining design-based, process-based and operational enablers can be linked to integrated design where operational management issues are considered during the initial design. In turn this presents an opportunity for the facilities manager to have a more integrated and overarching role including the design, construction and operational phases of the building.

As noted by Brand (1997), "All buildings are predictions. All predictions are wrong", so delivering long-term building performance will always be challenging when considering a range of unknowns. Jones, Mulville and Brookes, (2013) and Mulville and Stravoravdis (2016b, 2016c) suggest a role for regulation to embed a degree of resilience within the initial design. This is in turn supported by Roders (2015) who, while noting that greater regulation can have drawbacks such as limiting opportunities for innovation, suggests the need for governance strategies that increase anticipatory adaptations to climate change. However, Kingsborough, Borgomeo and Hall (2016) suggest that in order for adaptation planning to be successful, a flexible approach is required to allow implementation over time and adjustment as needed, and any suggested regulations should take account of this. The use of such a flexible approach reduces the risk of maladaptation while supporting long-term planning and medium-term decision making. If addressed on a risk basis over time (as suggested by Jones, Mulville and Brookes (2013) and Jones et al. (2015)) it may be possible to, by ensuring both the building and the user can adapt as and when needed, reduce the likelihood of the building becoming prematurely obsolete.

3.3 Building Performance

Building performance can have a wide range of meanings in a wide variety of contexts. In the broadest terms Douglas (1996) suggests that buildings have three key functions:

1. The enclosure of space;
2. To act as a climate barrier and/or modifier;
3. To offer protection and privacy.

From this a range of criteria emerge, Khalil, Kamaruzzaman and Baharum (2016) suggest that these can be categorised as technical (heat, insulation, fire), functional (functionality, applicability, adaptability), social (comfort, health, safety), economic (Life Cycle Costing [LCC], cash flow, market value) and environmental (energy use, materials use). Although some of these criteria may overlap, it can be argued that the current focus (related to the delivery of sustainable built environments) is on the technical aspects of environmental performance. Addressing all of these factors and criteria equally well may not be feasible at the scale of a single building. It has been argued (Voinov and Farley, 2007) that increased sustainability in one ‘system’ (or arguably increased performance in one area) may come at a cost in another.

Gosling et al. (2013) identify ‘user fitness’ and ‘technical fitness’ as factors of building performance, where either or both of these factors are suboptimal there is need for adaptation. A time factor related to this will influence the risk of a building becoming obsolete. Where buildings have resilience and adaptive capacity they will have a short time horizon. Where the time horizon is long (or potentially infinite), indicating a lack of adaptive capacity, there is a risk of premature obsolescence. Thus buildings that are primed for adaptation (as discussed in Jones, Mulville and Brookes, (2013), Jones et al. (2015) and Mulville and Stravoravdis (2016b, 2016c, 2016a)) have less risk of obsolescence. Gosling et al. (2013) go on to suggest the need for cost-benefit analysis tools that can measure adaptability. Arguably the work of this author (Jones, Mulville and Brookes, 2013; Jones et al., 2015) begins to address this need by presenting approaches that considered adaptive capacity in relation to predicted climate change impacts supported by cost-benefit analysis.

The British Council for Offices [BCO] (cited in Sanderson and Edwards (2016) defines building performance as:

> “the way that a building supports occupiers’ differing aims and needs including driving quality and value, meeting sustainability objectives and providing environments that meet the needs of users, resulting in efficient and effective workplaces” (p. 32)

The above definition can be linked to the idea of user and technical fitness noted by Gosling et al. (2013). However, in the context of the previous discussion, arguably the definition differs from the current drive for sustainability in the built environment in that it focuses on the user or occupant. As discussed in Mulville and Stravoravdis (2016a) this presents a number of challenges to built environment professionals as, although users are considered at the design stage, user behaviour is not often considered in depth beyond pre-set assumptions.

3.4 The Building Performance Gap

Perhaps unsurprisingly, given the range of contributory factors noted above, the idea of a building performance gap is widely recognised (van Dronkelaar et al., 2016; Menezes et al., 2012b; de Wilde, 2014). van Dronkelaar et al. (2016) identifies specification uncertainty, occupant behaviour and poor operating practices along with the impacts of early design decisions (and modelling uncertainty) as among the key contributors identifying a regulatory, static and dynamic performance gap. This is supported by Lewry and Hamilton (2017) who identify a compliance based gap linked to design/ modelling assumptions versus real usage and the impact of unregulated energy, and an operational (or real/actual) gap linked to poor operational practices. It is argued that the compliance based gap can be reduced with more realistic modelling and this is a developing area of research (for a review see Yan et al. (2015)). However, the operational gap is larger in magnitude but less well understood and has been linked to management structure and governance, a lack of maintenance, data limitations and the limited availability of practical and affordable solutions.

The factors identified by van Dronkelaar et al. (2016) and (Lewry and Hamilton, 2017) can be linked to the occupant, behavioural and workplace culture factors (Mulville, Jones and Huebner, 2013; Mulville, Callaghan and Isaac, 2016; Mulville et al., 2016)and climate change impacts (Jones, Mulville and Brookes, 2013; Jones et al., 2015; Mulville and Stravoravdis, 2016c, 2016b) considered within this submission. In particular the research included in this submission provides practical solutions to help minimise the operational performance gap.

Although much of the discussion around the ‘performance gap’ remains focused on energy use (and particularly regulated energy use) given the long-lived nature of the built environment (Eisenberg, 2016), climate change also has the potential to significantly impact on building performance over time (see for example Gething and Puckett, 2013; Jenkins et al., 2014b; Jones, Mulville and Brookes, 2013; Jones et al., 2015; Mulville and Stravoravdis, 2016b, 2016c). In addition, Butt et al. (2015) note the potential for such climate change impacts to contribute to building obsolescence. Furthermore, as previously noted, the role of building occupants is increasingly recognised as a key aspect of building performance and a contributory factor to the building performance gap (Karjalainen, 2016; Mulville, Callaghan and Isaac, 2016; Mulville, Jones and Huebner, 2013; Mulville et al., 2016).

As such, attempts to close the building performance gap need to consider both operational energy targets and the needs of occupants along with their interactions with the building. These considerations need to ensure that reductions in energy use do not have negative impacts on occupant health, wellbeing, satisfaction and productivity. Overtime occupant behaviour could become a key factor in climate change adaptation. For this to be achieved user centred designs with an active approach to building management are required.

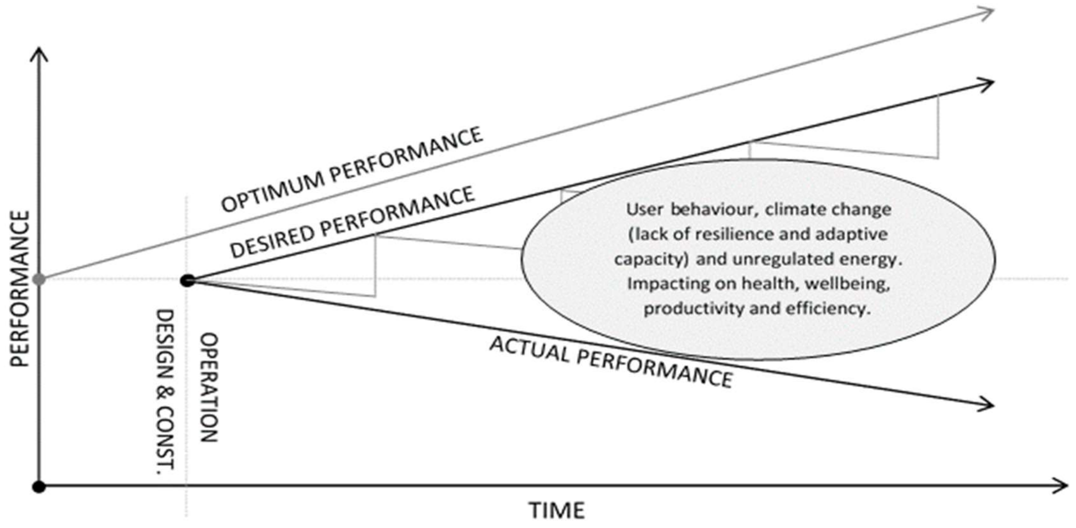

Figure 7. Long-Term Building Performance Gap

(Source: Mulville and Stravoravdis, 2016a, adapted from Jones et al., 2015)

Given the potential impacts of climate change and the role of occupant behaviour, a wider performance gap may exist and may grow over time (Camilleri, Jaques and Isaacs, 2001; Mulville and Stravoravdis, 2016a). The potential performance gap is depicted in Figure 7. Although this diagram is conceptual in nature and, as such, a starting point to the performance gap discussion, it highlights the potential impact of the unintended consequences of current practices, climate change and the role of occupant behaviour. Arguably this widening building performance gap can be linked back to the current approach to sustainability in the built environment which, although not without merit, maintains a focus on near-term regulated energy.

The work included in this submission (Mulville, Jones and Huebner, 2013; Mulville, Callaghan and Isaac, 2016; Mulville et al., 2016) argues that a greater understanding of occupant behaviour is required and that this would help to close the building performance gap. This is in turn supported by van Dronkelaar et al. (2016) who highlight the potential for a greater understanding of occupant behaviour to reduce energy use and the performance gap. Furthermore, Tetlow et al. (2014) suggest that the delivery of low carbon buildings should not be focused on technological aspects alone, with a focus on occupants' interactions with controls and therefore behaviour also of importance. Such an approach would ensure that occupants' behaviour is aligned with the intended building operation and thus help to deliver health and wellbeing, efficiency and long-term performance.

Potential climate change impacts on buildings include issues associated with overheating (Adekunle and Nikolopoulou, 2016; Dengel and Swainson, 2012) and increased flooding and materials degradation among others (Gething and Puckett, 2013), with corresponding implications for occupant health and wellbeing. Mulville and Stravoravdis (2016b, 2016c) note that the current regulatory approach to overheating risk assessment may not be fit for purpose and that dwellings designed and delivered today may need significant adaptation if building performance is to be maintained. Those papers go on to suggest a regulatory approach to dealing with such risk. Jones, Mulville and Brookes (2013) and Jones et al. (2015) propose an approach to climate change adaptation planning to embed resilience and adaptive capacity in the initial building design, which in turn can be managed throughout the operational life of the building.

In order to reduce the risk of the building performance gap growing over time (as suggested in Figure 7), it is suggested that climate change adaptation planning and occupant behaviour are areas for further exploration.

3.5 Occupant Behaviour

Appel-Meulenbroek (2016) notes that it is increasingly recognised that occupant behaviour is an area of significant importance in terms of achieving successful outcomes in buildings. In this context Dantsiou and Sunikka-Blank (2015) note that, although limited, there is a growing body of academic work focusing on socio-technical issues (for example, see discussions in Summerfield and Lowe (2012)). Within this, the importance of a greater understanding of occupant behaviour to deliver energy savings and low carbon buildings has been highlighted (van Dronkelaar et al., 2016; Mulville, Jones and Huebner, 2013; Mulville et al., 2016; Tetlow et al., 2014; Tweed, 2013), while it has also been suggested that behaviour is influential in occupant health, wellbeing and productivity (Haynes, 2007; Mulville, Callaghan and Isaac, 2016).

However, Karjalainen (2016) pointing to Mulville, Jones and Huebner (2013) as an example of the potential benefits, notes that there is a limited amount of research focused on behaviour in non-domestic buildings. This is supported by Dantsiou and Sunikka-Blank (2015) who suggest a knowledge gap exists around the behavioural processes involved, and Ouf, Issa and Merkel (2016) who suggest that the role of occupant behaviour is often overlooked. Ouf, Issa and Merkel (2016) go on to suggest that greater consideration of occupant behaviour could help to close (or at least reduce) the building performance gap. Hewitt et al. (2016) build upon this suggesting that a greater understanding of automatic and habitual behaviour can help building designers better respond to the occupants' influence on building performance.

In energy terms, much of the identified savings associated with behaviour change can be related to variations in energy use between occupants. Tetlow et al. (2015), citing Mulville, Jones and Huebner (2013) in relation to the importance of habitual behaviour, found that habit and therefore occupant behaviour accounted for 11% of the variation in workstation energy consumption. Furthermore, Martani et al. (2012) found (across two buildings) a 63% and 69% variation in electricity consumption due to occupant behaviour. Studies by Mulville et al. (2016) and Mulville, Jones and Huebner (2013), through the implementation campaigns linked to feedback, information and goal setting were able to reduce that variation and in turn deliver energy savings of close to 20% (desk level energy in this case). Given that, as previously noted, occupant behaviour may also be of importance in health, wellbeing and productivity, it can be argued that such behaviour change campaigns could be extended to also deliver improvements in those areas (Mulville, Callaghan and Isaac, 2016; Mulville and Stravoravdis, 2016a).

Karjalainen (2016) points out that in the workplace a focus on building performance to deliver productivity may offer greater returns than a focus on energy use. In support of this it is widely recognised that employee cost can significantly outweigh energy and other building-related costs (CABE and BCO, 2005; Clements-Croome, 2000). Furthermore, there is a significant and growing body of evidence linking the physical environment, including ambient environmental issues, to occupant performance (Creagh et al., 2014). Clements-Croome and Kaluarachchi (2000) note that occupant performance (and by extension productivity) is dependent on healthy buildings. In turn, lack of productivity in buildings has been linked to absenteeism, arriving late, leaving early, taking longer breaks and a general frustration with the work environment (Clements-Croome, 2015). Mulville, Callaghan and Isaac (2016) supplement this thinking by exploring the impact of the building environment on occupant health, wellbeing and by extension productivity. That paper highlighted that, in addition to ambient environmental conditions, occupant behaviour is a key factor in delivering such performance. In turn this is supported by Haynes (2007) who highlighted the importance of the behavioural environment (including interaction and distraction) in delivering productivity. Ultimately it may be a combination of the physical, environmental and behavioural factors that contributes to health, wellbeing and by extension productivity in buildings (see Figure 8).

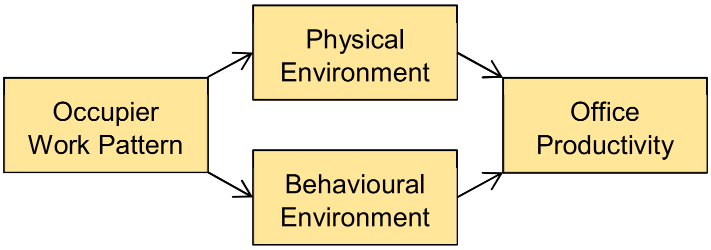

Figure 8. Theoretical Framework of Office Productivity (Adapted from Haynes, 2007)

3.6 Drivers for Behaviour Change

Tetlow et al. (2015) points out that the drivers for occupant behaviour are not being used to influence building design, with assumptions instead being made about the rational behaviour of occupants focused on attitude and conscious behaviour. However, as noted by Mulville, Jones and Huebner (2013); Mulville, Callaghan and Isaac (2016) and Mulville et al. (2016) and supported by Tetlow et al. (2015) this may be unrealistic. Arguably, these issues point toward the need for user-centred building design to aid preferred/desired behaviour supporting energy saving and productivity as suggested in Mulville and Stravoravdis (2016a). Building upon this, it has been suggested (Hewitt et al., 2016) that designers need to rethink building design and user technologies as users are unlikely to change habits. This can be linked back to the potential benefits of behaviour change strategies such as those used in Mulville, Jones and Huebner (2013) and Mulville et al. (2016) and a need to consider how they could be embedded in building design and operation. This could perhaps be supported by building intelligence.

Ackerly and Brager (2013) note the potential role of social and psychological factors in influencing occupant behaviours, while Hewitt et al. (2016) go on to suggest that values influence beliefs, which should influence personal norms and in turn guide behaviour. However, Mulville, Jones and Huebner (2013) and Mulville et al. (2016) note that in the non-domestic setting energy savings through behaviour change can be realised without any significant changes to environmental attitude. This is a key difference to the domestic setting and it may be that in the non-domestic setting workplace culture and the social norm this creates takes precedence over underlying environmental attitudes. The occupants attitude towards the given workplace culture may therefore be of importance.

Azar and Al Ansari (2017) suggest that, in terms of the impact of pro-environmental messages, there may be a degree of transfer from the home to the workplace. However, the same study notes that the degree of transfer from the workplace to the home may be less successful. As noted by Dantsiou and Sunikka-Blank (2015) the more immediate presence of a financial incentive in the domestic setting and a greater level of personal control may be influential in this difference. In non-domestic settings, as noted by Mulville et al. (2016), the alignment of the wider workplace culture with the preferred behaviour may be important and can be linked to the active approach to building management suggested (Haynes (2007), Mulville, Callaghan and Isaac (2016), Mulville et al. (2016) and Mulville and Stravoravdis (2016a). Similarly, Azar and Al Ansari (2017) suggest that a ‘human in the loop’ approach may help support building performance. This active approach may include occupant behaviour change campaigns with feedback, information and goal-setting (human in the loop) (as suggested by Mulville et al. (2016) and Mulville, Jones and Huebner (2013)). In turn, this could be supported by an aligned workplace culture (Mulville et al., 2016) to deliver energy savings and improve health, wellbeing and productivity.

3.7 Technological vs. Behavioural Interventions

There is an ongoing discussion around the merits of technological solutions versus an occupant behaviour focus (Bull et al., 2014). Karjalainen (2016) for instance, suggests a role for greater automation coupled with more realistic views of occupants' behaviour. Such an approach would need a greater understanding of occupant behaviour in terms of interaction with the building and building controls (Mulville, Jones and Huebner, 2013; Mulville, Callaghan and Isaac, 2016; Mulville et al., 2016; Tetlow et al., 2014), which in turn can be linked to the importance of perceived personal control in user satisfaction (Danielsson and Bodin, 2009).

Bull (2015) notes that Information and Communication Technologies [ICT] can both help and hinder energy saving behaviour suggesting that monitoring and control systems can drive up consumption. Furthermore, Tetlow et al. (2014) suggest that more automation could lead to a decrease in energy saving behaviour, perhaps by removing a degree of personal control. Ouf, Issa and Merkel (2016) in a study exploring energy use across a range of school buildings, found that newer schools used a greater amount of electricity than predicted (in comparison with older schools). The increased electricity usage was linked to greater automation in those, newer, buildings. However, it is suggested that simpler behavioural controls may offer benefits and there may still be a role for ICT within this (Bull, 2015). In this context Dantsiou and Sunikka-Blank (2015) note that technological infrastructure can have a significant impact on energy use practices. Dantsiou and Sunikka-Blank (2015) go on to explain that where systems and interfaces are difficult to understand, users are more likely to be passive in the system interaction. This in turn demonstrates why, in some circumstances, greater automation can have drawbacks. The interface between controls and the user is key and a number of issues must be considered when thinking about this interface, including that:

- Controls are designed by engineers but used by non-experts;
- Complex control systems will be less well understood (van Dronkelaar et al., 2016) and may reduce reliability;
- A 'passive' (Dantsiou and Sunikka-Blank, 2015) approach from occupants can result in sub-optimal usage;
- These issues contribute to the building performance gap;

- Localised controls coupled with wider automation and simpler interfaces (Bull, 2015; O'Neill, 2010) may offer benefits (maintaining personal control).

Bull et al. (2014) suggest that occupants are still seen as a hurdle to be overcome as opposed to a resource to be utilised. In this context perhaps an active approach to building management utilising automation to encourage active user behaviour (Wei et al., 2016) and feedback may offer benefits. Bull et al. (2014) and Bull (2015) suggest that the use of more interactive information (in place of simple feedback) may offer benefits. Building upon this, Ackerly and Brager (2013) conducted a study exploring the use of active window opening signalling to reduce energy use and improve comfort. They found that the most successful approach occurred when the signals were clearly visible and the supporting reasoning behind the signals easy to understand and linked to an explicit internal policy (perhaps linked to workplace culture noted by Mulville et al. (2016)). Those occupants who found value in the signals were more likely to be satisfied with personal control, pointing to potential benefits in such automation. Overall the study suggests that occupants need to be active participants in their work environment with opportunities to adapt their environment and access to personal control. Potentially similar approaches may help to reduce the detached, disconnected and disempowered feelings (Bull et al., 2014) building users may have in relation to building management.

This more interactive approach could be linked to the active approach to workplace management suggested by the author (Mulville, Callaghan and Isaac, 2016; Mulville et al., 2016; Mulville and Stravoravdis, 2016a). In such a scenario, supported by automation, spaces could be actively monitored and feedback gathered which could inform occupant behaviour change campaigns to reduce energy use and improve health, wellbeing, satisfaction and productivity. As part of any behaviour change campaign, continuous reinforcement may be required (Darby et al., 2016) to ensure the behaviour becomes habitual and again automation may offer benefits in this context. Where greater levels of automation are to be used, this continuous reinforcement may also be necessary to ensure occupants can see a compelling reason to engage with the feedback and information available (Ackerly and Brager, 2013). Although challenges remain in encouraging anticipation over reaction in relation to user interaction with controls, there is potential for a degree of automation to offer benefits.

As suggested by Ackerly and Brager (2013), it may be that coordination between engineering and occupant based solutions is needed. This can be linked back to the idea of intelligent buildings and how such intelligence could be utilised to support and not hinder preferred/desired behaviour and building performance. Within this Wei et al. (2016) suggest that encouraging the active behaviour (as opposed to passive) of occupants through building intelligence may be of benefit. Again this can be linked to the idea of an active approach to building management (Mulville, Callaghan and Isaac, 2016; Mulville et al., 2016; Mulville and Stravoravdis, 2016a). In turn, such approaches, using greater building automation but coupling this with greater user interaction and information provision, could perhaps be used to deliver preferred behaviours without reducing perceived personal control.

3.8 Climate Change Impacts

The University College London [UCL] Lancet Commission on managing the health impacts of climate change called climate change “the biggest global health threat of the 21st century” (Costello et al., 2009). Furthermore, the 2015 Lancet Commission on Health and Climate Change (Watts et al., 2015) highlighted that, as noted by the World Health Organization [WHO], there could be an additional 250,000 deaths per year between 2030 and 2050 from the impacts of climate change. Climate change is predicted to have a number of direct impacts on buildings including overheating, materials degradation and increased flood risk (Adekunle and Nikolopoulou, 2016; Dengel and Swainson, 2012; Gething and Puckett, 2013) with corresponding impacts on occupant satisfaction and building performance.

Although cold-related deaths may reduce due to the impacts of climate change, these will be outweighed by heat-related mortality which is expected to be a key contributor to overall excess mortality rates (Watts et al., 2015). This is supported by Waddicor et al. (2016) who highlight that for southern Europe any reduction in heating load in buildings is likely to be outweighed by increases to cooling demand. However, the same study notes that in more northern locations heat savings may outweigh cooling increases. There is also potential for human acclimatisation to rising temperatures

(Zaidi and Pelling, 2013) and wider urban-scale adaptation may reduce the risk too (Stone et al., 2014) (through reducing the Urban Heat Island [UHI] effect). As a result, actual overheating may be lower than predicted. However, given the seriousness of the issues noted above and the evidence included in this submission, the potential overheating risk remains (see for instance Jones, Mulville and Brookes (2013) and Mulville and Stravoravdis (2016b)). This may be particularly problematic in buildings that are unable to adapt, where adaptations prove costly (as suggested by Hills (2012)) or where occupants are vulnerable. In turn, this has significant implications for the built environment and long-term building performance.

Toledo, Cropper and Wright (2016) note that government strategies to reduce heating demand have led to a number of unintended consequences including comfort, ventilation, air quality and overheating issues. This is particularly prevalent in ‘new’ and ‘energy efficient’ buildings. While, as noted above, occupants may be able to acclimatise to temperature change, they are not able to adapt to poor air quality (Clements-Croome, 2015). Eisenberg (2016) highlights that regulatory systems are reactive and therefore backward-looking in nature and that problems and hazards previously viewed as harmless, potentially such as the climate change related overheating risk, are often resisted long after they are recognised. Eisenberg (2016) goes on to highlight that with the long-lived nature of buildings they will need to perform in conditions that are different than those that exist today. As a result there is a need to address this at a regulatory and policy level.

3.9 Managing Climate Change Impacts

Toledo, Cropper and Wright (2016) found that climate change risks (specifically overheating risks) were associated with both design decisions and occupant behaviour. From the design perspective, climate change impacts need to be considered at the design stage to ensure that buildings are ‘fit for purpose’ at the end of their lifespan (Din and Brotas, 2016). In a culture of regulatory minimums representing standard practice, and in the context of the backward-looking nature of such regulations (Eisenberg, 2016), this is challenging. A limited amount of research has considered the role of regulations in enabling buildings to deal with the impacts of climate change and to deliver long-term buildings performance. As noted by Meacham (2016), historically, issues of sustainability and climate change resiliency have been outside building regulations (although sustainability measures focused on mitigation are now more common). Furthermore, such issues are still seen as less important than minimum health and safety standards, and governance of potential climate impacts remains fragmented (Meacham, 2016).

Several studies have explored the potential impacts of climate change on domestic buildings (for example see Dengel and Swainson (2012) and McLeod, Hopfe and Kwan (2013)). These, generally, consider the potential impact on a particular building type (i.e. timber frame, steel frame, refurbished building) and look forward at the potential impacts and adaptations. However, Visscher, Laubscher and Chan (2016) note that regulatory based solutions are needed if the potential climate change impacts identified are to be addressed and, as noted above, research in this area is limited. The papers included in this submission (Mulville and Stravoravdis, 2016b, 2016c) attempt to address that gap by providing risk-based regulations incorporating adaptation planning for dwellings. Significantly less research has been carried out into the impacts on non-domestic buildings, potentially due to the large variation in building types presenting a challenge in generalising the findings to a wider audience. The work included in this submission (Jones, Mulville and Brookes, 2013; Jones et al., 2015) also aims to address that gap by exploring how the potential impacts of climate change can be managed throughout the buildings lifetime, with a focus on operational adaptation planning.

Jenkins et al. (2013), in a study focused on overheating risk, presents an approach based on frequency curves which accounts for likelihood and risk and could be expanded on to consider potential user and technical adaptations (Jenkins et al., 2014a). The main advantage of this proposal was the significant reduction in amount of building simulation required compared with other studies in this area. However, for that approach significant knowledge of the buildings’ characteristics is still required. Mulville and Stravoravdis (2016c) provided a similar approach to the proposal set out by Jenkins et al. (2013) but expanded on this by basing the assessment on set types, significantly reducing the specialist knowledge and simulation input required and thus presenting an industry-focused solution. It is suggested that this approach could be embedded in the regulatory framework (Mulville and Stravoravdis, 2016b).

Arguably, adaptation over time offers advantages in that it may avoid the risk of planning for future climates (which is inherently unpredictable) having a negative impact on near-term building performance. In that context Jones, Mulville and Brookes (2013) and Jones et al. (2015) suggested mechanisms concerned at the design stage to assess levels of risk associated with climate change impacts. Where risk levels are found to be a cause for concern, works would be carried out to enable or prime the building for future adaptations without actually implementing full adaptations until needed (for example, the provision of fixings for additional shading, additional riser space to cooling or modular heating/cooling systems). Those papers present a hybrid backcasting/forecasting methodology embedded in the design process but focused on long-term built asset management planning aimed at improving resilience and adaptive capacity.

As noted previously, occupant behaviour can have a significant impact on building performance. In the context of potential climate change impacts, behaviour change may offer managerial-based adaptations beyond the more commonly considered technical and regulatory solutions (as noted in Jones, Mulville and Brook, (2013) and Jones et al. (2015)). In turn this would provide greater adaptive capacity to the potential impacts of climate change based on user behaviour.

3.10 Delivering Long-Term Building Performance

As noted there is a widely recognised building performance gap which to date has focused largely, although not exclusively, on near-term regulated energy. However, occupant behaviour both in relation to regulated and unregulated energy and wider building performance aspects (health, wellbeing, satisfaction and productivity) can be a significant contributory factor to the performance gap (van Dronkelaar et al., 2016). Furthermore, the potential impacts of climate change could impact upon this building performance gap over time (Mulville and Stravoravdis, 2016a). Ultimately, as depicted in Figure 7, where there is a lack of resilience and adaptive capacity and a lack of understanding around the role of occupant behaviour, such issues could result in premature building obsolescence.

The importance of user behaviour in delivering building performance has been increasingly recognised. However, there is a need for greater research in this area with a number of questions remaining (Dantsiou and Sunikka-Blank, 2015). There is a debate regarding the role of greater building automation versus behaviourally focused interventions in closing the building performance gap (Ackerly and Brager, 2013; Karjalainen, 2016; Tetlow et al., 2014). Karjalainen (2016) argues that greater levels of automation may reduce energy usage, however as noted by Ouf, Issa and Merkel (2016) this may not always be the case. Greater automation can also serve to reduce personal control, which in turn has been linked to lower levels of occupant satisfaction and productivity (Danielsson and Bodin, 2009; Leaman and Bordass, 1999). Ultimately, a combination of both may be required with a greater understanding of users' interactions with the building to support the preferred/desired user behaviour (as suggested in Mulville and Stravoravdis (2016a)). In addition, an active approach to building management utilising monitoring, feedback, information and goal-setting may also have the potential to help close this gap (as discussed in Mulville, Callaghan and Isaac (2016), Mulville et al. (2016) and Mulville and Stravoravdis (2016a)). Within this, any user behaviour interventions need careful consideration, particularly in relation to the role of the wider building environment and attitude, habit and intention, in order to ensure they are successful. As noted in Mulville et al. (2016) in non-domestic situations, workplace norms may be an important facilitating factor taking precedence over the underlying environmental attitude of occupants. While more widely the need for continuous reinforcement (Darby et al., 2016) linked to the need for active management remains.

Over time, the potential impact of climate change may serve to increase the building performance gap (as suggested in Figure 7), especially where a focus on near-term regulated energy reduction remains. As demonstrated by Mulville and Stravoravdis (2016b, 2016c) the current regulatory framework may not be 'fit for purpose' in its approach to dealing with the potential impacts of climate change. To minimise the risk of climate change increasing the performance gap over time, buildings need to have resilience and adaptive capacity (which mirrors the view of sustainability suggested by Cox, Nielsen and Rode (2015)). At the design stage this could include a risk-based approach to the potential impacts of climate change as part of the design process, possibly embedded into the regulatory framework and informed by built asset management plans (as considered in Jones, Mulville and Brookes (2013), Jones et al. (2015) and Mulville and Stravoravdis (2016b)). In turn this would provide the building with an ability to adapt over time.

A greater understanding of occupants and an active approach to building management (as suggested in Mulville, Callaghan and Isaac (2016), Mulville et al. (2016) and Mulville and Stravoravdis (2016a)) could also help reduce the potential impacts of climate change. A greater understanding of occupants could ensure users are enabled to behave in an optimum manner, providing greater adaptive capacity for the building. Furthermore, an active approach to building management could include behaviour change campaigns (similar to those utilised in Mulville, Jones and Huebner (2013) and Mulville et al. (2016)) to improve wellbeing and productivity and to allow for user based adaptations to the impacts of climate change. These measures, as ‘operational enablers’, begin to address the need for managerial/behavioural as well as technical solutions to climate change adaptation (as suggested in Jones et al. (2015)).

Ultimately, as suggested in Figure 9, the combination of such approaches may help to deliver long-term building performance, reducing the performance gap and the risk of premature obsolescence. This can be achieved by reforming the regulatory framework and approaches to building/ operational management to give balance between the efficient use of resources and human needs for safety, health, comfort and wellbeing in productive and supportive environments.

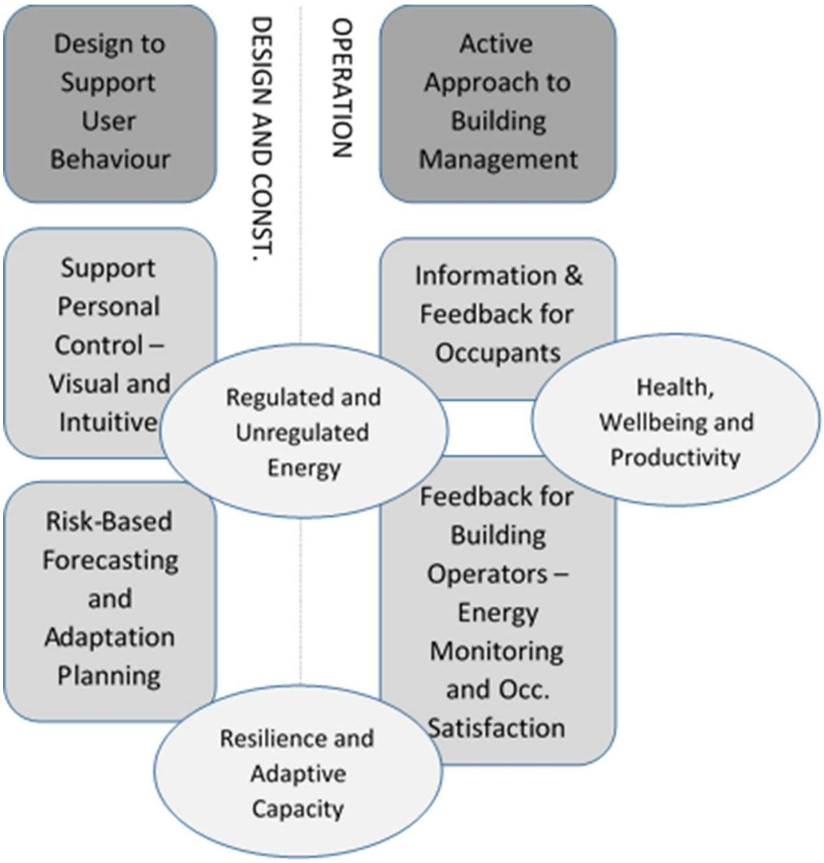

Figure 9. Model of Building Performance

(Source: Mulville and Stravoravdis, 2016a)

4 DISCUSSION

As previously noted, there is a widely recognised building performance gap that could contribute to building obsolescence. To date most research relating to this gap has focused on near-term regulated energy usage. Although occupant behaviour is increasingly recognised as an influential factor in building performance, research in this area remains limited (although growing). Likewise, although the potential impacts of climate change have been explored, mechanisms to deal with such impacts using the regulatory framework and through operational management remain limited. The research included in this submission set out to explore the factors that are likely to influence long-term building performance. This focused on both occupant behaviour and the potential impact of climate change, and how such issues could contribute to the building performance gap. It is argued that if these issues are not considered, with a lack of resilience and adaptive capacity, there is a risk of the building performance gap increasing over time, ultimately resulting in premature building obsolescence. The research has produced tools and techniques in relation to harnessing occupant behaviour to improve building performance, and regulatory mechanisms and approaches to facilities/ built asset management in relation to improving resilience to the potential impacts of climate change. In addition the research has produced a model considering and explaining the impact of these factors on long-term building performance (see Figures 7 and 9).

The research included in this submission utilised a mixed methods approach based on case studies, participatory action research and scenario-based futures studies. This allowed for the role of occupant behaviour (Mulville, Jones and Huebner, 2013; Mulville, Callaghan and Isaac, 2016; Mulville et al., 2016) and the role of regulations and approach of the design and facilities management team to the potential impacts of climate change (Jones, Mulville and Brookes, 2013; Jones et al., 2015; Mulville and Stravoravdis, 2016b, 2016c) to be explored. The futures studies approaches considered contributed to those case studies by generating predicted (forecast) or desired (backcast) future scenarios to be considered. In turn this allowed for risk-based approaches to dealing with the associated predictions to be developed based on the resultant findings.

The research conducted and presented in the eight papers included in this submission has been able to demonstrate that occupant behaviour can have a significant impact on both building performance and occupant satisfaction. Furthermore, it is demonstrated that behaviour change strategies (utilising feedback, information and goal-setting) have the potential to alter occupant behaviour, reduce energy use and improve occupant satisfaction, thus adding resilience and adaptive capacity. It is argued that such tools and techniques could be extended to also improve occupant health and wellbeing, thus further impacting on building performance. It is also demonstrated that the current regulatory approach and operational management approach to considering the potential impacts of climate change may not be *‘fit for purpose’*. New, more robust, regulatory and operational management approaches are presented that may help to ensure that the buildings designed and constructed today, do not become the *‘hard to treat’* buildings of the future. This could be achieved through the implementation of risk-based adaptation planning (and enabling works where necessary) at the design stage and throughout the operational life of the building, supported by the regulatory framework. It is argued that over time the role of occupant behaviour may become increasingly influential in these areas and if utilised could add to the overall adaptive capacity of buildings.

Overall, the research argues that a greater understanding of occupants to enable/support desired behaviour, risk-based assessments of the potential impacts of climate change supported by the regulatory framework, and an active approach to building management are required in order to deliver long-term building performance (see Figure 9).

4.1 Research and Practical Implications

The research included in this submission builds upon the growing body of research concerning the role of occupant behaviour (for example see Haynes (2007), Karjalainen (2016) and Tetlow et al. (2015)) and the potential impacts of climate change and how to address such impacts (for example see Jenkins et al. (2014a), McLeod, Hopfe and Kwan (2013) and Sanders and Phillipson (2010)). Within these areas the work submitted considers research gaps concerning the role of occupant behaviour in relation to building performance (as noted by Karjalainen (2016) and others), regulating for the potential impacts of climate change (Eisenberg, 2016; Meacham, 2016; Visscher, Laubscher and Chan, 2016) and integrating climate change adaptation strategies into long-term built asset management planning (Desai and Jones, 2010).

The research included in this submission has implications for the regulatory framework in the built environment in that it has highlighted a number of deficiencies that need to be addressed in order to deliver long-term building performance. These issues are associated with the role of occupant behaviour and the users' building interaction in relation to building performance and the potential impacts of climate change. For building designers the role of occupant behaviour, particularly when this is extended beyond regulated energy to health, wellbeing and productivity, presents a challenge as much of this is outside normal considerations. This also has implications for building owners and operators in encouraging preferred/desired occupant behaviour to deliver building performance (and resilience to climate change). The potential impacts of climate change present a challenge to building designers (and regulators) in accounting for often intangible and difficult-to-predict measures. However, as the work highlighted, if these issues are not addressed it could result in premature building obsolescence. As before, the impacts of climate change also have implications for building owners and managers in maintaining resilience and adaptive capacity over time and in optimising health, wellbeing and productivity.

The work is of benefit to building designers, owners, occupants and operators in that it provides mechanisms to improve energy efficiency and user satisfaction through behaviour change techniques that could also be used to improve occupant health and wellbeing. Within this the research demonstrates that there is a role for workplace culture and active management in delivering building performance. The behaviour change tools and techniques presented could, arguably, also be used to provide occupant-based adaptive capacity to the potential impacts of climate change. The work is also of benefit to building designers, facilities managers and operators in that it provides mechanisms to ensure the unpredictable potential impacts of climate change can be accounted for at the design stage and managed throughout the operational life of the building. More widely, the research has the potential to offer societal benefits by reducing the environmental impact of the built environment while improving productivity and overall occupant wellbeing.

4.2 Impacts and Contributions

The impact and contribution of the research included in this submission is discussed in this section. Further details including citations and impact-related statistics are provided in Appendix A of the submission alongside the submitted papers themselves. All of the papers included in this submission have been published in peer-reviewed publications. In turn these publications have resulted in a number of citations, invited presentations and have generated discussion and interest in both research and industry circles. The nature of the work has also meant that it has had direct impacts on a number of buildings and businesses. This includes additional adaptive capacity for the case study building used in Papers Two and duffy four s,s', a greater understanding of occupant satisfaction for the business in Paper Five and a greater understanding of the role of occupant behaviour in building performance for the business in Papers One and Seven.

In socio-economic terms the body of research included in this submission has impact in that it demonstrates how greater resource efficiencies and energy savings can be achieved at relatively low costs (Papers One and Seven), thus reducing the environmental impact of the built environment. The approaches detailed in the research can be used to deliver greater levels of health, wellbeing and productivity thus offering societal benefits (health and wellbeing) and wider economic benefits (productivity). This is achieved through a focus on occupant behaviour (Papers One, Five and Seven) and in delivering buildings with greater levels of resilience and adaptive capacity (Papers Two, Three, Four and Six). User centred buildings that support energy conscious behaviour can offer benefits beyond the workplace. Furthermore, reducing the risk of premature building obsolescence gives greater justification to the magnitude of the human resource and embodied energy associated with the design and construction process, thus increasing overall productivity and sustainability.

Paper One (Mulville, Jones and Huebner, 2013), was included in a special edition of the journal *Architectural Engineering and Design Management* that considered 'the impact of the building occupant on energy consumption'. The paper was one of the first of its type applied in a non-domestic setting and since its initial publication it has received a wide range of citations (see Appendix A for details). Authors citing the work have used the paper to highlight the importance of occupant behaviour in energy use, the degree of energy wastage outside office hours and the potential for associated savings when equipment is not in use. Paper Seven (Mulville et al., 2016), which is related to Paper One and built upon its findings, has received significant attention since its publication with a high 'altmetric' score (see impacts statistics in Appendix A) placing it in the top 25% of all research outputs scored. These papers made an original contribution to knowledge by demonstrating how occupant behaviour change tools and techniques can and should be used to improve building performance. The role of workplace culture is identified as an important facilitating condition which may be more important than underlying environmental attitude. This is a key difference from behaviour in the domestic sector (research around occupant behaviour in the domestic sector is more developed than the non-domestic sector).

Papers Two and Three (Jones, Mulville and Brookes, 2013; Jones et al., 2015) had immediate impact upon the design and delivery of a new £75m educational building with a number of alterations adopted during the design stage to improve long-term adaptive capacity. Paper Three was based on an earlier conference paper (not included in this submission – see Appendix C). That paper won a 'best paper award' at the International Council for Building [CIB] Facilities Management Conference in 2014 and was thus invited for publication in *Facilities* (Paper Three). These papers made a contribution to knowledge by demonstrating how the potential impacts of climate change can be considered during the design stage and managed during the operation phase of the building's life. The papers present a new hybrid backcasting/forecasting approach to built asset management planning.

Paper Four (Mulville and Stravoravdis, 2016b) was published in a special edition of *Building Research and Information* and has been widely shared and disseminated. The paper received the 'Merit Award' from the Chartered Institute of Building's [CIOB] International Innovation and Research Awards 2016. The paper has also received significant attention with a high 'altmetric' score placing it in the top 5% of all research outputs scored A working group meeting on the subject was held at the CIB World Building Congress [WBC] (This author followed up the work with a paper presented at the WBC (Paper Six (Mulville and Stravoravdis, 2016b)). The presentation associated with Paper Six (Mulville and Stravoravdis, 2016c) was well received, with further engagement from industry representatives. The research contained in these two papers formed the basis of evidence submitted by the Chartered Institute of Architectural Technologists [CIAT] to the recent public consultation on the proposed changed to the Standard Assessment Procedure [SAP]. These papers made an original contribution to knowledge by demonstrating that the current approach to overheating risk assessments in the built environment may not be fit for purpose. The papers note that this could result in the buildings we design and deliver today becoming the ‘hard to treat’ buildings of the future. The papers suggest an alternative risk-based adaptation planning approach (linking to Papers Two and Three) to overheating risk assessments embedded in the regulatory framework.

Paper Five (Mulville, Callaghan and Isaac, 2016) was published in a special edition of the *Journal of Corporate Real Estate* with the author securing a competitive funding grant to enable the research to take place. The author has provided the business which participated with a report on the project and is currently discussing follow-up interventions in the building. In the short term, the research has impacted upon the business as they have focused their workplace adjustments on its findings. This paper made an original contribution to knowledge by demonstrating that both ambient environmental conditions and occupant behaviour are important in terms of user satisfaction. The paper suggests the need for an active approach to building management incorporating monitoring and feedback in relation to occupant behaviour and ambient environmental conditions in order to maximise building performance. Linking with the other research by the author, it is suggested that occupant behaviour change tools and techniques can be used in order to deliver greater levels of user satisfaction.

Paper Eight (Mulville and Stravoravdis, 2016a) which aimed to tie together many of the ideas discussed in the other papers included in this research formed the basis for a presentation at the SEEDS International Conference (September 2016). The reviewers were generally positive and supportive about the paper noting that it was “a very interesting paper, well written in the main and covering an interesting topic in a thought provoking way" and that the "paper covers an important topic and the idea behind Figure 2 is interesting and has far-reaching consequences". The same 'Figure 2' is included in this submission as Figure 9. The paper provides an explanatory model considering how occupant behaviour and climate change may impact upon long-term building performance (see Figure 7). The research goes on to suggest what measures may be put in place to begin to address these issues (see Figure 9). These suggestions include:

- A user centered design supporting personal control;
- Risk based climate change adaptation planning embedded in the regulatory framework and as part of built asset management plans and;
- An active approach to building management incorporating a continuous loop of information, feedback and monitoring coupled with occupant behaviour change strategies.

4.3 Limitations

The body of work included in this submission should be considered in the context of a number of limitations. Each paper presented includes its own discussion of specific limitations. For completeness, limitations related to the overall body of work submitted are considered below.

As noted, much of the research included in this submission utilised a case-study approach which allowed, in most cases, quantitative data to reinforce qualitative data. In most examples, single longitudinal case studies, as opposed to cross-sectional cases, were utilised and this may raise questions of reliability. However, the case studies used to a greater or lesser extent can be considered to be 'typical' and therefore representative of the wider stock, thus allowing for generalisations to be made. Furthermore, the multiple case studies used across the body of work in this submission include a degree of overlap and thus add to overall reliability. However, additional cross-sectional case studies may add further reliability.

The body of research set out to explore long-term building performance and the risk of obsolescence. The work focused particularly on two key contributory factors (the potential impacts of climate change and the role of occupants’ behaviour). It should be recognised however, that building performance and obsolescence are complex and there are contributory elements that do not easily fit under those key factors. This includes the role of the wider economic environment and the drive, in a commercially focused industry, to deliver buildings that maximise short-term returns on investment. This is particularly challenging where ‘sustainability’ measures, in traditional terms at least, often offer intangible benefits that do not easily fit valuation methods. Although research into these measures has been developing in recent years, they are beyond the scope of the research included in this submission. Likewise, social and locational factors that may contribute to obsolescence are beyond the scope of this research.

5 CONCLUSIONS AND FUTURE WORK

The focus of the research included in this submission was on delivering long-term building performance and reducing the risk of premature building obsolescence by addressing issues surrounding occupant behaviour and the potential impacts of climate change. Within this the research set out to address a number of objectives, namely:

1. To investigate, through a critical review of the literature, the potential impacts of climate change on, and the role of occupant behaviour in, building performance (across all papers);
2. To develop tools and techniques that can harness occupant behaviour in order to improve building performance (Papers One, Five, Seven and Eight);
3. To develop regulatory mechanisms and approaches to facilities/built asset management in relation to the potential impacts of climate change that can be used to improve resilience and increase adaptive capacity in buildings (Papers Two, Three, Four, Six and Eight) and;
4. To develop a model that explains the role of occupant behaviour and the potential impacts of climate change on long-term building performance (Paper Eight).

The following paragraphs set out how these objectives have been met. Objective one has been met by combining the literature review and exposition included in this submission and the literature reviews from the submitted papers. This has demonstrated that climate change has the potential to have a significant impact on long-term building performance (Adekunle and Nikolopoulou, 2016; Dengel and Swainson, 2012; Gething and Puckett, 2013). In particular, overheating risk is highlighted as a challenge where buildings are being optimised for heat retention to reduce near-term energy usage (Mulville and Stravoravdis, 2016c). Although there is a developing body of research around the climate change impacts on buildings, research gaps relating to regulating for such impacts (Eisenberg, 2016) and climate change adaptation planning are identified (Desai and Jones, 2010). Furthermore, it is noted that the role of occupant behaviour in building performance is increasingly recognised, with users interactions with controls, a lack of perceived behavioural control and a passive/ reactionary approach to building interaction highlighted (Dantsiou and Sunikka-Blank, 2015; van Dronkelaar et al., 2016; Karjalainen, 2016). However a research gap, particularly in the non-domestic sector (Dantsiou and Sunikka-Blank, 2015; Karjalainen, 2016; Tetlow et al., 2014), is identified.

Objective two is met by Papers One, Five, Seven and Eight. These papers highlight that a significant variation in energy usage can exist between occupants in similar buildings undertaking similar tasks and note how this can contribute to the performance gap and building obsolescence. It is demonstrated that up to 23% of energy use occurs outside of occupied or productive hours, reducing efficiency and productivity. Furthermore, it is demonstrated that occupant behaviour can be a significant factor in perceived environmental comfort and wellbeing, with statistically significant differences found between occupants within individual buildings. In turn this has an impact on productivity. The research provides occupant behaviour change tools and techniques that can be used to improve building performance. These are based on the use of feedback, education and goal setting and it is demonstrated that such an approach can result in energy savings of up to 20%. It is suggested that such techniques can be extended to benefit health, wellbeing and productivity. Furthermore, it is demonstrated that such behaviour change can be achieved without changes to underlying environmental attitude and perceived social norms, instead it is argued that workplace culture as a ‘facilitating condition’ is an important factor in such behaviour change. To take account of this finding an altered version of the theory of planned behaviour is presented. Overall, the papers argue that to achieve such behaviour change and ensure it has longevity, user centred design (for instance intuitive and accessible controls to support perceived personal control) and an active approach to building management is required, with active management incorporating occupant behaviour change campaigns.

Objective three is met by Papers Two, Three, Four, Six and Eight. These papers demonstrate the potential impact of climate change on long-term building performance and how this could contribute to premature building obsolescence. They highlight that the current regulatory approach to climate change overheating risk assessment is not ‘fit for purpose’ with the use of historic climatic data and unrealistic user adaptations. Within this there remains a focus on near-term performance which optimises the building for heat retention, this could, over time, result in a switch from winter to summer time fuel poverty. The research also demonstrated that, beyond overheating risk assessments which are not fit for purpose, climate change risk assessments at the design stage are largely absent. The research provides a regulatory based overheating risk assessment that addresses the shortcomings previously noted. This utilises the depth of analysis possible using dynamic building simulation while providing an approach that is readily accessible by industry. The research also provides a hybrid forecasting/ backcasting approach to long-term facilities and asset management planning. Initiated at the design stage this can be used to deliver greater resilience and adaptive capacity in the face of the predicted impacts of climate change. It is argued that the facilities manager is key in delivering successful climate change adaptation planning and in ensuring whole of life thinking is applied. The research calls for a user centred approach to design to ensure user based adaptive capacity can be delivered (utilising the behaviour change techniques previously noted). In addition, an active approach to building management incorporating continuous monitoring and feedback (along with occupant behaviour change) to ensure that required adaptations can be identified and implemented before building performance is reduced, is recommended.

Objective four is met by Paper Eight and supported by the preceding research in Papers One to Seven. It is argued that the potential impacts of climate change and the role of occupant behaviour could lead to premature building obsolescence. The current focus on near-term regulated energy is highlighted as a key contributory factor in this and it is argued that consideration of long-term performance and whole of life thinking is required. The research argues that a user centred approach to building design to support preferred/ desired user behaviour coupled with a risk based climate change adaption planning (implemented through the regulatory framework and as part of built asset management planning), to increase resilience and adaptive capacity, is required. It is also argued that an active approach to building management incorporating monitoring, feedback, information and goal setting and supported by the wider workplace culture, is required to monitor performance over time and reinforce the design intention. Such an approach (user centred design and an active approach to building management) can help to close the building performance gap and reduce the risk of premature building obsolescence.

Ultimately, based on the findings of this research, the body of work included in this submission calls for the key stakeholders involved in the design, management and operation of buildings to take action. The relevant stakeholders and actions include:

- Regulators: Adopt overheating risk assessments that take account of predicted climate change impacts and encourage/ incentivise the use of risk based climate change adaptation planning tools in built asset management planning;
- Designers: Take a user centred approach to building design particularly in relation to the control to user interface. Allow for design, process and operational based enablers at the design stage to deliver greater levels of resilience and adaptive capacity. Take an integrated, lifetime design approach embedding the facilities manager in the design process;
- Owners/Facilities Managers: Engage in an active approach to building management to reinforce personal control and support occupants' health and wellbeing while increasing resource efficiency by utilising information/ education, feedback, monitoring and behaviour change techniques in a continuous feedback loop. Implement a workplace culture that is supportive of the preferred occupant behaviours;
- Occupants: Supported and enabled by user centred design, active building management and the relevant workplace culture engage with the building, controls and workplace environment in an active and anticipatory manner (this can only be achieved once the preceding steps noted have been taken).

5.1 Future Work

The research included within this submission points towards a number of possible directions for further future research. Each paper presented in this submission includes its own discussion regarding future research needs. For completeness, a summary of the future research needs related to the overall body of work submitted is provided below.

The behaviour change research included could be expanded to test how effective such approaches are in changing occupant behaviour in relation to their own health and wellbeing and interaction with building systems and controls. If the active approach to building management suggested were to be adopted with a focus on building performance and user satisfaction (not just energy use), the further development of such behaviour change techniques may be important. Furthermore, such techniques may benefit from a degree of automation of feedback, education and information, along with continuous reinforcement, and this presents an interesting avenue for further research. More specifically, in relation to the potential of overheating related to climate change, there is a need for a greater understanding of the likely user adaptations and behaviour during warm periods. This could explore window opening behaviour (and other user adaptations) particularly in urban areas where noise, pollution and security may have a mediating effect. This could link back to the wider active approach to building management suggested and may have implications for building intelligence through encouraging anticipatory behaviour.

Further research in relation to the likelihood of building occupants naturally acclimatising to a generally warming climate over time would also be of benefit. Such research may face a number of practical and ethical barriers such as the requirement for longitudinal studies that explore the impacts of incremental increases in internal temperatures and the potential health impacts of these. An alternative approach to such research may be required, perhaps based on the experience of occupants of similar buildings across differing climates. More generally, the potential for user behaviour and user-focused adaptations along with managerial interventions to increase building resilience and adaptive capacity present an interesting and underdeveloped area of inquiry. Further research in these areas could supplement the more commonly considered technical adaptations.

The approaches set out in this research in relation to climate change adaptation and adaptation planning either through the regulatory framework or built asset management planning would benefit from further exploration. The regulatory approaches suggested could be explored in practice or tested qualitatively to understand the likely industry reaction and approach, should such mechanisms be put in place. The adaptation planning mechanisms focused on facilities and built asset management plans would benefit from further research that seeks to develop additional tools and techniques to support such approaches. These areas could also be further explored to test the theory generated against a wider range of building types.

6 REFERENCES

Ackerly, K. and Brager, G. (2013) Window signalling systems: control strategies and occupant behaviour, *Building Research & Information*, 41(3), pp. 342–360.

Addis, W. and Schouten, J. (2004) *Principles of design to facilitate reuse and recycling*, *CIRIA*, London, CIRIA.

Adekunle, T. O. and Nikolopoulou, M. (2016) Thermal comfort, summertime temperatures and overheating in prefabricated timber housing, *Building and Environment*, 103, pp. 21–35.

Al-Homoud, D. M. S. (2005) Performance characteristics and practical applications of common building thermal insulation materials, *Building and Environment*, 40(3), pp. 353–366.

Amaratunga, D., Baldry, D., Sarshar, M. and Newton, R. (2002) Quantitative and qualitative research in the built environment: application of “mixed” research approach, *Work Study*, 51(1), pp. 17–31.

Appel-Meulenbroek, R. (2016) Editorial, *Journal of Corporate Real Estate*, 18(3), pp. 162–163.

Azar, E. and Al Ansari, H. (2017) Framework to investigate energy conservation motivation and actions of building occupants: The case of a green campus in Abu Dhabi, UAE, *Applied Energy*, 190, pp. 563–573.

Baum, A. (1991) *Property investment depreciation and obsolescence*, London, Routledge.

Bosher, L. (2014) Built-in resilience through disaster risk reduction: operational issues, *Building Research & Information*, 42(2), pp. 240–254.

Brand, S. (1997) *How buildings learn: what happens after they’re built*, 2nd ed, London, Phoenix.

Bull, R. (2015) ICT as an enabler for sustainable development: reflections on opportunities and barriers, *Journal of Information, Communication and Ethics in Society*, 13(1), pp. 19–23.

Bull, R., Lemon, M., Fleming, P. D., Stuart, G. and Everitt, D. (2014) Digitally Engaging and Empowering Employees for Energy Demand Reduction: A New Approach for the Next Generation?, [online] Available at: https://www.dora.dmu.ac.uk/xmlui/handle/2086/10205 (Accessed 21 January 2017).

Butt, T. E., Camilleri, M., Paul, P. and Jones, K. G. (2015) Obsolescence types and the built environment : definitions and implications, *International Journal of Environment and Sustainable Development*, 14(1), pp. 20–39.

CABE & BCO (2005) *The impact of office design on business performance*, Commission for Architecture & the Built Environment and the British Council for Offices, [online] Available at: http://www.designcouncil.org.uk/resources/report/impact-office-design-business-performance (Accessed 21 January 2017).

Camilleri, M., Jaques, R. and Isaacs, N. (2001) Impacts of climate change on building performance in New Zealand, *Building Research & Information*, 29(6), pp. 440–450.

Clements-Croome, D. (ed.) (2000) *Creating the productive workplace*, 1st ed, Spon/Routledge.

Clements-Croome, D. (2015) Creative and productive workplaces: a review, *Intelligent Buildings International*, 7(4), pp. 164–183.

Clements-Croome, D and Kaluarachchi, Y. (2000) Assessment and Measurement of Productivity, In Clements-Croome, Derek (ed.), *Creating the productive workplace*, 1st ed, Spon/Routledge, pp. 129–166.

Costello, A., Abbas, M., Allen, A., Ball, S., Bell, S., Bellamy, R., Friel, S., Groce, N., Johnson, A., Kett, M., Lee, M., Levy, C., Maslin, M., McCoy, D., McGuire, B., Montgomery, H., Napier, D., Pagel, C., Patel, J., de Oliveira, J. A. P., Redclift, N., Rees, H., Rogger, D., Scott, J., Stephenson, J., Twigg, J., Wolff, J. and Patterson, C. (2009) Managing the health effects of climate change, *The Lancet*, 373(9676), pp. 1693–1733.

Cotterell, J. and Dadeby, A. (2012) *The passivhaus handbook a practical guide to constructing and retrofitting buildings for ultra-low energy performance*, Totnes, Green, [online] Available at: http://lib.myilibrary.com/browse/open.asp?id=533851&entityid=https://idp.gre.ac.uk/oala/metadata (Accessed 10 February 2017).

Cox, R. A., Nielsen, S. B. and Rode, C. (2015) Coupling and quantifying resilience and sustainability in facilities management, *Journal of Facilities Management*, 13(4), pp. 314–331.

Creagh, R., McGann, S., Marian, T., Jonine, J. and Pages-Oliver, R. (2014) Between the user and the building, In Madeo, F. and Schnabel, M. . (eds.), *Across: Architectural Research through to Practice*, Genoa, Italy, The Architectural Science Association & Genova University Press, [online] Available at: http://anzasca.net/wp-content/uploads/2014/12/05_19_105.pdf (Accessed 21 January 2017).

Creswell, J. W. (2009) *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 3rd ed, London, Sage.

Dainty, A. (2008) Methodoligical pluralism in construction management research, In Knight, A. and Ruddock, L. (eds.), *Advanced research methods in the built environment*, Chichester, U.K. ; Ames, Iowa, Wiley-Blackwell, pp. 1–12.

Danielsson, C. B. and Bodin, L. (2009) Difference in satisfaction with office environment among employees in different office types, *Journal of Architectural and Planning Research*, 26(3), pp. 241–257.

Dantsiou, D. and Sunikka-Blank, M. (2015) Why does energy use feedback not work in workplaces? Insights from social practice theory, In *First Fuel now*, Toulon, France, pp. 2227–2236.

Darby, H., Elmualim, A., Clements-Croome, D., Yearley, T. and Box, W. (2016) Influence of occupants' behaviour on energy and carbon emission reduction in a higher education building in the UK, *Intelligent Buildings International*, 8(3), pp. 157–175.

Dengel, A. and Swainson, M. (2012) *Overheating in new homes: a review of the evidence*, NHBC Foundation.

Department for Communities and Local Government (2015) *2010 to 2015 government policy: energy efficiency in buildings*, DCLG, [online] Available at: https://www.gov.uk/government/publications/2010-to-2015-government-policy-energy-efficiency-in-buildings/2010-to-2015-government-policy-energy-efficiency-in-buildings (Accessed 21 January 2017).

Desai, A. and Jones, K. (2010) Examination of existing facilities management approaches to climate change and future directions, In *Proceedings of the São Paulo 2010 CIB W070 International Conference*, Sao Paolo, Brazil, Department of Construction Engineering, Escola Politécnica, University of São Paulo, pp. 585–596, [online] Available at: https://www.mysciencework.com/publication/show/85cc7083470d3dc198abceb37cb718f2 (Accessed 12 February 2017).

Din, A. and Brotas, L. (2016) The evaluation of the variables of domestic overheating in the UK under TM52 using a future climate model - Guidance for designers, In Windsor, UK, pp. 855–866, [online] Available at: http://nceub.org.uk/W2016/pdfs/proceedings/Proceedings_Windsor_Conference_2016.pdf (Accessed 21 January 2017).

Douglas, J. (1996) Building performance and its relevance to facilities management, *Facilities*, 14(3/4), pp. 23–32.

van Dronkelaar, C., Dowson, M., Burman, E., Spataru, C. and Mumovic, D. (2016) A Review of the Energy Performance Gap and Its Underlying Causes in Non-Domestic Buildings, *Frontiers in Mechanical Engineering*, 1(17), [online] Available at: http://journal.frontiersin.org/article/10.3389/fmech.2015.00017.

Duffy, F. (1990) Measuring building performance, *Facilities*, 8(5), pp. 17–20.

Eichholtz, P., Kok, N. and Quigley, J. M. (2012) The Economics of Green Building, *The Review of Economics and Statistics*, 95(1), pp. 50–63.

Eisenberg, D. A. (2016) Transforming building regulatory systems to address climate change, *Building Research & Information*, 44(5–6), pp. 468–473.

Foulds, C., Powell, J. and Seyfang, G. (2013) Investigating the performance of everyday domestic practices using building monitoring, *Building Research & Information*, 41(6), pp. 622–636.

Gething, W. and Puckett, K. (2013) *Design for climate change*, London, RIBA.

Gosling, J., Sassi, P., Naim, M. and Lark, R. (2013) Adaptable buildings: A systems approach, *Sustainable Cities and Society*, 7, pp. 44–51.

Häkkinen, T. and Belloni, K. (2011) Barriers and drivers for sustainable building, *Building Research & Information*, 39(3), pp. 239–255.

Haynes, B. P. (2007) Office productivity: a theoretical framework, *Journal of Corporate Real Estate*, 9(2), pp. 97–110.

Hewitt, E. L., Andrews, C. J., Senick, J. A., Wener, R. E., Krogmann, U. and Sorensen Allacci, M. (2016) Distinguishing between green building occupants' reasoned and unplanned behaviours, *Building Research & Information*, 44(2), pp. 119–134.

Hills, J. (2012) *Getting the measure of fuel poverty. Final Report of the Fuel Poverty Review*, *Case Report 72*, DECC, [online] Available at: http://sticerd.lse.ac.uk/dps/case/cr/CASEreport72.pdf (Accessed 21 January 2017).

Intergovernmental Panel on Climate Change (2014) *Climate Change 2014 Synthesis Report: Summary for Policymakers*, [online] Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf (Accessed 21 January 2017).

Jenkins, D. P., Ingram, V., Simpson, S. A. and Patidar, S. (2013) Methods for assessing domestic overheating for future building regulation compliance, *Energy Policy*, 56, pp. 684–692.

Jenkins, D. P., Patidar, S., Banfill, P. and Gibson, G. (2014a) Developing a probabilistic tool for assessing the risk of overheating in buildings for future climates, *World Renewable Energy Congress – Sweden, 8–13 May, 2011, Linköping, Sweden*, 61, pp. 7–11.

Jenkins, K., Hall, J., Glenis, V., Kilsby, C., McCarthy, M., Goodess, C., Smith, D., Malleson, N. and Birkin, M. (2014b) Probabilistic spatial risk assessment of heat impacts and adaptations for London, *Climatic Change*, 124(1), pp. 105–117.

Jones, K., Desai, A., Mulville, M. and Jones, A. (2015) Asset management using a hybrid backcasting/forecasting approach, *Facilities*, 33(11/12), pp. 701–715.

Jones, K., Mulville, M. and Brooks, A. (2013) FM, risk and climate change adaptation, *The International Journal of Facilities Management*.

Karjalainen, S. (2016) Should we design buildings that are less sensitive to occupant behaviour? A simulation study of effects of behaviour and design on office energy consumption, *Energy Efficiency*, 9(6), pp. 1257–1270.

Kellenberger, D. and Althaus, H.-J. (2009) Relevance of simplifications in LCA of building components, *Building and Environment*, 44(4), pp. 818–825.

Khalil, N., Kamaruzzaman, S. N. and Baharum, M. R. (2016) Ranking the indicators of building performance and the users' risk via Analytical Hierarchy Process (AHP): Case of Malaysia, *Ecological Indicators*, 71, pp. 567–576.

King, R. C., Villeneuve, E., White, R. J., Sherratt, R. S., Holderbaum, W. and Harwin, W. S. (2017) Application of data fusion techniques and technologies for wearable health monitoring, *Medical Engineering & Physics*, 42, pp. 1–12.

Kingsborough, A., Borgomeo, E. and Hall, J. W. (2016) Adaptation pathways in practice: Mapping options and trade-offs for London's water resources, *Sustainable Cities and Society*, 27, pp. 386–397.

Kingsborough, A., Jenkins, K. and Hall, J. W. (2017) Development and appraisal of long-term adaptation pathways for managing heat-risk in London, *Climate Risk Management*, [online] Available at: //www.sciencedirect.com/science/article/pii/S2212096317300050.

Knight, A. and Turnbull, N. (2008) Epistemology, In Knight, A. and Ruddock, L. (eds.), *Advanced research methods in the built environment*, Chichester, U.K. ; Ames, Iowa, Wiley-Blackwell, pp. 64–74.

Kok, N. and Jennen, M. (2012) The impact of energy labels and accessibility on office rents, *Energy Policy*, 46, pp. 489–497.

Krauss, S. E. (2005) *Research Paradigms and Meaning Making: A Primer*, *The Qualitative Report*, pp. 758–770, [online] Available at: http://nsuworks.nova.edu/tqr/vol10/iss4/7 (Accessed 8 January 2017).

Leaman, A. and Bordass, B. (1999) Productivity in buildings: the 'killer' variables, *Building Research & Information*, 27(1), pp. 4–19.

Lee, W. L. (2013) A comprehensive review of metrics of building environmental assessment schemes, *Energy and Buildings*, 62, pp. 403–413.

Lewry, A. and Hamilton, L. (2017) Finding the performance gap, *Modern Building Services*, [online] Available at: http://www.modbs.co.uk/news/fullstory.php/aid/17011/Finding_the_performance_gap.html (Accessed 25 July 2017).

Martani, C., Lee, D., Robinson, P., Britter, R. and Ratti, C. (2012) ENERNET: Studying the dynamic relationship between building occupancy and energy consumption, *Energy and Buildings*, 47, pp. 584–591.

McCaul, M., Glennon, T. and Diamond, D. (2017) Challenges and opportunities in wearable technology for biochemical analysis in sweat, *Current Opinion in Electrochemistry*, [online] Available at: http://www.sciencedirect.com/science/article/pii/S2451910317300558.

McLeod, R. S., Hopfe, C. J. and Kwan, A. (2013) An investigation into future performance and overheating risks in Passivhaus dwellings, *Building and Environment*, 70, pp. 189–209.

Meacham, B. J. (2016) Sustainability and resiliency objectives in performance building regulations, *Building Research & Information*, 44(5–6), pp. 474–489.

Menezes, A. C., Cripps, A., Bouchlaghem, D. and Buswell, R. (2012a) Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap, *Energy Solutions for a Sustainable World - Proceedings of the Third International Conference on Applied Energy, May 16-18, 2011 - Perugia, Italy*, 97, pp. 355–364.

Menezes, C. ., Tetlow, R., Beaman, C. ., Cripps, A., Bouchlaghem, D. and Buswell, R. (2012b) Assessing the impact of occupant behaviour on the electricity consumption for lighting and small power in office buildings., In *7th International Conference on Innovation in Architecture, Engineering & Construction*, Sao Paolo, Brazil.

Miller, N., Pogue, D., Gough, Q. and Davis, S. (2009) Green Buildings and Productivity, *Journal of Sustainable Real Estate*, 1(1), pp. 65–89.

Mulville, M., Callaghan, N. and Isaac, D. (2016) The impact of the ambient environment and building configuration on occupant productivity in open-plan commercial offices, *Journal of Corporate Real Estate*, 18(3), pp. 180–193.

Mulville, M., Jones, K. and Huebner, G. (2013) The potential for energy reduction in UK commercial offices through effective management and behaviour change, *Architectural Engineering and Design Management*, 10(1–2), pp. 79–90.

Mulville, M., Jones, K., Huebner, G. and Powell-Greig, J. (2016) Energy-saving occupant behaviours in offices: change strategies, *Building Research & Information*, pp. 1–14.

Mulville, M. and Stravoravdis, S. (2016a) Delivering long-term building performance: A user-centred approach, In Gorse, C. and Dastbaz, M. (eds.), *International SEEDS Conference*, Leeds, UK, ., pp. 82–93.

Mulville, M. and Stravoravdis, S. (2016b) Regulating for climate change related overheating risk in dwellings, In Kahkonen, K. and Keinanen, M. (eds.), *Creating Built Environments of New Opportunities*, Tampere, Finland, Tampere University of Technology, pp. 829–840.

Mulville, M. and Stravoravdis, S. (2016c) The impact of regulations on overheating risk in dwellings, *Building Research & Information*, 44(5–6), pp. 520–534.

O'Neill, M. J. (2010) A model of environmental control and effective work, *Facilities*, 28(3/4), pp. 118–136.

Ouf, M., Issa, M. and Merkel, P. (2016) Analysis of real-time electricity consumption in Canadian school buildings, *Energy and Buildings*, 128, pp. 530–539.

Proverbs, D. and Gameson, R. (2008) Case Study Research, In Knight, A. and Ruddock, L. (eds.), *Advanced research methods in the built environment*, Chichester, U.K. ; Ames, Iowa, Wiley-Blackwell, pp. 64–74.

Ratcliffe, J. (2008) Built environment futures research: The need for foresight and scenario learning, In Knight, A. and Ruddock, L. (eds.), *Advanced research methods in the built environment*, Chichester, U.K. ; Ames, Iowa, Wiley-Blackwell, pp. 216–227.

Robson, C. (2011) *Real world research: a resource for users of social research methods in applied settings*, 3rd ed., Chichester, Wiley.

Roders, M. (2015) Partnering for climate change adaptations by Dutch housing associations, PhD Thesis, Delft University of Technology.

Rodi, W. N. W., Hwa, T. K., Said, A. S., Mahamood, N. M., Abdullah, M. I. and Rasam, A. R. A. (2015) Obsolescence of Green Office Buildings: A Literature Review, *International Accounting and Business Conference 2015, IABC 2015*, 31, pp. 651–660.

Rohracher, H. (2001) Managing the Technological Transition to Sustainable Construction of Buildings: A Socio-Technical Perspective, *Technology Analysis & Strategic Management*, 13(1), pp. 137–150.

Ross, B. E., Chen, D. A., Conejos, S. and Khademi, A. (2016) Enabling Adaptable Buildings: Results of a Preliminary Expert Survey, *ICSDEC 2016 – Integrating Data Science, Construction and Sustainability*, 145, pp. 420–427.

Sanders, C. H. and Phillipson, M. C. (2010) UK adaptation strategy and technical measures: the impacts of climate change on buildings, *Building Research & Information*, 31(3–4), pp. 210–221.

Sanderson, D. and Edwards, M. (2016) Determinants of satisfaction amongst tenants of UK offices, *Journal of Corporate Real Estate*, 18(2), pp. 102–131.

Schoen, L. . J. and Fellow, P. E. (2010) *Preventive Maintenance Guidebook*, Building Owners and Managers Association.

Schweber, L. and Leiringer, R. (2012) Beyond the technical: a snapshot of energy and buildings research, *Building Research & Information*, 40(4), pp. 481–492.

Seppanen, O., Fisk, W. J. and Lei, Q. (2006) Effect of temperature on task performance in office environment, *Lawrence Berkeley National Laboratory*.

Smith, A. and Pitt, M. (2011) Sustainable workplaces and building user comfort and satisfaction, *Journal of Corporate Real Estate*, 13(3), pp. 144–156.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M. and Miller, H. (eds.) (2007) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*, [online] Available at: https://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html (Accessed 21 January 2017).

Stevenson, F., Baborska-Narozny, M. and Chatterton, P. (2016) Resilience, redundancy and low-carbon living: co-producing individual and community learning, *Building Research & Information*, 44(7), pp. 789–803.

Stone, B., Vargo, J., Liu, P., Habeeb, D., DeLucia, A., Trail, M., Hu, Y. and Russell, A. (2014) Avoided Heat-Related Mortality through Climate Adaptation Strategies in Three US Cities, *PLoS ONE*, 9(6), [online] Available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0100852 (Accessed 29 January 2017).

Summerfield, A. J. and Lowe, R. (2012) Challenges and future directions for energy and buildings research, *Building Research & Information*, 40(4), pp. 391–400.

Sunikka-Blank, M. and Galvin, R. (2012) Introducing the prebound effect: the gap between performance and actual energy consumption, *Building Research & Information*, 40(3), pp. 260–273.

Tetlow, R. M., Beaman, C. P., Elmualim, A. A. and Couling, K. (2014) Simple prompts reduce inadvertent energy consumption from lighting in office buildings, *Building and Environment*, 81, pp. 234–242.

Tetlow, R. M., van Dronkelaar, C., Beaman, C. P., Elmualim, A. A. and Couling, K. (2015) Identifying behavioural predictors of small power electricity consumption in office buildings, *Building and Environment*, 92, pp. 75–85.

The World Green Building Council (2014) *Health, Wellbeing and Productivity in Offices: The next chapter for green buildings*, The World Green Building Council, [online] Available at: http://www.worldgbc.org/news-media/health-wellbeing-and-productivity-offices-next-chapter-green-building.

Thomsen, A. and van der Flier, K. (2011) Understanding obsolescence: a conceptual model for buildings, *Building Research & Information*, 39(4), pp. 352–362.

Toledo, L., Cropper, P. and Wright, A. (2016) Unintended consequences of sustainable architecture: Evaluating overheating risks in new dwellings, In Roche, P. (ed.), *Cities, Buildings, People: Towards Regenerative Environments*, Los Angeles, USA, [online] Available at: https://www.dora.dmu.ac.uk/xmlui/handle/2086/12275 (Accessed 21 January 2017).

Tweed, C. (2013) Socio-technical issues in dwelling retrofit, *Building Research & Information*, 41(5), pp. 551–562.

United Nations Environment Programme (2009) *Buildings and Climate Change: Summary for Decision-Makers*, Paris, France, UNEP, [online] Available at: http://www.unep.org/sbci/pdfs/SBCI-BCCSummary.pdf (Accessed 21 January 2017).

Visscher, H., Laubscher, J. and Chan, E. (2016) Building governance and climate change: roles for regulation and related polices, *Building Research & Information*, 44(5–6), pp. 461–467.

Voinov, A. and Farley, J. (2007) Reconciling sustainability, systems theory and discounting, *Ecological Economics*, 63(1), pp. 104–113.

Waddicor, D. A., Fuentes, E., Sisó, L., Salom, J., Favre, B., Jiménez, C. and Azar, M. (2016) Climate change and building ageing impact on building energy performance and mitigation measures application: A case study in Turin, northern Italy, *Building and Environment*, 102, pp. 13–25.

Watts, N., Adger, W. N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., Chaytor, S., Colbourn, T., Collins, M., Cooper, A., Cox, P. M., Depledge, J., Drummond, P., Ekins, P., Galaz, V., Grace, D., Graham, H., Grubb, M., Haines, A., Hamilton, I., Hunter, A., Jiang, X., Li, M., Kelman, I., Liang, L., Lott, M., Lowe, R., Luo, Y., Mace, G., Maslin, M., Nilsson, M., Oreszczyn, T., Pye, S., Quinn, T., Svensdotter, M., Venevsky, S., Warner, K., Xu, B., Yang, J., Yin, Y., Yu, C., Zhang, Q., Gong, P., Montgomery, H. and Costello, A. (2015) Health and climate change: policy responses to protect public health, *The Lancet*, 386(10006), pp. 1861–1914.

Wedawatta, G. and Ingirige, B. (2012) Resilience and adaptation of small and medium-sized enterprises to flood risk, *Disaster Prevention and Management: An International Journal*, 21(4), pp. 474–488.

Wedawatta, G., Ingirige, B. and Amaratunga, D. (2011) Case study as a research strategy:investigating extreme weather resilience of construction SMEs in the UK, In *7th Annual International Conference of International Institute for Infrastructure, Renewal and Reconstruction*, [online] Available at: http://eprints.aston.ac.uk/23751/ (Accessed 11 February 2017).

Wei, S., Pan, S., Xie, L., Xu, C., Xiong, Y., Greenwood, D., Hassan, T. M. and De Wilde, P. (2016) A field study on occupants' ventilation behaviour through balcony doors in university students' apartments during transitional seasons in Beijing, In Brotas, L., Roaf, S., Nicol, F., and Humphreys, M. (eds.), *Making Comfort Relevant*, Windsor, UK, Network for Comfort and Energy Use in Buildings (NCEUB), pp. 1041–1051, [online] Available at: https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/22452 (Accessed 21 January 2017).

de Wilde, P. (2014) The gap between predicted and measured energy performance of buildings: A framework for investigation, *Automation in Construction*, 41, pp. 40–49.

de Wilde, P., Tian, W. and Augenbroe, G. (2011) Longitudinal prediction of the operational energy use of buildings, *Building and Environment*, 46(8), pp. 1670–1680.

Wilkinson, S. J. and Reed, R. G. (2006) Office buildings and the environment : the increasing importance of ESD, *PRRES 2006 : Proceedings of the 12th Annual Conference of the Pacific Rim Real Estate Society*, pp. 1–13.

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

Zaidi, R. Z. and Pelling, M. (2013) Institutionally configured risk: Assessing urban resilience and disaster risk reduction to heat wave risk in London, *Urban Studies*, 52(7), pp. 1218–1233.

APPENDIX A – SUBMITTED PUBLICATIONS

List of Publications Included:

1). **Mulville, M., Jones, K. and Huebner, G. (2013).** The potential for energy reduction in UK commercial offices through effective management and behaviour change. *Journal of Architectural Engineering and Design Management,* Vol. 10, 1-2, pp. 79-90.

2). **Jones K., Mulville, M. and Brookes, A. (2013).** FM, risk and climate change adaptation. *In FM for a Sustainable Future, 12th EuroFM Research Symposium, Prague, Czech Republic, 22-24 May 2013. International Journal of Facilities Management, pp.120-128.* ISBN: 978-94-90694-02-9.

3). **Jones, K., Desai, A., Mulville, M. and Jones, A. (2015).** Asset management using a hybrid backcasting/forecasting approach. *Facilities,* Vol. 33, 11-12, pp. 701-715.

4.) **Mulville, M. and Stravoravdis, S. (2016).** The impact of regulations on overheating risk in dwellings. *Journal of Building Research and Information,* Vol. 44, 5-6, pp. 520-553.

5). **Mulville, M., Callaghan, N and Isaac, D. (2016).** The impact of the ambient environment and building configuration on occupancy productivity in open-plan commercial offices. *Journal of Corporate Real Estate,* Vol. 18, 3, pp. 180-193.

6.) **Mulville, M. and Stravoravdis, S. (2016).** Regulating for climate change related overheating risk in dwellings. *In proceedings of the CIB World Building Congress 2016: Creating Built Environments of New Opportunities Conference 30 May - 2 June 2016, Tampere, Finland*. ISBN: 978-952-15-3741-7

7.) **Mulville, M., Jones, K., Huebner, G. and Powell, J. (2016).** Energy saving occupant behaviour change strategies in the workplace. *Journal of Building Research and Information.* http://dx.doi.org/10.1080/09613218.2016.1212299

8). **Mulville, M. and Stravoravdis, S. (2016).** Delivering long-term building performance: a user-centred approach. In; Gorse, C. and Dastbaz, M. (Eds) International SEEDS Conference, 14-15 September 2016, Leeds Beckett University, UK, Sustainable Ecological Engineering Design for Society. ISBN: 978-0-9955690-1-0.

Paper One

Mulville, M., Jones, K. and Huebner, G. (2013). The potential for energy reduction in UK commercial offices through effective management and behaviour change. *Journal of Architectural Engineering and Design Management,* Vol. 10, 1-2, pp. 79-90.

Citations:

Bull, R. (2015*). ICT as an enabler for sustainable development: reflections on opportunities and barriers*. Journal of Information. Communication and Ethics in Society, Vol. 13:1, pp. 19-23;

Bull, R., Lemon, M., Everitt, D. and Stuart, G. (2015). *Moving beyond feedback: energy behaviour and local engagement in the United Kingdom*. Energy Research & Social Science, Vol. 8, pp. 32-40;

Bull, R., Lemon, M., Fleming, P., Stuart, G. and Everitt, D. (2014). Digitally Engaging and Empowering Employees for Energy Demand Reduction: A New Approach for the Next Generation? *American Council for an Energy Efficient Economy Conference Proceedings 2014*. Asilomar, CA. Available from: http://aceee.org/files/proceedings/2014/data/papers/7-99.pdf;

van Dronkelaar, C., Dowson, M., Spataru, C. and Mumovic, D. (2016). *A Review of the Regulatory Energy Performance Gap and Its Underlying Causes in Non-domestic Buildings*. Frontiers in Mechanical Engineering, Vol. 1:17, doi:10.3389/fmech.2015.00017;

Gibson, R.W. (2014). *Energy behaviour change and army net zero energy; gaps in the army's approach to changing energy behaviour.* U.S. Army Command and General Staff College. Available from: www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA610963*;*

Karjalainen, S. (2016). *Should we design buildings that are less sensitive to occupant behaviour? A simulation study of effects of behaviour and design on office energy consumption*. Energy Efficiency, Vol. 9:6, pp. 1257-1270;

Ouf, M., Issa, M. and Merkel, P. (2016). *Analysis of real-time electricity consumption in Canadian School Buildings*. Energy and Buildings, Vol. 128, pp. 530-539;

Stuart, G., Snape, J.R. and Fleming, P.D. (2016). Closing the feedback loop: a systems approach to supporting community-wide behaviour change in non-domestic buildings. *In proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings.* ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA. Available from: https://www.dora.dmu.ac.uk/xmlui/handle/2086/12340;

Tetlow, R.M., Beaman, C.P., Elmualim, A.A. and Couling, K. (2014). *Simple prompts to reduce inadvertent energy consumption from lighting in office buildings*. Building and Environment, Vol. 81, pp. 234-242;

Tetlow, R.M., van Dronkelaar, C., Beaman, C.P., Elmualim, A.A. and Couling, K. (2015). *Identifying behavioural predictors of small power electricity consumption in office buildings*. Building and Environment, Vol. 92, pp. 75-85;

Wei, S., Hassan, T.M., Firth, S.K. and Fouchal, F. (2016). *Impact of occupant behaviour on the energy saving potential of retrofit measures for buildings in the UK*. Intelligent Buildings International, doi:10.1080/17508975.2016.1139538;

Wei, S., Hassan, T.M., Firth, S.K. and Fouchal, F. (2016). Impact of occupant behaviour on the energy saving potential of retrofit measures for buildings in the UK. *In proceedings of Intelligent Buildings International, Conference: The 7th International Conference of SuDBE2015*. 27-29 July, 2015, Reading, UK.

Other Impacts:

Indexed in the Association of Researchers in Construction Management (ARCOM).

Since the publication of this paper, the candidate has become a reviewer for this journal.

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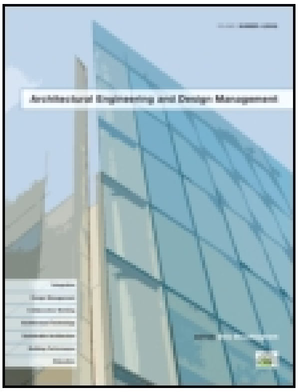

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The potential for energy reduction in UK commercial offices through effective management and behaviour change

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The potential for energy reduction in UK commercial offices through effective management and behaviour change

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General office equipment can be responsible for a significant proportion of overall electrical energy consumption in UK offices and this is predicted to rise significantly over the coming years [Webber, C. A., Roberson, J. A., Brown, R. E., Payne, C. T., Nordman, B., & Koomey, J. G. (2001). *Field surveys of office equipment operating patterns*. Berkley: CA: Lawrence Berkley National Laboratory]. As a significant contributor to overall energy use, this equipment has a corresponding cost and carbon impact. The legally binding requirements of the climate change act [Department of Energy and Climate Change. (2008). *The climate change act*. London: The Ministry of Justice] present a need to address the impact of office equipment, especially within the less-efficient existing building stock. In this study the range of energy consumption patterns observed across workstations in two typical UK, air-conditioned office spaces covering 90 desks and the potential effect of using feedback to encourage energy reduction through behaviour change are explored. The project monitored energy consumption over a four-month baseline period. Taking into account technical, behavioural and environmental influences this baseline established that a significant variation in consumption patterns exists between workstations providing the same function, in comparable locations and over the same period of time. Following the establishment of the baseline data further monitoring took place to assess the effect of behaviour change interventions through the provision of comparative feedback. The core driver behind the variation in consumption identified was found to be occupant behaviour over technical and environmental considerations. The study establishes that it is possible to reduce energy use, carbon emissions and cost associated with desk-level electricity consumption by up to 20% through behaviour change in typical UK office spaces. Further savings are possible through energy management and procurement policy, but behaviour change offers significant initial reductions for limited investment.

Keywords: energy; small power; office; CO_2; unregulated energy; feedback; behaviour change

Introduction

The impact and pattern of usage relating to regulated energy within the building stock are generally well understood. Consumption patterns associated with unregulated energy such as small power and desktop equipment are less well understood. Junnila (2007) notes that the existing literature on energy efficiency in office buildings does not provide good data for estimating energy reduction potential through occupant behaviour change. Furthermore as discussed by Menezes, Cripps, Bouchlaghem, and Buswell (2012) this lack of understanding of unregulated energy

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use can be identified as a contributory factor to the ‘performance gap’ between predicted/design and actual/in-use energy performance. In UK office spaces this performance gap has in some cases resulted in in-use carbon emissions 2–3 times that of the original design estimate (Bordass, Cohen, & Field, 2004). The UK target of a 34% reduction in CO_2 emissions over 1990 levels by 2020 (The Climate Change Act, 2008) has resulted in the construction industry introducing increasingly stringent energy performance regulations. As building regulations and other statutory mechanisms drive down the consumption associated with regulated energy, an understanding of unregulated energy becomes increasingly important. Information and communication technology (ICT) can be responsible for 20% or more (Chartered Institution of Building Services Engineers [CIBSE], 2004) of overall electrical energy consumption in a typical office space. Improvements in the energy efficiency of IT equipment have reduced consumption of individual units. Conversely increased processing power and range of equipment utilised has resulted in predictions that small power will continue to have a significant impact (Jenkins, Singh, & Eames, 2009) and that energy consumption associated with office eqiupment will continue to grow globally in the near future (Vereecken et al., 2010; Webber et al., 2001).

As noted by Junnila (2007) few studies have focused on quantifying the end-user influence on energy consumption; furthermore most energy managers believe end users’ influence to be minimal (Lukas, 2000, cited in Junnila, 2007, p. 331). However it has previously been established that energy use of desktop equipment is highly influenced by occupant behaviour and is flexible in nature (Zhang, Siebers, & Aickelin, 2011). This view is supported by a study by Kawamoto, Shimoda, and Mizuno (2003) which estimated that for an average working day the actual in-use utilisation of desktop equipment may commonly be as low as 43%. Additionally many office workers do not power down equipment at the end of the working day (Berl & de Meer, 2011) and even fewer unplug equipment that may still draw power when turned off. A US field survey of office equipment operating patterns (Webber et al., 2001) found that only 44% of computers and 32% of monitors were turned off at night; a similar UK-based study (Zhang et al., 2011) found that 60% of occupants do not power down at night time, with 31% powering down just occasionally and only 9% powering down regularly. Comparison of these two studies would seem to suggest that organisational or cultural background may have an influence on the rate of power down and reinforces the view that small power consumption patterns are generally not fully understood but offer significant potential for savings.

The flexible nature of desktop energy consumption supports the view that there is significant potential for energy reduction through behaviour change. Ward (2008) identifies increasing IT usage in commercial offices as one of the main barriers to reducing energy use; however if occupant behaviour were better understood it may be possible to overcome such barriers while allowing for the increased use of IT equipment. There is evidence that the use of behaviour change mechanisms can significantly reduce overall energy consumption in commercial buildings. It has been estimated that workstation energy use can account for 73–88% of total office equipment energy use and that a combination of behaviour change, energy management and procurement policy could contribute to a 60–80% reduction in this (Junnila, 2007). With this in mind a focus on desk-level equipment would appear valid when considering energy reduction from general office equipment. Carrico and Riemer (2011), in a study considering university-based office spaces in the USA, note that energy use reductions of up to 15% should be possible through the implementation of behaviour change measures alone, by using group-level feedback and peer education.

Jenkins et al. (2009) predict that offices spaces in London and the south of the UK are likely to increasingly tend towards being cooling dominated. As, in most UK offices, internal heat gains are the main contributing factor to cooling loads, the reduction in consumption associated with desktop equipment and corresponding heat gains could offer an indirect benefit by decreasing the corresponding cooling load (Jenkins, Liu, & Peacock, 2007).

This study considers energy consumption patterns across 90 desks in two air-conditioned offices spaces in South-East England. The variation in consumption patterns identified is considered and analysed, and a series of behaviour change interventions are made with the goal of reducing consumption associated with desktop equipment by at least 20%.

Methodology

Over the course of an unoccupied weekend 90 workstations (each workstation consists of a single screen, desktop computer or laptop and docking station, with two desk-level plugs) were fitted with energy-monitoring devices. The devices look like standard extension leads with four plug locations. Computers, screens, a desk-level plug and any other desktop devices present were plugged into the monitoring device. The device was installed so that it became the most accessible plug point for the occupant at each workstation. There were other plug locations available (from which the monitoring device itself is plugged) but these were out of sight and hidden within cable trays on the underside of the desk. This approach ensured all small power consumed at desk level could be monitored. The device used takes an hourly reading, which is then wirelessly transmitted to be stored on a central server in the office of the monitor provider; data can then be downloaded remotely for analysis. The device itself was tested and found to draw 0.8 W which was accounted for in the discussions to follow.

The initial baseline monitoring period began and ended on the same day in both locations, lasting from 17 June 2011 to 26 September 2011 (100 days). Following the conclusion of the baseline period a series of field surveys were conducted to identify which pieces of equipment were plugged into which monitor and to ensure that only monitors with a full profile (monitoring at least the screen and computer at the location) were taken forward for analysis. Additionally, field surveys were able to identify where additional equipment such as mobile phone chargers, other personal ICT devices, desk fans, desk lamps and heaters had been plugged in. Of the additional small power devices identified the most prevalent was mobile phone chargers with 21% of all workstations having chargers plugged in during the survey (many without a mobile phone connected).

Using the baseline data it was possible to establish total, daily and hourly consumption patterns at both site-wide and individual workstation levels. Allowance was made for absence from the workplace through filtering the data to only cover days when the location was occupied. Further corrections were made to ensure readings from individual workstations were not skewed due to longer working hours. This was achieved through establishing an out-of-hours baseline power density (the average power density at the desk location when not in use) and an operational power density (the average power density at the desk during operating hours). From this it was possible to ensure feedback provided made allowance for extended working hours without unduly penalising the workstation occupant. This was achieved by applying average working and non-working hours based on site-wide data as opposed to individual usage, thus allowing like-for-like comparison. The baseline analysis identified a small number of unexpected peaks in energy use; based on the timing and frequency of the peaks they were attributed to the cleaning cycle at each location (Figures 1 and 2).

Once the baseline data were analysed they were compared to widely accepted industry benchmarks to understand the impact of small power within the benchmarks. For office location A it was possible to compare this back to overall electricity consumption for the site and produce per m² comparisons. It was not possible to indentify the same data for office location B as the

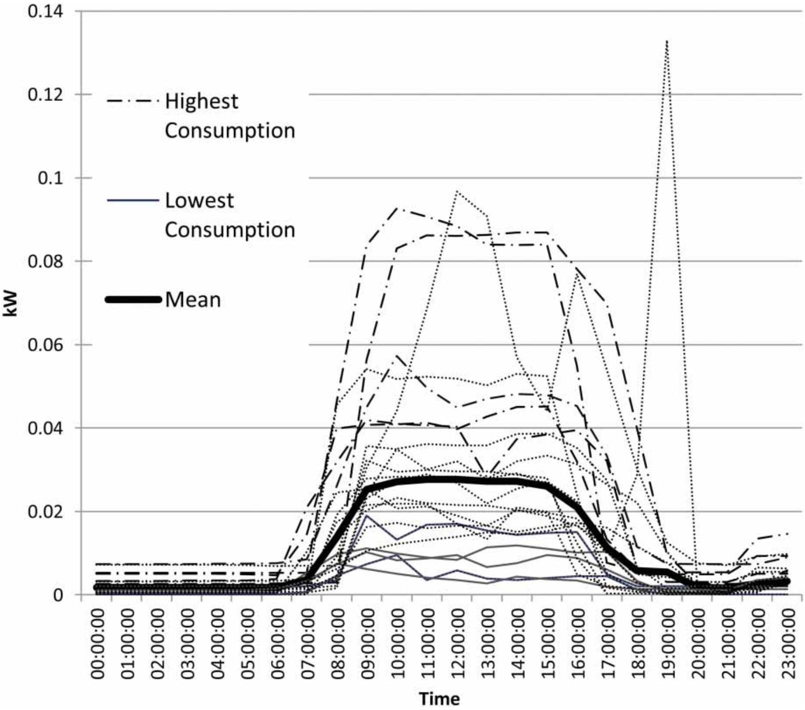

Figure 1. Daily profile location A.

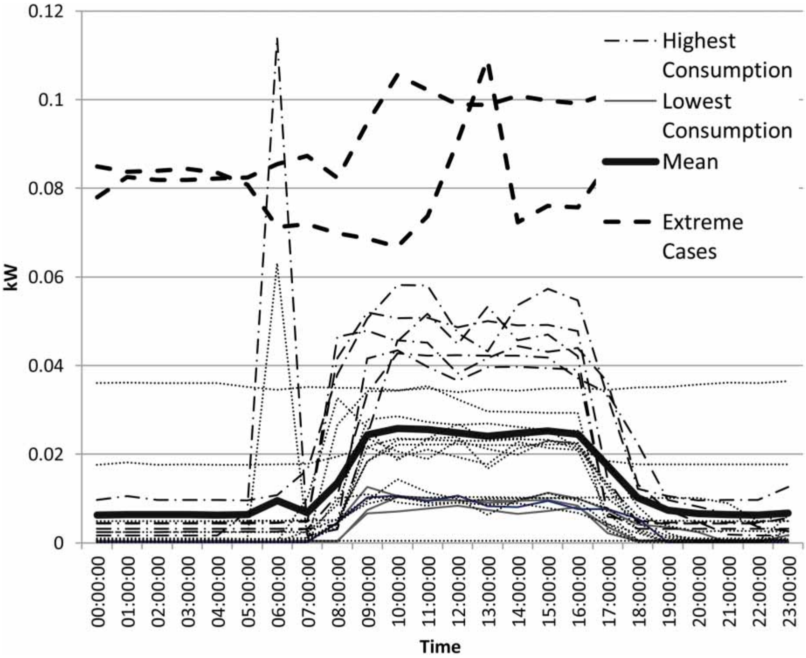

Figure 2. Daily profile location B.

data could not be disaggregated; therefore any such comparisons are based only on the data from office location A.

As the aim of the study was to understand variation in energy consumption and the influence of occupant behaviour, it was important to take account of ongoing changes within the office structure (turnover of staff, change of location) so that a clear picture of behaviour could be established. Working with the management team at both locations, in addition to the follow-up field surveys, it was possible to ensure that only desks where the individual could be followed were included in the monitoring. This reduced the number of desks considered for post-intervention analysis.

Following the baseline period a number of interventions were made prior to and during the follow-up monitoring period. Interventions began in early March 2012 and continued until the end of June. Two types of feedback interventions were used in conjunction with goal-setting. Comparative feedback interventions considering the consumption of an individual or a group in relation to an average have been successful in reducing energy consumption in households, as has historic feedback (Abrahamse, Steg, Vlek, & Rothengatter, 2005). The basic idea of comparative feedback is to evoke a feeling of competition, social comparison or social pressure which then leads to changed behaviour to correspond more closely to the norm. In order to prevent a pull towards the mean performance in those who already show the desired behaviour (in this case, below-average energy use), an appraisal of the behaviour is employed, often in the form of a negative or positive smiley face. The first intervention consisted of providing regular historic (approximately every fortnight) feedback on energy consumption at an office-based level. This was combined with goal-setting; hence, at the beginning of the intervention, a reduction of 20% was calculated and given as a target. The second intervention was conducted with individual-level feedback to half of the occupants within an office and group-based feedback to the other half. Consumption was split up into a day and night-time component in order to highlight the wastage associated with leaving equipment on standby overnight.

Comparing the data generated from the follow-up monitoring period it was possible to quantify the impact and longevity of the interventions made.

Benchmark comparison

There is a wide range of industry benchmarks relating to regulated energy, unregulated energy, small power loads, occupant density and other related metrics. These are supported and supplemented by academic research and field studies. An understanding of these benchmarks can help to gauge the overall impact of workstation energy use patterns, in relation to the overall energy use framework. The figures discussed below feed into the floor- and desk-level analysis which follows.

Technical Memorandum 46 (TM46) (CIBSE, 2008) provides widely recognised energy benchmarks for UK buildings; however the 95 kWh/m^2/year for typical electrical energy consumption in UK offices identified within TM46 includes only regulated energy use. Therefore it is necessary to look to the *Energy consumption guide 19* (ECG19) (Department of the Environment, Transport and the Regions [DETR], 2003) which identifies a regulated electrical energy usage of 145 kWh/m^2/year in air-conditioned offices with an additional 63 kWh/m^2/year allowed for unregulated energy of which 31 kWh/m^2/year is attributed to office equipment. If, as identified by Junnila (2007), 73–88% of this relates to desktop equipment, office equipment would typically be expected to consume 22–27 kWh/m^2/year. The *Chartered Institution of Building Services Engineers (CIBSE) guide F* (CIBSE, 2004) further supplements this discussion by identifying office equipment as being responsible for 20% of overall electrical energy consumption with two-thirds of this attributed to desktop equipment. Applying this to the ECG19 benchmark, desktop energy usage can be calculated as 27.45 kWh/m^2/year, aligning well with the findings of Junnila (2007). Good practice guide 11 (Department of the Environment, 1997) would seem to contradict these predictions with a much more significant proportion of electrical energy use in air-conditioned offices assigned to small power. Given the publication was produced in 1996 and ICT equipment and building performance have moved on significantly over this period it has been discounted for this study.

Based on the above benchmark data, workstation energy consumption in the region of 22–27.45 kWh/m^2/year would seem to be a credible prediction for the offices under investigation.

Floor-level analysis

The two office spaces under consideration in this study largely utilise laptop computers with docking stations and LCD screens; occasionally a desktop lamp, desktop fan, fan heater or mobile phone charger was also plugged in. Over the initial four-month monitoring period average energy consumption per day at each workstation and for each site was established as an indicator of the overall consumption pattern. When the average daily consumption is considered it can be seen that both sites are comparable and have similar daily profiles (Figures 1 and 2). Across all desks the average daily consumption for the initial four-month monitoring period at office A is 236 Wh/desk/day (for an average working day of 8.37 h, normalised to 8 h = 225 Wh) while at office B this is 307 Wh (for an average working day of 10.4 h, normalised to 8 h = 236 Wh). There is a significant deviation from the mean consumption (Figures 3 and 4) which indicates a range of behavioural and equipment-related factors affecting consumption patterns. The standard deviation for average daily consumption at office A was 147 Wh/day and at office B standard deviation was 143 Wh/day[1] indicating high but similar levels of variation. Therefore it can be said that two-thirds of desks at office A consume between 89 and 383 Wh/day and at office B this is between 162 and 448 Wh/day.

In order to take account of the variation in the duration of a typical working day and equipment performance, it is necessary to consider the power density, both during working and non-working hours. The average power density during working hours at office A was 25.2 W while

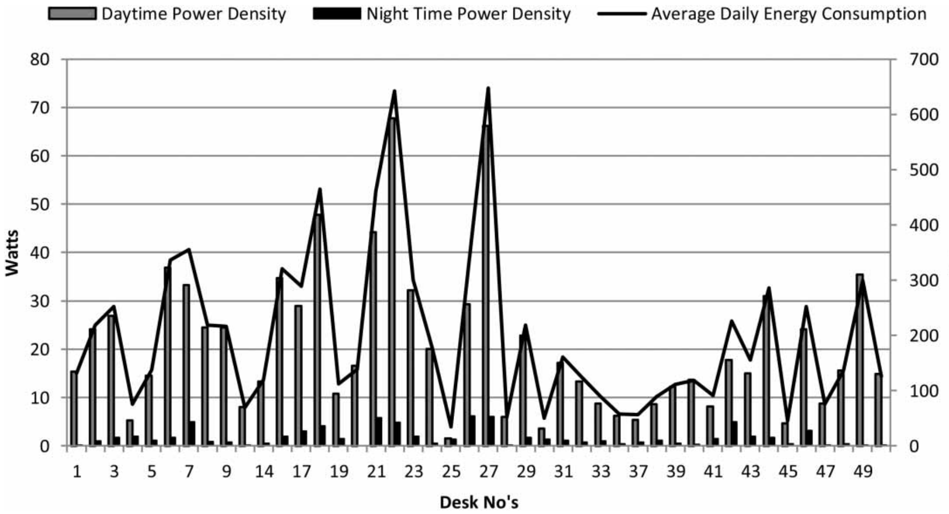

Figure 3. Power density and energy consumption location A.

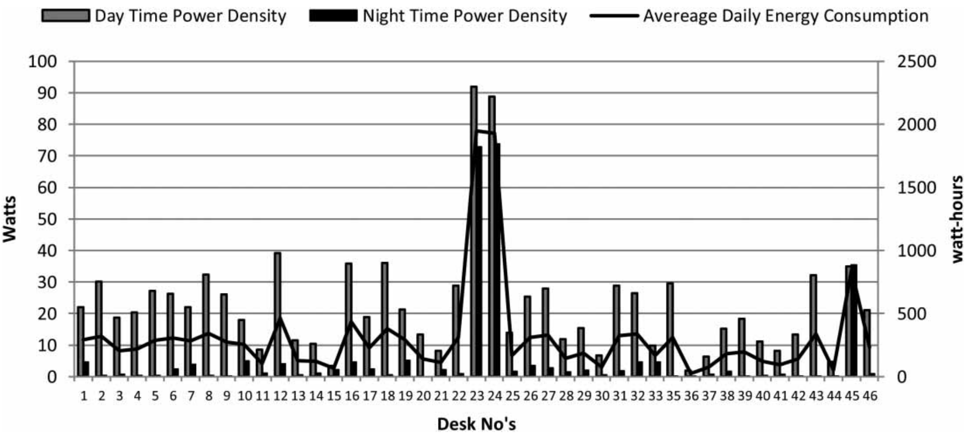

Figure 4. Power density and energy consumption location B.

at office B this was slightly lower at 22.2 W (Figures 3 and 4). As with the average daily energy consumption there was a significant variation in the power density at each desk over the baseline period, with a standard deviation of 14.7 and 10.3[2] W at offices A and B, respectively. This reflects the range of laptops, computers and screens in use and the presence of printers, phone chargers and other small power items in various locations. The power density identified is significantly smaller than the typical benchmark of 160 W per desk space predicted for energy use in Offices (DETR, 2003). Working on the basis of an average occupant density of 12 m^2/person (Gibson & Bamidele, 2010) these power loads equate to desk-level power of 2.1 W/m^2 and 1.85 W/m^2, respectively. Assuming that this equates to two-thirds of overall small power (Energy efficiency in buildings, 2004) this in turn equates to a small power load of 3.15 and 2.775 W/m^2/year at locations A and B, respectively. This compares favourably to the findings of Dunn and Knight (2005) who found small power loads of 17.5 W/m^2 in air-conditioned UK office spaces. These figures equate to overall daytime workstation energy consumption of just 13.4 and 11.8 kWh/m^2/year based on the same occupancy density as before and an 80% attendance rate. These figures demonstrate that in comparison to industry-accepted benchmarks, the locations used for the study already perform above expectation. The performance above benchmark norms of the office equipment can be attributed to the low energy procurement policy already in place at the two sites under consideration, where laptop computers have been favoured over traditional desktops. Not only is the typical power usage of laptops significantly less than that of typical desktop personal computers (20 versus 200 W, on site measurement) but the power-down rate of laptops tends to be in excess of that of personal computers (Kawamoto et al., 2003), reducing the corresponding overnight wastage.

To establish where increased energy consumption or power density at a workstation can be related to equipment being left on outside of office hours it is necessary to consider the power density outside of normal working hours (when equipment not in use but may be on) at each location. This was established by taking a reading for each desk at midnight over the initial baseline period. From this it can be seen that the overnight power density for office A was 1.72 W, equating to just under 7% of the average power density; for office B the overnight power density was 5.4 W, equating to just over 24%[3] of the average (Figures 1 and 2). Taking into account the average length of a working day in each location and despite the relatively strong performance of the sites in comparison to benchmarks, up to 23% of the overall energy consumption at desk level can be attributed to non-working hours. This indicates that there is a significant out-of-hours consumption when productivity is at its lowest; it also supports the theory that it is possible to achieve energy and corresponding CO_2 and cost reductions through behaviour change.

Desk-level analysis

As the device used to monitor the energy consumption at desk level itself draws 0.8 W it can be said that anything above this reading overnight is likely to relate to power being drawn from an additional piece of equipment. Given that a typical laptop will draw 10–60 W (measured) and that this is likely to reduce by 22–51% when idle (Cartledge, 2008) and that a typical 17″ LCD screen draws 40 W (measured) reducing by a similar amount when idle it is possible by using the baseline data to estimate when workstations are powered down overnight and when they are not. Desktop lamps, heaters and mobile phone chargers were also found to be present during field surveys. Given the number of variables involved in equipment and equipment specification it was not possible to fully confirm from the data alone which specific devices if any were left drawing power out of hours.

The data, based on readings taken at midnight for each desk at office location A, demonstrate that during occupied days all desks have devices left plugged in, and often turned on, with reading in excess of 0.8 W (0.8 W drawn from the monitoring device) being recorded regularly. One desk at office location B in the baseline study regularly powered down all equipment. As screens (3 W, measured), laptops (2 W, measured), mobile phone charges (0.3 W measured) and other devices have been known to continue to draw small amounts of power when plugged in but turned off, a larger base load above that drawn by the monitoring device was set at 3 W (equating to 26 14;kWh/year). Thus, 3 W was used to identify where power down has not occurred outside office hours. From this it was found that during the baseline monitoring period 72% of workstations at location A and 70% at location B powered down overnight. The identified power-down rate is significantly less than that found by Kawamoto et al. (2003) which observed power-down rates as high as 80–97% in Japanese offices spaces. Conversely a similar US-based study found power-down rates of just 36% (Roberson et al., 2006). Coupled with the initial findings of this study, bringing UK power-down rates in line with those observed in the Japanese study could offer significant savings; however there is a risk that without interventions more energy could be wasted as demonstrated in the US study. Furthermore the power-down rate identified reinforces the view that despite the use of efficient equipment at the sites under consideration savings due to behaviour change are still possible.

As can be seen from Figure 4, office location B has two workstations where daily energy consumption falls significantly outside the mean. Desks 23 & 24 feature significantly increased power densities of 91.8 and 88.7 W, respectively, as compared to the site-wide average of just 22.2 W. Following the field survey, desks 23 & 24 were found to have standard arrangements with the addition of mobile phone chargers. Comparing the power densities at these desks for working and non-working hours it was found that the workstation equipment was running 24 h a day, indicating the system power management was not enabled. Excluding these two desk locations from the analysis has a significant impact, reducing average daily consumption by 24% to 236.9 Wh (previously 307 Wh), thus bringing it closer to the average daily consumption at location A (236 Wh). This correction is carried forward into the remaining analysis.

There is a valid argument that not all deviation from mean energy consumption can be attributed solely to behavioural issues. The specification, performance, age and configuration of the equipment being used can have a significant effect on the potential to reduce energy consumption. With this in mind, the daily consumption patterns of the top and bottom five consumers at each location were analysed (Figures 1 and 2). At location A it would appear that power management is enabled at all workstations under consideration as a significant overnight reduction is observed throughout. At location B three workstations do not appear to have power management enabled as minimal or no reduction is observed overnight. Average power density overnight compared to the average during working hours for the five lowest energy users was found to reduce by 96 and 90% at locations A and B, respectively. Conversely the top five energy consumptions reduced by 87% and 43% at locations A and B, respectively. The overall average reduction at location A was 90% and location B 82.1%. The lower reduction rate at location B can be attributed to the lack of power management in three locations. Given that older equipment with higher power densities are likely to also have less potential for energy saving in sleep or idle mode, it is difficult without further studies to fully assign the variation in observed energy consumption to equipment or behaviour. However as will be seen later in the study significant reductions can be achieved without changing workstation equipment and configurations.

Impact of interventions

Following the conclusion of the monitoring period it was found that overall reductions in line with the 20% target had been achieved. There were however significant fluctuations in the observed savings, albeit with an overall downward trend. At both locations energy use initially increased before steadily decreasing; this was somewhat unexpected, although it could be interpreted as an initial reluctance to implement change. This is similar to the findings of the report by Cox, Higgins, Gloster, and Foley (2012) on low-carbon behaviours in the workplace which found a reluctance to implement change in some cases. The focus of this paper however is not to consider the psychology behind why the interventions have an impact, but to consider the potential magnitude of that impact. The behavioural aspects of why the interventions have an impact are considered in a separate paper.

Overall the average power density during working hours at occupied desks reduced by 11% at location A and 7% at location B. The power-down rate at location A increased to 79% from 72% while at location B the power-down rate increased to 83% from 70%; these rates compare favourably with the findings of Kawamoto et al. (2003) who observed power-down rates of 80–97% in air-conditioned Japanese office buildings, although further improvements may still be possible. Furthermore it would appear that 46% of users at location A and 56% of users at location B have removed additional items overnight (mobile chargers, fans, heaters, etc.) and potentially unplugged computers and screen as readings of below 0.8 W (monitoring device draws 0.8 W) were observed on a regular basis.

The increased power-down rate and corresponding energy reduction equates to an overall reduction in night-time power density of 5–10% over the follow-up monitoring period at both locations. Applying the relevant working and non-working hours at both locations overall reductions in daily desk-level energy consumption equate to 17.9% at location A and 20% at location B. The increased overall reduction observed at location B over location A can be attributed to the 13% increase in the night-time power-down rate.

Looking more closely at the consumption of the five highest energy users at both locations it can be seen that considerable savings have been made with 34.2 and 33.9% reduction at locations A and B, respectively. In contrast the five lowest energy consumers at each location have made little or no energy savings and indeed at location A an overall increase is observed (27%), thus indicating a push to the middle. Given the locations under consideration already perform well in comparison to industry benchmarks a lack of energy savings at the lower end should not be surprising. However the push towards the middle at location A (although from a low base) is a cause for concern and further investigation beyond the scope of this paper is required to fully understand the causes of this statistic. It could be speculated that this increase is as a result of the lower energy user's feedback demonstrating above-average performance, resulting in less focus on energy savings. The large standard deviation demonstrates that there is a wide variation in the levels of energy reduction achieved across the locations considered. This lack of consistency could indicate a tendency to revert back to previous habits; thus behaviour is still fluid. This would appear to support the findings of Cox et al.'s (2012) study on workplace initiatives for low-carbon behaviour which found that persistence is needed to ensure behaviours become habit. However there is a danger of communication fatigue within this when a backlash against the preferred behaviour can be experienced. This can be hampered by high turnover rates or changes within the office structure; such changes did occur at the locations under consideration in this study and this perhaps could help to explain the level of variation observed.

Discussion

This paper has been able to demonstrate that simple interventions can result in relatively significant energy and corresponding carbon savings. This positions the paper in line with the findings of Carrico and Riemer (2011) and Junnila (2007), where in the USA and Nordic countries, respectively, it was demonstrated that minor interventions resulted in similar savings. The reduction in energy consumption observed[4] equates to carbon savings in the order of 603 $kgCO_2$/year. In the context of a single building these savings are minor (relates to just 90 desks in this case); however if scaled up to the regional or national level and given the limited investment required it can be argued that the carbon savings are significant. In the context of existing buildings, where the cost of carbon savings through reductions in regulated energy can be expensive, the approach outlined can potentially offer carbon reduction of unregulated energy on a cost-effective basis.

As noted by Cox et al. (2012) in the report on workplace initiatives for low-carbon behaviours with studies of this type there is a risk of behaviour reverting to the previous norm if mechanisms cannot be found to encourage a longer-term habitual change. Ensuring the longevity of the savings achieved needs further research; however there is potential for the integration of automated mechanisms for measuring desk-level consumption, encouraging savings and flagging above-average usage.

To achieve such longevity, more constant monitoring and feedback are required. Such monitoring and feedback should aim to encourage energy-saving habits and a culture of continuous improvement through behaviour change aligned with energy-focused building management and procurement processes. This approach could be incorporated into the Building Management System, allowing Facilities Managers to understand energy consumption at the desk level and to measure how interventions impact upon usage patterns. Alternatively it may be possible to develop desktop applications that inform the user of their impact and energy consumption directly over a longer period. These applications could be used as a reminder of usage and to reinforce the preferred behaviour. While the monitoring and feedback mechanisms are important, procurement also has a part to play. As discussed previously, laptop computers generally use less power than traditional desktops and have been observed to result in increased overnight power-down rates (Kawamoto et al., 2003). Automatic shutdown software programmes are commercially available and, as demonstrated by James (2010), can contribute to energy-use reductions as part of a wider savings strategy targeting unregulated energy use.

Conclusions

This study has been able to demonstrate that there is a significant variation in desk-level energy consumption within typical office spaces. It has found that even in offices with relatively efficient equipment exceeding predicted benchmark performance, there is still significant potential for further reductions through behaviour-changing interventions. Up to 23% of energy usage associated with workstation equipment may occur outside of productive working hours. Additionally there is potential for significant wastage throughout the working day depending on work patterns. Power management and equipment procurement policy do offer energy savings; however even simple interventions such as an awareness of being monitored can have an impact on end user behaviour and corresponding energy use if carefully applied.

The challenge going forward is to find mechanisms that ensure the observed energy savings are maintained over time and that there is no creep back towards previous performance. To achieve this, the behaviours that resulted in energy savings need to become habitual.

Notes

1. Exclude extreme cases at desks 23 and 24; see desk-level analysis and Figure 2 (381 W including 23 and 24).
2. Excludes extreme cases at desks 23 and 24; see desk-level analysis and Figure 2 (17.8 including 23 and 24).
3. Ten per cent when extreme cases of desks 23 and 24 are excluded.
4. Based on a grid carbon intensity of 443 g/kWh (Department of Energy and Climate Change, 2012).

References

Abrahamse, W., Steg, L., Vlek, C., & Rothengatter, T. (2005). A review of studies aimed at household energy consumption. *Journal of Environmental Psychology*, *25*, 273–291.

Berl, A., & de Meer, H. (2011). An energy consumption model for virtualized office environments. *Future Generation Computer Systems*, *27*, 1047–1055.

Bordass, W., Cohen, R., & Field, J. (2004). *Energy performance of non-domestic buildings: Closing the credibility gap.* Proceedings from the Building Performance Congress, Frankfurt.

Carrico, A. R., & Riemer, M. (2011). Motivating energy conservation in the workplace: An evaluation of the use of group-level feedback and peer education. *Journal of Environmental Psychology*, *31*, 1–13.

Cartledge, C. (2008). *Sheffield ICT footprint commentary*: *Report for SusteIT.* Retrieved from http://www.susteit.org.uk

Chartered Institution of Building Services Engineers. (2004). *Energy efficiency in buildings: CIBSE guide F.* London: CIBSE Publications.

Chartered Institution of Building Services Engineers. (2008). *Energy benchmarks: Technical memoranda 46*. London: CIBSE Publications.

Cox, A., Higgins, T., Gloster, R., & Foley, B. (2012). *The impact of workplace initiatives on low carbon behaviours: Case study report*. Scottish Government Social Research. Retrieved from http://www.scotland.gov.uk/Publications/2012/03/2237

Department of Energy and Climate Change. (2008). *The climate change act.* London: The Ministry of Justice.

Department of Energy and Climate Change. (2012). *Digest of United Kingdom energy statistics 2012*. London: National Statistics Office.

Department of the Environment. (1997). *Managing energy use. Minimising running costs of office equipment and related air-conditioning: Good practice guide 118*. Watford: Building Research Energy Conservation Unit.

Department of the Environment, Transport and the Regions. (2003). *Energy use in offices: Energy consumption guide 19*. DETR Energy Efficiency Best Practice Programme. Watford: Building Research Energy Conservation Unit.

Dunn, G., & Knight, I. (2005). Small power equipment loads in UK office environments. *Energy and Buildings*, *37*, 87–91.

Gibson, G., & Bamidele, J. (2010). *Property in the economy: A digest and review of key data and statistics*. London: RICS.

James, P. (2010). *Energy efficient improvement opportunities in ICT, evidence of the SusteIT project.* Proceedings from energy efficient ICT workshop, Nottingham Trent University, Nottingham.

Jenkins, D. P., Liu, Y., & Peacock, A. D. (2007). Climatic and internal factors affecting future UK office heating and cooling energy consumptions. *Energy and Buildings*, *40*, 874–881.

Jenkins, D. P., Singh, H., & Eames, P. C. (2009). Interventions for large-scale carbon emission reduction in future UK offices. *Energy and Buildings*, *41*, 1374–1380.

Junnila, S. (2007). The potential effect of end-users on energy conservation in office buildings. *Facilities*, *25* (7), 329–339.

Kawamoto, K., Shimoda, Y., & Mizuno, M. (2003). Energy saving potential of office equipment power managment. *Energy and Buildings*, *36*, 915–923.

Menezes, A. C., Cripps, A., Bouchlaghem, D., & Buswell, R. (2012). Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied Energy*, *97*, 355–364.

Roberson, J. A., Webber, C. A., McWhinmey, M. C., Brown, R. E., Pinkard, M. J., & Busch, J. F. (2006). After-hours power status of office equipment and energy use of miscellaneous plug-load equipment. *Energy*, *31*, 2823–2838.

Vereecken, W., Deboosere, L., Simoens, P., Vermeulen, B., Colle, D., Develder, C., Pickavet, M., Dhoedt, B., & Demeester, P. (2010). Power efficiency of thin clients. *European Transactions on Telecommunications*, *21*, 479–490.

Ward, C. I. (2008). What are the energy and power consumption patterns of different types of built environment? *Energy Policy*, *36*, 4622–4629.

Webber, C. A., Roberson, J. A., Brown, R. E., Payne, C. T., Nordman, B., & Koomey, J. G. (2001). *Field surveys of office equipment operating patterns*. Berkley, CA: Lawrence Berkley National Laboratory.

Zhang, T., Siebers, P. O., & Aickelin, U. (2011). Modelling electricity consumption in office buildings: An agent based approach. *Energy and Buildings*, *43*, 2882–2892.

Paper Two

Jones, K., Mulville, M. and Brookes, A. (2013). FM, risk and climate change adaptation. *In FM for a Sustainable Future, 12th EuroFM Research Symposium, Prague, Czech Republic, 22-24 May 2013. International Journal of Facilities Management, pp. 120-128.* ISBN: 978-94-90694-02-9.

Invited Presentations:

This paper formed the basis for presentations by the candidate at the following events:

- Building Performance in a Changing Climate. Low Carbon Buildings and Communities in the Sustainable Built Environment. British Council Researcher Links Programme, 23-26 February 2015, Istanbul, Turkey;
- Delivering Sustainable Built Environments. Guest Lecture, Rushmore Business School, 16 May 2014, Mauritius.

Other Impacts:

This research had a direct impact on the building that formed the basis for the case study with, as detailed in the paper, a number of proposed adaptations being adopted. This acts to increase the adaptive capacity and resilience of the building, thus improving overall sustainability. The research also had a direct impact on industry as it was carried out alongside the projects design team. In turn a case study publication focused on industry applications was developed from the research.

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FM, Risk and Climate Change Adaptation

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ABSTRACT

Improving the sustainability of built assets in the light of uncertain futures is a major challenge facing the Facilities Management profession. A changing climate poses significant challenges to the performance of built assets in-use and could potentially render many built assets prematurely obsolete. How business clients plan for such changes formed the focus of a research project undertaken by the authors. This paper presents the findings of a 12 month Action Research project that sought to identify the impact of future climate change on the performance of a new £75m education building over the first 60 years of operation. The Action Research project involved a series of meetings and workshops between the building's design team (Architects, Engineers and Cost Consultants) and the Client's Facilities Management Department where the impact that a range of future weather scenarios could have on the buildings performance in-use were evaluated. Technical and operational adaptation solutions were developed for those scenarios that were deemed 'high impact' and selected interventions were integrated into the building life cycle as pro-active adaptation steps in the built asset management plan. This paper will describe the adaptation framework used to inform the development of the various scenarios/adaptation solutions and discuss the role of the Facilities Manager in the process. The paper concludes that the presence of the Facilities Management Department in the design team was critical to the development of viable climate change adaptation solutions.

Keywords

Risk, Adaptation, Climate Change, Resilience, Facilities Management

1. INTRODUCTION

There is a tendency in the construction industry to design and deliver new buildings based around the requirements of the 'here and now'. However, buildings are developed on a design life of 60 years plus and clients' needs from their buildings will change over time. Failure to address this issue places the building at risk of premature obsolescence (Jones, 2002). Whilst this issue has been known for many years, it is compounded by the potential impact of climate change on the physical performance of buildings in-use, and in particular the need for building owners to consider how they might adapt their buildings to different future weather patterns. These concerns are in turn being relayed to design teams who are increasingly under pressure to consider the implications of their design decisions through the whole-life of a building. This paper presents the findings from an Action Research project that used an adaptation framework, supported by future scenarios and back-casting, to inform the development and evaluation of adaptation solutions as part of the built asset management process.

2. BACKGROUND

There is broad scientific consensus that the global climate is changing in ways that will have a profound impact on both human society and the built environment. In addition to average global temperature rise, the frequency and severity of extreme weather events are expected to increase (IPCC, 2007) and impact on the performance of buildings in-use (Jones, 2002). In response to climate change, the UK has implemented The Climate Change Act UK (2008), setting legally binding targets for the reduction of greenhouse gasses by 2050. However, even if the rest of the world follow suit, and the targets are met, there will still be a need to adapt to the consequences of inevitable climate change bought about by current Greenhouse Gas levels. Whilst adaptation does not solely affect the built environment, it does pose a major challenge to those responsible for its operation and renewal. Indeed failure to adapt buildings to climate change could render many prematurely obsolete (Jones, 2002). The challenge facing Facilities Managers is to recognise the potential impact of climate change on their built assets and develop adaptation solutions that ensure the assets continue to perform their required function. However, current approaches to asset management rarely address this issue.

Over the last decade, the UK has experienced significant increases in extreme weather events (EWEs). Heavy rainfall (Fowler & Kilsby, 2003) resulting in both localised urban flooding and more widespread fluvial flooding resulted in £500M worth of insurance claims in the UK in 2000 (RMS, 2000) and £2.2 billion in 2004 (OST, 2004). In addition to flooding the incidence of heat waves (Good et al, 2006) and associated droughts (Blenkinsop & Fowler, 2007) have increased with, in August 2003 over 2000 premature deaths being attributed to the heat wave in southern England alone (Kovats et al, 2006). As a consequence the UK Government established the Adaptation Sub-committee to undertake a UK climate change risk assessment and develop an adaptation programme for England (ASC, 2009). In an assessment of the preparedness of the UK for flooding the Committee identified the need for greater uptake of property-level measures to protect against floods both for new and existing buildings. However, the requirement to consider these issues only applies where development is planned in an existing flood plain, even though the report identified pluvial flooding as a significant problem for the future (ASC, 2012). Thus, given the risks, how should building clients address this issue?

The ability to effectively respond to an EWE depends upon the vulnerability, resilience and adaptive capacity of the building under threat. Whilst there is considerable debate over the precise definitions of the terminology (Gallopin, 2006), from a built environment perspective: vulnerability is normally considered to be the likelihood of exposure to hazards (EWEs) and the adverse consequences resulting from them; resilience, as the ability of the building to prevent, withstand and recover from the impacts of the hazard; and adaptive capacity, as the ability of the building to change (adapt) to meet the new conditions brought about by any permanent changes to the original operating conditions (Jones & Few, 2009). However, organisation's find it difficult to recognise their vulnerabilities let alone assess the resilience of their buildings and develop adaptation solutions to address them (Berkhout, 2004). Organisation's need to consider the likelihood of an EWE occurring and the impact that it could have if it does occur. Also, hazards need to be interpreted relative to a frame of reference that the individual and business can relate to and solutions need to be measurable against clear operational indicators.

Assessing the impacts of hazards on an organisation normally involves the assessment of the risk of an event occurring and the development of contingency plans to deal with the consequences. Whilst risk based assessments are not new to Facilities Managers, using them as part of future climate change scenario planning is. Whilst generic climate change risk assessment models have been developed (Willows & Connell, 2003; UKCIP, 2008; Sustainable Homes, 2012) they are primarily awareness tools that assess whether a management action has been taken, rather than providing practical guidance on how to assess vulnerability, resilience and adaptive capacity. This paper addresses this shortcoming by describing the development of a series of practical steps that can be used to ensure that new buildings are designed in a way that allows for future adaptation to climate change.

3. A CLIMATE CHANGE ADAPTATION FRAMEWORK

There are a number of risk models (UKCIP, 2010; BCI, 2007) currently available to assess vulnerability, resilience and adaptive capacity to EWEs. Whilst each model addresses the problems of risk in slightly different ways, they all follow the same generic methodology. An initial scoping exercise contextualises the system being studied and identifies system boundaries. Once the system boundaries are established, the types of risk (what is at risk, whom is at risk, the causes of the risk, the impacts of the risk, and the threshold levels at which the risk becomes unacceptable) that can affect the system are identified. For each identified risk, a risk appraisal is undertaken where the consequences of the threshold being exceeded are examined and strategies for managing the consequences considered. This process invariably involves the use of scenarios to both identify the potential consequences and evaluate alternative management strategies. Once the risk appraisal is complete, a risk evaluation takes place where the various options are prioritised. Finally the highest priority options are instigated and their performance is monitored. Unfortunately, whilst this generic approach to risk assessment is fairly well understood, its application, particularly in the UK, is patchy and its use at the design phase of new buildings is largely missing. In this paper the generic approach is combined with future climate change scenarios to develop an adaptation framework for assessing the impact of EWEs on the performance of existing buildings and integrating this into the built asset life cycle (Figure 1).

The first Stage of the framework establishes the impact of antecedent EWE hazards on the inherent vulnerability of the building. This should ensure acceptance of the risks by the organisation as they will have first-hand knowledge of the impacts. The second Stage of the model extends the range of EWEs to take into account the impact of future climate change on the type, nature and intensity of events. This phase inevitably involves the use of future scenarios to develop a range of weather patterns that can be superimposed onto the building and its surrounding area to allow specific hazard impacts to be developed for each scenario (e.g. flooding, etc.). These impacts can then be related in relative terms to the antecedent assessments carried out in Stage 1. In this way stakeholders can assess the relative significance of an EWE scenario against a frame of reference that they are familiar with. Once the currency of the scenarios has been established, the impacts of each EWE on the building can be assessed and those components which are highly vulnerable and have low inherent resilience (coping capacity) can be identified. For each of these components adaptations can be developed, either to reduce the vulnerability of the components or improve coping capacity. These can then be prioritised and introduced into the design, at either the initial design phase, or where the impact is expected to be delayed (e.g. not expected to occur until 20 years into the life cycle), as part of the built asset management plan. The operationalization of the adaptation framework model and its ability to integrate effectively with the building life cycle was examined in this study.

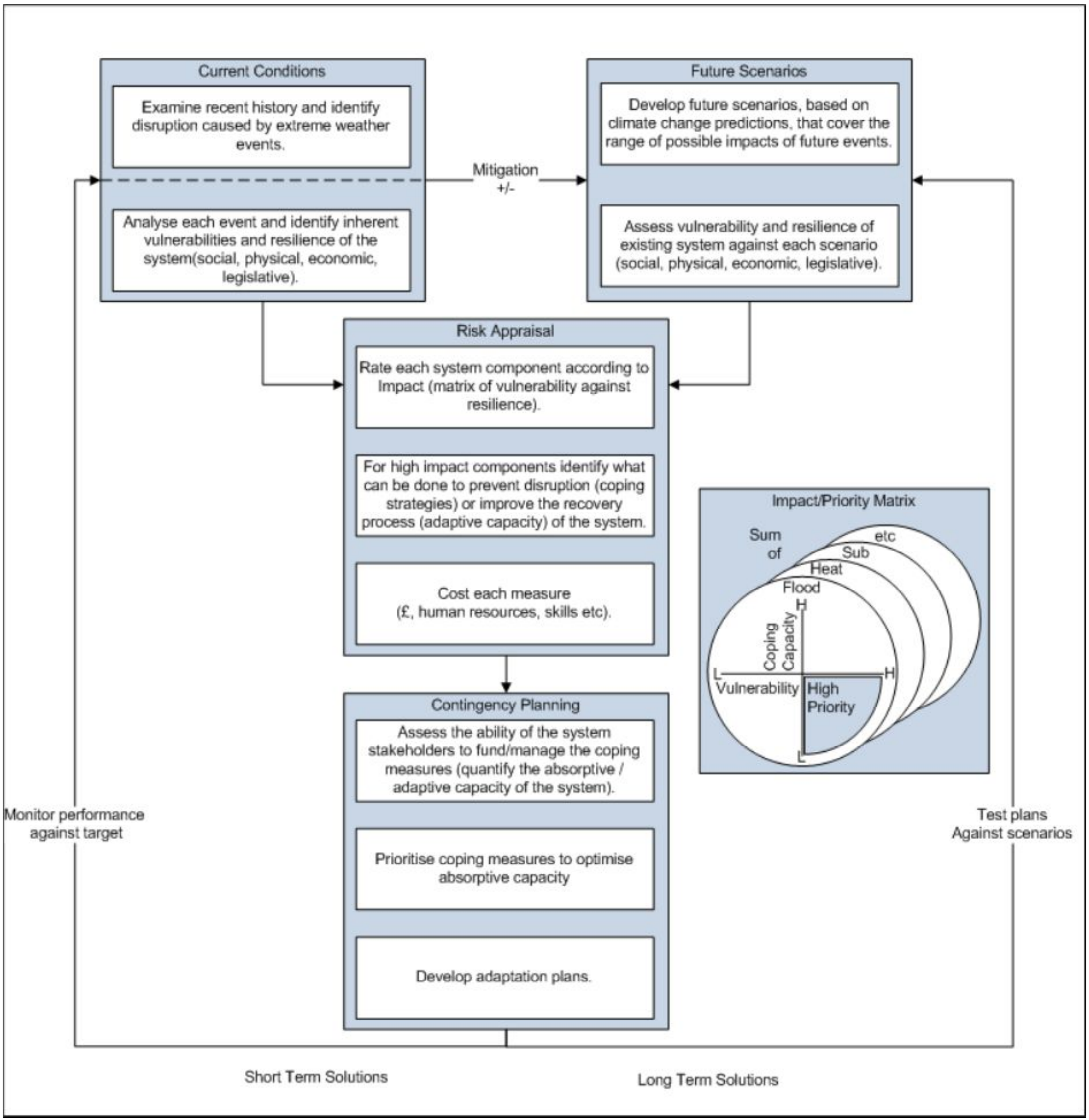

Figure 1. Climate Change Adaptation Framework Model

4. RESEARCH METHODOLOGY

This project applied an Action Research methodology that involved a team of researchers and practitioners examining the issues associated with the implementation of the climate change adaptation framework model to the design phase (RIBA Stage D) of a new £75m educational building being developed by the University of Greenwich. Action Research seeks to use theory to drive changes in practice by studying the impact that context has on the journey towards an end-goal. Through a series of iteration cycles (Planning; Implementation; Reflection; Review) the impact of theory is assessed and refined until the end-goal is achieved or the journey is abandoned. (Lewin & Cartwright, 1975; Heron & Reason, 2001). This approached fitted well with the research challenge of this project.

The Action Research project commenced in October 2010 and was completed in June 2011. The Action Research team comprised representatives from the Architects; Building Services Engineers; Structural Engineers; Quantity Surveyors; the Client (represented by the Facilities Management Department); and the authors to this paper. In addition, specialist input to the project was provided by a climate change expert who developed the climate impact models.

The Action Research team met formally on 4 occasions. Each of these meetings was in the form of a 1 day workshop. Between workshops members of the team worked in small groups to develop, test and refine their inputs. The first meeting established the focus for the project; developed a set of questions for the partners to investigate; agreed procedures for data gathering/analysis; and outlined a set of deliverables for the second meeting, which were mainly concerned with an assessment of the antecedent EWEs (Current Conditions in Figure 1) and the identification of future climate change risks (Future Scenarios in Figure 1).

At the second meeting the Action Research team received a climate change risk report that identified current and expected risks aligned to the predicted first and second refit of the building (2020 and 2040) and design life (2080). The risk reports were generated using the UKCP09 (median prediction emissions scenarios) to produce likely weather scenarios and associated building impacts on: Internal Comfort & Building Façade; External Comfort; Structural Stability; Infrastructure; Water Supply; Drainage & Flooding; Landscaping; and the Construction Process. Although a wide range of EWEs were examined, due to limitations in national data sets the final analysis was limited to issues of thermal performance, where a 3.8-4.8^{o}C rise in annual mean temperature above the control period was predicted by 2080 and pluvial flooding, where an increased risk was identified to the basement areas and attenuation tank capacity.

Once the weather data had been presented, the Facilities Management members of the Action Research team developed performance specifications, in terms of operational expectations for 2020, 2040 and 2080, and the design members analysed how their design solutions would perform against each specification (Risk Appraisal in Figure 1). In particular 4 questions were considered: 1) Would rooms overheat in the future? 2) What will be the impact on the annual energy loads? 3) Can the chiller specification cope with the increased load? 4) How will solar gain change in the future? These analyses were presented to the whole Action Research team at the third workshop. As this project was solely concerned with the impact of climate change no account was taken of other future scenarios (e.g. economic, political etc).

The third Workshop examined the design implications of the questions outlined above. The performance specifications provided the 'operational targets' from which costed adaptation solutions were 'back-cast' to ensure that the building would meet its targets over its life-cycle (Risk Appraisal in Figure 1). This process identified twenty five adaptation measures which were tagged as ‘do now’, ‘2020’, ‘2040’ or ‘2080’. Each adaptation was evaluated against the following principles:

1. Measures that required structural alteration were recommended to be undertaken immediately irrespective of their actual required implementation time.
2. Measures that required changes to system or component capacity were only to be implemented when required but consequential structural and space planning issues were implemented (as 1)
3. Each measure was considered in terms of its impact on the current design and modifications introduced to facilitate a future retrofit.
4. Those measures that were identified but for which the UKCP09 weather data provided no firm direction were assessed on their merits. This particularly applied to the risk of flooding where preparation was undertaken even though the likelihood of future events was uncertain.

At the final workshop each of the detailed adaptations were considered and either adopted or rejected by the client team (Contingency Planning in Figure 1). Of the 25 detailed adaptations developed through this process, seven were adopted immediately and included in the final detailed design. The remainder formed part of the future asset management plan. The full list of adaptation measures can be seen in Table 1.

Table 1. Adaptation measures and implementation schedule

Risk	Adaptation/ Comment	Implementation			
		Now	2020	2040	2080
Overheating	Alter the current glazing system to allow for openable windows to be easily installed in future			•	•
	Install additional chillers on the roof		•	•	
	Future thermal design modifications should be based on an adaptive comfort model		•	•	•
Overheating and Energy Use	Introduce a 'siesta'. Behavioural adaptations were seen as benefitial and could limit the predicted thermal issues. However it would impact on the usability of the building.		•	•	•
Reduced Heating Load	Replace boilers with an increased number of smaller sized units			•	
Insufficient comfortable external areas	Allow all building users to access the roof areas Introduce shading to external spaces Introduce external water features	•			
Increase in cooling load	*Allow for an increase in plant and riser space	•			
Infrastructure failure (electric)	*Add access control to the standby generator	•			
Infrastructure failure (gas)	Include for an electric back-up form of heating (GSHP)			•	
	Increase hot water storage			•	
Infrastructure failure (water)	Increase the cold water storage			•	
Infrastructure failure (drainage)	Increase size of Attenuation tank				•
Increase in storm activity	Increase capacity of rainwater pipes & drainage Increase roof capacity to store rainwater				•
	*Permanent flood protection measures to basement areas *Include adaptable door frames for door dams Increase the height of the retaining walls	•			
Failure of drainage system	*Connect drainage system to the BMS	•			
Increase in groundwater level	*Provide adequate build-up above the tank to avoid flotation	•			
Increase in water costs	Introduce waterless urinals Add a rainwater recycling system			•	
Waste from refurbishments	Upgrade facade systems with recyclable materials	•			
Insufficient cycle storage spaces	*Increase the cycle store capacity	•			
*denontes that the adaptation identified was approved and preparatory work was implimented at the design stage to allow future upgrade when the need became critical (e.g. in 2020, 2040 or 2080)					

The adaptations generally fell into three categories; immediate implementation of the adaptation solution as part of the original build; implementation of preparatory work as part of the immediate build to allow for a planned future upgrade; or operational changes to the building. An example of an immediate implementation was the inclusion of a backup generator to run essential services in the event of a flood. Although the building was not currently at risk of flooding, the future flood risk assessment had identified a potential risk to the critical power infrastructure that supplies the building. This risk, whilst unquantifiable at present, was never the less considered serious enough for the Facilities Management team to advise the client of the need to build in a contingency against this possibility as part of the initial design solution. Examples of preparatory work include an increase to the plant and riser space within the building to accommodate a future increase in chiller capacity for cooling (circa 2020) and allowance for a change to a modular based boiler installation to accommodate a reduction in installed heating capacity as demand reduces over time. Examples of operational changes were adopting a relaxed dress code (staff) and not programming classes for the middle of the day to encourage behavioural adaptations to the thermal environment within the building. The changes were expected from 2020 onwards.

5. DISCUSSION

There is an emerging body of work considering the likely impact of climate change on building performance that are based on simulated predictions and risk based decision making. This study outlines how such an approach could be applied in a systematic manner and embedded in the building design/asset management process. The study aimed to consider the likely climate change impacts to the building on a whole-life basis, identifying adaptations that could be included in the original design, or/and implemented with the 2020, 2040 or 2080 interventions. Such an approach will help to produce a more realistic picture of the buildings likely resilience to climate change. The focus of this paper was to test an adaptation framework and identify the barriers to its application in the design/built asset management process. An Action Research approach was used to refine the original theory in light of the barriers encountered.

The original theory envisaged a 4 stage model to assess and plan building level adaptations to climate change. A number of difficulties/issues arose at each stage of the model.

At Stage 1: There was limited information available to assess the current impact of EWEs on the performance of the building. As such, creating a realistic frame of reference from which to explore the impact of future climate change proved difficult. Indeed, there was considerable scepticism amongst the design team as to the impact that future climate change would have on the building and resistance to considering these impacts at the design stage. These concerns were heightened at Stage 2 of the model where the inability of the UKCP09 projections to produce quantifiable weather patterns at the building scale (UKCP09 is based on a 5km^2 grid and scaling this down to a particular site is difficult) made it difficult for design professionals to develop specific adaptation solutions. This was especially true of predictions relating to rainfall intensity and flood risk which potentially will have greatest impact on the usability of the building going forward. At both these Stages it was the presence of the Facilities Management team in the group that drove the project forward, constantly reinforcing the importance of this project from the client’s perspective and ensuring that the design team took the scenarios seriously and didn’t simply play lip-service to the development of adaptation solutions. To reinforce the scenarios the Facilities Management team developed a series of future performance specifications for the building that required detailed adaptation solutions to be developed, tested and programmed into the built asset management strategy. These specifications effectively set the end point (e.g. system requirement in 2020, 2040 or 2080) from which the various design teams had to work their adaptation solutions back from. In this way interim solutions that would be required on the adaptation journey could be clearly identified and, where necessary, changes made to the initial design to accommodate the adaptation solution. This approach represents a change to the traditional forecasting model of built asset management.

At Stage 3 of the model the main issue to arise was timing of adaptations. The professional design team working on the research project were also working on the main building project. As such, they had a detailed understanding of the building and were able, once they had accepted the climate change projections, to develop technical adaptation solutions (although there was some resistance when their previous decisions were revisited or called into question). What the design team found more difficult was to visualise how these adaptations would be implemented at the 2020, 2040 and 2080 points of the buildings life-cycle. This was particularly true where future adaptations required preparatory work to be included at the initial design stage. For example, the potential need for a larger attenuation tank by 2080 was identified but providing the infrastructure for this at the design stage would significantly increase building cost. The members of the design team responsible for this area did not want their solutions to appear expensive and were very reluctant to change their design to accommodate a future upgrade. Again, it was the presence of the Facilities Management team, and the reassurance this gave to the design team that the increased costs would not be held against them should they bid for future work, that insured the design team took the issue seriously and developed a planned upgrade route should a larger attenuation tank ever be required.

Stage 4 of the model proved the least problematic (probably because the decisions could not be tested until the adaptations were required), with the Facilities Management team able to identify those adaptations which they believed would have the greatest potential impact on the building. Those measures that would not have an immediate impact were scheduled for later building upgrades unless other steps were needed to enable the later adaptation. In addition, a series of thresholds were identified as triggers for inclusion of adaptations into built asset management plans. Whilst quantifiable triggers were not set as part of this project, the built asset management strategy that will inform future maintenance and refurbishment planning does contain specific upgrade routes that can be followed should the climate impacts be realised.

6. CONCLUSIONS

This project tested an incremental approach to developing building adaptation plans that address future climate change. An Action Research approach was used to test and refine the theoretical model underpinning the approach and to identify practical barriers to the application of this approach at the design stage of a new building. The project confirmed the applicability of the approach and identified the proactive role that the Facilities Manager played in ensuring the project success. The Facilities Manager ensured that whole-life considerations overrode the short term considerations of the design team. Without the Facilities Managers setting future performance targets it is unlikely that the design team would have produced detailed adaptation based solutions for 2020, 2040 or 2080. Whilst this may not be a traditional role for a Facilities Manager, if adaptation to climate change is to be taken seriously then the authors would suggest that they should be key members of the design team.

7. REFERENCES

ACS (2009) 'Preparing for Climate Change', available at http://downloads.theccc.org.uk/ASC/ASC%20Booklet%20-%20SCREEN.pdf, (accessed 21/12/2012).

ASC (2012) 'Climate Change – Is the UK preparing for flooding and water scarcity' available at http://hmccc.s3.amazonaws.com/ASC/2012%20report/1586%20ASC_ES_Summary.pdf, (accessed 21/12/2012)

BCI (2007) 'Expecting the unexpected – Business continuity in an uncertain world', available at http://ww.thebci.org, (accessed on 21/12/2012).
Berkhout, F. Hertin, J. & Arnell, N. (2004) 'Business and climate change: measuring and enhancing adaptive capacity', Technical Report 11, Tyndell Centre for Climate Research.
Blenkinsop, S. & Fowler, H.J. (2007) 'Changes in drought frequency and severity over the British Isles projected by the PRUDENCE regional climate models', *Journal of Hydrology,* 342, pp 51-71.
DECC, (2008) 'The Climate Change Act (UK)', The Department of Energy and Climate Change.
Fowler, H.J., & Kilsby, C.G. (2003) 'A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000', *International Journal of Climatology*, Vol 23, No 11, pp 1313-1334.
Gallopin, G.C. (2006) 'Linkages between vulnerability, resilience and adaptive capacity', *Global Environmental Change*, Vol 16 pp 293-303.
Good, P., Barring, L., Giannakopoulos, C., Holt, T., & Palutikof J. (2006) 'Non-linear regional relationships between climate extremes and annual mean temperatures in model projections for 1961-2099 over Europe', *Climate Research*, Vol 3, No 1, pp19-34.
Heron, P. & Reason, J. (2001) 'Theory and Practice: the Mediating Discourse' Handbook of Action Research' Reason, P. & Bradbury H. (ed), SAGE, ISBN 9780761966456.
IPCC (2007) 'the 4th Assessment Report: Working Group 1 - The Physical Science Basis', Chapter 3.8. available at
http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html, accessed on (27/07/2010).
Jones, K (2002) 'Best Value in Construction, Chapter 15, Sustainable Building Maintenance: Challenge for construction professionals – Kelly J (ed)', Blackwell Science, ISBN 0-632-05611-8.
Jones, K & Few, R (2009) 'Community resilience to extreme weather events: a review of theory', Proceedings of the RICS COBRA 2009, Cape Town, pp 630-640.
Kovats, R.S., Johnson, H.,& Griffiths C. (2006) 'Mortality in southern England during the 2003 heat wave by place of death', Office of National Statistics, Health Statistics Quarterly, Vol 29, Spring 2006.
Lewin, K. & Cartwright, D (1951) 'Field Theory in Social Sciences: Selected Theoretical papers', Harper & Brothers. ISBN 9780837172361.
OST (2004) 'Foresight: Future Flooding: Executive Summary', available at http://www.foresight.gov.uk/Previous_Projects/Flood_and_Coastal_Defence/Reports_and_Publications/Executive_Summary/executive_summary.pdf, accessed on (21/12/2012)
RMS (2000). 'U.K. Floods, Nov 2000: Preliminary report of U.K. flood damage from increased rainfall in November 2000' available at
http://www.rms.com/Reports/UKFLOODS_NOV2000.pdf, accessed on 21/12/2012).
Sustainable Homes, (2012) 'National Existing homes Adaptation Tool (NEAT)' available at http://www.sustainablehomes.co.uk/resources/neat-intro, accessed on (21/12/2012).
UKCIP (2010) 'Adaptation Wizard' available at
http://www.ukcip.org.uk/index.php?option=com_content&task=view&id=147&Itemid=273. Accessed on 27th July 2010, accessed on (21/12/2012)
Willows R & Connell C (2003) Climate adaptation: Risk, uncertainty and decision-making. UK Climate Impacts Programme.

Paper Three

Jones, K., Desai, A., Mulville, M. and Jones, A. (2015). Asset management using a hybrid backcasting/forecasting approach. *Facilities,* Vol. 33, 11-12, pp. 701-715.

Citations:

(From associated conference paper – Jones, K., Desai, A. and Mulville, M. (2014) – See Appendix C).

Cox, R.A., Nielsen, S.B. and Rhode, C. (2015). *Coupling and quantifying resilience and sustainability in facilities management*. Journal of Facilities Management, Vol. 13:4, pp.314-331;

Cox, R.A., Rode, C., Nielsen, S.B., and Tarhan, S. (2015). Climate Change and Its Impact on the Operation and Maintenance of Buildings. (BYGDTU. Report; No. 312). Available from: http://orbit.dtu.dk/ws/files/122664317/Climate_change_and_its_impact.pdf

Other Impacts:

The associated conference paper to this publication (see above and Part D) won the best paper award at the CIB Facilities Management Conference in 2014. In their assessment of the paper the judges noted that:

> "*The first paper, by Jones, Desai, Mulville and Jones, was one of the contributions concerning sustainability in terms of taking the effects of climate change into account in the formation of long-term built asset management strategies. The paper presents an original approach using a combination of backcasting and forecasting principles and illustrates the methodology on a new university building in the UK. At the closing session of the conference, this paper achieved the best paper award sponsored by Facilities. The selection of the paper for the award was uncomplicated, as it was the only paper, which both reviewers recommended, to be considered as the best paper*"

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This research had a direct impact on the building that formed the basis for the case study with, as detailed in the paper, a number of proposed adaptations being adopted. This acts to increase the adaptive capacity and resilience of the building, thus improving overall sustainability. The research also had a direct impact on industry as it was carried out alongside the projects design team. In turn a case study publication focused on industry applications was developed from the research.

Since the publication of this paper, the candidate has become a reviewer for this journal.

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Asset management using a hybrid backcasting/forecasting approach

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Abstract

Purpose – The purpose of this paper is to present an alternative approach to facilities and built asset management adaptation planning to climate change based on a hybrid backcasting/forecasting model. Backcasting envisions a future state and examines alternative "pathways of approach" by looking backwards from the future state to the present day. Each pathway is examined in turn to identify interventions required for that pathway to achieve the future state. Each pathway is reviewed using forecasting tools and the most appropriate is selected. This paper describes the application of this approach to the integration of climate change adaptation plans into facilities and built asset management.

Design/methodology/approach – The researchers worked with various stakeholders as part of a participatory research team to identify climate change adaptations that may be required to ensure the continued performance of a new educational building over its life cycle. The team identified 2020, 2040 and 2080 year end-goals and assessed alternative pathways of approach. The most appropriate pathways were integrated into the facilities and built asset management plan.

Findings – The paper outlines a conceptual framework for formulating long term facilities and built asset management strategies to address adaptation to climate change.

Research limitations/implications – The conceptual framework is validated by a single research case study, and further examples are needed to ensure validity of the approach in different facilities management contexts.

Originality/value – This is the first paper to explore backcasting principles as part of facilities and built asset management planning.

Keywords Backcasting, Forecasting, Adaptation, Climate change, Building refurbishment, Built asset management

Paper type Research paper

1. Introduction

The impacts that climate change could have on built assets is well documented (Camilleri *et al.*, 2001; Sanders and Phillipson, 2003; Liso *et al.*, 2003; Levermore *et al.*, 2004), as is the suitability of alternative adaptation strategies to address these impacts

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(Garvin *et al.*, 2005; Hacker *et al.*, 2005; DCLG, 2010; Tillsona *et al.*, 2013). What is less clear from literature is how adaptation strategies can be integrated into long-term built asset management planning (Desai and Jones, 2010). Desai and Jones (2010) argued that the uncertainty associated with climate change; the long-term nature of future climate projections; and the short-term operational demands placed on buildings make it difficult for facilities managers to prioritise climate change adaptations over other interventions that have a more immediate benefit. However, failure to address climate change in a timely fashion could render many buildings prematurely obsolete. Desai and Jones (2010) further argue that current forecasting tools used by facilities managers to set built asset management plans could exacerbate potential future problems by restricting the scope of possible long term "futures" to an extrapolation of current experiences and performance trajectories. Such an approach limits the inclusion of step change scenarios that may be required to address the impacts that future climate change could have on many buildings.

This paper presents an alternative theoretical approach to developing long-term "futures" based on backcasting, supported by forecast modelling which is used to identify potential adaptations that may be required to improve a building's resilience to future climate change, specifically increased flooding and overheating. The focus of the paper is a new £75 m educational building which, at the time of this research project, was at the detailed design stage. The building will occupy a 0.65-hectare brown field site located within a world heritage site. The building will be bounded by transport infrastructure on two sides and residential/commercial buildings on two sides. The building will have an internal area of 15,267 m^2. The building will house Academic Departments, a University Library and provide a series of shop fronts onto the main street. The building has been designed to achieve building research establishment environmental assessment methodology (BREEAM) excellence [...]. The paper reviews the theory of backcasting against the backdrop of the building described above and outlines the participatory research approach that was used to develop a 70-year climate change adaptation strategy for the building. In turn, the paper presents a theoretical model by which the learning from the project could be applied more generally as a part of the strategic built asset management process. The paper concludes that backcasting could provide the theoretical base to support the step change in thinking about built asset management performance that is required to address future climate change. The paper also identifies the need for new life cycle analysis tools to support a backcasting approach.

2. State-of-the-art

Future studies have been used for policy planning; in depicting economic and market trends; and for setting organisational strategies. In this context Chatterjee and Gordon (2006) identified a "futures" spectrum and described a range of approaches to deal with uncertainty and ambiguity at one end of the spectrum (e.g. behavioural simulations, scenario planning and modelling etc.) and certainty at the other end of the spectrum (e.g. forecasting, exploration etc.). Based on this, Miola (2008) (citing Banister and Stead, 2004) mapped the different types of scenario to distinct the future studies (Table I).

"Probable" and "Possible" future studies are viewed as forecasting approaches which use predictive and exploratory scenarios based on quantitative data generated from surveys, past and current trend monitoring and explanatory modelling to develop views of the future. These approaches require a stable and framed system and manageable time frames. "Preferable/Desired" future studies are viewed as backcasting approaches which use visionary and prospective scenarios based on a mix of quantitative and qualitative data generated through workshops, focus groups and Delphi techniques to develop views of the future. These approaches are more tolerant of unstable and unframed systems and of long time scales. In all future studies, the future views provide the criteria against which success or failure of alternative solutions can be evaluated.

The term backcast is widely attributed to Robinson (1982, 1990), who defined it as a normative method in which a desired long-term end-point is set and then used as the reference point to "look back" to the current day position to identify the various stages at which actions are required to achieve a successful journey from the current day position to the preferred future position. In a review of backcasting Dreborg (1996) concluded that the approach was most applicable to situations where:

- the problem being addressed is complex and a change in the existing trend is required;
- time frames are long and deliberate choices (interventions) need to be made;
- dominant trends are part of problem; and
- the problem scope is wide and externalities are crucial.

The application of "backwards-looking-analysis" was pioneered in exploring energy policy in the USA (Lovins, 1976), and it continues to be applied to a variety of energy challenges today, including developing plans for 100 per cent renewables within countries (ICARB, 2014). Backcasting has also been used in the Transition Town movements (Hodgson and Hopkins, 2010) as a participatory tool where workshops, built around visioning exercises and a "Transition Timeline", allowed individuals to envisage particular future events over a 20-year timeline; in environmentally sustainable transport (Geurs and van Wee, 2004) and water infrastructure (Gleick *et al.*, 1995) projects; and for sustainable employment planning (Koves *et al.*, 2013). Also, Quist (2007) reviewed a number of case studies that used backcasting methods in food and land use studies and concluded that the backcasting approach was useful in developing a shared vision of the future from which follow-up or spin off activities could be generated.

In addition to policy studies, backcasting has also been applied in commercial settings. Nike, Ikea and Interface used the Natural Step[1] to inform their medium- to long-term business strategies. However, in this application, rather than imagining a single future (which they argued was too difficult to achieve among a large number of people with different perspectives) the Natural Step generates a set of principles that

Future studies	Questions	Scenario
Probable	What is likely to happen	Precautionary/predictive scenarios
Possible	What might happen	Explorative/projective scenario
Preferable/desired	What would we prefer to happen	Visionary/normative prospective scenario

Source: adapted from Miola (2008)

Table I.
Future studies and respective scenarios

define a sustainable future space. Backcasting is then applied to identify alternative pathways of approach to arrive at the desired future space.

Finally, although most research studies have treated backcasting and forecasting as separate, distinct approaches, Hojer and Mattsson (2000) suggest that they can be combined in situations where forecasting alone suggests the future end-point is unlikely to be reached. In this case, backcasting provides the futures vision and pathways, while forecasting is used to quantify the ability of interventions to bring about the desired future.

The author's contend that the backcasting approaches reviewed above map well to the problems associated with integrating climate change into future facilities and built asset management decision-making models where:

- climate change scenarios are complex and subject to uncertainty;
- facilities and built asset management time scales are long, typically 30-70 years;
- short-term thinking tends to dominate over long-term objectives; and
- potential solutions involve multiple stakeholders and external agencies.

Further, because of the wide range of stakeholders involved in developing and delivering long-term facilities/built asset management plans, the authors suggest that a modified version of backcasting, participatory backcasting, can be used to develop long-term future visions and transition pathways with a version of forecasting used to quantify the impact of alternative interventions to deliver the desired end goal. This approach mirrors closely the five-stage model, suggested by Quist and Vergragt (2006):

1. *Stage 1:* Strategic problem orientation.
2. *Stage 2:* Specification of external variables.
3. *Stage 3:* Construction of future visions or scenarios.
4. *Stage 4:* Backcasting: backwards-looking analyses.
5. *Stage 5:* Elaboration and defining follow-up and an action agenda.

This approach is reviewed in the remainder of this paper.

3. Research methodology

3.1 Research project

The subject of the research project was a £75m (capital cost) new educational building. As part of the initial design, the client requested their Facilities Management Department to work with the design team to undertake a review of the potential impact that climate change could have on the building and develop a long-term facilities and built asset management strategy to ensure that the building continued to perform at an acceptable level over a 70-year period. Researchers from the Sustainable Built Environment Research Group were part of the Client Organisation and acted in an observational capacity during project team meetings (although the authors did comment on specific issues at the request of other team members). The data presented in this paper is the result of a post-project process review undertaken by the authors after the completion of the building design phase.

3.2 Participatory research process

The research project commenced in October 2010 and was completed in June 2011. The project team comprised representatives from the Architects; Building Services Engineers; Structural Engineers; Quantity Surveyors; the Client (represented by the Facilities Management Department); and members of the Sustainable Built Environment Research Group as observers. In addition, specialist input to the project was provided by a climate change expert who developed the climate impact models. The project team met formally on four occasions. Each of these meetings was in the form of a one-day workshop. Between workshops, members of the team worked in small groups to develop, test and refine their inputs. The first meeting established the focus for the project; developed a set of questions for the partners to investigate; agreed procedures for data gathering/analysis; and outlined a set of deliverables for the second meeting, which was mainly concerned with an assessment of the antecedent climate threats and the identification of future climate change risks.

At the second meeting the project team received a climate change risk report that identified current and expected risks aligned to the predicted first and second refit of the building (2020 and 2040) and design life (2080) (these dates were chosen to align with the timeframes of the UK Climate Projections [UKCP09] projections for the 2020s, 2050s and 2080s, although the first refit is early in the buildings life, projections for the 2020s indicate the potential for a significant temperature rise which could have an adverse impact on the building). The risk reports were generated using the UKCP09 (median prediction emissions scenarios) to produce likely weather scenarios and associated building impacts on: internal comfort and building facade; external comfort; structural stability; infrastructure; water supply; drainage and flooding; landscaping; and the construction process. Although a wide range of extreme weather events were examined, on review, the client side stakeholders decided to focus primarily on issues of thermal performance, where 3.8-4.8°C rise in annual mean temperature above the control period was predicted by 2080 and pluvial flooding, where an increased risk was identified to the building's basement areas and attenuation tank capacity.

Once the weather data had been presented, the facilities management members of the project team developed performance specifications, in terms of operational expectations of the building for 2020, 2040 and 2080, for each of the impacts identified above. The design side stakeholders analysed how their design solutions would perform against each specification. By way of example, for internal comfort and building facade four questions were asked:

Q1. Would rooms overheat in the future?

Q2. What would be the impact on the annual energy loads?

Q3. Can the existing chiller specification cope with any increased load?

Q4. How will solar gain change in the future?

The results of these analyses were presented to the whole project team at the third workshop. Similar analyses were presented for the other impact areas. As this project was solely concerned with the impact of climate change, no account was taken of other future scenarios (e.g. economic, political etc.).

The third workshop examined the design implications of the questions outlined above. The performance specifications provided the "operational targets" (end-points) from which costed adaptation solutions were "backcast" to ensure that the building would meet its targets over its life cycle. This process identified 42 possible adaptation measures of which 25 were tagged as "do now", "2020", "2040" or "2080". Each adaptation measure was evaluated against the following principles:

- Measures that required structural alteration were recommended to be undertaken immediately irrespective of their actual required implementation date.
- Measures that required changes to system or component capacity were only to be implemented when required, but consequential structural and space planning issues were implemented as mentioned in 1 above.
- Each measure was considered in terms of its impact on the current design and modifications introduced to facilitate a future retrofit.
- Those measures that were identified, but for which the UKCP09 weather data provided no firm direction, were assessed on their merits. This particularly applied to the risk of flooding, where preparation was undertaken even though the likelihood of future events was uncertain.

At the final workshop, each of the detailed adaptations were considered and either adopted or rejected by the client team. Of the 25 detailed adaptations developed through this process, eight were adopted immediately and included in the final detailed design. The remainder formed part of the future facilities and built asset management plan. Further details of the technical and managerial interventions proposed and adopted, and the reasoning behind these decisions can be found in the technical paper reviewing climate change adaptation associated with this case study by Jones *et al.* (2013). The full list of adaptation measures proposed can be seen in Table II.

4. Integrating adaptation into built asset management

Following completion of the building design phase, the research team analysed the activities of the project team to identify the generic decision-making process that had been used in assessing climate change risk. From this review, a generic six-stage approach to the integration of climate change adaptations into facilities and built asset management was identified.

4.1 Stage 1: set end goal

The first task undertaken by the project team was to establish the desired outcomes (in terms of building performance criteria) that any adaptation solution would need to satisfy. This process involved reviewing corporate documents and long-term strategic plans to establish the future context within which the building would have to operate. The outcomes were then expressed as a facilities management problem orientation statement. The statement said that any adaptation strategy should seek to ensure that:

> […] the performance of the new built facility in terms of its future resilience to climate change, and ability to fulfil mitigation targets, should be achieved without compromising user comfort and future operational demands.

This in essence was the project's strategic end-goal.

Risk	Adaptation/comment	Implementation			
		Now	2020	2040	2080
Overheating	Alter the current glazing system to allow for openable windows to be easily installed in future [T][a]			•	•
	Install additional chillers on the roof [T][a]		•	•	
	Future thermal design modifications should be based on an adaptive comfort model [M]		•	•	•
	Allow for an increase in plant and riser space [T][a]	•			
	Introduce a 'siesta'. Behavioural adaptations were seen as beneficial and could limit the predicted thermal issues. However, it would impact on the usability of the building. [M][b]		•	•	•
Reduced heating load	Replace boilers with an increased number of smaller sized units [T][a]			•	
Insufficient comfortable external areas	Allow all building users to access the roof areas [M][c]	•			
	Introduce shading to external spaces [T][c]				
	Introduce external water features [T][c]				
Infrastructure failure (electric)	Add access control to the standby generator [T][c]	•			
Infrastructure failure (gas)	Include for an electric back-up form of heating (GSHP) [T][c]			•	
	Increase hot water storage [T][c]			•	
Infrastructure failure (water)	Increase the cold water storage [T][c]			•	
Infrastructure failure (drainage)	Increase size of attenuation tank [T][b]				•
Increase in storm activity	Increase capacity of rainwater pipes and drainage [T][a]				•
	Increase roof capacity to store rainwater [T][b]				
	Permanent flood protection measures to basement areas [T][c]	•			
	Include adaptable door frames for door dams [T][c]				
	Increase the height of the retaining walls [T][c]				
Failure of drainage system	Connect drainage system to the BMS [T][c]	•			
Increase in groundwater level	Provide adequate build-up above the tank to avoid flotation [T][c]	•			
Increase in water costs	Introduce waterless urinals [T][b]			•	
	Add a rainwater recycling system [T][b]				
Waste from refurbishments	Upgrade facade systems with recyclable materials [T][a]	•			
Insufficient cycle storage spaces	Increase the cycle store capacity [M][c]				

Notes: [T]: Technical intervention, [M]: Management/behavioural intervention; [a] Implementation of preparatory work as part of the immediate build to allow for a planned future upgrade (date noted is the date of the future adaptation – unless future date required is unclear in which case "do now" is noted i.e. the date of the preparatory work); [b] Future change to the building; [c] Adaptation implemented as part of the original build; the dots represent the time period in which the adaptation should take place

Table II.
Adaptation measures and implementation schedule

4.2 Stage 2: set performance targets

Once the future building expectations had been articulated, the project team established specific performance criteria against which alternate adaptation options could be evaluated. In the case of this project, the key criteria were future CO_2 reduction, energy-efficiency improvements and resilience of the building to the impacts of flooding (identified as a consequence of increased storm intensity and the inability of the local drainage system to cope with the expected volume of water). Wherever possible, quantitative performance targets were set (e.g. future overheating thresholds) against which adaptations to future climate change projections could be evaluated. Where this was not possible (e.g. behavioural responses to overheating), qualitative performance targets were set as a guide to future expectations. This stage expressed the strategic end-goal as a series of performance targets.

4.3 Stage 3: develop future scenarios

Setting the expected "end-point" or "target" of future adaptations provided a focus for the development of alternative pathways that could be taken to achieve the end-point. A range of future pathways (technical and operational) was identified that could form the basis of alternative adaptation pathways. As a starting point, the project team established the business as usual scenario as a reference point for envisioning alternative scenario pathways based on reflection and shared knowledge of the organisation. Five further scenario pathways were then developed:

(1) *Scenario 1 (business as usual pathway)*: For this base scenario, the energy load because of heating and cooling was presumed to increase while the energy supply source remained the same (i.e. energy supplied using a mix of gas and electricity). The resulting CO_2 levels would be offset by buying carbon credits to ensure the organisation hits expected UK government targets for their sector. No additional adaptation measures for flooding resilience were considered with the consequences of any future flooding event being dealt with through existing disaster recovery and business continuity plans.

(2) *Scenario 2 (management pathway)*: Considering the UK Government drive for renewable energy, this scenario envisioned new procurement contracts for renewable energy supply. The scenario also envisaged new workplace strategies to encourage energy efficient behaviour (e.g. incentives and acknowledgements for energy efficient departments and employees). A new disaster recovery plan using a flood warning system to trigger a flood management strategy was also envisaged.

(3) *Scenario 3 (design pathway)*: This vision outlined the use of landscaping and natural ventilation systems to reduce cooling loads in the event of an increase in overheating in the future. Building users would also be encouraged to make use of external spaces, particularly the roof gardens. The landscape would be designed using sustainable urban drainage systems (SUDS) principles, and this would also make the site more resilient to flood events.

(4) *Scenario 4 (technical pathway)*: This scenario assumed a range of technical adaptations would be retrofitted to the building as and when they were needed. The difference between this approach and a traditional refurbishment model is that the building would be designed with specific retrofit upgrades in mind. This would include initial preparatory works being undertaken during the original construction phase to allow subsequent retrofit in the future. Measures for flood resistance such as floodgates are put in place; the electrical sockets are placed above the flood level; and the basement would have resilient fixtures and fittings. No critical

services would be placed at the basement level and flood kits would be provided for after flood cleaning processes.

(5) *Scenario 5 (combined technical/management pathway)*: This scenario outlined the use of a combination of technical (e.g. additional air condition units or portable fans during overheating events) and management (e.g. staff encouraged to adopt a casual dress code and make use of outdoor spaces during breaks) adaptations similar to those described above.

These scenarios are shown conceptually in Figure 1. Although the scenarios were not developed against any specific backcasting approach, they do demonstrate the application of backcasting principles. Figure 1 shows the gap between the required performance and expected performance of the building over time. The dotted line represents “a time in the near future”, where the actual performance of the building under a “business as usual scenario” is below the optimum that would be desired (the top line). The assumption in the diagram is that this underperformance is due in part to the then current impacts of climate change. The bottom line represents the improvements in performance over time that could be expected from application of existing facilities and built asset management plans. The top line represents the required performance as derived from the envisioning scenarios to address the impact of climate change (the desired end-goal). The space between the two lines represents the future adaptation space. The lines within the adaptation space represent alternative adaptation pathways that were backcast (the arrows) from the future end-goal. Design and technology adaptations are assumed to be lagging solutions; management and behavioural adaptations are assumed to be leading solutions. At this point, the model is explanatory and not intended to identify the most the appropriate adaptation route for a building.

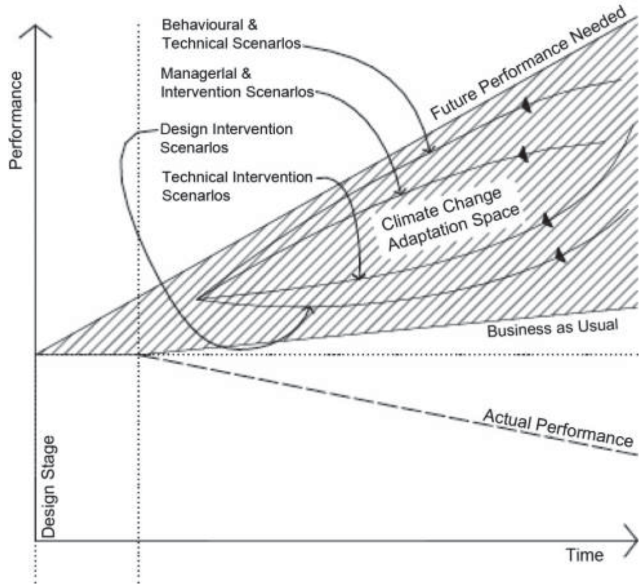

Figure 1. Explanatory model of the backcasting approach

4.4 Stage 4: evaluate adaptation options

To work out the operational and financial feasibility of alternative adaptations, a building simulation modelling exercise was undertaken (a forecasting approach). Each adaptation was considered against the eight principle design criteria: internal comfort and building facade; external comfort; structural stability; infrastructure; water supply; drainage and flooding; landscaping; and the construction process. Each scenario was then considered against the 2020, 2040 and 2080 time frames. The feasibility studies identified 42 possible adaptations, the majority of which were technical in nature. The fact that technical adaptations dominated discussions was not surprising as the majority of the project team were engineers and architects who were familiar with undertaking technical assessments. Indeed, the lack of an approach for evaluating the behavioural and managerial strategies for climate change adaptation was one of the key findings to emerge from this part of the study.

4.5 Stage 5: identify adaptation path

The project team reviewed the adaptation options identified in Stage 4 to identify when in the building time line each would need to be enacted. Although a full-life cycle cost analysis was beyond the scope of the project, an initial assessment of the cost, based on the cost of the proposed adaptation at current rates, and benefits that each adaptation would have on the building's performance (or severity of the impact of not implementing the adaptation) over time was considered. The adaptations were allocated to one of the three categories; immediate implementation of the adaptation solution as part of the original build; implementation of preparatory work as part of the immediate build to allow for a planned future upgrade; or future operational changes to the building (Table II). An example of an immediate implementation was the inclusion of a backup generator to run essential services in the event of a flood. Although the building was not currently at risk of flooding, the future flood risk assessment had identified a potential risk to the critical power infrastructure that supplies the building. This risk, while unquantifiable during the project, was nevertheless considered serious enough for the facilities management team to advise the client of the need to build in a contingency against this possibility as part of the initial design solution. An example of preparatory work was to increase the plant and riser space within the building to accommodate future increase in chiller capacity for cooling (circa 2020) and support a change to a modular-based boiler installation to allow for a reduction in installed heating capacity as demand reduces from 2040 onwards. Examples of operational changes were adopting a relaxed dress code (staff) and not programming classes for the middle of the day to encourage behavioural adaptations to the thermal environment within the building. The changes were expected from 2020 onwards.

4.6 Stage 6: implementation

Those adaptations identified for immediate implementation, or where preparatory work was required at the design stage to support their later implementation, were included as changes to the original building design. These changes were estimated to cost the client an additional 0.4 per cent of total project cost. Those adaptations that were potentially required in the future were programmed into the building's long-term built asset management plan. The cost of these changes was estimated at 2.2 per cent of total project cost.

Although the above process is based on the analysis of only one building project, the authors believe that it could form the basis of integrating adaptation (to climate change) planning into built asset management.

5. Discussion and practical implications

The project described in this paper did not set out to explicitly test the application of backcasting and forecasting to built asset adaptation planning. Indeed, the project reported was not ostensibly a research project but was a real life-building project in which the author's primary role was as observers to the design phase. This said, the authors did provide input to the project team on request and were involved in discussion with the client's facilities management team outside of the formal projects meetings. As such, the findings presented in this paper represent a post-project analysis in which backcasting and forecasting were identified as the theoretical approach that best described the actions of the project team as they sought to integrate adaptation to climate change into the design and built asset management process. Based on the post project analysis, an explanatory model (Figure 2) summarising the general approach to the application of a hybrid backcasting/forecasting approach to facilities and built asset management was developed.

In applying the hybrid backcasting/forecasting model to the integration of climate change adaptation into the built asset management process facilities managers need to concern themselves with preferred/desired (rather than the probable/possible) scenarios to set the end goal (Figure 2: Stage 1) and performance criteria (Figure 2: Stage 2) against which alternative adaptation solutions can be evaluated. These views need to detach themselves from existing trajectories (building and operational) and be responsive to

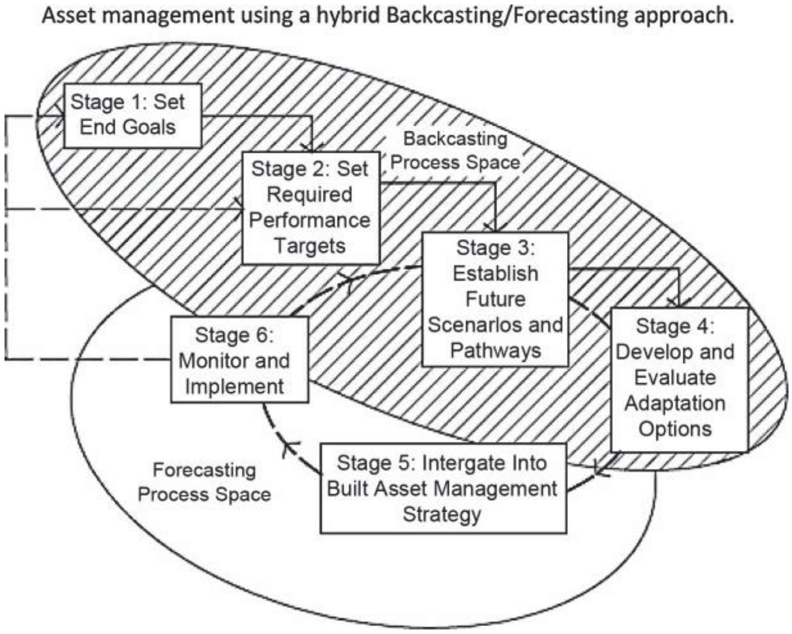

Figure 2. Integration of backcasting and forecasting applied to facilities and built asset management

long-term timescales and inconsistent data. In practical terms, these need to be developed through collaborative exercises that reflect the views of the diverse stakeholder groups that are involved in a building's future and need to use approaches that can accommodate conflicting opinions (e.g. focus groups, workshops, Delphi Groups etc.). In essence, they need to establish a future scenario space rather than a single end point.

Once the future vision is established, alterative pathways of approach need to be identified (Figures 1 and 2: Stage 3) that reflect the strategic aspirations of the organisation. At this stage, the pathways of approach should be considered a management tool to focus discussion about the implications of alternative adaptation strategies (e.g. technical, managerial, behavioural or combined intervention) rather than a planning tool in which detailed adaptation solutions are programmed into built asset management plans. In essence, the alternative pathways provide the strategic guidance which will inform future evaluations.

The approach described above maps well to the participatory backcasting approach reviewed previously. However, to integrate adaptation solutions into built asset management plans, a forecasting approach is also required.

With the end goal set and alternative pathways of approach identified, individual adaptation solutions can be developed and evaluated against the performance criteria set in Stage 2. The design and evaluation of each adaptation option (Figure 2 Stage 4) needs to identify the time in the future that the adaptation might be needed (or establish a mechanism to monitor building performance over time) and consider the cost and benefit of each option in achieving the required improvement in performance. Those adaption options that are considered cost effective are then programmed into the built asset management plans (Figure 2: Stage 5).

Implementation (Figure 2: Stage 6) should occur as and when the building performance falls below the threshold associated with the chosen adaptation pathway (Figure 2: Stage 3). Any preparatory work required to accommodate the future adaptation should be included in the original design.

6. Conclusions

This paper outlined a hybrid approach which integrated backcasting and forecasting principles into the development of building adaptation plans to address future climate change. The hybrid approach emerged from a participatory research project of a £75m new educational building. The processes developed by the project team confirmed the applicability of a hybrid backcasting/forecasting approach to developing and integrating adaptation to future climate change into facilities and built asset management strategies.

Backcasting can provide facilities managers with a vehicle to envision future scenarios based on the complex and uncertain data associated with climate change predictions and identify alternative solution pathways by looking backwards from the future end-goal to the present day. Because such solution paths are not constrained by short-term thinking or current dominating trends, they can address a much wider range of possible solutions, including management strategies, as well as technical interventions, than would normally be associated with the traditional building centric approach to facilities and built asset management planning. Although in this project the adaptation solutions developed tended to be biased towards technical retrofit solutions, this most likely reflected the balance of the project team, and the lack of an accepted approach for quantifying the cost benefit of management strategies for climate change adaptation, rather than an inherent weakness in the backcasting approach.

Forecasting tools still have a role to play in adaptation planning, as they provide the models that allow the alternative solution paths can be quantified and evaluated. This was particularly true for this project where cost/benefit analyses were needed to justify changes to the initial design to accommodate potential future retrofit.

Although the hybrid backcasting/forecasting approach to adaptation planning described in this paper does provide the facilities manager with a new way of integrating climate change adaptations into facilities and built asset management planning, there are a number of issues that need to be addressed before the full benefits of the approach can be realised. The most pressing area for research is the development of a range of life cycle analysis tools that can realistically provide robust cost/benefit assessments for the range of managerial/ behavioural solution paths that will allow their direct comparison with technical solution paths. Failure to develop such tools will invariably result in technical solution paths being favoured over managerial/behavioural solutions, which the authors contend would reinforce the dominant (technically focused) trend which is part of the adaptation problem trying to be solved. In addition, the availability of such life-cycle assessment tools would enable the design team to overcome the initial apprehension (as was experienced here) to the project, as a more systematic approach may be possible, which closer reflects the everyday practice of the professionals involved.

The approach detailed here is based on a single case study with a willing client (a significant benefit to the project), and this must be considered as a limitation. However, the authors believe that this approach could be applicable to a range of non-domestic buildings where external climatic conditions and changes in these conditions have the potential to impact upon the performance/operation of the building over time, especially if the tools suggested above can be developed. Each building however must be considered on its merits, for instance in the case considered here the building already featured a number of passive and low energy measures which potentially improve the buildings resilience to climate change (at least in some categories). The limitations and uncertainty contained within the climate change projections available also present a limitation, particularly in relation to flooding. As such, the design team needs to be able to "buy-in" to the potential implications of climate change in order for an engaged approach to be taken and for this, they need a degree of confidence in the projections being put forward.

Note

1. www.naturalstep.org/en/backcasting

References

Banister, D. and Stead, D. (2004), "The impact of ICT on transport", *Transport Reviews*, Vol. 24 No. 5, pp. 611-632.

Camilleri, M., Jaques, R. and Issacs, N. (2001), "Impacts of climate change on building performance in New Zealand", *Building Research Information*, Vol. 29 No. 6, pp. 440-450.

Chatterjee, K. and Gordon, A. (2006), "Planning for an unpredictable future: transport in Great Britain in 2030", *Transport Policy*, Vol. 13 No. 3, pp. 254-264.

DCLG (2010), *Guidance and Standards for Drying Flood Damaged Buildings – Signposting Current Guidance – BD2760*, Department of communities and local government (DCLG), London.

Desai, A. and Jones, K. (2010), "Examination of existing facilities management approaches to climate change and future directions", *Proceedings of the São Paulo 2010 CIB W070 International Conference, CIB Proceedings, Department of Construction Engineering, Escola Politécnica, University of São Paulo, São Paul*, pp. 585-596.

Dreborg, K.H. (1996), "Essence of backcasting", *Futures*, Vol. 28 No. 9, pp. 813-828.

Garvin, S., Reid, J. and Scott, M. (2005), *Standards for the Repair of Buildings Following Flooding*, Construction Industry Research and Information Association (CIRIA), London.

Geurs, K. and van Wee, B. (2004), "Backcasting as a tool for sustainable transport policy making: the environmentally sustainability transport study in the Netherlands", *EJTIR*, Vol. 4 No. 1, pp. 47-69.

Gleick, P.H., Loh, P., Gomez, S.V. and Morrison, J. (1995), *California Water 2020: A Sustainable Vision*, Pacific Institute, Oakland, CA.

Hacker, J., Belcher, S. and Connell, R. (2005), "Beating the heat: keeping UK buildings cool in a warming climate", UKCIP Briefing Report, UK Climate Impact Program, Oxford.

Hodgson, J. and Hopkins, R. (2010), *Transition in Action: Totnes and District 2030, an Energy Descent Action Plan*, Green Books, available at: //www.greenbooks.co.uk/transition-in-action

Hojer, M. and Mattsson, L. (2000), "Historical determinism and backcasting in future studies", *Futures*, Vol. 32 No. 7, pp. 613-634.

ICARB (2014), "Scotland's future energy visions: 100% renewable by 2030: backcasting: planning for the future", Report on the Backcasting Event, 12 March, Initiative for Carbon Accounting.

Jones, K., Mulvillle, M. and Brooks, A. (2013), "FM, risk and climate change adaptation", *Proceedings of the 12th EuroFM Research Symposium 2013*, *Prague*, pp. 120-128.

Koves, A., Kiraly, G., Pataki, G. and Balazs, B. (2013), "Backcasting for sustainable employment: a Hungarian experience", *Sustainability*, Vol. 5 No. 7, pp. 1991-3005.

Levermore, G., Chow, D., Jones, P. and Lister, D. (2004), "Accuracy of modelled extremes of temperature and climate change and its implications for the built environment in the UK", Technical Report 14, Tyndall Centre for Climate Change Research.

Liso, K., Aandahl, G., Eriksen, S. and Alfesen, K. (2003), "Preparing for climate change in Norway's built environment", *Building Research and Information*, Vol. 31 Nos 3/4, pp. 200-209.

Lovins, A.B. (1976), "Energy strategy: the road not taken?", *Foreign Affairs*, Vol. 55 No. 1, pp. 63-96.

Miola, A (Ed.) (2008), *Backcasting Approach for Sustainable Mobility*, Joint Research Centre – Institute for Environment and Sustainability, Ispra.

Quist, J.N. (2007), "Backcasting for a sustainable future: the impact after 10 years", PhD Thesis, Technische Universiteit Delft, Eburon Academic Publishers.

Quist, J. and Vergragt, P. (2006), " Past and future of backcasting: the shift to stakeholder participation and proposal for a methodological framework", *Futures*, Vol. 38 No. 9, pp. 1027-1045.

Robinson, J. (1982), "Energy backcasting – A proposed method of policy analysis", *Energy Policy*, Vol. 10 No. 4, pp. 337-344.

Robinson, J. (1990), "Futures under glass: a recipe for people who hate to predict", *Futures*, Vol. 22 No. 8, pp. 820-842.

Sanders, C.H. and Phillipson, M.C. (2003), "UK adaptation strategy and technical measures: the impacts of climate change on buildings", *Building Research & Information*, Vol. 31 Nos 3/4, pp. 200-221.

Tillsona, A., Oreszczyna, T. and Palmerbet, J. (2013), "Assessing impacts of summertime overheating – some adaptation strategies", *Building Research & Information*, Vol. 41 No. 6, pp. 652-661.

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Paper Four

Mulville, M. and Stravoravdis, S. (2016). The impact of regulations on overheating risk in dwellings. *Journal of Building Research and Information,* Vol. 44, 5-6, pp. 520-553.

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Barbosa, R.M.M. (2016). *Staying Cool: Towards and integrated vulnerability approach to climate change in southern Europe housing.* University of Lisbon PhD Dissertation. Available from: https://run.unl.pt/handle/10362/19884;

Birchmore, R., Davies, K., Etherington, P., Tait, R. and Pivac, A. (2016). *Overheating in Auckland homes: testing and interventions in full-scale and simulated houses*. Building Research & Information, doi:10.1080/09613218.2017.1232857;

Hatvani-Kovacs, G., Belusko, M., Pockett, J. and Boland, J. (2016). Overheating risk in the Australian Nationwide Housing Energy Rating Scheme: A case study for Adelaide. In, Zuo, J., Daniel, L., Soebarto, V. (eds.), *Fifty years later: Revisiting the role of architectural science in design and practice: 50th International Conference of the Architectural Science Association 2016,* pp. 437-446, The Architectural Science Association and The University of Adelaide.

Invited Presentations:

This paper formed the basis for presentations by the candidate at the following events:

- CIB World Building Congress 2016: Creating Built Environments of New Opportunities Conference 30 May – 2 June 2016, Tampere, Finland.

Other Impacts:

This paper won the Research Paper ‘Merit Award’ from the CIOB International Innovation and Research Awards 2016 http://iandrawards.ciob.org/node/111.

The research contained in this paper (along with Paper Six) formed the basis of evidence submitted by the Chartered Institute of Architectural Technologists (CIAT) to the recent public consultation of the proposed changes to the Standard Assessment Procedure [SAP].

Altmetric notes this paper as:

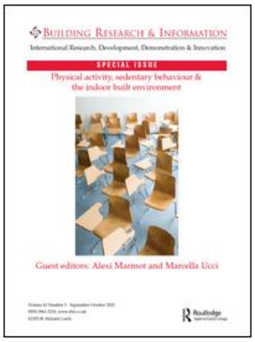
“In the top 5% of all research outputs scored by Altmetric”

“Among the highest scoring outputs from this source (#13 of 276)”

“High attention score compared to outputs of the same age (91st Percentile)”

“High attention score compared to outputs of the same age and source (82nd Percentile)”.

Since publication of this paper the candidate has joined Task Group 79 (Building Regulations and Control in the Face of Climate Change) at the International Council for Building [CIB].



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The impact of regulations on overheating risk in dwellings

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RESEARCH PAPER

The impact of regulations on overheating risk in dwellings

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Many new and emerging regulations and standards for buildings focus on climate change mitigation through energy and carbon reduction. In cool climates, such reductions are achieved by optimizing the building for heat retention. It is increasingly recognized, however, that some degree of climate change is now inevitable. New and existing buildings need to consider this to ensure resilience and an ability to adapt over time. In this context, the current approach to regulation that largely remains focused on the 'point of handover' may not be fit for purpose. This paper focuses on a 'typical' dwelling designed to a range of standards, representing current or emerging approaches to minimizing energy use, using a range of construction methods, where a number of adaptations are available to occupants. It considers, through the use of building performance simulation, how each configuration is likely to perform thermally over time given current climate change predictions. It is demonstrated that the current approach to assessing overheating risk in dwellings, coupled with the regulatory focus on reducing energy consumption, could result in significant levels of overheating. This overheating could, in the near future, present a risk to health and result in the need for significant interventions.

Keywords: adaptation, building regulations, building simulation, climate change, dwellings, overheating

Introduction

The UK Committee on Climate Change (2014) noted that one-fifth of homes in England could already experience overheating (in a mild summer) and that this percentage is likely to increase in a warming climate and therefore it called for new building standards to be developed to address the overheating risk in dwellings. Parry, Canziani, Palutikof, van der Linden, and Hanson (2007) reported that the 2003 heatwave in Europe accounted for in the region of 35 000 excess deaths. This increased mortality was related to high internal temperatures over an extended time period (Wright, Young, & Natarajan, 2005) and affected the most vulnerable in society, such as the elderly, infants and those with underlying health problems (Johnson et al., 2005). If such events are to become more common (which is predicted, with a similar event affecting southern Europe in 2007), this could have significant consequences for health, housing design (Wright et al., 2005) and arguably the regulatory framework in the built environment.

The UK building regulations primary focus is one of health, safety and well-being. The growing realization, though, that CO_2 emissions associated with the built environment can have a significant negative impact on the environment and contribute to climate change (in 2009 buildings were responsible for 43% of all CO_2 emissions in the UK; Department for Communities and Local Government (DCLG), 2015) has resulted in the requirements of national and regional legislation (such as the UK Climate Change Act and The European Energy Performance of Buildings Directive) being interpreted through building regulations. In recent years building regulations in the UK (UK Part L revisions 2010 and 2013) (Figure 1), European Union (European Energy Efficiency Directive) and, indeed, globally (Dubai Green Building Regulations and Specifications, Green Building Code of Peoples Republic of China) have increasingly sought to set more stringent energy performance targets. In cool or temperate climates such as mid-latitude and northern Europe, characterized by extended winter heating seasons, these regulations aim to mitigate the worst effects of climate change by reducing CO_2 emissions and optimizing buildings for heat retention. However, as noted by McLeod, Hopfe, and Kwan (2013), it is

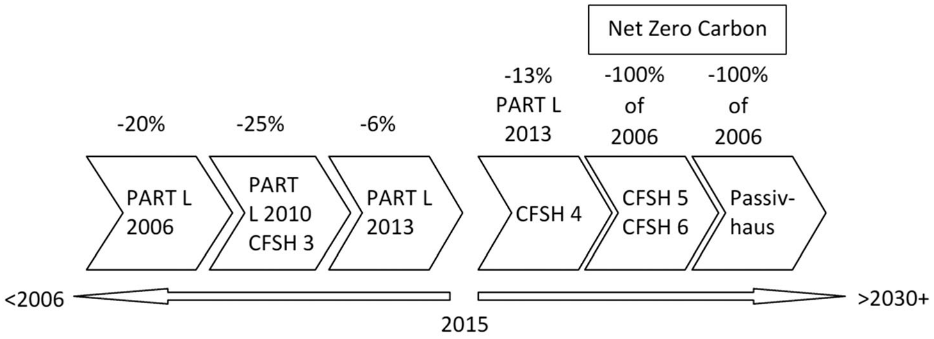


Figure 1 Timeline of energy-related regulations and emerging standards (UK) including energy-reduction targets

being increasingly recognized that higher global emissions scenarios are becoming more likely, increasing the risk of greater levels of warming. As a result, it has been suggested that dwellings in cool climates may in future suffer from overheating, and indeed there is evidence that this may already be happening (Dengel & Swainson, 2012). de Wilde and Coley (2012), in a review of the implications of climate change for buildings, point out that the rationale and requirements of the building regulations in relation to overheating are largely based on historic data and may not therefore enable a realistic assessment of the potential future overheating risk.

Taking this into consideration, this paper explores the idea that the current focus of increased levels of insulation and other heat loss-reduction measures for new or recently constructed dwellings may, at least during warm periods, be counterproductive. As noted by Eames, Kershaw, and Coley (2011), overheating could have severe health implications and as such could result in uninhabitable buildings that are technically obsolete due to the 'locked-in' (de Wilde & Tian, 2011) impacts of climate change. The paper, supported by detailed probabilistic predictions, demonstrates the level of overheating that could be experienced depending on the standard or regulation the dwelling is constructed to and suggests how an alternative, more robust approach to overheating risk assessment could be developed.

Background

Evidence of overheating

Until recently the general assumption in relation to domestic overheating has been that older dwellings were more vulnerable, with increased levels of insulation protecting new dwellings from such issues (Dengel & Swainson, 2012). However, there is now increasing evidence that new and low-energy dwellings may suffer significant problems in future and indeed that many such dwellings may already experience high levels of overheating (Dengel & Swainson, 2012; Lomas & Kane, 2013; Mavrogianni, Taylor, Davies, Thoua, & Kolm-Murray, 2015; Peacock, Jenkins, & Kane, 2010; Rodrigues, Gillott, & Teltow, 2013). It has been suggested that lightweight, air-tight dwellings with little access to cross-ventilation (such as single-aspect flats) may be at a particularly high level of risk of overheating (Dengel & Swainson, 2012).

What is clear is that overheating presents a significant risk to dwellings and occupant health and that this could impact a wide range of buildings and building types. Using probabilistic assessment, Jenkins et al. (2014) found that by the 2030s up to 76% of flats and 29% of detached dwellings could be at risk of overheating. Furthermore, Rodrigues et al. (2013), in a study considering the performance of a low-energy steel frame house design under current and future weather scenarios, found that the building could be uncomfortably warm for 30% of the year.

As noted by de Wilde and Coley (2012), there appears to be at least some debate in relation to highly insulated buildings, with Crawley (2008) noting greater resilience and Wang, Chen, and Ren (2010) noting less resilience to the impacts of climate change. Gupta and Gregg (2012) cite the Passiv-on project which found that the high levels of insulation in Passive House buildings in southern Europe worked to keep the building cool during warm weather. However, McLeod et al. (2013) cites a number of studies (Larsen & Jensen, 2011; Mlecnik et al., 2012; Schnieders, 2005) in relation to Passive House dwellings in several European locations where it is noted that there may be a risk of overheating in the current climate unless a number of alterations including active cooling were implemented. McLeod et al. (2013) do, however, point out that Passive House dwellings may offer marginally more protection from overheating than other highly insulated options. (Findings for the 2050s heavy weight Passive House are greater than 25°C for 6.6% of the year, whereas a heavy weight 'well insulated' building is greater than 25°C for 8.2% of the year.) The core reasons for these differences are unclear, although Gupta and Gregg (2012), when considering a range of 'typical' dwelling types in Oxford, found insulation's position to be of importance. As such insulation may be a 'double edged sword' (Hacker, Holmes, Belcher, & Davies, 2005) with increased insulation reducing winter heat loss but increasing overheating risk especially in air-tight buildings where it is difficult to dissipate internally generated gains. This is further supported by Orme and Palmer (as cited in Dengel & Swainson, 2012) who noted that increasing the level of insulation in dwellings resulted in higher levels of overheating.

Peacock et al. (2010) note the potential for increased internal gains through the proliferation of electronic devices in the home which could lead to higher internal temperatures. They go on to note that despite this climatic effects are still likely to be more influential than internal gains and for the UK such internal gains are likely to remain useful throughout the heating season. Building on this, it can be argued that measures designed to mitigate future climate change must also take account of the impact these measures may have on overheating risk. The research presented in this paper attempts to take this into consideration. There is evidence that behavioural and technical adaptations may at least in some part be able to address overheating risk (Coley, Kershaw, & Eames, 2012); however, as noted by Hills (2012) for low-income households any requirement for technical intervention through artificial cooling may result in summer fuel poverty. This is particularly important for countries like the UK as installed cooling capacity remains low (Hulme, Beaumont, & Summers, 2011).

Overheating adaptation

A number of authors have explored potential solutions to overheating in domestic buildings (*e.g.*, Gupta & Gregg, 2012; van Hoff, Blocken, Henson & Timmermans, 2015; Porritt, Cropper, Shao, & Goodier, 2012). These studies found that adaptation measures such as shutters and fixed shading, reductions in solar/fabric gains, increased surface albedo and the use of thermal mass may help reduce future overheating, although the magnitude of the influence of thermal mass has been questioned (Kendrick, Odgen, Wang, & Baiche, 2012). Gupta and Gregg (2012) found that user-controlled shading, surface albedo and thermal mass could help reduce overheating risk, although it was also found that no 'passive' measures alone could completely remove the risk and that behavioural and active measures may also be needed. Jones, Mulville, and Brooks (2013) set out an approach to adaptation planning related to the potential impact of climate change where the lifecycle of the building is taken into consideration. It suggests that where risks are identified at the design stage, an adaptation plan can be developed, and where such adaptations in future may otherwise prove prohibitively expensive, preparatory or enabling works can be carried out during the construction phase to enable the future adaptation. As noted by Gupta and Gregg (2012), mitigation measures to reduce the contribution of the built environment to climate change and adaptation measures to allow the building to adapt to climate change that does occur should not negatively impact on the performance of the building. Combining the adaptation planning approach suggested by Jones et al. (2013) with the measures that have been shown to reduce overheating risk may have the potential to ensure the buildings can perform over time. In such a scenario adaptation measures are enabled at the design stage but only implemented when needed, therefore not having a negative impact on current performance (such as increasing winter heat load due to increased solar shading).

Literature review

UK regulatory framework

In the UK, building regulations do not stipulate a single maximum temperature in the workplace or the home. For domestic buildings, checks are required at the design stage, comparing mean summer internal temperature with a threshold temperature (using the Standard Assessment Procedure – SAP) to assess the risk of overheating (Zero Carbon Hub, 2015). Further guidance that does refer to specific temperature is provided by the Chartered Institution of Building Services Engineers (CIBSE) (2015), but this is beyond the requirements of the regulations. The UK Workplace (Health, Safety and Welfare) regulations (Health and Safety Executive, 2013) specify minimum but not maximum temperatures in the workplace; the same standards do not exist for private residential buildings, but minimum and maximum temperatures may apply to other residential-type buildings (see, for example, Northern Irelands Residential Care Homes minimum standards; Department of Health, Social Services and Public Safety, 2011).

By way of comparison, for new dwellings, the Danish Code for Indoor Thermal Climate (DS 474) sets a maximum of 100 hours not in excess of 26°C and not more than 25 hours above 27°C, calculated using a simple software tool (BE10) (Kunkel, Kontonasiou, Arcipowska, Mariottini, & Atanasiu, 2015) similar to the UK SAP. The Swedish Building Code sets minimum room temperatures and maximum surface temperatures, but not maximum room air temperatures (Kunkel et al., 2015). The Republic of Ireland follows a similar approach to that of the UK with the Dwelling Energy Assessment Procedure (DEAP) used to carry out an overheating risk assessment (Sustainable Energy Authority of Ireland, 2013), although this assessment is optional and not mandated by regulation. The Norwegian building regulations have implemented requirements for the consideration of solar gains in non-domestic buildings, but not domestic buildings (Schild, 2009). As can be seen from the above comparisons, set maximum summer temperatures for dwellings in cool climates are still uncommon. Where such standards do exist, the assessment method used tends to be simplistic in nature and, as will be discussed below, may not be fit for purpose.

Metrics

There remains considerable discussion with regard to the most appropriate metrics for defining overheating (de Dear, Kim, Candido, & Deuble, 2015; Hacker et al., 2005; Nicol & Spires, 2013; Nicol, Hacker, Spires, & Davies, 2009; de Wilde & Tian, 2011) with the merits of single-temperature exceedance or a traditional approach versus adaptive comfort standards (Nicol & Spires, 2013), considerations of potential health and mortality impacts (Dengel & Swainson, 2012; Jenkins et al., 2014), along with considerations of the relevant importance of night-time temperatures (Dengel & Swainson 2012; Peacock et al., 2010), forming the main points of discussion.

The main criticism of the single-temperature exceedance method (which sets an allowable exceedance of a percentage of occupied hours above a given temperature) is that there is evidence of a correlation between acceptable internal temperatures and external temperature (Nicol & Humphreys, 2010), and as such the comfort range is in reality a moving target that a single-temperature criterion cannot take account of. Furthermore, a single-temperature criterion does not give an indication of the severity of overheating experienced, while the adaptive comfort approach considers both severity and length of exposure (Nicol & Spires, 2013). Length of exposure is of particular importance in relation to potential health impacts with, as previously noted, many of the premature deaths associated with the 2003 European heatwave being related to the extended period of high temperatures (Wright et al., 2005). The adaptive thermal comfort approach as detailed by Nicol and Humphreys (2010) is built on field studies that note the ability of occupants to adapt to climatic changes, whereas the temperature exceedance approach, it could be argued assumes a more passive approach taken by occupants. However, as noted by Beizaee, Lomas, and Firth (2013), EN15251, which forms the basis of the adaptive comfort approach for 'free running' buildings, was developed primarily for commercial buildings and the adaptations available for occupants of dwellings are significantly different to those of an office. Furthermore, Mavrogianni et al. (2015) question how under such conditions vulnerable and potentially immobile people may be able to adapt. It has been noted (Roaf, Brotas, & Nicol, 2015) that the single-temperature exceedance method (in comparison with the adaptive comfort method) would appear to overestimate the overheating risk and that, in reality, the risk may be lower than many studies in this field have predicted. With the potential health risks associated with overheating such assertions need to be approached with caution and, as suggested by Mavrogianni et al. (2015), it may be wise to combine the adaptive comfort approach with a static overheating criterion.

What is clear from the literature is that high temperatures in bedrooms overnight are a significant risk (Naughton et al., 2002, as cited in Peacock et al., 2010) and that temperatures above 24°C may begin to impair sleep and have other associated health impacts (Dengel & Swainson, 2012). With the lack of a clear definition of overheating in dwellings, studies in this area are as a result subject to a degree of uncertainty (Dengel & Swainson, 2012).

Overheating assessment methods

In addition to lack of clarity regarding the appropriate metrics used to define overheating, there is evidence that the current methods of assessing overheating risk in dwellings may not be reliable (Jenkins, Ingram, Simpson, & Patidar, 2013). It has been noted that much of the data used to analyse current overheating risk come from the past (de Wilde & Coley, 2012) and, therefore, do not make allowance for the potential impacts of a changing climate. The overheating prediction method currently used in the SAP (Department of Energy and Climate Change (DECC), 2014) assigns a level of risk to potential overheating, where higher levels of overheating are detected the assessor has the option to use window opening to alleviate these problems (window opening may help to reduce overheating by increasing the ventilation rate, which will reduce the ambient room temperature where outside air is cooler and can also help aid personal cooling through the evaporation of moisture from the skin). Although this may be suitable in rural areas, in areas subject to high levels of pollution and noise (Mavrogianni et al., 2015) this may be unrealistic and in both cases (urban and rural) such an approach may present a security risk (Mavrogianni, Wilkinson, Davies, Biddulph, & Oikonomou, 2012). This is supported by the findings of Skinner and Grimwood (2005) who note that 54% of dwellings in the UK during the daytime and 67% during night-time are exposed to noise levels in excess of World Health Organisation (WHO) guidelines. In addition, there are strong safety-related arguments for the inclusion of restrictors on upper-floor windows (McLeod et al., 2013) which reduce the potential for increased ventilation. As such, the reliance on window opening may be over-optimistic and, furthermore, as suggested by several authors (*e.g.*, Peacock et al., 2010; Roaf et al., 2015) there may in future be an upper limit to the effectiveness of window opening in reducing overheating.

The Passive House Standard, as developed by the 'Passivhaus Institut' (Cotterell & Dadeby, 2012) (see http://www.passiv.de), uses a separate method of overheating risk assessment administered through the Passive House Planning Pack (PHPP). Although, like the other standards discussed here, the data contained in PHPP are from the past, the exceedance limitation of 25°C for a maximum of 10% of the year (Feist, 2013) assessed through PHPP would appear to be more robust than the SAP assessment method (below 23.5°C) as it is not wholly based on a reliance on window opening.

Building performance simulation

In most cases of overheating risk assessment at the design stage, there is some form of building performance prediction, usually through building performance simulation (such as the compliance assessments used in SAP and PHPP or dynamic simulation more commonly used in research such as that of Coley et al. (2012)). Although widely used, there are some significant uncertainties that must be taken into account when considering building simulation-based performance assessments. As noted by de Wilde and Tian (2011), this includes modelling, numerical and specification uncertainty along with scenario uncertainties related to occupant behaviour and, when considering performance over time, predicted climatic conditions and likely renovation scenarios. Future weather files are a key component of any climate change impact study using building simulation. In the UK, the data used to generate such weather files (as used in building simulation studies) originate from the UK Climate Change Projections (UKCP) (Jenkins et al., 2009). It has been argued that due to the inherent difficulty in predicting future weather scenarios a probabilistic approach should be taken (de Wilde & Tian, 2011), and in that sense the UKCP09 offers a significant advantage over the previous UKCP02 as it offers a wide range of probabilistic scenarios. This has the knock-on impact of introducing additional complication to such prediction due to the required processing. With the goal of addressing this, the PROMETHEUS project at the University of Exeter developed a range of weather data files based on the UKCP09 predictions which represent a range of probabilities (10th, 50th and 90th percentiles for low, medium and high scenarios respectively) for three timescales (2030s, 2050s and 2080s) producing both test reference years (TRYs) to represent a 'normal' year and design summer years (DSYs) to represent a 'near extreme' year. The methods used to develop the files are detailed by Eames et al. (2011). Several studies considering domestic overheating have used these weather data files (*e.g.*, Coley et al., 2012; Gupta & Gregg, 2012; Mavrogianni et al., 2012), and although the methods used to develop the files reduce the computing needed, some considerations remain in relation to how the files are implemented in climate change impact studies. Gupta and Gregg (2012) suggest that climate impact studies carried out using worst case scenarios (90th percentile) would ensure resilient designs. Coley et al. (2012), however, suggest that a more median approach (50th percentile) with allowance only for 'hard' adaptations to resolve any overheating, as this would allow designers to avoid potentially unnecessary and costly adaptations. Jenkins et al. (2013) suggest that both the DSYs, which are intended to test the building for overheating, and TRYs, used to represent more normal conditions for energy estimates, be used so that both 'near extreme' and higher probability scenarios can be represented. This in turn allows for at least some of the probabilistic capabilities of UKCP09 to be realized, although, as noted by Coley et al. (2012), for some UK cities DSYs may show a cooler climate than TRYs and use of DSYs therefore should be approached with caution.

Methods

For this research, five building standards were chosen to represent a range of construction specifications, requiring increasing levels of energy savings. This included the regulatory minimums of Part L 2006 and 2010, the voluntary standards of the Code for Sustainable Homes (CfSH) levels 4 and 5, and the Passive House Standard. Figure 1 depicts how the energy consumption predictions for each standard noted relate to each other. As can be seen, they follow the push towards 'net zero carbon' dwellings in the UK (National House Building Council Foundation, 2009), and although this has recently been put on hold (HM Treasury, 2015) it is likely to remain a long-term goal.

Once the relevant standards were established, a 'typical' UK dwelling was developed based on a dwelling stock analysis of England and the wider UK. This indicated that since 2001, 66% of dwellings constructed were houses (DCLG, 2014a; National House Building Council, 2014); approximately one-third of these were semi-detached, with an average of three bedrooms and an average floor area of 91.7 m^2 (DCLG, 2014b). Of the total dwelling stock in England and Wales (24.6 million, DCLG, 2014c; Statistics for Wales, 2015), 30% or 7.38 million are semi-detached houses (Office for National Statistics (ONS), 2011). Although flats/apartments and particularly single-aspect flats have been shown to be at high risk of overheating (Mavrogianni et al., 2015), and several studies have explored these issues (Dengel & Swainson, 2012), detailed exploration of the impact on houses is less prevalent, and given the number of dwellings involved (7.38 million), consideration of the potential impacts on these units is merited. Following this, a three-bedroom semi-detached property aligning with these criteria, with a glazing ratio of 22.5% and layout based on Roberts-Hughes's (2011) 'case for space' guidelines, was chosen to represent the 'typical' dwelling.

The dwellings did not include solar shading, other than in places where the regulation or standard in question required it. It is accepted that details of design will have a significant impact on overheating risk and it is a limitation of this work that the 'typical' case presented here cannot be fully representative of the stock of semi-detached dwellings. The criteria used aim to ensure that the 'typical' case reflects the likely approach to delivering such dwellings built to the standards and regulations under consideration in this paper.

The fabric specifications of the dwellings were developed in accordance with the relevant compliance assessment for the given standard: SAP (DECC, 2014) for Part L, Passive House Planning Pack (Feist, 2013) for Passive House and the DCLG (2011) recommendations for the Code for Sustainable Homes for CfSH levels 4 and 5. For each specification three variants were established, representing three levels of thermal mass, and three different construction methods: low mass approximately 100 kJ/m^2 K, medium mass about 250 kJ/m^2 K and high mass about 450 kJ/m^2 K, based on SAP 2012 (DECC, 2014). Predicted internal loads were then established in accordance with CIBSE Guide A (CIBSE, 2015). Details of the specifications used can be found in Table 1.

This 'typical' building was then modelled in 3D using the Ecotect software (Marsh, 1996), before being exported to the Heat Transfer in Buildings 2 (HTB2) software (Lewis & Alexander, 1990) for thermal performance simulation and analysis. Exporting to HTB2 was necessary as this software allows for more in-depth analysis and also simulates the building dynamically as opposed to the admittance or steady-state method used in Ecotect.

Once the various versions of the buildings had been developed, models were run using current and future probabilistic reference years based around the UKCP09 weather generator as developed by the PROMETHEUS project at the University of Exeter and detailed by Eames et al. (2011). For the purposes of this study the 50th percentile predictions of the median scenario where used for both TRYs (representing the more likely prediction) and DSYs (representing near extreme predictions). It is accepted that using a range of predictions (10th, 50th and 90th percentiles for low, medium and high scenarios respectively) would give a wider indication of probability; however, as Coley et al. (2012) note, using the 50th percentile provides a more median result, allowing for consideration of overheating risk while avoiding designing to the worst-case scenario. Such an approach also reduces the risk of interventions made now to avoid future overheating risk, increasing current energy use.

Table 1 Model input parameters

Element	Units	Part L 2006	Part L 2010	CFSH 4	CFSH 5/6	Passive House
Roof *U*-value	W/m^2 K	0.18	0.15	0.13	0.1	0.1
Wall *U*-value	W/m^2 K	0.28	0.23	0.18	0.15	0.15
Floor *U*-value	W/m^2 K	0.2	0.18	0.15	0.1	0.1
Window *U*-value	W/m^2 K	1.8	1.4	1.4	1.1	0.8
Window *G*-value	0–1	0.72	0.64	0.64	0.60	0.54
Air permeability	m^3/h/m^2 at 50 pa	10	5	3	1	0.7
Ventilation rate	As noted	27 l/s	27 l/s	27 l/s	27 l/s	30 m^3/h/person
Thermal bridging	W/m^2 K	0.15	0.08	0.06	0.04	0.04
Window position ventilation rate[a]		Slightly open: one air change per hour (ACH)				
		Half open: four ACHs				
		Fully open: eight ACHs				

Notes: [a]Based on SAP 2012 (DECC, 2014) and Technical Memorandum 36 (Hacker et al., 2005).
For the 'typical' building to comply with Passive House overheating criteria a 600 mm shading device was included on the south facade (or west for an alternative orientation).
Passive House air permeability of 0.7 relates to 0.6 ACH at 50 pa for a building with a volume of 219.65 m^3.
Mass was varied by choosing between raised timber floors and slab on grade, timber frame construction, cavity wall construction and blockwork with external insulation and between low- and high-mass party walls and internal partitions.

As building occupants are likely to adapt to warmer climates, four 'anytime' window-opening scenarios (closed, slightly open, half open, fully open) and two night-time purge-ventilation scenarios (half or fully open) were included in the simulations, with associated ventilation rates for each (Table 1). The findings of the 'night purge' window positions are only included for the high thermal mass scenarios where they had the greatest impact. In each case the software used enabled the window-opening position to be triggered by internal temperatures of 23.9°C. This aligned with the work of Jenkins, Patidar, Banfill, and Gibson (2011) who suggested that 23.9°C was the temperature at which occupants are likely to begin to adapt.

Along with building standard, thermal mass and ventilation rate (window position), orientation can be expected to have an impact on overheating risk. For this study two possible orientations were considered (north–south and east–west). These were chosen to reflect potential extremes of solar gain (high gains for south facing, but easier to control versus the east–west scenario). It is a limitation of the study that a wider range of orientations could not be considered, which arguably would be more representative of the as-built stock.

Overall five building standards, built using three thermal mass variations, in two orientations with up to six possible window positions, were simulated (Table 2), along with some additional simulations for comparison between London and Edinburgh (a full set of scenarios/models were run for London with a selection for Edinburgh for comparative purposes), which resulted in 1788 individual model runs.

As discussed previously, there is some debate regarding the most appropriate metrics to be used for predicting overheating in free-running dwellings. To allow for further comparison between the two most common approaches (single-temperature exceedance and the adaptive comfort method), both were included in this study. Overheating criteria 1–3 are based on adaptive comfort standards as detailed by Nicol and Spires (2013), while criteria 4 and 5 are based on the more traditional single-temperature exceedance criteria; the specifics of each criterion can be found in Table 3. For each of the adaptive comfort criteria, the threshold used is a function of the relationship between the running mean outdoor temperature and the indoor temperature. As the software used was not capable of calculating a running mean of temperature (directly at least), the data generated were exported and manually analysed to create a running mean, thus allowing for a consideration of the adaptive comfort measures. As noted by Nicol and Spires (2013), exceedance of any two of these criteria is considered to represent overheating.

Results

Figure 2 displays the findings of the building simulations carried out for London (with a comparative for Edinburgh included in the 2080s) combining the building standard, thermal mass, window position and climatic scenario for a dwelling with either a north–south or an east–west aspect. Although as noted by Coley et al. (2012), for some UK cities DSY (for testing near extreme) may show a cooler climate than TRY (for a more normal climate). This was not found to be an issue in this scenario as TRY was consistently cooler than DSY. As a result of this, the findings presented in this section are based on DSYs only.

A number of initial observations can be drawn from the analysis, such as an increase in overheating over time, as can be seen in Table 4. Taking the CfSH level 4, medium thermal mass, north–south orientation with slightly

Table 2 Sample modelling plan (Part L 2010 – model images are included for illustration)

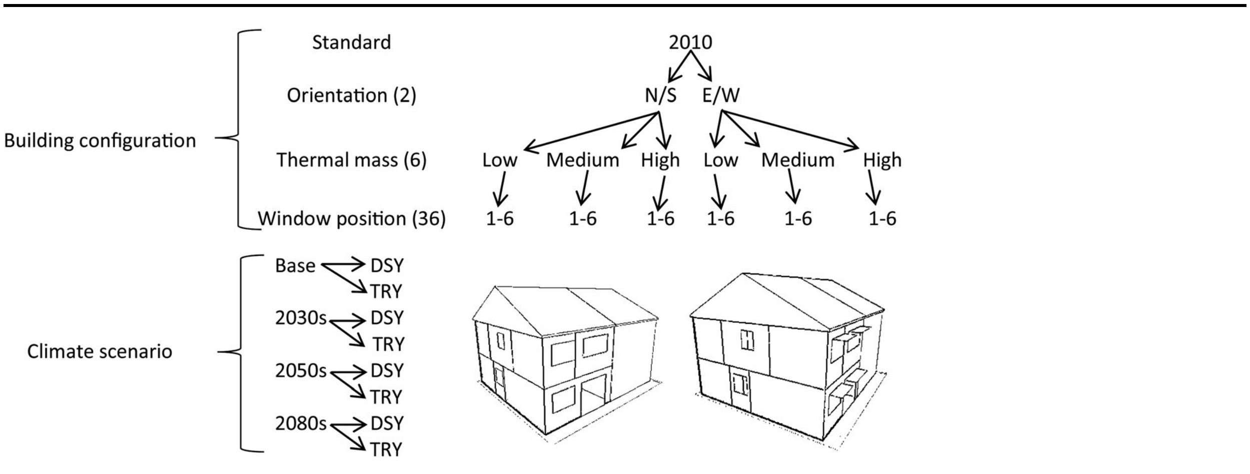


Table 3 Traditional and adaptive comfort overheating criteria

Adaptive comfort method[a]	
Criterion 1	Limits the how often the internal temperature exceeds the comfort range (by 1 K for 3% of occupied hours) during the summer months (May–September inclusive)
Criterion 2	Considers the severity of overheating in any one day based on how much the space overheats (by how many degrees the space exceeds the prescribed temperature) and for how long, again during the summer months
Criterion 3	Sets an absolute maximum temperature that reflects the point at which normal adaptations may be insufficient to ensure comfort
Traditional method[b]	
Criterion 4	Sets a limit of 1% of occupied hours above 25°C, which relates to the temperature at which discomfort may begin
Criterion 5	Sets a limit of 1% of occupied hours above 28°C, which relates to an unacceptably high temperature

Sources: [a]Nicol and Spires (2013).
[b]Hacker et al. (2005).

open windows possible and measured against exceedance of two of the three adaptive comfort criteria (criteria 1–3) no overheating occurs in the base case; however, for the 2030s exceedance occurs 7.8% of the time, 11.1% for the 2050s and 27.4% for the 2080s. Interestingly, when measured against the more traditional steady-state criteria (criterion 4), predicted overheating increases significantly (base 25.2%, 2030s 54.8%, 2050s 64.8% and 2080s 75%) highlighting, as noted by Roaf et al. (2015), that the traditional criteria predict higher levels of overheating than adaptive comfort standards. This research did not explore the merits of the adaptive comfort versus traditional steady-state overheating criteria in detail; for clarity the remainder of this study focuses on the adaptive comfort standards.

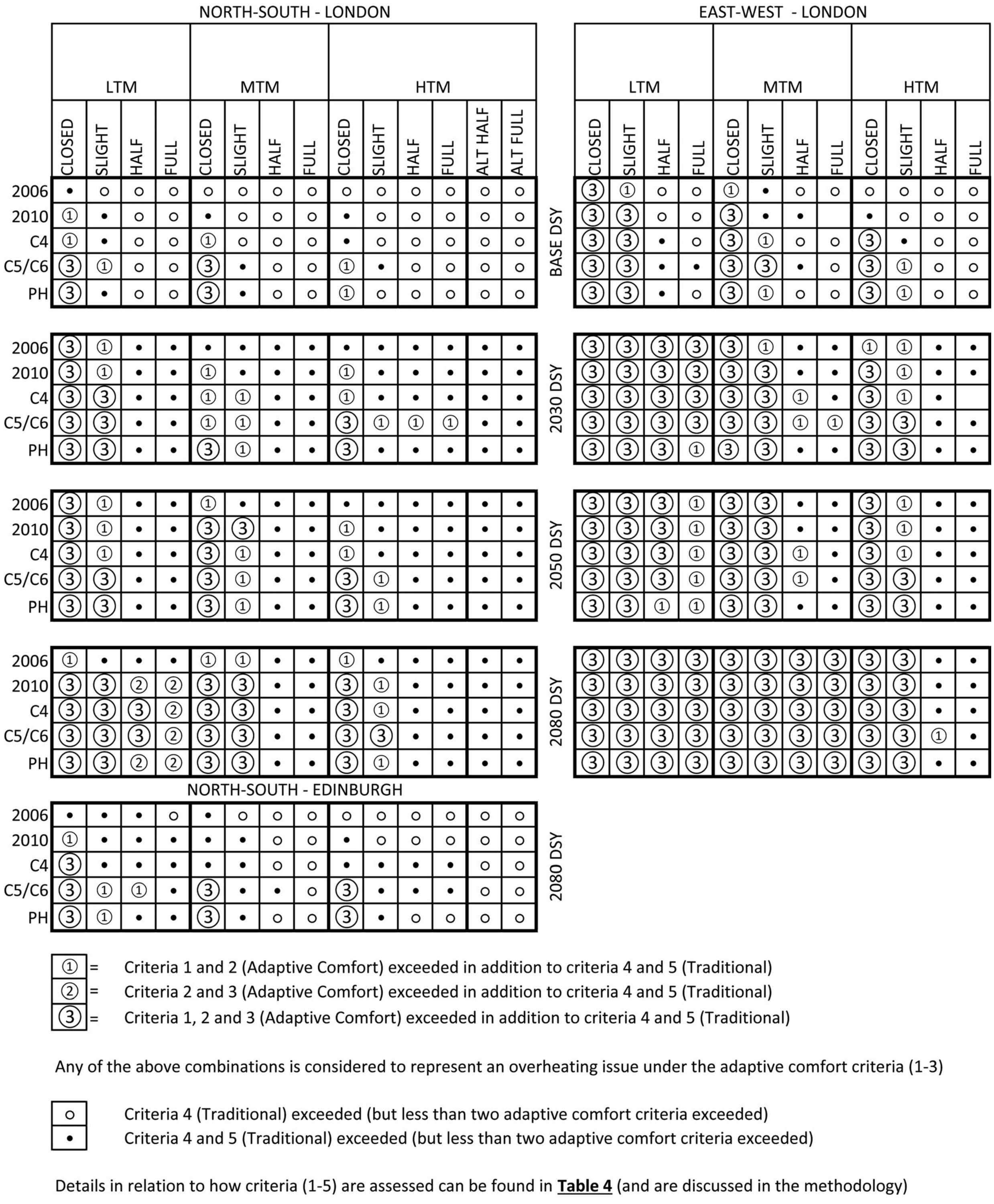
Secondly, buildings with higher thermal mass are at less risk of overheating than more light-weight buildings when the construction standard built to is kept constant (for instance, built to CfSH level 4, but the thermal mass varied) (Table 5). Taking Part L 2010 as an example, in the 2030s higher thermal mass can help to reduce incidents of overheating by up to 15.0%, by 15.6% in the 2050s and by 19.6% in the 2080s (all based on slightly open windows when temperatures are appropriate to take advantage of thermal mass). Furthermore, thermal mass becomes more important as insulation levels increase, while at higher levels of insulation (CfSH level 5 and Passive House) the benefit of thermal mass reduces between the 2050s and 2080s as the climate warms. This is based on the difference in the percentage of overheating observed between the low and high thermal mass versions across the building standards, as noted in Table 5.

This reduction in the benefit of thermal mass is likely a result of the decrease in diurnal temperature ranges over time and, as can be seen in Figure 3, the general reduction in the difference between internal and external temperatures. This has the impact of reducing the ability of ventilation and thermal mass to store or transfer energy to the cooler outside air. Figure 3 also demonstrates that along with the potential for increased overheating over time, temperatures in excess of 24°C in bedrooms at night-time may be regularly experienced from the 2030s onwards, which presents a particular cause for concern.

When considering the performance of the buildings across the range of standards (Part L 2006 to the Passive House Standard), during peak temperatures (taken as August) it was found that as the levels of insulation increase and external temperatures increase over time, increasing levels of fabric gains are observed overnight (Figure 4). This overnight gain maybe a contributory factor in high night-time bedroom temperatures. Figure 4 is based on mean daily temperature ranges for August, showing a comparison between the 2050s and 2080s for dwellings built to the Part L 2006 and CfSH level 5 building standards.

As previously noted, the adaptive comfort criteria include an assessment of the severity and duration of the overheating (criterion 2 in this study). As can be seen in Figure 2, in the low and medium thermal mass scenarios, as higher levels of insulation are introduced (CfSH level 4 and 5 and Passive House) from the 2030s onwards this criterion is regularly exceeded unless windows are in the half-open position. Such window opening as previously noted may be impractical due to noise, pollution or security issues. Consistent exceedance of this criterion is an additional cause for concern as persistent exposure to elevated temperatures can result in serious health impacts, particularly when they occur at night-time (Dengel & Swainson, 2012). This criterion does not consider longer-term exposure to higher temperatures (beyond the length of time within a single day), which although of importance was beyond the scope of this paper.

Using the adaptive comfort criteria, a cross-analysis between the five building standards (Table 5) found that, for the slightly open window position in the



NORTH-SOUTH - LONDON

	LTM				MTM				HTM						
	CLOSED	SLIGHT	HALF	FULL	CLOSED	SLIGHT	HALF	FULL	CLOSED	SLIGHT	HALF	FULL	ALT HALF	ALT FULL	
2006	•	○	○	○	○	○	○	○	○	○	○	○	○	○	BASE DSY
2010	①	•	○	○	•	○	○	○	•	○	○	○	○	○	
C4	①	•	○	○	①	○	○	○	•	○	○	○	○	○	
C5/C6	③	①	○	○	③	•	○	○	①	•	○	○	○	○	
PH	③	•	○	○	③	•	○	○	①	○	○	○	○	○	
2006	③	①	•	•	•	•	•	•	•	•	•	•	•	•	2030 DSY
2010	③	①	•	•	①	•	•	•	①	•	•	•	•	•	
C4	③	③	•	•	①	①	•	•	①	•	•	•	•	•	
C5/C6	③	③	•	•	①	①	•	•	③	①	①	①	•	•	
PH	③	③	•	•	③	①	•	•	③	•	•	•	•	•	
2006	③	①	•	•	①	•	•	•	•	•	•	•	•	•	2050 DSY
2010	③	①	•	•	③	③	•	•	①	•	•	•	•	•	
C4	③	①	•	•	③	①	•	•	①	•	•	•	•	•	
C5/C6	③	③	•	•	③	①	•	•	③	①	•	•	•	•	
PH	③	③	•	•	③	①	•	•	③	①	•	•	•	•	
2006	①	•	•	•	①	①	•	•	①	•	•	•	•	•	2080 DSY
2010	③	③	②	②	③	③	•	•	③	①	•	•	•	•	
C4	③	③	③	②	③	③	•	•	③	①	•	•	•	•	
C5/C6	③	③	③	②	③	③	•	•	③	③	•	•	•	•	
PH	③	③	②	②	③	③	•	•	③	①	•	•	•	•	

EAST-WEST - LONDON

	LTM				MTM				HTM			
	CLOSED	SLIGHT	HALF	FULL	CLOSED	SLIGHT	HALF	FULL	CLOSED	SLIGHT	HALF	FULL
BASE DSY												
2006	③	①	○	○	①	•	○	○	○	○	○	○
2010	③	③	○	○	③	•	•		•	○	○	○
C4	③	③	•	○	③	①	○	○	③	•	○	○
C5/C6	③	③	•	•	③	③	•	○	③	①	○	○
PH	③	③	•	○	③	①	○	○	③	①	○	○
2030 DSY												
2006	③	③	③	③	③	①	•	•	①	①	•	•
2010	③	③	③	③	③	③	•	•	③	①	•	•
C4	③	③	③	③	③	③	①	•	③	①	•	
C5/C6	③	③	③	③	③	③	①	①	③	③	•	•
PH	③	③	③	①	③	③	•	•	③	③	•	•
2050 DSY												
2006	③	③	③	①	③	③	•	•	③	①	•	•
2010	③	③	③	①	③	③	•	•	③	①	•	•
C4	③	③	③	①	③	③	①	•	③	①	•	•
C5/C6	③	③	③	①	③	③	①	•	③	③	•	•
PH	③	③	①	①	③	③	•	•	③	③	•	•
2080 DSY												
2006	③	③	③	③	③	③	③	③	③	③	•	•
2010	③	③	③	③	③	③	③	③	③	③	•	•
C4	③	③	③	③	③	③	③	③	③	③	•	•
C5/C6	③	③	③	③	③	③	③	③	③	③	①	•
PH	③	③	③	③	③	③	③	③	③	③	•	•

NORTH-SOUTH - EDINBURGH

	LTM				MTM				HTM						
	CLOSED	SLIGHT	HALF	FULL	CLOSED	SLIGHT	HALF	FULL	CLOSED	SLIGHT	HALF	FULL	ALT HALF	ALT FULL	
2006	•	•	•	○	•	○	○	○	○	○	○	○	○	○	2080 DSY
2010	①	•	•	•	•	•	○	○	•	○	○	○	○	○	
C4	③	•	•	•	•	•	○	○	•	•	•	•	○	○	
C5/C6	③	①	①	•	③	•	•	○	③	•	•	•	○	○	
PH	③	①	•	•	③	•	○	○	③	•	○	○	○	○	

① = Criteria 1 and 2 (Adaptive Comfort) exceeded in addition to criteria 4 and 5 (Traditional)
② = Criteria 2 and 3 (Adaptive Comfort) exceeded in addition to criteria 4 and 5 (Traditional)
③ = Criteria 1, 2 and 3 (Adaptive Comfort) exceeded in addition to criteria 4 and 5 (Traditional)

Any of the above combinations is considered to represent an overheating issue under the adaptive comfort criteria (1-3)

○ Criteria 4 (Traditional) exceeded (but less than two adaptive comfort criteria exceeded)
• Criteria 4 and 5 (Traditional) exceeded (but less than two adaptive comfort criteria exceeded)

Details in relation to how criteria (1-5) are assessed can be found in **Table 4** (and are discussed in the methodology)

Figure 2 Overheating risk assessment (semi-detached house, cross-ventilation possible)

2030s (near future) and low thermal mass construction, the 2006 building overheats 5.9% of the time, the 2010 building overheats 15% of the time, CfSH level four 18.2% of the time, CfSH level five 35.9% of the time and the Passive House building 31.3% of the time, all measured during the summer months (May–September inclusive).

Building on this, and extrapolating the data in Table 5, it can be said that in the above scenario building

Table 4 CfSH 4 overheating risk as a percentage, during summer months (May–September)

	Low thermal mass				Medium thermal mass				High thermal mass			
Overheating criteria	**Adaptive**		**Traditional**[a]		**Adaptive**		**Traditional**[a]		**Adaptive**		**Traditional**[a]	
Window position	**Slightly open**	**Half open**	**Slightly open**	**Half open**	**Slightly open**	**Half open**	**Slightly open**	**Half open**	**Slightly open**	**Half open**	**Slightly open**	**Half open**
Base	1.3	0	31.1	14.8	0	0	25.2	12.2	0	0	24.5	11
2030s	18.3	5.8	55.8	34.4	7.8	1.9	54.8	32.8	2.6	0	53.8	32.7
2050s	20.2	9.1	66.6	41.7	11.1	2.6	64.8	39.6	4.5	0	63.8	40.5
2080s	42.4	11.7	77.5	55.1	27.4	3.2	75	52.8	19.6	0	74.7	53.3

Note: [a]Traditional overheating criteria relates to criterion 4 only.

Table 5 Overheating risk as a percentage of occupied hours during summer months (slightly open wins – north-south orientation)

	Part L 2006			Part L 2010			CfSH 4			CfSH 5			Passive House		
Thermal mass	**Low**	**High**	**Difference**	**Low**	**High**	**Difference**	**Low**	**High**	**Difference**	**Low**	**High**	**Difference**	**Low**	**High**	**Difference**
Base	0	0	0	0	0	0	1.3	0	1.3	11.7	0	11.7	7.8	0	7.8
2030s	5.9	0	5.9	15	0	15	18.2	2.6	15.6	35.9	15	20.9	31.3	11.7	19.6
2050s	11.1	2.6	8.5	15.6	0	15.6	20.2	4.5	15.7	41.8	21.5	20.3	36	15	21
2080s	13	5.2	7.5	32	12.4	19.6	42.4	19.6	22.8	61.4	45	16.4	58.1	41	17.1

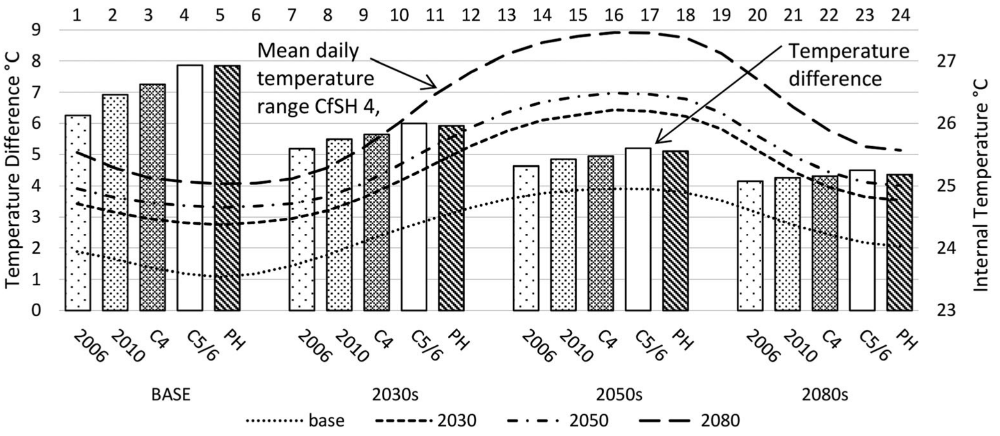


Figure 3 Internal to external temperature difference (high thermal mass)

standard (assuming thermal mass is kept constant) can increase potential incidents of overheating by up to 11.7% in the base case (11.7–0), for the 2030s this can increase to 30% (35.9–5.9), 30.7% in the 2050s (41.8–11.1) and for the 2080s 48.4% (61.4–13). It is worth noting that although the fabric specifications of CfSH level 5 and the Passive House Standard are similar (when in ‘free running’ mode), there is evidence that the overheating assessment criteria in the Passive House Standard are more robust. Reductions in incidents of overheating of 6.6% were observed for the 2030s, 6.8% for the 2050s and 7.2% for the 2080s for the Passive House Standard in comparison with the CfSH level 5, all based on a medium thermal mass scenario with slightly open windows (the data are stated but not presented in a separate table). As noted below, however, orientation presents a significant overheating risk for the Passive House Standard, which, if shading is not carefully considered, may reduce or reverse the benefit.

As can be seen from Figure 2, changing the orientation of the building from north–south to east–west has a noticeable impact on the incidents of overheating across all standards, when measured against the adaptive comfort criteria. This highlights the importance of solar shading and the impact it can have on overheating (east–west orientations are more difficult to shade than north–south orientations due to the low sun angle). For the east–west orientation, in line with the findings from the north–south orientation, further increases in incidents of overheating are experienced as the building standard increases (greater levels of insulation and reduced infiltration), and the building is optimized for heat retention.

For comparative purposes, thermal performance simulations were also carried for Edinburgh in the 2080s (Figure 2). Unsurprisingly, this resulted in significantly reduced levels of predicted overheating, with, in all scenarios, only the low thermal mass version of CfSH level 4 and all thermal mass versions of CfSH level 5 and the Passive House Standard presenting significant overheating issues. By comparison, for London all standards exhibited at least some incidents of significant overheating, with the low thermal mass version (excluding the 2006 version) experiencing this across all window-opening positions.

Implications

The preceding results suggest that the current standards used in relation to overheating risk in dwellings in cool or temperate climates may no longer be fit for purpose. The lack of regulation in relation to maximum allowable temperatures and the opportunity for designers to utilize potentially unrealistic adaptations at the design stage, such as window opening, results in unreliable predictions. Coupled with this, the use of historic climatic data means that the current approach cannot make predictions about likely overheating risk beyond the point of handover, thus ignoring the lifecycle of the building and potential impact of climate change. As noted by Meikle and Connaughton (2006), new and existing housing is predicted to have to last for an extended period, and in many cases this may be beyond the end of the century. In this context, an alternative approach is required if the regulatory framework is to ensure the delivery of comfortable and healthy dwellings that offer resilience to predicted climate change.

In addition to the issues raised with the approach to assessing overheating risk in dwellings, the drive to reduce energy use in new dwellings through current and emerging regulations and building standards (thus optimizing the building for heat retention) has the potential to increase the overheating risk. The high proportion of CO_2 emissions that have been linked to the built environment (43% of all CO_2 emissions in the UK; DCLG 2015), and the link between this and

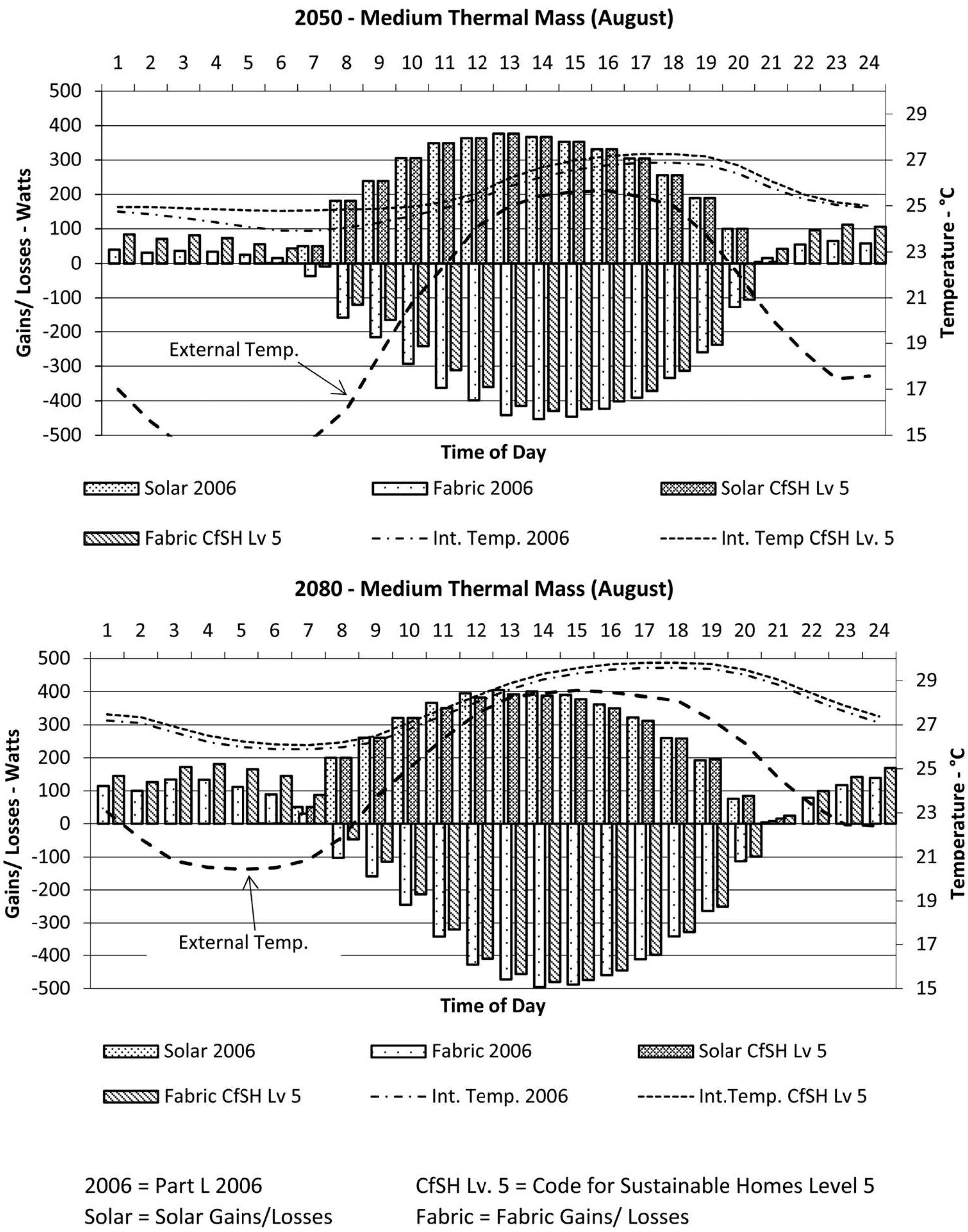


Figure 4 Gains and losses (2050 and 2080 comparing Part L 2006 and CfSH level 5)

anthropogenic climate change, creates a particular challenge for regulation in the built environment, where increased short- or near-term energy savings must be balanced against increased long-term overheating risk.

The approach outlined in this paper and the findings as presented in Figure 2 could be used as the basis of an alternative risk-based overheating assessment method that takes account of predicted climate change. This would require a careful definition of how exposure to high temperatures for a specific period of time constitutes an unacceptable overheating risk, which would provide clarity and allow methods to be developed and refined accordingly (Holmes, Phillips, & Wilson, 2016). In addition to this, such an approach could also incorporate climate change adaptation planning at the design stage, as outlined by Jones et al. (2013), thus ensuring that short- or near-term energy efficiency is not compromised for longer-term comfort (by, for instance, adding shading now that may reduce future overheating risk but also increase current heating loads).

Conclusions

Although the current drive within the regulatory framework of the built environment to reduce heat loss (in cool climates) is not without its merits, as levels of insulation increase and infiltration decreases, there is increasing risk of summer-time overheating linked to climate change, particularly in urban areas. Furthermore, there is a risk of extended periods of overheating and unacceptably high temperatures in bedrooms overnight. The current standards in the UK used for predicting overheating risk may not be fit for purpose as they are based on historic data which take no account of potential climate change and make unrealistic assumptions in terms of occupant adaptations. Higher levels of thermal mass and the potential for increased ventilation rates offer benefits, however these may reduce over time as internal to external temperature differences decrease. Although this investigation is based on modelling UK domestic dwellings and the predicted changes to the UK climate, other countries with similar climates may experience similar risks.

Predicting overheating in buildings, given the range of variables involved, is complex and subject to a degree of uncertainty. Instead of a single temperature or hours of exceedance metric requiring complex building simulation to predict overheating, a risk-based scale may be more appropriate. This risk-based assessment, embedded in regulations and standards, could take account of the duration of the high temperatures experienced and the predicted impact of climate change (taking account not only of increased temperatures but also of the reduced ability of thermal mass and ventilation to minimize overheating). The approach to climate change risk assessment in dwellings as detailed in this paper could be expanded upon to provide such a design-stage risk assessment for a range of dwelling types. This approach presents a clear role for standards and regulations in defining anticipated scenarios in relation to overheating risk linked to climate change with the aim of ensuring resilience in both the predicted ‘normal’ future climate and during ‘extreme’ events.

This research must be considered in the context of a number of limitations. Future predictions of overheating risk based on building simulation are subject to uncertainty and rely on a number of assumptions in relation to variables that cannot be easily predicted (such as internal gains, occupancy patters and occupant adaptations). The paper has tried to reduce this uncertainty through the use of 50th percentile climate predictions (using weather data files produced from the PROMETHEUS project), offering a range of possible adaptations (window opening) and taking conservative predications in relation to internal gains, in order to avoid more extreme and potentially less realistic predictions. The research presented is based on a single building type, namely a semi-detached dwelling where cross-ventilation is possible, but consideration of a wider range of buildings using the same methodology would be of benefit. Further granularity could be added to the predictions by considering a range of shading configurations. For all standards considered the buildings are assumed to be in ‘free running’ mode, as such this ignores the potential for a dwelling with a mechanical ventilation system to implement purge ventilation, although, as noted, the benefits of increased ventilation may reduce over time.

Further research is needed to consider how occupants of dwellings, particularly vulnerable occupants, may adapt to overheating. This could, for example, include further research in relation to window-opening patterns in urban areas where noise, pollution or security may place restrictions on such adaptations.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Beizaee, A., Lomas, K., & Firth, S. (2013). National survey of summertime temperatures and overheating risk in English homes. *Building and Environment*, *65*, 1–17. doi:10.1016/j.buildenv.2013.03.011

Chartered Institution of Building Services Engineers. (2015). *CIBSE guide A: Environmental design*. London: Chartered Institution of Building Services Engineers.

Coley, D., Kershaw, T., & Eames, M. (2012). A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures. *Building and Environment*, *55*, 159–166. doi:10.1016/j.buildenv.2011.12.011

The Committee on Climate Change. (2014). *Managing climate risks to well-being and the economy: Adaptation Sub-Committee progress report 2014*. Retrieved from Committee on Climate Change: https://www.theccc.org.uk/wp-content/uploads/2014/07/Final_ASC-2014_web-version.pdf

Cotterell, J., & Dadeby, A. (2012). *The Passivhaus handbook: A practical guide to constructing and retrofitting buildings for ultra-low energy performance*. Totnes: Green Books.

Crawley, D. (2008). Estimating the impacts of climate change and urbanization on building performance. *Journal of Building Performance and Simulation*, *1*, 91–115. doi:10.1080/19401490802182079

de Dear, R., Kim, J., Candido, C., & Deuble, M. (2015). Adaptive thermal comfort in Australian school classrooms. *Building Research & Information*, *43*, 383–398. doi:10.1080/09613218.2015.991627

Dengel, A., & Swainson, M. (2012). *Overheating in new homes: A review of the evidence*. Retrieved from the Zero Carbon Hub: http://www.zerocarbonhub.org/sites/default/files/resources/reports/Overheating_in_New_Homes-A_review_of_the_evidence_NF46.pdf

Department of Communities and Local Government. (2014a). *House building: September quarter 2014*. Retrieved from gov.uk: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/382244/House_Building_Release_-_Sept_Qtr_2014_-_revised.pdf

Department of Communities and Local Government. (2014b). *English housing survey headline report*. Retrieved from Gov.uk: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/406740/English_Housing_Survey_Headline_Report_2013-14.pdf

Department of Communities and Local Government. (2014c). *Dwellings stock estimates 2013, England*. Retrieved from gov.uk: https://www.gov.uk/government/uploads/system/

uploads/attachment_data/file/285001/Dwelling_Stock_Estimates_2013_England.pdf

Department of Energy and Climate Change. (2014). *The government's standard assessment procedure for energy rating of dwellings*. Retrieved from the Building Research Establishment: http://www.bre.co.uk/filelibrary/SAP/2012/SAP-2012_9-92.pdf

Department for Communities and Local Government. (2015). *2010–2015 government policy: Energy efficiency in buildings*. Retrieved from Gov.uk: https://www.gov.uk/government/publications/2010-to-2015-government-policy-energy-efficiency-in-buildings/2010-to-2015-government-policy-energy-efficiency-in-buildings

Department of Health, Social Services and Public Safety. (2011). *Residential care homes: Minimum standards*. Retrieved from rqia.org.uk: http://www.rqia.org.uk/cms_resources/care_standards_-_residential_care_homes_August_2011.pdf

Departments of Communities and Local Government. (2011). *Cost of building to the code for sustainable homes*. London: Departments of Communities and Local Government.

Eames, M., Kershaw, T., & Coley, D. (2011). On the creation of future probabilistic design weather years from UKCP09. *Building Services Engineering Research and Technology*, *32*, 127–142. doi:10.1177/0143624410379934

Feist, W. (2013). *The Passive House Planning Package* (PHPP). Darmstadt: Passivhaus Institute.

Gupta, R., & Gregg, M. (2012). Using UK climate change predictions to adapt existing English homes for a warming climate. *Building and Environment*, *55*, 20–42. doi:10.1016/j.buildenv.2012.01.014

Hacker, J., Holmes, M., Belcher, S., & Davies, G. (2005). *Climate change and the indoor environment: Impacts and adaptation*. London: The Charted Institution of Building Services Engineers.

Health and Safety Executive. (2013). *Workplace (health, safety and welfare) regulations 1992*. Retrieved from Hse.gov.uk: http://www.hse.gov.uk/pUbns/priced/l24.pdf

HM Treasury. (2015). *Fixing the foundation: Creating a more prosperous nation*. Retrieved from Gov.uk: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/443897/Productivity_Plan_print.pdf

Hills, G. (2012). *Getting the measure of fuel poverty, final report of the fuel poverty review* (CASE report 72). Retrieved from London School of Economics and Political Science: http://sticerd.lse.ac.uk/dps/case/cr/CASEreport72.pdf

van Hoff, T., Blocken, B., Henson, J., & Timmermans, H. (2015). On the predicted effectiveness of climate change adaptation measures for residential buildings. *Building and Environment*, *82*, 300–316. doi:10.1016/j.buildenv.2014.08.027

Holmes, S. H., Phillips, T., & Wilson, A. (2016). Overheating and passive hability: Indoor health and heat indices. *Building Research & Information*, *44*(1), 1–19.

Hulme, J., Beaumont, A., & Summers, C. (2011). *Energy follow-up survey 2011, report 9: Domestic appliances, cooking & cooling equipment* (BRE report number 288143). Retrieved from Gov.uk: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/274778/9_Domestic_appliances__cooking_and_cooling_equipment.pdf

Jenkins, D., Ingram, V., Simpson, S., & Patidar, S. (2013). Methods for assessing domestic overheating for future building regulation compliance. *Energy Policy*, *56*, 684–692. doi:10.1016/j.enpol.2013.01.030

Jenkins, D., Patidar, S., Banfill, P. F., & Gibson, G. (2011). Probabilistic climate projections with dynamic building simulation: Predicting overheating in dwellings. *Energy and Buildings*, *43*, 1723–1731. doi:10.1016/j.enbuild.2011.03.016

Jenkins, G. J., Murphy, J. M., Sexton, D. M., Lowe, J. A., Jones, P., & Kilsby, C. G. (2009). *UK climate projections: Briefing report*. Retrieved from metoffice.gov.uk: http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=87868&filetype=pdf

Jenkins, K., Hall, J., Glenis, V., Kilsby, C., McCarthy, M., Goodess, C., … Smith, D. (2014). Probabilistic spatial risk assessment of heat impacts and adaptations for London. *Climate Change*, *124*, 105–117. doi:10.1007/s10584-014-1105-4

Johnson, H., Kovats, R. S., McGregor, G., Stedman, J., Gibbs, M., & Walton, H. (2005). *The impact of the 2003 heat wave on daily mortality in England and Wales and the use of rapid weekly mortality estimates*. Retrieved from Eurosurveillance.org: http://www.eurosurveillance.org/ViewArticle.aspx?ArticleId=558

Jones, K., Mulville, M., & Brooks, A. (2013). FM, risk and climate change adaptation. In K. Alexander (Ed.), *EuroFM journal: International Journal of Facilities Management: Conference papers 12th EuroFM research symposium* (pp. 120–128). Naarden: EuroFM Publ.

Kendrick, C., Odgen, R., Wang, X., & Baiche, B. (2012). Thermal mass in new build UK housing: A comparison of structural systems in future weather scenarios. *Energy and Buildings*, *48*, 40–49. doi:10.1016/j.enbuild.2012.01.009

Kunkel, S., Kontonasiou, E., Arcipowska, A., Mariottini, F., & Atanasiu, B. (2015). *Indoor air quality, thermal comfort and daylight: Analysis of residential building regulations in eight EU member states*. Retrieved from Bpie.eu: http://bpie.eu/uploads/lib/document/attachment/120/BPIE_IndoorAirQualityThermalComfortDaylight_2015.pdf

Larsen, T., & Jensen, R. (2011, November). *Comparison of measured and calculated values for the indoor environment in one of the first Danish Passive houses*. Paper presented at building simulation 2011: Conference of international building performance simulation association (IBPSA), Sydney, Australia. Retrieved from https://www.ibpsa.org

Lewis, P., & Alexander, D. (1990). HTB2: A flexible model for dynamic building simulation. *Building and Environment*, *25*, 7–16. doi:10.1016/0360–1323(90)90035-P

Lomas, K. J., & Kane, T. (2013). Summertime temperatures and thermal comfort in UK homes. *Building Research & Information*, *41*(3), 259–280.

Marsh, A. (1996, December). *Performance modelling and conceptual design*. Paper presented at building simulation 1996: Conference of international building performance simulation association (IBPSA), Sydney, Australia. Retrieved from https://www.ibpsa.org

Mavrogianni, A., Taylor, J., Davies, M., Thoua, C., & Kolm-Murray, J. (2015). Urban social housing resilience to excess summer heat. *Building Research & Information*, *43*, 316–333. doi:10.1080/09613218.2015.991515

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P., & Oikonomou, E. (2012). Building characteristics as determinants of propensity to high indoor summer temperature on London dwellings. *Building and Environment*, *55*, 117–130. doi:10.1016/j.buildenv.2011.12.003

McLeod, R. S., Hopfe, C. J., & Kwan, A. (2013). An investigation into the future performance and overheating risks in Passivhaus dwellings. *Buildings and Environment*, *70*, 189–209. doi:10.1016/j.enpol.2010.08.027

Meikle, J., & Connaughton, J. (2006). How long should housing last? Some implications of the age and probable life of housing in England. *Construction Management and Economics*, *12*, 315–321. doi:10.1080/01446199400000041

Mlecnik, E., Schütze, T., Jansen, S., de Vries, G., Visscher, H., & van Ha, A. (2012). End-user experiences in nearly zero-energy houses. *Energy and Buildings*, *49*, 471–478. doi:10.1016/j.enbuild.2012.02.045

National House Building Council. (2014). *Housing supply update* (Issue 68). Retrieved from National House Building Council: http://www.nhbc.co.uk/ExternalAffairs/documents/HousingNewsletters/filedownload,57892,en.pdf

National House Building Council Foundation. (2009). *Zero carbon homes – An introductory guide for house builders*. Retrieved from the Zero Carbon Hub: http://www.zerocarbonhub.org/sites/default/files/resources/reports/

Zero_Carbon_Homes_Introductory_Guide_for_House_Builders_%28NF14%29.pdf

Naughton, M., Henderson, A., Mirabelli, M., Kaiser, R., Wilhelm, J., Kieszak, S., … Rubin, C. (2002). Heat-related mortality during a 1999 heat wave in Chicago. *American Journal of Preventative Medicine*, *22*, 221–227. doi:10.1016/S0749-3797(02)00421-X

Nicol, F., Hacker, J., Spires, B., & Davies, H. (2009). Suggestion for new approach to overheating diagnostics. *Building Research & Information*, *37*(4), 348–357.

Nicol, F., & Humphreys, M. (2010). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment*, *45*, 11–17. doi:10.1016/j.buildenv.2008.12.013

Nicol, F., & Spires, B. (2013). *Climate change and the indoor environment: Impacts and adaptations*. London: The Charted Institution of Building Services Engineers.

Office for National Statistics (ONS). (2011). *Social trends: Housing*. Retrieved from Ons.gov.uk: http://www.ons.gov.uk/ons/rel/social-trends-rd/social-trends/social-trends-41/housing-chapter.pdf

Parry, M., Canziani, O., Palutikof, J. P., van der Linden, P., & Hanson, C. (Eds.). (2007). *Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change, 2007*. Cambridge and New York: Cambridge University Press.

Peacock, A., Jenkins, D., & Kane, D. (2010). Investigating the potential of overheating in UK dwellings as a consequence of extant climate change. *Energy Policy*, *38*, 3277–3288. doi:10.1016/j.enpol.2010.01.021

Porritt, S., Cropper, P., Shao, L., & Goodier, C. (2012). Ranking of interventions to reduce dwelling overheating during heat waves. *Energy and Buildings*, *55*, 16–27. doi:10.1016/j.enbuild.2012.01.043

Roaf, S., Brotas, L., & Nicol, F. (2015). Counting the cost of comfort. *Building Research & Information*, *43*, 269–273. doi:10.1080/09613218.2014.998948

Roberts-Hughes, R. (2011). *The case for space: The size of England's new homes*. Retrieved from Architecture.com: https://www.architecture.com/Files/RIBAHoldings/PolicyAndInternationalRelations/HomeWise/CaseforSpace.pdf

Rodrigues, L., Gillott, M., & Teltow, D. (2013). Summer overheating potential in a low-energy steel frame house in future climate scenarios. *Sustainable Cities and Societies*, *7*, 1–15. doi:10.1016/j.scs.2012.03.004

Schild, P. G. (2009). *Norway: Impact, compliance and control of EPBD legislation*. Retrieved from Buildup.eu: http://www.buildup.eu/publications/8491

Schnieders, J. A. (2005). *A first guess passive home in southern France*. Passive-On Project report. Retrieved from Une maison passive à Nice: http://www.maison-passive-nice.fr/documents/FirstGuess_Marseille.pdf

Skinner, C., & Grimwood, C. (2005). The UK noise climate 1990–2001: Population exposure and attitudes to environmental noise. *Applied Acoustics*, *66*, 231–243. doi:10.1016/j.apacoust.2004.07.009

Statistics for Wales. (2015). *Dwelling stock estimates for Wales, 2013–2014*. Retrieved from Gov.wales: http://gov.wales/docs/statistics/2015/150429-dwelling-stock-estimates-2013-14-en.pdf

Sustainable Energy Authority of Ireland. (2013). *Introduction to DEAP for professionals*. Retrieved from Seai.ie: http://www.seai.ie/Your_Building/BER/BER_Assessors/Technical/DEAP/Introduction_to_DEAP_for_Professionals.pdf

Wang, X., Chen, D., & Ren, Z. (2010). Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Building and Environment*, *45*, 1663–1682. doi:10.1016/j.buildenv.2010.01.022

de Wilde, P., & Coley, D. (2012). The implications of a changing climate for buildings. *Building and Environment*, *55*, 1–7. doi:10.1016/j.buildenv.2012.03.014

de Wilde, P., & Tian, W. (2011). Towards probabilistic performance metrics for climate change impact studies. *Energy and Buildings*, *43*, 3013–3018. doi:10.1016/j.enbuild.2011.07.014

Wright, A., Young, A., & Natarajan, S. (2005). Dwelling temperatures and comfort during the August 2003 heat wave. *Building Services Engineering Research & Technology*, *26*, 285–300. doi:10.1191/0143624405 bt136oa

The Zero Carbon Hub. (2015). *Assessing overheating risk: Evidence review*. Retrieved from Zerocarbonhub.org: http://www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH-OverheatingEvidenceReview-Methodologies.pdf

Paper Five

Mulville, M., Callaghan, N. and Isaac, D. (2016). The impact of the ambient environment and building configuration on occupancy productivity in open-plan commercial offices. *Journal of Corporate Real Estate,* Vol. 18, 3, pp. 180-193.

This paper was developed on the basis of funding secured from a bid where the candidate was the principal investigator. This allowed for the purchase of relevant equipment and for the candidate to develop a number of research links. The candidate has maintained these links and is currently in discussion with the relevant parties about potential collaborations.

This paper had a direct impact on the business in question, with a summary report being provided to the Facilities Management and Senior Management team. This report is, in turn, being considered in the context of the maintenance and rehabilitation plans for the building and offices spaces. The candidate has been asked to comment on this and is currently in discussions with the business about the potential for follow-up studies. These follow-up studies may consider both the impact of any physical changes and the implementation of Behaviour Change Campaigns (aligning with research findings of Papers One and Seven in addition to this paper).

Since the publication of this paper, the candidate has become a reviewer for this journal.

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The impact of the ambient environment and building configuration on occupant productivity in open-plan commercial offices

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The impact of the ambient environment and building configuration on occupant productivity in open-plan commercial offices

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Abstract

Purpose – This paper sets out to understand the impact of the ambient environment on perceived comfort, health, wellbeing and by extension productivity in the workplace.

Design/methodology/approach – The research combined an occupant survey considering satisfaction with the ambient environment, health and wellbeing and workplace behaviour with the monitoring of ambient environmental conditions.

Findings – The paper demonstrates that the ambient environment can have a significant impact on occupant comfort, health and wellbeing, which in turn has implications for built asset performance. Within the ambient environmental factors considered, a hierarchy may exist with noise being of particular importance. Occupant behaviour within the workplace was also found to be influential.

Research limitations/implications – The research was limited to a single commercial office building, and a wider range of case studies would therefore be of benefit. The research was also limited to the summer months.

Practical implications – The findings show that an active approach to asset management is required, by continuously monitoring internal environment and engaging with occupants. This must carefully consider how ambient environmental factors and workplace behaviour impact upon occupants' comfort, health and wellbeing to ensure the performance of the built asset is maximised.

Originality/value – This paper demonstrates that both occupiers' workplace behaviour and ambient environmental conditions can have an impact on occupant comfort, health, wellbeing and productivity. The paper strengthens the case for the active management of the workplace environment through environmental monitoring and behaviour change campaigns supported by corresponding changes to workplace culture.

Keywords Behaviour, Health, Productivity, Wellbeing, Asset management, Comfort

Paper type Research paper

Introduction

There is a growing body of evidence linking the physical environment (including the ambient environment) to occupant performance (Creagh *et al.*, cited in Madeo and Schnabel, 2014) which recognises that in the commercial office environment, employee costs significantly exceed energy and maintenance costs (CABE, 2005). In this context, thinking must extend beyond regulated energy use and occupants per square metre and should consider occupant wellbeing to deliver healthy, comfortable, efficient and resilient built environments.

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Clements-Croome and Kaluarachchi (2000) suggest that occupant performance is dependent on healthy buildings; in support of this, Gensler (2005) adds that a better working environment could increase productivity by 19 per cent. Occupant wellbeing should therefore be of importance to business owners. However, according to Kok (2012), employees' interests are not always top of the agenda in the business environment, and organisations often focus on increased performance for lower costs (van der Voordt, 2004).

Most studies in this field take a cross-sectional or comparative office-type approach (Bodin Danielsson and Bodin, 2009; Lee, 2010; Feige *et al.*, 2013; Kim and de Dear, 2013) or focus on specific factors such as natural and artificial lighting, noise, control or the ambient environment (Wyon, 2004; Lee and Brand, 2005; Lan *et al.*, 2011; Haans, 2014; Seddigh *et al.*, 2015; Lamb and Kwok, 2016). Haynes (2007) argues that behavioural aspects are also of importance but not widely considered, although more recently behaviour change studies in relation to energy savings have become more prevalent (Mulville *et al.*, 2013; Tetlow *et al.*, 2013; Gulbinas and Taylor, 2014).

This research explores how both the range of ambient conditions and occupant behaviour, which appears to be less widely considered, within a given office environment impacts upon occupants' self-reported health, wellbeing and by extension productivity.

The research demonstrates that while ambient environmental conditions are of importance, occupant behaviour can also be influential in terms of health, wellbeing and productivity in the workplace and suggests that an active approach to workplace management is required. This active approach may include both continuous monitoring of ambient conditions and occupant behaviour change campaigns. Such behaviour change campaigns may need to be supported by wider changes to workplace culture in order to maximise productivity.

Literature review

There are a wide range of factors that can influence employee performance and productivity in the workplace, including a range of business environment factors (workplace culture, social ambience and industry performance) (Chandrasekar, 2011) and personal or social factors (general health, motivation, personality, age, gender and behaviour) (Haynes, 2007; Cubel *et al.*, 2014). Although several of these factors may at first appear to be external to the immediate building, it can be argued that the physical building environment, including the ambient environment, has at least some impact. This is supported by a body of evidence linking the physical building environment to productivity (Clements-Croome, 2015). In that context, the review that follows focused on the physical building environment including ambient environmental factors.

Measurement

As highlighted by Clements-Croome (2015) a lack of productivity in the workplace can be equated to many issues such as absenteeism, leaving early, arriving late and taking longer lunch breaks along with a general frustration with the work environment. According to Feige *et al.* (2013), worker performance can be linked to productivity, but both are rarely measured in the workplace, which can prove especially difficult where there is no universally accepted measure of office productivity (Haynes, 2008a). It is instead suggested that measuring self-reported subjective productivity through questionnaires may be appropriate (Haynes, 2008b; Feige *et al.*, 2013). Measuring productivity gains in an office environment remains difficult, and there would appear to be a lack of consensus in the literature about the potential magnitude of such gains with, for instance, Clements-Croome (2013) suggesting 4-10 per cent gains, while Gensler (2005) notes 19 per cent gains.

Haynes (2007) sets out a theoretical framework for office productivity noting the importance of occupier work patterns and the behavioural environment (how occupants interact with the environment) in addition to the physical environment (office layout and comfort, including the ambient environment) which is more regularly considered. Building upon this, it is suggested (Haynes, 2007) that the behavioural environment (framed as interaction and distraction) may impact more on people's productivity than the physical environment. In this context, there is evidence that behaviour change interventions in the workplace can be successfully used to reduce energy use (Mulville *et al.*, 2013), it may be that a similar approach would also be successful in relation to productivity. There is however also evidence that the physical environment (including the ambient environment) has a significant impact on occupant performance (Clements-Croome, 2015) and arguably the behavioural and physical environments are interlinked.

What is widely accepted is that male and female occupants experience the office environment differently, with differences observed in levels of satisfaction with the ambient environment, stress levels and sick leave rates (Kim *et al.*, 2013; Bodin Danielsson *et al.*, 2014).

Office layout, distraction and control

Bodin Danielsson and Bodin (2008) define a range of office types from single occupancy to open-plan variations. This in turn has allowed for consideration of the impact of office type on occupants to be explored with issues of stress and sickness rates, personal control (Bodin Danielsson, 2010; Pejtersen *et al.*, 2011; Bodin Danielsson *et al.*, 2014) and noise and disturbance (Bodin Danielsson and Bodin, 2008; Seddigh *et al.*, 2015) being highlighted, with open-plan offices often performing poorly. In open-plan offices, increased stress levels may be related to disturbance and a lack of personal control (Bodin Danielsson, 2010), while sickness rates may also be associated with increased densities being linked to greater risk of infection (Bodin Danielsson *et al.*, 2014).

There is evidence that, in open-plan offices, occupants may be more sensitive to backgrounds noise than would be otherwise expected (van der Voordt, 2004) and that medium and large open-plan offices may be particularly problematic (Bodin Danielsson and Bodin, 2009). Jahncke *et al.* (2011) found that memory performance declined in high noise environments while issues related to tiredness and motivation were also observed. Although enclosed or small shared offices may offer benefits in terms of acoustic sensitivity and privacy (Lee, 2010), van der Voordt (2004) notes that some occupants may respond more positively to the increased stimuli in open-plan offices. This may suggest a role for consideration of the level of concentration required for the work being undertaken (Seddigh *et al.*, 2014) and supports the suggestion that an active approach to workplace management may be of benefit (Haynes, 2008c).

Bodin Danielsson and Bodin (2009) note that personal control is a fundamental feature of human behaviour and that it is strongly related to environmental satisfaction. In support of this, Lee and Brand (2005) found a positive correlation between perceived personal control and self-reported job satisfaction. In open-plan offices this presents a particular challenge for Facilities Managers and perhaps supports the argument for enhanced user control which, as noted by O'Neill (2008a), can improve employee performance and can be further enhanced by training.

Open-plan offices may also offer benefits. The more flexible arrangements contribute to sustainability by offering energy savings, reduced materials use and providing adaptability (van der Voordt, 2004), thus reducing the cost of change (O'Neill, 2008b). In addition, open-plan situations may aid interaction, although the benefits in comparison to other office types have been called into question (Lee, 2010). Veitch *et al.* (2007) found that those open-plan office workers who were more satisfied with their work environment where also satisfied with their jobs, suggesting a role for the physical environment (including ambient environmental factors) in wellbeing and productivity. In addition O'Neill (2008a) suggests that greater control through the provision of adjustable workspaces may aid satisfaction. It may be therefore, through careful design, that the benefits of open-plan environments can be maintained (Kim and De Dear, 2013).

The ambient environment

It has been suggested that the move over the past 50 years towards air conditioned buildings coupled with the more recent energy efficiency drive has helped create the conditions for sick building syndrome, and that in turn this may have had a direct impact on occupant productivity (Smith and Pitt, 2011). Clements-Croome (2013) highlights that the most frequent complaints in office environments relate to thermal comfort and air quality (in addition to overcrowding) and notes that improvements in environmental conditions could result in a 4-10 per cent increase in productivity. Pejtersen *et al.* (2006) notes that occupants in open-plan offices are more likely to perceive poor air quality, thermal discomfort and noise (and experience associated wellbeing issues) than occupants of more enclosed spaces. However, Bodin Danielsson and Bodin (2009) found no significant difference in complaints about the ambient environment (when noise was excluded) between office types, and low overall levels of self-reported dissatisfaction with the ambient environment in comparison to issues of noise and privacy. This perhaps supports the view of Haynes (2007) who suggests the behavioural environment to be of particular importance. However, it can be argued that noise and distraction are influenced by layout, configuration and the ambient environment. The importance of the relevant factors may vary with the type of work undertaken with for instance, comfort being found to be of most importance to "group" and "individual process workers" (as defined by Laing *et al.* cited in Haynes, 2008a). What is clear is that health, wellbeing and productivity in the office environment is complex. Contributing to this complexity, it has been suggested that one environmental factor may have a mediating effect on another (Bodin Danielsson and Bodin, 2009).

Indoor Air Quality (IAQ) has been shown to have a significant impact on occupant health, wellbeing and productivity (Dorgan and Dorgan, 2005; World Green Building Council, 2014) which in turn could impact on absenteeism (Bodin Danielsson *et al.*, 2014). Clements-Croome (2015) notes the importance of ventilation, comparing it to the human need for water and highlights the interrelationship between ventilation rate, temperature and humidity noting that increasing levels of ventilation are required to maintain feelings of "freshness" as temperatures increase (Clements-Croome, 2015). This is of particular importance in the context of the predicted impacts of climate change on the built environment (Jones *et al.*, 2013), where for instance, commercial buildings in the UK and particularly in the South-East are expected to become increasingly cooling dominated (Jenkins *et al.*, 2009).

While Bodin Danielsson and Bodin (2009) did not find significant differences between office types in terms of ambient environment complaints, the highest level of complaints in medium sized open-plan offices were in relation to artificial lighting conditions. This may be due to occupants being conscious that they may be sitting further away from a window and therefore natural daylight. Goodrich (Smith and Pitt, 2011) notes that windows and views are psychologically important to workers, offering a chance to refocus while reducing fatigue and stress. Furthermore, Haans (2014) states that the preference for natural lighting, which builds upon the human preference for natural products, can have additional health benefits which although not fully understood must be considered when focusing on occupant productivity. This is supported by Yildirim *et al.* (2007) who found that visual access to a window positively affects employee satisfaction. However, providing views out must be carefully balanced with the potential impacts of high levels of glazing on overheating and glare (Hee *et al.*, 2015).

Methodology

As noted by Feige *et al.* (2013), measuring performance and productivity in the commercial office environment can be challenging and often indirect measures such as absenteeism and staff turnover etc. may be used, alternatively self-reported productivity (occupant surveys) may be used. This research aims to understand the impact of the ambient environment on perceived comfort, health, wellbeing and by extension productivity in an example of the modern office environment while also exploring the potential impact of occupant workplace behaviour on those factors. The research uses a self-reported (occupant survey) technique, supported by the monitoring of ambient environmental factors.

Four zones on each of three floors of the case study building were identified, three were excluded as they were in alternative use, leaving nine zones in total. The zoning was reflected in the monitoring of ambient environmental conditions and the zones were also identified within the occupant survey. The zones on each floor corresponded to quadrants of the floor plan (Zone 1 = south-west, 2 = south-east, 3 = north-east, 4 = north-west). Each zone had approximately 30 workstations, and there were no physical barriers between the zones. This approach allowed for consideration of the impact of local variations within the building to be taken into account.

A physical survey based on a visual inspection was carried out in addition to the monitoring of temperature, CO_2, humidity and noise levels, thus allowing for comparison back to accepted benchmarks and occupants' experiences. Readings were taken throughout the zones and daily figures calculated to mitigate the effects of any erroneous readings due to other factors. Continuous monitoring over a five-week period provided a detailed insight into the ambient environment. It was not possible to monitor CO_2 in each zone; however, manual readings were taken to confirm an even distribution across floors, before one CO_2 logger was placed on each floor. Temperature, humidity and CO_2 readings were recorded at 10-minute intervals and sound level readings were taken at 10 second intervals (shorter intervals would have been of benefit in increasing accuracy, but was not possible with the equipment in use) but over a shorter overall period (one week) and then converted into equivalent continuous noise levels (dBA Leq(h8)) for working hours. The direct measurement of daylight levels was not possible, and self-reported satisfaction was relied upon instead.

The environmental monitoring was supported by a corresponding survey of the occupants' workplace satisfaction. This survey was carried out anonymously using a targeted sampling technique and 95 members of staff responded, giving a response rate of 33.9 per cent. As the response rate is subject to some sample limitations which make generalisation difficult, a higher response rate would be beneficial. The survey was designed and administered online, and participants were informed and invited to participate by e-mail. According to Evans and Mathur (2005), online surveys allow for question diversity, controlled sampling and often result in a faster, more efficient process. Moreover, it allows the methodology to be easily repeated in large-scale studies. The questions addressed a range of influences directly related to the ambient environment such as air quality, temperature, humidity, noise and lighting. In addition, more general questions related to occupant behaviour, health and wellbeing at work were assessed along with nominal data such as gender, location and proximity to windows. Occupants were given a series of statements and asked to respond on a five-point Likert scale with space provided for additional comments.

The research approach allowed for the impact on occupants' comfort, health and wellbeing associated with local variations such as layout, proximity to windows and the ambient environment, to be further explored. The research was conducted during the summer months only which may influence the overall results and must be considered a limitation. It is therefore suggested that repeating this approach quarterly would be beneficial.

Building description

The building used in this study is a three-storey commercial office located on the outskirts of the Greater London area, South-East England. The building has a glazing ratio of approximately 85 per cent and features shading to three facades. The building is square in plan, with 50-75 per cent of each floor plate given over to open-plan office space, and these spaces can be categorised as large open-plan offices (greater than 24 occupants) as defined by Bodin Danielsson and Bodin (2008). The open-plan spaces feature half-height partitions between individual workstations (1 m), and these areas have an occupancy density of 8.9 m^2 Net Internal Area (NIA) per workspace. This density is higher than the British Council of Offices (BCO, 2013) occupier density survey, which found an average density of 10.9 m^2 NIA per workplace. However, 38 per cent of the workplaces considered in that study fell within the 8-10 m^2 range, so the case considered here can be said to be representative. The occupants participating can be considered to be a combination of "individual" and "group process workers" as defined by Laing *et al.* (Haynes, 2008b). As detailed in the results section, the ambient environmental conditions in the building are generally within accepted parameters when measured against common standards so it can be argued that the building environment is, to an extent, representative of the wider stock.

Approach to analysis

Descriptive statistics (mean and standard deviation) were used to understand the measured environmental data (temperature, humidity, CO_2 and noise) and to explore the

Likert type data (mean, mode, median) gained from the occupant surveys. The ordinal data created from the occupant surveys was further analysed using spearman rank correlations for the main self-reported factors (level of satisfaction with environmental conditions, wellbeing and workplace patterns). This helped to explain for example, the relationship between dissatisfaction with noise and frequency of headaches. Furthermore, chi-squared tests were used to understand how nominal factors (gender, location, etc.) impact upon the findings of the Likert type data gathered.

Results

Environmental conditions

For the temperature and humidity parameters, there was little measured difference between zones. When all floors were considered together, the first floor (mean = 24.2°C, SD = 0.09°C) was found to be warmer than the ground (mean = 23.85°C, SD = 0.28°C) and second floor (mean = 23.66°C, SD = 0.09°C). The overall temperature profile is generally below the Chartered Institution of Building Services Engineers (CIBSE) benchmark overheating criteria of 25°C (CIBSE, 2005). The corresponding humidity data also show consistency between zones and lower overall humidity on the first floor. Measured humidity in all zones was predominantly in the 40-50 per cent range, which is within the recommended range of 40-60 per cent for health and comfort noted by CIBSE (2015). CO_2 levels were measured by floor and not zone, the ground floor (mean 546 parts per million (ppm), SD 30 ppm) was generally within the IAQ (IDA) 2 classification of medium quality (400-600 CO_2 ppm) as classified by the European Committee for Standardisation (CEN, 2007), and the first floor (mean 655 ppm, SD 46 ppm = IDA3) was slightly over this level (taken as a mean during occupied hours). The second floor however, was closer to and often in the IDA4 (low quality) category (mean 970 ppm, SD 76 ppm). In relation to the acoustic environment, again there is little difference in performance between zones; however, there is a noticeable increase in background noise level when moving from the second floor (53.87dBA Leq(h8)) to the ground floor (57.98dBA Leq(h8)).

Survey results

Findings of the occupant survey are presented in Figure 1, for the purpose of clarity in the presentation of these results, where possible, Likert type items were combined into single Likert scale items (where four or more similar questions exist). Where factors (such as skin/eye irritation) were found to be of little influence, they have been excluded from the figure.

The Spearman rank correlations found that how often occupants take breaks was correlated to how often occupants experienced headaches ($rs = 0.265$, $p = 0.010$) indicating more headaches for less breaks, frequency of breaks was also negatively correlated to satisfaction with IAQ ($rs = -0.232$, $p = 0.024$), thermal comfort ($rs = -0.222$, $p = 0.031$) and noise ($rs = -0.264$, $p = 0.010$) with lower satisfaction corresponding to less breaks. A negative correlation was found between incidents of headache and the perceived impact of the workplace on productivity ($rs = -0.328$, $p = 0.001$) with those experiencing more headaches perceiving a greater workplace impact. In addition, incidents of headaches were also negatively correlated to satisfaction with noise ($rs = -0.518$, $p = <0.001$) and IAQ ($rs = -0.474$, $p = <0.001$) with lower satisfaction corresponding to more frequent headaches. The relationships between other wellbeing

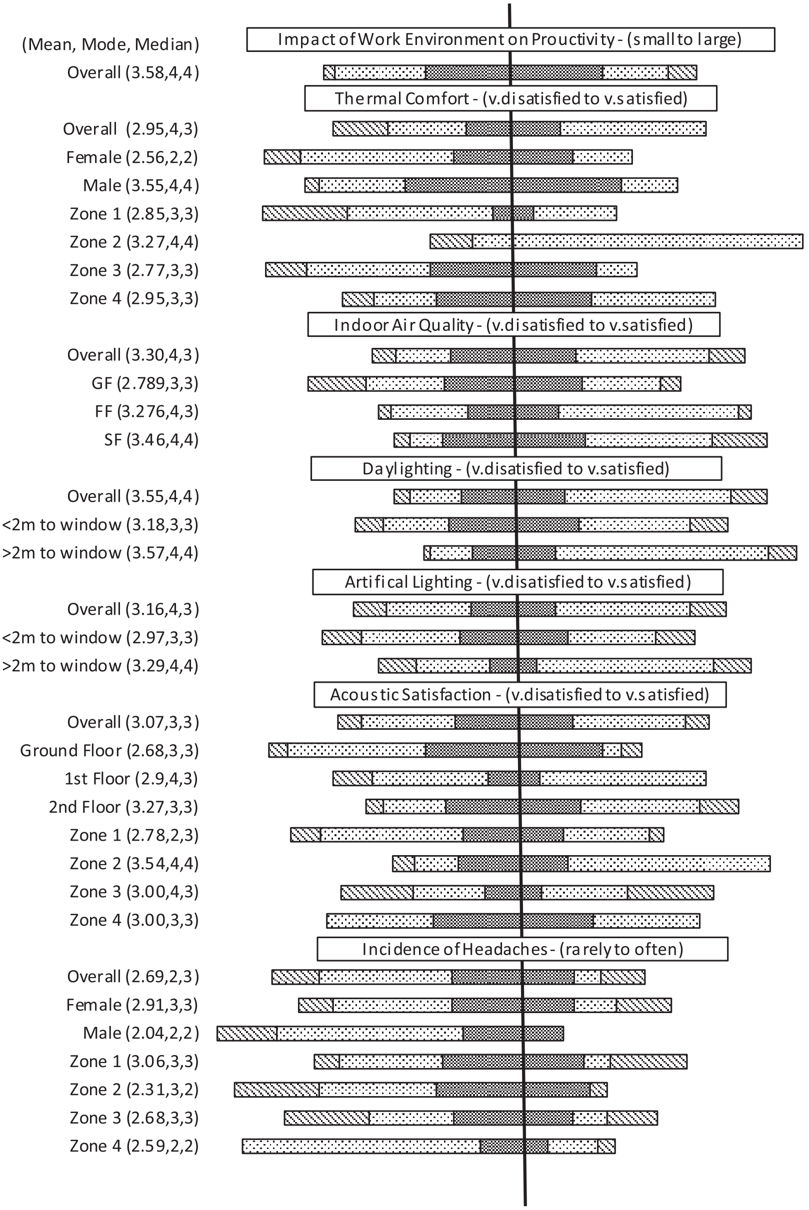

Figure 1.
Occupant survey results

factors (eye and skin irritation, sore and or dry throat and fatigue) and overall comfort and the impact of the building on productivity were found not to be significant. Finally, the analysis also found a negative correlation between the importance of access to controls and overall perceived comfort levels ($rs = -0.402$, $p = <0.001$) indicating those less satisfied with overall comfort believed access to controls to be important.

The chi-squared tests found significant relationships existed between gender and problems with IAQ ($(1, n = 95) = 8.191, p = 0.001$), thermal comfort ($(1, n = 95) = 8.568$, $p = 0.003$), room temperature ($(1, n = 95) = 9.58$, $p = 0.002$), overall comfort ($(1, n = 95) = 14.452, p < 0.001$) and the occurrence of headaches ($(1, n = 95) = 11.674$, $p = 0.001$) with females more likely to note more significant issues. The zone that occupants were located in had a significant relationship with thermal comfort ($(1, n = 95) = 13.922$, $p = <0.001$) and although Figure 1 would appear to suggest similar relationships between zone and acoustic satisfaction and incidence of headaches, this was found not to be significant. Further relationships did exist between floor and thermal comfort ($(1, n = 95) = 13.348, p < 0.001$), noise ($(1, n = 95) = 4.964, p = 0.026$) and IAQ ($(1, n = 95) = 5.425$, $p = 0.020$). The relationship between proximity to windows and satisfaction with daylight was found to be significant ($(1, n = 94) = 3.84$, $p = 0.05$); however, the relationship with artificial lighting satisfaction was not. Furthermore, the relationship between proximity to windows perceived comfort and proximity to windows and the perceived impact of the workplace on productivity were found not to be significant.

Discussion

The research has been able to highlight a number of key issues in relation to occupant health, wellbeing and by extension, productivity in the commercial office environment. The research reinforced the findings of Kim *et al.* (2013) and others, demonstrating that perceptions of environmental comfort and health can be significantly influenced by gender, with females more sensitive to thermal and acoustic issues. When considered along with the correlation between users who are less satisfied with overall comfort levels and a preference for access to control, this presents a challenge where open-plan offices are common and opportunity for local controls are limited. However, as noted by O'Neill (2008a), the provision of local controls in conjunction with adjustable workstation features has the potential to help address such issues. Noise and privacy issues may be more challenging to address and present a particular challenge to designers, asset and corporate real estate (CRE) managers if the benefits of open-plan offices are to be realised.

Interestingly, measured data suggested that the second floor provided the poorest levels of IAQ (mean $CO_2 = 970$ ppm) with the ground floor offering the highest quality (mean CO_2 ppm = 564 ppm), and the findings of the occupant survey found a significant difference in perceived IAQ by floor; however, this indicated the ground floor offered the lowest levels of satisfaction (Figure 1). Conversely, the ground floor recorded the highest levels of background noise (57.98dBA Leq(h8)) while the second floor the lowest (53.87dBA Leq(h8)). This finding was somewhat unexpected and may suggest that a hierarchy exists between the overall factors that influence environmental comfort, especially where the relative differences are of small magnitude (such as within a single building). In this case (a large open-plan office), the acoustic environment would appear to have a larger impact. This is supported by Bodin Danielsson and Bodin (2009) who found that when noise was excluded, there was no significant difference in levels of complaints about the ambient environment between office types and also suggested that one environmental factor may have a mediating effect on another. This is perhaps further supported by the correlation found between those less satisfied with the acoustic environment and a greater frequency of headaches, with those experiencing more frequent headaches also believing the workplace had a greater impact on their productivity. Although it should be noted that perceived IAQ was also correlated to incidents of headaches. The presence of such a hierarchy, which arguably may change by season, would require the asset manager to engage in continuous monitoring of the space (beyond reactions to complaints) to maximise productivity.

In addition to differences between floors, a significant difference between zones in relation to perceived thermal comfort was identified (Figure 1) with those in Zone 2 (south-east) more satisfied. This difference was noted despite little measured variation between environmental conditions across zones. For example, maximum measured difference between mean temperatures (during occupied hours) across all zones was ±0.72°C (Zone 1-2). At the same time, no significant relationship was found between zones and acoustic satisfaction or incidents of headaches, and the immediate reason for the variation in perceived thermal comfort between zones is unclear.

In the case of this research, proximity to windows (and therefore access to views and daylight) was not found to be a significant influencing factor on overall comfort or the perceived impact of the workplace on productivity. Although it did not appear to influence overall workplace satisfaction, there was a relationship with daylight satisfaction, this perhaps supports the idea of a hierarchy of importance in terms of ambient environmental conditions.

In addition to the issues of location, the study found occupants' workplace behaviour to be a significant factor in terms of health and wellbeing, with evidence that those who take breaks more often being less likely to experience headaches and less likely to be dissatisfied with IAQ, thermal comfort and noise. This can be linked back to Haynes (2007) who suggests the behavioural environment to be of particular importance. Changes in behaviour may therefore change the perception of environmental conditions. This could be as a result of breaks increasing wellbeing, or it could be also related to increased casual interaction which as noted by Haynes (2007) can be of benefit to productivity.

In this context, in addition to active monitoring of ambient environmental conditions, it may also be necessary for CRE managers to engage in occupant behaviour change campaigns (for instance in relation to the frequency of breaks) to improve overall health and wellbeing and in turn maximise productivity. This active approach builds upon the suggestion of Haynes (2008c) that an active approach to workplace management to support both the organisation and the individual may be of benefit. Changing the behaviour of occupants in the workplace can however be difficult (Maréchal, 2010), and a change in workplace culture may be necessary (Chandrasekar, 2011) to achieve a positive outcome. This presents a challenge to CRE managers. There is however evidence that such behaviour change campaigns can be successful in other contexts (Mulville *et al.*, 2013).

Conclusion

This research aimed to understand how a range of ambient environmental conditions and occupant behaviour may impact upon perceptions of comfort, health, wellbeing and ultimately productivity in the workplace.

The research demonstrates that significant differences can exist in relation to comfort, health, wellbeing and by extension productivity within individual buildings, and that this may not always be reflected in measurable differences in directly related ambient conditions. This suggests that, within the generally accepted comfort ranges, there may be a hierarchy of the influence of environmental factors, with noise levels of particular importance. Gender factors and access to controls present further challenges in providing productive workspaces in open-plan configurations, where desk level control (of local conditions) may be of benefit. Furthermore, occupant workplace behaviour was found to be a significant factor in perceived environmental comfort and wellbeing. It may be that changes in occupant behaviour, in this case frequency of breaks, can improve satisfaction and wellbeing.

From the CRE management perspective, the research highlights the importance of an active approach to management of the workplace environment. This could include both continuous environmental monitoring and behaviour change campaigns.

Further research would be of benefit in relation to the potential for occupant behaviour change interventions to help improve occupant wellbeing. Greater consideration of occupant satisfaction in the workplace has the potential to contribute to the delivery of a sustainable built environment. This has benefits at societal level by improving health (and reducing health care costs) and increasing productivity and output, thus having a positive impact on the wider economy.

References

Bodin Danielsson, C. (2010), "Office design's influence on employees' stress levels", available at: www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab087211.pdf

Bodin Danielsson, C. and Bodin, L. (2008), "Office-type in relation to health, well-being and job satisfaction among employees", *Environment & Behaviour*, Vol. 40 No. 5, pp. 636-668.

Bodin Danielsson, C. and Bodin, L. (2009), "Difference in satisfaction with office environment among employees in different office types", *Journal of Architectural Planning and Research*, Vol. 26 No. 3, pp. 241-257.

Bodin Danielsson, C., Chungkham, H.S., Wulff, C. and Westerlund, H. (2014), "Office design's impact on sick leave rates", *Ergonomics*, Vol. 57 No. 2, pp. 139-147.

British Council of Offices (2013), "Occupier density study 2013", available at: www.architectsjournal.co.uk/Journals/2013/09/10/c/y/n/BCO-Occupier-Density-Study-Final-report-2013.pdf (accessed 24 October 2015).

CABE (2005), "The impact of office design on business performance", available at: http://webarchive.nationalarchives.gov.uk/20110118095356/http:/www.cabe.org.uk/files/impact-office-design-full-research.pdf (accessed 20 October 2015).

Chandrasekar, K. (2011), "Workplace environment and its impact on organisational performance in public sector organisations", available at: www.ijecbs.com/January2011/N4Jan2011.pdf (accessed 15 October 2015).

CIBSE (2005), *TM36 Climate Change and the Indoor Environment: Impact and Adaptations*, Chartered Institution of Building Services Engineers, London.

CIBSE (2015), *Guide A: Environmental Design*, Chartered Institution of Building Services Engineers, London.

Clements-Croome, D. (2015), "Creative and productive workplaces: a review", *Intelligent Buildings International*, Vol. 7 No. 4, pp. 164-183.

Clements-Croome, D. (Ed.) (2013), *Creating the Productive Workplace*, Routledge, Oxon.

Clements-Croome, D. and Kaluarachchi, Y. (2000), "Assessment and measurement of productivity", in Clements-Croome, D. (Ed.), *Creating the Productive Workplace*, Routledge, Oxon.

Cubel, M., Nuevo-Chiquero, A., Sanchez-Pages, S. and Vidal-Fernandez, M. (2014), "Do personality traits affect productivity?", available at: http://ftp.iza.org/dp8308.pdf (accessed 9 October 2015).

Dorgan, C.E. and Dorgan, C.B. (2005), "Assessment of link between productivity and indoor air quality", in Clements-Croome, D. (Ed.), *Creating the Productive Workplace*, Routledge, Oxon.

European Committee for Standardisation (2007), *EN 13799: Ventilation for Non-Residential Buildings – Performance Requirements for Ventilation and Room Conditioning Systems*, European Centre for Standardization, Brussels.

Evans, J.R. and Mathur, A. (2005), "The value of online surveys", *Internet Research*, Vol. 15 No. 2, pp. 195-219.

Feige, A., Wallbuam, H., Janser, M. and Windlinger, L. (2013), "Impacts of sustainable office buildings on occupants comfort and productivity", *Journal of Corporate Real Estate*, Vol. 15 No. 1, pp. 7-34.

Gensler (2005), *These Four Walls: The Real British office, Gensler*, London.

Gulbinas, R. and Taylor, J. (2014), "Effects of real-time eco-feedback and organizational network dynamics on energy efficient behaviour in commercial buildings", *Energy and Buildings*, Vol. 84, pp. 493-500, doi: 10.1016/j.enbuild.2014.08.017.

Haans, A. (2014), "The natural preference in people's appraisal of light", *Journal of Environmental Psychology*, Vol. 39, pp. 51-61.

Haynes, B. (2007), "Office productivity: a theoretical framework", *Journal of Corporate Real Estate*, Vol. 9 No. 2, pp. 97-110.

Haynes, B. (2008a), "An evaluation of the impact of the office environment on productivity", *Facilities*, Vol. 6 Nos 5/6, pp. 178-195.

Haynes, B. (2008b), "The impact of office comfort on productivity", *Journal of Facilities Management*, Vol. 6 No. 1, pp. 37-51.

Haynes, B. (2008c), "The impact of office layout on productivity", *Journal of Facilities Management*, Vol. 6 No. 3, pp. 189-201.

Hee, W.J., Alghoul, M.A., Bakhtyar, B., OmKalthum, E., Shameri, M.A., Alrubaih, M.S. and Sopain, K. (2015), "The role of window glazing on daylighting and energy saving in buildings", *Renewable and Sustainable Energy Reviews*, Vol. 42, pp. 323-343.

Jahncke, H., Hygge, S., Halin, N., Green, A.M. and Dimberg, K. (2011), "Open-plan office noise: cognitive performance and restoration", *Journal of Environmental Psychology*, Vol. 31 No. 4, pp. 373-382.

Jenkins, D.P., Singh, H. and Eames, P.C. (2009), "Interventions for large-scale carbon emission reduction in future UK offices", *Energy and Buildings*, Vol. 41 No. 12, pp. 1374-1380.

Jones, K., Mulville, M. and Brookes, A. (2013), "FM, risk and climate change adaptation", in Alexander, K. (Ed.), *International Journal of Facilities Management Proceedings of the 12th EuroFM Research Symposium*, 22-24 May, 2013, Czech Republic, Prague.

Kim, J. and de Dear, R. (2013), "Workspace satisfaction: the privacy-communication trade-off in open-plan offices", *Journal of Environmental Psychology* Vol. 36, pp. 18-26.

Kim, J., de Dear, R., Cândido, C., Zhang, H. and Arens, E. (2013), "Gender differences in office occupant perception of indoor environmental quality (IEQ)", *Building and Environment*, Vol. 70, pp. 245-256.

Kok, N. (2012), "What's next in real estate? Reintegrating the value chain", available at: http://nilskok.typepad.com/nils-kok/2012/04/whats-next-in-real-estate-reintegrating-the-value-chain.html (accessed 10 October, 2015).

Lamb, S. and Kwok, K.C.S. (2016), “A longitudinal investigation of work environment stressors on the performance and wellbeing of office workers”, *Applied Ergonomics*, Vol. 52, pp. 104-111.

Lan, L., Wargock, P. and Lian, Z. (2011), “Quantitative measurement of productivity loss due to thermal discomfort”, *Energy and Buildings*, Vol. 43 No. 5, pp. 1057-1062.

Lee, S.Y. (2010), “Office layout affecting privacy, interaction, and acoustic quality in LEED-certified buildings”, *Building and Environment*, Vol. 45 No. 7, pp. 1594-1600.

Lee, S.Y. and Brand, J.L. (2005), “Effects of control over office workspace on perceptions of the work environment and work outcomes”, *Journal of Environmental Psychology*, Vol. 25 No. 3, pp. 323-333.

Madeo, F. and Schnabel, M.A. (Eds) (2014), *Proceedings of the 48th International Conference of the Architectural Science Association, The Architectural Science Association & Genova University Press, Genoa*, pp. 239-250.

Maréchal, K. (2010), “Not irrational but habitual: the importance of ‘behavioural lock-in’ in energy consumption”, *Ecological Economics*, Vol. 69 No. 5, pp. 1104-1114.

Mulville, M., Jones, K. and Huebner, G. (2013), “The potential for energy reduction in UK commercial offices through effective management and behaviour change”, *Journal of Architectural Engineering and Design Management*, Vol. 10 Nos 1/2, pp. 79-90.

O’Neill, M. (2008a), “A model of environmental control and effective work”, *Facilities*, Vol. 28 Nos 3/4, pp. 118-136.

O’Neill, M. (2008b), “Open plan and enclosed private offices. Research review and recommendations” available at: www.knoll.com/media/878/738/OpenClosed_Offices_wp.pdf

Pejtersen, J., Allermann, L., Kristensen, T.S. and Poulsen, O.M. (2006), “Indoor climate, psychosocial work environment and symptoms in open-plan offices”, *Indoor Air*, Vol. 16 No. 5, pp. 392-401.

Pejtersen, J., Feveile, H., Christensen, K. and Burr, H. (2011), “Sickness absence associated with shared open-plan offices – a national cross sectional questionnaire survey”, *Scandinavian Journal of Work, Environment & Health*, Vol. 37 No. 5, pp. 376-382.

Seddigh, A., Bernston, E., Jönsson, F., Bodin Danielson, C. and Westerlund, H. (2014), “Concentration requirements modify the effect of office type on indicators of health and performance”, *Journal of Environmental Psychology*, Vol. 38, pp. 167-174.

Seddigh, A., Bernston, E., Jönsson, F., Bodin Danielson, C. and Westerlund, H. (2015), “The effect of noise absorption variation in open-plan offices: a field study with a cross-over design”, *Journal of Environmental Psychology*, Vol. 44, pp. 34-44.

Smith, A. and Pitt, M. (2011), “Sustainable workplaces and building user comfort and satisfaction”, *Journal of Corporate Real Estate*, Vol. 13 No. 3, pp. 144-156.

Tetlow, R.M., Beaman, C.P., Elmualim, A.A. and Couling, K. (2013), “Targeting automatic behaviour to reduce small power electricity consumption in office buildings”, paper presented at the 4th Annual TSBE Eng. D. Conference, Reading.

van der Voordt, T.J.M. (2004), “Productivity and employee satisfaction in flexible workplaces”, *Journal of Corporate Real Estate*, Vol. 6 No. 2, pp. 133-148.

Veitch, J.A., Charles, K.E., Farley, K.M.J. and Newsham, G.R. (2007), “A model of satisfaction with open-plan office conditions: COPE field findings”, *Journal of Environmental Psychology*, Vol. 27 No. 3, pp. 177-189.

World Green Building Council (2014), “Health, wellbeing and productivity: the next chapter for green building”, available at: www.worldgbc.org/activities/health-wellbeing-productivity-offices (accessed 10 October 2015).

Wyon, D.P. (2004), "The effects of indoor air quality on performance and productivity", *Indoor Air*, Vol. 14 No. 7, pp. 92-101.

Yildirim, K., Akalin-Baskaya, A. and Celebi, M. (2007), "The effects of widow proximity, partition height, and gender on perceptions in open-plan offices", *Journal of Environmental Psychology*, Vol. 27 No. 2, pp. 154-165.

Further reading

Fisk, W.J. (1999), "Estimates of potential nationwide productivity and health benefits from better indoor environments: an update", in Spengler, J.D., Samet, J.M. and McCarthy, J.F. (Eds), *Indoor Air Quality Handbook*, McGraw-Hill, New York, NY.

Roelofsen, P. (2002), "The impact of office environments on employee performance: the design of the workplace as a strategy for productivity enhancement", *Journal of Facilities Management*, Vol. 1 No. 3, pp. 247-264.

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Paper Six

Mulville, M. and Stravoravdis, S. (2016). Regulating for climate change related overheating risk in dwellings. *In proceedings of the CIB World Building Congress 2016: Creating Built Environments of New Opportunities Conference 30 May - 2 June 2016, Tampere, Finland*. ISBN: 978-952-15-3741-7

Invited Presentations:

This paper formed the basis for presentations by the candidate at the following events:

- CIB World Building Congress 2016: Creating Built Environments of New Opportunities Conference 30 May - 2 June 2016, Tampere, Finland.

Other Impacts:

The research contained in this paper (along with Paper Four) formed the basis of evidence submitted by the Chartered Institute of Architectural Technologists (CIAT) to the recent public consultation of the proposed changes to the Standard Assessment Procedure [SAP].

Although the paper was subject to a number of alterations prior to publication, the reviewers were generally positive about the paper and satisfied once the issues raised were addressed. The reviewers noted that: “The paper presents very interesting and substantial contents. There are very detailed and reliable technical analyses.”

CIB World Building Congress 2016

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Volume I

Creating built environments of new opportunities

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Regulating for climate change related overheating risk in dwellings

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Abstract

There is broad scientific consensus supporting the link between CO_2 emissions and climate change. In cool and temperate climates such change is predicted to result in (among other impacts) warming ambient temperatures. As in recent years buildings in such locations have been increasingly optimised for heat retention (through regulations and standards), a warming climate has the potential to have a significant impact on the built environment and there is already evidence of overheating in new and recently constructed buildings.

Regulations in the built environment are largely designed to address issues of health and safety. In recent times however, such regulations have increasingly sought to incorporate issues related to energy efficiency while being used to implement national carbon reduction targets at the building scale. Arguably, building regulations remain focused on the 'point of handover' or near term performance, which given the uncertainty associated with predictions (such as climate change, occupant behaviour or technological change) is understandable. Such an approach however, in a situation where the current existing stock is seen as a major barrier to carbon reduction, risks buildings delivered today becoming prematurely obsolete due to the impacts of climate change.

Current overheating risk assessments in building regulations may not be appropriate as they are largely based on historic climate data. There remains a role however for regulations and standards that take account of the potential impacts of climate change. Building upon earlier research by the authors that demonstrates the potential magnitude of the overheating risk for UK dwellings, this paper suggests a risk based regulatory approach to overheating assessment based on climate change predictions while incorporating a requirement for adaptation planning. The approach put forward is based on semi-detached dwellings, built to new and emerging standards and regulations and aims to ensure that short term efficiency is not compromised for long term performance and comfort, thus minimising the potential for premature obsolescence related to overheating.

Keywords: Adaptation planning, Building regulations, Climate change, Dwellings, Overheating risk

1. Introduction

The built environment is responsible for a large proportion of global energy use and corresponding CO_2 emissions, with the residential sector using 18% of energy in 2011 (U.S. Energy Information Administration, 2015). In that context and with the drive to reduce such CO_2 emissions and thus mitigate against climate change, there has in recent years been a drive to make our dwellings more energy efficient. Building regulations have set increasingly ambitious energy reduction targets while other standards and assessment methods have emerged which go beyond the minimums of the building regulations (such as the Passivhaus standard). In cool and temperate climates increasing efficiency largely means optimising buildings for heat retention, with increasing levels of insulation and air tightness significantly reducing energy consumption.

Although the drive to improve efficiency, reduce emissions and minimise the potential for climate change is well founded, as noted by the IPCC (2007) a certain amount of warming is now inevitable. In cool and temperate climates there is evidence that this change may result in overheating (for example Jenkins et al., 2014a and Dodoo et al., 2014). Adaptations to alleviate overheating (Porritt et al., 2012) may help reduce the risk, however such adaptations may result in costs that some sectors of society cannot afford (Hills, 2012). In this context there is a need for building regulations to consider the impacts of predicted climate change. Furthermore, as ambient temperatures warm it is likely that occupant behaviour may become an increasingly important factor where clothing, work and lifestyle patterns may have to adjust.

This paper, which builds upon an earlier publication by the authors that sought to understand the magnitude of the potential for climate change related overheating (Mulville and Stravoravdis, 2016), presents a risk based approach for dealing with such overheating. Such as approach could form part of a regulatory framework that considers the potential impacts of climate change. The proposed approach aims to ensure that short term efficiency does not result in an unacceptably high overheating risk in the long term, thus attempting to take account of the lifetime performance of the building.

2. Literature Review

Roaf et al. (2015) suggest that the long life of buildings presents a challenge in developing *'fit for purpose'* regulations and standards in the context of climate change.

Most studies that seek to explore overheating related to climate change in dwellings do so using predictive building simulation models, considering how building specification, building type and/or location can impact on the magnitude of the overheating (for example see Peacock et al., 2010 and McLeod et al., 2013). Some studies consider the potential benefit of technical building adaptations to reduce overheating (such as Porritt et al., 2012) while others also consider the role of occupant adaptations linked to behaviour (such as Mavrogianni et al., 2014). In this context the review that follows focuses on the evidence for current and predicted overheating, how this may be avoided, how the current overheating assessment methods may contribute to this and what alternative approaches may be of benefit.

2.1 Evidence of overheating

There is evidence that new, recently constructed and well insulated dwellings may already be experiencing overheating, especially during warm summers (Dengel and Swainson, 2012). In support of this McLeod et al. (2012) suggest that highly insulated buildings in the UK, Ireland and Northern Europe may be at risk of overheating, arguably as they have been optimised for heat retention.

Going forward, the frequencies of such problems are predicted to increase. Jenkins et al. (2014a) suggest that by the 2030s, 76% of flats and 29% of detached dwellings in the UK could be at risk of overheating. Furthermore, Dodoo et al. (2014) in a study considering the potential impact of climate change on overheating risk for 'conventional' and 'Passive House' dwellings in Sweden, predicted significant increases in cooling demand by 2050 (reductions in heating load were also predicted). The research predicted a proportionately greater increase in cooling demand for the highly insulated Passive House building. In support of this Orme and Palmer (cited in Dengel and Swainson, 2012) note that increasing levels of insulation can result in increasing overheating risk. De Wilde and Tian (2012) suggest that buildings may be more resilient to climate change than expected due to the relatively short life expectancy of systems, presence of additional capacity in those systems and opportunities to install new systems. However, Peacock et al. (2010) note that an increase in installed air conditioning could result in occupant behaviour that accentuates energy consuming behaviour. A challenge in how to deal with overheating risk remains.

It has been suggested that raised temperatures in bedrooms overnight is a particular risk (Naughton et al., 2002 as cited in Peacock et al., 2010), where temperatures above 24°C have been linked to impaired sleep and health implications (Dengel and Swainson, 2012). In this context Peacock et al. (2010) suggest that where high bedroom temperatures overnight are problematic, the use of a 'cooling nights' metric may be of benefit.

2.2 Overheating assessment methods

Given the evidence of overheating in new and recently constructed buildings it can be argued that the current approach to overheating risk assessment may not be fit for purpose. In regulations, assessments related to overheating risk are often made using relatively simplistic steady state tools (such as SAP UK (Department of Energy and Climate Change [DECC], 2014). This may be due to the complexity and resource needed to conduct, potentially more accurate, dynamic simulation based assessments (Jenkins et al. 2013). It has been argued that the current approach cannot account for the potential impacts of a warming climate as much of the climate data used is historic (de Wilde and Coley, 2012). Furthermore, it has been suggested that the current approach to overheating risk assessment may also allow for unrealistic user adaptations, such as window opening (Mulville and Stravoravdis, 2016).

Peacock et al. (2010) note that there remains a role for policy in addressing elevated temperatures in dwellings. Jenkins et al. (2013) suggest that using an alternative approach based on overheating frequency curves derived from regression analysis of a range of climate predictions and analysed using dynamic simulation for specific buildings, may improve predictions and allow for the consideration of risk. Expanding on the proposed overheating risk curves (Jenkins et al., 2014b), it is suggested that potential user adaptations, such as opening windows and technical intervention (such as shading and the reduction of internal gains) could be included in the assessment. The approach does still require significant knowledge of the building operation and building characteristics, however it greatly reduces the amount of simulation required and may help designers to contextualise the problem (Jenkins et al., 2013). Jenkins et al. (2013) argues that any methodology used to assess overheating should be industry focused and able to include a range of building types, glazing ratios, building characteristics and locations.

2.3 Reducing overheating risk

McLeod et al. (2013) found that in highly insulated dwellings, external shading followed by adjustments to south-facing glazing ratios had the greatest potential to reduce overheating risk. Supporting this, Porritt et al. (2012) suggest that the control of solar gains (shading, shutters, glazing specification), solar reflective coatings and insulation (the study was based on dwellings with low levels of existing insulation) could also help reduce overheating risk. Furthermore, increased ventilation (Porritt et al., 2012) and higher levels of thermal mass (Gupta and Gregg, 2012) have also been shown to be of benefit although in both cases there are potential limitations. Peacock et al. (2010) note that although during the day time thermal mass would appear to have significant advantages, overnight the measured benefits may reduce as stored heat from day-time heat gains is radiated back into the spaces. This is supported by McLeod et al. (2013) who found that although overall temperatures in high thermal mass buildings were lower than in others, bedrooms in light weight buildings cooled more rapidly (in the 2080s). Where raised temperatures in bedrooms have been shown to be problematic (Dengel and Swainson, 2012) this potentially presents a risk and the perceived benefits of thermal mass in dwellings may be questionable.

Window opening may help to reduce overheating risk. However, Mavrogianni et al. (2015) suggest that window opening in urban centres may have negative health impacts, with Tong et al. (2016) highlighting the link between raised indoor air pollution and proximity to roads. This is supported by Peacock et al. (2010) who note that window opening is likely to be limited by noise, pollution and security in urban areas. In addition to the discussion about window opening behaviour there is evidence that in the future the benefits of such window opening may reduce. Peacock et al. (2010) found that although increased ventilation still had benefits this was not enough to overcome the overheating issues predicted for London in the 2030s.

Gupta and Gregg (2012) note that adaptations to reduce overheating risk could result in some increase in heating demand and suggest that phased adaptations over the lifetime of the building may be of benefit. In this context Jones et al. (2015) set out an approach to adaptation planning related to the predicted impacts of climate change. Although based on a non-domestic building, the approach suggested that where future problems were identified an adaptation plan could be developed to enable the building to be altered on a cost-effective basis when required. Where interventions in the future may prove prohibitively expensive, but predicted risk is high, enabling works to allow the future adaptation could be incorporated into the initial construction phase.

3. Methodology

As detailed in the earlier paper associated with this research (Mulville and Stravoravdis, 2016), and summarised here, this study used dynamic simulation modelling for a ‘typical’ (UK) semi-detached dwelling coupled with climate change predictions to understand the level of overheating risk. To understand how the heat retention parameters of the fabric impact upon the potential overheating risk, five standards were chosen and associated construction specifications developed to reflect these construction standards (UK Part L 2006 and 2010, ‘Good Fabric’, ‘Advanced Fabric’ and the Passivhaus standard). The construction system used was also varied to reflect a range of potential levels of thermal mass (low, medium and high options). For the purposes of this paper the analysis and results presented are based on a North-South orientation only.

3.1 Simulation approach

The ‘typical’ building was modelled using Ecotect® software (Marsh, 1996) which was then exported to Heat Transfer in Buildings 2 (HTB2) software (Lewis & Alexander, 1990) for the purpose of dynamic simulation and analysis. The models were then ‘run’ for the summer months using a range of current and probabilistic future reference years (climate files) based around the prediction of the UKCP09 weather generator and developed as part of the PROMETHEUS project at the University of Exeter (as detailed by Eames et al., 2011). For the purposes of this work the 50th percentile medium scenario predictions were chosen. The results presented in this paper are based on Design Summer Years (DSYs) representing near extreme scenarios. In addition a range of possible window opening positions, where included in the modelling.

3.2 Overheating assessment approach

The adaptive comfort approach to predicting overheating as detailed by Nicol and Spires (2013) was used to determine when overheating may have occurred and to gauge the magnitude of the overheating identified. This is represented by three overheating criteria. Criteria one was based on the comfort threshold being exceeded, criteria two considered the severity of the overheating in a given day and criteria three set an absolute maximum allowable temperature. In each case the temperatures were related to a running mean of outdoor temperature and were analysed based on the outputs of the preceding modelling approach. Exceedance of any two of these three criteria, as detailed by Nicol and Spires (2013), was then considered to represent an unacceptable level of overheating. As noted in the preceding research to this paper (Mulville and Stravoravdis, 2016), there remains a debate about the most appropriate metrics to be used. As a result, additional analysis was carried out based on exceedance of specific temperatures.

4. Overheating Risk

This research sought to consider the potential impact of a warming climate on dwellings. In this case a ‘typical’ semi-detached dwelling was chosen and analysed using dynamic building simulation and probabilistic climate scenarios for a southern UK climate.

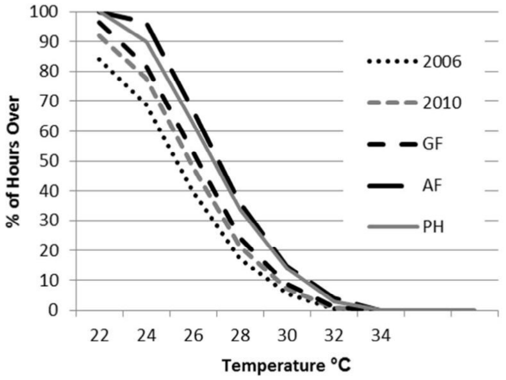


Figure 1: Temp. frequency curve – Across standards

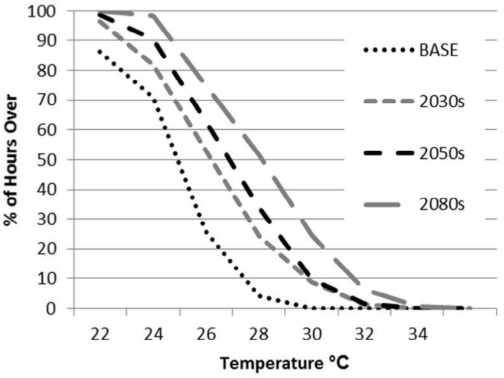


Figure 2: Temp. frequency curve – Overtime

4.1 Predicted overheating patterns

Figures 1 and 2 are based on scenarios where windows are able to be opened to the ‘slightly opened’ position (triggered by internal temperatures thresholds and appropriate outdoor temperatures to aid cooling) which represents one air change per hour and a medium thermal mass construction. As can be seen in Figures 1 and 2there is a general increase in temperatures and therefore overheating risk as fabric heat retention criteria increase (insulation levels, air tightness, glazing specification etc.) and the climate warms. This was also reflected in the wider analysis across all thermal mass and window opening scenarios. The Passive House standard did appear to offer some protection from overheating when compared with the ‘Advanced Fabric’ building, with 6.6% reductions in the 2030s, 6.8% in the 2050s and 7.2% in the 2080s observed in certain scenarios (see Mulville and Stravoravdis, 2016). This is arguably due to the greater emphasis on solar protection required by the Passive House standard and possibly a more robust overheating assessment. Thermal mass was also found to offer benefits in reducing levels of overheating with reductions of 15% observed in the 2030s, however the benefit for highly insulated options (Advanced Fabric and Passive House) may reduce between

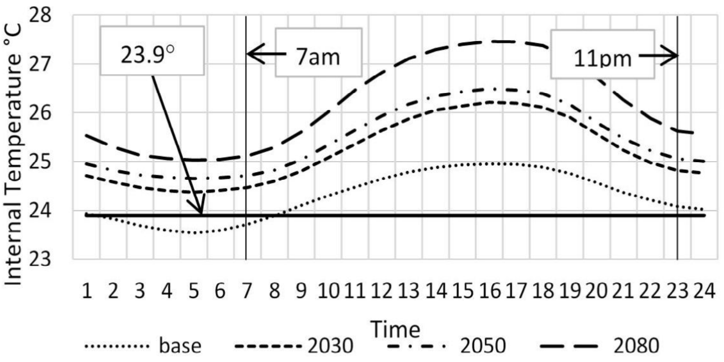


Figure 3: Daily temperature profile (HTM, Good Fabric)

the 2050s and 2080s. This could be related to a reduction in internal to external temperature differences over time, with for instance a reduction in the mean internal to external temperature difference for the Advanced Fabric building of 3.36°C observed between the base case and the 2080s. This in turn reduces the ability of ventilation air to cool the building fabric. As demonstrated in Figure 3, which is based on slightly open windows, as the temperature warms due to the impacts of climate change, night-time bedroom temperatures frequently exceed the 23.9°C threshold (as noted by Peacock et al, (2010) this is the temperature at which bedroom occupants at night may begin to feel uncomfortable and may seek to change the conditions) during peak summer. This does reduce where windows can be opened further (see Figure 4, based on 'half open' windows in the 2030s), but the issue remains. Exploring this in more detail it is found that although thermal mass can, as noted above, reduce overall levels of overheating (measured against the adaptive comfort criteria), temperatures are higher overnight for the high thermal mass solution compared to the low thermal mass solution (see Figure 4). This can be related back to the suggestion by McLeod et al. (2013) that heavy weight buildings may contribute to raised temperatures in bedrooms overnight due to the re-admittance of stored gains into the space. As demonstrated by comparing Figures 3 and 4 window opening to increase ventilation offers benefits, although as previously noted such benefits may reduce over time and concerns regarding air pollution, noise and security remain.

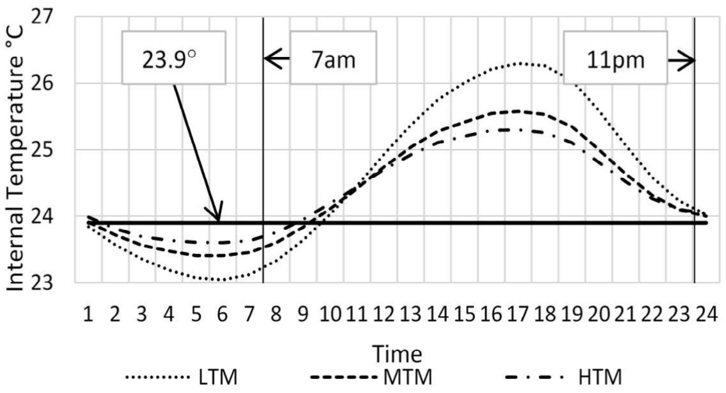


Figure 4: Daily temperature profile (Good Fabric – 2030s)

In the context of the analysis presented here, it can be argued that there is a need for more robust building regulations that take a longer term view in relation to overheating risk assessment. There is also a need to explore overheating metrics in relation to overnight bedroom temperatures.

4.2 Building overheating risk categorisation criteria

Based on the preceding discussion (and findings of the previous research to this paper (Mulville and Stravoravdis, 2016)) it can be argued that the main risk criteria related to overheating in dwellings are overall fabric heat retention parameters (insulation levels, air tightness, window specification), thermal storage parameters (mass) and opportunities for occupant adaptation (window opening). There remains questions around both thermal mass and window opening in relation to long term benefits, overnight temperatures and urban environments. In addition, building on the findings from previous studies, building configuration (semi-detached, terraced, flat etc. and orientation (including shading)) and insulation position (which could be included in the 'heat retention parameters') are also risk categories. This study did not seek to rank the relevant importance of these risk categories, but instead considered how the potential combinations of these criteria are likely to contribute to overall overheating risk (see Figure 6).

4.3 Proposed risk based assessment approach

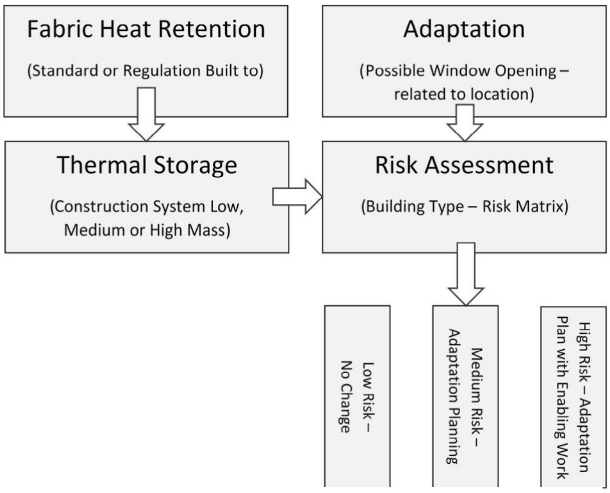
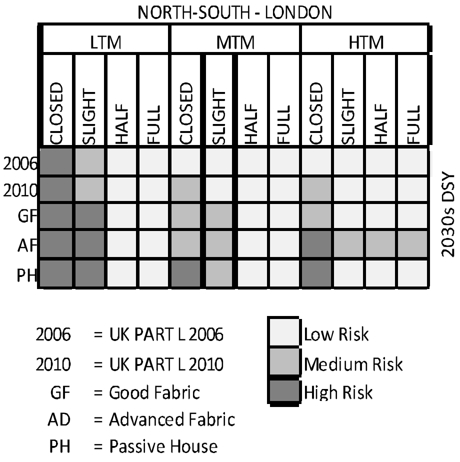


Figure 5: Proposed Approach – Flow Chart

As noted by BJM (2009) cited in de Wilde and Tian (2012) a risk can generally be stated as 'probability x consequence'. In this case the probability is that overheating risk derived from dynamic building simulation and the consequence is the impacts of that overheating. In any risk assessment the weightings of parameters used should reflect their relative importance. In this case exceedance of the adaptive comfort criteria is used to determine the level of risk. This is based on the relevant running mean of acceptable temperatures. As raised bedroom temperatures at night time have been shown to be problematic and as the benefits of thermal mass in reducing overheating during the day may reverse overnight, a debate remains regarding the most appropriate metrics to use. If raised temperatures in bedrooms overnight (above 23.9°C) was used as the overheating metric in this study the risk matrix presented in Figure 6 would be significantly different. The adaptive comfort criteria as described, coupled with the risk criteria previously noted (fabric heat retention parameters, thermal storage parameters, adaptation options and building configuration) are combined to create the risk matrix displayed in Figure 6. A flow chart of the assessment process is presented in Figure 5, detailing the steps taken to reach the appropriate point on the risk matrix. One of the key input criteria for the proposed approach is the possible window opening position. Permissible window opening positions must be linked to the location of the building and a decision made based on exposure to pollution and noise along with an assessment of potential security concerns. The risk matrix as presented considers the 2030s only, arguably a weighted matrix could also include predictions for the 2050s and 2080s. However, as noted by de Wilde and Tian (2012) longer term predictions become increasingly uncertain due to the range of assumptions association with maintenance, systems and renovations etc. As a result, in this case a shorter term assessment is presented, although longer term predictions may also have merit where the level of uncertainty can be taken into account.

As noted by Gupta and Gregg (2012) interventions made now could result in increased heating demand. In this context regulations dealing with overheating should aim to optimise lifetime building performance while minimising the risk of future overheating. An approach integrated with adaptation planning and backcasting/forecasting (Jones et al., 2015) could help to deliver whole life performance. Therefore, the output of the proposed approach is requirements for adaptation planning, adaptation planning with enabling works or a change in the approach taken based on the level of risk identified. As an example, taking a dwelling in an urban area where only slightly open windows may be possible. If built to the ‘Good Fabric’ condition with low thermal mass, this dwelling would be at high risk of overheating (see Figure 6) and would require an adaptation plan with enabling works to allow for future adaptations (such as preparations for the installation of shading). As this is likely to add cost, it may be that the designer/ developer would choose to avoid such a scenario. In that case, a change in construction system to a medium thermal mass level has the effect of reducing the risk and removing the requirement for enabling works, while a high thermal mass solution would move the building into a low risk scenario. This approach must be considered in the context of the previous comments about the potential impact of thermal mass on overnight temperatures in bedrooms. However, if appropriate overheating metrics could be assigned, the approach outlined could help to ensure that current performance is not compromised to avoid longer term overheating. The approach, as such, incentivises the designer/developer to favour a low risk scenario while accounting for a range of building characteristics (as suggested by Jenkins et al., 2013) and favouring phased adaptations (as suggested by Gupta and Gregg, 2012).



	LTM				MTM				HTM			
	CLOSED	SLIGHT	HALF	FULL	CLOSED	SLIGHT	HALF	FULL	CLOSED	SLIGHT	HALF	FULL
2006	■	▒	□	□	□	□	□	□	□	□	□	□
2010	■	▒	□	□	▒	□	□	□	▒	□	□	□
GF	■	■	□	□	▒	▒	□	□	▒	□	□	□
AF	■	■	□	□	▒	▒	□	□	■	▒	▒	▒
PH	■	■	□	□	■	▒	□	□	■	□	□	□

2006 = UK PART L 2006
2010 = UK PART L 2010
GF = Good Fabric
AD = Advanced Fabric
PH = Passive House

□ Low Risk
▒ Medium Risk
■ High Risk

Figure 6: Risk Matrix (adapted from – Mulville and Stravoravdis, 2016)

5. Discussion & Conclusion

The overall installed capacity of artificial cooling in UK dwellings remains low (Hulme et al., 2011). However, if the potential increase in overheating as predicted is realised the installed capacity could increase significantly (Peacock et al., 2010). Although there is likely to be a corresponding reduction in heating demand (Dodoo et al., 2014) and with technological change the overall increase in carbon emissions may be minimal, increased use of artificial cooling could have a negative impact on the energy use behaviour of occupants (Peacock et al., 2010). Furthermore, if the overheating risk is not addressed a shift from winter to summer time fuel poverty could be observed, with corresponding health, wellbeing and societal impacts. As discussed, the current approach to overheating risk assessment may not be fit for purpose as it does not take account of climate change projections and may assume unrealistic adaptations.

The proposed approach to overheating risk assessment utilises the increased accuracy of dynamic building simulation modelling (when compared to steady state assessments) (Jenkins et al., 2013), while reducing the amount of resource required and presents an approach that could be applied by industry. If risk matrices for a range of building types, in a range of locations could be developed a large proportion of the ‘typical’ new stock could be represented. The requirement for adaptation planning based on the level of risk identified would help to ensure that pathways focused on long term performance can be developed for the dwellings in question. This approach could be tied to the likely major refurbishment points for the building, such as when windows etc. have reached the end of their useful life.

The findings of this research demonstrate that, by using risk based assessments implemented through the building regulations, it may be possible to take account of the potential impacts of climate change (in this case overheating) while considering the inherent uncertainty of such predictions. The implications for building regulations is a shift from a *'point of handover'* approach towards a forecasting role. Such forecasting must be approached with caution and an appreciation of risk and probability to avoid unintended consequences. Arguably, given the potential impacts of overheating on occupants, this refocuses on the traditional health and safety role of the building regulations while accounting for energy performance on a whole of life basis.

As noted, the metric used can have a significant impact on the level of risk identified. This is particularly true in relation to temperatures in bedrooms overnight, where issues related to the relevant benefit and drawbacks of thermal mass may also be important. Further research in relation to developing overheating metrics in dwellings that takes these issues into account would be of benefit. In addition, as the research demonstrated, window opening to increase ventilation can have a significant impact on reducing overheating risk. However, in some scenarios presumed window opening behaviour may be unrealistic or may result in negative health impacts related to pollution. Further research into window opening behaviour in dwellings, particularly in urban areas subject to noise, pollution and security issues would be of benefit.

6. Limitations

The approach taken in this study must be considered in relation to a number of limitations. A medium level, 50th percentile prediction was used and a wider consideration of potential climate scenarios may add depth to the assessment. In addition the building simulation approach used includes a number of assumptions related to internal gains and occupancy patterns that cannot be easily predicted. Although a range of 'typical' buildings could be addressed if this approach was expanded to include other configurations, the criteria that define 'typical' would need to be carefully developed. A range of dwellings that cannot be easily categorised would remain and these would require more resource intensive building specific assessments.

References

Dengel, A and Swainson M. (2012). *Overheating in new homes: A review of the evidence* (available online http://www.zerocarbonhub.org/sites/default/files/resources/reports/Overheating_in_New_Homes-A_review_of_the_evidence_NF46.pdf [accessed on 30/03/2016])

Department of Energy and Climate Change (2014). *The government's standard assessment procedure for energy rating of dwellings* (available online: http://www.bre.co.uk/filelibrary/SAP/2012/SAP-2012_9-92.pdf [accessed on 30/03/2016])

Eames M., Kershaw T. and Coley D. (2011). "On the creation of future probabilistic design weather years from UKCP09." *Building Services Engineering Research and Technology* **32:** 127-142.

de Wilde P. and Coley D (2012) “The implications of a changing climate for buildings.” *Building and Environment* **55:** 1-7.

de Wilde P and Tian W (2012) “Management of thermal performance risks in buildings subject to climate change.” *Building and Environment* **55**: 167-177.

Dodoo A, Gustasson L and Bonakdar F (2014) “Effects of future climate change scenarios on overheating risk and primary energy use in Swedish residential buildings.” *Energy Procedia* **61:** 1179-1182.

Gupta R. and Gregg M. (2012) “Using UK climate change predictions to adapt existing English homes for a warming climate.” *Building and Environment* **55:** 20-42.

Hills, G. (2012). *Getting the measure of fuel poverty, final report of the fuel poverty review* (available online http://sticerd.lse.ac.uk/dps/case/cr/CASEreport72.pdf [accessed on 30/06/2016])

Hulme, J, Beaumont A. and Summers C. (2011). *Energy follow-up survey 2011, Report 9: Domestic appliances, cooking & cooling equipment* (available online https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/274778/9__Domestic_appliances__cooking_and_cooling_equipment.pdf [accessed on 30/06/2016])

IPCC (2007) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* (available online https://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm [accessed on 30/03/2016])

Jenkins D, Ingram V, Simpson S and Patidar S (2013) “Methods for assessing domestic overheating for future building regulation compliance.” *Energy Policy* **56:** 684-692.

Jenkins K, Hall J, Glenisbi V, Kilsby C, McCarthy M, Goodess C, ……Smith D. (2014a) “Probabilistic spatial risk assessment of heat impacts and adaptations for London.” *Climate Change* **124:** 105-117.

Jenkins D, Patidar S, Banfill, P and Gibson G (2014b) “Developing a probabilistic tool for assessing the risk of overheating in buildings for future climates.” *Renewable Energy* **61:** 7-11.

Jones, K., Desai, A., Mulville, M. & Jones, A. (2015) “Asset management using a hybrid backcasting/forecasting approach.” *Facilities* **33:** 701-715.

Lewis P and Alexander D (1990) “HTB2: A flexible model for dynamic building simulation.” *Building and Environment* **25**: 7–16.

Marsh A (1996) *Performance Modelling and Conceptual Design*, (available online https://www.ibpsa.org [accessed on 19/03/2016])

Mavrogianni A, Davies M, Taylor J, Chalabi Z, Biddulph P, Oikonomou E, Das P and Jones B (2014) “The impact of occupancy patterns, occupant-controlled ventilation and shading on indoor overheating risk in domestic environments.” *Building and Environment* **78**: 183-198.

Mavrogianni A, Taylor J, Davies M, Thoua C and Kolm-Murray J (2015) “Urban social housing resilience to excess summer heat.” *Building Research and Information* **43**: 316-333.

McLeod R S, Hopfe C J and Kwan A (2013) “An investigation into the future performance and overheating risk in Passivhaus dwellings.” *Buildings and Environment* **70**: 189-209.

Mulville and Stravoravdis (2016) “The impact of regulations on overheating risk in dwellings.” *Building Research and Information* doi:10.1080/09613218.2016.1153355

Nicol F and Spires B (2013) *Climate Change and the Indoor environment: impacts and adaptations*, London, The Charted Institution of Building Services Engineers.

Peacock A, Jenkins D and Kane D (2010) “Investigating the potential for overheating in UK dwellings as a consequence of extant climate change.” *Energy Policy* **38**: 3277-3288.

Porritt S, Cropper P, Goodier C (2012) “Ranking of interventions to reduce dwelling overheating during heat waves.” *Energy and Buildings* **55:** 16-27.

Roaf S, Brotas L and Nicol F (2015) “Counting the cost of comfort” *Building Research and Information* **43**: 269-273.

Tong Z, Chen Y, Malkawi A, Adamkiewicz G and Spengler J D (2016) “Quantifying the impact of traffic-related air pollution on the indoor air quality of a naturally ventilated building.” *Environment International* **89-90**: 138-146.

U.S. Energy Information Administration (2015) *frequently asked questions,* (available online https://www.eia.gov/tools/faqs/faq.cfm?id=447&t=3 [accessed on 30/03/2016])

Paper Seven

Mulville, M., Jones, K., Huebner, G. and Powell, J. (2016). Energy saving occupant behaviour change strategies in the workplace. *Journal of Building Research and Information.* http://dx.doi.org/10.1080/09613218.2016.1212299

A representative of the French Environment and Energy Management Agency has contacted the candidate in relation to this paper, with a view to exploring the potential for future collaboration.

Altmetric notes this paper as:

"In the top 25% of all research outputs scored by Altmetric"

"High attention score compared to outputs of the same age (85th Percentile)"

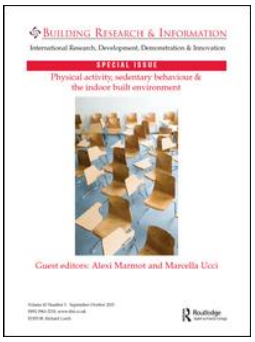
"Good attention score compared to outputs of the same age and source (68th Percentile)"

Impact on the business:

This paper had direct impact on the business involved who were keen to understand the role of occupant behaviour on energy consumption. The findings of the research were presented to the Facilities Management and Senior Management teams at the business.

Reviewers' comments:

Although the paper was subject to a number of alterations prior to publication, the reviewers were generally positive about the paper and satisfied once the issues raised were addressed. The reviewers noted that "It is relevant to an international interdisciplinary audience and to BRI. The material is novel and provides valuable insight and justifies publication …" "Excellent wide and deep review of the literature on behaviour change and energy saving in workplaces, including recent publications …" "Overall this paper addresses an important area of research, which is relatively unexplored."



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RESEARCH PAPER

Energy-saving occupant behaviours in offices: change strategies

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ABSTRACT

As regulated energy consumption in buildings is reduced, the proportional importance of unregulated energy consumption increases. Reducing unregulated energy use in the commercial office requires an understanding of the factors that influence workplace behaviour. To date these factors have been assumed to be similar to those that influence behaviour in the home. However, the social dynamics of the workplace are different to those in the home. This study examines the degree to which theories of behaviour change generated largely in a domestic building setting could be used as the basis for designing interventions to reduce unregulated energy consumption in the workplace. It studies the unregulated energy consumption of 39 workers engaged in office-type activities in two separate locations. Following a 100-day monitoring period, three behaviour change interventions were developed and their impact measured over a 100-day period. Results from the study found, on average, an 18.8% reduction in energy use was achieved. Furthermore, by comparing pre- and post-intervention responses to an environmental questionnaire, it was evident that savings were realized without significant changes to pro-environmental attitude or perceived social norms, which may have implications for energy-saving interventions in the commercial sector.

KEYWORDS

behaviour change; building management; demand-side management; energy; energy-use behaviour; feedback; social norms

Introduction

The European Commission's 2030 climate and energy framework (2014) has targeted a 27% increase in energy efficiency to support a low-carbon economy and achieve sustainable growth. In 2011 non-residential buildings (European Union, Switzerland and Norway) consumed approximately 146 Mtoe (million tonnes of oil equivalent) of fuel; this represents 32% of the total consumption across all buildings, but for only 25% of the total building stock (Building Performance Institute Europe, 2011). If the European Union is to meet its 2030 targets, non-residential buildings must reduce their energy consumption.

Changes to the built environment regulatory framework (such as Part L of the UK Building Regulations) aim to reduce the heating, cooling and lighting (regulated) energy consumption in new buildings. Additionally, environmental/energy-assessment methods and standards such as Passive House, BREEAM and LEED should encourage designers and developers to go beyond the minimum standards required by regulations. However, as these savings are predominantly technical interventions targeted at new buildings, and due to the legacy of the existing stock, their impact on overall energy consumption will take considerable time to realize. In comparison, reductions in unregulated energy are largely unaffected by legacy design and, as such, impacts here could be realized much more quickly. However, it is unclear what approaches could best be used to reduce unregulated energy in commercial buildings.

Unregulated energy use in non-domestic buildings is that energy associated with small power devices, office equipment, desktop and laptop computers and localized heating, cooling and lighting. Although the energy efficiency of individual pieces of equipment is likely to have improved in recent years (Mulville, Jones, & Huebner, 2014), the increased range of equipment used has led to predictions that small power will continue to have a significant impact on overall energy use in future (Jenkins, Singh, & Eames, 2009). Energy used at individual workstations may account for up to 88% of total office equipment energy use (Junnila, 2007). At the same time, actual utilization of equipment by occupants,

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while the equipment is powered on, may be as low as 43% (Kawamoto, Shimoda, & Mizuno, 2003), indicating that large savings may be possible and that occupant behaviour could have a significant impact on this (Zhang, Siebers, & Aickelin, 2011). Arguably, many campaigns to reduce energy use in the workplace are based on information provision only, driven by corporate social responsibility. However such a passive approach, as noted by Carrico and Riemer (2011), may not be enough for significant savings to be achieved.

Until recently most studies that have examined energy-saving behaviour have done so in a domestic setting (for a review, see Abrahamse, Steg, Charles, & Rothengatter, 2005) taking an individualistic approach to energy-saving behaviour and suggesting the individual's beliefs and attitudes towards pro-environmental behaviour are paramount. However, whilst an individual's approach, beliefs and attitudes towards pro-environmental behaviour may be transferable to the workplace, it is likely that organizational factors (culture, organizational focus and structure) (Tudor, Barr, & Gilg, 2008) and job satisfaction (Brent & Freathy, 1997) will influence their importance. In the workplace the disconnect between the energy user and who pays the bills, the high density of occupants and perceived lack of control may also be influential as users feel disconnected from the space they occupy (Bull, Lemon, Fleming, Stuart, & Everitt, 2014). Therefore, this calls into question the applicability of theories adopted from residential sector to energy-saving behaviour within the commercial sector (Carrico & Riemer, 2011; Siero, Bakkerm, Dekker, & van der Burg, 1996, cited in Chen & Ahn, 2014; Nilsson, Andersson, & Bergstad, 2015). Application of energy-saving behaviour theories in the commercial office setting have to date been limited to a small but growing number of studies (*e.g.*, Gulbinas & Taylor, 2014; Murtagh et al., 2013; Tetlow, Beaman, Elmualim, & Couling, 2013). This study aims to build on those preceding studies and examines the effectiveness of behaviour change interventions using feedback, goal setting and social normative influence on energy consumption within commercial office buildings.

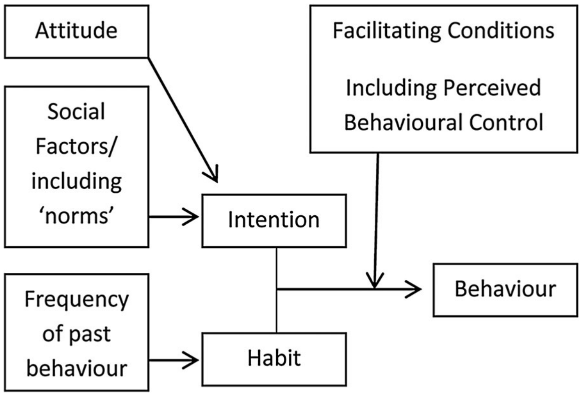


Figure 1. Simplified version of Triandis' 'Theory of Interpersonal Behaviour'.
Source: adapted from Chatterton (2011).

Theoretical framework

As noted by Chatterton (2011) there has been significant developments in the understanding of behaviour since the 1960s. As a result, a range of theories have emerged that can assist with the exploration of behaviour and potentially influence it. More recently, a range of approaches have been developed in relation to energy-use behaviour, particularly in domestic buildings (for a review, see Chatterton, 2011). These approaches include economic, psychological, sociological and educational theories, and when considered in the context of a behavioural model it may be possible to use them to influence behaviour (Chatterton, 2011). There is a wide range of models of behaviour; they often overlap or build upon one another and can be seen as complementary. Triandis' 'Theory of Interpersonal Behaviour' has been shown to be useful in relation to energy-use behaviour (Chatterton, 2011) and is used here (Figure 1) to highlight the interrelationships between the factors discussed in the remainder of this review.

Habit, attitude and intention

Chatterton (2011) argued that intentions and behaviour, over time, form habit or 'locked-in' practice (Maréchal, 2010), which is difficult to change. In the short-term it may be possible to change behaviour through conscious effort, but unless this becomes habitual the change is unlikely to persist. Maréchal (2010) suggests that habit, as a barrier to change, is unconscious (and as such is automatic); while conscious decisions occur rarely, habits are embedded in everyday routines. The time taken for a habit to become automatic (as defined by Bargh, 1994, cited in Chatterton, 2011) is reported to be approximately 66 days (Lally, van Jaarsveld, Potts, & Wardle, 2010). Where a given issue (such as climate change) is perceived to be beyond the individual's immediate self-interest, changing a habit may be more challenging (Stern & Gardener, 1981). Francis et al. (2004) noted strong links between attitude, intention and behaviour. A change in behaviour may require a change in values and/or attitude; however, there is some evidence that this is not always the case, De Young et al. (1995), for instance, found that recyclers and non-recyclers did not differ in their attitudes toward recycling.

Social norms

Social norms are those attitudes or behaviours that are considered to be the 'norm' within the group that the individual belongs to, *i.e.*, it is what the majority of one's peers say, think do etc. Social norms can be particularly influential where people seek to be praised or rewarded by others (Chatterton, 2011). A group's social norms are usually an implicit set of rules for acceptable behaviours, values and beliefs (Miller & Prentice, 1996) within the group. Those who do not conform are perceived to be different, difficult and a general hindrance to maintaining social order. A realization of a mismatch between one's own behaviour and social norms may lead to feelings of guilt (Baumeister, 1998).

Normative social influence has been explored in relation to pro-environmental behaviours (Hopper & Nielsen, 1991; Nolan, Schultz, Cialdini, Goldstien, & Griskevicius, 2008; Scherbaum, Popovich, & Finnlinson, 2008). Nolan et al. (2008) explored the extent to which norms influenced energy conservation behaviours. They found that individuals who had been given a descriptive normative message containing information about the conservation behaviours of the majority of others made significant energy savings. The study demonstrated that social norms, whether true or not, can actually motivate people to conserve energy. Scherbaum et al. (2008), in a study influenced by value–belief–norm (VBN) theory (Stern, 2000; Stern, Dietz, Abel, Guagnano, & Kalof, 1999), suggests that environmental personal norms and environmental worldviews can be leveraged by organizations in their interventions to reduce employee energy use.

Some studies have shown that communicating social norms can actually increase an undesirable behaviour (*e.g.*, Perkins, Haines, & Rice, 2005; Wechsler et al., 2003; Werch et al., 2000). Schultz, Nolan, Cialdini, Goldstein, and Griskevicius (2007) provided a descriptive normative message to 290 residents detailing energy consumption, households who were low-energy consumers, once given the message increased their energy use. This is because individuals use their perceptions of peer norms as a standard against which to compare their own behaviour. However, Schultz et al. (2007) also found that when an injunctive norm (the perception that the behaviour is commonly approved or disapproved within the group) was combined with the descriptive normative message low-energy users continued to consume energy at the desirable amount.

Perceived behavioural control

Perceived behavioural control, as noted by Francis et al. (2004), is made up of two components: the person's control over the given or encouraged behaviour (*e.g.*, the presence of suitable environmental controls in an office environment) and the person's confidence that they will be able to perform the behaviour (*e.g.*, successfully interacting with the given environmental controls). Perceived behavioural control is closely related to the presence of 'facilitating conditions' (Chatterton, 2011, in relation to Triandis 'Theory of Interpersonal Behaviour'), which can make an encouraged behaviour easy or difficult, the knowledge of which may influence attitude and thus behaviour.

Perceived behavioural control is a key element of the Theory of Planned Behaviour (with social norms and attitude) as developed by Ajzen (1991), and there is evidence that it can be influential in the success of energy-saving measures in the commercial building sector. Menzes et al. (2012), in a study considering the turning off of lights and small appliances in the office setting, found a statistically significant relationship between perceived behavioural control and energy consumption, with those with higher perceived control saving more energy. In addition, the same study found the impact of both social norms and attitude not to be significant, further highlighting the importance of perceived control. Bull et al. (2014) note, however, that non-domestic building users can often feel detached or disconnected from the spaces they occupy, which can be linked back to perceived control. This presents a particular challenge for building managers.

Feedback

Feedback can be a big motivator for encouraging sustainable behaviours (Bostrom & Fischhoff, 2001). Both individual and group-level feedback has been shown to influence pro-environmental behaviour positively (Dwyer, Leeming, Cobern, Porter, & Jackson, 1993; Schultz, Oskamp, & Mainieri, 1995). For feedback to be most effective, it should be presented as close as possible in time and space to the behaviour that is being promoted and in such a way that it is simple to interpret (Benders, Kok, Moll, Wiersma, & Noorman, 2006; Carrico & Riemer, 2011; Katzev & Mishima, 1992; Siero et al., 1996), so that individuals can identify the relationship between their behaviour and the feedback (Seligman, Becker, & Darley, 1981). The effectiveness of feedback in the residential sector is shown to diminish once feedback is removed suggesting that feedback in order to be effective must be maintained in the long-term (Dwyer et al., 1993). However, studies in commercial settings (Gulbinas & Taylor, 2014; Murtagh et al., 2013) have found that although engagement with feedback reduces over time, energy savings may not occur until later in the study (when engagement with feedback has reduced). This perhaps suggests the commercial sector is less ‘elastic’ (Murtagh et al., 2013) than the residential in terms of the impact of feedback; however, in some situations the non-domestic sector has been shown to be more elastic (*e.g.*, as Wakiyama, Zusman, & Monogan, 2014). Darby, Elmualim, Clements-Croome, Yearley, and Box (2016), in an office environment within a higher education institution, found that when the level of feedback communicated (designed to reduced energy use) reduced there was a corresponding increase in energy consumption, suggesting that even where the response may be less elastic, continuous behavioural reinforcement may still be required to ensure persistence.

Comparative feedback, where the energy consumption of an individual or group is compared with the average, has been successful in reducing energy consumption in households, (Abrahamse et al., 2005). Comparative feedback works by evoking a feeling of competition via social comparison, or social pressure, which then leads to changed behaviour in order either to correspond more closely to the ‘norm’ or to ‘perform better’ than the group or other individual. This normative information can be provided by allowing individuals to believe that their performance will be compared with that of the other group (Jackson & Zedeck, 1982; Shalley, Oldham, & Porac, 1987). Appraisal of the behaviour relative to the average consumption (or other group) can be given in the form of a positive (smiley/happy) or negative (unhappy) face. This phenomenon is explained by two different processes: social identity, where people will generally strive for a positive self-image (Tajfel, 1978), and competition.

Some promising research in commercial settings has demonstrated the positive effect of comparative feedback on reducing energy consumption (*e.g.*, Gulbinas & Taylor, 2014; Siero et al., 1996; Siero, Boon, Kok, & Siero, 1989). Siero et al. (1996) examined the effects of both group feedback (energy use of the group) and comparative feedback (energy use of other groups) in two units of a metallurgical company. Employees in the comparative feedback condition saved more energy than those who only received information about their own performance, even half a year after the intervention. Additionally, behaviour change took place with hardly any changes in attitudes or intentions. Gulbinas and Taylor (2014), in a study designed to understand the impact of feedback in a commercial office setting (where both comparative and individual feedback was used), found those who received individual feedback engaged less with the feedback and saved less energy than the comparative group. There may, however, be negative consequences to comparative feedback as people tend to avoid comparisons with others who perform better (Dakin & Arrowood, 1981; van Knippenberg, Wilke, & de Vries, 1981).

Goal setting

Van Houwelingen and van Raaij (1989) note that goal setting offers motivation by setting out a desired future situation, achieving the desired outcome offers satisfaction which may also aid persistence through self-motivation. Reviewing preceding work in the area, the authors go on to note that goals should be challenging yet achievable if savings of significance are to be realized. If the goal is too difficult and participants see no progress they are like to disengage, while goals that are too easy to achieve do not present the same rewards as more challenging ones. Abrahamse, Steg, Charles, and Rothengatter (2007) expand on these ideas noting the potential benefits of goal-setting when combined with feedback, which enables participants to understand their progress while working towards the prescribed goal.

Rationale for interventions

Based on the findings of the preceding review, for this study it was decided to combine feedback through a descriptive normative message (Cialdini, Kallgren, & Reno, 1991) to allow the participant to understand the impact of their behaviours (Katzev & Mishima, 1992) and goal setting (as per the findings of Abrahamse et al., 2007) with educational information (including information on how to save energy) to modify personal norms by appealing to the employees sense of environmental responsibility (Scherbaum et al., 2008). Darby (2006) notes in a review of the effectiveness of feedback on energy conservation that savings in the region of 20% may be possible and this was adopted for this study.

Taking this approach (feedback, goal setting and education), three groups were devised to explore further the effectiveness of (1) basic group feedback (to test the impact of feelings of group membership and social normative influence on energy savings), (2) detailed group-level comparative feedback (to build upon that of the first group and test the impact of feelings of competition) and (3) individual and basic group feedback (to allow for comparison with the other groupings and understand the impact of social normative influence and feelings of guilt) in the commercial office setting.

To avoid a push towards the mean for those already using low amounts of energy (as highlighted by Schultz et al., 2007), the descriptive normative information in the form of regular feedback on energy use was combined with an injunctive normative information (supported by Schultz et al.) in the form of a positive (smiley/happy) or negative (unhappy) face.

Methods

Energy consumption monitoring and procedure

The energy use of 90 desks in two office buildings (within the same company) were monitored using 'Enistic' energy-monitoring devices. These devices resemble an extension lead with four plug points and wirelessly logged energy readings on an hourly basis, which was stored on a web-accessible server. The devices were installed during an unoccupied period at each location and placed in a hidden cable tray under each desk. All desk-top equipment was then routed through the Enistic device (screens, computer, laptop docking station etc.), including two desk-top plugs made available for ad-hoc small power (fans, phone chargers and other small electronic devices).

Following installation a 100-day 'baseline' period was established. This baseline period is longer than that used in other similar studies (*e.g.*, Gulbinas & Taylor, 2014; Nilsson et al., 2015) and was intended to increase the reliability of the data by ensuring they were not heavily influenced by short periods of high or low energy use, which could be otherwise interpreted as energy savings (or increases). The consequence of this longer baseline period is a higher dropout rate, the implications of which are discussed below. The data gathered during the baseline period were analysed to establish baseline energy consumption for each participant. Corrections were made to allow for variations in working hours and staff absence. This was achieved through the establishment of out-of-hours power densities (the average power density at the desk location when not in use, which was taken as midnight on each day during the baseline period) and operational power densities (taken as the average during the working day). The data were then interrogated (every two weeks during the baseline and follow-up monitoring period) to identify prolonged periods of low power densities, indicating equipment was in sleep mode or had been powered down for an extended period, which was then used to establish the absence of the participants. The same approach (operational and out-of-hours power densities) was used to establish the average working hours for each participant, which then allowed for the correction of the energy consumption data to ensure those who worked longer hours (or those who had been on leave) were not misrepresented, with the same working hours applied across all groups.

Following the completion of the baseline period, a series of field studies were carried out to verify the range of equipment plugged into each monitor with only those participants with a full profile (monitoring at least the screen and the computer at the location) taken forward in the study. Where the baseline period had identified unusual energy-use profiles, locations and equipment were further investigated to ensure the equipment in use was comparable across the study. Those found to be using older computers and less efficient cathode ray tube screens (although small in number) were excluded from the final study. The power ratings and efficiency of individual pieces of desktop equipment were not explored directly as the study focused on the change in user behaviour and their interaction with the equipment. This does mean that differences in the efficiency of equipment used between groups may place initial energy use at different levels; hence, overall findings are presented as percentage savings from baselines as opposed to direct energy-use comparisons. The field studies also allowed the research team to identify where additional small power items (such as mobile phone chargers (21.1%), desktop fans (12.2%) and desk heaters (5.5%)) were present, which was found to be similar across all groups.

Following this, participants were divided into three groups between the two locations (sites A and B) for the provision of feedback and information; this feedback period lasted a similar duration to the baseline period (100 days). Site A contained a single group on a single floor of the building; site B contained two groups on separate floors of the same building. Before and after occupant surveys were also conducted, along with the provision of energy-saving advice before and during the feedback period. The approach to groupings ensured that there were situational similarities between groups, which has been shown to be of importance when leveraging social norms (as noted by Goldstein, Cialdini, & Griskevicius, 2008). As the research was based in the field, the potential for alternative grouping options was limited. It was noted that those in the 'individual and basic group feedback' set started with lower overall energy use than the other groups (there were variations between all three groups) and this was taken into account in the analysis that follows.

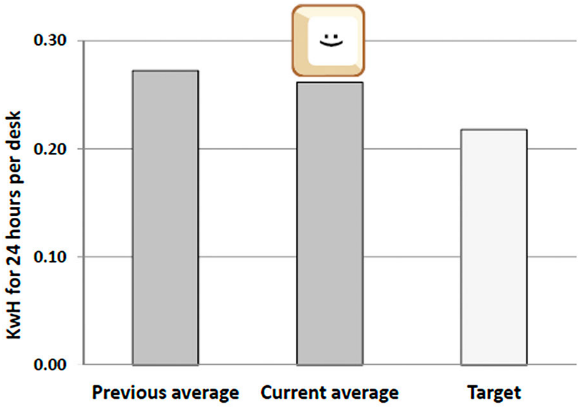
Participants

Across all groups the mean age of participants was 45 years (range of 27–63). There was a gender ratio of 44% to 56% male to female. Participants were provided with guidance on the process and purpose of the study and the opportunity to opt in or out. The participants can be said to be a combination of individual and group process workers, as defined by Laing et al. (cited in Haynes, 2008), working in what can be described as 'large open-plan' offices as defined by Bodin Danielsson and Bodin (2008).

Although 90 desks were originally included in the study, due to internal reconfigurations and staff turnover (and exclusions associated with inconsistencies found in the data), the number of participants reduced to 39. Larger sets of group-level data were available; however, to improve reliability only those individuals who could be followed throughout the study were included. As previously noted, the reduction in the number of participants was a factor of the longer baseline period that intended to improve the reliability of the overall dataset and to ensure that short-term variation in energy use was not misinterpreted as energy savings. The remaining participants can be said to be representative of the wider group in terms of job function, gender and age, with an even distribution across groups. The large reduction in the number of participants must be noted as a limitation of the study, and the findings are presented in that context.

Feedback

Following the baseline period feedback was provided in the form of a visual chart for easy interpretation e-mailed to participants (Figures 2 and 3), in each case feedback was administered every two weeks. A positive (smiley/happy) face was used to indicate savings in line with the prescribed goals, and a negative (unhappy) face indicated performance not as desired. The day–night breakdown was included to show wastage associated with leaving equipment on overnight.



The red bar reflects the average consumption for 24 hours per desk in the period from the 9th of March to the 23rd of March; the green bar shows the target and the grey one the previous consumption average.

So you are on the right track! Keep it up – and keep switching it off and unplugging it in mind!

Figure 2. Basic group feedback.

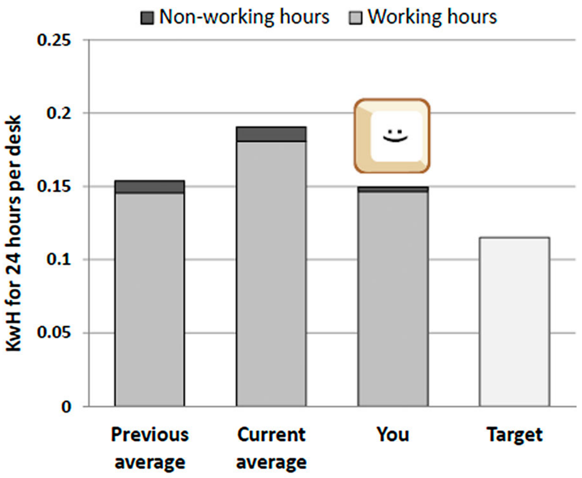
Members of the first 'basic feedback group' (*N* = 16) (located at site A) were provided with basic group-level feedback with a goal reduction of 20%, no breakdown of day and night energy consumption and information both on the previous and current averages. See Figure 2 for an example of the feedback provided.

Members of the 'detailed comparative feedback group' (*N* = 12) (located at site B) were provided with detailed group-level comparative feedback (comparing performance with another group) with a goal reduction of 20%, a breakdown of day and night energy consumption and information both on the previous and current averages.

Members of 'individual and basic group feedback' set (*N* = 11) (located at site B) were provided with individual feedback detailing personal consumption along with a goal reduction of 20% and information about their groups performance, highlighting the difference between group performance and their own individual performance, again current and historic feedback was provided. See Figure 3 for an example of the feedback provided.

Education/information

Prior to the first feedback point information detailing the importance of saving energy (social norms/attitude) and how to save energy specifically within the workplace (perceived behavioural control) was given to each participant electronically, this included guidance about unplugging unused chargers etc., powering down



Good job! Your energy consumption is below the average!

However, there is still a long way to go to reach the target (green bar). In fact, across the office, the energy consumption has increased over the last two weeks (red bar against grey bar)!

So please remember – and spread the word – to switch it off and unplug all equipment!

Figure 3. Group and individual feedback.

computers and turning off screens both at the end of the working day and during the day when away from the desk (30 and 120 minutes). As the study progressed this guidance was reinforced along with the provision of feedback.

Survey

A range of psycho-social factors were also assessed following the baseline monitoring period and prior to the interventions through an online survey. The survey was divided into questions covering a number of broad themes related to the theories previously reviewed namely, pro-environmental attitude (including issues related to sustainability at home and in the workplace), habit/intention (including issues related to powering down equipment during the day and overnight, use of small electronic devices and turning lights off during the day etc.) and social norms (feelings of pressure to behave a certain way and guilt when not done). Questions were administered on a five-point Likert scale ranging from ‘strongly disagree’ to ‘strongly agree’ allowing for the generation of Likert-scale data. The survey was repeated at the end of the intervention period to assess the impact the interventions made. A number of addition questions were added to the follow-up survey to gauge participant engagement and also to judge levels of perceived behavioural control (in terms of how easy or difficult it is to save energy in the workplace). Thirty-seven participants completed the survey administered before the interventions period and this reduced to 22 for the survey administered at the end of the intervention period. Due to the level of reduction in the number of participants in the survey carried out after the interventions, the results (of the follow-up survey) must be viewed with a note of caution.

Approach to statistical analysis

Energy use and standard deviations (SDs) were calculated for each group both for the baseline and the feedback period. Statistical analysis of the energy data was carried out in a number of steps. First, across all groups energy use at the baseline and at each feedback point was considered using a repeated-measures analysis of variance (ANOVA). Where significant variation was identified ($p \leq 0.05$) *post-hoc* Bonferroni-corrected ($p = .00714$) t-tests were conducted to identify where the significance occurred. To understand the variation in savings between groups, a further repeated measures ANOVA was carried out.

For the before and after surveys a test of internal consistency was carried out using Cronbach’s α, which is used to determine if multiple questions in a questionnaire related to the same variable, for instance social norms, reliably measure that variable. In this case it was applied to questions relating to social norms, perceived behavioural control and pro-environmental attitude, with $\alpha > 0.7$ found in each case, thus indicating a good level of internal consistency.

Before and after survey results were considered using paired t-tests across all groups. These were supported by a repeated-measures ANOVA to consider differences between the three groups, again where significant differences were identified ($P \leq 0.05$) (from the ANOVA) these were followed up by *post hoc* Bonferroni corrected ($p = .0167$) t-tests. Further Pearson correlation tests were carried out to understand the relationship between a number of key elements considered in the survey (age and baseline energy and energy savings, pro-environmental attitude and energy savings, perceived behavioural control and energy savings, and feelings of guilt (social normative influence) and energy savings).

Results

Measured energy savings

For the ‘basic feedback group’ (office location A) the pre-intervention mean (and therefore baseline) was 303 watt-hours with a SD of 125 watt-hours, for the ‘detailed comparative feedback group’ (office location B) the mean was 343 watt-hours with an SD of 128 watt-hours and for the ‘individual and basic group feedback’ set (office location B) the mean was 284 watt-hours with an SD of 118 watt-hours.

The ‘basic feedback group’ (location A) achieved energy savings of 18% (SD = 94 watt-hours), ‘detailed comparative feedback group’ (location B) 28% (SD = 118 watt-hours) and ‘individual and basic group feedback’ (location B) 10% (SD = 115 watt-hours) with an overall reduction in range and SDs (Figure 4). Those who across all groups started with a baseline energy consumption in excess of the overall mean saved on average 28.6%, conversely those whose consumption was below the mean of the initial baseline saved on average just 9%. Across all groups it was found that overall energy savings were significant ($F(7,288) = 2.58$, $p = .0134$) and that these significant differences occurred at feedback points 1 (9% reduction from baseline) ($t(72) = 3.15$, $p = .002$), 4 (12% reduction from baseline) ($t(72) = 3.04$, $p = .003$) and 6 (21% reduction from baseline) ($t(72) = 4.14$, $p \leq .001$). Although as can be seen in Figure 5 there would appear to be an early move towards an increase in energy use (around intervention point 2), which is particularly noticeable for the ‘detailed

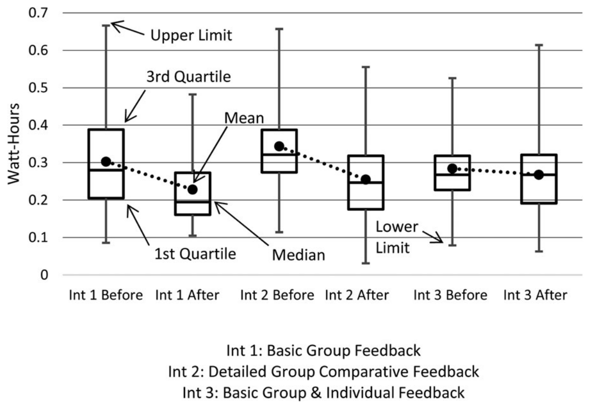


Figure 4. Box plots before and after interventions.

comparative feedback group’ and ‘individual and basic group feedback’ sets, this was found not to be significant (5% increase from baseline) ($t(72) = 1.55$, $p = .06$). Follow-up analysis found no significant difference in the energy savings made between groups during the feedback period ($F(2,34) = 1.03$, $p = .365$).

Behavioural questionnaires

Participant surveys found no significant differences across all groups combined between the before and after surveys in terms of pro-environmental views ($t(22) = 1.35$, $p = .094$) and feelings of guilt ($t(22) = 0.98$, $p = .167$); however, a marginally significant improvement in overall self-reported pro-environmental behaviour (which focused on measures around energy use in the office, such as power down rates etc.) was identified ($t(22) = 1.74$, $p = .047$). Between groups no significant difference in self-reported behaviour was found ($F(2,17) = 1.83$, $p = .189$).

The follow-up survey contained a number of questions that were not included in the pre-intervention survey (including the provision of overall feedback to the research team). Between groups a significant difference was found in terms of perceived behavioural control ($F(2,18) = 8.26$, $p \leq .01$) with these differences being found to occur between the ‘basic group feedback’ (mean = 3.63) and ‘individual and basic group feedback’ (mean = 2.00) ($t(13) = 3.94$, $p \leq .01$) and between ‘detailed comparative group feedback’ (mean = 2.66) and ‘individual and basic group feedback’ ($t(15) = 2.63$, $p \leq .01$). This suggests that those who received individual feedback (along with feedback on their own group) felt they had less control than those who received just group-level feedback or comparative group-level feedback. The reason for this is not immediately clear; however, the individual feedback group did save the least amount of energy (10% versus 18% and 28% for the other groups), which may be influential, as may the stronger feelings of group membership in the other groups with individuals alone feeling they have little influence.

Combined energy saving and questionnaire results

Combining the observed energy savings and questionnaire responses this study found no significant correlation between pro-environmental attitude and energy savings ($r = 0.29$, $p = 0.86$), perceived behavioural control and energy savings ($r = 0.52$, $p = 0.98$), energy savings and feelings of guilt (social normative influence) ($r = 0.01$, $p = 0.5$) or energy savings and age ($r = 0.46$, $p = 0.96$).

Discussion

This study demonstrated that significant energy savings are possible in the commercial office environment through the use of feedback, goal setting and education/information. The savings achieved overall were in line with the findings of Darby (2006) who suggested 20% saving should be possible. Not unexpectedly those who started with a baseline energy consumption above the overall mean (and therefore with greatest potential for energy savings) saved the most energy. If the highest energy users across all groups in the study could reduce energy consumption to the mean, 38% energy savings could be realized; furthermore, if those at the mean level could reduce to the minimum (which is technically possible, although in practical terms may be unlikely), savings of up to 41% could be realized, thus savings of 38–41% should be theoretically possible. This is comparable with the findings of Murtagh et al. (2013) who noted possible savings of up to 32% in a university context.

Pattern of energy savings

Dwyer et al. (1993) note that in the residential setting removing feedback results in a quick reduction in energy savings. However, studies in commercial settings (Gulbinas & Taylor, 2014; Murtagh et al., 2013) note that the impact of feedback reduces more gradually, while at the same time energy savings may take longer to take hold than the residential setting and as such are less ‘elastic’ than the residential sector (Murtagh et al., 2013). This is, however, in contrast to the findings of Wakiyama et al. (2014), who found that during an exogenous shock (in that case the Fukushima nuclear crises) households responded more gradually than large electricity users

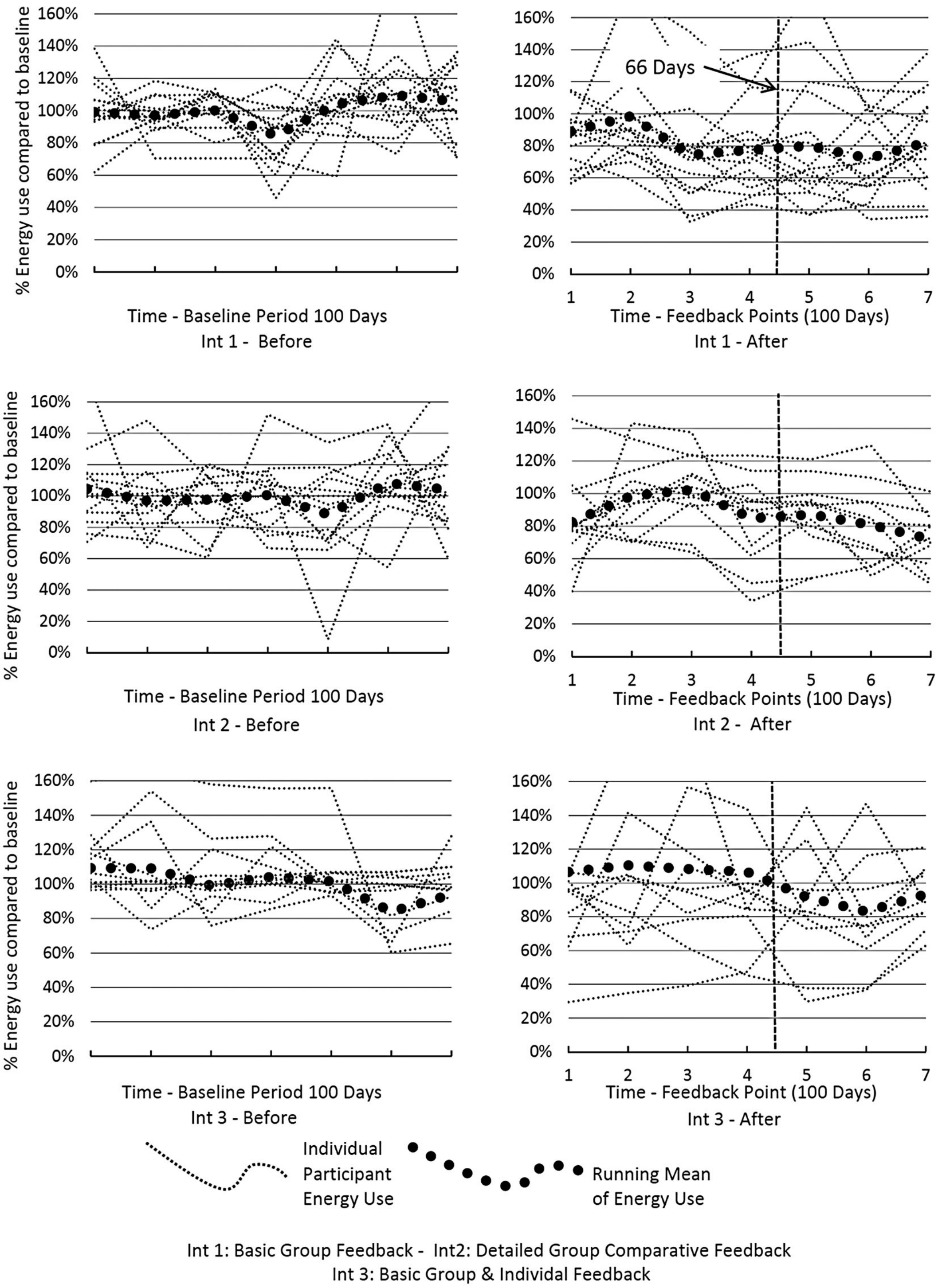


Figure 5. Energy-use patterns.

(but the reductions were more likely to persist). The present study reinforces the findings of Murtagh et al. (2013) and Gulbinas and Taylor (2014) as, despite an initially significant reduction in energy (feedback point 1), consistent and significant energy savings did not occur until later in the study (feedback points 4 and 6). This finding also highlights the importance of the length of the monitoring (and baseline) period as shorter periods may have pointed to a different outcome (in terms of elasticity). Furthermore, in the residential sector it has been observed that notable energy reduction can be observed in the two to three days following the provision of feedback (Peschiera, Taylor, & Siegel, 2010); however, in this study no significant energy reduction was noted in that timeframe. As such the impact of feedback in the commercial sector would appear to function differently to that of the residential sector; the elasticity of the change in each sector may, however, be influenced by the immediacy of the driving force behind any reduction (such as an exogenous shock). For each group when 66 days of feedback (between feedback points 4 and 5) have passed, which is, as noted by Lally et al. (2010), the median time taken for the 'automaticity' (as defined by Bargh, 1994, cited in Chatterton, 2011) of an action to peak, a downward trend in energy consumption emerges suggesting that feedback may be beginning to form a habit. However, as can be seen from the statistics and Figure 5, this downward trend does not stay persistent and there remains a question over how long-lasting the impact of feedback may be. As noted by Darby et al. (2016), a degree of behavioural reinforcement may still be required.

Changes in attitude, perceived behavioural control and social norms

As noted, the before and after surveys found no significant difference across all groups in terms of pro-environmental views (attitude) and feelings of guilt (social norms); however, a significant difference was found in terms of self-reported pro-environmental behaviour. This indicates that change in habit may have occurred without a change in attitude and aligns well with other studies in the non-domestic setting (Siero et al., 1996; Tetlow, van Dronkelaar, Beaman, Elmualim, & Couling, 2015). This can be highlighted as a key difference to the domestic sector where pro-environmental attitude is seen as a key factor of energy saving (Abrahamse et al., 2005) and would appear to contradict Francis et al. (2004) who noted a strong link between attitude and intention, and behaviour. However, as noted by Chatterton (2011), this may be related to the 'value-action gap' where stated values do not necessarily correspond to action. This change in habit without an underlying change in attitude may also be a factor of a range of issues encountered in the workplace that could influence behaviour and are not commonly encountered in residential settings – culture, organizational focus and structure (Tudor et al., 2008) and jobs satisfaction (Brent & Freathy, 1997).

Although initially this research would seem to support the theory that comparative feedback among groups is more successful than individual feedback (*e.g.*, Gulbinas & Taylor, 2014; Siero et al., 1996), the observed difference was not statistically significant in this case. This perhaps suggests that the links made to group membership and competition (Wit & Wilke, 1992) may not be as strong as the theory suggests when applied in the commercial office environment.

However, as noted by Abrahamse et al. (2007), large in-group variation combined with the smaller number of participants within each group ('basic feedback group' $N = 16$, 'detailed comparative feedback group' $N = 12$, 'individual and basic group feedback' $N = 11$) may be a contributory factor to this, making it difficult to find significance in variation between groups and, therefore, intervention types, thus this result should be considered in that context. It is worth noting, however, that those in the 'individual and basic group feedback' set started with lower overall energy use than the other groups, suggesting less potential for energy savings. It could be argued that this supports the idea that group membership was less influential. As noted below, however, group membership may impact on perceived behavioural control, which may, in some cases, also impact upon energy-saving behaviour. As such, the benefits of group membership may need further exploration in studies with long-term baseline and intervention periods.

The importance of perceived behavioural control in the commercial sector has been highlighted by previous authors (*e.g.*, Menzes et al., 2012; Tetlow et al., 2013). Although a difference between groups was found in terms of perceived behavioural control (with the 'individual and group feedback' set having the lowest level of perceived behavioural control), no correlation was found between levels of perceived behavioural control and realized energy savings. As the level of control available across all three groups are similar, it is not immediately clear why perceived behavioural control would be lower in one group. It could be related to a realization that the levels of energy savings achieved are below target (this was the case for the 'individual and group feedback' set) and a need to put forward a reason due to social normative influence. It may be that those who received group-level or group comparative feedback (as opposed to individual feedback) have a stronger sense of group membership, which increases levels of perceived behavioural control, compared with individuals who feel they can have little influence. Furthermore, no correlation was found between pro-environmental attitude or feelings of guilt (social norms) and energy savings. This further supports theory that in the commercial sector habit may be changed without changing attitude through the provision of feedback and information.

Implications

For the building manager, although the methods used here resulted in significant energy savings, as underlying environmental attitudes have not changed it may be that a less individualistic approach where externalities (to the individual) such as workplace culture and practice are taken into account, could be of benefit. Campaigns to reduce workplace energy use may be more successful if feedback and goal setting were combined with a management campaign highlighting the accepted workplace culture (or expected workplace norm) and practice. In this context, energy-saving campaigns in the workplace may not need to target the underlying environmental attitude of occupants (which aligns with the findings of Siero et al., 1996), with accepted workplace culture (or norms) instead used to influence workplace behaviour.

Changes to such workplace culture and practice may contribute to ‘facilitating conditions’ as an ‘external enabler’. As perceived behavioural control, other than desk-level control, in the commercial office may be largely invisible, it may be that focusing on workplace practice and culture can also be used in conjunction with feedback, through an active approach to workplace management, to reconnect occupants to the space they occupy enhancing the wider ‘facilitating conditions’. Figure 6 presents an outline of such a model (and is a modified version of Figure 1).

As noted by Haynes (2008) and supported by Mulville, Callaghan, and Isaac (in press) an active approach to workplace management supporting the needs of the user and the organization may be of benefit in understanding occupant satisfaction and encouraging preferred behaviours. Darby et al. (2016) suggests that providing users with the means to understand the impacts of their own actions could help to change the energy culture in the building, making control move visible while increasing personal responsibility. In practical terms an active approach to workplace management could include monitoring and feedback in a continuous closed-loop system (as suggested by Darby et al., 2016), which could take advantage of the capability of information technology systems, building automation and more innovative facilities management systems. The feedback required could be provided electronically with opportunities for building users in turn to engage with the feedback. Such an approach could align with the observed growth in the use of ‘performance leases’ (Janda, Bright, Patrick, Wilkinson, & Dixon, 2016) and offer the potential for enhanced facilities management services which could be combined with efforts to improve workplace health, wellbeing and productivity. Where feedback is coupled with education and information regarding user controls, such approaches could help to reduce the building performance gap, which has been linked to the influenced occupant behaviour (van Dronkelaar, Dowson, Spataru, & Mumovic, 2016).

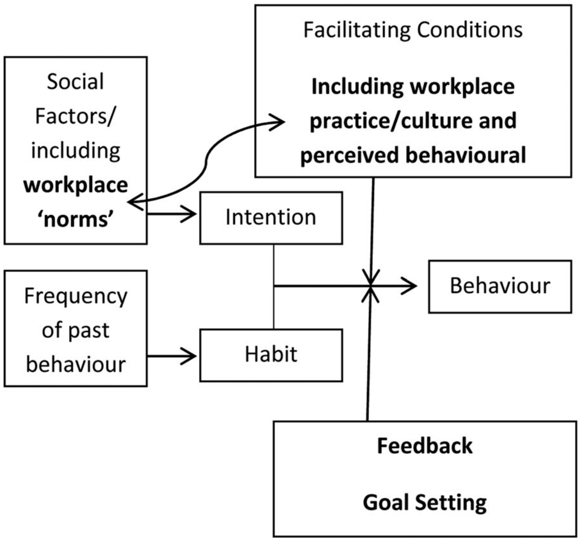


Figure 6. Revised version of Triandis’ ‘Theory of Interpersonal Behaviour’.
Source: adapted from Chatterton (2011).

More widely, in the context of the European Commission’s ambitious plans to improve energy efficiency and given the growing recognition of the influence of occupant behaviour on energy use (Darby et al., 2016), this is an area likely to come into increasing focus. At a policy level, incentive schemes to encourage businesses to engage in such behaviour change campaigns, embedded in active approaches to workplace management, could offer improvements in efficiency and reductions in emissions at relatively low costs (in comparison with interventions association with the building fabric, systems and renewables). Arguably, such approaches could help to address some of the challenges presented by the existing stock and in turn offer benefits beyond the workplace.

Conclusions

The study demonstrated that in the commercial office setting it is possible to save energy through behaviour change by utilizing the provision of feedback, goal setting and information. It also suggests that it may be possible to achieve these savings without a corresponding change to pro-environmental attitude or perceived social norms. On average the study found savings of 18.8% to be possible, with savings of 28% for the comparative feedback group, 18% for the basic feedback group and 10% for the individual and basic feedback group. The impact of group membership and perceived behavioural control were in this case found not to be as significant as previously expected, but may still contribute to the wider facilitating conditions.

For the building manager, feedback and goal setting may help improve workplace behaviour in relation to energy consumption. Within this a focus on workplace culture and practice may be of greater importance than focusing on the underlying environmental attitude of occupants. This suggests that a less passive and individualistic approach by senior management to behaviour change may be of benefit in such campaigns in the workplace. Arguably, such an approach may improve levels of perceived behavioural control, thus harnessing the potential benefits. In practical terms an active approach to workplace management with a continuous feedback loop may be of benefit.

As this study focused on a single business, it was not possible to test the above suggestions across sectors, and this is an area for further research, along with consideration of how job function has an impact on energy-use behaviour. However, the potential energy savings suggested do, in broad terms, align well with other studies in the field (*e.g.*, Darby et al., 2016, and Gulbinas & Taylor, 2014), suggesting the findings could be generalized to other situations. At the scale of an individual building, the savings noted may be relatively small; however, if such savings could be scaled up across multiple built assets or at a national or regional scale, the cost savings and emission reductions may be significant.

The findings of this paper need to be considered in the context of a number of limitations. The original study began with 90 desk locations between two locations with three groups; however, due to internal reconfigurations and staff turnover (and exclusions associated with identified inconsistencies in the data) it was possible to follow only 39 of these individuals through to the completion of the study. In addition, not all participants completed the before and after survey, with 37 completing the before survey and 22 the after survey, and again this has an impact on the findings. A total of 95% of those who completed the survey at the end of the study indicated that they did engage with the feedback provided regularly. This suggests that those who did participate in the follow-up survey were perhaps more engaged with the overall study than the wider group. The format in which feedback was delivered did not make it possible to confirm this (engagement with feedback) with empirical data and, as such, this is self-reported engagement that may be unreliable. If those who did not complete the follow-up survey did not engage with feedback, the overall level of engagement drops to 56.7%, which is similar to the findings of Murtagh et al. (2013).

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Abrahamse, W., Steg, L., Charles, V., & Rothengatter, T. (2005). A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology*, *25*, 273–291. doi:10.1016/j.jenvp.2005.08.002

Abrahamse, W., Steg, L., Charles, V., & Rothengatter, T. (2007). The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviours, and behavioural antecedents. *Journal of Environmental Psychology*, *27*, 265–276. doi:10.1016/j.jenvp.2007.08.002

Ajzen, I. (1991). The theory of planned behaviour. *Organisational Behaviour and Human Decision Processes*, *50*, 179–211. doi:10.1016/0749-5978(91)90020-T

Bargh, J.A. (1994). The four horsemen of automaticity: Awareness, intention, efficiency and control in social cognition. In R.S. Wyer, Jr. & T.K. Srull (Eds.), *Handbook of social cognition* (2nd ed.) (pp. 1–40). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Baumeister, R. F. (1998). The Self. In D.T. Gilbert, S.T. Fiske & G. Lindzey (Eds.), *Handbook of social psychology* (4th ed.) (pp. 680–740). New York, NY: McGraw-Hill.

Benders, R., Kok, R., Moll, H., Wiersma, G., & Noorman, K. (2006). New approaches for household energy conservation: In search of personal household energy budgets and energy reduction options. *Energy Policy*, *34*, 3612–3622. doi:10.1016/j.enpol.2005.08.005

Bodin Danielsson, C., & Bodin, L. (2008). Office-type in relation to health, well-being and job satisfaction among employees. *Environment & Behaviour*, *40*, 636–668. doi:10.1177/0013916507307459

Bostrom, A., & Fischhoff, B. (2001). Communicating health risks of global climate change. *Research in Social Problems and Public Policy*, *9*, 31–56. doi:10.1016/S0196-1152(01)80023-5

Brent, R., & Freathy, P. (1997). Motivating the employee in the Independent retail sector. *Journal of Retailing and Consumer Services*, *43*, 201–208.

Building Performance Institute Europe. (2011). Europe's buildings under the microscope. In *A country by country review of the energy performance of buildings*. Belgium: Building Performance Institute Europe. Retrieved from bpie.eu: http://bpie.eu/publication/europes-buildings-under-the-microscope/

Bull, R., Lemon, M., Fleming, P., Stuart G., & Everitt, D. (2014). *Digitally Engaging and Empowering Employees for Energy Demand Reduction: A New Approach for the Next Generation?* Paper presented at American Council for an Energy Efficient Economy Conference 2014, Asilomar. Retrieved from acee.org: http://aceee.org/files/proceedings/2014/data/papers/7-99.pdf

Carrico, A., & Riemer, M. (2011). Motivating energy conservation in the workplace: An evaluation of the use of group-level feedback and peer education. *Journal of Environmental Psychology*, *31*, 1–13. doi:10.1016/j.jenvp.2010.11.004

Chatterton, T. (2011). *An introduction to thinking about 'Energy Behaviour': A multi-model approach*. Retrieved from gov.co.uk: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48256/3887-intro-thinking-energy-behaviours.pdf

Chen, J., & Ahn, C. (2014). Assessing occupants' energy load variation through existing wireless network infrastructure in commercial and educational buildings. *Energy and Buildings*, *82*, 540–549. doi:10.1016/j.enbuild.2014.07.053

Cialdini, R. B., Kallgren, C. A., & Reno, R. R. (1991). A focus theory of normative conduct: A theoretical refinement and re-evaluation of the role of norms in human behaviour. *Advances in Experimental Psychology*, *24*, 200–234.

Dakin, S., & Arrowood, A. (1981). The social comparison of ability. *Human Relations*, *34*, 89–109. doi:10.1177/001872678103400201

Darby, H., Elmualim, A., Clements-Croome, D., Yearley, T., & Box, W. (2016). Influence of occupants' behaviour on energy and carbon emission reduction in a higher education building in the UK. *Intelligent Buildings International*, *8* (3), 157–175. doi:10.1080/17508975.2016.1139535.

Darby, S. (2006). *The effectiveness of feedback on energy consumption. A review for DEFRA of the literature on metering, billing and direct displays*. University of Oxford: Environmental Change Institute.

De Young, R., Boerschig S., Carney, S., Dillenbeck, A., Elster, M., Horst, S., … Thomson, B. (1995). Recycling in multi-family dwellings: Increasing participation and decreasing contamination. *Population and Environment: A Journal of Interdisciplinary Studies*, *16*, 253–267. doi:10.1007/BF02331920

Dwyer, W., Leeming, F., Cobern, M., Porter, B., & Jackson, J. (1993). Critical review of behaviour interventions to preserve the environment: Research since 1980. *Environment and Behaviour*, *25*, 275–321. doi:10.1177/0013916593255001

European Commission. (2014). *The 2030 climate and energy framework*. European Commission. Retrieved from http://ec.europa.eu/clima/policies/strategies/2030/index_en.htm

Francis, J., Eccles, M. P., Johnston, M., Walker, A. E., Grimshaw, J. M., Foy, R., … Bonetti, D. (2004). *Constructing questionnaires based on the theory of planned behaviour: A manual for health services researchers*. Newcastle upon Tyne: Centre for Health Services Research. Retrieved from openaccess.city.ac.uk: http://openaccess.city.ac.uk/1735/1/TPB%20Manual%20FINAL%20May2004.pdf

Goldstein, N. J., Cialdini, R. B., & Griskevicius, V. (2008). A room with a viewpoint: Using social norms to motivate environmental conservation in hotels. *Journal of Consumer Research*, *35*, 472–482. doi:10.1086/586910

Gulbinas, R., & Taylor, J. (2014). Effects of real-time eco-feedback and organizational network dynamics on energy efficient behaviour in commercial buildings. *Energy and Buildings*, *84*, 493–500. doi:10.1016/j.enbuild.2014.08.017

Haynes, B. (2008). The impact of office comfort on productivity. *Journal of Facilities Management*, *6*, 37–51. doi:10.1108/14725960810847459

Hopper, J., & Nielsen, J. (1991). Recycling as altruistic behaviour: Normative and behavioural strategies to expand participation in a community recycling program. *Environment and Behaviour*, *23*, 195–220. doi:10.1177/0013916591232004

Jackson, S., & Zedeck, S. (1982). Explaining performance variability: Contribution of goal setting, task characteristics, and evaluative contexts. *Journal of Applied Psychology*, *67*, 759–768. doi:10.1037/0021-9010.67.6.759

Janda, K. B., Bright, S., Patrick, J., Wilkinson, S., & Dixon, T. J. (2016). The evolution of green leases: Towards inter-organisational environmental governance. *Building Research and Information*, *44*, 660–674. doi:10.1080/09613218.2016.1142811

Jenkins, D. P., Singh, H., & Eames, P. C. (2009). Interventions for large-scale carbon emission reduction in future UK offices. *Energy and Buildings*, *41*, 1374–1380. doi:10.1016/j.enbuild.2009.08.002

Junnila, S. (2007). The potential effect of end-users on energy conservation in office buildings. *Facilities*, *25*, 329–339. doi:10.1108/02632770710753352

Katzev, R., & Mishima, H. (1992). The use of posted feedback to promote recycling. *Psychological Reports*, *71*, 259–264. doi:10.2466/PR0.71.5.259-264

Kawamoto, K., Shimoda, Y., & Mizuno, M. (2003). Energy saving potential of office equipment power management. *Energy and Buildings*, *36*, 915–923. doi:10.1016/j.enbuild.2004.02.004

Lally, P., van Jaarsveld, C. H. M., Potts, H. W. W., & Wardle, J. (2010). How are habits formed: Modelling habit formation in the real world. *European Journal of Social Psychology*, *40*, 998–1009. doi:10.1002/ejsp.674

Maréchal, K. (2010). Not irrational but habitual: The importance of "behavioural lock-in" in energy consumption. *Ecological Economics*, *69*, 1104–1114. doi:10.1016/j.ecolecon.2009.12.004

Menzes, A. C., Tetlow, R., Beaman, C. P., Cripps, A., Bouchlaghem, D., & Buswell, R. (2012). *Assessing the impact of occupant behaviour on the electricity consumption for lighting and small power in office buildings*. Paper presented at the 7th International Conference on Innovation in Architecture, Engineering & Construction, Sao Paolo, Brazil.

Miller, D., & Prentice, D. (1996). The construction of social norms and standards. In A. W. Kruglanski & E. T. Higgins (Eds.), *Social psychology: Handbook of basic principles* (pp. 799–829). New York, NY: Guilford Press.

Mulville, M., Callaghan, N., & Isaac, D. (in press). The impact of the ambient environment and building configuration on occupant productivity in open-plan commercial offices. *Journal of Corporate Real Estate*.

Mulville, M., Jones, K., & Huebner, G. (2014). The potential for energy reduction in UK commercial offices through effective management and behaviour change. *Architectural Engineering and Design Management*, *10*, 79–90. doi:10.1080/17452007.2013.837250

Murtagh, N., Nati, M., Hadley, W. R., Gatersleben, B., Gluhak, A., Ali Imran, M., & Uzzell, D. (2013). Individual energy use and feedback in an office setting: A field trial. *Energy Policy*, *62*, 717–728. doi:10.1016/j.enpol.2013.07.090

Nilsson, A., Andersson, K., & Bergstad, C. J. (2015). Energy behaviours at the office: An intervention study of the use of equipment. *Applied Energy*, *146*, 434–441. doi:10.1016/j.apenergy.2015.02.045

Nolan, J., Schultz, P., Cialdini, R., Goldstien, N., & Griskevicius, V. (2008). Normative social influence is under-detected. *Personality and Social Psychology Bulletin*, *34*, 913–923. doi:10.1177/0146167208316691

Perkins, H., Haines, M., & Rice, R. 2005. Misperceiving the college drinking norm and related problems: A nationwide study of exposure to prevention information, perceived norms, and student alcohol misuse. *Journal of Studies on Alcohol*, *66*, 470–478. doi:10.15288/jsa.2005.66.470

Peschiera, G., Taylor, J. E., & Siegel, J. A. (2010). Response–relapse patterns of building occupant electricity consumption following exposure to personal, contextualized and occupant peer network utilization data. *Energy and Buildings*, *42*, 1329–1336. doi:10.1016/j.enbuild.2010.03.001

Scherbaum, C., Popovich, P., & Finnlinson, S. (2008). Exploring individual-level factors related to employee energy-conservation behaviours at work. *Journal of Applied Social Psychology*, *38*, 818–835. doi:10.1111/j.1559-1816.2007.00328.x

Schultz, P., Nolan, J., Cialdini, R., Goldstein, N., & Griskevicius, V. (2007). The constructive, destructive and reconstructive power of social norms. *Journal of Psychological Science*, *18*, 429–434. Retrieved from https://www.jsmf.org/meetings/2008/july/social%20norms%20Cialdini.pdf doi:10.1111/j.1467-9280.2007.01917.x

Schultz, P., Oskamp, S., & Mainieri, T. (1995). Who recycles and when? A review of personal and situational factors. *Journal of Environmental Psychology*, *15*, 105–121. Retrieved from http://americarecyclesday.org/wp-content/uploads/2013/07/Schultz-Oskamp-1995.pdf doi:10.1016/0272-4944(95)90019-5

Seligman, G., Becker, L., & Darley, J. (1981). Encouraging residential energy conservation through feedback. In A. Baum & J. Singer (Eds.), *Advances in environmental psychology, energy conservation: psychological perspectives* (Vols. *3*). (3rd ed., pp.93–111). New York, NY: Psychology Press.

Shalley, C., Oldham, G., & Porac, J. (1987). Effects of goal difficulty, goal setting method, and expected external evaluation on intrinsic motivation. *Academy of Management Journal*, *30*, 553–563. doi:10.2307/256014

Siero, F., Bakkerm, A., Dekker, G., & van der Burg, M. (1996). Changing organisational energy consumption behaviour through comparative feedback. *Journal of Environmental Psychology*, *16*, 235–246. doi:10.1006/jevp.1996.0019

Siero, S., Boon, M., Kok, G., & Siero, F. (1989). Modification of driving behaviour in a large transportation organisation: A field experiment. *Journal of Applied Psychology*, *74*, 417–423. doi:10.1037/0021-9010.74.3.417

Stern, P. (2000). New environmental theories: Toward a coherent theory of environmentally significant behavior. *Journal of Social Issues*, *56*, 407–424. doi:10.1111/0022-4537.00175

Stern, P., Dietz, T., Abel, T., Guagnano, G., & Kalof, L. (1999). A value-belief-norm theory of support for social movements: The case of environmental concern. *Human Ecology Review*, *6*, 81–97. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download? doi=10.1.1.195.5410&rep=rep1&type=pdf

Stern, P., & Gardener, G. (1981). Psychological research and energy policy. *American Psychologist*, *36*, 29–342.

Tajfel, H. (1978). Social categorisation, social identity and social comparison. In H. Tajfel & J. Turner (Eds.), *Differentiation between social groups: Studies in the social psychology of intergroup relations* (pp. 61–76). London: Academic Press.

Tetlow, R. M., Beaman, C. P., Elmualim, A. A., & Couling, K. 2013. *Targeting automatic behaviour to reduce small power electricity consumption in office buildings*. Paper presented at the 4th Annual TSBE Eng. D. Conference, Reading, UK.

Tetlow, R. M., van Dronkelaar, C., Beaman, C. P., Elmualim, A. A., & Couling, K. 2015. Identifying behavioural predictors of small power electricity consumption in office buildings. *Building and Environment*, *92*, 75–85. doi:10.1016/j.buildenv.2015.04.009

Tudor, T., Barr, S., & Gilg, A. (2008). A novel conceptual framework for examining environmental behaviour change in large organisations: A case study of the Cornwall National Health Service (NHS) in the United Kingdom. *Environment and Behaviour*, *40*, 426–450. doi:10.1177/0013916507300664

van Dronkelaar, C., Dowson, M., Spataru, C., & Mumovic, D. (2016). A review of the regulatory energy performance gap and its underlying causes in non-domestic buildings. *Frontiers in Mechanical Engineering*.

van Houwelingen, J., & van Raaij, F. (1989). The effect of goal-setting and daily electronic feedback on In-home energy use. *Journal of Consumer Research*, *16*, 98–105. doi:10.1086/209197

van Knippenberg, A., Wilke, H., & de Vries, N. (1981). Social comparison on two dimensions. *European Journal of Psychology*, *11*, 267–283. doi:10.1002/ejsp.2420110303

Wakiyama, T., Zusman, E., & Monogan III, J. E. (2014). Can a low-carbon-energy transition be sustainable in post Fukushima Japan? Assessing the varying impacts of exogenous shocks. *Energy Policy*, *73*, 654–666. doi:10.1016/j.enpol.2014.06.017

Wechsler, H., Nelson, T., Lee, J., Seiberg, M., Lewis, C., & Keeling, R. (2003). Perception and reality: A national evaluation of social norms marketing interventions to reduce college students' heavy alcohol use. *Quarterly Journal of Studies on Alcohol*, *64*, 484–494. Retrieved from http://diseaseriskindex.harvard.edu/cas/Documents/social_norms/484-Wechsler.pdf doi:10.15288/jsa.2003.64.484

Werch, C., Pappas, D., Carlson, J., DiClemente, C., Chally, P., & Sinder, J. (2000). Results of a social norm intervention to prevent binge drinking among first-year residential college students. *Journal of American College Health*, *49*, 85–92. doi:10.1080/07448480009596288

Wit, A., & Wilke, H. (1992). The effect of social categorisation on cooperation in three types of social dilemmas. *Journal of Economic Psychology*, *3*, 35–151.

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

Paper Eight

Mulville, M. and Stravoravdis, S. (2016). Delivering long-term building performance: A user-centred approach. In; Gorse, C. and Dastbaz, M. (Eds) *International SEEDS Conference, 14-15 September 2016, Leeds Beckett University, UK, Sustainable Ecological Engineering Design for Society*. ISBN: 978-0-9955690-1-0

Invited Presentations:

This paper formed the basis for presentations by the candidate at the following events:

- International SEEDS Conference, 14-15 September 2016, Leeds Beckett University, UK;
- The paper was well received, raising strong interest and discussion about long-term building performance.

Other Impacts:

Although the paper was subject to a number of alterations prior to publication, the reviewers were generally positive about the paper and satisfied once the issues raised were addressed. The reviewers noted that it was “a very interesting paper, well written in the main and covering an interesting topic in a thought provoking way” and that the “paper covers an important topic and the idea behind Figure 2 is interesting and has far-reaching consequences”.

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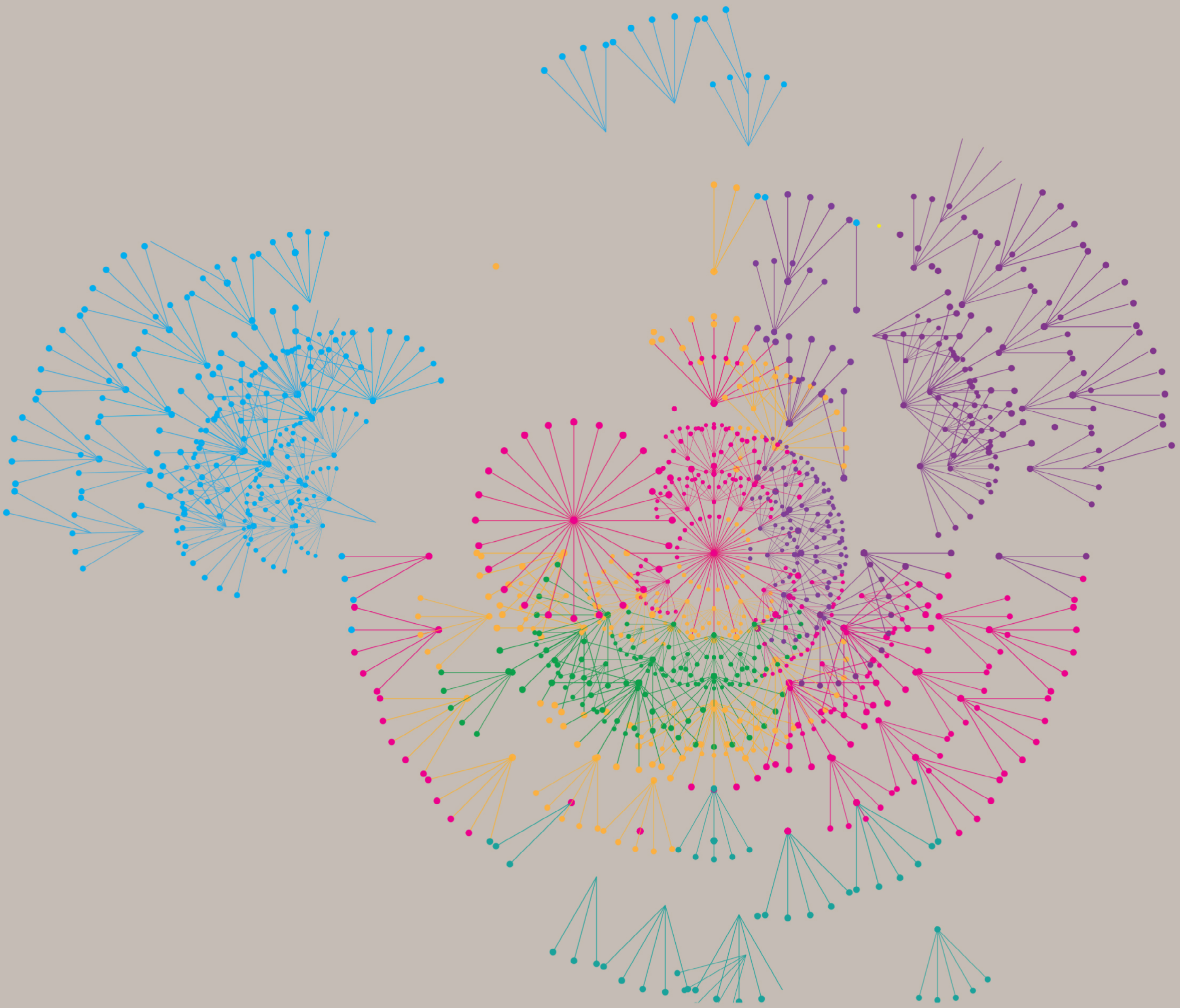

DELIVERING LONG-TERM BUILDING PERFORMANCE: A USER-CENTRED APPROACH

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Keywords: Building Performance, Climate Change, Occupant Behaviour, Wellbeing.

ABSTRACT

In recent years the drive for the delivery of sustainable built environments has resulted in a focus on energy efficiency (regulated energy) in order to reduce CO2 emissions and mitigate against climate change.

However, as regulated-energy is decreased the proportional importance of un-regulated energy (small power etc.), which is heavily influenced by occupants, is predicted to increase. In addition there is a body of evidence linking occupant health, wellbeing and productivity to both occupant behaviour and the building environment and it has been suggested that predicted climate change has the potential to impact further on comfort, energy use and the wider building environment.

In this context the short term focus on regulated energy efficiency, although not without merit, risks ignoring the influence of occupants and may impact upon occupant wellbeing, energy performance and ultimately long term building performance. Such a scenario could result in premature building obsolescence.

This paper, building on a body of research by the authors (and others) and supported by a review of the relevant literature, suggests that while consideration near term regulated energy remains important, this alone may not deliver long term performance. The paper presents a theoretical model of long-term building performance, highlighting the need to consider the impact of occupant behaviour on energy use, the impact of the building environment on occupant wellbeing and the potential impacts of climate change. The paper suggests that a user focused approach to design considering long term performance and an active approach to building management is require

INTRODUCTION

The built environment is responsible for a significant proportion of global energy use and CO_2 emissions (U.S. Energy Information Administration, 2015), these emissions have in turn been linked to climate change (Intergovernmental Panel on Climate Change [IPCC], 2014). In this context there has in recent decades been a growing focus on delivering more energy efficient built environments.

To date this has been focused on regulated energy (heating, cooling and lighting), where a number of cost-effective savings can be realised. The implementation of increasingly stringent building regulations will reduce energy use in new buildings, while refurbishment programmes may help to reduce energy use in the existing stock. As regulated energy is further reduced (through regulations and refurbishment) it can be argued that the proportional importance of un-regulated energy (small power, desk level equipment etc.), which is influenced by occupant behaviour, may increase (Mulville et al., 2013). Furthermore, in addition to ambient environmental factors occupant behaviour has been shown to have a significant impact on occupant wellbeing (Haynes, 2007, Mulville et al., 2016).

It has been suggested that the movement towards air conditioned buildings and increasing levels of energy efficiency has resulted in negative impacts on occupants' health, wellbeing and productivity (Smith and Pitt, 2011). Increases in energy efficiency, particularly those focused on heat retention and air tightness may, in some cases, result in unintended consequences such as overheating linked to climate change (Mulville & Stravoravdis, 2016 and Jones et al., 2013), moisture issues and poor air quality (Al-Homoud, 2005).

Linked to these potential unintended consequences, it has been widely recognised that a significant building performance gap and particularly an energy performance gap exists (for a review see van Dronkelaar et al., 2016). Van Dronkelaar et al. (2016) links the performance gap to modelling uncertainty, occupant behaviour and poor operational practices and notes that complexity in design can lead to problems during construction which ultimately may impact upon building performance. These factors may be influenced by design stage assumptions about occupant behaviour, occupant decision making, occupant practices (as noted by Karjalainen, 2015) and the role of unregulated energy (Menezes et al., 2012). Arguably the performance gap may, over time, be further widened by the predicted impacts of climate change (Camilleri et al., 2001, Mulville & Stravoravdis, 2016 and Jones et al., 2013).

Figure 1 suggests how, based on the above issues, a performance gap may manifest itself over time. The 'optimum' line represents the performance that would be expected of a new building at any given point in time if it could be delivered instantaneously. The 'desired' performance line represents the performance owners/developers and occupiers/users would envisage based on returns on investment (developer), comfort (for wellbeing and productivity) and energy use (occupier). This is supported through periodic maintenance and refurbishment, as indicated by the light grey lines attached to the desired performance line. However, a gap emerges where the above issues are not addressed, as this gap grows the building may become increasingly obsolete.

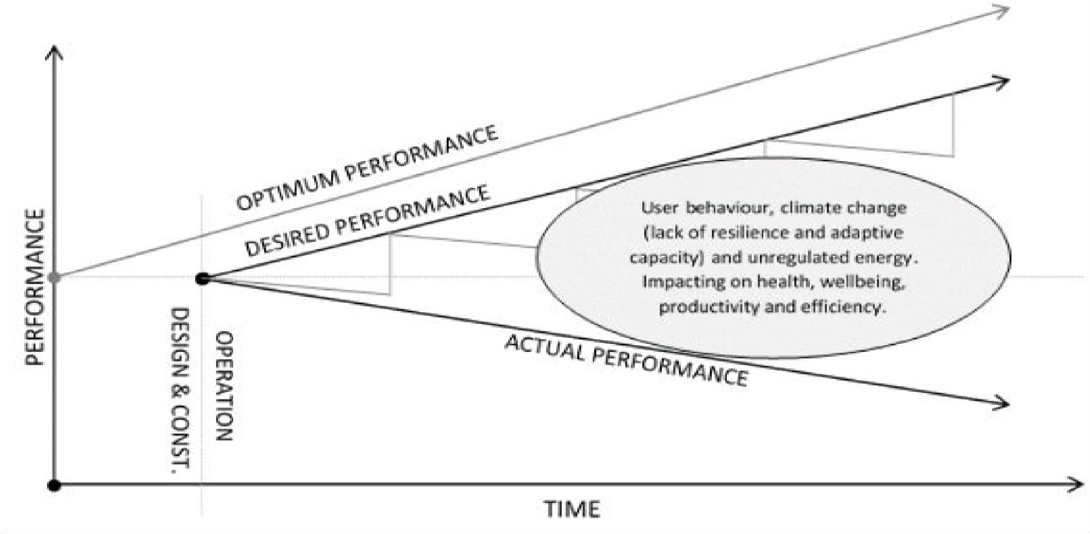

Figure 1. Long Term Building Performance Gap (Adapted from Jones et al., 2015)

The discussion that follows explores the issues noted in **Figure 1** in greater detail. It is argued that, in order to deliver a truly sustainable built environment, a focus on long term building performance beyond the 'point of handover', that considers the influence of occupant behaviour and the potential impacts of climate change is required.

LONG TERM BUILDING PERFORMANCE

The British Council of Offices [BCO] (BCO, 2015 in Sanderson & Edwards, 2016) defines building performance as:

> "the way that a building supports occupiers' differing aims and needs including driving quality and value, meeting sustainability objectives and providing environments that meet the needs of users, resulting in efficient and effective workplaces" (pg.32)

This multifaceted goal presents a number of challenges to both building designers and operators in delivering user centred buildings that are sustainable, efficient and effective. As noted by Cox et al. (2015) sustainability in the built environment largely refers to reducing the environmental impacts of buildings, as such, it may not be holistic sustainability but a relative term focused on particular aspects. Indeed, it has been argued (Voinov & Farley, 2007) that increased sustainability in one system or area may come at the cost of less sustainability in another. This discussion rings true in the built environment where there is often difficulty in finding the economic value of sustainability beyond immediate returns on cost (Keenan, 2015). In this context it can be argued that the sustainability debate in the built environment focuses largely on returns on energy savings. However, in many non-domestic buildings such as commercial offices, employee costs may significantly outweigh energy costs (CABE, 2005). The non-energy benefits or 'co-benefits' of user focused sustainable buildings may be more difficult to measure (such as better Indoor Environmental Quality [IEQ]). However, as noted by Sanderson and Edwards (2016) there is increasingly a move towards a customer centred approach to property management (reflected in the above definition) and as a result the recognition and perceived value of these 'co-benefits' may rise.

Adaptation and Resilience

As noted by Jones et al. (2013) there is a tendency to design and deliver buildings based around the needs of the 'here and now', however most buildings are developed on the assumption of a 60 year plus design life. In this context buildings must have a degree of resilience to and ability to adapt to economic, social and environmental change. Although efforts to mitigate the impacts of climate change have been increasing, often through increasingly ambitious energy performance targets, it is now widely accepted that a certain amount of climate change is inevitable (IPCC, 2007). In this context, in recent years, several research projects have explored the resilience of existing and recently constructed buildings to the impacts of predicted climate change (for example see Camilleri et al., 2001, Jones et. al., 2013 and Mulville and Stravoravdis, 2016). Cox et al. (2015) notes that a building's resilience is a measure of how well it continues to function after an event (and arguably during the event), while Bosher (2014), reviewing previous research, identifies four categories of resilience: 1) resistance, robustness and aspirations, 2) recovery "bouncing back", 3) planning, preparing and protecting and 4) adaptive capacity. In this context the ability of the building to adapt to change becomes a key aspect of resilience and therefore the overall sustainability of the building. Keenan (2015) argues that the sustainability of a building or system fits within the adaptive cycle of the building and that adaptation may be dependant on wider sustainability issues such as the availability of resources. Adaptation therefore could be viewed as, where resources are available, an opportunity to increase the resilience of the building. Where a building is unable to adapt or has limited resilience it may be at risk of premature obsolescence due to poor performance and such a building could be considered 'high risk' (Cox et al., 2015).

Climate Change and Building Performance

It can be argued that the sustainability aspects of the current regulatory framework in the built environment are largely (although not exclusively) focused on the mitigation of climate change. However, as noted above a certain amount of climate change may now be inevitable (IPCC, 2007) and the buildings we construct and refurbish today, must be capable of performing in or adapting to a changing climate (Mulville and Stravoravdis, 2016). That ability to adapt may be key to the buildings long term performance.

As noted, there is a growing body of research exploring the potential impacts of climate change on domestic and non-domestic buildings, which considers the potential impacts of a warming climate and more frequent extreme weather events. It has been argued that, although not without merit, the current drive to reduce energy use may risk optimising buildings in cool climates for heat retention and several studies have predicted an increasing overheating risk in such buildings (for example see Jones et al., 2013 and Mulville and Stravoravdis, 2016). Jones et al. (2013) in a study of a new educational building, note a number of potential climate change related impacts including a reduction in heating load and increased overheating risk overtime (with some overheating predicted as soon as the 2020s). Overheating has the potential to have significant impacts on occupant health and wellbeing (Mulville and Stravoravdis, 2016) with, in the non-domestic sector, corresponding impacts on productivity (Mulville et al., 2016). The wider impacts of climate change may include increased flood risk, which could impact on critical infrastructure, and more rapid materials degradation (Gething and Puckett, 2013).

As noted by Jones et al. (2013) and supported by Mulville and Stravoravdis (2016) adaptation planning and climate change risk assessments at the design stage, and possibly incorporated into the building regulations, may help to minimise the negative impacts of climate change on long term building performance.

Unregulated Energy

As regulations and other associated mechanisms drive down regulated energy (heating, cooling and lighting) the proportional importance of unregulated energy increases (Mulville et al, 2013). Menezes et al. (2012) suggests that a lack of understanding of unregulated energy is a contributory factor to the energy performance gap. Although small power items and other equipment associated with unregulated energy have increased in efficiency (and will likely continue to do so), the proliferation of devices means that small power is likely to remain an important factor in overall usage (Jenkins et al., 2009). In a study considering desk level energy use Mulville et al. (2013) found that up to 23% of energy used may occur outside normal working hours suggesting significant savings may be possible. Supporting this Kawamoto et al. (2003) found that in use utilisation of desk top equipment may be as low as 43%. Mulville et al (2013) found that savings of up to 20% at a desk level may be possible through monitoring, feedback and education. However, the same study suggests that to ensure the longevity of the savings, more constant monitoring and feedback may be required in order to reinforce the preferred behaviour.

Occupant Behaviour

As previously noted, it has been argued that building performance can be heavily influenced by occupant behaviour. Karjalainen (2015) notes, that there is a body of evidence that suggests occupants often do not understand the principles of how a building may function and as a result may use it in a non-optimal way. For instance, it has been noted that in the office environment artificial lights are often on despite the availability of natural light (Nicol, 2001). Where occupants realise their system understanding is poor they may be passive in their interactions with their environment (Karjalainen, 2015). Arguably as a consequence of this passive approach in commercial offices, much energy consumption may occur outside of working hours (Mulville et al., 2013). Karjalainen (2015) suggests that building designs that are less sensitive to user behaviour may result in significant energy savings. This less sensitive building design may be one where users have less to learn about the building, with more intuitive systems motivating users to save energy (Karjalainen, 2015). However, in such a scenario personal control should not be sacrificed (Karjalainen, 2015). Darby et al. (2016) suggest that a mixture of automatic and manual controls could both minimise energy consumption and maximise occupant wellbeing, by providing a high degree of personal control in an intelligent work environment.

There are several theories related to occupant behaviour both in the domestic and more recently, commercial office environment (for a review see Chatterton, 2011), what is clear from this work is that occupant behaviour is complex. Chatterton (2011) suggests that over time intentions and behaviour form habit and habit is difficult to change. Furthermore, Murtagh et al. (2013) note that self-reported pro-environmental behaviour may not always correlate to energy saving behaviour. Arguably, this could be linked back to the occupants' limitations in terms of understanding the intended function of the building.

Several studies (for example see Mulville et al. 2013 and Murtagh et al. 2013) have noted the potential for behaviour change campaigns supported by feedback, information and education to reduce energy use and potentially to encourage behaviour that is supportive of health, wellbeing and ultimately productivity (Mulville et al. 2016).

Health, Wellbeing and Productivity

Occupant behaviour and work patterns, the ambient environment and building configuration have all been linked to health, wellbeing and productivity in buildings (Mulville et al. 2016, Haynes 2007). Haynes (2007) suggests that the behavioural environment and occupant work patterns, including interaction and distraction, are important in terms of productivity in the workplace. This is supported by Mulville et al. (2016) who found that occupants who took less frequent breaks from their desk, and therefore have less interaction with co-workers, were more likely to experience headaches which may in turn impact upon productivity.

Singh et al. (2010) suggest that better IEQ, which is linked to better health and wellbeing, can lead to lower absenteeism rates. In support of this Bevan (2010) suggests that health and wellbeing improves productivity, while a lack of wellbeing may result in presenteeism (Hamar et al., 2015). Mulville et al. (2016) found that both the ambient environment and workplace behaviour have an impact on health, wellbeing and by extension productivity. That study found that where background noise levels were higher (in comparison to other areas) occupants were less satisfied with environmental conditions, despite air quality and temperature being more amenable than in other areas. This suggests that a hierarchy of environmental conditions may exist in relation to occupant satisfaction with noise being of particular importance. In turn, as previously noted (by Haynes, 2007) this can be linked back to interaction and distraction, thermal comfort and air quality however remain important factors (as noted by Callaghan et al., 2015 and Clements-Croome, 2013). Clements-Croome (2013) notes that improved IEQ can result in productivity gains of 4-10%, which given the importance of employee costs supports the case for a focus on occupant satisfaction.

Building configuration and, in the commercial office space, layout, can have a significant impact on employee satisfaction (Mulville et al. 2016). Open plan offices have been associated with increased levels of stress, a lack of perceived personal control, noise and disturbance (Bodin Danielsson, 2010; Pejtersen et al. 2011; Seddigh et al., 2015). Occupants of open plan offices may be more sensitive to background noise and may suffer from a lack of privacy although some benefits may remain (Van der Voordt, 2004). Levels of perceived personal control (which in some layouts may be minimal) can have an impact on overall satisfaction (Lee and Brand, 2005) and it has been suggested that enhanced, possibly desk level, user controls may be of benefit (O'Neill, 2008) in the workplace.

As suggested by Haynes (2008) and supported by Mulville et al. (2016) an active approach to workplace management may help building managers to understand the impact of the building environment on occupiers and to adjust accordingly. Such an approach could, through the provision of feedback and information, also incorporate behaviour change campaigns to reduce energy use and encourage behaviour in support of health, wellbeing and productivity.

DELIVERING LONG TERM BUILDING PERFORMANCE

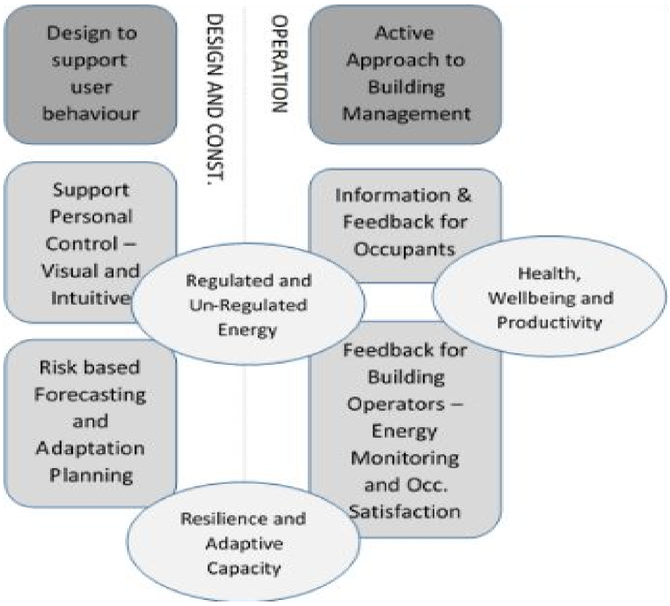

Figure 2. Model of Building Performance

Based on the preceding discussion, if a sustainable built environment that provides long term performance is to be provided, building design and operation must take a user focused approach that delivers health, wellbeing, efficiency, resilience and adaptive capacity. This requires whole of life thinking in terms of building performance. **Figure 2** sets out how such an approach could be delivered with, at the design stage, user centered design to support the preferred/desired behaviours and risk based adaptation planning to consider the potential impacts of climate change. This is then supported at the operational stage by an active approach to building management incorporating feedback, information and education to reinforce the design intention to occupants and provide building managers with guidance on the key issues to address or adapt to as required. The discussion that follows expands upon these suggestions.

User Centred Design

As suggested by Karjalainen (2015) building designs that are less sensitive to occupant behaviour may offer benefits, especially where more realistic views of occupant behaviour can be taken into account and the building itself is supportive of the preferred behaviour. As noted by Delmas and Lessem (2014) users will not devote much time to learning how the building works. Therefore, less behaviour sensitive designs should include for intuitive controls systems that also take into account the users reactionary as opposed to anticipatory approach to interaction with building systems (Leaman, 1999 in Karjalainen, 2015). This could be in the form of systems that suggest or recommend to users when and how action should be taken, thus providing users with feedback and education and supporting the active approach to workplace management as suggested below. Although fully automated controls may offer benefits in terms of energy consumption they could reduce the perception of personal control which is an important factor in occupant satisfaction, thus highlighting the importance of a user centered approach. As a result, in a building with wider automation the need for personal control would remain, this could be in the form of enhanced local or desk level controls which have been shown to be of benefit (O'Neill, 2008). At the design stage such an approach would require careful consideration of how users are likely to interact with building control systems, this could be informed by input from facilities managers and potential occupants or lessons learnt from the post occupancy evaluations. A requirement for mandatory post occupancy evaluations, implemented through building regulations or environmental assessments to help inform such decisions could be of benefit. Such a user centered approach may help to reduce the performance gap associated with both regulated and un-regulated energy use while improving occupants' satisfaction and productivity.

Risk Based Adaptation Planning

In the context of climate change it has been suggested (Jones et al. 2015) that adaptation planning (incorporating backcasting and forecasting) at the design stage may allow for realistic and cost effective strategies to be developed that take account of the level of risk associated with the predicted impacts. Jones et al. (2013) in a study of a new educational building, in conjunction with the project design team, facilitated the development of a range of potential adaptations, including technical (the use of modular boilers, increased duct sizes for additional cooling capacity etc.), managerial and behavioural adaptions (changes to operational schedules and dress codes) which were then evaluated within a risk framework. This allowed for a number of adaptations to be either implemented during the construction phase or planned in advance and where necessary enabling works conducted to ensure future adaptations could be implemented on a cost effective basis. It has been suggested (Mulville and Stravoravdis, 2016) that a similar approach (all be it that study was discussing domestic buildings) could be incorporated into the regulatory framework through regulations that take a 'forecasting' and risk based approach to climate change, while Camilleri et al. (2001) suggest the use of a climate change sustainability index to identify vulnerable buildings. Such an approach (implemented via the building regulations) could provide users or potential users with a greater understanding of the building's resilience prior to purchase or occupation, much in the same way that Display/ Energy Performance Certificates [DECs/ EPCs] provide comparative information. This approach to adaptation planning could help ensure the building has resilience and adaptive capacity which in turn may improve or maintain energy efficiency and user satisfaction over time.

Active Approach to Building Management

For the operational phase, as suggested by Haynes (2008) and supported by Mulville et al. (2016), an active approach to workplace management may be required to support the organisation and the user. Such an active approach could incorporate measures to encourage energy saving behaviour (such as those noted by Mulville et al., 2013) and behaviours that enhance health, wellbeing and productivity (as noted by Mulville et al. 2016) while providing more detailed building specific performance metrics.

Several studies have demonstrated that behaviour change campaigns can be successful in reducing energy consumption (for example see; Mulville et al., 2013 and Murtagh et al., 2013). While it has also been suggested that similar campaigns could be used to improve occupant health and wellbeing by altering workplace patterns (Mulville et al., 2016). Such campaigns utilise monitoring, feedback and goal setting, education and information, using social norms and competition to encourage the preferred behaviour. An active approach to building management, utilising such measures, should incorporate a continuous feedback loop (Darby et al., 2016) to reinforce the preferred behaviour among occupants and inform building managers of issues arising. As noted by Darby et al. (2016), such continuous reinforcement may be required to ensure that any observed benefit associated with a change in behaviour is not just a short term phenomenon and may, over time, become habitual. This active approach to workplace management could allow, as suggested by Sanderson and Edwards (2016), property managers and occupiers to work together in maximising building performance. The approach suggested could also increase the availability of performance metrics related to the building and help capture user satisfaction which could in turn be made available to potential tenants (as suggested by Sanderson and Edwards, 2016).

These metrics could be incorporated into 'performance leases', which as noted by Janda et al. (2016) have seen increasing use in certain sectors, or, as previously suggested could be incorporated into an alternative versions of a DECs that focus on building performance metrics and risks. In support of this Sanderson and Edwards (2016) suggest that occupiers place greater emphasis on quality over cost when defining building performance and that finding ways to enhance occupiers' business profitability could be of greater importance than cost savings. The approach outlined here, where tied to performance leases or DECs, may help in emphasising the presence of quality (or otherwise) in the workplace while providing greater information for decision making.

DISCUSSION & CONCLUSION

User centred design and an active approach to building management could help to reduce the building performance gap. Considerations of the potential impacts of climate change, through climate impact risk assessments may increase resilience and adaptive capacity and combined, these approaches may help to deliver long term building performance. This could be supported by the use of a climate change index and user satisfaction surveys with performance leasing and an alternative approach to DECs to increase the availability of comparative building performance information.

For building designers, while regulated energy use will remain important, the approach proposed would require a refocusing on the building user. This may present a number of challenges as user behaviour is not commonly considered in depth during the design process beyond a number of predetermined assumptions. It may be that the incorporation of facilities managers into the design stage or mandatory requirements for post occupant evaluations (to provide feedback) may enable designers to deliver such user focused buildings. Where adaptation planning (for climate change) is to be incorporated, the presence of potential users and facilities managers will help to ensure that realistic adaptation proposals can be developed. During the operational stage building owners and property managers may need to take a more active and less reactive approach to delivering building performance. This would require ongoing monitoring, feedback, information and evaluation linked to user satisfaction. More widely ensuring preferred behaviours (to reduce energy use and improve productivity) may require a change of workplace culture so it is seen throughout all levels of the organisation.

At a regulatory level, climate change risk assessment and adaption planning may need to be considered in order to ensure resilience over time, especially where (in the case of commercial offices) most development may be speculative and focus on short term returns. Greater availability of occupant satisfaction and performance in use data may help to increase the use of performance leasing. Such data, in conjunction with climate change risk data, could be made available as part of an alternative or revised approach to DECs.

REFERENCES

Al-Homoud, M.S. (2005). Performance characteristics and practical applications of common building thermal insulation materials. *Building and Environment*, Vol. 40, No. 3, pp.353-366.

Bevan, S. (2010). The business case for employees' health and wellbeing. Available online: http://www.theworkfoundation.com/DownloadPublication/Report/245_245_iip 270410.pdf [accessed on 06/06/2016].

Bodin Danielsson, C. (2010). Office design's influence on employees' stress levels. Available online: http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab087211.pdf [accessed on 06/06/2016]

Bosher, L. (2014). Built-in resilience through disaster risk reduction: operational issues. *Building Research and Information*, Vol. 42, No. 2, pp.240-254.

CABE (2005).The Impact of Office Design on Business Performance. Available online: http://webarchive.nationalarchives.gov.uk/20110118095356/http:/www.cabe.org.uk/files/impact-office-design-full-research.pdf [accessed on 05/06/2016].

Callaghan, N., Mulville, M, Di-Maura, S. and Isaac, D (2015). The non-energy benefits of employee focused building design. Proceedings from the 2015 RICS/COBRA Conference. Sydney, Australia, 8-10th July.

Camilleri, M., Jacques, R and Isaacs, N. (2001). Impacts of climate change on building performance in New Zealand. *Building Research and Information*, Vol. 29, No. 6 pp.440-450.

Chatterton, T. (2011). An introduction to thinking about 'Energy Behaviour': A multi-model approach. Available online: http://eprints.uwe.ac.uk/17873/ [accessed on 04/06/2016].

Clements-Croome, D. (Ed.) (2013). Creating the Productive Workplace. *Routledge*, Oxon, UK.

Cox, R.A., Nielsen, B. and Rode, C. (2015). Coupling and quantifying resilience and sustainability in facilities management. *Journal of Facilities Management*, Vol. 13, No. 4, pp.314-331.

Darby, H., Elmualim, A., Clements-Croome, D. Yearly, T. and Box, W. (2016). Influence of occupants' behaviour on energy and carbon emissions reduction in a higher education building in the UK. Intelligent Buildings International. DOI:10.1080/17508975.2016.1139535

Delmas, M.A. and Lessem, N. (2014). Saving power to conserve your reputation? The effectiveness of private versus public information. *Journal of Environmental Economics and Management*, Vol. 67, No. 3, pp.353-370.

van Dronkelaar, C., Dowson, M., Spataru, C and Mumovic, D. (2015). A review of the regulatory energy performance gap and its underlying causes in non-domestic buildings. Frontiers in Mechanical Engineering. DOI: http://dx.doi.org/10.3389/fmech.2015.00017

Gething, B. and Puckett, K. (2013). Design for Climate Change. RIBA Publishing, London, UK.

Hamar, B., Coberley, C., Pope, J.E. and Rula, E.Y. (2015) Well-being improvement in a midsize employer: changes in well-being, productivity, health risk, and perceived employer support after implementation of a well-being improvement strategy. *Journal of Occupational and Environmental Medicine*, Vol. 57, No. 4, pp.367-73.

Haynes, B. (2007). Office productivity: A theoretical framework. *Journal of Corporate Real Estate*, Vol. 9, No. 2, pp.97-110.

Haynes, B. (2008). The impact of office layout on productivity. *Journal of Facilities Management,* Vol. 6, No. 3, pp.189-201.

Intergovernmental Panel on Climate Change (2014). Climate change 2014: Synthesis report, summary for policy makers. Available online: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf [accessed on 06/06/2016].

Intergovernmental Panel on Climate Change (2007). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Available online:https://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm [accessed on 30/03/2016].

Janda, K.B., Bright, S., Patrick, J., Wilkinson, S. and Dixon, T.J. (2016). The evolution of green leases: Towards inter-organisational environmental governance. *Building Research and Information*, Vol. 44, No. 5-6, pp.660-674.

Jenkins, D.P., Singh, H. and Eames, P.C. (2009). Interventions for large-scale carbon emission reduction in future UK offices. *Energy and Buildings*, Vol. 44, No. 12, pp.1374-1380.

Jones, K., Desai, A., Mulville, M. and Jones, A. (2015). Asset management using a hybrid backcasting/forecasting approach. *Facilities*, Vol. 33, No. 11-12, pp.701-715.

Jones, K., Mulville, M. and Brooks, A. (2013). *FM, risk and climate change adaptation*. The International Journal of Facilities Management, Proceedings from The 12th EuroFM Research Symposium, Prague, Czech Republic 22-24th May.

Karjalainen, S. (2015). Should we design buildings that are less sensitive to occupant behaviour? A simulation study of effects of behaviour and design on office energy consumption. *Energy Efficiency*. DOI:10.1007/s12053-015-9422-7

Kawamoto, K., Shimoda, Y. and Mizuno, M. (2003). Energy saving potential of office equipment management. *Energy and Buildings*, Vol. 36, No. 9, pp.915-923.

Keenan, J.M. (2015). From sustainability to adaptation: Goldman Sachs' corporate real estate strategy. *Building Research and Information*, Vol. 44, No. 4, pp.407-422.

Lee, S.Y. and Brand, J.L. (2005). Effects of control over office workspace on perceptions of the work environment and work outcomes. *Journal of Environmental Psychology,* Vol. 25, No. 3, pp.323-333.

Menezes, A.C., Tetlow, R., Beaman, C.P., Cripps, A., Bouchlaghem, D. & Buswell, R. (2012). *Assessing the impact of occupant behaviour on the electricity consumption for lighting and small power in office buildings*. Proceedings from the 7th International Conference on Innovation in Architecture, Engineering & Construction, Sao Paolo, Brazil, 15-17th August.

Mulville, M., Callaghan, N. and Isaac, D. (2016). The impact of the ambient environment and building configuration on occupant productivity in open-plan commercial offices. *Journal of Corporate Real Estate*. In Press.

Mulville, M., Jones, K. and Huebner, G. (2013). The potential for energy reduction in UK commercial offices through effective management and behaviour change. *Architectural Engineering and Design Management*, Vol. 10, No. 1-2, pp.79-90.

Mulville, M. and Stravoravdis, S. (2016). The impact of regulations on overheating risk in dwellings. Building Research and Information, Vol. 44, No. 5-6, pp.520-534.

Murtagh, N., Nati, M., Headley, W.R., Gatersleben, B., Gluhak, A., Ali Imran, M. and Uzzell, D. (2013). Individual energy use and feedback in an office setting: A field trial. *Energy Policy,* Vol.62, pp.717-728.

Nicol, J.F. (2001). *Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans*. Proceedings from Building Simulation, Seventh International IBPSA Conference, Rio de Janeiro, Brazil, 13-15th August.

O'Neill, M. (2008). A model of environmental control and effective work. *Facilities,* Vol. 28, No. 3-4, pp.118-136.

Pejtersen, J., Feveile, H., Christensen, K. & Burr, H. (2011). Sickness absence associated with shared open-plan offices – a national cross sectional questionnaire survey. *Scandinavian Journal of work, Environment and Health,* Vol. 37, No. 5, pp.376-382.

Sanderson, D.C. & Edwards, V.M. (2016). Determinants of satisfaction amongst tenants of UK offices. *Journal of Corporate Real Estate,* Vol. 18, No. 2, pp.102-131.

Seddigh, A., Berntson, E., Jönsson, F., Bodin Danielson, C. & Westerlund, H. (2015). The effect of noise absorption variation in open-plan offices: A field study with a cross-over design. *Journal of Environmental Psychology,* Vol. 44, pp.34-44.

Singh, A., Syal M.S., Grady, S.C, Korkmaz, S. (2010). Effects of Green Buildings on Employee Health and Productivity. American Journal of Public Health. Available online: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2920980/ [accessed on 20/04/2015].

Smith, A. and Pitt, M. (2011). Sustainable workplaces and building user comfort and satisfaction. *Journal of Corporate Real Estate*, Vol. 13 No. 3, pp.144-156.

U.S. Energy Information Administration (2015). Frequently asked questions. Available online: https://www.eia.gov/tools/faqs/faq.cfm?id=447&t=3 [accessed on 30/03/2016].

van der Voordt, T.J.M. (2004). Productivity and employee satisfaction in flexible workplaces. *Journal of Corporate Real Estate*, Vol. 6, No. 2, pp.133-148.

Voinov, A. & Farley, J. (2007). Reconciling sustainability, systems theory and discounting. *Ecological Economics*, Vol. 63, No. 1, pp.104-113.

Other Impacts & Activities

Citations:

McNaboe, B. and Stevenson, E.V. (2011). Thermal mass and patterns of occupancy in the refurbishment of Irish housing stock. *Proceedings of NCEUB Network for Comfort and Energy Use in Buildings Conference: People and Buildings*. 23 September, 2011, London, UK;

Stevenson, E.V. and McNaboe, B. (2014). *The importance of occupancy patterns on the analysis of heating energy relating to housing refurbishment*. Journal of Building Survey, Appraisal & Valuation, Vol. 2:4, pp. 332-346.

Conference/ Invited Presentations:

The conference and or invited presentations, delivered by the candidate and as listed below, were all directly related to the body of research included in this submission.

- International SEEDS Conference, 14-15 September 2016, Leeds Beckett University, UK;
- CIB World Building Congress 2016: Creating Built Environments of New Opportunities Conference 30 May – 2 June 2016, Tampere, Finland;
- Building Performance in a Changing Climate. Low Carbon Buildings and Communities in the Sustainable Built Environment. British Council Researcher Links Programme, 23-26 February 2015, Istanbul, Turkey (fully funded);
- Delivering Sustainable Built Environments. Guest Lecture, Rushmore Business School, 16 May 2014, Mauritius;
- Delivering Sustainable Built Environments Open Lecture Series at the University of Greenwich (September 2013 – March 2014).

Research Groups:

- Member of the Sustainable Built Environments Research Group [SBERG] at the University of Greenwich and cluster leader for ‘Building Performance’ within the wider group.

Research Funding:

- British Council Travel Grant: Low Carbon Buildings in the Sustainable Built Environment, Istanbul, 2015;
- Research Assessment Exercise (RAE) competitive funding grant 2014 (£27k): The ‘non-energy benefits’ of low energy buildings (Principal Investigator).

APPENDIX B – ASSESSMENT OF MULTI-AUTHOR CONTRIBUTIONS

Paper One

Initial conception and research design – 50%

The PhD candidate contributed to the initial research design and approach in conjunction with the co-authors, with the overarching idea being led by a senior research professor. The candidate provided input around energy use in buildings to help inform the research design.

Acquisition, analysis and interpretation of data – 70%

The candidate was (in conjunction with one of the other co-authors) responsible for logging and recording the data during the monitoring period. The candidate took the lead on converting the data into useful information in a systematic manner and was responsible for developing the approach to correcting the data for inconsistencies, developing the approach to analysis and interpreting the findings.

Drafting of the article – 90%

The candidate took the lead on structuring and drafting the research paper producing all sections of the published paper. Co-authors contributed by providing feedback and advice.

Review process through to final publication – 90%

The candidate managed the review process, considering and responding to reviewers' comments and developing the revised paper. Co-authors provided feedback and advice on the proposed approach.

Paper Two

Initial conception and research design – 50%

The initial research idea formed part of a Technologies Strategies Board [TSB] (now Innovate UK) funding bid. Although not heavily involved in the initial bid the PhD candidate did make a substantial contribution to the refinement of the research design, exploring the practicalities of the initial concept in conjunction with the project lead (a senior research professor).

Acquisition, analysis and interpretation of data – 70%

The candidate attended (and contributed to where necessary) all of the workshops that formed part of the research project. During this process the candidate recorded all key information, gathered relevant data and took the lead on the interpretation of that data.

Drafting of the article – 70%

The candidate took the lead on structuring and drafting the initial paper, seeking input and feedback from co-authors, which in turn helped in revisions to the work.

Review process through to final publication – 70%

The candidate managed the review process, considering and responding to reviewers' comments and developing the revised paper. The project lead provided feedback on the proposed approach prior to the submission of the revised paper.

Paper Three

Initial conception and research design – 50%

The initial research idea formed part of a Technologies Strategies Board [TSB] (now Innovate UK) funding bid (as per Paper Two). Although not heavily involved in the initial bid, the PhD candidate did make a substantial contribution to the refinement of that design, exploring the practicalities of the initial concept in conjunction with the project lead (a senior research professor).

Acquisition, analysis and interpretation of data – 50%

Although not as heavily involved in this project as with Paper Two (which is linked to this paper), the candidate did make a significant contribution to the acquisition, analysis and initial interpretation of data. For this paper one of the co-authors took the lead on developing the theoretical framework against the findings of Paper Two, the candidate contributed to that process through providing feedback and guidance. The candidate helped the research team to visualise the theoretical framework by creating figures and tables.

Drafting of the article – 30%

The candidate made contributions to the initial drafting of this work by providing feedback on the structure, content and approach and providing the figures and tables to be used in the work.

Review process through to final publication – 70%

The candidate took a leading role in responding to reviewers' comments and in developing the revised paper. The revised paper was developed in conjunction with the project lead who supported the approach put forward by the candidate.

Paper Four

Initial conception and research design – 90%

The research idea for this paper was initiated by the PhD candidate and the concept and design were also largely developed by the candidate with technical guidance regarding approaches to building simulation provided by the co-author (who is a building simulation expert).

Acquisition, analysis and interpretation of data – 100%

The candidate generated/acquired, analysed and interpreted all data related to this research.

Drafting of the article – 90%

The candidate developed the initial structure of the paper and drafted the article with the co-author providing feedback on the proposed approach.

Review process through to final publication – 90%

The candidate managed the review process, providing responses to reviewers' comments and producing the revised paper. The co-author provided feedback on the proposed approach.

Paper Five

Initial conception and research design – 80%

The research idea for this paper was initiated by the PhD candidate who also developed the initial concept and the research design. Co-authors assisted the candidate by providing feedback on the approach put forward.

Acquisition, analysis and interpretation of data – 90%

The candidate was responsible for the acquisition, analysis and interpretation of the data including the development of the approach to statistical analysis. Co-authors provided feedback on the proposed approach and reviewed the initial outputs.

Drafting of the article – 80%

The candidate developed the structure of the paper and drafted the article. One of the co-authors drafted some sections of the methodology and part of the literature review with the other co-author providing feedback on the overall coherence of the paper.

Review process through to final publication – 90%

The candidate managed the review process, providing responses to reviewers' comments and producing the revised paper. The co-authors provided feedback on the proposed approach.

Paper Six

Initial conception and research design – 100%

The research idea and design for this paper, which builds upon Paper Four, was developed by the PhD candidate.

Acquisition, analysis and interpretation of data – 100%

The candidate generated/acquired, analysed and interpreted all data related to this research.

Drafting of the article – 90%

The candidate developed the initial structure of the paper and drafted the article with the co-author providing feedback on the proposed approach.

Review process through to final publication – 90%

The candidate managed the review process, providing responses to reviewers' comments and producing the revised paper. The co-author provided feedback on the proposed approach.

Paper Seven

Initial conception and research design – 70%

The research idea of this paper, which follows up on Paper One, was developed by the PhD candidate with the support of one of the co-authors (a senior research professor).

Acquisition, analysis and interpretation of data – 80%

The approach to statistical analysis was developed by the candidate with support and guidance provided by one of the co-authors who has specific expertise in that area. Interpretation of the data was led by the candidate.

Drafting of the article – 80%

The candidate took the lead on structuring and drafting the research paper producing all sections of the published paper. Two of the co-authors contributed by providing the framework for the literature review which was then further developed by the candidate. The remaining co-author provided feedback on the initial draft.

Review process through to final publication – 90%

The candidate managed the review process, providing responses to reviewers and producing the revised paper. One of the co-authors (a senior research professor) provided feedback on the proposed approach.

Paper Eight

Initial conception and research design – 100%

The research idea and design for this paper, which combines elements of the preceding research noted in this submission, was developed by the PhD candidate.

Acquisition, analysis and interpretation of data – 100%

The candidate acquired, analysed and interpreted all data related to this research. As this was a literature-based piece of work, the analysis largely involved extracting and combining ideas from the candidate's previous papers and supporting this with a review of the existing literature.

Drafting of the article – 90%

The candidate developed the initial structure of the paper and drafted the article with the co-author providing feedback on the proposed approach and the overall idea it presented.

Review process through to final publication – 100%

The candidate managed the review process, providing responses to reviewers' comments and producing the revised paper.

APPENDIX C – OTHER PUBLICATIONS BY THE CANDIDATE

Speedie, C. and Mulville, M. Educational buildings as educational buildings: Can sustainable architecture help support sustainability in the curriculum? *Proceedings from Passive Low Energy Architecture (PLEA) Design to thrive conference, 3-5 July 2017, Edinburgh, Scotland.* **Under Review;**

Korkmaz, N., Mulville, M. and Sertyeşilışık, B. Optimising the thermal performance of high-rise office buildings in Istanbul by taking the Passive House approach. *Proceedings from the International Conference on Building Envelope Systems and Technologies (ICBEST), 15-18 May 2017, Istanbul, Turkey.* **Under Review;**

Callaghan, N., Mulville, M., Di-Maura, S. and Isaac, D. (2015). The non-energy benefits of employee focused building design. *Proceedings from the RICS/COBRA conference, 8-10 July 2015, Sydney, Australia.* Available from: http://www.rics.org/uk/knowledge/research/conference-papers/the-non-energy-benefits-of-employee-focused building-design/;

Mulville, M. (2015). Building Performance in a Changing Climate. *Proceedings from Low Carbon Buildings and Communities in the Sustainable Built Environment, 23-25 February 2015, Istanbul, Turkey.* ISBN 978-0-9928878-0-3;

Korkmaz, N., Mulville, M. and Sertyesilisik, B. (2015). Optimising the thermal performance of high rise office buildings in Mediterranean climates: a passive house approach. *Proceedings from Low Carbon Buildings and Communities in the Sustainable Built Environment, 23-25 February 2015, Istanbul, Turkey.* ISBN 978-0-9928878-0-3;

Ching, F.D.K. and Mulville, M. (2014). European Building Construction Illustrated, *Wiley.* ISBN 978-1-119-95317-3. Available from: http://eu.wiley.com/WileyCDA/WileyTitle/productCd-1119953170.html;

Jones, K., Desai, A. and Mulville, M. (2014). Employing backcasting principles for the formation of long-term built asset management strategies – A theoretical approach. *Proceedings from the CIB Facilities Management Conference, 21-23 May 2014, Copenhagen, Denmark.* Available from: http://hdl.handle.net/10540/581945 (best paper award);

Mulville, M. (2010). A guide to renewable energy technologies, *the CPD Study Pack Club.* Available from: *https://www.cpdconnect.co.uk/cpd-renewable-energy-technologies.html;*

Mulville, M. (2009). Measuring the performance of sustainable construction, *the CPD Study Pack Club.* Available from: https://www.cpdconnect.co.uk/measuring-performance-sustainable-construction.html;

Mulville, M. (2008). Reducing the energy use of the existing housing stock in Ireland through fabric upgrade: a cost-benefit analysis of hollow block walled housing (unpublished MSc thesis).

APPENDIX D – CURRICULUM VITAE (SUMMARY)

The following section provides a brief curriculum vitae covering relevant activities of the candidate.

Mark Mulville is Academic Leader for the MSc portfolio of built environment related programmes in the department of built environment at the University of Greenwich. A Chartered Architectural Technologist (MCIAT) and Building Engineer (F.CABE, C.Build Eng.) before joining academia in 2010, Mark had a career in architectural practice and technical consultancy with roles in Ireland, Australia and the UK. Industry-based roles include experience working on a range of social housing, commercial, industrial, retail, education, health care and hospitality projects. While working as a technical consultant, Mark was involved in Technologies Strategies Board and Scottish Government funded research projects.

Research Activities:

- Cluster leader for 'building performance' with the Sustainable Built Environments Research Group [SBERG] at the University of Greenwich;
- Journal reviewer for Facilities;
- Journal reviewer for Architectural Engineering and Design Management;
- Journal reviewer for the Journal of Corporate Real Estate;
- Organised and chaired the 'Delivering Sustainable Built Environments Open Lecture Series' at the University of Greenwich (September 2013 – March 2014). This included presentations by both the author and guest lectures concerning the research ideas included in this submission;
- Deliver a guest lecture at Rushmore Business School (Mauritius) concerning the research included in this submission (May 2014).

Awards and Grants:

- Research paper 'Merit Award' (for Paper Four) from the CIOB International Innovation and Research Awards (2016);
- British Council Travel Grant: Low Carbon Buildings in the Sustainable Built Environment, Istanbul, 2015;
- Research Assessment Exercise (RAE) competitive funding grant 2014: the 'non-energy benefits' of low energy buildings (Principal Investigator);

- Best paper award at the CIB Facilities Management Conference, 2014. (see Appendix C). www.emeraldinsight.com/doi/full/10.1108/F-06-2015-0042.

Teaching Activities:

- Developed and leads the Delivering Sustainable Built Environments module (core to several MSc programmes) built around the research of the Sustainable Built Environments Research Group [SBERG];
- Developed the MSc Sustainable Building Design and Engineering programme;
- Course coordinator for the MSc Dissertation module and contributor to the Research Methods module;
- Visiting tutor at Hong Kong University SPACE;
- Visiting tutor at Yunnan University of Finance and Economics.

Professional Body Activities/ Memberships:

- Chartered Architectural Technologist (MCIAT);
- Chartered Building Engineer (C.Build Eng.) and Fellow of the Chartered Association of Building Engineers (F.CABE);
- Fellow of the Higher Education Academy (FHEA);
- Membership assessor for the Chartered Institute of Architectural Technologist;
- Certified Passive House Designer.

Other Activities:

- Designed, developed and delivered a Continuous Professional Development (CPD) workshop on Post Occupancy Evaluation (POE);
- Designed, developed and delivered a CPD workshop on the Green Deal.