Human-Centred Smart Buildings
Reframing Smartness Through the Lens of Human-Building Interaction

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For my Grandfather,
who taught me about buildings

Abstract

Smart buildings backed by data and algorithms promise reduced energy use and increased value for businesses and occupants. Yet, this has typically been considered from an engineering and systems perspective. Given increasing integration of sensing and ubiquitous computing technologies in modern built environments, a growing Human-Computer Interaction (HCI) and Human-Building Interaction (HBI) community has begun to advocate for the human-centred design of building technologies.

This dissertation argues that there is a need for an inclusive, socially just and sustainable HBI agenda, to enable smarter buildings and facilities management. Deconstructing 'smart' rhetoric within HCI/HBI discourse and highlighting the values and ethics underpinning it, I argue that existing approaches to 'smartness' privilege automation and efficiency over the needs of human occupants. I undertake a qualitative inquiry into the roles of data and digital technologies in human-centred smart buildings through three case studies:

i) How retrofitted environment sensors facilitate smarter energy auditing practices. I contribute a methodology for using sensor toolkits in auditing, technical design of the BuildAX sensing platform, and insights into sensor-augmented audits and how future standards might support these.

ii) How data and digital technologies foster collective experiences of thermal comfort for office workers. I contribute a data elicitation interview method, design of the ThermoKiosk experience survey system, and considerations for integrating office tensions into workplace comfort management.

iii) How HBI can support agency and participation in the everyday management and adaptation of a contemporary smart building. I contribute a 'building walks' method to elicit conversations on the future of building technologies, new understandings of how student occupants conceptualise and evaluate spaces, and how buildings of the future might better enable occupant agency.

Through these, I contribute a re-framing of smartness to be more human-centred, including concerns for collaboration, inclusion, and human decision-making which does not consider occupants a 'problem' to be solved. The results of the case studies are synthesised into a set of six principles for the design of technology within human-centred smart buildings, re-grounding the field of HBI in the philosophy of environmental and social justice.

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Selected Publications

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Chapter 1: Introduction

Buildings excel at improving with time, if they are given the chance.

STEWART BRAND, *"HOW BUILDINGS LEARN" (1994)*

1.1 The Smart Building Vision

What makes a building 'smart?' With the rise of the smart building, non-domestic buildings are becoming increasingly hi-tech, augmented with highly granular sensing and actuating capability. This is fertile ground for innovation, and the potential for automated and intelligent (i.e. 'smarter') forms of management of these spaces backed by data and algorithms holds great promise for both reducing energy use and increasing their value for occupants and businesses alike. Yet, exactly what makes a building 'smart' is contested: definitions which appear to be largely in agreement can be underpinned by wildly diverging design motivations.

Smart buildings are not by any means a new or novel concept. As Buckman *et al.* (2014) note, such systems first began to be explored in the academic literature as 'intelligent buildings' in the 1980s, though the term has evolved and expanded over time losing its focus and clarity. In attempting to distil a more comprehensive definition of the 'smart building,' Buckman and colleagues consider the holistic nature of building design, with "*intelligence, enterprise, control, and materials and construction as an entire building system, with adaptability, not reactivity, at the core, in order to meet the drivers for building progression: energy and efficiency, longevity, and comfort and satisfaction.*" This definition contains at its core an argument that smart buildings should flexibly integrate technological systems and architecture to achieve longevity, energy efficiency and occupant satisfaction. Smart buildings, by Buckman's definition, should therefore move beyond intelligent buildings by being highly adaptable, reconciling "*both human control and automation*" to achieve these desired outcomes.

This definition is substantiated by existing smart building projects. 'Smart' has long been synonymous with 'efficient,' with more efficient systems management having demonstrable effects on energy usage, in turn lowering operating costs. Microsoft's 500-acre campus headquarters are a good example of this. Connecting disparate building management systems (BMS) across the site and extracting and analysing the wealth of data produced resulted in remarkable cost savings and drastically changed the way in which those buildings are managed (Microsoft Corporation, 2013). Yet in the press release which accompanied this project, the 40,000-odd occupants of the buildings on the Redmond campus are almost an afterthought, just one factor in the optimisation process: "*algorithms can balance out the cost of a fix in terms of money and energy being wasted with other factors such as how much impact fixing it will have on employees who work in that building.*" Smart buildings to Microsoft are an exercise in big data analytics and optimisation: a systems-focused, rather than people-focused approach, and primarily an opportunity for operational cost saving.

Over the course of 2017, office buildings consumed 21.3TWh electricity, 6% of the total supply in the UK (Department for Business Energy & Industrial Strategy, 2018), making them a domain of eminent concern for sustainability research. Attempts to improve the sustainability of these buildings have often been approached from an engineering perspective, seeking to produce more efficient designs for building fabric and HVAC (heating, ventilation and air conditioning) systems. Optimising the energy used by office buildings has been the focus of a significant body of scientific literature, with much of this work balancing the tension between occupant comfort and energy efficiency (Dounis and Caraiscos, 2008). Therefore, aside from technical requirements such as building standards compliance, smart buildings are designed largely in alignment with an underpinning agenda of optimisation, the aim being to use sensors and data to optimise the comfort of occupants, in order to maximise productivity while minimising energy consumption (Alavi *et al.*, 2016). Yet, within the context of office buildings, it has also been recognised that user behaviour is an uncontrolled variable in this equation (Hameed *et al.*, 2014) known to cause significant difficulty in achieving reductions in energy usage.

Optimisation approaches such as these reduce productivity, comfort, energy and so on to variables that can be tweaked and refined. This aligns with the modernist philosophy described by Brynjarsdóttir *et al.* (2012), based on (Weber, 2002) among others: *"that people can and should change the world for the better by analyzing present conditions and improving scientific and technical knowledge. Modernism rejects the idea that tradition should be the guide for action and seeks instead to rethink and optimize our life conditions through rational planning."* While common, this is not an approach without its flaws, as I will explore further in Chapter 2. Energy efficiency is perhaps the most commonly touted selling-point of the ‘modernist’ smart building vision, but it hardly offers a complete picture.

Buildings are also big business. Office buildings, according to a 2017 industry report (Property Industry Alliance, 2017), accounted for 31% of the value of all commercial property ownership in the UK: the second largest sub-sector of commercial property just behind retail premises. British Land, a FTSE100 real estate investment trust with a commercial property portfolio valued around £12.3bn, published in 2017 a white paper which collates “six key benefits” of the smart office vision (The British Land Company PLC, 2017). This report is noteworthy as it casts the net wider than just energy efficiency and its associated cost benefits. Three of the six benefits it outlines are human-centred: enhanced productivity, better retention of staff, and supporting employee health and wellbeing. They state that “*smart offices can create an enhanced user experience that helps to increase productivity, attract and retain talent, support wellbeing and promote corporate brand values.”* This approach contains within it an implicit assertion that a smarter office environment can be a place where people *want* to work. A smart office should therefore be desirable for businesses, following the maxim that happier employees produce better work. Yet, this is hardly philanthropic: as found by ActionAid (2011) the British Land Company stands among the worst offenders for tax avoidance, using offshore tax havens to hide business profits. Looking after one’s workers is likely more profitable. This approach to smart buildings is underpinned by a neoliberal philosophy which places “*economic prosperity ahead of other political goals (such as equality or social justice)”* (Dourish, 2010), limiting the design of these buildings by focusing on productivity. There is a need to move beyond this narrative towards a more inclusive smart building vision that takes account of the wider political and ethical goals of environmental and social justice as a vehicle to deliver on comfort and wellbeing.

Within the context this work addresses, smart buildings form part of a utopian blueprint for highly functional and usable office buildings. The two common features of the modernist smart building vision are therefore: (1) algorithmically intelligent, interconnected BMS with remote sensing and actuation, which make management easier and reduce operational energy use (improving environmental sustainability); and (2) the promise of a happier, healthier, more productive workforce arising as the natural consequence of a building designed for enhanced occupant comfort. Yet, there is a problematic assumption in this utopian vision: that a smart building design as described in (1) will automatically result in an outcome of (2), with a corresponding improvement in occupant experience. It will be necessary to unpick the difficulties which arise from this technologically solutionist assumption.

1.1.1 Terminology and Context

Although there should now be some clarity on the definition of smart buildings adopted by this work, there is value in finding the best terminology to use for the contexts I have studied, and a surprising amount of subtlety and complexity which is necessary to address. To discuss the relevance and generalisability of this work, these terms need to be pinned down to a certain extent. A term which has often been used in the research literature, perhaps without quite enough care, is 'non-domestic building.' There are many examples of this terminology being used in research where the core study is actually undertaken in office buildings, e.g. (Menezes *et al.*, 2012; Lockton *et al.*, 2014). Statistics relating to the whole non-domestic sector are used to motivate studies which focus only on the office context, as Morgan *et al.* (2018) highlight. While office buildings are a subset of non-domestic buildings, it is unclear whether the authors would claim that their findings would easily generalise to, say, a steel mill or a shopping centre. The terminology of 'non-domestic' is not specific enough.

The solution might be to find another term which fits the context more comfortably. Oldenburg (1989) writes in support of 'third places,' for example coffee shops or restaurants: places people gather which are not home ('first') or work ('second') places. The contexts studied in this work would be the 'second places' of the staff and students who are our research participants, but it wouldn't make sense to use this as a cross-cutting term. 'Offices' is more specific—but really *too* specific, as the locations studied in this dissertation also include university buildings with lecture theatres and seminar rooms, and the findings of the studies I have undertaken may generalise to other places beyond these contexts. For example, researchers investigating thermal comfort in classrooms might find some relevance to their work. While school classrooms aren't directly generalisable from open offices (for example, school children are not afforded the same kinds of adaptive actions for managing their comfort as adults in an office might be) there will be parallels which might be of use when designing interventions for this context: school buildings will use the same kinds of BMS and HVAC controllers, for example.

Much of the focus of this dissertation is on ‘workplaces’, so how does this term fare as a candidate? Unfortunately, ‘workplaces’ suffers from a similar problem to ‘non-domestic’ as it includes almost any location where labour is undertaken, and worse, excludes study environments such as university lecture halls. This work investigates workplaces where knowledge workers[1] and other white-collar workers (such as administrative staff) are based, encompassing office work across a range of professions, and also examines students and the buildings they use (labs, seminar rooms, lecture theatres). Further complicating the picture, knowledge work lends itself well to flexible or remote teleworking (Su and Mark, 2008), the incidence of which has risen dramatically in recent years. It would not be sufficient to state that this dissertation focuses on smart buildings where knowledge workers are based, as this would by extension include smart *homes*. So, although this work focuses on smart buildings, it does not claim that its outcomes will easily generalise to smart homes: there is already a large enough corner-case to potentially cause confusion.

I invite the reader to consider the context of the work when reading terms such as ‘workplace,’ ‘office,’ or ‘non-domestic building’ in this dissertation. There is a richness and complexity behind the use of each term, and through their use I am not making wider claims of relevance to contexts distant to those studied: I do not, for example, claim that findings made in an open-plan office are easily applicable to blue-collar workers who perform manual labour in heavy industry. These are terms which *are* reductive but do have relevance, and I do not use them interchangeably but rather with careful consideration of the contexts to which this work can generalise.

1.1.2 Basis in HCI (and related fields)

There are good reasons to suspect that the human-centred outcomes promised by the smart building vision cannot be achieved by treating them only as an optimisation problem. Significant questions in the design and provision of smart buildings cannot be resolved without a more holistic consideration of the various factors influencing a successful outcome. What, therefore, does a human-centred (or occupant-centred) approach to smart buildings look like? The field of human-computer interaction (HCI) has a rich history of human-centred and participatory design, and a lot to bring to the smart building arena. There has been significant work in HCI on smart homes, as reviewed by Desjardins,

[1] Knowledge workers or ‘information workers’ are employees whose job involves “*developing and using knowledge rather than producing goods or services*” (Cambridge Business Dictionary)

Wakkary and Odom (2015). Much of this work shares themes such as thermal comfort and interactions with and within the sensed environment, though non-domestic contexts in general remain underrepresented. The sub-field of Sustainable HCI has dealt with a wide range of research topics (DiSalvo, Sengers and Brynjarsdóttir, 2010) including sustainable interaction design (Blevis, 2007), persuading end-users to make 'greener' choices (Woodruff, Hasbrouck and Augustin, 2008), and user studies seeking to better understand the complexity of technologies which attempt to engage with environmental issues (Aoki *et al.*, 2009).

Human-Building Interaction (Alavi *et al.*, 2016) or 'HBI' is a domain of growing interest within HCI, as researchers have recognised a need to investigate existing and emergent forms of interaction with built estates, both as a way of understanding existing practice and in an envisioned move towards smart buildings as the 'new normal'. The ways in which we interact with buildings are changing as a result of their ongoing technological enablement, and HBI posits that buildings "*should be designed and nurtured in a dialogue with their users at the individual as well as social levels.*" Researchers are looking at smart buildings as part of this work, from collaboration with different stakeholders during the design process (Verma, Alavi and Lalanne, 2017), to engaging in deeper questions of energy use, data and the drive for efficiency (Bates and Friday, 2017). This builds on a considerable corpus of work around many of the same technologies and challenges which underpin smart buildings as cyber-physical systems: see (Lazarova-Molnar and Mohamed, 2017) for a review.

In looking beyond smart buildings as an exercise in mechanical optimisation, the field of CSCW (Computer-Supported Co-operative Work) also offers a rich background for examining the design and development of technologies that affect groups, organizations, and communities. Building on understandings drawn from architecture and urban design, Harrison and Dourish (1996) discuss how people experience the places they inhabit, and how social factors determine the behaviours and interactions which a (physical and/or virtual) space affords. These interrelated concepts of 'space' and 'place' continue to be a useful framing to understand situated systems of practice and, as Dourish (2006) notes, CSCW research has moved beyond a focus primarily on the office workplace. In the sustainability context, Dillahunt and Mankoff (2014) discuss energy consumption of and among domestic households, pointing out that it is insufficient to design a technology which aims to promote energy conservation without consideration of the practices of the target community.

Similarly, Morgan *et al.* (2018) investigate the co-design of technologies for behaviour-based energy use reduction within the office, highlighting the complex ways in which practices influence energy use. While behavioural-change-based approaches are common within this literature corpus, the approach of focusing on persuading users to adopt green behaviours has been criticised for its reliance on a limited 'modernist' framing of sustainability (Brynjarsdóttir *et al.*, 2012). Such approaches assume that it is possible to address complex issues by quantifying and improving the efficiency of human life through technology, a philosophy sometimes referred to as 'technological solutionism' (Morozov, 2013). It is necessary to look beyond the systems-focused approach, bringing the smart building vision together with prior human-centred research in order to create a building which works for all of its users. A more thorough dive into the prior research which motivates this thesis can be found in *Chapter 2*.

1.1.3 Human-Centred Design of Smart Buildings

Buildings can be a site of conflict. They are designed to meet the requirements of multiple stakeholders, but the values which inform their design are often opaque, and requirements can even be in conflict (Hasselqvist and Eriksson, 2018). These stakeholders are building occupants, managers, and designers, and they all bring their own assumptions and motivations to the table. Occupants are just one group among a number of different stakeholders in a building's design, but even within these roles there are different levels of input and different power dynamics at play. All non-domestic spaces are imbued with the design values of their architects and the organisations which commission them. A manager will have a different set of requirements and a different set of ideas for the needs of their employees than the employees themselves. The architect or engineering firm working on the project will have external factors including building standards (called 'building codes' in the US) to consider. The commissioning organisation or financier will have a budget.

Commercial vendors of smart building solutions target their products towards organisations who might install them in their buildings, so advertising materials speak of systems "*better aligned with the priorities of property owners and managers*" (Intel Corporation, 2017). Although it is hardly surprising that system vendors design for the market they sell to, from the very point of inception the role of the occupant is cast as passive, as a recipient of a service which by its nature is designed to be invisible. Even the terminology of 'occupant' is loaded, reflecting their precarious status as tenants in a building. In such a paradigm, office buildings are reduced to 'machines' designed to support, enable and extract the labour of their occupants, whose needs are considered in respect to the space and comfort required to facilitate their occupational outputs (Murphy, 2006). The end-users of a 'smart' building system are segregated from its commissioning, even though the people who work desk jobs in these buildings could be considered the 'majority stakeholder' in their working environment.

Building occupants are not only distanced from the design of the computer systems which control and regulate their buildings, but also from the ongoing management of those built spaces. It is common in the UK to outsource the management of buildings to professional management services, and interaction with facilities managers is often funnelled through the mechanism of complaints. This presents a problem for the management of these buildings because there is little ongoing insight into how the building is performing in terms of occupant experience, unless conditions deteriorate to such an extent that a complaint is made (Parag and Janda, 2014). This is a significant problem for existing (non-smart) buildings, where tightly provisioned automated HVAC systems, coupled with bureaucratic management processes, reduce occupants' sense of control over their space (Hellwig, 2015). Further, while some kinds of building occupants may have some agency over the conditions of their space (e.g., business tenants, who can take their custom elsewhere if dissatisfied), others (e.g., workers) may find that tolerating the space is a condition of their employment. In any case, researchers have long identified that a 'comfort-as-product' approach alone cannot meaningfully address energy reduction, as thermal comfort is inherently subjective (Clear *et al.*, 2014). In order to achieve optimal comfort, a building design which takes account for occupant behaviours is required, but these are both complex (Lazarova-Molnar and Mohamed, 2017) and unreliable as an operational parameter. Human beings are not rational actors: most do not spend the day agonising over energy usage, and far from all of us are motivated by a green agenda (Strengers, 2014).

It is evident that there are significant parallels in the design of smart buildings to the 20th century development of air-conditioning. Indeed, the underpinning motivation of both HVAC and smart buildings is very similar: to provide better buildings. In practice, 'better' seems to have been understood as 'uniform' and improvement has been driven through the use of automation to provide tightly climate-controlled working environments. Western society has normalised the existence of air conditioning to such an extent that we expect or assume it will be provided (Arsenault, 1984), and there is a tendency to forget that this has not always been the case: Arsenault's history of air conditioning in the southern USA (*ibid.*) makes for fascinating reading on the subject.

Air-conditioning is a technology built on the assumption that 'one size fits all,' a failure well understood by women in air-cooled office buildings, who often report feeling colder than their male colleagues. A commonly cited reason for this is that the standards for office air temperature were developed using comfort measurements taken from men sitting in climate-controlled boxes (Murphy, 2006). ASHRAE, the American Society for Heating and Refrigeration Engineers, contend that this is not the case and that standards have since been updated to take account of this. Rather, female workers' clothing, being different from the suit-and-tie professional dress standards expected of their male colleagues, are often made from lighter fabrics (ASHRAE, 2015, p. 20). In any case, the generic, heavily optimised technology of AC sits in contrast to other definitions of 'smart' which, rather than striving to be 'optimal', embrace personalised, customisable or adaptive design.

I question whether the optimisation approach is fit for purpose, or if it is a trend which runs counter to the interests of building occupants. People can be comfortable in a much wider temperature range than that specified in building standards. Indeed, translating between the subjective notion of comfort and objective measurements of temperature is notoriously difficult (Chappells and Shove, 2005), and the standard-specified range of 'acceptable' temperatures that building occupants have come to expect (and demand) is a socially constructed norm. In recent years there has been a revival of natural ventilation in office designs, reflecting the drive to address sustainability concerns through the adoption of less wasteful technologies (De Dear, 2011) while still maintaining an acceptable level of comfort. Sytse de Maat (2015) writes that "*the trend in engineering to design buildings that function more and more autonomously in order to save energy is likely to lead to psychological and social discomfort, since such buildings afford less insidedness*[2] *and thus less place attachment.*" As such, a smart building which as a product of its design deprives occupants of control is likely to have an impact on satisfaction regardless of perceived comfort (Hellwig, 2015).

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[2] De Maat uses Sherry Boland Ahrentzen's definition of 'insidedness', "*an implicit awareness, an experiential familiarity with the physical features of a place as a result of repeated use*" (Ahrentzen, 1992)

Although attempts to involve the end-users of a building in the design process are common, some stakeholders have closer involvement in the process or more socio-organisational power, and their voices can outweigh others. While this work does not examine the architectural design process itself, it begins to look at ways in which buildings can be 'smarter' outside of the established technologically-driven norms which are the current driving forces for smart building architects and designers. My aim is not to replace or innovate on building techniques, but to establish a critique of their motivations that can work to encourage broader consideration of the needs and practices of building occupants.

To this end, a key part of a human-centred approach to smart buildings must be to establish a guiding ethical agenda, which can be used as a critical lens onto existing practice. In recent years, HCI scholars have begun to realise that sustainability concerns need to take account of the wider political context of research, design and interventions, leading towards an agenda and interlinked understanding of environmental and social justice (Bates *et al.*, 2018), these forming the critical lens which I employ within this work. As I will more fully discuss in Chapter 2, technologies designed without critical engagement can idly reproduce existing systemic inequity (Dombrowski, Harmon and Fox, 2016), or indeed miss the wider context for practices and behaviours which are the real drivers of energy consumption behaviour (Shove, Watson and Spurling, 2015). Human Building Interaction has thus far done little to engage with underrepresentation and inclusivity within the built environment, and where this has been engaged with it has been from the domestic perspective (Hasselqvist and Eriksson, 2018). In the next section, I discuss my approach for investigating this problem.

1.2 Research Approach

The aim of this research is to investigate ways of innovating on the smart building vision, by examining and critiquing its scope, rather than unquestioningly following the conventional practices and trajectories of building design. To avoid the pitfall of technological solutionism, we need to take a holistic approach to the design of technologically enabled buildings, asking: "*who* are smart buildings smart *for*?" Are they smart for the worker-occupant, the facilities manager, or for the organisations which own or lease them? Or can they be smart for all of these stakeholders? Through this work I examine a number of these stakeholder perspectives, taking the position that a smart building should support both its occupants and managers, enabling their work and allowing them to work ‘smarter’. As discussed above, sustainability is a motivating factor of this work, and smarter built environments hold significant promise for energy reduction. However, the approach of optimising energy use against comfort is not sufficient as it uncritically follows existing structures of building design and governance, which may in and of themselves be unsustainable.

I argue through this work that there is a need to broaden out smartness to mean ‘*fitness for purpose*’. Fit-for-purpose smart buildings meet the needs of their various stakeholders, such that they are usable and well-used. They are sustainable in not just the environmental sense, but also in the social sense, having in mind at the design stage an understanding of the (often invisible) structures and norms of how buildings are designed, maintained and lived in. This raises the question of how we might measure ‘fitness for purpose’. How do we go about evaluating a smart building in a way which empowers the occupant and takes account of the complex sociotechnical systems of which they are a part? There are several existing methods for evaluating non-domestic buildings, the one most relevant to this context being post-occupancy evaluation (POE) which examines factors including occupant feedback on comfort and working conditions, and the predicted-vs-actual energy performance of the building fabric. The BUS (Building Use Studies) methodology (Leaman, 2017), developed since the 1980s, is one example of a methodology aiming to quantify occupant satisfaction which may be used as part of a POE. BUS uses a multiple-choice survey to gather occupant feedback on a number of pre-determined comfort criteria (thermal comfort, light, noise, etc.), to produce a report on the subjective performance of the building. However, the question remains open as to how accurately such surveys reflect the lived experiences of occupants.

This work contributes understandings of how data and digital technologies might assist in the goal of creating smarter, human-centred, more useable, fit-for-purpose buildings, with building occupants closely involved in their ongoing development as a key stakeholder. I undertook three case studies to investigate distinct issues within this area, each addressing a sub-question. These were undertaken between 2014 and 2018, and are described along with their context in this dissertation in the next section. Their results are synthesised through a discussion in Chapter 7, where I condense the findings of the case studies to distil a framework for understanding buildings as a site for collaboration, and a set of six principles guided by environmental and social justice, which form a manifesto for future HBI work in this area.

1.3 Thesis Outline

Chapter 2: Related Work

In Chapter 2, I develop a literature review of relevant work in HCI and beyond, and identify the research questions I have targeted for intervention and study in this work. I present a deep dive into the HCI literature, asking what it means for a building to be 'smart', and construct definitions of smartness which align with HCI paradigms. In seeking to develop new notions of smartness, I review HCI and HBI work on smart homes following the typology of smart homes presented by (Wilson, Hargreaves and Hauxwell-Baldwin, 2014), of 'functional', 'instrumental' and 'socio-technical' smart homes. I discuss where occupant agency is both enhanced and deprioritised within this typology, in making a case for smart buildings which are designed with the autonomy of individuals rather than automated systems in mind. Further, I examine how smart buildings are understood as workplaces within the literature, and how CSCW thought has evolved with regards to work environments. Following the literature gaps identified within these discourses, I develop a high-level research question asking "*what are the roles of data & digital technologies in creating human-centred smart buildings?*" I investigate this high-level research question by dividing it into three sub-research questions, each corresponding to a case study presented in this work.

Chapter 3: Methodology

In Chapter 3, I detail the methodology employed in the investigation of these research questions, describing my social-constructivist epistemic viewpoint and why a qualitative approach was selected for this work. I outline a methodological basis in prior HCI work for the methods employed and developed in the investigation of my research questions, including a background of relevant qualitative methodologies including participatory design (PD), research through design, cultural and technology probes, and speculative methods. The approach to data collection and analysis is described, with the use of interviews and focus groups forming the backbone of the human-centred approach, and thematic analysis employed in the inductive analysis of the transcribed data corpus. Finally, I revisit the research questions identified in Chapter 2 to examine why a case study approach is appropriate for the investigation of this topic, and describe the research design of each of the three case studies in turn.

Chapter 4: Case Study 1—Augmenting Audits

Chapter 4 introduces the first case study, "*Augmenting Audits.*" The future of buildings cannot be considered without engagement with the present. In considering how we might shift from a modernist to a human-centred perspective on smart buildings, and having identified in Chapter 2 that building automation in its current form functions to exclude building occupants by reducing the agency they experience, this case study identifies and investigates opportunities for inclusion of building occupants in buildings management.

Figure 1: Merz Court, one of the buildings audited in the first case study, built in 1963. Photo by A. Curtis, used under Creative Commons CC-BY-SA 2.0 licence

Facilities managers audit buildings to identify inefficiencies in building design and operation, to reduce running costs, and ensure compliance with standards. A key part of the modernist smart building vision relies on highly granular environmental sensing and data-logging, and facilities professionals can use this to train models, diagnose potential problems, and as an evidence base for funding applications. Microsoft's Redmond campus project, mentioned earlier, demonstrated that older buildings can be made 'smart' too: this vision is not limited to the shining new-build developments invoked in the marketing material of architect firms and smart building solutions providers. Yet, making older buildings smarter presents unique challenges, as the vast majority of existing built estate is not augmented with the necessary sensing technologies. Building management systems in older buildings, if installed at all, are typically limited to single-point sensing of temperature, or simple metering of resources such as gas used for heating systems (which might be a percentage of an aggregate figure).

This first case study follows four older buildings on a UK red-brick university campus, constructed between[3] 1955 and 1975 (Figure 1). Managers of these facilities undertook audits using a battery-powered sensor toolkit, BuildAX, to collect data which these buildings' ageing BMS could not provide. A group of students based within the building learned to undertake environmental audits, and worked with the facilities management team to deploy sensor toolkits in these buildings. As occupants of the building, students were chosen as the target study population to investigate how occupants could be better included in such management processes. Collected data sets were used to diagnose problems and create a business case for funding upgrades for more efficient lighting through the Salix funding scheme. The study addresses the ways in which both novice and professional auditors used sensor toolkits to identify problems in these buildings, and how they made sense of data the sensors provided. Through workshops and interviews, I explored the experiences of these novice auditors as they learned to interact with the toolkits, began to understand their limitations, and developed skills in using them to audit these buildings.

The findings highlight factors to consider when designing for sensor-augmented audits with both novice auditors and professionals, and, with respect to *RQ1*, give light to how building occupants might themselves be empowered to participate in these auditing processes. By understanding what participation in existing audit practices might look like, strategies can be developed for more deeply involving building users in the ongoing management of their space, and I present one such framework for this in the chapter in the form of a set of recommendations towards a sensor deployment protocol. Student auditors were a particularly useful group to investigate this, as their level of expertise was broadly comparable to that of office occupants, and as occupants of the studied buildings themselves it could be argued they too hold a stake in maintaining an ongoing positive experience of the space. The results of this study hold value for HBI and HCI practitioners in designing future studies and smart building interventions, but also contain insights for the professional facilities management community who will be the driving force in operationalising occupant inclusion in their managed built estate, providing a novel

[3] Buildings examined by students in the first case study were built 1955, 1963, 1964 and 1975 respectively.

perspective on how this might be accomplished. The discussion offers directions for how building occupants might be empowered to participate in auditing practices to address concerns, and considerations for supporting (or challenging) standards and policies.

Chapter 5: Case Study 2—Negotiating Comfort

Figure 2: The Newcastle University Business School, a 7-year-old building housing the administrative office where the 'ThermoKiosk' study took place

In Chapter 5 I present the second case study, "*ThermoKiosk*". This study expands on the understandings developed of the role of occupants as knowledge sources in the spaces where they live and work. The issue of thermal comfort in offices can be polarising for occupants and is often a source of complaints for building managers, who are positioned as providing comfort as-a-service to their occupant 'customers'. This creates a need for negotiation between occupants and the facilities management team, to address issues when things go wrong and to attempt to correct them. The studied office, located in a 4-year-old (at the time of the study) office building at a UK university, had a history of complaints of both overheating and overcooling. Following investigation of the HVAC system by facilities managers, who concluded that the system was operating as per its specification, manual control of the HVAC mode was given to the office occupants. As practices were moving away from automated tight control of a static temperature, this resulted in negotiation between occupants of the office as opposed to with an external party, and presented a context to study the role of data in comfort management.

A 3-week deployment of a prototype situated survey device, ThermoKiosk, was undertaken with 26 participants. ThermoKiosk was designed to collect situated real-time feedback on occupant comfort, displayed on a tablet interface adjacent to the wall-mounted HVAC controller. Data was collected over a 3-week deployment, including environmental data collected using the BuildAX sensors. 14 office occupants then participated in a 20 to 30-minute semi-structured interview, during which they explored data from the sensors and surveys using visualisations of the measured temperature overlaid with samples from the survey devices, and discussed their interactions with the devices within the social context of the office. Although subjective measurement of comfort is not a novel technique, the ways in which subjective data were appropriated, contextualised and put to use by occupants and management when it was made available to them helped to initiate dialogue to understand and handle tensions, and ultimately led to a greater sense of agency.

Considerations are developed in the study for designing for collective experience and shared understandings between office occupants. I reflect on weaving subjective data into workplace comfort negotiations, and consider how passive occupants might become active inhabitants through the realisation that comfort is a collective experience. ThermoKiosk demonstrates that automation is not synonymous with comfort, demonstrating a new direction for the development of smart buildings, and a role for HBI in guiding occupant-building interactions in future. The chapter contributions can be of use to thermal comfort researchers and practitioners, and provide a way of re-framing comfort of use to professionals in dealing with similar intractable comfort complaints.

Chapter 6: Case Study 3—Engaging Occupants

Chapter 6 presents the third and final case study, (CS3) "*Participatory Auditing*", which examines how we might move beyond the scope of the usual complaints process through which occupant feedback is gathered. Buildings are a resource, and that resource is wasted if not used effectively: 'sustainable' space must be usable, as well as comfortable. In ensuring that such buildings are human-centred, a deep understanding of social fabrics and how these interact with wider organisational process is required. In the previous case studies, I developed understandings of the role of occupants as knowledge sources; the third and final case study examines how occupants interact with a brand-new building, asking how they might be supported to participate and have agency in the everyday adaptation and management of space within it.

Figure 3: The Urban Sciences Building, the site of the third case study

The context for this work was the 'Urban Sciences Building' a newly developed building opened in 2017 on the Newcastle University campus. The USB is a 'living lab' for sustainability research, designed to the BREEAM 'excellent' standard with a modern BMS and highly granular environmental sensing capability. This building could be considered 'smart' by some definitions, but as I have argued this is a modernist, technosolutionist outlook: it is not sufficient for a building to simply collect granular data for use by facilities management in order to be 'smart.' Within this work, the building offers a testbed for investigating issues of occupant agency within the building and wider organisation.

An initial set of scoping interviews with managerial staff were used to develop workshops with the student population, seeking to understand their needs in the building, how well the building was serving those, and what the building might look like in future. The workshops comprised a planning session, a series of occupant-led building walks where students collected photographic evidence of spaces they regularly used or had some interest in, and a design task where students used speculative fictions of technologies for the 'smart building' future to describe how the currently provisioned space did not meet their needs. Drawing on the findings, I expound how occupant-manager interaction might move beyond the scope of the usual complaints process through which occupant feedback is gathered, proposing the concept of 'participatory audits' which aim to ensure that a building is 'fit for purpose', i.e., it provides appropriate space which is being used effectively. The chapter concludes with considerations for how data and digital technologies might be leveraged to operationalise such audits in future smart buildings, and issues a call to examine existing processes and practices for where these result in entrenched inequity, with social justice and feminist lenses being one route to identifying these. These insights will be valuable for HBI practitioners and HCI researchers working on smart building design and evaluation, and offer an opportunity for facilities managers to reflect on how their buildings are managed and whether their approach excludes some occupants more than others.

Chapter 7: Discussion

In Chapter 7, I collect and summarise my research results with regards to the sub research questions answered within the case studies, and expand on these in answering the research question "*what are the roles of data and digital technologies in creating human-centred smart buildings*?" Through this exploration, I produce a framework for understanding the different types of collaboration which can be designed for within the smart building, between the different stakeholders. I identify the necessary factors for human-centred smartness, discuss implications for environmental sustainability, democracy and civics, and collate these in a set of six principles for technology in human-centred smart buildings. These include ways of thinking about buildings, recommendations for design, and calls to action for researchers engaging in, and working with practitioners in, this nascent area. This functions both as a summary of my research outcomes, and a manifesto for the HBI field in the future positioning of the research field, identifying useful points of contribution and assumptions which should be challenged in future work.

Chapter 8: Conclusion

Chapter 8 concludes the presentation of my dissertation with a short summary of the results of my case studies, and of the positioning formulated in the discussion. Finally, I summarise the take-homes of this work with a lasting message for HBI.

1.4 Summary and Contributions

Through this work, I contribute to discourse in human-building interaction (HBI) and the sustainable HCI agenda. My methodological contributions are threefold, corresponding to the three case studies presented in this dissertation: new directions for the use of retrofittable sensor toolkits in built environment auditing practices; a data-elicitation interview method which helps to draw out occupant experiences of a building; and a building walks methodology for uncovering occupant practices and thoughts on the future design of their building. Two technical contributions also arise from this work: the design and development of the BuildAX environmental sensor platform; and that of the ThermoKiosk subjective experience survey system.

The results of the case studies contribute new understandings and design considerations for the design of human-centred smart buildings. In CS1, presented in Chapter 4, I raise design implications for toolkits to support sensor-augmented audits, recommendations towards a deployment protocol, and broader considerations for how future standards and policies might be adapted to leverage this potential. In CS2 (Chapter 5), I raise consideration for shared experiences of comfort in the form of ‘collective comfort’, and opportunities for technology within adversarial office social fabrics. CS3 (Chapter 6) led to new understandings of how student occupants conceptualise and evaluate spaces through accounts of occupant involvement and participation in ‘smart’ facilities management processes. The study raises questions for how buildings management of the future might better leverage occupant agency, and contributes towards the design of such processes in smart buildings. The discussion presented in Chapter 7 brings together the understandings arrived at through my investigation of the three case studies, presenting a manifesto for HBI and set of principles for technology in human-centred smart buildings.

In the next chapter, I present a literature review of work in HCI and related fields. I investigate how human-centred smart buildings have been previously understood and discussed, culminating in a set of research questions to be investigated in this work.

Chapter 2: Related Work

The good news is that technology can make us smart…

Don Norman, "Things That Make us Smart" (1993)

2.1 Review Scope

In the introduction to this work, I identified some of the issues with the modernist smart building vision and defined the terms which I will use to discuss it. This may not be the only vision of smart buildings, but it is yet a pervasive narrative. I have argued that in order for smart buildings to fully address the problems of comfort and energy use, we must re-frame the notion of smartness to place the human at the centre of the design of technologically enabled buildings. HCI is well placed to address smart buildings as an application domain, and this chapter presents a review of the related literature which forms the conceptual framework for this dissertation. I explore the foundations of this work as situated in the HCI discipline, including critiques of existing approaches within HCI, concluding with a position for this work to address a gap in knowledge within the field.

This review examines a corpus of work drawn from buildings-related research in and around HCI. Buildings in HCI have been explored from several conceptual directions, with wide-ranging motivations: architecture (Dalton *et al.*, 2012); health and wellbeing (Gallacher *et al.*, 2015); sustainability (Schwartz *et al.*, 2010); community (Schnädelbach *et al.*, 2017); and combinations of these with others. My literature inquiry is guided by the investigation of the questions: *"what does it mean for a building to be smart*?" and "*what are the underlying assumptions and motivations in 'smart' rhetoric?"* Through this, I examine how the problem of human-centred smart buildings might be approached, and identify directions for work to contribute to this agenda.

As we have seen, approaches to the commercial development of smart building solutions operate on different definitions of 'smart.' Existing research frames '*smartness'* in relation to multiple different concepts, the built environment being just one. I develop my own notion of 'smart' from critiques of this literature, and identify a research gap to address in this dissertation. I examine how 'smartness' functions as a property of artefacts (of which built spaces are a sub-category) through the review of space and building-related work in HCI, as well as major external influences on the field (e.g. architecture, sociology and psychology).

2.2 Constructing 'Smartness': What does it mean for a building to be smart?

What does it mean for a building to be 'smart'? Efficiency, control, intelligence, and maximised productivity were among the values identified in the introduction of this work. My aim for this review is to identify and critique discourses which have influenced researchers' conceptions of smartness. Some definitions of smartness, for example that of the Cambridge Academic Content Dictionary ('Smart', 2017), emphasise "independent action". Such a system would be smart if it is capable of undertaking actions independently of an operator, in such a way that improves its efficiency, or accuracy. By prioritising the independence of computing systems, this kind of 'smartness' takes humans out of the loop, out of the decision-making process.

This is a problematic foundation for smartness, and one that we are beginning to see wider criticism of. Independence is not always desirable: e.g. a computer being in control of drone strikes is not a popular idea with the public, human rights organisations, or indeed the employees and shareholders of some of those companies developing such solutions (Romm and Harwell, 2019). It is also, as Strengers (2014) argues, a predominantly masculine conception. This seems at best a limited characterisation and doesn't reflect the broad range of contexts to which technologists and researchers have assigned the moniker 'smart'.

In working towards a re-definition of smartness within HCI, it is necessary to consider the range of contexts in which it has been investigated. At the time of writing, a keyword search for "smart" within the ACM Digital Library returns 58,230 results relating to electrical distribution systems (smart *grids*) (Ramchurn *et al.*, 2012), learning technologies (smart *classrooms)* (Saini and Goel, 2019), smart universities, smart transport, cities, and governments, and smart devices (watches, cameras, showers), among many others. It seems unlikely that these disparate research areas all operate on a unified definition of smartness.

2.2.1 HCI Paradigms: Framing Smartness

In "Things that Make us Smart" (Norman, 1993) cognitive scientist Don Norman takes a human-centred approach to smartness, in which technology is situated as aiding the human, rather than replacing them. Everyday objects like pen and paper, post-its, and filing cabinets aid us in daily tasks of work. Norman calls these "cognitive artefacts": tools which aid human cognition by allowing us to externalise our thought processes. They are not ‘smart’ in and of themselves, but they are objects which make people smarter by distributing the process of cognition beyond the mind. Such distributed cognition can help overcome the limitations of human attention span (about 10 seconds) and working memory in accomplishing these tasks. Technology can assist with this if it is well designed– and distract if it is not.

This is because accuracy, precision and logic are not human traits. We are not computers! Creativity, problem-solving, social interaction and empathy are. The problem with inventing technologies to aid our pursuit of the former is that they can displace more natural ways of working, and have unintended side-effects. Some of these effects are relatively benign: frustration with a user interface which over-reports the available options, making it difficult to understand and use. Other effects are more serious: a ‘human’ error reading the cockpit instruments in an aircraft, or a control panel light indicating the status of a valve at a nuclear power plant. Increased complexity increases the difficulty of comprehension by humans: ‘to err’ may be human, but more often than not these systems are not designed with a fallible person in mind. We have come to exist in a technology-focused, machine-centred world. The role of humans has been to provide accurate input, and to troubleshoot where automation fails. But humans aren’t good at precision, or noticing small errors in machine readouts. We’re not very good at existing in such a world, and where problems occur they are blamed on the person: ‘human error’.

Norman argues for a more humane technology, ‘informating’ rather than ‘automating,’ and uses the concept of ‘hard’ vs ‘soft’ technology to illustrate this. Hard technology is designed with the requirements of the machine, rather than the human in mind. Soft technology refers to more flexible, information-rich systems which acknowledge human flexibility and intuition. Returning to an example from the built environment, air conditioning is a ‘hard’ technology: to provide comfort, it requires an accurate input of a desired temperature. It is difficult to work with the fuzzy descriptions of comfort which humans deal in, purely because of the number of variables at hand. The consequence of this is that it often doesn’t achieve its stated aim, and air-conditioned people are often uncomfortable. The overarching message is that more automation isn’t necessarily a good thing— or, indeed, a smart thing.

There is evidently a tension here in how we conceive of ‘smartness’. On the one hand, automation, independence and efficiency. On the other, assisting human decision-making.

Technology has the potential to support smartness, rather than de-skilling humans through automation, and HCI as a discipline is well-placed to support this. To understand and discuss this difference in more depth, it may be useful to situate it within the paradigms of HCI research. There are currently understood to be three (to four) distinct paradigms of work within HCI, with the terms "paradigm" and "wave" (as in, first wave, second wave) used interchangeably within HCI discourse (Blevis *et al.*, 2014). Each wave builds upon the understandings of the former, rather than replacing it.

First Wave

The first wave was concerned with "human factors": those design constraints which might be optimised to best fit the human to the machine. Work within this paradigm is characterised by empiricism, using quantitative methodologies and aiming to reduce user error. For example, given the task of designing a user interface for a nuclear power station, a first-wave practitioner of HCI would ask how best to evaluate the interface, with the goal of eliminating mistakes, making it safer or easier to use. The role of the user is passive, as a system operator only. It would be strange to ask that user how they would design the interface under a first wave framing, because users (being untrained in ergonomics or engineering) simply do not have the domain expertise to contribute to the design task.

By way of an example from a related discipline, faults in high voltage electrical networks may need to be corrected manually by an engineer, who must switch the isolator manually at a high voltage substation. The problem is, an engineer being called out at 4am is likely to make a mistake, perhaps setting the switchgear to the wrong position: the 'reflex' on realising this mistake is to return the isolator back to its original position. Although this switchgear is excellent at *making* a circuit, due to the high voltages (say, 11kV) involved, switching the isolator back to *break* it will result in a massive electrical arc. Engineers have died of severe burns from the arc flash, or in the cloud of high-temperature vaporised coolant. Anti-reflex operating handles were designed by the manufacturers of switch gear to reduce operational error and prevent accidents (HSE, 2002). The handles used to switch the isolator are now designed one-way: they need to be removed and rotated through 180° to switch the isolator back to its original position, introducing the necessary seconds of thinking time required for the engineer to realise that this would be a *very bad idea.* This is an example of a design intervention introduced to prevent human error, improving the interface between the man and the machine (I use the gendered term intentionally) to reduce costly mistakes in terms of both human life and operational downtime. It is very much of the school of thought which dominated first wave HCI design, too.

Second Wave

Moving from the “*design first, ask questions later”* approach of the first wave, towards the second wave researchers began to view people as situated in contexts where they interact with technology less as passive users but as active participants, as part of a move from “human factors” to “human actors”. People began to be seen as able to “*regulate and coordinate [their] behaviour, rather than being a passive element in a human-machine system*” (Bannon, 1991). Much of the focus of second wave HCI was in work contexts, with a recognition that people work as members of groups: the field of CSCW (Computer Supported Cooperative Work) has its origins in the second wave (as I will discuss in section 2.5.1) and Norman’s work on soft technology is also situated roughly within it. Users in the second wave were understood as information processors, coupled to the machines they are using (Harrison, Tatar and Sengers, 2007). The role of the interface, and therefore the HCI practitioner, is to optimise the transfer of information between the user’s brain and the machine, requiring an understanding of both. Cognitive science and psychology contributed a theoretical underpinning to second wave HCI, with a move away from the largely quantitative towards more qualitative methods (including participatory design) albeit with a strong emphasis on verifiability, generalisability and reproducible results.

Writing in *Scientific American* in 1991, Mark Weiser predicted the “disappearance” of technologies into the fabric of everyday life (Weiser, 1991). That said, academics and designers are not neutral actors and to some extent the prediction of this Wiserian vision has had a circular effect, promoting disappearance as design-goal. We have designed smaller, faster computers, and hidden them within our built environments: they have been intentionally (rather than passively) faded and blended into the architectural background. Further, as users of ‘calm’ technology, to a great extent the technologies that we do interact with have been normalised: we choose not to see the machine, it is ubiquitous to the point of mundanity. Yet, despite the many benefits which ubiquitous technology has brought, this vision of ‘calm’ computing is at odds with consequences of those same technologies to distract, other, malign, exclude and control. (Weiser and Brown, 2001) later reflected on some of these unintended consequences, including the power of technology to distract: “*Late at night, around 6am while falling asleep after twenty hours at the keyboard, the* *sensitive technologist can sometimes hear those 35 million web pages, 300 thousand hosts, and 90 million users shouting 'pay attention to me!'*" Calm computing has also been criticised for providing a kind of unsustainable "*omnipresent control*" (Jensen, Strengers, *et al.*, 2018) which requires devices to consume small amounts of energy at all times. Ubiquitous computing was motivated by a belief in the power of technology to aid human cognition, and in that respect it could be argued that it began as a second-wave vision, but the effects of this technology in turn required new ways of thinking and a new wave of HCI.

Third Wave

Third wave HCI arose partially as a response to the rise of ubiquitous computing in the early 2000s, and the resultant need to engage with the new kinds of human-machine interaction (and social complexity) which appeared as a result (Weiser and Brown, 2001). Especially outside of workplace contexts, research began to examine areas of human life including emotion, experience and culture (Bødker, 2006), with a corresponding shift in domain away from examining computers purely as cognition-aids, towards contexts such as recreation and the home. Third wave work often draws heavily from social science, moving away from the broadly positivist-postpositivist and objectivist methods and approaches of the first and second wave (Duarte and Baranauskas, 2016) towards social-constructivist and phenomenological standpoints.

Harrison, Tatar and Sengers (2007) designate this third paradigm the "phenomenological matrix", as it "*contains a variety of perspectives and approaches whose central metaphor is interaction as phenomenologically situated*". In practice, this means that the third wave engages with individuals through an array of varied perspectives and approaches, examining related phenomena. It is often underpinned by a philosophy of embodiment: humans as embodied actors, engaging with computer systems across a multitude of contexts. Third-wave work is not limited to the design of technologies or interfaces (though naturally this often features as an outcome, particularly within work published at the CHI conference), but looks at contexts and uses wicked problems including the environment, the economy, inequality, and society, as application domains. Areas where technology exists should be examined, asking how it is being used, and technologies should be introduced to new contexts, requiring careful study to understand their effects.

Fourth Wave

Further, some authors including Blevis *et al.* (2014) have written about an emerging fourth wave of HCI, though this is not well taken-up by the wider HCI community at present, and the definitions are not all in agreement. Blevis et al. discuss the fourth wave with an orientation towards teaching interaction design and note that while there is utility in tightly specifying these four waves for the purpose of discussing them, there is still a great deal of overlap between them. Nevertheless, Blevis designates this new paradigm the 'transdisciplinary design paradigm,' and distinguishes it from third wave work in that *"values, ethics, and politics are not the primary foci of these first three waves."* Accordingly, orientations such as social justice, environmental sustainability, feminisms, and so on, move away from being used as critical theories within the research approach, to become the central foci of fourth paradigm works. Fourth wave HCI is not politically- or values-neutral (in fact, it embraces the notion that technologies *cannot* be neutral) and draws on concepts such as marginalisation to broaden and expand understandings of how certain user groups are excluded or less well served than others. However, I would argue that some explicitly third wave work does centre social issues within its motivation and methodological approach: Shaowen Bardzell, for example, centres the changing epistemologies and design practice of third wave HCI in her manifesto for feminist HCI (Bardzell, 2010).

More recently, Comber *et al.* (2019) set these political and social justice implications of the 4^{th}-wave as just one factor within a '*post-interaction HCI*' framing, arguing that although consideration of these in HCI is not new, there is increasing urgency to the study of technologies which affect the wellbeing of individuals, relationships and societies. As a result of these at-scale considerations, there is less focus within HCI practice on designing direct interaction, and indeed a muddying of what "interaction" actually entails. Given the increasing invisibility of the computing technologies around us, our interaction with them is being designed in increasingly indirect ways. Data mining, analytics and advertising are examples: the data produced by our interaction has tremendous economic value, but also feeds algorithms which operate outside of our control. The temporal scales which these technologies operate on are invisible and imperceptible to us as humans: from the micro-second transactions of ultra-fast stock market trading, to the multi-century timescales of environmental sustainability.

2.2.2 New Notions of Smartness

Why consider HCI's waves, then? How does this all relate to smartness? Notions of smartness can be framed in relation to these waves, though it should be noted that the current state-of-the-art in HCI entertains multiple and conflicting definitions. Bearing this in mind, this typology is still of utility to categorise smartness: first wave HCI definitions of smartness could be considered to revolve around automation, making the machine itself smarter by limiting the actions humans need to contribute to enable its function. Yet, the benefits and deficits of this approach are reviewed by Bainbridge (1983), who notes that in automating away the operator of a system, the designers' oversights (the things which the system does not do) are then taken on by said operator. As such, notions of smartness which focus specifically and narrowly on automation are in danger of being technologically solutionist (Morozov, 2013).

Second wave smartness moves into distributed cognition and man-machine coupling, looking for ways to use technology to make the human smarter. The Active Badge Location System developed by Xerox in the early 1990s (Want *et al.*, 1992) might represent a second wave attempt to design technology within the office domain which seeks to address the problem of connecting people in the office by tracking their location. What, then, would a third wave definition of smartness look like? Perhaps an anti-solutionist (Blythe *et al.*, 2016) 'smartness' which enables and supports humans, considering their context and the situated actions they make within it? Although solutionism does not sit strongly within any particular wave of design thinking in HCI, recent work, for example (Pargman *et al.*, 2017) on design fictions, comes closer than ever to challenging it. I would situate Pargman's work at the boundary between the third wave and a notional fourth wave, per Blevis' definition.

In order to be able to re-define (or create new notions of) smartness in the built environment, it is necessary to turn to the values, ethics and politics orientations of the third (and the emerging fourth) wave in informing this. Environmental sustainability, for instance, can provide one lens through which to examine smartness, and this in turn sits as part of a wider picture which includes issues of governance, ethics, and values. Climate change cannot be tackled through environmental sustainability without considering these wider issues, as discussed in the social justice literature which I visit next.

2.3 Social Justice, Feminism and (S)HCI

Social justice has become a topic of significant interest in HCI, and is a motivating factor for this work. Fox *et al.* (2016) define social justice as being concerned with how individuals experience oppression, including how "*benefits, burdens, obligations, power, opportunity, and privilege have been equitably (or not) distributed within society and how to make a given context more equitable to various stakeholders given competing needs, goals, and resources.*" While it is this definition that I take up in this work, it is recognised that social justice is pluralistic in its conception[4]: there is "*no single, agreed-upon definition [of social justice], and no clear consensus on how to work towards it or to verify its achievement"* (Dombrowski, Harmon and Fox, 2016). In the previous section, I discussed how centring values and ethics is necessary to create a new "third-wave" understanding of smartness: social justice is one such ethical and moral framework, and one which underpins and guides this work.

Further, social justice and environmental sustainability are linked concepts, and the question of how we might use technology for social and environmental good, to address "*entrenched inequities and discrimination, as well as a shrugging acceptance of business-as-usual"* (Bates, Thomas, Remy, Friday, *et al.*, 2018) has captured the attention of researchers and led to calls for these issues to be raised to a higher profile within the CHI community. As Dombrowski, Harmon and Fox (2016) point out, a *just* sustainability cannot be approached without consideration of systemic inequities, and how these are reinforced or challenged through design, being "*inextricably tied up in, rather than isolated from, the politics of class, race, labor, economy, and geography*". They describe a social justice orientation to the practice of interaction design, sensitive "*to inequality and marginalized voices*" through six design foci: "*transformation, recognition, reciprocity, enablement, distribution, and accountability."*

Prior work in HCI has employed a social justice lens to examine a range of human rights issues and social and economic inequalities. Often, this work takes a labour perspective: e.g., examining delivery processes for gig-economy delivery couriers, a form of work which "*erode[s] workers' rights… whilst making use of discourses of empowerment (e.g. flexibility, entrepreneurial values)*" to present it as desirable (Bates *et al.*, 2020). Workers are a

[4] The term "social justice" has been weaponised online as a pejorative sentiment (similarly to 'politically correct') primarily in harassment of women and journalists (e.g., "social justice warrior"). That meaning is divorced from the work presented here, which is concerned with worker equality, fairness and inclusivity.

systemically marginalised group within the landscape of consumerist low-cost next or even same-day delivery processes, leading Bates and Friday (2018) to ask what the limits of this are and how they might be imposed, suggesting union action and government regulation, challenging consumerist viewpoints, and dismantling the broader social culture of consumerism, as three possible routes towards a more socially just delivery economy.

HCI does often exhibit a "*tendency to assume that technologies are able to solve complex issues*" (Strohmayer, Clamen and Laing, 2019). Far from being unique to social-justice-oriented HCI, similar observations have also been made in Sustainable HCI (Brynjarsdóttir *et al.*, 2012). Technologies designed without critical engagement can idly reproduce existing power structures, further marginalising people (and groups). Researchers can instead try to understand the challenges faced in designing and positioning technologies in relation to these broad societal issues[5]. Social justice work in HCI exemplifies how this can be approached with regards to marginalised populations. Steiger *et al.* (2021), for instance, studied online content moderators whose exposure to disturbing and often extreme online content pits their psychological and emotional wellbeing against the success of the online communities which they help to operate. By taking a social justice perspective on content moderation, their study examines how technological interventions might be evaluated, and suggest a range of organisational measures to reduce harm: clearly, these recommendations are just as important to worker wellbeing as the design of the content moderation technologies they use. In another example, home health aides are care workers placed with insufficient training into poorly paid, highly stressful situations, leading researchers to ask how we might design technologies to improve equity (Tseng *et al.*, 2020). The study surfaces the complexities and conflicts which arose from their design intervention, and makes visible the roles of other stakeholders in the home healthcare context, proving that rights issues are often more complex than they initially appear. Finally, sex workers' labour practices sit within a regulatory framework which perpetuates harm by criminalising safer ways of working (Strohmayer, Laing and Comber, 2017). Technology can be an empowering tool for social justice and harm-reduction with this population, when designed with sensitivity to the context and the "*social, historical, political, and legal circumstances*". In short, designing for and with marginalised populations requires reflection on, and awareness of, the wider societal context.

[5] Of course, it is entirely reasonable to do this through the design and evaluation of technologies, as I will discuss further in relation to my study methodology in Chapter 3.

Much of this work is motivated by feminist theory. Shaowen Bardzell's (2010) description of the state-of-the-art and conceptualization of a feminist HCI framework (the "*qualities of feminist interaction*") is highly cited within this space, offering a design perspective which accounts for "*agency, fulfilment, identity and the self, equity, empowerment, diversity, and social justice.*" Yet, a citation analysis of the work (Chivukula and Gray, 2020) indicates that many feminist HCI papers published at the CHI and DIS conferences use Bardzell's work to signpost the interaction between HCI and feminism, rather than leveraging or critically engaging with the framework offered. The authors argue there is *"potential for improvement of conceptual precision in future research and design outcomes."* Still, this suggests that much HCI work *does* draw from feminist perspectives without specifically taking up Bardzell's qualities. Bardzell argues that in order for a work to differentiate itself (e.g., from third wave HCI) as a specifically feminist HCI work, the design qualities must appear *"together in a critical mass*". However, given the observation of Chivukula and Gray that only a small minority of papers successfully engage with the qualities, I would argue that these are better placed as a specific evaluation framework or analytical lens, rather than for gatekeeping what *is* or *is not* feminist HCI. Work which draws from feminist theory or is motivated from a feminist perspective (as with this work) can usefully leverage these concepts in formulating a contribution, regardless of whether that contribution is then labelled 'feminist HCI'.

Feminism, given its "*potential to identify and disrupt hegemonic structures*" (Chivukula and Gray, 2020) is useful both as a framework by which to undertake research, and as a tool by which to critically examine power structures within ACM SIGCHI and the HCI community itself. Issues of social justice have come to the fore at CHI and have fed into feminist grassroots diversity and inclusion efforts at the conference itself (Strohmayer *et al.*, 2018). A feminist special interest group (SIG) brought together scholars to "*discuss issues of intersectional feminism in HCI"* (Bellini *et al.*, 2018), but in practice also provided a space for feminist solidarity in light of a controversial keynote presented at CHI that year[6] which many felt went against the principles of diversity, inclusion and social justice they had met to discuss.

[6] The Twitter hashtag #CHI2018 documents the depth of feeling (archive: https://archive.is/71VXq), perhaps best summarized by @CHINOSAUR: "*I FELL ASLEEP AND HAVE AWOKEN IN 1973 #CHI2018 #CHIVERSITY"*

Much of this work draws on the theory of intersectionality: the recognition that minority groups have been and continue to be marginalised by structures of power and societal norms through overlapping "*matrices of oppression*" (Rankin and Thomas, 2019) for example, gender, race, class, sexuality, and disability. Coined by legal scholar and civil rights advocate Kimberlé Crenshaw (1991), intersectionality builds on Black Feminism (Rankin, Thomas and Joseph, 2020) and uses the lens of human diversity to highlight and challenge ingrained power structures. It begins in the oppression of women of colour, for whom marginalisation on the basis of gender cannot be separated from marginalisation on the basis of race. *"Intersectionality invites reflection and deeper thought about what is happening in the world around us and why"* (Rankin, Thomas and Joseph, 2020). To challenge injustice, social justice research in HCI must involve researcher reflexivity: as such, my engagement with the subject matter below therefore incorporates reflection based on my own social positioning.

To challenge unjust or unsustainable power structures, we must first understand how they affect people. Social justice, sustainability, and intersectional feminism are linked concepts that can be utilised as a critical lens in designing technologies. Human Building Interaction and smart technology have thus far done little to engage with underrepresentation and inclusivity within the built environment. Instead of attempting to 'solve' the problem of inclusive HBI, we can build understandings of the context by applying the values and ethics of 'just' environmental sustainability. This dissertation therefore links to this ideological position to put underrepresentation at the core of smart building design and evaluation, to address an extant need for an inclusive, socially just and sustainable HBI agenda, and enable smarter buildings and smarter facilities management.

2.4 Smart Homes

In the following pages I will explore two areas within the HCI and built environment literature which purport to be "smart": smart homes (the domestic context) and smart buildings (non-domestic and workplace contexts). Within these, I aim to critique discourses of smartness, and highlight the wider values and ethics underpinning their use. HCI has extensively investigated smart homes, far more so than other kinds of 'smart' space: as such, consideration must be devoted to how these spaces factor into smartness, agency, and interaction of the kind I target through this work.

The smart home is perhaps the quintessential smart space. Researchers and practitioners first began to talk about 'smart houses' in earnest in the 1980s, and although home automation standards such as X10 had begun to emerge in the late 1970s (Driscoll Jr., 2003) the earliest examples emerged even before that. The December 1950 issue of *Popular Mechanics* featured the Jackson, Michigan home of hobbyist inventor Emil Mathias, whose six-room house incorporated 7,000 ft. of low-voltage wiring, connecting switches, relays and motors serving to automate myriad basic everyday tasks (Railton, 1950). Later, patents using the phrases "electric house" and "smart house" began to be filed in the mid 1980s, describing automation and control systems with microprocessors embedded into the fabric of residential buildings (Hermstein *et al.*, 1986; MacFadyen *et al.*, 1987; Launey *et al.*, 1989; Welty, 1989). Academic work from this era also focuses on the design and implementation of home automation systems (Hunt *et al.*, 1986). Automation could therefore be considered the design goal at the core of the first wave of smart home technologies. This section examines smart home research in an attempt to understand the gulf between the ideal and the reality of smart built spaces.

Aldrich (2003) defines a smart home as "*a residence equipped with computing and information technology which anticipates and responds to the needs of the occupants, working to promote their comfort, convenience, security and entertainment through the management of technology within the home and connections to the world beyond."* While previous work focused primarily on the technical details of the smart home, Aldrich's work sits within the first generation of research to apply a social science lens, concerned that the sociocultural factors of the smart home were being overlooked in the rush to develop home automation technologies. Aldrich argues that the foundation for smart homes, with the introduction of ICTs in the 1980s-90s opening up new possibilities for a plethora of services and devices, is to further increase the quality of life afforded by the domestic technology of the 20th century. Yet, while many of these technologies were sold as "time-saving" (e.g., the domestic washing machine) standards (of hygiene and cleanliness) rose as a result. Following the 1950s propaganda programme to return women to roles in the home following the second world war, much of this extra work was taken on by housewives in a form of forced domesticity (D'Ignazio and Klein, 2020). It is perhaps curious, then, that recent home technologies based on ICTs have often been marketed towards male consumers (Strengers, 2014).

More recently, Brush *et al.* (2011) found that smart home applications included heating automation, but also lighting, security and media systems. Work in the smart home genre has been diverse, though researchers have generally identified three broad themes emergent within the smart home literature: automation being a feature common across all of them. Balta-Ozkan *et al.* (2013) aggregate the themes from their systematic review into the categories of safety, energy management, and lifestyle support. Wilson *et al.* (2014) build on this by contributing three 'views' or 'grand narratives' within the smart home literature: functional; instrumental; and socio-technical. This is not the only framing, but is one of the more complete and others tend to loosely relate to it: e.g. (Jensen, Strengers, *et al.*, 2018) and (Strengers *et al.*, 2019) also provide categorisations which I examine in further detail in section 2.4.3.

In the *functional* smart home, home automation technologies offer myriad benefits to residents (described as "end-users") building on existing services to enhance the experience they provide, and solving a swathe of problems. These range from applications such as control of a range of systems (Lee and Zhang, 2005) e.g. TVs and kitchen appliances, to security, to assisted living technologies which aim to use technology to alleviate difficulties encountered in the home by occupants with disabilities, or enable older adults living with debilitating conditions such as dementia to maintain their independence (Chan *et al.*, 2008). This is perhaps the longest-lived vein of smart home research, matching closely with the field as-described by Allen (1996): "*The term 'Smart House' is commonly used to refer to a living or working environment, carefully constructed to assist people in carrying out required activities, using various technical assistive systems*".

Secondly, the *instrumental* smart home contains technologies for reducing energy use and increasing comfort, which often centre around home energy management systems (HEMS) (Schwartz *et al.*, 2014). "Smart metering" of resource supplies (gas/electricity/water) falls into this category, with early interventions generally based in persuasive technology design (Fogg, 1998) to nudge home-owners (who may or may not be the bill-payer) to reduce their energy usage (Knowles *et al.*, 2014). The narrative motivating these technologies, certainly within HCI, has been tightly bound to environmental sustainability: although this is often nebulous or badly-defined in published work (Pargman and Raghavan, 2014), has been criticised for narrowing our vision of sustainability (Brynjarsdóttir *et al.*, 2012), and of leaving homeowners with a feeling of 'helplessness' despite raising awareness of their environmental impact (Prost, Mattheiss and Tscheligi, 2015). Hargreaves and Wilson (2013) suggest that smart-metering technologies fundamentally benefit energy companies and policymakers over residents.

Finally, in the *socio-technical* smart home, the integration of digital devices into the household has not been led by some grand ideology but has instead “co-evolved” alongside society. It appears, given hindsight, that this is the closest vision to the lived-reality of homes today: as Harper notes in *The Connected Home* (Harper, 2011), the smart home has not materialised in the way that researchers of the 1990s and 2000s had imagined. Instead of designing and wiring ‘smart’ technologies into the electrical fabric of the home to automate away our every need, our homes instead host a range of ad-hoc smart devices which intertwine with our social practices, including smartphones, tablets, and laptops, which allow us to consume media and stay connected to family members. ‘Smart’ computer systems connect us together, helping us to maintain our family contacts and our social relationships (Taylor *et al.*, 2007): we have seen the positive effects of this first-hand during the 2020 Coronavirus pandemic.

Smart home research can alternately be viewed within the waves of HCI described in the first part of this chapter. While early work focused exclusively on the technological development of smart home software and devices, e.g. (Hunt *et al.*, 1986), more recent work emphasises the need for a human-focused view, bringing in concepts from psychology and sociology, and examining everyday lived experience. A review conducted by Desjardins *et al.* (2015) identified no less than seven different genres of domestically-situated research. Their review highlights the smart home genre’s central questions: “*What is a smart home?*” and “*How do people live in, maintain, and install a smart home?*” Research specifically about smart homes was found to occupy its own distinct sub-genre of research within HCI in the home, and while it does still share methodologies and motivations with work on technology in the wider home environment, it was found to focus more on the development of the technological aspects of smart homes, rather than “*eliciting peoples’ long-term lived experiences*”. This seems to indicate that, at least as of 2015, the focus of smart home research was still on home automation.

This critique of the smart home domain, that it focuses too much on technological development and not enough on the human, is not a new one. Taylor and Swan (2005) studied low-tech household systems of organisation, which are typically operated by and through a central matriarch: Mum. Calendars, notes, answering-machines, and “clutter bowls" are ad-hoc organising systems used to support the practices and social order of every-day family life. These systems are personalised, bespoke, and change over time, "*gradually adopted in homes in a piecemeal fashion.*" Indeed, the work by Neustaedter *et al.* (2009) on family calendar use as an organising tool demonstrates the challenges inherent in moving from a paper-based format to a technology-supported one, despite there being clear benefits to doing so[7].

These works demonstrate the human complexity of what HCI is actually trying to achieve in the smart home domain, and the inherent difficulties of drop-in solutions and one-size-fits-all product design. Harper (2011) asks why smart home technologies have not enjoyed wider uptake, but perhaps it should not have been all that surprising that pre-designed informational artefacts do not easily fit into the tailored, personalised, co-designed reality of home life. Human agency, or autonomy, is centre to this complexity. These works demonstrate the impact of human agency, and the need to pay attention to it, at least in the design of domestic environments. As Taylor and Swan (2005) suggest; "*Technological artifacts should be designed so they can be integrated with everyday routines and, critically, so that they provide new opportunities that do not restrict how people come to order their home lives*". This calls for a smart home paradigm which supports agency and control, rather than using automation to take the human out of the loop.

Therefore, as a framing for my critique of the smart home literature, I turn to 'agency', which I here define in terms of autonomy: the capacity of a human actor (or actors) to *make and act on their own decisions*, realised from their own considerations (which may be both emotional and/or rational) in how they act on the world around them and interact with other people, society, and computer systems. This can of course include decisions on what to abstract away or automate, as aligned with the vision of the smart home.

A similar argument is developed by Mennicken *et al.* (2014), which frames this balance of automation vs autonomy as "*Human-Home Collaboration".* Mennicken *et al.* criticise the use of "smart" as a marketing term for automation, instead defining the smart home as

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[7] It is a pity that the work on calendar organisation in HCI is rooted in studies of heterosexual and/or monogamous nuclear families (although this criticism could be applied widely in academia, as the little discussion that I was able to find on the topic is almost entirely journalistic). We could learn a lot, for example, by examining the appropriation of technologies like Google Calendar in polyamorous relationships (Kale, 2018): although never designed specifically for organising one's time with multiple partners, many find it indispensable in managing their plural relationships.

increasing comfort, but also enabling functionality which would be impossible without computing technologies. They argue that a re-framing of automation as collaboration is needed in balancing automation and the human need for control, suggesting that the smart home of the future might include "*capability to provide suggestions or simulations regarding different configurations*". While the smart home philosophy prioritises the outsourcing of menial tasks to machines (and machines are certainly good at some types of tasks) it is nevertheless an ideology which disguises the fact that computers cannot inherently understand the needs of the human user, who does not operate according to rational reasoning or protocol (Norman, 1993). Yet, while the goal that "*smart homes will collaborate with their inhabitants instead of only being controlled by them*" is a noble one, there remains an open question insofar as whether any computer system can yet be 'smart' enough to take part in any meaningful collaboration. Collaboration implies reciprocity and negotiation. A technological tool, however cunningly designed, is not necessarily able to function with the agency of a human collaborator.

In further examining the question of human agency in the smart home, I turn to prior work in the domain to discuss where it meets or fails this 'agency test': whether it allows for human agency within the context of automation, or whether it limits creativity by restricting how people integrate them into their everyday routines. I document through critique what is missing from these visions and through this tell the story of smart home research leading to today.

2.4.1 The Functional Smart Home: Assisted Living

I begin with the *functional* smart home, "*a way of better managing the demands of daily living through technology*" (Wilson, Hargreaves and Hauxwell-Baldwin, 2014), focusing in particular on the area of assisted living (or "supported living"). Assisted living smart home environments are designed to meet such users' perceived needs through a range of assistive technologies. In theory, such technologies enable people with disabilities to more fully participate in society, or assist people living with a diagnosis of dementia enabling them to live independently and avoid being taken into care (for example, by acting as a memory-aid or remote-alert monitoring system). 1998 saw the beginning of a research initiative to develop smart home technologies within the "Aware Home" facility at the Georgia Tech Broadband Institute Residential Laboratory (Kidd *et al.*, 1999). The project was primarily concerned with the design, prototyping and assessment of technologies for supporting older adults ('ageing in-place') and children with special needs. Given the recognised difficulties with studying people in their own homes (including changing practices and differences in behaviour) the Georgia Tech Aware Home aspired to provide an authentic setting for the interdisciplinary design, deployment and evaluation of new residential technologies, as a "living laboratory". The research and development of associated technologies seems to have been largely problem-focused, addressing problems relating to these three themes, such as assisting older adults with the use of medical devices. Further, the design of ubiquitous computing "building blocks" such as wireless pervasive sensing technologies provided a platform for the design of future interventions (Kientz *et al.*, 2008).

Living labs like this allow for experimentation and interaction design in a lived-in setting. It should be noted, however, that the scope of so-called living lab research has significantly broadened in the 20 years since the inception of this project, with Alavi *et al.* (2020) commenting on the "*rapid departure from the initial premises of living lab*," with now no less than five different trends of research now being conducted under this banner. In Alavi *et al.*'s taxonomy of living labs, the Aware Home would be classified as a "visited place": a "*real house where routine activities and interactions of everyday home life can be observed.*" Although the primary motivation for the development of these settings was to help provide a more realistic setting for research than the laboratory, there is a criticism that individuals moving into the home to take part in a study will be removed from both their own practices and habits, and from the urban area where their own "*daily individual and social activities*" take place, thus biasing their observed actions in unknown ways. Even a custom-built research facility has many factors marking it in separation to participants own homes, which proves a limitation to such studies. Individual autonomy and agency is very likely inhibited by the differing circumstances of the research setting. Changes to the space by residents are likely to be limited, even more so than in rented accommodation. This kind of research site is perhaps closer to a smart hotel than it is to a smart home.

The Ambient Kitchen (Olivier *et al.*, 2009; Pham *et al.*, 2012) was a research prototype based at Newcastle University's Culture Lab between 2008 and 2015. It explored the design of assisted-living technologies to support older adults living with early-stage dementia. A "*lab-based replication of a real kitchen,*" the Ambient Kitchen made use of loosely coupled sensor technologies to provide an environment for developing assistive solutions to prolong independent living. With RFID integrated into food containers (e.g. for sugar, oil, and salt) and long-range readers into the countertop, wireless accelerometers embedded into kitchen utensils, and a network of custom capacitive sensors integrated into the floor, the kitchen provided a data-rich site for the development of real-time activity recognition algorithms. A range of software support applications were built on top of this platform, including activity support systems for guiding users through complex activities such as making a cup of tea (Hoey *et al.*, 2011). The authors note that while the Kitchen is appropriate for evaluating the functional requirements of these technologies, the question of whether the technology is useful in practice can "*only really be answered by installing the technology in a range of real contexts.*"

In fact, many (though not all) of the smart home projects listed in a 2008 review (Chan *et al.*, 2008) appear to be prototype projects based in Universities or research institutions, rather than in individuals' homes. The authors reviewed smart home assistive technologies, describing the main targets for smart home assistive systems as "*improving comfort, dealing with medical rehabilitation, monitoring mobility and physiological parameters, and delivering therapy.*" Reflecting the ideology of the time, Chan *et al.* mark the difference between a set of discrete assistive devices and an "assistive smart home" as the *integration* of these devices into a holistic system which contributes to one or more of these targets. As we will see in the following section on the instrumented smart home, there is some overlap here in terms of types of systems envisioned: personal comfort continues to be a problem which smart home designers consider tractable (despite, perhaps, evidence to the contrary).

Chan *et al.* further discuss a number of challenges for the design of smart homes: from technical factors, to legal and ethical issues, to cost-effectiveness and uptake. Technical factors include the reliability of sensor systems and software, and standardisation on a common protocol to allow interoperability: while these issues are salient in the prototype development context of the research institution, they have not necessarily been major contributors to the lack of wider uptake. The legal and ethical issues, however (for example of practitioner liability in the event of malpractice) present more of a direct barrier to the implementation of the telemedicine agenda. The regulatory environments which Chan *et al.* describe are fragmented and differ wildly between countries, and the privacy of patients and their medical data remains a conundrum which continues to be cited in many smart home papers up to today, without apparent solution. Further, when a smart home system is presented as a medical intervention, this raises the question of who pays for it: private insurance companies are reticent to cover such interventions, which perhaps explains why many are still led by and confined to the research community, never really moving out of the research lab into mainstream acceptance and usage. While the authors discuss this in terms of the economic savings of delivering care at home rather than in hospital, such an argument does not demonstrate a strong link between the efficacy of remote medical assessments by a (human) medical practitioner, versus the perceived benefit provided by the installation of (automated) smart home assistive systems.

Neither does this paper deal with whether smart home systems are desirable for the envisioned end-users, other than through the vague design language of "meeting users' needs". Although participants in trial studies report a high level of personal satisfaction[8] with the developed systems, there is a gulf between the research context of these studies and their real-world deployment and use. It may be that many existing assisted living projects are grounded in technosolutionism (Morozov, 2013): inappropriately focused on designing solutions to discrete problems such as 'how can we extend the independent living ability of a person with dementia?' with the assumption that this must, always, be 'solved' through technology. Kellie Morrissey (2017) points out that such a design approach reduces its users to "*a set of deficits rather than a holistic person*" which dehumanises the people being designed for, and does nothing to reduce stigma. Health and social care is not a problem that can be solved by a single automated system, however carefully or intelligently designed: a range of other services are required, including adaptations to the building to improve physical accessibility, medical care, and a change in healthcare provision models. For this last item to occur in-practice, the efficacy of an intervention must be well demonstrated.

So, are assistive technology interventions on the scale of the home actually effective? A 2016 systematic review of assistive smart home technologies (Liu *et al.*, 2016) found that the level of technology-readiness for smart homes and home health monitoring technologies was still low, and that "*there is no evidence that smart homes and home health monitoring technologies help address disability prediction and health-related quality of life, or fall prevention.*" The authors began with a corpus of 1,863 papers, reduced to 48(!) following the

[8] An anecdote. In my own experience as a researcher, I worked for six months with Bristol University on the SPHERE project. One hundred smart home systems would be deployed to participating households in the general public, integrating various sensors into a holistic monitoring system. Participants were enthusiastic about the project. Despite researcher assurances to the contrary, it was generally perceived that these systems would 'help,' e.g. through the detection of falls: a feature entirely absent from this particular system. It left us with an ethical conundrum: participants generally believed what they wanted to about the system, and we were thus led to question how meaningfully they were really engaging with the process of informed consent.

application of inclusion/exclusion criteria: in short, peer-reviewed studies relevant to the complex needs of older adults, addressing smart home and home health monitoring technologies. Randomised controlled trials (RCTs) are used in medical research to provide clinical evidence for the efficacy of an intervention, and while Liu *et al.* (*ibid.*) found seven RCT studies on smart home technologies that met their inclusion criteria, the evidence was not conclusive. Although smart home technologies may help older adults maintain their physical and cognitive health and their activities of daily living, the evidence for the support of other conditions or disabilities was patchy at best. However, there is some evidence that assistive technologies can be effective for monitoring function, and cognitive and mental health. RCTs are only one way to evaluate a system, and reveal little about the real-world use and emergent behaviours that a qualitative study might uncover. Still, it is likely that HCI studies over-assert the impact of assistive technologies, and in that regard better empirical evidence can help to temper these claims.

This review indicates that there is clearly a problem with demonstrating the real-world efficacy of these systems, and in installing, setting up, and maintaining an assistive smart home. The vision far exceeds the reality, with a significant number of barriers to its realisation and adoption. Certainly, it appears that nothing in the smart home assistive technology sector has seen success or adoption on anything like the revolutionary scale of personal assistive devices like, say, the hearing aid. Or in another example, the assistance button, a miniature transmitter on a lanyard which "*can be worn around the neck or wrist, or carried in a pocket*" became one of the most popular assistive technology interventions and has been around since the 1980s (Chan *et al.*, 2008). The piecemeal adoption and slow accretion of smaller smart technologies has proven to be a more realistic model of uptake than the grand vision: in general, holistic smart homes do not exist. As we have seen from the works discussed in this section, such projects are almost always based in universities, their goals are idiosyncratic and diverse, and how they are implemented varies wildly. The lived reality of the smart home is very different to the research vision. This is no longer a question of novelty: smart home technologies are reaching their 40^{th} anniversary. It may be that interventions on the scale of small devices, following the connected home argument of (Harper, 2011), are inherently easier to adopt. Further, the practical everyday reality of what technologies people have at their disposal is very different to that of the vision: smart home solutions remain the domain of those with the fiscal power to purchase them, remaining beyond the means of people of lower economic status (which, in turn, correlates with factors such as gender and race).

It is here that the question of agency comes to the fore. While assisted living as a concept attempts to increase the agency of older adults, seeking to allow them to continue to live independently, this comes at a cost. Solutions imagined within the smart home vision always seem to lie in automating away agency: through outsourcing of health monitoring, and/or the release of personal data. There are multiple questions here of whether the definition of agency taken up in the smart home vision correlates with the definition of agency I presented earlier in this review. Is it simply that when a person's cognitive faculties degrade, their agency is deprioritised, treated as lesser? And what of choice? Are assistive technologies being forced upon older people in care settings who might prefer a caring *human* face? Are some assistive technologies even a money-saving exercise in this respect, a cost-cutting measure designed to ensure the ageing population causes less fiscal damage in the neoliberal economy? Evidently, the approach that has been taken has not been human-centred. Attempts that have been made to implement the assistive smart home vision have been technology-centric, about exploring what technology can do in terms of automation, and how to extend those boundaries, rather than focusing on the agency of the person who has to use it in the end.

2.4.2 The Instrumental Smart Home: HEMS and Environmental Sustainability

HEMS, Home Energy Management Systems, are perhaps the original smart home solution, with control of heating thermostats and lighting being a key feature. The key motivation behind this class of smart homes is environmental sustainability: Desjardins *et al.* (2015) found that concerns of sustainability cut across "*almost all genres of research*" within the smart home. Some of the works in the following section are illustrative of the wider discourse around HEMS: I describe these within the context of this section because they enable a wider understanding the underlying motivations of the topic.

HEMS are the culmination of almost 200 years of innovation in heating automation and control (or even 2,000 considering that one of the first home heating systems, the hypocaust, was invented by the Romans). I briefly discussed the history of air conditioning in the introduction, and although primitive BMS (Building Management Systems) appeared in non-domestic buildings before the 90s, homes generally would not have been equipped with anything more complex than the hot water thermostat, an invention dating back to the late 1800s (Newman, 1888). Earlier thermostatic control designs did exist, but did not see wide uptake (Ramsey, 1945). As with the *functional* smart home described above, the first such electronic control and monitoring systems began to appear in computing research by the mid 1980s, with Hunt *et al.* (1986) describing a system involving electricity-monitoring plug-socket adapters operating interlinked via powerline networking. There is still some appetite for the breed of instrumented automation systems described in that work, though in many respects it has aged about as well as the "master/slave" terminology used to delineate the sockets from the central hub: not well at all.

The modern progression towards low-cost and widely available sensing technologies enables the collection of diverse data streams, as in (Froehlich *et al.*, 2009; Gupta, Reynolds and Patel, 2010), allowing automation systems to base algorithms on real-time data from a range of sources. However, the automation of energy systems in the home does not in-isolation lead to energy savings. This realisation, that people are part of the picture, is not an especially modern one either. HEMS are fundamentally wound-up with the practices and behaviours which play a central role in consumption, with early interest in technologies which provide electronic feedback coming from the field of psychology. Motivated by the dual concerns of energy conservation and control over spending, any reduction in energy consumption is predicated on the necessity to first visualise and understand it. Houwelingen and Raaij (1989) designed a controlled experiment which ran from 1983 to 1985, combining energy feedback with the setting of goals to reduce average consumption of natural gas by 10 percent. Participants in the study achieved an average energy reduction of 12.3 percent. Yet, while some level of usage reduction continued following the study, perhaps due to habit-forming and greater awareness of appliance consumption, there appear to be several confounding factors in transforming a short-term reduction in energy into long-term positive change.

That is certainly not to say that there is no role for technology in energy use reduction. Garg and Bansal (1999), for example, demonstrated that the use of smart occupancy sensors in non-domestic buildings could reduce lighting energy consumption by a further 5% than PIR (passive infrared) sensors alone. This kind of incremental optimisation continues to be a theme in the energy technology literature, though as we will see has since been roundly criticised. In the smart home field specifically, Stephen Intille argued in 2002 that MIT's House_n: Home of the Future project would be designed to not "*use technology primarily to automatically control the environment but instead will help its occupants learn how to control* *the environment on their own*" (Intille, 2002). Intille discusses how important personal agency in the home is to peoples' psychological wellbeing, and the project's design goal of creating pervasive technologies which do not strip this away. This represents an early departure from the discourse on home automation, of optimisation and decision-making algorithms. House_n instead focused on presenting information about the house to users, leaving them "*in control of making decisions.*" Regrettably, the result manifests as a kind of Fordist mechanisation where the system tells the user what to do, the user themselves being treated as just another cog in the machine. This is not values-neutral: it may have the side-effect of leveraging control over the user through a ramping up of guilt in not doing what the system decides is sustainable. This is a problematic framing: the human-in-the-loop is treated as a rational resource manager (Strengers, 2011), capable of making better decisions than the computer with their better understanding of contextual detail.

In a further illustration of the phenomenon of the not-so-smart[9] device, products such as the Nest thermostat (Google, 2020), acquired by Google in 2014, might be considered to lie at the opposite end of the automation spectrum. The Nest integrates so-called 'intelligent' features, such as automatically scheduling heating of the home and detecting when occupants have left the household. An investigation by Yang and Newman (2013) revealed limitations to the learning algorithm which made changes to the heating schedule which were not desired by users, "*making erroneous assumptions about their intent*". While the interface of the Nest was enjoyable to use, the black-box nature of the system led to difficulty understanding, and therefore accurately controlling, the temperature of the home. To recall Don Norman, as discussed earlier in this chapter, the complexity of the system made it difficult to operate (Norman, 1993). Perhaps more concerningly, the Nest "*did not clearly lead to energy savings.*" While a strong focus on occupant comfort created a saleable product, it did not follow that automation features deliver a sustainable change in the occupants' energy use: there exists a tension between comfort and energy use in the very design of heating systems. Those occupants who did achieve energy savings made manual adjustments to the system, motivated by the novelty of the product and their own intrinsic motivations to reduce their energy demand. Further, Yang and Newman's participant

[9] The use of 'dumb' as the opposite of 'smart' is used often in the literature: present in (Norman, 1993), (Harper, 2011), and (Morozov, 2013). It should be warned that this can be considered an ableist slur. The inability to speak should not be conflated with a lack of intelligence by hearing/speaking people, nor should there be an inherent value judgement that intelligence is connected to the ability to express via spoken word.

recruitment *(ibid.)* revealed a significant gender imbalance in the users of such products: only one of the 19 participants was female, and the authors had significant difficulty finding women who had purchased the Nest. This is indicative of an existing and well-known bias in home energy management (Strengers, 2011) towards male users who are relatively affluent (given the cost of the device), generally have a high level of technical skill, and are enthusiasts for new technology. Yet, the approach of the Nest may not in-and-of-itself be fruitless: the PreHeat system developed by Scott *et al.* (2011), much like the Google Nest, also uses occupancy detection to build predictive routines of heating. In that study, the authors found that their technology reduced gas usage between 8 and 18%: though it should be noted that this study was more limited in scope with fewer participants.

Persuasive energy feedback in HCI originally became a theme in the mid-2000s, with papers often utilizing the theoretical underpinning of B.J. Fogg's theory of persuasive computers (Fogg, 1998), who referred to the budding area of computers as persuasive technologies (CAPT) as "captology." Others take inspiration from Blevis' call to include sustainability as a central tenet of interaction design (Blevis, 2007): encouraging designers to think about renewal and reuse over the current paradigm of invention and disposal which encourages the waste and rapid obsolescence of IT products. By 2010, roughly half of all persuasive technology papers within Sustainable HCI rooted their investigations and/or design processes in the framework provided by Fogg, as found by DiSalvo *et al.* (2010). DiSalvo *et al.* report that "*within this genre, the standard approach is to design systems that attempt to convince users to behave in a more sustainable way.*" One such early project (Bång, Torstensson and Katzeff, 2006; Gustafsson and Bång, 2008), investigated personal energy consumption within the home through the design of persuasive computer games. The early PowerHouse game design (Bång, Torstensson and Katzeff, 2006) appears to be entirely virtual, a PC computer game, taking an educational approach to energy awareness with an interface obviously inspired by Maxis' *The Sims.* The later Power Agent game described in (Gustafsson and Bång, 2008) is a pervasive game, connecting the energy goals within the game to real-world energy saving actions monitored by automatic-meter-reading (AMR) technology. The experiment was set up as a competition, with a number of families competing to lower their real-world energy consumption to 'win' the game. Although participants were able to reduce their consumption over the game period, the short-term nature of this type of intervention exposes one of the major difficulties in persuasive design, the authors noting that "*We have not been able to see any long terms effects of our approach;*

energy consumption returns to normal a few weeks after the game sessions." Persuasion to change a given behaviour often does not 'stick'.

Eco-feedback (sometimes called 'eco-accounting') is another HEMS-related area of research which leverages HCI's existing expertise in data processing and visualisation to produce interfaces which display information on energy use to end-users. Early work from Jensen (2003) at the Danish Building and Urban Research (DBUR) group shows that energy meters used in-isolation do not make any significant difference. Jensen posits that benchmarks and visualisations are also needed in order to understand consumption. This has been a staple design requirement of HEMS, leading to investigation of intuitive ways of displaying information: such as through the power-aware cord (Gustafsson and Gyllenswärd, 2005), a power strip that uses electroluminescent wires to visualise the real-time electricity consumption of appliances connected to it, and Bartram *et al.* (2011) who explore the use of an energy-reactive visual artwork, an 'ambient canvas' which visualises energy use beyond the bar-chart. The effects of provision of energy feedback were investigated by Schwartz *et al.* (2013), asking what people do with such feedback in everyday life: how it is appropriated and how it informs practices. Their study involved the deployment of a HEMS into 7 households, including a network of point-sensing power monitors connected to appliances, and a visualisation package delivered through the homes' TVs. Householders developed their understandings of energy use and built up a competence in managing the consumption of their appliances: a skill which the authors term *energy literacy*. One criticism of this approach might be that an individual may need some intrinsic (e.g. their sense of justice around ecological issues) or extrinsic (e.g. being the bill-payer) motivation in order to fully engage with such a system, and develop the energy literacy required to transform the feedback from the HEMS into behavioural action.

Various other psychological approaches to persuasion have been investigated in HCI, drawing from a rich background of research in behavioural science. Such attempts have been connected to psychological models in an effort to promote pro-environmental behaviour (Froehlich, Findlater and Landay, 2010). Other work (Riche, Dodge and Metoyer, 2010) outlines a three-stage approach for behavioural change: raising awareness, informing complex change, and maintaining sustainable routines. Noticing that much early work on persuasion in HCI relied on positive reinforcement, Kirman *et al.* (2010) created a design concept (were it published later they may have termed it a 'design fiction') which instead issues negative reinforcement in the form of punishment for bad environmental behaviour.

The Nabaztag (Violet, 2009) was a robotic rabbit device, one of the first generation of always-connected IoT devices, intended to relate internet content through a discrete and personable interface. The *Nag-baztag*, as imagined by Kirman *et al. (ibid.)*, would monitor home energy use through sensors and metering devices, and complain if the user uses too much energy: the idea being that the user will work to avoid the negative stimulus of being 'nagged' by the rabbit. Further, if the user persists in their bad behaviour, the rabbit will issue a series of graded punishments, being connected to actuators which allow it to entirely turn off various kitchen appliances, disallowing their use. The concept captured the imaginations of HCI researchers, demonstrating that HEMS need not always be faceless, disembodied computer systems or tablet displays: more humanistic and fun designs are possible.

Yet, Brynjarsdóttir *et al.* (2012) bring a major criticism of persuasion within sustainable HCI. The authors argue that persuasion is a modernist enterprise: modernism being the 20th Century philosophy which posits that humans can and should change the world for the better (i.e. "make progress") through knowledge. Persuasive technology shifted the discourse in achieving energy reductions from the optimisation of automated systems towards the optimisation of human behaviour. But this is still reductive: a limited framing and "*narrowing of vision*" which results in a reduced scope and understanding of what can be addressed as 'sustainability' by HCI, and further "*places technologies incorrectly as objective arbiters over more complex issues of sustainability*". Such a framing conflates sustainability with resource minimisation/optimisation, a much more tractable problem which can feasibly be solved through data-gathering and automation. Individual consumer behaviours become the focus, and designed solutions become commercial products which offer an energy saving, the investment perhaps even paying itself back over the product lifetime. The authors urge HCI designers to move "*beyond the individual,*" instead examining wider issues such as policy reform, and the interactions between wider groups, organisations, and governments: to work at-scale, as Dourish (2010) put it.

Home energy management system designs continue to experience difficulty against this challenge. Brynjarsdóttir *et al.*'s paper had fallout: after 2012, the ACM digital library shows that the rate of growth in persuasive HCI research flat-lined for 4 years, before picking up again in 2016. Yet, the modernist criticism remains a valid one: effort is still spent solving artificial problems. Rather than designing systems which achieve a 5% reduction in air-conditioning use, could we just open the windows instead, alleviating the need for air-conditioning entirely? Further, per (Strengers, 2011), the smart home concept is still targeted very much towards middle and upper-middle class householders, who are simply the most likely consumer group to buy smart home products. "*The fact that disadvantaged social groups have limited means (including financial, physical or educational) to interact with these systems needs to be analysed further*" (Balta-Ozkan et al., 2013). What might a smart home look like for people in social housing?

In moving beyond the individual (and the wealthy), to a more collective view of energy usage, Tawanna Dillahunt and Jennifer Mankoff have examined social communication around HEMS in renter communities in the U.S., both in terms of the social tensions and conflicts within the landlord-tenant relationship (Dillahunt, Mankoff and Paulos, 2010), and how this affects engagement in energy conservation behaviours (Dillahunt and Mankoff, 2014). In their 2014 work, the researchers deployed a community HEMS which visualised energy usage comparative to other households. Households in this study were of mixed to low income, and one of the two apartment buildings was rented to lower-income tenants whose electricity costs were included in the rent. While previous interventions have included a social or competitive aspect, this work acknowledges the wider social context and how networks of householders interact in an energy-saving context. Within the study, the more affluent community appeared to be tighter-knit, whereas the lower-income community experienced considerably less cohesion. The authors hypothesise that "*issues of trust and length of residence may have contributed to a lack of social engagement around our application".* While more affluent residents generally engaged better, using the tablet provided by the researchers as a HEMS interface as-intended (engaging with community energy usage, e.g. by checking the leaderboard), lower-income residents used it for job-hunting, or entertaining the children. Social comparisons of energy use relied on contextual knowledge about the building, which the less-cohesive community had less opportunity to build. This paper demonstrates a different way of 'doing' HEMS and smart homes, which deviates from the dominant narrative of smart systems purchased by energy-conscious (male) consumers. The HEMS-instrumented smart home of (Wilson, Hargreaves and Hauxwell-Baldwin, 2014) is evidently influenced by class factors. In a smart home paradigm where the responsibility for energy use is borne by the individual, to be able to fully consider one's energy use relies on the class-privileges of time and money.

Hanna Hasselqvist's work with Swedish housing co-operatives investigates how various stakeholders can share responsibility for energy use. She discusses how we might account for such shared responsibility in design, with energy managers and interested amateurs in (Hasselqvist, Bogdan and Kis, 2016) and with a wider group including consultancies and utility companies in (Hasselqvist and Eriksson, 2018). The diverse stakeholder engagement approach presents a novel alternative to the energy feedback technologies discussed above and, like Dillahunt's work, positions energy as a collective responsibility rather than an individual one. In (Hasselqvist, Bogdan and Kis, 2016), the authors produced an app designed to support peer-learning within communities of volunteer 'amateur energy managers' in Stockholm, and with professional energy managers whose expertise is essential in planning energy-saving interventions and actions. Within the app, it is possible to view energy data from the co-operative building, and to annotate it with the actions taken to reduce energy usage. The authors state that "*linking energy data to actions is not only to support peer learning between energy managers in different cooperatives, but also to support learning within a cooperative when energy managers and other people in the board leave and are replaced by new members.*" Hasselqvist points out that the core focus of eco-feedback technologies has been electricity, which she argues is a consequence of the focus on individuals: it is a factor which individuals are perceived (at least by HCI researchers) to be in control of. If considering electricity-use in isolation is reductionist (per Brynjarsdóttir *et al.* (2012)), Hasselqvist focuses on the wider actions (including one-time actions such as renovation) which can be taken to reduce energy usage, and in the context of housing co-operatives this must be done at the whole-building/community level. In some ways, shifting this focus from the household level to the building level has parallels with the management of non-domestic buildings such as offices, and illustrates both the opportunity for consideration of wider energy factors and the limits of our individual ability to regulate energy use at-scale.

We must also consider how the language of energy can be difficult for users of home energy systems. After all, a kilowatt-hour to the lay person is just a unit, and is meaningless without some comparative measure of the work done. Fischer *et al.* (2016) explored how the practices of professional home-energy advisors might be augmented with environmental sensor technologies, allowing "*insights into the domestic environment (temperature, humidity, etc.)*". Yet, the professional does not– cannot– work in isolation. The authors demonstrate how sensemaking of collected sensor data occurs through interaction between the client, who has specialised knowledge of the practices and processes of their home, and the energy advisor, who has the professional experience to accurately interpret this data. They term the practice of sense-making "data work" and outline its phases: from planning the sensor deployment; interpreting the data; to drawing conclusions and proposing solutions. Although sensor data allowed the professionals to increase the value of the advice they provided, the authors are clear that the data work is a collaborative practice which establishes "*what the data is really all about and what should really be done in response.*" The homeowner cannot meaningfully be left out of the loop because the data is *indexical*: it depends on context which only they can provide. This is further explored by Tolmie et al. (2016) who describe how participants articulate understandings of their everyday interactions as captured through sensor data. The authors demonstrate that the reverse case is also true: "*personal data […] is opaque when considered in isolation,*" without the necessary context. This challenges often-cited privacy concerns in sensor data capture and big data analytics, as the data became illegible when stripped of its context.

Thermal comfort itself sits in tension with energy usage: there is a reason that we have been encouraged to 'turn down the thermostat' to save energy for more than fifty years, as a October 1973 article in the New York Times entitled "*Nixon Asks Householders to Save Heat by Lowering Thermostat 4 Degrees*" (Cowan, 1973) demonstrates. While in that instance America and the west faced a scarcity of supply due to the embargoes of the 1973 oil crisis, today we seek to reduce energy use to limit our abundant greenhouse gas emissions. Yet, as Nicol and Humphreys (2002) argue, designers of standards had not historically "*seen it as part of their task to consider sustainability,*" though thankfully progress has been made in the last 20 years with new standards and certifications such as BREAAM (BRE, 2020). Nicol and Humphreys suggest an adaptive model of thermal comfort, in which occupants have the ability to make changes to their environment to maintain their own comfort, rather than tightly specifying the thermal conditions of the building: a process which may use energy-intensive technologies such as air conditioning to create uniform environments.

Critical of the traditional 'comfort-as-a-product' approach, Clear *et al.* (2014) examined the role of HCI in creating a transition towards such an adaptive approach, including how existing mechanically heated and cooled buildings might be retrofitted, and how occupant expectations of uniformly conditioned environments might be addressed. Their study focuses on the residential context of University halls in northern England, where heat is provided as part of the infrastructure in a similar manner to that of Hasselqvist *et al.*'s housing co-operatives. The manually controlled thermostatic radiator valves in students' rooms were replaced with wireless motorised valves, and the room temperature was automatically maintained within a temperature zone. This temperature zone was gradually decreased towards a 16˚C minimum by a fraction of a degree each day, requiring participants to press a 'make it warmer' button to boost the temperature by up to 3˚C instead of maintaining it uniformly. Changing the practices of thermal comfort resulted in a rise in temporary discomfort, but also reduced unsustainable practices such as opening the window to let the heat out, and promoted the use of heavier clothing to maintain comfort instead of heating the environment. Clear and colleagues argue that the transition into adult life represented by a move into University halls represents an ideal point to change expectations around thermal comfort at home.

It is a fact that thermal comfort is subjective: people experience the sensation of temperature differently, and this fact supports the argument for personalised and adaptive rather than uniform measures of comfort. Murphy (2006) argues that the standardised comfort of the building machine requires a standardised body: indeed, a white, male, and abled body[10]. Murphy unpicks the environment-chamber experiments which were used to construct the 'comfort-zone chart' of the early thermal comfort standards, their research participants being young, college-age white men: "*not just any human bodies but the bodies of trustworthy engineers trained in rationality.*" The bias inherent in considering that particular form and configuration of human body to represent the average 'standardised' human was invisible within the white, male office culture of the twentieth century: or invisible at least to those with the ability and power to change it. "*The humanist notion of universal comfort implicit in ventilation standards was in practice an environmental marker of a historically particular, racialized class privilege.*" And, as we learn from (Strengers, 2014), the biases of the twentieth century continue to be reflected in the smart technologies of the twenty-first. The 1938 ASHVE standard developed from this research later made its way into the ASHRAE standard 55 in 1966, which continues to be revised and applied to this day. Further demonstrating that women's comfort remains a problem, Karjalainen (2007) highlights that women are more sensitive to deviations in temperature, and generally prefer a higher temperature than their male colleagues. In contrast to the 1938 ASHVE studies, Karjalainen recommends that "*because females are more critical of thermal environments in real-life situations than males, female subjects should primarily be used in field studies on thermal comfort.*" While better listening to women's voices can only be a positive thing for

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[10] I would add 'cisgender' to this list! I would love to see a large-scale study of thermal comfort among trans and non-binary people, though it might be difficult to find a representative sample size.

thermal comfort research, it does lead me to question whether this might lead to research which views women as research subjects first, and people second.

So, what of other bodies? Bodies which are not white, male and abled? Germaine Irwin (2017b) considers the design of smart home energy interfaces for people with a cancer diagnosis or menopausal symptoms: conditions characterised by hot flashes and chills, with a strong effect on perception of temperature and therefore personal comfort. A universalised thermal comfort is simply not possible for these participants, who "*discussed the difficulty in setting a home temperature that is comfortable for everyone in the house*" via the thermostat, instead utilising adaptive actions: changing their level of clothing, taking a shower, or even *"putting their head in the freezer."* This preliminary work led to a questionnaire study of 136 households (Irwin, 2017a), women being the primary respondents. Irwin suggests that HEMS might be made more responsive to the needs of these users through the gathering of personal temperature data (such as through an ear-worn personal thermometer) or by integrating voice activation technology (such as through Amazon's Alexa) into the control system. However, the question of collective comfort (whether others in the multiple-occupancy household would also be comfortable) is not engaged with in this work, nor are the potentially increased energy costs incurred in regulating the environment tightly. Irwin's design conclusions are drawn are around automation, of ways in which the thermal comfort of individuals with health concerns could be integrated into the system. However, in my opinion, this work can also be read as a statement that there is no such thing as universal automated thermal comfort.

In this section, we have learned how the instrumental smart home has its roots in the early thermostat technologies of the twentieth century, and how smart home automation of these systems is a logical next step in the development of home heating and energy technologies. However, automation in-isolation does not equate to sustainability, as our energy use is fundamentally interlinked with our practices and behaviours. Systems and automation can make approximations of our behaviours through, for example, occupancy prediction, but may be insufficient in producing real-world energy savings. Instead, the focus within HCI has shifted: first towards improving the provision of information to energy users through eco-feedback technologies, and then (following criticism of its focus on the individual) away to wider, 3rd or even 4th wave HCI considerations of values and contexts beyond the white, middle-class, male consumers who typically engage with the economy of smart home devices. Towards the end of the last decade, we have begun to see energy use as a shared responsibility, and have begun to investigate how it can be meaningfully made sense of in a collaborative process. In terms of agency, we can think of this as moving away from a focus on the individual to collective forms of decision making. There appears, though, to remain an open question as to how shared, rather than individual responsibility might be nurtured in creating sustainable change.

2.4.3 The Socio-Technical Smart Home

My final consideration within the domestic context is of the *socio-technical* smart home (Wilson, Hargreaves and Hauxwell-Baldwin, 2014), which demonstrates a form of smartness which has "co-evolved" alongside society as opposed to being explicitly designed: just "*the next wave of development in the ongoing electrification and digitalisation of everyday life*". Wilson and colleagues note that this third perspective emerges as a distinct theme alongside the functional and instrumental genres that dominate the literature, with an underlying assertion that the development of smart homes and associated technology is dependent on changes and trends occurring in wider society. In a paradigm where smartness is not 'designed,' from where does it arise? And what are the ways in which our agency as occupants operate?

One potential answer is given by Taylor *et al.* (2007), who view the home "*as already smart, smart not in terms of technology, but in terms of how people conduct their lives in the home*". Smartness here is not 'built in' to the home, it is a property arising from the people who inhabit it. This argument draws a disconnect between the 'house,' a space which can be augmented with technology, and the home, a place constructed through the practices and lived experiences of those who make it such[11]. The authors note that the appeal of smart homes to the wider population is narrow, implying that the practice of 'making' a smart home is one with limited appeal. As such, the technologies envisioned in this work function as aids to the practice of homemaking, focusing on occupants' "*intelligent*" use of surfaces in the home such as notice boards and fridge doors. By way of example, it is a common practice for families to annotate the surface of the fridge with magnets, documents and post-its, using it as a noticeboard. Interventions can take the form of digital augmentations to these human practices, e.g. fridge magnets which glow according to a schedule or allow voice recordings: these become a simple way of augmenting home organisation activities.

[11] The authors do not invoke the language of 'space' and 'place', as discussed in section 2.5.1, though one could draw parallels here in terms of how the home as a place is socially constructed.

Similarly, a tablet interface mimics the kinds of notes left on a kitchen table within the family home, adding remote note-making functionality to extend existing low-tech note-leaving practices in new, playful and sentimental ways. Taylor *et al.*'s construction here frames the human occupants as the 'smart' actors in the 'smart home', in contrast to other work which frames smartness as automation. The vision of automation-as-smartness is rejected in favour of a more nuanced consideration of the almost symbiotic role of the human and the machine. The kinds of smartness built-in to Taylor *et al.*'s interventions are not about rationality or problem-solving: they are about supporting thoughtfulness, tenderness and familial relationships, and about *"offering people in homes further resources to act and think*" rather than attempting to steer their behaviours or take responsibility (and control) over household functions.

Another technology designed to fit into the "*existing structure of users' everyday life"* is BinCam (Thieme *et al.*, 2012). The design of this study follows the persuasive approach discussed above in 2.4.2, attempting to improve awareness and allow for re-evaluation of recycling behaviours. The designed intervention, a camera-augmented rubbish bin which posts photographs of its contents to Facebook, has parallels with Taylor *et al.*'s smart objects. It is a digital augmentation of the existing human practice of recycling. The prototype bins used in the study incorporate a smartphone embedded in the lid to take photos of participants' refuse. A Facebook app was developed by the team (to provide social surveillance as part of their persuasive approach) which integrated neatly into participants existing social media routines. The authors found as a result that "*all participants appreciated that using the BinCam bin was effortless and that they didn't have to change their routine.*" Of course, the criticisms outlined above in my examination of persuasive technologies also apply to this research: the focus on the individual, the reduction of a complex problem into a tractable one. In the opening pages of *"To Save Everything, Click Here",* Morozov (2013) lampoons the technosolutionism evident in BinCam. The gamification elements in particular receive considerable opprobrium: "*whoever wins the most bars and tree leaves, wins. Mission accomplished; planet saved!"* Although Morozov raises questions on the ethics of a social-media approach to garbage[12], neither he nor the BinCam authors engage with the question of how our over-reliance on plastic as a society might be approached: the problem is easier to address when constrained. Is the embodied

[12] The use of low-paid Amazon Mechanical Turk workers to classify images is something I share a strong ethical objection to.

energy contained within the smartphone bin-cam even cancelled out by the positive impact of the intervention on recycling? I would suspect that the answer is ‘no’. One might even ask whether the agency one has to choose to send plastic to landfill should be limited by such a technology. Mark Blythe notes the consumerist viewpoint inherent in these criticisms, pointing out that: “*as a research prototype BinCam was all the more interesting because it generated such a furious backlash*” (Blythe, 2014). In being provoked, Morozov misses the value of this research as a provocation.

Yet, smart home technologies can still be social, and can enhance and enrich our environments with fewer ethical conundrums. The study by Woodruff *et al.* (2007) of Orthodox Jewish families’ use of home automation for religious purposes demonstrates how automation technologies can fit in with and enhance social and spiritual practices. Home automation here becomes a way for families to adhere to the requirements of the Sabbath as outlined in Jewish law, while enabling the schedules and practices of family life to occur. Woodruff et al. report that the associated restrictions around the use of technology on the Sabbath day arise from modern rabbinical interpretations of the *halacha*, or religious law, and that “*one of the most significant modern interpretations is that it is forbidden to turn electrical devices on or off.”* Home automation systems like *X10* lend themselves to this purpose, enabling a wide range of timed and sensor-based mechanisations and making schedule-based changes (e.g. to lighting) in the home possible despite the necessity to refrain from interaction with devices. It is interesting that while these families used a high degree of home automation, they weren’t necessarily tech savvy: a middle actor, the systems developer with whom clients had a well-established relationship, was often used as an interface to the system. Although these examples are rooted strongly in automation, these families exhibit very different motivations to the stereotypical smart home consumer, the image of whom I have discussed above. End-goals for the use of the technology also varied: reflecting the goals of the Sabbath, participants ceded control to automation technology on these days, allowing them to focus on the important parts of the day. Surrender of control was seen as desirable and a valuable religious lesson, even where errors in the automation resulted in inconvenience. This narrative varies from the usual design assumptions of smart home technologies in that agency is voluntarily ceded to the machine, as opposed to being an undesirable side-effect of automation as in e.g. (Intille, 2002). Further, there is an acknowledged opportunity for fallibility in that it can still be okay if the system fails. As one participant puts it: “*if it works it works, and if it doesn’t that’s what*

God wants." Smart home systems in other contexts are also fallible, but this study is unique in that the system's fallibility can be treated as an opportunity rather than a failure. The implication for agency is that a user of a system may have strong reasons for wanting to leave control of the house to a computer system, but that this reasoning comes in forms which are unlikely to be expected by traditionalist smart home systems designers.

Framing smart home development through the lens of desire can help us understand how these sociotechnical systems evolve over time. Jensen *et al.* (2018) argue that it is the experiences which a technology gives that are valued, rather than the technology itself. Using the framing of 'desiderata' (a concept or set of strategies which help to understand desires embedded in design) Jensen *et al.* categorise smart homes into three 'personas': the helper, the optimiser and the hedonist. I note that the first two of these broadly align with Wilson *et al.*'s (2014) functional and instrumental smart home typologies: the helper assists "*households to control appliance and housing features and functionality,*" and the optimiser "*is characterised by its desired ability to use energy more efficiently*" (Jensen, Strengers, *et al.*, 2018, pp. 4–6). The hedonistic smart home on the other hand is a "*desirable and beautiful living space*" which creates "*aesthetic experiences that are nourishing, personal, and pleasurable.*" Such homes demonstrate householders' individuality, creating unique experiences and beautiful atmospheres, and nourish occupants by "*making everyday life more convenient, comfortable and secure*" (Jensen, Strengers, *et al.*, 2018, pp. 7–8). These smart home experiences are highly personalised: while there seems to be categories of practice which technologies can support (e.g. dimming lighting at bedtime), these functionalities were very much designed by the study participants around their unique practices.

Much like (Harper, 2011) Jensen and colleagues' work outlines a type of smart home consisting of a plethora of individual (though often interoperable) smart home products which are designed to be desirable, but highlights how bringing these always-on technologies into the home (e.g. Amazon Alexa or Google speakers, Phillips Hue lighting, etc) introduces new energy draws which accumulate in an organic way over time, and introduce new power draws which conspire to "*undermine [householders'] desire to save energy.*" Jensen *et al.* place responsibility for this partly on product designers, "*as they tend to inscribe visions into the design of these technologies [...] without much consideration of possible energy implications,*" highlighting a necessity to challenge embedded expectations of "*comfort, convenience and cleanliness*" within the smart home vision. If this sounds familiar, it may be because it harkens back to Aldrich's argument (Aldrich, 2003) that smart homes extend the desirable 20th Century vision of labour-saving and comfort through home automation, as I previously outlined when I began this discussion of smart homes in the prior pages. Smart homes in this respect could easily be seen as the 'natural' sociotechnical evolution of this (energy-intensive) vision. Yet, this raises a question: what agency do smart home users truly have in terms of regulating their energy use, if energy use is not an explicit consideration of the designers and vendors of these technologies?

Whether designed-in or naturally evolved, smart home technologies also reflect the gendered biases of our society (Strengers *et al.*, 2019). Drawing on a background of feminist and sustainable HCI (Rode 2011, Rode and Poole 2018) and prior work by the lead author (Strengers, 2011), this 2019 work argues that "*prior work in HCI has foregrounded the tech-oriented masculine guru in smart home research.*" This shares with Jensen *et al.* (2018) a centring of the responsibility of smart home designers, though in this case for gendered design: gender bias in technology is a result of not considering gender in design. Jensen *et al.*'s personas (helper, optimiser, hedonist) are closely interrelated with the categories of "*protection, productivity and pleasure*" which Strengers *et al.* (2019) adopt from Intel's ambient computing vision for the home. And echoing Taylor *et al.* (2007), many of the 'smart' technologies in Strengers *et al.*'s study support the practices of householders: keeping the house safe and securing it from intruders; providing small conveniences such as seeing who's at the front door; and creating 'ambience' by augmenting the sensory experience of the home through 'smart' lighting. In these cases, one could again argue that it is not the technology itself that is smart, but the householders who have gained benefit from integrating it into their practices (particularly as Strengers *et al.* discuss how the maintenance and setup of these technologies is in-and-of itself a time-consuming labour activity, albeit one which can be pleasurable).

Critically, however, this work highlights how setting up a smart home is a gendered activity. Much of the work of configuring these systems is taken on by 'the man of the house', allowing *"men in our study to express a form of care-full masculinity, in which technology (a traditionally masculinized domain) was applied to practices of care (traditionally feminized).*" This can be framed as a kind of *digital housekeeping* in requiring time to maintain the technological ecosystem of the home, but also as an enjoyable geeky practice of *pottering*, a source of pleasure derived (typically by men) in setting up technology. The gender-roles of the smart home are re-enforced by the performance of these practices, and the authors point out that "*while masculinity remains closely tied to demonstrating prowess with technology, men are more likely to continue playing this role, meanwhile women (whose performance of femininity is not commonly tied to technology proficiency) are likely to have less tolerance and time for 'playing around' with tech.*" Different approaches to smart home device programming, for example using "*if-this-then-that*" triggers (Ur *et al.*, 2014), show promise in extending smart home programming practices to inexperienced users, finding that this type of task definition did not significantly correlate with participants' gender in indicating success at solving tasks.

The case studies of works I have outlined in this section represent a brand of smartness which integrates seamlessly into everyday life. Human practices are the focus here: the role of technology is to digitally augment those practices. Desirable outcomes can result from this: helping families to maintain their relationships with each other, and even with their spirituality. However, negative outcomes can also arise in terms of negative impacts on energy use, or further entrenching household gender roles. The design of sociotechnical smart home environments is reportedly undertaken both by householders (in shaping the environment they live in) and by product designers. Yet, it is this which leads me to reject the notion presented by Wilson *et al.* (2014) that smart home technologies have 'co-evolved with society' in the natural sense. Using the language of evolution, and treating the evolution of smart buildings technology as a natural fact (Dourish, 2010), is almost an abdication of responsibility, and of agency. Rather, it seems more that the wider issues such as gendered labour, or how practices affect energy use, have largely been unconsidered in the design of desirable technological solutions such as smart speakers and lightbulbs. This presents as a 'natural evolution' as it reflects and does not deviate from the existing biases of society, but is in fact designed-in: perhaps not by intention, but by ignorance. The practices and behaviours which arise from the adoption of these technologies are of as much if not more importance to consider. We, as human agents, exercise our agency within the primary social bounds of society and the secondary bounds of these technologies (those being created by individuals living within society). The range of our actions is constrained within these bounds.

2.4.4 Implications of the Smart Home for HBI

Agency is a kind of empowerment: there are clear benefits when we are empowered to make our own choices. Yet, in the work I have reviewed within the smart domestic technology space, we often see tensions between agency and the constraints introduced through the design of technologies. In the assisted living research space, agency is in-practice automated away, contrary to the stated goals of the movement which seek to aid people with disabilities. In Wilson *et al.*'s 'instrumental' smart home, agency can be limited by automated systems which make decisions on behalf of the user, in the name of environmentally sustainable outcomes. But, conversely, in the socio-technical smart home, smartness arises out of the agency of the technology users: this research space exhibits pro-social (and arguably more socially just) forms of smart home technology that do not limit occupant choice and integrate into lived routines. Rather than taking a modernist, problem-solving approach to the space, this research is designed with sensitivity to the context in which it is to be used.

So what does this mean for HBI? While the smart domestic environment literature provides lessons on how *not* to design technology, as I have discussed above, there is a fledgling emergence of the kind of smartness which I have previously discussed: smartness which accounts for values, ethics and politics, is considerate of contexts and practices, supporting the agency of their occupants in making changes. Yet, there remain gaps in how existing work in HCI/HBI frames smartness and agency within this picture which this research can take up, and some of these extend beyond the domestic environment. Firstly, there is an obvious need to address collective forms of agency and decision-making for building occupants, and in particular a lack of underrepresentation and inclusion commentary within this: when the focus shifts from individual to group interaction, it is largely unknown how this should be designed for. And secondly, as the feminist/social justice literature tells us, there is a plethora of work which presents potential solutions to environmental and social problems: a need arises from this to design for support rather than solution.

2.5 Smart Buildings and the Workplace

Having covered the smart home in depth, in this section I investigate another kind of building in which many of us spend our time: the workplace. Although the workplace for HCI researchers has proven a less popular context than the home, there is a significant heritage of interdisciplinary Computer Supported Cooperative Work (CSCW) research which examines the office. Much of this research historically involved 'groupware:' software to support co-ordination, information sharing and communication between teams of workers (Poltrock and Grudin, 1999). Indeed, some researchers considered the two areas synonymous. But, by the mid-2000s, CSCW had re-oriented towards the social-sciences: the largest cluster of research being "*theories and models, ethnography, user studies"* (Jacovi *et al.*, 2006). While certainly not a new area for the field, this shift reflects a third-wave awareness that technologies cannot be designed in a vacuum. Still, less thought has been given to the buildings in which teams of workers reside, although as I shall discuss, the new area of HBI or *Human-Building Interaction* (Alavi, Lalanne, *et al.*, 2016) has begun to address this.

Dalton *et al.* (2014) point out the abundance of architectural metaphor in user interface (UI) design: "*we have the home button, we navigate to a page, we surf the web and the 'information super highway,' we click the back button, we mine information, the website is under-construction, we get lost in cyberspace…*" and so on. The design of UIs has long emulated the office. Desktop GUIs on personal computers began to appear in the mid-80's (Digital Research's GEM, and of course Microsoft Windows), replacing the DOS command line with graphical metaphors designed around the office desk: files, folders, and filing cabinets (representing disks). These design metaphors persist today in modern desktop operating systems. In the BBC's November 1986 TV broadcast of '*Micro Live'* (BBC, 1986) psychologist David Canter presents an architectural analogy for the computer filesystem: of finding your way around an unfamiliar building. Towards the end of the show, he comments that "*there's always a risk of people getting lost inside computer systems until we have front-ends that are much more intelligent,"* defining 'intelligence' as the ability for the computer to "*understand what you're trying to do, and then help you to do it.*" Intelligence can of course be taken to mean 'smartness,' and this is a very different kind of smartness than that embodied by the automated building. This anecdote frames much of the CSCW thought on worker-computer interaction at its inception as a field the mid-1980s. It's curious that in the 35 years hence, how much less consideration has been applied in the opposing direction, asking how buildings might understand and help their occupants accomplish their work. Perhaps if we thought about smart buildings more as collaborative technologies, rather than treating 'smart' as a synonym for 'automation' as Mennicken *et al.* (2014) have hinted at in the context of the home, that might be a very good thing.

Having covered the home so extensively, there will be some overlap with the topics discussed in this section, but it is important to give separate treatment as the issues do diverge. I will refer back to these sections where appropriate. The function of the workplace is, after all, different to the home: productivity and collaboration could be seen as the primary considerations, as opposed to relaxation and personal activities such as cooking and sleeping. As such, I begin with a treatment of CSCW thought on the workplace, including work on the built environment. Secondly, I examine the ways in which buildings have been considered within HCI, including work relating to the pervasive environmental sensor technologies which enable many of the functions of the smart building.

2.5.1 Computer-Supported Cooperative Work

This section focuses on CSCW in the workplace, including the office, and how technologies can support it. It is impossible to discuss HCI/CSCW's interaction with architecture and the built environment without touching on the concepts of 'space' and 'place', as understandings of these provide a lens for people's lived experience within them. 'Space' is generally understood as the "*geometrical and physical configurations of infrastructure*" (Bilandzic, Schroeter and Foth, 2013), while 'places' are constructed socially through the meanings and understandings which people attach to them. Yet, as Crivellaro (2016) explains, the concepts are often used interchangeably and there is a lack of a shared definition, though "*many recognise that place - like space and time - is a social construct.*" Harrison & Dourish's influential development of these notions in relation to CSCW neatly captures the distinction: "*Space is the opportunity; place is the understood reality*" (Harrison and Dourish, 1996). Key to this is the consideration that places are experienced differently by different people: Massey (1991) presents place as highly heterogeneous, differing through gender, class, race, and other inequalities, having different meanings and nuances depending on the individual. Places are a complex interplay of power, politics and people, the meanings of which are continuously created by those who inhabit them: as Massey notes, "*places are processes, too*".

Oldenburg's triadic typology of place is often used in the CSCW literature (Oldenburg, 1989): 'first' places are our homes; 'second' places are workplaces, and 'third' places are social spaces such as cafes and other community hangouts. Experiences of these places draw meaning from their location in space and time, and this is especially true for technologically enabled places. McCarthy and Wright's work on technology as experience (McCarthy and Wright, 2004) shows us that experiences are necessarily situated, being a site of flux that should not be viewed as static. Space syntax (Hillier, 1996) is a formalised approach, describing physical spaces in terms of both their topology and the sociological constraints which dictate their design and use. However, Dourish (2006) argues against the dualism in separating the two concepts, as both space and place are created as "*products of social* *practice, albeit different systems of practice,*" calling for a view of space which also takes into account its social origins. Space, while strongly related to the physical aspects, is not limited to them: spaces are designed by human actors and changed by those situated within, and are influenced by these individuals' own socio-technical worlds.

The notion of the cooperative building was proposed by Streitz *et al.* (1998), a "*flexible and dynamic environment that provides cooperative workspaces supporting and augmenting human communication and collaboration,*" perhaps the first joining together of groupware with the physical environment of the workplace. Notably "*the building does not only provide facilities but it can also (re)act 'on its own' after having identified certain conditions,*" and will "*adapt to changing situations and provide context-sensitive information according to knowledge about past and current states.*" This seems extraordinarily close to definitions of the 'smart building'. Yet, this form of embedded smartness also differs from the classic automated-environment approach in its motivation to support the working practices of occupants. Streitz *et al.* envisioned this being implemented via embedded ubicomp technologies, better enabling collaboration between workers through the blending of the fabric of physical space with the virtual 'information space:' walls, doors, and furniture becoming ubiquitous interfaces to documents and other digital resources. The concept was dubbed 'Roomware.' Users of these devices would be automatically recognised by sensor infrastructures embedded in the building, customising the interfaces to suit and acting as a form of access control. Of course, this never happened. After 1998, smartphones and tablet computers became commonplace and relatively low-cost: we could take our information with us, in our pockets. In the end, it made much more sense for devices which enable information access to be personal, in the same way that personal devices emerged in the smart home in preference to centralised home systems (Harper, 2011). Perhaps this relates to our neoliberal, market-driven economy: it is more profitable to sell people personal devices than to sell an organisation a building which embodies collaborative values.

Mixed Reality Architecture (Schnädelbach *et al.*, 2006) could be viewed as an evolution of this concept, linking physical spaces together in a shared virtual space to enable new and different forms of teamwork. MRA sits within the multi-disciplinary field of Adaptive Architecture, the sensor-augmented nature of which I will return to in section 2.5.2. The

MRA system was implemented via an audio/video link[13], with individual cells in the system able to be brought together in the virtual space to allow their inhabitants to contact each other. It demonstrates that places can also be virtual, or incorporate virtual elements. Participants (inhabiting a virtual 'cell') used these intersecting virtual spaces for arranged meetings, and contacting other workers. Chance encounters also occurred when the virtual spaces just happened to be linked and someone passed through or entered one of the physical rooms at either end, with audio cues such as doors opening prompting an interaction. I shall discuss these chance encounters in more detail presently.

Yet, in many ways, both of these approaches view the office (the work*place)* as rooted in a traditional narrative of 'work': one in which we travel to the office; labour for eight hours; then return home for leisure and social life, five days a week. Early CSCW did make an assumption of these conditions as defaults, but has since broadened and evolved to take account of the lived reality. Work (as a practice) is not limited in space or place, but interacts with both. We as workers are no longer confined to an office desk or cubicle: much knowledge-work in modern practice takes place via computer, including our interactions with colleagues. This has resulted in the architectural changes reflected in the wide adoption of open-plan offices[14], but also changes to our work practices, promoting variation in both the physical location in which these practices take place, and necessary (or resultant) changes to how work is done as a result. Hot-desking, for instance, is one of these changes: workers, in theory, no longer need a fixed desk, and should be able to work from anywhere. Yet, Hirst (2011) found that although employees with no fixed desk may choose any location within the office, there is a tendency for people to "settle" in a comfortable location such as in proximity to a window for good access to natural light. And without the personalisation that is possible with a fixed desk, there is also potential for feelings of isolation and loss of ownership of the space. Bødker and Christiansen (2006) explore how

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[13] Privacy is a strong concern for smart buildings, especially where data collection and/or video cameras are involved. The authors dedicate an entire page of their findings to privacy concerns raised by MRA. Non-participating staff in the study building showed concern about the video links, "*asking for meetings to be conducted elsewhere"* and even "*walked through [...] holding a sheet of A4 paper in front of their face*." The authors state that this was "*confined to a small minority of people,*" but non-consenting staff were made to feel anxiety, and deal with the presence of the system in ways which affected work practices. This may say something about the ethical approval process of the authors' institutions, but no further detail on this is given.

[14] The origins of the open-plan office, at DuPont in 1967, are discussed in (Murphy, 2006) who notes that the "*seemingly random arrangement of furniture*" which ostensibly levelled the social/class hierarchies of the office was quickly watered down, such that "*executives and high-level managers retained their private offices.*" Class issues are intrinsically wound-up in how we use space, as argued by Massey (Massey, 1993).

such flexible workers might maintain 'social awareness', a sense of what their colleagues are doing. The authors study how social cues of presence and identity are advertised to visitors and colleagues in a small open-plan office, supporting awareness of colleagues "*as a person, not only as a unit of labor.*"

Chance encounters or 'serendipitous interactions' are investigated by Brown *et al.* (2014), who note that such encounters "*may lead to enhanced productivity, collaboration and knowledge dissemination*" in knowledge-based workplaces. Brown *et al.* attempt to measure and quantify these interactions using a framework of cultural roles. Face-to-face interactions between staff were captured using lightweight electronic badges, and Brown *et al.* argue that being able to quantify these chance interactions in the workplace may be useful for organisations to improve "*team coordination, cohesiveness and productivity,*" for example by re-designing office layouts. However, I must highlight that Brown *et al.* uncritically use Geert Hofstede's 1970s theory of 'cultural dimensions' (Hofstede, Hofstede and Minkov, 2010) in their work, drawing a conclusion "*that those who interact with people of different roles tend to come from collectivist and person-oriented cultures comfortable with social hierarchies.*" Hofstede's work has been widely criticised on both epistemic (Ailon, 2008) and postcolonial (Moulettes, 2007) grounds, as the value dimensions framing forces a eurocentric (Kwek, 2003) set of assumptions and ideals, and conflates culture and nationality. For example, the dimension of binary gender roles ('masculinity' vs 'femininity') is forced onto other cultures, assuming these roles to be a universal constant and also erasing the existence of non-binary and transgender people. The theory was based on surveys of middle-class IBM workers at the company's offices around the world, realistically limiting its conclusions to this demographic. Hofstede himself has taken such criticism of his work personally (Ailon, 2009). It is also likely that the theory is misapplied in Brown *et al.*'s case, as it extends work which considers cultural groups to individuals: individuals vary substantially, and it is ethically problematic to draw conclusions about individual people based on their culture. There is danger in making categorical assumptions about building occupants based on outdated assumptions which can be erroneous: it is more useful to critique such essentialist theory, particularly that of 1970's-1980's social psychology, rather than making easy claims that research is well-informed simply by employing it as an analytical lens. A different approach is required, which takes seriously how people exist within space, as opposed to making blanket categorisations.

In conclusion, while CSCW has extensively examined the practices of work, and has developed a strong understanding of how these are affected by the location, design and augmentations of the space in which it is undertaken, this does not seem to have made its way into the smart buildings literature. There doesn't seem to have been any return to the motivations underpinning (Streitz, Geißler and Holmer, 1998), of smart buildings which can support cooperation: it has been left behind in the pursuit of environmental automation. Further, while architectural/physical space can be designed to support collaboration, we cannot ignore the social factors which give meaning to a place. There also appears to be a literature gap here in the forms of work which CSCW examines: office work; knowledge work. Work, in short, tied up with the creation of economic value. Other kinds of work exist, though perhaps they are harder to find technological solutions for. Still, technology can be an enabling tool, and CSCW shows us the necessity of a deep understanding of the cultural and social fabric of the context it is designed for. If we want to think about smart buildings as collaborative technologies, it is likely that solutions which consider the context of their deployment will be more effective than appropriated ones.

2.5.2 Non-Domestic Buildings in HCI

Just as buildings are a context for our lives, they are a context for HCI research: HCI researchers have begun to argue that more work should centre the building itself, rather than being necessarily situated within it. Yet, the nexus of digital technology and architecture has long been a site of interest for HCI practitioners. I have already considered Weiser's ubiquitous computing vision (Weiser, 1991) earlier in this chapter: the increasing weaving of pervasive sensing and ubicomp into the fabric of new buildings now allows environmental data flows to be continuously monitored. The beginnings of this paradigm shift of computing into the physical realm are examined in *Digital Ground* (McCullough, 2004). Within the sociocultural ramifications arising as a result of this meeting of ubicomp and architecture, and the proliferation of microchips in everyday things, McCullough criticises ubicomp's universalised, contextless vision, the 'one-size-fits-all' approach. The solution, for McCullough, lies in interaction design: examining how humans act in (and interact with) systems, and how our habits, practices and behaviours work to streamline technological integrations, or exclude us from them.

Yet, interaction design is a young discipline compared to architecture[15], and as Ingram (2009) argues we might do well to learn from it. Ingram makes the case that the ephemerality of the digital realm makes it difficult to see the impacts of one's design decisions, in contrast to a building, which "*changes its surrounding environment in a way that makes the architect's responsibilities readily apparent to most people.*" There remains a challenge in the practice of interaction design in maintaining dialogue about the impacts of our work, especially where the physical and digital realms blend in computer-augmented spaces. Further, while McCullough approaches computing from an architectural perspective, the works collected in *Architecture and Interaction* (Dalton *et al.*, 2016) position buildings as artefacts which humans interact with, reinforcing that interaction design research is as much relevant to the domain of buildings as it is to artefacts. They, too, highlight in the book's introduction that HCI practitioners could learn from the field of architecture, the design of complex systems (both computers and buildings) being central to both disciplines.

These considerations are not by any means new: there is overlap in the ways in which we think as practitioners of these disparate disciplines. Given the move towards technologically-enabled buildings, it follows that the HCI community should seek to apply its broad human-centred design expertise to built environments which are themselves moving into the computing domain. It is therefore notable that the HCI community is developing a strong interest in architecture. A string of workshops every couple of years at the major HCI conferences have pulled together researchers and practitioners spanning HCI and architecture:

- Dalton *et al.*'s *Ar-CHI-tecture* (2012) workshop at CHI 2012 brought together practitioners and researchers in architecture and HCI.
- … and at CHI 2014, Dalton *et al.* (2014) met again to examine the role of space in interface, considering how we configure interaction in the context of spatiality.
- Separately at CHI 2016, Alavi, Lalanne *et al.* (2016) proposed the term 'Human-Building Interaction' (or HBI), highlighting the critical need for proactive consideration of built environments in HCI.
- At DIS 2017, Schnädelbach *et al.* (2017) discussed the role of personal data in adapting environments, and the concerns for privacy in an IoT-enabled building.

[15] 30 years, as opposed to, say, six thousand. While the discipline of architecture is a more recent evolution, humans have been doing architecture, as a practice, for longer than we've had historical records as a species.

- Hasan *et al.* (2018) at CHI 2018 discussed "*optimizing the interaction between humans and their indoor and outdoor environments*" in the context of living labs.
- Finally, the *HabiTech* workshop proposed for CHI 2020 (Dalton *et al.*, 2020) was to consider the implications of technologically-enabled buildings for ethics, community, and democracy[16].

While there is obviously significant interest in the topic, there is as-yet little cross-pollination between the disparate sub-communities formed around these workshops. These are relatively small communities of researchers, cliques. Further, researchers who do not attend these conferences have little opportunity to engage with the community. The common thread between these discussions is interaction in built environments, and therefore the framing of this emerging sub-discipline as 'Human-Building Interaction' is a compelling one: it unites these disparate approaches. In their ACM *Interactions* article, Alavi, Churchill, *et al.* (2016) introduce a number of future HBI research opportunities, looking at how we might better enable interaction with built environments. Among other directions, they highlight the need for research which fronts human agency (as I have discussed earlier in this chapter), barriers to adoption of HBI solutions, and of the role of governance and standards: challenges I take up in this work.

That said, there is still no unified vision, despite the theoretical grounding provided by McCullough, Norman, Hillier, and others. Much of the discussion remains speculative, and lacks a body of empirical research which might further the field. Work is often published in edited collections, rather than journals or conferences, which may be limiting its impact on wider HCI. Conversations on buildings in HCI therefore remain mostly at the speculative 'meta' level: a lot has been said about what this field could be, but we are lacking a strong peer-reviewed evidence base to support it. There could be a couple of reasons for this:

1) Large scale studies require infrastructure: large sensed environments. Access to existing facilities which provide this is limited. There are very few studies retrofitting this infrastructure, and these are not at-scale.
2) The opportunities for the construction of new buildings to do this research on (or in) are few and far between. Buildings are expensive, and getting the institutional and

[16] Though the workshop was sadly cancelled, as was CHI2020 itself, due to the coronavirus pandemic. I was able to attend Hasan *et al.*'s 2018 workshop, and had a position paper accepted at the cancelled 2020 one.

stakeholder buy-in needed to construct, maintain, operate and continue to support research in these experimental environments is difficult.

A few authors (often those involved in the CHI workshop communities above) have already brought an architectural perspective to HCI, or have contributed an HCI perspective in the opposing direction. Adaptive Architecture is "*concerned with buildings that are designed to adapt to their environments, their inhabitants and objects as well as those buildings that are entirely driven by internal data*" (Schnädelbach, 2010, p. 523). Schnädelbach presents a conceptual framework for understanding this broad category of environments, but notes that the field (situated at the nexus of architecture, computing science, the arts and engineering) is not well defined. The paper considers the stimuli to which a building might be responsive, and the adaptive elements which then change within a building. Adaptivity can be achieved both automatically and through manual human intervention: automation is framed as but one strategy by which architecture might be made adaptive. This should perhaps remind us, as designers, that there are still contexts in which manual adaptation is desirable. Adaptation can also blend the manual and automated: I discussed one example of this in section 2.4.2, an adaptation in the context of sustainable thermal comfort which disrupted "*routine reliance on mechanical heating*" (Clear *et al.*, 2014, p. 1023) by requiring a button-press to 'make it warmer'.

Still, in a computing science context, adaptation is most commonly considered alongside automation, in systems "*consisting of sensors, systems (software) and actuators*" (Schnädelbach, 2010, p. 540). We consider things which can be sensed, how we might process their data streams, and things that might be actuated, automated or displayed in response. The opportunities for sensing are becoming more developed than ever before: reading environmental factors "*wind speed, temperature, light levels, air pressure, air quality and noise levels among others*" from the surroundings, embedding sensors into buildings to detect the whereabouts of inhabitants, and processing these signals to enable recognition of human activity. Pervasive sensing has been heavily investigated in HCI and Ubicomp, developing understandings of where and how sensing technologies can be applied to enable desired outcomes. Following Weiser's ubiquitous computing vision (Weiser, 1991) there are now more types of sensor, more ways available of collecting and processing data on the physical world than ever before. We've come a long way from Xerox's Active Badge positioning technology of the late 1980's (see section 2.2.2). Often, the motivations for ubicomp technology designs centre on reduction of energy use as their target context: Jahn *et al.* (2011) explored how presence, lighting, power consumption, window state (open or closed) and radiator temperature were collected through various sensor platforms to track sustainable (and unsustainable) office behaviours. Khan *et al.* (2014) studied how occupancy estimations might be used to identify potential energy savings in HVAC system usage. And Costanza *et al.* (2016) examine how ambient public displays can bring staff 'into the loop' of managing office heating through their design of a 'Temperature Calendar' visualising electricity and gas consumption.

Wearable technologies have also begun to allow for sensing of the physiological properties of the human body. The data produced can also be used to produce responsive and interactive environments: the case for a 'breathing building' is made by Schnädelbach *et al.* (2012), who examined how an actuated building envelope might communicate biofeedback data to building users. 'ExoBuilding' functions as a form of ubiquitous display, a tent-like structure which expands and contracts, moving up and down in response to an EEG/ECG (electroencephalogram/electrocardiogram) data feed from hooked-up participants, "*gathered using three electrodes placed on the participant's chest and torso.*" Given the invasiveness of the data collection method, it isn't surprising that "*only a subset of participants also found this experience relaxing*"! While novel, ExoBuilding is effectively an actuated tent, a building in principle alone, and this is a limitation of the work. There is a problem of scale here. It is impossible to extrapolate the experience of two people sat on desk chairs under a sheet to that of an office full of workers. It gives us little real understanding of what it would be like to live in a building which actuates according to one's biorhythms. This is not an everyday working environment. Exercises in speculation are of huge value for defining an initial idea, or for better understanding a context or population, but can be limited until scaled-up to make something solid.

Living Labs (previously mentioned in section 2.4.1) offer an opportunity to conduct research in such an everyday environment. Alavi *et al.*'s study of human-centric sustainable architecture (Alavi *et al.*, 2018) was conducted in such an environment, a hot-desking space at the Smart Living Lab in Fribourg, Switzerland. The low occupancy rate of these spaces ("*around 20%*") presented a sustainability problem as the building still needs to be heated and ventilated: a constant environmental cost. The authors, in collaboration with interior architects, undertook a co-design exercise with building occupants, uncovering concerns for visual privacy and spontaneous collaboration. The results were used by the architects to re-design these workspaces, which were then re-modelled. They then undertook a user study of 33 office occupants over 8 weeks to understand how the spatial design of the newly refurbished workspaces influenced the ways in which building users occupied and used them. To accomplish this a methodology was developed involving the deployment of a pervasive sensor system, including Bluetooth beacon bracelets to track occupants' location as they move between rooms in the building, and motion-capture IR cameras to study smaller-scale intra-office behaviours. This is far less invasive mode of data collection than presented in the *ExoBuilding* study, therefore being more likely to accurately reflect the lived reality of office occupants. The study demonstrates the value of pervasive sensing as part of a research methodology. While it could be criticised for reducing sustainable space use to an optimisation problem in order to constrain and make it tractable (something we should be wary of, per (Brynjarsdóttir *et al.*, 2012)), it is also part of a minority of HCI research tackling the needs of building occupants, and there is definitely value in the application of HCI methodologies to architectural projects.

That said, there is an industry precedent for the involvement of occupants. Post-occupancy evaluation or 'POE' (Preiser, 1995; BRE, 2019) is one method by which occupant satisfaction in a finished building can be assessed, giving a metric for user experience in architectural design, ensuring design mistakes which affect occupants are not repeated in future buildings and providing a mechanism for real-world performance evaluation of the building fabric. Built into standards (BRE Global Ltd, 2016), POE is now another tool in the architect's toolbox, albeit a (notoriously) rarely implemented one as it creates liability issues for firms after a building has been handed over. Further, building user engagement within POE often takes the form of static questionnaires, which do not necessarily give a full picture. Other ways of including occupants in conversations around a building exist. Verma *et al.* (2017) employed the dataset produced by the Bluetooth sensor deployment in (Alavi *et al.*, 2018) to study use of space in the wider building. The collected data was visualised using jitter plots and explored and annotated in collaboration with participants and stakeholders. The process of working through data in participation with building users generated insight into their workstyles and space-use behaviours, and informed further quantitative analysis. As the authors note, while the results of this study are not generalisable to other buildings, they can be used as a proof-of-concept of the methodology, and contribute to a broadening of scope in what can be assessed as part of a post-occupancy evaluation. Yet, there comes a point when an architect must disengage from the commissioning of a building (even if this is after a number of years, as in a Soft Landings process (Way and Bordass, 2005)), and there remains an open question of how users are engaged in the continued operation of a building into the future, and little standardisation of how facilities managers undertake this ongoing process.

One existing process through which facilities managers maintain an ongoing awareness of the state of the buildings they manage is by means of audits. There are research opportunities to engage with auditing as an application area for sensor technologies: beyond simply presenting an opportunity for tighter building controls through the collection of fine-grained data as in (Jiang *et al.*, 2009; Erickson *et al.*, 2013). Such data can assist in audits to check if the building and organisation meets the compliance requirements of standards for thermal comfort such as ASHRAE 55:2004 (ANSI/ASHRAE, 2010). Recent work in HCI has examined the use of novel technologies in auditing, such as automated aerial thermography using quadrotor drones (Mauriello, Norooz and Froehlich, 2015) to assist in understanding heat loss from building structures. However, as I have previously discussed (section 2.4.2) the comfort of occupants is not guaranteed by standards adherence: comfort is subjective and influenced by many factors. Tight regulation may be unhelpful as it diminishes the responsibility of the building occupant in their use of energy-reliant systems (Clear, Mitchell Finnigan and Comber, 2016), but does raise opportunities for building management policies and technologies to recognise the subjectivity of thermal comfort (Luo *et al.*, 2016) by allowing for adaptive actions for personal thermal control.

Engaging the stakeholders involved in the process of commissioning and running buildings is essential to the success of much of this research. Hasselqvist *et al.*'s aforementioned work on energy management (Hasselqvist, Bogdan and Kis, 2016) serves as an example of this in the residential sector. Hasselqvist's work can be viewed as one way through which the agency of residents in housing co-operatives might be addressed. Building occupants are themselves actors in this process, and positive engagement between management and occupants can go a long way towards addressing issues. In the non-domestic sector, work by Schwartz *et al.* (2010) shows that office workers are able to understand and act on energy consumption information from their workplace by changing their practices. Therefore, although the complexity of the systems at work may require specialist knowledge, building users themselves are also stakeholders in the effects of management: the actions of facilities managers affect building occupants, and vice versa. Yet, this approach still focuses on trying to change the energy-using practices and behaviours of building occupants. Instead, Bedwell *et al.* (2016) undertook workshops with management and building occupants about energy consumption using visualised building data to foster communication between management and occupant.

There is an apparent research gap when it comes to up-skilling staff, giving them the tools (and agency) to examine their buildings, energy use, and thermal comfort, instead of making these the sole purview of facilities management or researchers. Prior HCI work in participatory sensing can give some direction on how this might be approached in buildings. DiSalvo *et al.* (2010) highlighted the emergence of pervasive and participatory sensing in HCI, noting the role sensors can play in enabling amateur participation and sense-making through citizen science. Some studies have gathered and employed sensor data to infer the experience of cyclists (Eisenman *et al.*, 2007) and drivers (Honicky *et al.*, 2008), enabling these groups to investigate the health implications of air pollution. The use of this data is strongly coupled with the place in which it is collected (Taylor *et al.*, 2015), and different "*parties invest in and (re-)inscribe data with particular understandings, across time and space*" *(ibid.)*. As Reddy *et al.* point out in their study of participatory sensing of cycling (Reddy *et al.*, 2010), these 'amateurs', in having an in-depth knowledge of the context, may be experts in their own right and can give context to data that engineers or researchers might otherwise miss. In another example, Aoki *et al.* (2009) attached air quality monitoring sensors to vehicles to explore how such sensors can provoke community action over air quality, providing a community with the tools to capture air quality and the legitimacy to enact change, though challenges remain in proving the validity of amateurs' data to professionals. In the residential sector, sensor toolkits have been used to assist the work practices of energy advisors (Fischer *et al.*, 2016), as discussed in section 2.4.2. This leaves open the opportunity for HCI work in the non-domestic buildings sector, an underdeveloped area of research, to address some of the same questions.

As seen in this section, while there is great interest from a community of researchers within HCI in the built environment, empirical work in the field is only just beginning to appear, and there is a research gap when it comes to understanding the users of these buildings. There are a couple of barriers to doing such research in terms of the availability of sensing infrastructure to conduct studies, and of a lack of institutional stakeholder buy-in. There is therefore scope to conduct research in real lived-in environments, and a problem to address in terms of how this can be accomplished. I have covered some existing work which can help to guide this inquiry, connecting Ubicomp and HCI research to sustainable policy and standards, and the auditing practices which may be considered a starting point for change.

2.6 Literature Gap: Reframing Smartness

How is it that, so often, the group forgotten in the design of smart building technologies is the occupants? We (the HCI/HBI research community at-large) are sleepwalking into smart buildings if we follow this trajectory, but it is building occupants who will bear the consequences of it. So, how might we re-frame smartness to address this? This section outlines the research questions through which I investigate how smart building technologies can move beyond a narrative of engendering productivity, towards a more inclusive smart vision that can deliver improved comfort and wellbeing.

I have reviewed how existing work in HCI/HBI frames smart buildings within the context of the first, second and third waves (or 'paradigms') of HCI, and highlighted how efficiency and optimisation are treated as core values to question what 'smart' might mean if sustainability and social justice were core values instead. The 'modernist' smart building vision can be thought of as rooted in a first wave understanding of smartness, as I outlined at the beginning of this chapter: creating automated, tightly thermally controlled spaces which 'provide' comfort, but limit human agency (for example, opening windows to cool the space). The ways in which this automation acts to limit the agency of occupants can be understood through Wilson *et al.*'s (2014) functional, instrumental and socio-technical smart homes, and that of non-domestic buildings work in CSCW, HCI and HBI. There is a literature gap here in addressing how we might design for increasing agency and re-prioritising choice for occupants.

The focus on efficiency and modernism prevalent within much of this work engenders technological solutionism, which leads to a problem-driven approach: in assistive technology, this 'problem' has often been people. In the instrumental smart home, the 'problem' has often been environmental sustainability. As per Brynjarsdóttir *et al.* (2012), we need to look for less reductive framings, and per Strengers *et al.* (2019) we also need to look at values and contexts beyond the (predominantly male) consumers who purchase smart products. There is an extant literature gap in HBI that can be filled by work which applies the values of sustainability and social justice in the smart building space, with a view to addressing underrepresentation and breaking the closed control loop of the automated smart building. There is an apparent need for notions of smartness which do not treat people as a problem to be solved and (as seen in the sustainability and social justice literature) instead engage with the wider social context to ask how we might design for occupant empowerment within HBI.

Further, researchers and designers are not neutral: we imbue our research with our own values. I have argued that treating the evolution of smart buildings as a natural fact (Dourish, 2010, p. 2) is an abdication of responsibility by designers. The socio-technical smart home lens offers a different approach, as it does not use a problem framing, instead designing for support, rather than solution (Taylor *et al.*, 2007). As Hasselqvist (2016) and Dillahunt (2014; 2015) have done in the domestic space, there is a need for studies which raise the voices of underrepresented occupants in the non-domestic buildings space. And it is necessary to bear in mind that non-domestic spaces are not private: changes made to benefit one group of stakeholders may have different effects on another. Collaborative technologies therefore offer another lens through which to re-frame smartness: while Streitz *et al.*'s (1998) vision of the collaborative building did not come to the fore, studying how the organisation and its processes operate can provide a novel HBI approach when designing new smart building technologies, and there is a lack of literature examining this.

2.6.1 Research Questions and Aims

I therefore frame my research questions around the participation and inclusion of occupants in the processes of the collaborative smart building. Within this, I investigate the design and deployment of digital technologies which facilitate this kind of smartness, within the three different built environment contexts described in the introduction. Further, I investigate how data-driven tools assist negotiations and nurture shared responsibility in energy use, and examine considerations for the contexts into which they might be deployed. The overarching research question which this dissertation seeks to address is therefore:

What are the roles of data & digital technologies
in creating human-centred smart buildings?

Through this question, I seek to contribute towards the broader development of smart buildings which centre the human over processes of automation. This dissertation collects and examines three case studies I have undertaken to investigate this research. These are presented in the following chapters, each exploring one of three interrelated sub research questions:

> RQ1: *How can retrofitted sensor data augment facilities management processes, and how might building users be empowered to participate in these?*

RQ1 (and therefore case study CS1) investigates how sensor data can facilitate conversations around the built environment. As I have discussed (section 2.5.2), a major barrier in the undertaking of HBI research is the availability of sensor-augmented environments. There is little work on how we might retrofit older buildings to become smart(er). This research question proposes the installation of retrofitted sensors into an older building, and attempts to involve both professional facilities managers and novice student auditors in discussions around this data, similar to other recent approaches (Bedwell, Costanza and Jewell, 2016; Verma, Alavi and Lalanne, 2017). CS1 follows a group of environmental auditing postgraduate students, as regular occupants of the building which they are learning to audit using sensor toolkits, and a number of professional facilities managers who used the data these sensors provided as part of their professional practice. The involvement of occupants as stakeholders in this process (Hasselqvist *et al.*, 2015) has not previously been attempted in the non-domestic buildings sector, and the literature motivates an approach which attempts to address underrepresentation, by making building data accessible to a wider group than just facilities management staff.

> RQ2: *How can data and digital technologies foster shared understandings and assist comfort negotiations in the office workplace?*

The second research question RQ2 is explored in case study CS2. I have argued that the smart building as currently presented lacks a human side. Quantitative sensor data only gives one view of a building, and does not address human experience. RQ2 explores how we might move from understandings based solely in data to more human and inclusive understandings of a common complaint factor: thermal comfort. Authors including Taylor *et al.* (2015) and Tolmie *et al.* (2016) have argued that such data is necessarily situated, and that human context is required to make use of it effectively. Therefore, this question is concerned with how interactive systems built around data might foster shared understandings that can aid in negotiation around complaints. CS2 examines the context of an office with a history of occupant thermal discomfort, to understand how smart features might be introduced into buildings in a more inclusive way.

> RQ3: *How can HBI support occupant agency and participation in the everyday management and adaptation of smart buildings?*

RQ3 therefore seeks to understand the lived reality of smart building environments, and develop methodologies for the democratic involvement of occupants as stakeholders in the ongoing life of such buildings, after the initial commissioning. While CS1 and 2 examine retrofitted building contexts, CS3 is situated within a brand-new smart building (opened 2017). I observed in this review that existing building evaluation methods such as POE are well established (section 2.5.2), but smart buildings may offer new opportunities for engagement with underrepresented building users in the ongoing management process. In order to design processes and infrastructure effectively for the smart buildings of the future, we require better developed understandings of the lived reality and sociotechnical fabric of the smart buildings of the now.

In the next chapter, I will expound my methodological and epistemic orientations to this thesis, and will outline how these research questions will be addressed.

Chapter 3: Methodology

You are not a computer. You are complex and undefined.

THE SPOOK SCHOOL, "BINARY" (2015)

Within the literature review conducted in the previous chapter, I have uncovered prior work which explores and examines smart built environments in HCI, arguing that the nature and meaning of 'smartness' in these environments varies substantially. In identifying a literature gap, I re-framed smartness in terms of the human building occupant, resulting in a research question asking, "*what are the roles of data & digital technologies in creating human-centred smart buildings?*" Methodological approaches utilised in the literature vary, but offer a range of techniques useful in guiding the approach taken here. In this chapter I outline how I will respond to the three sub research questions, and the argument I develop will guide the epistemic basis for the empirical work presented in this dissertation. While there is no single way to undertake this work, the nature of the research questions and the literature landscape guides it strongly towards a qualitative approach. As such, in this chapter, I cover the epistemic position and philosophy which motivates this approach, and how this is positioned within existing methodologies as used in HCI research. I further outline how I undertook the analysis of these studies, including the necessity for a case-study approach and why the studied contexts were chosen.

3.1 Research Ethics

Approval for this project was granted on 6th March 2016 through the Newcastle University ethical review process. As the project was deemed 'low risk' by the University's approval assessment tool, ethical approval was automatically granted without being reviewed by a panel in accordance with University policy. This was due to the research requirements not triggering protections legislation (e.g. around lab animals or human tissue sampling), participants can fully consent, and I did not recruit participants from 'vulnerable' groups (e.g. children). This approval covered the work undertaken in case studies CS1 and CS2. A further approval was granted on 24th October 2017 to cover the work undertaken in CS3, which departs in its methodology from the prior case studies. In line with data protection legislation requirements, participants were provided with information sheets and signed consent forms governing the use of their data in this research. Example participant information sheets and documentation of ethical approval can be found in Appendix A.

3.2 Research Design

This dissertation seeks to contribute to a body of knowledge relating to the human elements of the smart building: it is primarily concerned with people. The research questions I have defined relate to how humans ascribe meaning to and make sense of built environments in relation to their position within the organisation, their motivations and desires, and so on. Broadly speaking, this research employs a qualitative approach, driven by a social constructivist worldview and analysed through an interpretivist lens. To this end, it is of value to outline in this section the epistemic standpoint and philosophical basis in which my inquiry is grounded, as this informs my choice of approach.

Post-positivism is often known as 'the scientific method' and holds that there exists an objective 'reality' which it is possible to discover through measurement and observation (Creswell and Creswell, 2018, p. 44). While positivist philosophy holds that there is an 'absolute truth' which exists for discovery, postpositivists refute this, citing that evidence can be fallible and thus conclusions can (and must) be altered as new evidence arises. Empirical observations and measurements are used to attempt to verify a theory, or falsify a hypothesis, thus prioritising objectivity, rationality and the deterministic relationship of 'cause' and 'effect'. This is reductionist by nature: ideas must be refined to be testable and atomic in order to be challenged with evidence and provide verification. A postpositivist approach is well-suited to physical and behavioural sciences, with application in domains from physics to psychology.

Yet, the work on space and place I have discussed in the literature review positions people as situated within their environments, drawing meaning through their experiences, cultural norms, social backgrounds, and marginalisations. A positivist/postpositivist worldview is unsuited to this work as it does not allow for the development of situated and contextual understandings from which recommendations for future technologies, approaches and standards can be developed. Instead I employ a social constructivist/interpretivist worldview, as I attempt to gather considerations for how individuals understand the world which they inhabit (in this case, buildings) and "*develop subjective meanings of their experiences*" (Creswell and Creswell, 2018, p. 46). As such, the research questions I have developed are constructivist questions: open-ended, the aim being "*to rely as much as possible on the participants' views of the situation being studied.*" Social constructivism rejects objective realities, acknowledging that the meaning generated through the data is shaped by the researcher, whose "*personal, cultural, and historical experiences*" work to influence their subjective interpretation. Rather than viewing the researcher's perspective as a 'contamination' or 'bias', reflexively observing how one's own role influences the research process is arguably more scientifically rigorous than approaches which view the researcher as an objective actor, an outsider to the research context (Hayes, 2011). My approach is therefore an interpretivist one, and inductive rather than deductive. Inductive reasoning begins with an observation, and through the curation of these we are able to define findings. Deductive reasoning begins with a framework or theory and attempts to fit the evidence to it. As such, I curate ideas through the analysis of observations, as opposed to starting with an idea and attempting to validate it. Constructivist research is therefore well suited to the social sciences, and in turn to HCI approaches which centre 'human actors' over 'human factors' (Bannon, 1991).

There are generally understood to be three approaches to research: qualitative, quantitative, and mixed methods. Yet, these are not distinct, rigid categories but "*represent different ends of a continuum*" (Creswell and Creswell, 2018, p. 41). As I have stated, this work is qualitative by nature, which following Creswell's definition means "*an inductive style, a focus on individual meaning, and the importance of reporting the complexity of a situation.*" Braun and Clarke elaborate on the definition of qualitative research (Braun and Clarke, 2013), centring meaning-making, "*capturing some aspect of the social or psychological world*" as the factor which distinguishes it. Specifically, this is a "Big Q" qualitative approach: "*the application of qualitative techniques within a qualitative paradigm*". It is not (post-)positivist, and not about the testing of hypotheses or providing objective facts. Quantitative measures, calculations and numbers are of limited utility when trying to understand how people think about and give meaning to their environment and experiences.

Yet, I do also perform quantitative data-gathering using sensors in two of this work's case studies, as I will detail below. This work could therefore be considered to utilise a mixed-methods approach in places, though I do not assume that the quantitative data reflects a (post-)positivistic 'truth'. Instead, it is used as a research tool alongside and within the qualitative work, triangulating and situating the experiences of participants within the wider picture of the environment of the building. This research approach can also be viewed as situated within the third wave/paradigm of HCI (Harrison, Tatar and Sengers, 2007) as discussed in the literature review, with a bent towards a notional fourth wave as discussed by Blevis *et al.* (2014). "Big Q" qualitative research often has an explicit social justice orientation, which aligns with the more radical agenda proposed by this work: of moving towards building design and management which keeps the people who live and work in those buildings at its heart and critiques the existing structures of management, in which complaint represents the interface between building manager and occupant. Being thus situated has driven the development of my questions, methods for studying, and validation procedures.

3.3 Methodological Frameworks

Qualitative methods are the toolkit for this research. As such, in this work I draw from a diverse range of methodologies employed and discussed in HCI, which are outlined here. HCI as a discipline often blends user research with interaction design practice[17]. Bannon (1991) argues for a paradigmatic shift in methodology away from positivist-postpositivist approaches, advocating a re-positioning of the user at the centre of interaction design. A number of Bannon's recommendations are relevant for this work: moving from a focus on individuals to a focus on groups; from laboratory studies to in-situ studies of technology; from a view of users as novice to users as experts; and from cognitive-science based design to a philosophy that users be more directly involved in the design process. As such, participatory methods have been both independently developed and adopted from other disciplines. Much of the development of the discipline of participatory design (PD), for example, has its roots in projects undertaken in the 1970s-80s in Scandinavia, pursuing "*the active cooperation between researchers and workers of the organization to help improve their work situation*" (Sundblad, 2011). Techniques include the use of design workshops, low-tech mock-ups of technology 'prototypes' to test out new ideas, and 'toolkits' allowing user experimentation. These have been widely adopted and further developed within the CSCW and HCI communities over the past 30 years and are considered one of the key contributions of the second wave of HCI. As Bødker writes, researchers have continued to adapt methods into the third wave, building on (rather than replacing) the second: dealing with appropriation and contexts of emergent use of technology and "*embrac[ing] experience*

[17] I often think HCI is really three disciplines in a trenchcoat: social science, computer science, and design.

and meaning-making" (Bødker, 2015). This has meant looking outside the context of the workplace at "*the rest of life,*" where technological development has been driven strongly by consumer devices such as the iPhone. Bødker warns against studies that "dump" technology on people as part of "in-the-wild" research into emergent use (echoing the warnings against consumerism I have covered in the literature review) instead discussing how participatory prototyping and technical experiments can be of utility in a design space which is complex and open-ended. These methods continue to play an essential part in third-wave HCI and design work.

The Scandinavian tradition of participatory design provides a values-driven ideological basis for the work carried out in this dissertation: there is a significant lack of work considering the participatory design of future smart buildings. While this work is not seated within any single methodological discipline, it is strongly informed and influenced by a range of prior methods. One such approach is Action research (AR), *"a class of methods and approaches for conducting democratic and collaborative research with community partners*" in engaging real-world human problems (Hayes, 2011). AR represents a more democratic and inclusive way of doing research, involving a cyclic approach. Where a traditional user-centered design process involves a circle of analysis, design, development, and evaluation, AR can be represented as a repeating 'spiral' of planning, acting, and reflecting on a design, learning and iterating to create better outcomes as opposed to arriving at a single solution. Engagements with communities in AR often pan out over a long period of time (many years), generating "*highly contextualized, localized solutions with a greater emphasis on transferability than generalizability.*" As this dissertation takes a case-study approach, this length of engagement can be prohibitive to looking at a range of different contexts. So, while this dissertation does not use AR in its methodology, the three case studies are influenced by it in how stakeholders are engaged over the life of the projects, and in how they attempt to address democracy and inclusion in the management processes of the smart building.

The first two case studies described in this work examine designed artefacts inserted into real-world contexts. Design artefacts "*transform the world from its current state to a preferred state*" (Zimmerman, Forlizzi and Evenson, 2007). Research through design (RTD) work undertaken in HCI follows an iterative process similar to AR, but with a slant towards designerly thought and the kinds of contributions best made by a trained designer. Outputs include the series of "*models, prototypes, products, and documentation,*" artefacts from the process followed by the designer in constructing a concrete problem framing. The third wave's expressed desire to focus on 'wicked' societal problems (sustainability, ageing, democracy) which "*cannot be easily reduced*" (Zimmerman, Stolterman and Forlizzi, 2010) requires holistic approaches, and RTD attempts to address this not by seeking scientific 'truths' but by designing solutions which are "*optimal for the current situation.*" The second case study of this work can be viewed as being inspired by RTD, though it reduces the wicked problem of sustainability into the more tractable one of shared thermal comfort, investigating the design of a solution for the lived building context. Yet, this case study departs in its methodological approach from RTD in that I, the researcher, am a trained computer scientist rather than a trained interaction designer, and that the solution as-designed not iterated on. Rather, it is used as a technology probe as part of the wider research investigation.

Technology probes are "*an instrument that is deployed to find out about the unknown*" (Hutchinson *et al.*, 2003), deployed into a lived context and observed for a period of time. Technology probes share a heredity and motivation with cultural probes (Boehner *et al.*, 2007), though these encompass a wider design space and can involve artefacts such as card games, photographs and diaries. Technology probes are well-developed, albeit often simple, working technologies: "*not a prototype, but a tool to help determine which kinds of technologies would be interesting to design in the future*" and/or to learn about the context in which it is deployed. Reflection on and analysis of how probes impact and "*change the behaviour of our users*" is important in revealing insights into the deployment context: for instance, in (Hutchinson *et al.*, 2003)'s study of supporting communication in geographically separated families, the authors learned about "*practical needs and playful desires*" through how the probes "*provided real-life use scenarios to motivate discussion in interviews and workshops*". I further outline the technologies I have developed in section 3.5, and in the data chapters.

A further technique adjacent to the use of cultural/technology probes is the use of data as a boundary object. Boundary objects (Star and Griesemer, 1989) are a tool for forging understandings between people across divergent social groups. Star and Grisemer's original work focuses on naturalists, discussing their "*specimens, field notes, museums and maps*" as such objects. In this way, data on environments or buildings can be considered a boundary object, and used as a starting point for discussions to elicit participants' thoughts, feelings and ideas on the spaces they inhabit. As discussed in the literature review, it is easier than ever to collect this data given advances in pervasive sensing and IoT data systems. Talking over this data has been used by authors variously as a method for engaging stakeholders in a building, supporting professional practices, or refining and validating research questions. For example, (Verma, Alavi and Lalanne, 2017) use participatory data analysis in their study of space use: the visual co-exploration of this data allowed the researchers to validate their captured data by correlating it with building occupants' lived experience. (Fischer *et al.*, 2017) articulate the sense-making practices of professional energy advisors and their clients in interpreting and understanding such data, a process they term 'data work'. (Tolmie *et al.*, 2016) examine the articulation of sensed data to third parties ('articulation work'), uncovering the social nature of data and how it indexes human action. In two of the studies presented in this dissertation, sensed data is used in conversations with occupants, treating them as 'local experts'. Dialogue over data as a boundary object becomes the methodological tool for surfacing ideas, thoughts, feelings, and concerns about their environmental context.

While these methodologies are appropriate in the first two case studies, the third case study differs in its context, requiring a shift in approach to fill the methodological gap. While CS1 and 2 examine contexts retrofitted with smart technologies, CS3 examines a 'real' smart building: a context already augmented with sensors and thought about as 'smart' by occupants and management staff. In a sense, while the first two case studies examine artefacts inserted into the context of a building, the third studies the smart building as an artefact itself. I therefore engage with speculative design methods in the pursuit of this final case study. These originate in the aforementioned tradition of Scandinavian participatory design, "*opening up critical dialogue around technological alternatives*" (Elsden *et al.*, 2017), and can be viewed as a form of research through design. Speculative methods in HCI have been used to envision alternative futures and study perceptions of speculative technologies which do not yet exist. Various approaches exist to illustrate future technologies and contexts for users, such as design fiction (Blythe, 2014), physical prototypes and simulations (Jensen, Raptis, *et al.*, 2018), videos (Briggs *et al.*, 2012), and animated sketches (Rodden *et al.*, 2013). Ambiguity is also an important resource in speculative design processes (Gaver, Beaver and Benford, 2003) in order to leave space for participant interpretation and for "*critical and creative dialogue*" (Briggs *et al.*, 2012). Briggs et al. draw on this ambiguity explicitly through their videos of interaction scenarios: the speculative technologies in these are shot out-of-frame, making them invisible to the viewer. Further, Vines discusses provocation and humour as design resources, leveraging critique as "*a valuable resource for generating new ideas*" (Vines, 2018, p. 126).

Visions for the future, and narratives which support participants in imagining these, are a powerful tool within the practice of speculative design. Design fiction (Sterling, 2009) is one such method, originating in the observed power of science fiction literature for forging cultural imaginaries about technology: the *Star Trek* tricorder, for instance, or the *Back to the Future II* hoverboard. Design fictions are narratives or 'story worlds' (Lindley and Coulton, 2015) through which a researcher might invite participants to suspend their disbelief about a future technology, perhaps being used as a tool to provoke thought. Sterling defines design fiction as "*the deliberate use of diegetic prototypes to suspend disbelief about change*" (Bosch, 2012). These are not limited to the written word however, and can also include "*films [...] objects and semi-working prototypes*" (Blythe, 2014). Yet, as (Reeves, 2012) points out, "*envisionings only ever (and can only ever) reflect the concerns of the time.*" Through the practice of envisioning the futures represented by these diegetic prototypes, we rehearse the concerns of the present. Fictions have power to provoke these concerns. People cannot know how they will feel about the world of a hundred years' time, but can discuss imaginings of it based on their current context. While HCI researchers have widely adopted design fiction into their methodological toolkits, (Dunne and Raby, 2013, p. 100) caveat its use due to this "*dependence on referencing the already known*" and note that design fictions *"are rarely critical of technological progress and border on celebration rather than questioning."* Consequently, given that my approach shifts from probing the present into speculating on the future in the third case study, I develop a speculative design methodology combining a grounding in present concerns with speculation on the future.

In CS3, this grounding is undertaken through a walking exercise. This choice was inspired by a rich tradition in the social sciences and in HCI of the use of walking methodologies to explore peoples' relationships with place (Ingold, 2004; Ingold and Vergunst, 2008; Evans and Jones, 2011; Crivellaro *et al.*, 2015; Clarke *et al.*, 2016; Asimakopoulos and Dix, 2017), often in the context of outdoor environments such as the city or green spaces. As anthropologist Tim Ingold argues, the practice of walking is inherently intertwined with an individual's environment, and *"walking is itself a form of circumambulatory knowing*" of the spaces and places they frequent (Ingold, 2004, p. 331). Methodologically speaking, walking and walking *with* (i.e. with human and non-human others) offers snapshots of peoples' lives inaccessible through spoken or written accounts, which "*convey little or nothing of the* *embodied experience of the walker"* (Ingold and Vergunst, 2008, p. 10). Walking and on-the-move interview methodologies are reviewed by (Evans and Jones, 2011), indicating that "*a major advantage of walking interviews is their capacity to access people's attitudes and knowledge about the surrounding environment.*" They highlight a tension (and methodological choice) in whether the route is set in advance or roves about organically: pre-determining routes can be less natural, taking participants beyond their usual routines, but can focus the interview "*on specific places that are relevant to the goals of the research project.*" There are multiple examples of walking in HCI in the literature: Asimakopoulos and Dix's (2017) report and analysis of Alan Dix's ethnographic 1050-mile walk of the Wales Coast Path and Offa's Dyke; and Clara Crivellaro and Rachel Clarke's co-development of the "City Walks" method (Crivellaro *et al.*, 2015; Clarke *et al.*, 2016) as a reflective tool incorporating archive research, promoting discussion and sharing in-place understandings of historic and future change in the city centre. In the third case study, CS3, I contribute an application of walking methodologies to the context of large non-domestic buildings, these buildings being places where walking is the only acceptable method of traversing the space, in contrast to outdoors contexts where we may also cycle, drive, and so on. The development of this methodology is described in more detail in Chapter 6.

3.4 Data Collection and Analysis

Interviews and focus groups are the primary tool for data collection in this work. In general, I designed my data collection procedures in line with a narrative approach (Creswell and Creswell, 2018, p. 54) using open-ended interview questions. Through these, I sought to collect stories and personal experiences around the built environment context, and occupants' practices and their interactions with deployed technologies. In focus groups, a range of techniques were used to facilitate group discussions around varying issues: open-ended questions relating to their real-life use of technologies; dialogue over data as a boundary object; exploration of buildings through walking; photo-elicitation; and speculative prototypes. In both interviews and focus groups, the conversation was recorded using a voice recorder. High-quality, thorough orthographic transcripts (Braun and Clarke, 2013) were then produced either by myself or using a commercial transcription service. Transcripts were anonymised with participant identity being masked using identifiers (e.g. 'P1', 'P2') in preference to pseudonyms.

An open-ended, narrative-based approach such as this requires a suitable analysis method in order to make sense of the gathered data. My analysis approach in this work has been interpretative, rather than descriptive: rather than reporting on exactly what was said by participants and making sense of discrepancies (descriptive analysis), I attempt to 'look beneath the surface' or generate deeper understandings "*to try to understand how and why the particular accounts were generated and to provide a conceptual account of the data*" (Braun and Clarke, 2013). Therefore, method selected for the analysis of this audio/textual dataset was reflexive thematic analysis (Braun and Clarke, 2006, 2019). Thematic analysis (TA) is a "*a method for identifying, analysing and reporting patterns (themes) within data*" (Braun and Clarke, 2006, p. 79). TA is a popular and theoretically flexible approach to the analysis of qualitative data, agnostic to the epistemic viewpoint and (within reason) the methods chosen by the researcher. As a result, it has enjoyed wide adoption within HCI and related disciplines. Yet, while thematic analysis is employed in a range of different ways in the literature, it is "*often misconceptualized as a single qualitative analytic approach*" (Braun *et al.*, 2019). It is better understood as an umbrella term for a cluster of approaches for "*identifying themes and patterns of meaning across a dataset in relation to a research question*" (Braun and Clarke, 2013, p. 175).

Although TA is often used in different ways in the literature, in this work I generally follow the phases described in (Braun and Clarke, 2006) and clarified in (Braun and Clarke, 2019): familiarisation with the data; generation of initial codes; generation and review of initial themes; defining and naming these; before producing a report of the findings. The process of 'coding' textual data involves highlighting segments of the transcript, and labelling them with a word or short phrase which relates to the content. Themes are then generated by collecting codes representing a common idea or concept. In this research, the phase of code and theme generation has often been iterative: for example, in producing CS3 I returned to the data for a second (even third) coding phase in order to produce codes better relating to initial themes. Themes and findings are not related on a 1:1 mapping. Findings in my work were generated by considering how themes relate to the original research question(s), forming a narrative or "*central meaning-based concept*" (Braun and Clarke, 2019) which elucidates a discovery about the participants, the technology, or the context.

As I preference an inductive analysis in this work, my codes are primarily generated 'bottom-up' from the data as opposed to 'top-down' through the application of a theoretical framing. It is notable therefore that TA is a form of interpretivist analysis, and thus the perspective of the researcher is important as they are the one putting a lens on the data. This subjectivity is typically "*understood as a resource, rather than a potential threat to knowledge production*" (Braun and Clarke, 2019, p. 591). As such, one common pitfall in TA is to state that themes 'emerged' from the analysis process. But the researcher is not a passive observer[18]. Themes do not 'emerge': they are "*conceptualised based on the data*" (Brulé and Mitchell Finnigan, 2020) and curated and constructed by the researcher, who investigates a research question through a scholarly process of engagement with the dataset.

3.5 Case Study Approach

In this section, I outline how the methodological approaches described above are employed in the three case studies, and in targeting and addressing the research questions I have identified. These research questions are defined at the end of Chapter 2, but I highlight them again here for reference. The case studies take the form of situated design experiments which aim to identify factors relating to the role and design of data and digital technologies, within the scope of each of the three research questions. The three buildings chosen represent a spectrum of non-domestic built estate, from an ageing brutalist 1960s building through to a modern 'smart' building. This selection is important in achieving a representative sample of experience across three very different buildings, with different opportunities for occupant control and adaptation, and in addressing how smartness can be understood as more than just automation.

The three case studies, as discussed above in 3.3, engage with the research questions through application of slightly different methods. While I investigate RQ1 and RQ2 using technology probes, RQ3 requires a more speculative approach in learning about existing smart building technologies. Rather than exploring how a novel smart technology affects study participants' practices, the aim of RQ3 is to *observe* a context where participants are already embedded within the existing sociotechnical environment of a smart building.

All three studies are set in offices and buildings managed by a Higher Education provider. As I reflected on in the literature review, access to infrastructure and buildings to facilitate

[18] See also: the #themesDoNotEmerge hashtag on Twitter, and this tweet by Virginia Braun who along with Victoria Clarke has authored much of the post-2006 scholarly literature on Thematic Analysis which I cite extensively in this chapter. https://twitter.com/ginnybraun/status/1100204440659738625

smart non-domestic buildings research is limited. From a practical perspective, universities are a context where innovation is actively encouraged: it is easier to gain access to facilities and the expertise of management personnel, making it feasible to run the studies I propose here. Some of these contexts are easily generalisable: the office building and administrative staff examined in case study 2 do not differ substantially from other offices and workers within the private and public sector. Further, with respect to case studies 1 and 3 and linking to the underlying social justice agenda of this work, there is a lack of smart non-domestic buildings literature which examines populations who are not office workers. How university students interact with such buildings is an area of interest: as an underrepresented population, there is a need to investigate how this stakeholder group might be better involved in smart buildings management processes. This feeds into an overarching motivation of how best to design technologies that can help to raise the voices of populations who are not traditionally stakeholders in the buildings management process.

3.5.1 Case Study 1 (Chapter 4)

RQ1: How can retrofitted sensor data augment facilities management processes, and how might building users be empowered to participate in these?

Case Study 1 involves the development and deployment of an environmental sensor toolkit, BuildAX, following 4 professional facilities managers and a group of 12 student auditors as they learn to use it. This tackles the need for retrofitting of sensor systems as identified in the literature review, addressing the lack of available contexts to undertake studies, which is one of the major barriers to smart buildings research. The 1960s brutalist buildings in which the student-facing portions of the case study were undertaken sit about as far away from the 'smart building vision' identified in Chapter 1 as it is possible to get. The retrofitting of sensor technologies coupled with a strong understanding of usage and deployment practices may go some way to addressing this gap, creating 'smarter' facilities management processes. Yet, this case study was also interesting in that professional participation grew fairly organically as facilities managers heard about the sensor toolkits by word-of-mouth, and saw ways these could assist in their own practice.

Data collection within CS1 involved a two-pronged approach tailored to the participant groups involved. Student auditors participated in a focus group, two co-deployments of sensor toolkits with assistance from myself, and both individual and group interviews following their undertaking of their building audits. Students were chosen as a target population for this study as they inhabited the audited buildings. They were effectively novices in auditing and data analysis, but were likely to have contextual understandings of the building, e.g. usage, that professionals might not be aware of. They were useful as a point of comparison to professional facilities managers, and could give some insight into how non-expert users might engage with the sensor toolkits. Professional facilities managers participated in interviews, and were assisted with sensor deployments where this was desired (others were confident in their own ability to deploy the sensors independently). The toolkits acted as a technology probe (Hutchinson *et al.*, 2003) in this respect. The data produced by the sensors was used by the auditors in addressing their own questions about the building, but was also used as an elicitation tool in the interviews to get at factors relating to occupant participation in existing management processes. The interview corpus was thematically analysed, with findings pointing towards how auditors engage with existing systems and practices, the sense-making practices they employ in interrogating sensor data, and the tensions and challenges they encountered throughout the auditing process.

3.5.2 Case Study 2 (Chapter 5)

RQ2: How can data and digital technologies foster shared understandings and assist comfort negotiations in the office workplace?

Case Study 2, addressing RQ2, involved the development and deployment of a second technology probe, ThermoKiosk, within a modern non-smart office building constructed 2010-2012. This probe was designed to investigate how occupants can share understandings of their experience of thermal comfort in the workplace, in settings where they have minimal control over the thermal environment. The studied 7^{th} floor office was inhabited by 26 occupants, and was suggested as a suitable context for this work in conversations with building management staff as a result of its history of unresolved thermal comfort complaints. The ThermoKiosk probe is described in more detail in Chapter 5: situated feedback terminals deployed on staff desks collected data on subjective experiences of thermal comfort to augment the 'objective' sensor data collected through a second (researcher) deployment of BuildAX. This subjective data was displayed adjacent to the two HVAC controllers in the office to augment decision-making practices around the use of office air conditioning.

Data collection involved interviews with two facilities management staff responsible for maintenance, and 14 interviews with staff in the office which were undertaken with the help of a second researcher. Interviews were recorded with participant consent, and the corpus of transcribed interview data was thematically analysed, and findings produced. Quantitative sensor data was graphically analysed and used to support qualitative occupant accounts in a mixed-methods approach (per 3.2). The findings reveal office tensions connected to the ThermoKiosk probe, which interacted with the social fabric of the office in varied and complex ways, and have implications for the use of subjective data in intra- and extra-office negotiations, and how occupants understand and reason over their environments. The discussion draws out implications for how occupants can become active inhabitants, developing community notions of comfort, and opportunities for technologies within the adversarial social fabric of the office and organisation.

3.5.3 Case Study 3 (Chapter 6)

RQ3: How can HBI support occupant agency and participation in the everyday management and adaptation of smart buildings?

The final case study, CS3, looks towards the future of smart buildings through examination of the lived experience of occupant participants in a 'real' smart building, the construction of which was finished in 2017. As discussed above, this study required a shift in methodology to address RQ3, switching from a technology probe method to a future-oriented, speculative approach combining walking and a design activity. As I observed in Chapter 2, while CS1 and 2 examine retrofitted building contexts, CS3's context may offer new opportunities for occupant involvement in discussions of the ongoing process of management in a smart building, requiring a corresponding adaptation in the methodology through which I approach the research question.

Following a series of motivational interviews with 4 staff involved in the specification, construction, and management of the building, I developed a design workshop and recruited

16 student participants by advertising through a departmental mailing list. The design workshop operated in two phases: the first phase involving a grounding exercise which allowed students to explore the building and relate accounts of their experiences and perceptions of space; the second drawing on those experiences to critique a set of speculative technology designs and produce designs for future ways to address their perceived shortcomings of the building. The methodology, involving the use of speculative 'diegetic artefacts' developed through the thematic analysis of the staff interviews, is described in further detail in Chapter 6.

3.6 Summary

In this chapter, I have summarised my research approach, which follows a qualitative inquiry into the research questions with the use of some mixed methods to support the qualitative aspects. I adopt a social constructivist / interpretivist worldview within this, with implications for the design of the methods used. I have outlined a range of approaches which are well established within the HCI discipline, and described how these relate to the case studies I have chosen. In the next three chapters, I describe these three case studies, including their results and implications for the research questions.

Chapter 4: Case Study 1—Augmenting Audits

Clamp Centre is the most advanced smart building in America.
With the latest security, communications, and climate control...

GREMLINS 2: THE NEW BATCH (1990)

4.1 Introduction

For smart buildings to be inclusive and ethical, we must involve the people who live and work in them. Within the 'modernist' smart building agenda, the only group really empowered are facilities management, with smart buildings providing better tools and data for their work than traditional buildings. This chapter examines how this data might be made available and useful to groups beyond facilities management, motivated by the social justice agenda discussed in §2.3. I further challenge the notion that only new buildings can be 'smart', asking how old buildings might be made smarter, too: a 'modernist' smart building is financially exclusive, in that the benefits of smartness are limited to those companies and individuals who can afford to be situated within shiny, new real estate. But facilities management is an expert task (Goulden and Spence, 2015), and it is naïve to give access to this data to non-experts without any supporting infrastructure: data literacy forms part of this barrier to empowerment (Schwartz *et al.*, 2013), and moving from data towards action often requires multiple perspectives (Hasselqvist, Bogdan and Kis, 2016). In order to democratise smart building data, we first need to examine the processes in which this data is used and acted upon.

One such practice which might provide an infrastructure for the inclusion of amateurs is energy audits. Auditing energy consumption in buildings is a common practice for facilities managers (FMs) in medium to large organisations, and legally mandated in countries such as the United Kingdom. Energy audits seek to identify inefficiencies in building design and operation to reduce running costs and ensure standards-compliance (Alajmi, 2012). There is an emerging need for tools which can be used to retrofit older buildings to provide data collection and enable new forms of smartness, however, as the literature review demonstrates, there is yet little work in this respect reported on in the academic literature. In this case study, I seek to understand **RQ1**: "h*ow can retrofitted sensor data augment facilities management processes, and how might building users be empowered to participate in* *these?"* I investigate how sensor toolkits are used by FMs to augment their existing audit practices with additional data, and how novice auditors understand this process (and through it, their building) by studying deployments of an environmental sensor toolkit, BuildAX. This system sits at a mid-point of typically sensed variables, with flexibility and robustness for rapid deployment and reusability, addressing the needs of the auditors who participated in this case study.

Sensor toolkits are distinct from static systems such as building management systems (BMS, which control HVAC and capture limited environmental data). Sensor toolkits, in the sense in which I use the term here, can be considered to be repurposeable, redeployable, and retrofittable. They are *repurposeable* in that they are not designed for a single purpose and may therefore be used in a variety of contexts by a variety of different groups; *redeployable* in that may be removed after a period of time and deployed elsewhere to collect data for another project; and *retrofittable* in that they augment current infrastructure, and are not usually planned as part of a building design but may be installed at any point after construction. This does not preclude such kits from being used for extended periods of time in a single investigation, as building energy projects may require extended data sets, for example to account for seasonal variation in the outdoor climate. Additionally, the wording of *toolkit* is intentional in that it includes not just the hardware but also software systems and best practices which assist in analysis and interpretation of collected data. Examples (e.g. (Jahn *et al.*, 2011)) include temperature sensors for investigating the performance of building fabric (e.g. insulation and heat loss), light sensors for evaluating energy consumption by light fittings, and movement (PIR) sensors for understanding room occupancy.

FMs use data from various monitoring and metering systems, including BMS, in managing their organisation's energy consumption. However, existing data sources are often insufficient to meet the needs of modern FMs, for example: (i) in complying with building management standards; (ii) evidencing funding applications; and (iii) understanding where best to focus improvement efforts. I present findings on a deployment of the environmental sensor toolkits with FMs and student auditors (SAs), and a qualitative study of how these toolkits were used in the practice of energy management. These develop understandings of FMs' deployment strategies in the context of existing energy audits, accounts of how experience and tacit knowledge is leveraged, and discuss the tensions, challenges and design implications that emerged as a result.

In their capacity as professional auditors, FMs make recommendations for improvements to energy-intensive systems, such as Heating, Ventilation & Air Conditioning (HVAC) systems and lighting, as part of a resource optimisation process. This process requires comprehensive auditing procedures, utilising diagnostic tools and measurements of key energy factors, to generate actionable recommendations for improvement (Shapiro, 2009). Measurements are captured from existing infrastructure (e.g. electricity meters & BMS), and handheld sensors for specific data, such as lighting intensity, to meet various standards that are required for compliance (Alajmi, 2012). Formalised auditing and measuring of energy use are the primary tools used by FMs, based on industrial standards which give structure to sustainability goals and the investigation of energy consumption.

Measuring and verification protocols (e.g. the International Performance Measurement and Verification Protocol, or "IPMVP" (EEVS Insight Ltd, 2016)) are adopted by FMs to understand their organisation's energy consumption, and empower them to make actionable recommendations for improvement. Sensor toolkits could play a key role in capturing such measurements, but their utility is not currently well understood. In recent years, sensor toolkits have been the subject of research in Sustainable HCI (e.g. (Eisenman *et al.*, 2007; Aoki *et al.*, 2009; Jahn *et al.*, 2011; Houben *et al.*, 2016)). (Blevis, 2007) put forward a "*vision of incorporating sustainability into the research and practice of interaction design",* which has since matured into an ongoing concern for the HCI and Ubicomp communities with a push to develop new design patterns and rhetoric for sustainably-focused research (Knowles *et al.*, 2016).

In this chapter, I contribute to this agenda by investigating the utility of flexible sensor toolkits to support sustainability through existing energy auditing practices. I examine the context of internal audits in this case study: audits to gather data on facilities to correct gaps in knowledge, and to prepare for external audits by an outside organisation. The auditor participants in this case study therefore include facilities managers, energy managers (specialised facilities managers), and students performing audits with a facilities department for professional development or as part of a taught module.

4.2 Methodology

A unique facet of this project was that I, as the researcher, did not actively seek to recruit participants for this study. Rather, following the development of the *BuildAX* environmental sensor toolkit for a related project, my department was approached by facilities managers both within and external to the university. I contributed both the sensor toolkits and, where required, time in deploying sensors and collecting and analysing data. In return, participants provided accounts of their experiences. I was therefore positioned as a party providing a tool or service, though as a researcher rather than a commercial entity.

Deployments with postgraduate students were similarly exploratory in nature. The FMs who participated in this study recommended I contact the module leaders of a postgraduate course on environmental auditing. As part of this course, students undertake practical fieldwork, assisting FMs by conducting audits of buildings on campus: in effect, they are early-career auditors, contributing data to be used in preparation for external audits in the future. Two other postgraduate students within a different faculty made contact following this, seeking to use sensor toolkits as part of their auditing projects, working closely with the professional facilities managers I had spoken with previously. I also interviewed the module leaders of both postgraduate courses *(ML1, ML2)* to understand students' existing knowledge, how this is used in their auditing practice, and the professional standards from which the module curricula are constructed.

Interview questions were tailored to each respondent, as their job roles differed significantly, but followed common themes: participants' existing practices in collecting and using environmental data, their experiences of sensor toolkit deployment, and the process of analysing data collected using the sensors. Interviews lasted between 20 and 60 minutes. Furthermore, ethnographic field notes were kept where deployments were undertaken with the help of a researcher. Working with SAs, rather than solely FMs, allowed unique insights as students freshly encountered the processes that FMs were experienced with. As the findings of this case study report, this enabled new understandings of the ways in which sensor deployments were undertaken that leveraged FMs' tacit knowledge of the buildings and estate in suggesting projects and planning deployments.

The study took place over a 2-year period from 2015-2017, where deployments varied in length from 2 weeks to ongoing, semi-permanent installations lasting from 6 months to a year. While work predominantly took place within four 1960s-era buildings on the Newcastle University campus, this case study also includes data from two external buildings: a school in Manchester, and an office at another university in north west England. Trial sensor deployments with student auditors (SAs) were conducted over a period of 6 months, with qualitative data collected through interviews and a focus group with the students, which took place during a scheduled seminar on the taught module. The semi-structured interviews were transcribed verbatim and subject to thematic analysis, with the derived codes producing 3 main themes: *T1*, *acquiring* data; *T2*, *making sense* of data; and *T3*, *actioning* data. These themes were subsequently condensed and synthesised into the findings presented in this chapter.

4.2.1 Participants

Interview participants from professional roles included facilities managers of educational institutions in the north of England. I interviewed the Sustainability and Energy Managers at my own university as part of my initial exploration of the space, which helped to finalise the research direction and question for this project. I then interviewed individual facilities managers who had performed audits using the BuildAX toolkit. *FM1* and *FM2* work as part of the team responsible for sustainability on campus. *FM1* had additionally been a postgraduate student at the same institution in the past, and had conducted a project with the sensor toolkit. *FM3* is the estates team manager at another university in the North West. *FM4* is the head of estates at a secondary school.

Manager	Role	Audit information	Deployment
FM1	Sustainability Officer	Lighting audits, individual data analysis	Researcher-assisted
FM2	Sustainability Officer	Heating audits, individual data analysis	Using existing deployments
FM3	Head of Estates (University)	Individual data analysis	Self-deployed
FM4	Head of Estates (School)	Individual data analysis	Self-deployed

Table 1: Professional facilities manager participant information

Student	Project Type	Audit Information	Location
S1	Individual project	Lighting & Heating audit	Mechanical Engineering Building
S2	Individual project	Lighting audit	Geosciences Building
S3	Auditing Module	Professional development (multiple audits)	Multiple buildings (without sensor use)
S4, S5, S6	Auditing Module	Water & lighting audit (Auditing MSc)	Chemistry & Electrical Engineering Building

Table 2: MSc student auditor participant information

Facilities managers explored the sensor toolkits by using them as part of real-world auditing processes, often in multiple and varied locations: for example, one audit performed by *FM1* examined internal lighting, using the “Light” data stream as a proxy for the on/off status of lights within a building. This data was then used to prioritise an ongoing retrofit of lower energy LED fittings in T8 fluorescent lighting fixtures. As the BuildAX sensor toolkit is able to provide raw data in CSV format, FMs often used existing skill-sets in statistical data analysis and/or spreadsheet software to convert this into a meaningful form.

Student participants *S1* and *S2* performed data collection towards their Masters dissertations using the sensor toolkit. *S3* was a student on the Environmental Auditing MSc programme performing further audits with the estates department for professional development. *S4,5,6* responded to a request for interview from the group of 11 focus group participants. All Auditing MSc SAs participated in a researcher-led group deployment of the sensor toolkits which took place following the focus group, before performing their own deployments in the same building, which they filmed to document sensor placement. Other students were interviewed on their use of the toolkits (for example, an undergraduate using a kit to track humidity as part of an experiment), but were not included in the analysis as their work was not auditing related.

4.2.2 The BuildAX Sensor Toolkit

Figure 4: BuildAX Environmental Sensor Toolkit: including logger, sensor nodes and supplied cables

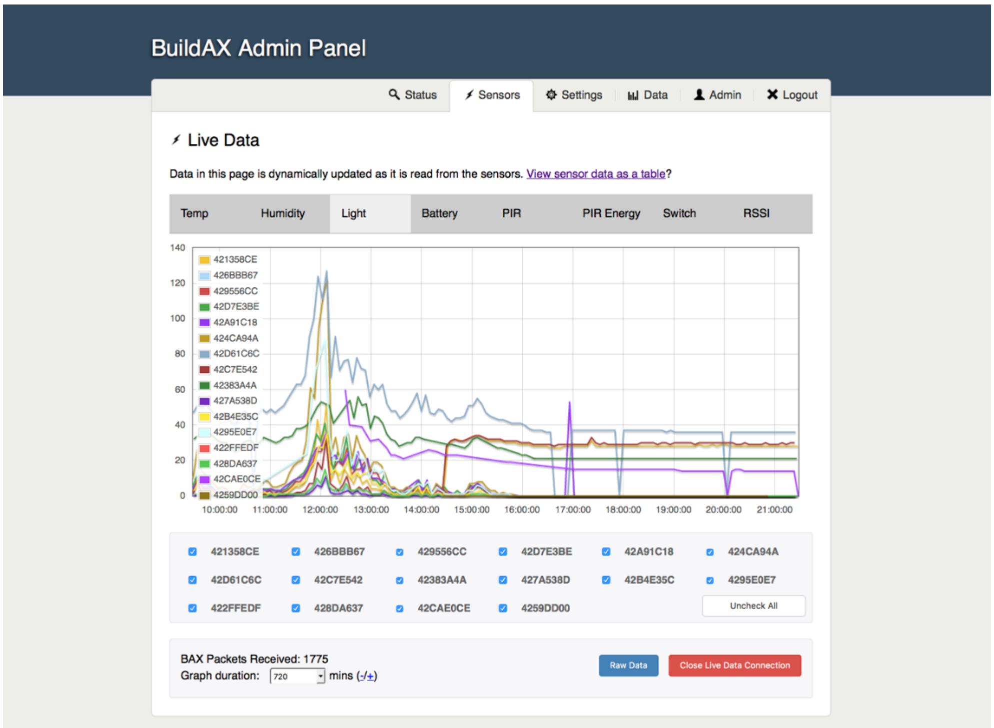

Figure 5: The BuildAX web admin panel, showing the live data stream from the environmental sensors

The sensor toolkit distributed to FMs and students consists of a base unit (Figure 4), called the LRS or "Logger, Router, Server", which receives data from sensor nodes with a range of approximately 100m line-of-sight and logs this to memory (SD card), with optional network access. The sensor nodes incorporate factory-calibrated temperature, humidity, light, passive infrared (PIR), and magnetic reed switch sensors[19]. The sensors were pre-configured to broadcast data packets at a resolution of 30 seconds, or 120 samples per hour, to allow analysis in tools such as Microsoft Excel which does not cope well with high resolution data, but does afford analysis capability to auditors without a background using statistical software packages. Additionally, I developed a simple online tool to generate PDF reports from uploaded sensor data files, to allow visual analysis of trends over time.

I developed the BuildAX toolkit in collaboration with colleagues at Open Lab, Newcastle University, over the course of 2014-2015, as part of an EPSRC-funded research project[20]. The platform selected for the hardware was the Microchip PIC family of microprocessors: a low-power 8-bit CPU for the sensor nodes, and a 16-bit processor for the base unit which allowed it to handle a richer suite of applications. My colleague Dr Karim Ladha designed the hardware and firmware for the sensors, and I led on the development of the base unit firmware, including its web-enabled features, associated tooling for data analysis, test tooling, and documentation. The hardware and firmware was open-sourced under the OpenMovement project, and I authored comprehensive documentation including a set of instructional YouTube videos, which are available online[21].

I contributed to firmware development in the C programming language using the Microchip SDK, authoring a lightweight HTTP web server to enable configuration and monitoring over the local network. The web interface, one page of which is shown in Figure 5, allows the user to pair sensors and monitor readings in real time. The administration web page was written in HTML and JavaScript, using websockets to enable live-streaming of incoming data from the sensors. It includes functionality to list sensors, adjust settings, and retrieve logged data in either CSV or binary format over the network, and is protected by a

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[19] Technical accuracy for BuildAX ENV sensor nodes: Temperature: -10°C to 50°C ±2°C, -7°C to 47°C ±1°C. 0.1°C resolution. Humidity: Operating range 20% to 90% saturation at 5°C to 60°C, 5% accuracy. 0.1% resolution. Light: ±30% gain error max, typical gain error ±10%. Inc. fluorescent lamp flicker filter.

[20] EP/L024489/1, *Pervasive Sensing for Collaborative Facilities Management.* Karim Ladha led on hardware development, and Tom Nappey designed the injection moulded plastic sensor casing.

[21] http://digitalinteraction.github.io/openmovement/buildax/site/

username and password. I further developed a website running on the University's local intranet to allow auditors participating in the study to generate PDF reports of the logged data. The PDF report generation tool was written in Python using the weasyprint library, and was also open-sourced[22]. An example report is attached in Appendix C.

A factory in Cramlington, Northumberland was contracted by my colleague to produce the hardware (populated PCBs) for the base units and sensor nodes, and I conducted a site visit in early 2015 to train a staff member in flashing firmware to the devices and in the operation of the unit testing framework. Injection-moulded ABS plastic housings for the sensor nodes were designed by Tom Nappey at Open Lab, and I assembled approximately 500 sensors (populated PCBs and housings) prior to deployment over the course of 2015-16. Finally, in distributing the sensor toolkits I developed packaging, both out of utility in sending these to the remote facilities managers, but also in line with the philosophy of technology probes as described in the methodology chapter, that these should be a well-developed technology (not a prototype). The toolkits were distributed in two boxes, each containing 16 sensors and a base unit.

The process of physically deploying a sensor toolkit involves distributing the sensor nodes within the space, setting up the base-unit, and (in a few deployments) accessing this from the network to retrieve data in real time. In the larger researcher-led deployments, I first conducted a range test with the auditor, ensuring that the sensor nodes would be within signal range of the base unit. Auditors were then directed to attach the sensors at a regular height with a supplied adhesive strip to ensure regular readings with regards to temperature stratification throughout the room, and encouraged to take note of how ambient heat sources (e.g. radiators), and the causes of heat loss (e.g. windows) affect readings. Indeed, in some of these deployments the auditors' intention was to quantify how these factors affect the thermal characteristics of the room. The position of all sensors was noted on print-outs of the floor plan of the building, which were later scanned and attached to the automatically generated report PDFs.

[22] The PDF report generation tool is open-sourced at https://github.com/sjmf/reportgen

Figure 6: BuildAX packaging as distributed to FMs and SAs in two boxes containing the router and sensors

4.3 Findings

Through analysis of the study data, understandings were developed of how auditors engage with existing systems and practices, detailed in section 4.3.1. Examined in 4.3.2 are the approaches, methodologies and tacit knowledge leveraged by auditors when addressing a task in which data collection is necessary, and the sense-making practices they employ in interrogating sensor data to ask questions of the built environment. Finally, the tensions and challenges encountered throughout the auditing process are dealt with in section 4.3.3, including instances where the realities of sensor toolkit use did not correlate with expectations.

4.3.1 Potential in Existing Audit Practices

Auditing provides a mechanism by which FMs may evaluate environmental sustainability, detect anomalies, and satisfy legal accountability. Central to this, some process of data collection is required: an FM undertaking an energy audit could collect electricity and gas meter readings for a building, compare them against an expected baseline, and make recommendations for improvement. A walk-around to gather information on physical aspects may also be required if this is not centrally recorded: SAs performed walk-around studies to record data on the types of light fittings installed, so that energy usage could be more accurately evaluated and upgrades prioritised.

FMs found that existing data sources could be augmented to collect higher granularity data, more conveniently. Sensor toolkits were employed, for example, to record usage of lights at a per-fitting granularity, or to evaluate the effects of solar gain on a room's temperature profile. While it may have been possible to collect this data previously, a staff member would need to travel to the building a few times a day to take measurements with a hand-held probe. This section examines how existing sociotechnical systems and practices were affected by the introduction of sensor toolkits, how these technologies informed ongoing audits, and how they provided the data FMs needed to generate understandings of the building fabric.

Change Through Understanding

Auditing is employed by FMs as a tool for questioning and informing change. Participants saw the sensor toolkits as 'another tool in the toolbox', utilised in the business of facilities management in combination with other techniques and systems to provide data for this process. An FM's role includes employing a diverse set of standards in their on-going improvement practices, particularly relating to energy management: this allows FMs to structure the improvements they make, and measure their associated progress. Audits are a way for the organisation to check they are complying with these standards. As part of her role working with the facilities management department, S3 has performed audits including checking compliance with defined procedures on *"pesticides and oil storage, so it's just looking at the procedure that we have in place, [...] compliance requirements, and then auditing the person responsible just to see if they're following everything that's in the procedure" (S3).* Compliance may also be a necessary consideration from a legal perspective, such as in the ESOS energy assessment scheme administered by the UK Environment Agency (GOV.UK, 2014).

However, FM1 notes that *"... with ESOS' research regulations, you have to do energy audits every 4 years unless [...] you have ISO 50001 certification*". ISO 50001 provides benefits beyond those that are legally mandated by specifying a process of continual improvement, such that FMs must demonstrate year-on-year actions to improve energy efficiency. Ways of measuring and understanding this improvement are provided by internationally verified and proven protocols, e.g. IPMVP (EEVS Insight Ltd, 2016). Energy managers rely on their experience in navigating the complexities associated with standards, and identify opportunities for employing sensor toolkits in proving their compliance and measuring efficiency as part of a process of continual improvement.

Supporting Funding Models

In acquiring the capital needed for improvements to buildings and infrastructure, FMs must apply for funding as part of their work. The application of sensor toolkits in this process allows FMs to build a base of evidence to support capital expenditure on improvements: *"If it was for a major case it would help us build a business case, based on evidence, based on data, to say, look this needs doing. In the simplest of terms" (FM2).* Certain types of projects are prioritised by evidence-based funding models, raising a necessity for data collection. From conversations with the FMs and SAs, it became apparent that the kind of data collected using the environment sensors lent itself well to providing the evidence needed for funding applications.

S1 talks about the recommendations he is making for lighting through his audit of the Geosciences building: "*The estates are using, it's called a Salix funding, so [...] they'll help to fund projects that have a payback of less than 5 years. So yeah for lighting that's one of the key ones, [...] because it ticks that box and they don't have to go and ask for more money" (S1).* This relates closely to the process of continual improvement specified by ISO 50001, and lays the foundations for justifying further funding from bodies such as Salix. There is a requirement for providing evidence to these funding bodies, and sensor toolkits provide a means for measuring those factors: "*We can, if we have this sensor data that basically takes, like a 3-week period or something, we can send that to Salix and say, this is our justification for why we believe the lights have been left on 24/7" (FM2).* While external audits are performed by these bodies, internal audits are an on-going way for FMs to understand progress.

Augmenting BMS as an Auditing Tool

Finally, BMSs are the primary tools that FMs use to understand, monitor, and remotely manage HVAC systems. Although technologically very powerful, BMSs come with practical limitations, which FM1 alludes to: *"... sometimes it's complicated. For example, if somebody puts a manual something, in there, in the distribution board, on the panel, the BMS won't show it" (FM1).* Similarly, FM3 raises their concern of the use of BMSs in assisting with the common practice of providing thermal comfort to building occupants: *"we tend to struggle to control our temperatures, so in that respect, the centralised control stuff doesn't seem to work particularly well" (FM3).* Older BMSs, which are still used, can complicate common practices further, as S2 notes from her experience working with an older BMS for an auditing task: *"With [the Engineering] building, the BMS system is basically rubbish[...] comparing it to that for the business school... and theirs was so straightforward, they had set points for every single room[...] It was just really confusing and not set out well at all" (S2).*

BMS systems across the campus can be several decades old. Having been retrofitted over many years, these may have limited sensing infrastructure and HVAC control. In addition, FMs use metering data for gas and electricity to feed in to calculations of usage, and check this is in line with estimates. However, the installed metering infrastructure does not correlate spatially with groups of people working within the buildings: *"... it's very, very unlikely that the installed metering infrastructure exactly matches the distribution of people in the building ... you're always working off assumptions [...] It's quite a coarse tool, I'm not massively happy with it" (FM3).* Though essential for the task, the data provided by BMS can be insufficient to meet the demands of modern facilities managers who strive for more than the minimum legislative compliance requirement. Augmentation with additional tools was attractive to these FMs as they can enable or strengthen ongoing continual improvement.

4.3.2 Questions and Answers: Making sense and use of data

Sensor toolkits are used for different purposes and in different ways by auditors. For example, one purpose might be to understand the question "how bright is the lighting in this area?" or "exactly how warm is it when occupants are raising complaints?" These questions lend themselves well to the application of sensors for inquiry. The findings of the second theme examine how the interviewed FMs and students approach and answer these kinds of questions, and how the functionalities and affordances of a sensor toolkit influence their approach to designing sensor deployments.

Targeted vs Exploratory Projects

FMs have clear ideas of projects where data would assist them in their working practice, but approaches to data collection vary: some FMs need targeted interventions to address a specific problem, others see potential in collecting a wider data set which *may* highlight other problems (though is not guaranteed to). This finding centres on the motivations of participating FMs and students: why they wanted to collect data using sensor toolkits, and how they planned to use that data. The professional facilities managers had clearly targeted intentions for how the sensors would be used as part of a lighting audit: *"It could be used [...] in two ways: one is for projects, and another is for anomalies. So you find that there is a big* *consumption and it's not coming down, [...] Could be [the] lighting is on all the time..." (FM1).* FM2 supports this, noting that fine-grained data allows for more accurate estimations of lighting usage: *"... by deploying a sensor we'd be able to get a better measurement of what the hours are, and use it in this calculation here" (FM2).* In this case, after the targeted deployment, FM1 would remove the sensors to re-use elsewhere: *"Thinking of projects, you know, probably it would be not permanently, just to check that the savings [...], that we are actually doing them" (FM1).*

Projects often centred around management of building occupants' thermal comfort. For FM3, extra data would inform the process of dealing with helpdesk queries and complaints: *"We've got people that are overheating... and we want to know more about that. [...] What I'd like to achieve is very much, a richer engagement... and a lot of that comes down to technology" (FM3);* FM4 also considered this a useful application, noting that many of the comfort complaints he received were seasonal: *"[In] part of one of our buildings, end users [...] were un-comfy in the surroundings. Whether it be too warm, or too cool. And depending on [...] the season that they were reporting the issue" (FM4).* Use was not limited to thermal comfort, however. Many different kinds of data were considered to be useful in diagnosing buildings' problems: *"Oh it could be anything, could be temp, it could be lux level, it could be occupancy, it could be temperature, it could be humidity. Basically, all these, probably maybe CO_2 levels..." (FM1).*

In addition to targeted data collection projects, participants could see potential for exploratory projects and continual monitoring: *"I would think if we had a set of sensors up, I don't think we'd ever want to take them down, really" (FM2).* These were often backed up with anecdotes about situations in which it would have been useful to have sensors, highlighting the expectations they had for what a sensor toolkit could provide. FM1 talks about augmenting the existing BMS system with additional sensor toolkits: *"... one of the sensors got frozen. So it was sending the signal that it was frozen outside all the time. Zero degrees. So, when it's frozen, in order to maintain the heating systems, the pipes, have to be quite warm, it starts working. So we were using gas and electricity for a month until we found the problem. But if you have a sensor— maybe you can use it instead" (FM1).* This finding indicates two approaches towards using sensor toolkits: firstly, using them for targeted interventions or mediations; secondly, those who did not have a specific application domain but wanted to explore the opportunities the sensor toolkit data provided.

Tacit Knowledge in Sensor Deployments

Tacit knowledge is gained experientially, but is difficult to transfer to other people directly through verbal or written means. FMs applied their tacit knowledge of the buildings and premises in targeted and exploratory deployments of sensor toolkits in the observed settings. Student Auditors drew attention to and highlighted the tacit knowledge which FMs possessed, but they did not, through the learning process they followed during their deployments.

Figure 7: Student auditors examine the environmental sensor nodes during a group deployment

S1 and S2 learned that well-planned sensor placement governed the usefulness of data they got back: "*it was sort of interesting to try and picture what you wanted from the data, or what the sensors can pick up in the best locations and what would affect that. So if you put it down a corridor that was not used very much, like on the 5th floor, then is it really worthwhile or are you just putting a sensor there for the sake of putting a sensor?*" (S1). In addition, S2 highlights the importance of consistent sensor placement, as the data she collected would be used to make recommendations based directly on the lighting (Lux) levels: "*I think I would probably think more carefully about putting them kind of in the same location in each room so that it's more fair*" (S2). Attention was paid to the density and placement of sensors, as SAs recognised that having too much data was not useful, making it difficult to analyse and interrogate: "*If you've got a fairly simple problem in a room, like a draft, you wouldn't want*

20 sensors in there [...] You only really need one in a non-draughty place and one in a draughty place" (S3).

In addition to positioning, careful interpretation of the sensor data is required to make sense of its meaning, relying either on tacit knowledge of structures and building physics, or following established practices for calculating desired metrics. S2, through a looser interpretation of the sensor data, formed hypotheses of the processes affecting the building which ruled out effects of solar gain: *"I was thinking that a part of the temperature could be based on something else, like, solar [gain] coming through the windows, but [it's] nothing really to do with the temperature outside [...] Maybe in a couple of rooms, it's slightly higher, like 1 degree higher, and that might be from the sun, but apart from that it's so constant" (S2).* An auditor more experienced in building physics may have better understood these results and perhaps drawn a different conclusion.

However, students from other backgrounds have different skills which allow them to contribute in ways an auditor with a purely technical background might not: *"They've took different approaches, so for example, [S2] went away and actually did some interviewing and questionnaires on top of the energy data, so that she had some user perspective on how they—how they thought about their own energy use within the building. [...] So, doing questionnaire and interview analysis was a skill she already had that she was able to apply to this situation" (ML2).* S2 confirms this: *"I've been doing [...] interviews and questionnaires of people that like work in the building, and basically every single one of them was saying that it's too hot, the building's hot all the time. So from that one it defined high temperature data..." (S2).* The skills which auditors employ therefore have a value beyond the purely technical.

For their part, FMs demonstrated that even if they didn't have tacit knowledge of a building, they had the ability to find assistance through contacts and a familiarity with the organisation's structure: FM1 knew *"people that work in this area in the medical school, and they know the medical school very well because it's a very complicated building. And say, which areas do you reckon we should monitor..." (FM1).* In the discussion, I address how such tacit knowledge might be leveraged in the deployment of a sensor toolkit, by outlining a protocol for augmented audits. I also consider how the target audience of sensor toolkits might be widened as a result, and what this would enable.

Incomplete Knowledge: Challenges and Complexity

Older estates are problematic in that FMs may not have complete knowledge of the fittings and appliances that exist there. Opportunities occur for performing audits of these: the facilities management team engaged MSc students to undertake water and energy audits in order to improve their understanding of these areas. However, due to the incomplete knowledge of the light fittings in the building, SAs encountered problems: *"[the spreadsheet] that the University provided us with needs a tag of lights. There were only a few but in fact, in reality, there were so many more types of light [...] because, it was not in the reference sheet" (S4).*

S1 explains that due to the age of the estate, some parts of the buildings have not been updated and contain very old light fittings, identifying these as a target for improvement: *"... in the [Geosciences] building all the toilets have got LED panels, and they've had it refurbished, but there's rooms in there that we haven't had any work to them for 30, 40 years" (S1).* There are also apparent difficulties in measuring the energy consumed by older buildings on campus, which are heated by a district heating system. As the energy is metered at the district level, heat use by buildings connected to the system must be split based on an estimated percentage: *"...for the electric and gas consumption it goes through the [Mech. Eng. building]. So there's no way of really metering it [...] And say, right, what sort of percentage [...] is it?" (S1).*

Yet, the challenges posed in the management of such an estate are not limited to older buildings on the campus: new buildings may be better specified and therefore have better records kept of the installed fittings, but may be more complex to manage as a result of design quirks or experimental building design. The complex nature of the HVAC systems designed to maintain living and working conditions in certain buildings on their estate cause difficulty for FMs 1 and 2:

> *FM2: "Yeah. Yeah, 'cos it's just- it's a complicated way that it's, well, both heated and cooled isn't it. I mean, particularly in the open plan bit, you've got these chill beams that come from the ceiling, and you get people that they complain it's far too cold. And... then the boiler, and..."*
>
> *FM1: "... they have a lot of solar gain as well..."*

These complex factors are dealt with through the strategy of comprehensive audits, which improve FMs knowledge of the buildings and help inform improvements: understanding that there is a gap in knowledge and seeking to fill this gap, though this may only impact savings in the longer term. This gives opportunity and motivation for the exploratory sensor deployments conducted by the FMs and SAs, to collect data and improve understandings of these buildings.

Analytic Ability

This finding demonstrates that sensor toolkits of the form in which BuildAX was developed and deployed are well suited for professionals, and documents the ways in which data was analysed. FMs are capable professionals, with the ability to undertake technical analysis of data, as are some students: *"I'm keen to understand that more, to try and do some hard-core analysis of the data, so we could build a simple model of [the admin office] and how it consumes energy, so we then know if the model is robust enough, what normal consumption could be at any instant in time" (FM3).*

Technical or statistics backgrounds were not uncommon for the facilities managers participating in this study, demonstrating a high level of skill. FM1 explains how he uses degree day analysis to correlate the energy use of the estate with external weather factors, through applied statistics: *"We do degree day analysis on gas consumption [...] it's a regression analysis on it, with the* R^2*... The* R^2 *is good, it means your consumption is in line with the degree days. So the colder it gets the more energy used. You always have baseline [usage]. Normally it's for hot water. [...] and you know, it's ax=ay+b... [...] this is consumption, this is degree days" (FM1).*

Other FMs analysed the data by creating views into it. FM4 simply removed extraneous data, leaving only the data relevant to the question he was interested in. In this case, the temperature curve of the 9-5 working day in rooms where temperature complaints were common: *"[I] filtered on the dates [...] and then I filtered on the time. So I only wanted to know, from 9 o'clock to 5 o'clock. [...] overnight I wasn't interested in, because it's outside of when the building, when the rooms were actually in use" (FM4).*

The student auditors participating in the study did not always have the technical ability to accomplish a thorough data analysis, but recognised the need and were able to outline the processing steps required before they could make use of the data: *"Because there was so much data, I needed averages because I couldn't do a graph showing all the data. So, I wanted 24-hour averages so I could kind of see how it changes over the course of the day..." (S2).*

Likewise, S1 had not used these skills for several years, but was willing to have a go: "*We did a bit of Statistics, SPSS stuff, for the first few years of Geography, but I'd probably be sort of teaching myself parts of it. [...] If there was something that was quite obvious in the graph, that stood out, that you could delve deeper and say, right, let's look at the need for that" (S1).*

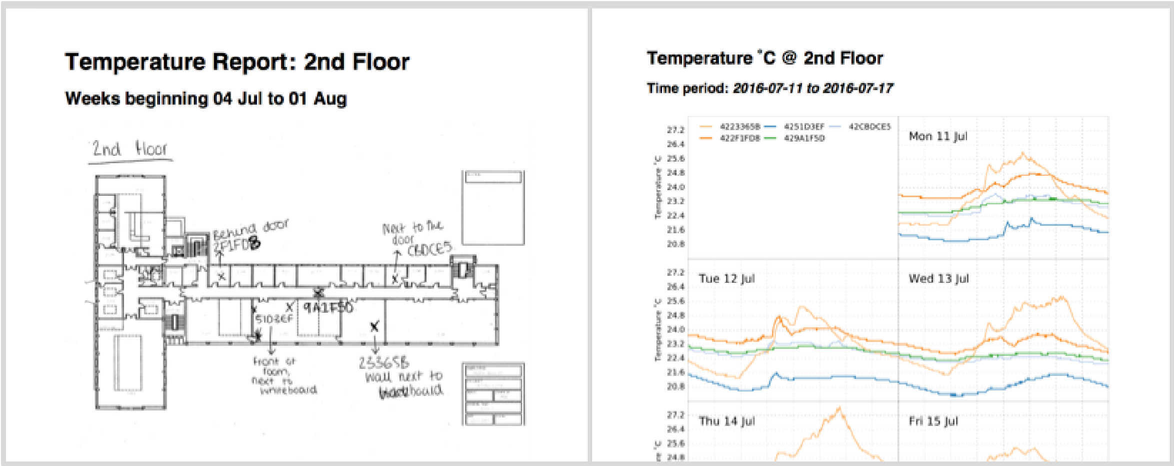

Figure 8: PDF reports for visual analysis of sensor data, generated by the BuildAX report generation toolkit

As I had provided a set of report-generation tools (Figure 8) for SAs to use, this generated some discussion of other ways of presenting sensor data, and how they would use these metrics to answer auditing questions: *"... it'd probably be quite useful to look at a 24-hour window [...] then a week-long window to see, here's the levels throughout the week, and then it goes down at the weekend, hopefully. If it stays the same at the weekend then you know people are, either, it's sort of base-load appliances or, people have left things on..." (S1).*

In order to move from data to action in the practice of environmental auditing, clear steps are taken which fit the data to the questions asked. To produce usable and actionable information, participants filtered data, calculated statistics, and performed more technical forms of analysis such as modelling. The degree to which this was possible was contingent on the skills of the auditor. In the discussion, I examine how these skills might be made more portable through sensor toolkit design.

4.3.3 Tensions and Challenges

This final finding relates to the tensions and challenges highlighted by what FMs and SAs did with the data after they had collected it, transforming or otherwise interrogating it, and how this allowed them to take action. I include examples of limitations, where FMs and SAs found that the toolkits did not function in accordance with their expectations.

Understanding Building "End Users"

Building occupants or "end users" factor strongly in the scope of FMs' working practice. Workplaces are living spaces and buildings are affected by the choices and actions of those occupying them. Building users may therefore be problematised by FMs, a consequence of their adversarial placement in dealing with front-line issues such as comfort complaints: *"'we need air conditioning'. [...] I think it's almost a flippant remark, which could cost you a lot in the long run. [...] You know, so if it is a warm day, they'll over-egg it say- oh it must have been 30 odd degrees in here, rather than 28" (FM4).* Occupants' primary concerns were often viewed as being related to comfort, rather than to sustainable energy use, as a matter of experience. This was picked up on by SAs working with the facilities management department. S1 describes his impression of building occupants in the building he audited for his MSc project: *"they don't really know how much energy that light bulb's using and how much you could save, and they don't really care" (S1).*

It was also recognised that FMs have a responsibility in this regard. Opportunities were seen in the use of data from sensor toolkits to promote engagement with occupants: *"I will also try and engage with a particular bunch of people and say based on some monitoring results, 'you've been using quite a lot of a Sunday night when the building should be empty, you know, what's going on?" (FM3).* However, to what extent should FMs be able to analyse the working practices of building occupants? When examining the data, SAs tended to infer the activities of building occupants from sensor data reports. This presents privacy issues in the deployment of sensor toolkits which warrant discussion. SAs could see these patterns, particularly in the lighting data:

> *S4: Maybe that person's there overnight. That's the way it looks [...]*
>
> *S5: And then I think someone forget [sic] something, and come and grab it. [...] I feel like we're kind of spying on them. I feel like a detective.*

Yet, S3 felt that it was unlikely to cause issues in practice, as without the contextual information behind it, the data would not afford an intrusive level of surveillance: *"Without actually having someone there, you don't really have the story behind the data [...] But it still can give you a clue as to what you need to check, for example, or people leaving the lights on all night" (S3).* I revisit how this tension of consent against the imposition of monitoring tools might be problematic in the discussion. Rather than being immediately actionable, understandings of building users' actions built a portfolio to guide FMs engagement processes, and assisted in responding to complaints.

Temporal Challenges

Many of the challenges discussed by participants were related to sensor deployments, rather than with processing of collected data. Firstly, the deployment contexts which often occurred during the course of the study were time-limited in nature. Collected data may therefore not accurately represent conditions within a building, as S2 identified when her data set was not able to answer the questions she was asking through her audit: *"Because we put the sensors in on, at the start of July, so since the middle of June, the heating system's been on the summer mode, which means basically it's hardly been on. [...] I don't understand how I'm linking this to making improvements in the heating system when the heating's not been on" (S2).* This is, in a sense, an artefact of deploying for a limited time in the summer months for a student research project, however, this is not uncommon in the context of environmental auditing.

FM1 also indicated a need to account for seasonal differences in a data set: *"... if you choose a baseline of three months, and there is some gas heating related data, probably you will have to take the next data in the same three months. Whereas if the patterns don't change very much in the energy consumption you can probably do it any month*" (FM1). One approach used by FMs to mitigate this is through the application of linear regression analysis using degree days, as previously mentioned in the finding on analytic ability. FM1 used the sensor data to augment his analysis of energy consumption in this way, to take into account the external conditions which affect energy usage: *"...you need also to, not only measure the consumption, but also all the variables that can affect the consumption. So you can then establish a baseline- previous baseline- then adapt the conditions after to the baseline, so you are measuring apples with apples, and not apples with pears"* (FM1).

The final temporal challenge was encountered in the timescales on which FMs are required to work. For short-term projects, a pay-back timeframe of 5 years is common: *"it's called a Salix funding, so that works nationally in the UK, and sort of universities and state bodies, that, so they'll fund projects, or help to fund projects that have a payback of less than 5 years."* However, S1 expresses a frustration with this arrangement, considering that longer-term approaches would present more possibilities: *"it should be a sort of, longer term view of* *changes. So yeah the estates team when they're working, they shouldn't be thinking, "right what's the cheapest option we've got?" or "what have we got a massive store room full of?" it should be a longer term thing."* In the discussion, I address how a history of data collection might be kept to enable longer-term monitoring and measuring, creating a knowledge footprint for future FMs and SAs to serve as a basis for comparison.

Usability Challenges

Another challenge related to users' ability to deploy sensor toolkits. In contrast to the professional facilities managers, student auditors often found the process intimidating. When asked about her experience of deploying the toolkit, S2 noted that the presence of a researcher, an expert on sensor toolkit deployment, was an essential source of guidance: *"It was easy because you were there. If I'd done it by myself, that would've been very challenging. It probably would've took me twice as long." (S2).* S1 provided thoughts on this: though he had received help with the deployment, he still felt it would be straightforward to follow instructions: *"[...] if there was a, a sort of step-by-step, that would be straightforward, definitely. Almost like an Internet home hub that; find the right cables, and the connections..." (S1).*

Figure 9: Student auditors pair sensors with a base unit during a deployment

However, in contrast to S1, a guide would not have been as useful for S2 to work from. The sensor deployment undertaken with the help of a researcher served as training: *"I think if you gave me a guide, it would still take me a lot longer than what it did with you- obviously just because you knew, exactly what you were doing [...] Now I've done it, it is straightforward and I'd be able to do it again by myself" (S2).* This indicates that for S2 the process of training through the deployment of a sensor toolkit was more effective than receiving a guide, and having to then understand and put it into practice.

For FM4, no researcher was present during the deployment of the sensor toolkit. While the procedure of deployment did not present a problem, there were limitations on where sensors could be safely deployed within the school environment: *"I think we were fortunate that issue resolved in, within the Girls' School. I think the girls are less likely to play around with anything on the walls. [...] In the Boys' School they might've gone missing" (FM4).* A sensor toolkit needs different usability affordances, tailored to the needs of different users with different levels of technical literacy. Sensor toolkits should not require exceptionally high knowledge or technical abilities, which I elaborate on in the discussion. In addition, we see here that sensor deployments in some environments may be challenging, with tampering by building users (e.g. school children) interfering with data collection. The sensor housings were designed to be easily removed from paintwork with an adhesive strip, not to prevent tampering. FM4 was able to resolve this by deploying the sensors in a location where they were less likely to be tampered with, but one can imagine other settings where such easily retrofittable sensors would be unsuitable due to this risk.

Deployment Challenges

The ethnographic field notes kept during deployments provide opportunity for reflection and learning from the challenges of deploying networked sensor toolkits in university environments. The toolkits included functionality for the base-unit, the BuildAX LRS, to be connected to a network, to make sensor data accessible in real time via the web interface without having to retrieve the data from the SD card in-person. In large organisations, wired and wireless networking infrastructure is locked down for security reasons: allowing the connection of unknown devices to a network is a significant risk to the health of computing equipment on-site, and it is desirable to prevent outages of this. At the design phase, myself and my electrical engineer colleague Karim were aware of the difficulty of associating devices with wireless networks within the university, requiring a campus user

IT account to authenticate with a RADIUS server via 802.1X. As such, we chose to implement a wired network ethernet socket on the loggers as this was considered simpler and would require less development time.

Data retrieval from the LRS base units was designed in a ‘pull’ configuration, where a script would retrieve logged data periodically (e.g. 5 minute intervals) and enter it into a database. To be accessible over the network, the MAC addresses of the logger devices needed to be registered with the campus IT service, which would then allow the DHCP server to assign an IP address. While this seems like a relatively minor barrier to entry, the network in a large campus environment is divided into VLANs, and a device plugged in in one location (e.g. to test) would work, but subsequently fail when deployed ‘for real’ in another building. To solve this, it was agreed through discussions with the IT support group that the devices could be assigned to a ‘roaming’ profile, which would assign an IP address to them wherever they were connected on campus. However, the problem with this was revealed only when I met with a group of facilities management stakeholders to demonstrate the sensor toolkits: the roaming IP address was randomly assigned, and so the devices were no longer accessible on the static IP address I had recorded for them. There are two sociotechnical learning points here. Aside from this being an embarrassing failure of the technology during a demonstration to stakeholders, it highlights a significant issue with reliance on local IT infrastructure as a medium to deploy networked sensor toolkits: it cannot be assumed that this network infrastructure will be accessible or reliable! Following the deployments reported on in this study, I wrote new base unit firmware to instead ‘push’ data by publishing to an MQTT message queue. This meant that the IP address of the device was no longer required to retrieve data, and improved the ease of deployment.

There were further difficulties with the deployment of the toolkits due to hardware limitations of the BuildAX LRS base unit. Ethernet ran at the slowest possible speed of 10Mbp/s half duplex, a limitation of the ENC28J60 ethernet controller hardware chosen, which caused concern with the campus IT service as 10BASE-T half-duplex devices can cause network congestion as devices attempt to back-off and resend broadcast packets which collided on the slow half duplex link. Further, the network link would intermittently lock up and neither transmit nor receive traffic, which proved impossible to debug and led to the implementation of a daily reset at 3AM to keep the base unit operational. While the design goal of the base unit was to keep the hardware as low-cost as possible for mass deployments, to alleviate these issues we later designed a USB dongle which would communicate with the sensors and could be plugged into a PC instead. This illustrates some of the trade-offs and difficulties that may be encountered when designing low-cost retrofittable sensor toolkits, and that low-cost hardware can sometimes sacrifice reliability and resilience.

4.4 Discussion

The findings I have described highlight how the application of sensor toolkits to existing practices demonstrates the tacit knowledge and sense-making practices of FMs and SAs. In this section, I discuss the above findings, linking with widely used technologies and Ubicomp and HCI research to produce sociotechnical considerations for the role of sensor toolkits in sustainable buildings management.

4.4.1 (Re)designing Sensor Toolkits

First, I consider what lessons may be learned about sensor toolkit design. The findings relating to existing practices, sense-making, and tensions highlight the complexity in facilities management, and the necessity of expert knowledge in navigating and actioning data. Sensor toolkit use has potentially problematic aspects, as FMs are not the only stakeholders in the context of building performance. While *performance* is taken to include energy efficiency, it also includes factors such as comfort (thermal and otherwise), which building occupants themselves have as much (if not more) of a stake in maintaining. This gives rise to a tension in that the provision of tools for FMs alone reinforces the manager/occupant power dynamic. Instances where there is an obvious financial or sustainable gain in using data to critique the concerns of building occupants, (such as where FM4 was able to argue against the installation of air conditioning through the data provided by the toolkit), could be considered taking advantage of authority, rather than addressing those concerns in a way which benefits both parties. Dillahunt's study of landlord/tenant conflicts (Dillahunt, Mankoff and Paulos, 2010) provides a domestic example where conflicts over energy use occur when one party fails to meet the expectations of the other: technologies to facilitate improved communication and shared information are suggested as ways to address this power imbalance.

There also exists a privacy issue: as SAs found, a sensor toolkit may also be used to infer the actions of building occupants. Tolmie et al. (2016) studied this phenomenon in homes, challenging the often-cited privacy threat of networked sensing systems as the legibility of this data hinges on insider knowledge and situated reasoning to account for various features. Though they conclude that personal data sharing in the domestic environment does not pose a threat, internal politics and vested interests in the work environment might. Fine-grained PIR movement data collected within personal offices can be used to extract the hours that an employee was present, and used regardless of the loss of context. This is further compounded if occupants are problematised by the processes and policies of an organisation, viewed only as a source of complaint. From an ethical standpoint, building occupants whose working environment is studied should be aware that such intrusions are possible. This is also a question of consent vs. imposition: as FMs leverage their position of power to deploy sensors in individuals' work environment, the sustainability benefits must be weighed against consent, and opting out must be possible at no disadvantage to the individual. A sensor toolkit for deployment in these locations might have cryptographically verifiable functionality to disable the movement data stream on the device, or simply be distributed with an information sheet informing occupants of its functionality, with a means for them to object to data being collected.

However, the basis for these tensions may lie in the positioning of facilities management as a service to end-users: current procedure does not involve occupants in the building management process, other than through complaints. Though there is an obvious role for democratisation technologies such as e-voting (Vlachokyriakos, Comber, *et al.*, 2014), another approach might be to redesign sensor toolkits to make them accessible for the novice user. How then, might expert knowledge be distilled and incorporated into the design of a sensor toolkit for augmenting audits? Conclusions FMs draw about the state of a building cannot yet be easily challenged by people who do not have the tools and expertise to do so. Simple audit procedures could be documented and provided as a manual along with the toolkit: adding rigour to the process of deployment can establish credibility and allay concerns of citizen scientists' data collection not involving 'good science' (Aoki *et al.*, 2009).

Though a toolkit (as defined in this work) is inherently *repurposeable,* by no means does this preclude designing in features which are useful specifically for the context of auditing. Additionally, the range of abilities encountered in this study prompt consideration of how sensor toolkits can be made accessible for these various groups: sensor toolkits should be designed to allow people with various levels of expertise to use them, from professionals with a high level of technical expertise to amateurs, such as those in Hasselqvist's study of amateur energy management (Hasselqvist, Bogdan and Kis, 2016). For example, the inclusion of simple software tools for common analysis tasks (which a professional might consider trivial) can lower barriers to performing in-depth analysis of sensor data.

4.4.2 Recommendations Towards a Deployment Protocol

What does an *augmented audit* look like? The design of the sensor toolkit alone is not sufficient to address concerns around rigorous data collection, power imbalances and data misuse. The challenge therefore is to define a *deployment protocol* which addresses these points of concern. I therefore provide guidelines based on the findings, which support and develop a sensitivity to the localised complexities of sensor toolkit deployment. Though the specifics of a deployment protocol are, of course, contextual, I suggest that such a protocol would:

1. Highlight assumptions made by the deploying party
2. Involve building users to gain insight on external factors through qualitative methods
3. Structure exploratory deployment processes by making clear the gap in knowledge which the deployment attempts to address
4. Define timespans for different investigation types, and a procedure for when to remove and re-deploy sensors
5. Be predicated on expert knowledge and best practices of how to measure environmental factors
6. Document deployment processes to increase openness using tools for analysing data

The first of these, to *highlight assumptions,* relates to the issue of *data-ism,* or over-reliance on data, as the assumptions that have been made about data and what it represents are not plainly visible. For example, the assumption that a sensor will be able to highlight issues with energy use by a failing HVAC (as FM1 expects in the finding on exploratory projects) can be thwarted by outside factors. If the heating system is stuck on, but building occupants open windows to cope, an effect will not always be visible in temperature data. A deployment protocol might make visible these assumptions by encouraging users to consider the factors affecting the measurement they are attempting to acquire, for example: the factors that affect temperature within a room; the placement of the sensor; and the usage of the space.

The second point of the protocol relates to this. Building occupants should be involved as the first point of contact for localised knowledge. They may *know* that the heating is on in summer, for example, but fail to report it for a variety of reasons. Building in qualitative data from occupants also reduces the possibility that gathered data will misrepresent the actuality: they might be empowered to annotate or otherwise comment on specific features that FMs identify. Yet, while one goal of this study is democratising data, care must also be taken to avoid non-representative sampling or 'cherry picking' data to evidence a case or complaint. A related issue is how tacit knowledge is required to avoid focusing on 'use time' energy demand where this could be masking more fundamental infrastructural problems. Professional auditors in our study had access to this tacit knowledge, which combined with the local knowledge of building occupants could lead to better and less reductive understandings of energy use: a collaborative approach such as suggested by Hasselqvist, Bogdan and Kis (2016) is of utility here.

The third and fourth protocol points ask: "*do people always know what they want from the data?*" Structuring exploratory deployment approaches reduces the risk of wasted time and energy in collecting data which may ultimately prove to be useless. This links to the findings on *exploratory projects* and *incomplete knowledge*, in that FMs saw potential in using sensor toolkits for protracted periods to explore the ongoing thermal properties of the building. However, following the design constraint that sensor toolkits should be *redeployable*, it holds that although continual monitoring is a valid reason to deploy a sensor toolkit, there should at all times be a research question which FMs are trying to answer. This avoids the issue of *too much data*, where patterns become difficult to spot. Defining timespans for different investigation types aids in the timely reuse and repurposing of the toolkit for other projects. For example, in a project looking for anomalies in lighting, two weeks may be sufficient, with a secondary deployment during a different season to account for variation. For heating, a longer period of up to a year may be necessary. If no anomalies are found within a timespan, FMs should deploy sensors elsewhere.

The fifth point of the protocol recommendations relates to the *tacit knowledge* of experts, which new auditors (including amateurs) deploying sensor toolkits may not have access to. The finding on *usability challenges* suggests that, where available, training is the best method to learn to use a sensor toolkit. As documenting tacit knowledge is a fundamentally contradictory task, training covering *what* to measure, *where* to deploy sensors and *how* to recover data may go some way towards helping novice users such as building occupants to collect data and contribute to facilities management processes.

The sixth and final item of the protocol recommendations relates to documentation: a method for documenting sensor placement should be given. Spatial granularity is required to make meaningful inferences about energy consumption: without this, it is not possible to understand where measurements are taken within a space. Formalising deployments would provide rigor and increase confidence in data collection, potentially allow outsourcing of analysis tasks, and increase the openness of the process by allowing data sharing.

By incorporating tools for analysis, raw sensor data can be transformed into representations that are useful for people to be able to take actions, or perform user engagement: there are circumstances where it might be productive for professional and novice 'auditors' to collaborate, such as on comfort issues where occupants have a vested interest in a successful outcome. By engaging with occupants, potentially in meeting to discuss data transformed by these tools, sustainable buildings management can become not just the responsibility of FMs, but democratised. Finally, this creates a record and a history for future FMs and auditors: archiving technologies could be built into the analysis tooling, creating a platform for future work and a way of resolving the challenges encountered by FMs in their incomplete knowledge of older buildings. This archiving of sensor data with appropriate documentation of the deployments preserves a footprint of data capture that can be used in the long term to inform future projects.

4.4.3 Standards and Policies

Standards are constantly under revision: ISO, the International Organisation for Standards revisits its standards every 5 years. However, these standards are designed by experts for organisations. The implication of this is that they are not accessible (or affordable) to individuals, building users, and novices. Through their use, sensor toolkits bring into focus the standards they were used to support.

This raises two questions for HCI and HBI researchers in future work: how can we *better support such standards*, and how can we *build technologies that question the standards and policies themselves*? Dourish (2010) calls for HCI to work at different scales, and as such international standards are a high-impact target for HCI research, as they feed into organisational and government policy in countries across the world. Though like ISO 50001

(ISO, 2018) these may contain provision for measuring and verification, they are mainly concerned with processes and organisational planning, and were also designed prior to the widespread availability of tools for the collection of high granularity data. Within the landscape of continual improvement and IPMVP-style monitoring and measuring, sensor toolkits are seen as a drop-in solution to fill the gaps identified by FMs and enable them to measure high-density data on older buildings, without the expense of upgrading BMSs. Effectively, sensor toolkits provide FMs with the tools they require to assist them in managing the energy used within their buildings and estates.

There is scope for design considerations in HBI to support and inform existing policies in buildings management, and gather data to support sustainability in commercial buildings. While providing a specific technology will change standards (because new standardisation is possible apropos of new technological affordances), as researchers we may need to look outside of our area of expertise (e.g. at other ISO standards), and at other areas relating to sustainability to find contexts where sensor toolkits may also be applied. One inroad to this may be through providing a setting for building occupants to contribute: the grassroots approach taken by ‘green’ initiatives both internal and external to organisations brings a bottom-up approach to sustainability. Schemes such as Green Impact (National Union of Students, 2016) have gained international recognition for their work supporting staff and students at universities in improving the sustainability of their campus: potential exists for future work to investigate such schemes, and to build provision for community-based sustainability into standards.

Throughout this case study there is an underlying motivation which seeks to promote inclusion: if smart buildings are to be truly smart, and avoid modernist technologically-solutionist pitfalls, standards and policies must take into account issues of social justice for building occupants. It is important to remember that environmental and social justice are interconnected: a *just* sustainability must account for systemic inequities, and acknowledge that these can be either reinforced or challenged through design. Sustainability is “*inextricably tied up in, rather than isolated from, the politics of class, race, labor, economy, and geography*” (Dombrowski, Harmon and Fox, 2016). One way to approach this, as advocated for in this case study, lies in providing structured ways in which novice users can become active in accounting for the energy usage of their buildings, supported by expert facilities management professionals.

4.4.4 Limitations

I recognise and foreground some limitations of this study into the use of sensor toolkits by facilities managers and student auditors, that future work might build on these. Firstly, I reflect on the role of the participating students as early-career auditors. By approaching the auditing task with limited experience, they revealed certain knowledge and skills which illustrate how potential users of a sensor toolkit might utilise it in the practice of auditing and buildings management. Student auditors acted in their capacity as early-career auditors, with agency to conduct their own investigations, and for many this was the first real audit they had performed and as such was a learning experience. It would be reasonable to expect some parallels here with the experiences of other facilities professionals first entering the industry and undergoing training. This was instrumental in demonstrating the effects of tacit knowledge on sensor deployment, and led me to develop accompanying analysis tools for early-career auditors whose background did not include statistics training. Some also displayed commendable dedication (the work formed part of their dissertations), and were more exploratory in their deployments with fewer preconceived notions of auditing processes.

While there is some generalisable value in these results this is not the only contribution of this work. This case study provides a close-up account of the experiences and perceptions of a small group of participants. This is a valid approach to begin to understand environmental audits as a design space: one that is new to the field of HCI but also to the participants of this study. This kind of technology-enabled auditing is relatively new to the facilities management industry. Hence, the findings I have presented are as much about understanding existing auditing practices and the directions that these new affordances and technological capabilities might take them in. As such, every perspective and experience is treated as a valid one. The practical and mental work (and interaction design required to support this) can be expected to be similar and transferable, and an important subject for future research. Yet, it would also be expected that the contexts and practices that these tools are employed in will vary across different organisations with varying management practices and objectives. These are important to understand if future research is to develop flexible, general tools, but also if it is to effectively design for more specific contexts within this domain. Additional areas of research such as citizen science, smart cities and homes, where the roll out of in-the-wild sensor deployments is increasing, may also find value in these findings.

4.5 Summary

This chapter presented a case study of facilities managers and student auditors, who used sensor toolkits in augmenting audit procedures. The collection and analysis of fine-grained data enabled FMs to create understandings of building efficiency and generate actionable recommendations for improvement. Sensor toolkits show promise for application in the buildings management sector through their affordances in being repurposeable, redeployable and retrofittable, and there is scope for building their use into standards and policies for energy management. The reflections presented through the findings of this study are distilled into recommendations to be used in the future definition of a deployment protocol to address some of the tensions and challenges encountered in the deployment of sensor toolkits. The contributions of this case study relate to understandings of the real-world practices of FMs using sensor toolkits, design considerations which address power, privacy and democratic concerns, and recommendations for future work to encourage integration of sensor toolkits into standards and policies for more environmentally and sustainably just smart buildings.

Chapter 5: Case Study 2—Negotiating Comfort

The brain is a wonderful organ; it starts working the moment you get up in the morning and does not stop until you get to the office.

ROBERT FROST

5.1 Introduction

Including novice building users in management processes, per CS1, is a promising approach to widening participation and incorporating tacit knowledge of occupants into decision-making. Yet, this method is still expert-led, and may present barriers to participation insofar as who is motivated and able to engage with auditing processes. To consider participation more fully, it is necessary to look for other ways of understanding occupants' lived experiences, concerns and complaints. In this second case study I examine the perspectives of a group of occupants working in an open-plan office with uncomfortable temperature conditions, and a significant series of complaints attempting to address this ongoing problem. This thermally uncomfortable office was the context for my investigation into **RQ2**: *How can data and digital technologies foster shared understandings and assist comfort negotiations in the office workplace?*

To investigate this question, I designed and deployed a situated technology probe: ThermoKiosk. Thermal comfort is commonly used as an indicator of indoor environment quality, and affects occupant productivity and wellbeing. As well as functioning as an instrument to aid in occupants' management of their thermal comfort in the workplace, ThermoKiosk also provided a mechanism through which to observe and develop qualitative understandings of thermal discomfort. Subjective experiences of workers' thermal discomfort in this office workspace often sit at-odds with the 'objective' picture given by metrics and sensor data, demonstrating that sensors alone cannot provide a holistic picture of a built environment. And, as I have hinted at in Chapter 3, neither is positivist data analysis and interpretation of environmental factors a politically or values-neutral endeavour, especially when the results of that analysis have the potential to affect the wellbeing of a group of people. Datasets and data collection are inherently political, and the design of measurement *"includes, often invisibly, the judgments, assumptions, and values of* *various decisions that have been interred in information infrastructures through measurement. This is political"* (Pine and Liboiron, 2015).

Facilities management teams are responsible for the maintenance and provision of HVAC (heating, ventilation and air conditioning) systems in modern buildings. And, as the findings of CS1 (Chapter 4) also demonstrate, complaints are the mechanism through which building users most often interface with the apparatus of facilities management. This can be viewed as a result of the adversarial positioning of facilities managers (FMs) as providers of comfort as-a-service, and of architectural designs which limit occupants' agency in adapting the space conditions to suit their bodily needs (Nicol and Humphreys, 2002). Further, FMs as actors are positioned at an intersection of (often conflicting) motivations, balancing occupant comfort against organisational energy use and the goals and drivers defined by senior management, presenting significant challenges in their negotiations with other stakeholders (Goulden and Spence, 2015). As such, FMs are intermediaries or middle-actors in the energy system, negotiating conflicting demands and policies and exerting influence on actors both 'upstream' senior management and 'downstream' occupants (Parag and Janda, 2014).

Although the specialist knowledge and expertise of these stakeholders is vital to understanding and reducing the energy footprint of the built estate they manage, this 'service provider' arrangement has resulted in an expectation on the part of building occupants that environmental regulation equipment will function to maintain their comfort. In providing static and standardised indoor climate conditions, there is also an assumption that these static conditions will be comfortable. As prior literature has demonstrated, this assumption does not necessarily hold (Murphy, 2006; Karjalainen, 2007) as thermal comfort is a personal and subjective experience. Further, there is a raft of work linking poor indoor environment quality to decreases in productivity[23] (Haynes, 2008; Al Horr *et al.*, 2017), negative health effects (Seppänen and Fisk, 2006), and lower overall satisfaction with the indoor environment (Zalejska-Jonsson and Wilhelmsson, 2013). As discussed in Chapters 1 and 2, the extent to which an occupant feels in control of their surroundings also influences satisfaction (Haynes, 2008), and tightly-provisioned automated HVAC systems coupled with bureaucratic management processes work to reduce occupants' sense of control over their

[23] Academic papers making claims about thermal comfort are so often framed around improving 'productivity' rather than wellbeing, which rather positions them towards a capitalist political outlook on labour.

space (Hellwig, 2015). There is an extant need for new ways of understanding this control-landscape within the context of the office, which can open new roads to the design and development of smarter buildings.

The office in which this case study was undertaken had a history of thermal discomfort documented through occupants' complaints of both overheating and overcooling. Facilities managers at the institution therefore undertook an investigation of the office HVAC system, concluding that it was operating correctly and per its specification. With no sign of resolution for occupant complaints and no obvious route through which to alleviate discomfort, manual control of the thermostat was turned over to the occupants in a final attempt to address these, contrary to usual policy and the standard operation of HVAC systems. As practices in the office were moving away from automated tight control of a static temperature, this presented a context for this case study into the role of data in comfort management. Yet, as this chapter reveals, this decision to turn over control turned out to be polarising for occupants, with office politics becoming the point of contention rather than complaints to facilities management. As suggested by RQ2, there are open possibilities for data and digital technologies to address this design-gap, examining how shared experiences and understandings can be fostered in the smart office buildings of today and the future.

This chapter contributes the design and implementation of the ThermoKiosk experience survey system, and a data elicitation interview method which was used in the study with office participants and managers. My findings relate to the social and environmental context of the office and organisation, and how the ThermoKiosk probe affected these; and the discussion raises novel design considerations for integrating office tensions into workplace comfort management.

5.2 Methodology

In the previous chapter, I described learnings about the practices of facilities professionals and amateur energy auditors. While I focus on the experiences of staff members in the office for this case study, these are (and must be) considered in the context of negotiations with facilities management. Staff working in offices are a crucial group to engage in this respect to achieve a balance of viewpoints between stakeholders and a more holistic evidence base for the argument forwarded in this dissertation.

The building in which the study was conducted was the Business School at Newcastle University: a modern building opened in March 2012 (4 years old at the time of this study), intended to have a low energy footprint. A 7th floor corner office in this building, inhabited by 26 staff working in administration and postgraduate support roles, was suggested as a 'problem office' and possible context for this study by the same FMs with whom I had a working relationship following CS1. As described above, it had a history of occupant discomfort and multiple unresolved complaints to the facilities management team. The room was equipped with an HVAC system consisting of four fan-coil units: these operate using a heat exchanger in combination with a fan to circulate the heated or cooled air. Two wall-mounted panel interfaces at each end of the room are used to turn this system on and off, toggle it between the auto or manual modes, heating or cooling modes, and to change the fan speed. One of these panels had been recently installed so that the fan coil units at each end of the room could be controlled separately. It was unusual that staff had access to environmental controls as the system would normally operate on an automated schedule to maintain the temperature at a setpoint defined within the BMS, in line with the 'comfort zone' of industry standards. Manual control was recently enabled following the failure to resolve the comfort complaints initiated by office staff. Due to the design of the building, it was not possible for staff to open the large, floor-to-ceiling windows[24] or to take other adaptive actions (Nicol and Humphreys, 2002). Therefore, the norm in which an automated HVAC system attempts to achieve static temperatures had been changed, with office practices moving to direct control by occupants. This presented a context for this study which allowed for investigation of collective experiences of control, and how subjective data on occupants' thermal comfort might be used as part of this intra-office negotiation process.

This case study was undertaken during the summer of 2016, and involved a four-week deployment of a technology probe (the design of which I describe below), in tandem with a deployment of the BuildAX sensors described in Chapter 4. Following this deployment, interviews were undertaken with facilities management staff and a sub-group of office occupants who responded to a request for interviews, during which the data produced throughout the deployment was examined.

[24] This is a standard approach in air-conditioned offices, the idea being that the HVAC system regulates the environment. Allowing the windows to open would mean that non-conditioned air can be exchanged with the outside environment, which is undesirable for both the efficiency and effectiveness of the fan-coil units.

5.2.1 ThermoKiosk

Figure 10: The ThermoKiosk survey device presenting users with a five-point Likert-type scale of thermal comfort by which to represent their experiences

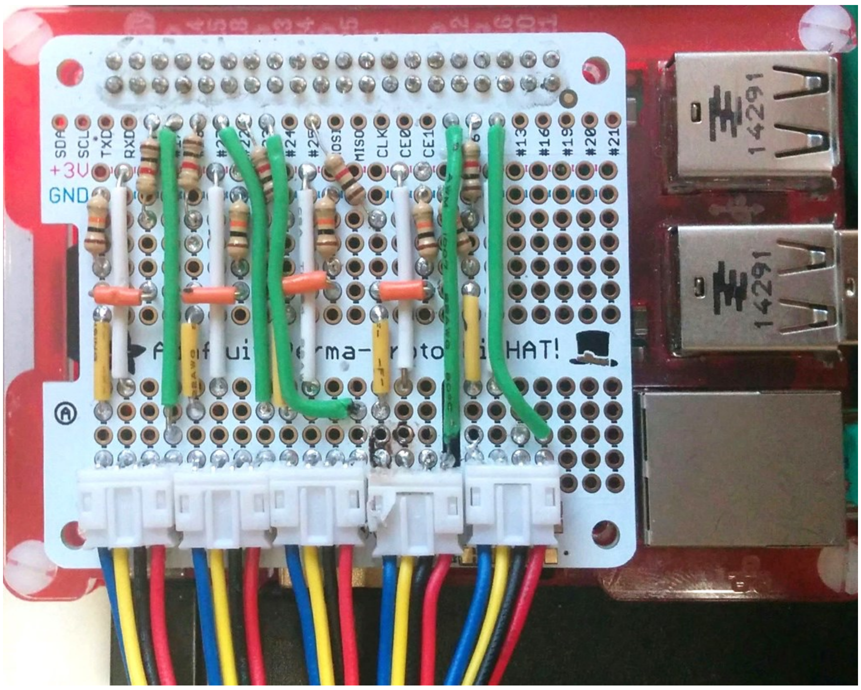

Figure 11: Wiring up the buttons on the prototyping board. The image shows the Raspberry Pi v3 used for development rather than the final Pi Zero

ThermoKiosk is a technology probe in three parts: a survey device, a tablet interface, and an environmental sensor network. It is a tool for auditing subjective experiences of thermal comfort. In contrast to CS1 where I developed the BuildAX technology in collaboration with a colleague, for CS2 I undertook the design, development, and manufacture of the ThermoKiosk system independently.

The probe design was inspired in part by prior approaches to the collection and use of subjective data. ThermoVote (Erickson and Cerpa, 2012) integrates occupant comfort data directly into the control loop of the BMS (building management system) to achieve more accurate estimates of PMV (predicted mean vote), a concept intended to provide an estimated comfortable temperature for a group of occupants, and part of the widely-adopted ASHRAE Standard 55 (ANSI/ASHRAE, 2010, p. 5) and ISO Standard 7730 (ISO, 2005). Yet, this case study is concerned with collective experiences and shared understandings rather than in feeding into existing tight control loops. In this respect, work on decision-making systems and digital voting in the workplace such as BallotShare (Vlachokyriakos, Dunphy, *et al.*, 2014) and PosterVote (Vlachokyriakos, Comber, *et al.*, 2014) provide examples of how online and situated voting systems can capture staff opinion and subjective data around a given issue. In applying a similar kind of approach to thermal comfort, the desire was to both elicit subjective accounts of conditions within the office, and provide data to back-up conversations on the effects of the office environment on the individuals working within it.

The survey device consists of a wooden cylinder or ‘hockey puck’ with 5 momentary pushbuttons mounted on top (Figure 10). Although initial prototypes of the survey device included other factors such as noise and humidity, the final probe for this case study focused on thermal comfort due to the specific nature of the discomfort reported in the studied office. This allowed data collection according to a five-point Likert-type scale, similar to those commonly used to measure thermal comfort and sensation. The inputs range from “I’m boiling” through “I’m fine” down to “I’m freezing”. I considered it important to include an “I’m fine” option as the nature of comfort complaints is such that a lack of engagement is naturally interpreted by facilities managers as occupants being ‘fine’, and making this explicit would allow to account for an expected decline in use over time due to the novelty of the devices wearing off. The following seven design requirements factored in the choice of this design:

1. **Physical** interface, not a website. In lowering the bar to participation, the thermal comfort probe had to be easy to interact with, and always on. The interface needed to be accessible on a whim, with a lower barrier to entry than picking up the phone or loading a web page, as participants were likely already fatigued from complaints. Airport security satisfaction feedback interfaces were one inspiration for this.
2. **Public**: samples were not associated with individual participants. ThermoKiosk is not a voting solution as it is neither verifiable nor unique. Buttons can be pressed multiple times e.g. to inflate the severity of the issue, but this may be desirable in a technology probe and it was expected that as participants as have a vested interest in their own comfort their use of the device would be in 'good faith'.
3. **Situated:** Samples collected through the devices were linked to the location of the box within the office space, and tagged with a timestamp to allow later analysis. This allowed for cross-referencing with the environmental data to understand how participants' subjective feelings of comfort aligned with objective measures.
4. **Quantifiable:** The 5-point Likert-type scale corresponds to a subset of the 7-point thermal sensation scale of ASHRAE 55 (ANSI/ASHRAE, 2010, sec. 5.2.1.2). Note that the intention was never to use the survey responses as inputs to a computer model to provide an estimation of PMV/PPD (per the standard) and as such this modification to a more manageable 5-point scale, for simpler user interaction, was acceptable.
5. **Personal**: Labels on the devices were phrased subjectively, using the personal pronoun contraction "I'm" (e.g., "*I'm cold!*") to reinforce that the survey devices were intended to collect experiential data relating to the user's own feeling, rather than any kind of estimation of the ambient office temperature.
6. **Furniture**: the choice of woodwork over a plastic (e.g. vacuum-formed) enclosure reflected a desire that the ThermoKiosk devices be pleasing objects, which would become 'part of the furniture' within the office. The case was laser-cut from sheets of 6mm plywood and layered together, then sanded using a belt sander to produce the desired finish.
7. **Real-time**: feedback from the devices was visible on a wall-mounted display, and would update in real time. This allowed participants to see how their input affected the holistic picture of shared comfort in the office, and make timely decisions when it came to modifying the HVAC settings.

Given the low volume of production for the devices (10 were produced in total over the course of November 2016), prototyping board (the Adafruit Perma-Proto Pi Hat) was used to wire up the probe in a reliable way for the deployment (see Figure 11). A low-profile JST-PH jumper assembly was used to connect the buttons in a reconfigurable way, rather than soldering them permanently to the board, as it was envisioned that in future deployments of the platform the buttons could be reconfigured arbitrarily. Finally, the faceplate was printed on A4 paper on a laser printer and cut to size using a laser cutter, a decision also intended to allow for re-deployment in future with different button configurations or surveys.

The device utilises an 802.11 wireless network connection to the campus WiFi, enabling real-time feedback by publishing button-presses to an MQTT broker (RabbitMQ). The broker forwards these data packets to two types of subscribers: an SQL database where button presses were logged for later analysis, and the two visual tablet displays in the office.

Figure 12: The tablet interface situated next to the HVAC controller in the office

The feedback displays complete the user-facing part of the experience survey probe (Figure 12). WiFi-connected android tablets were placed next to each of the HVAC control panels at each end of the office, displaying real-time data on survey inputs over a sliding window of the last hour using the d3.js library. This means that occupants could see the graph display updating as they pressed a button on the survey box, and as older survey inputs became less relevant they would disappear. The tablet interface was also available on an internal university website, advertised on the participant information sheets, though this did not see any use during the study, perhaps confirming that this approach would not have been effective for this context.

As well as the graph display, the tablet contained buttons which participants were instructed to press to record when changes were made to the HVAC system, as it was not possible to collect this data directly. Four options displayed in the right-hand column correspond to the actions which participants typically set on the air conditioning controller: selecting 'cooling' or 'warming' mode, and turning the fan on or off. Although the button text read 'made cooler' and 'made warmer', it should be noted that occupants had no control over the temperature setpoint, and these related only to the selection of the mode. The buttons did not control the HVAC system directly, but functioned as a secondary survey to record interactions with the HVAC controller.

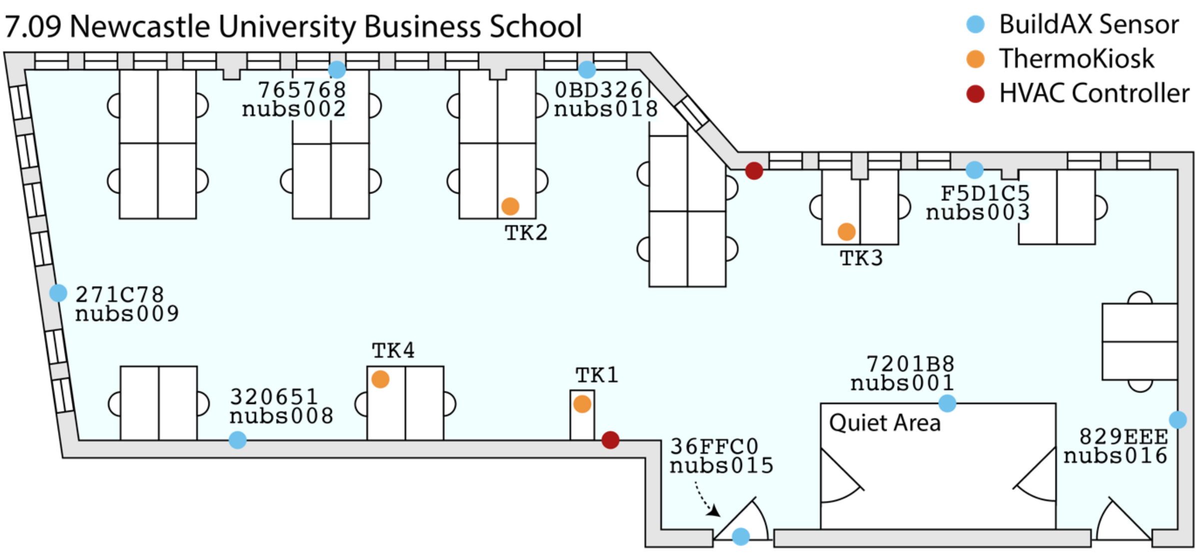

Figure 13: A map of the study office, showing BuildAX sensor locations, ThermoKiosk survey devices, HVAC control panels and occupant desks

Finally, a deployment of the BuildAX system was performed in the target office (see Chapter 4 for further information). Eight wall-mounted environment sensor nodes were deployed around the office, configured at a 7-second logging interval. Readings were timestamped and stored to allowed for correlation with the subjective inputs from the survey devices. These data were presented to participants during follow-up interviews, using graphs of objective temperature readings alongside the subjective data inputs. The full read-out of the sensor network, including the streams for temperature, humidity, light and PIR-detected movement is included for reference in Appendix C.

A 4-week deployment of ThermoKiosk was undertaken with the 26 office occupants between July 26th and August 23rd 2016. Four survey devices were positioned across the office in shared spaces, so that each occupants' desk was within a few meters of a device and they would not need to move far to engage with it. Figure 13 shows the locations of the BuildAX sensors and the ThermoKiosk survey devices, and the HVAC controllers which were augmented with the tablet interface seen in Figure 12.

5.2.2 Participants, Data Collection and Interview Methodology

Office participants worked in administrative roles: while some had recently joined the office, others had been there for several years and had been present before the HVAC system control had been handed over. Participants generally agreed that thermal conditions now were better than they had been previously, but expressed a range of thermal preferences, including being too warm, too cold, fine, or that their experience varied day-to-day. Of the two facilities staff interviewed, FM1 is the maintenance officer with responsibility for the study office, an experienced technician with expertise in HVAC systems, and their maintenance and operation. FM1 had overseen the study office since the building's commissioning, and expressed a deep frustration about the continued discomfort reported by occupants of the study office. FM2 is the campus sustainability manager, with deep knowledge of organisational heating policy and process, and an understanding of the BMS which underpins the operation of campus HVAC among other building systems.

Participants	Total	Min / Max / Avg Length	Codes Produced
Office Occupants (1:1) interviews (P1-14)	14 (11F/3M) M=P9,12,14	20:59 / 40:45 / 28:29	236
Facilities Manager interviews (FM1,2)	2 (2M)	47:41 / 1:03:02 / 55:21	70 (40 shared between corpora)

Table 3: Participant demographics, interview times, and thematic analysis codes

Staff in the office were invited to a 20 to 30-minute semi-structured interview during week 3 of the deployment. 14 office staff participated in interviews which were audio-recorded and transcribed. Interviews were also conducted with the two FMs from the campus estates service. These interviews were also used to discuss accounts from the occupant interviews to get managerial perspective on occupant responses, to understand facilities management practices of data measurement and HVAC system maintenance. Data collection during this part of the project was undertaken jointly: the interview schedule was co-designed with another researcher, who undertook the participant interviews. The schedule aimed to understand perceptions of the ThermoKiosk probe and experiences related to these in the office, and included a segment to explore the data in collaboration with participants, enquiring especially about how the data might be useful for building management and participant negotiations with them.

A key part of this interview process was data elicitation: the use of data within the interview to draw out accounts of thermal comfort management within the office (through agreement, disagreement, and curiosity), and expectations for what the data would show. Following the first part of the interview, formed around open qualitative questions regarding thermal comfort and perceptions of the ThermoKiosk devices, participants were shown printouts of graphs and histograms of the temperature from the installed BuildAX sensors, visualised along with subjective comfort data from the survey devices. In order to keep the dataset manageable, a subset of three sensors were chosen: one at the 'hot' end of the office (Figure 13, 'nubs009'), one at the 'cold' end ('nubs016'), and one in the centre ('nubs018'), to show a range of different conditions. These sensors were graphed across the timespan of the deployment (3 weeks up to the point of the interviews), and co-investigation of the dataset with participants began by showing an example day, for example the 1st of August. The possibility of data overload when presented with a book of sensor data graphs presents a risk of intimidating non-technical participants, though as presented in Chapter 4, this was not expected to be a difficulty with the professional facilities managers. The sensor deployment was described to participants, and the graphs, their axes, and the subjective data overlaid on them were explained. Participants were then prompted using a number of open questions, for example: "*is there anything you find particularly surprising about the data?*"; "*have you noticed differences in different parts of the office?*" ; regarding the subjective inputs, "*does the spread of the votes here on these graphs surprise you at all or is that what you would expect?*"; and were asked whether there were other representations of the data or other forms of data which they would find useful in understanding comfort within the office. These led to conversations surrounding participants' interpretations of the data set, and what they wanted from it in terms of managing the situation in the office.

Analysis

A total of 276 codes were produced from the thematic analysis of the interview corpus. The TAMSAnalyser software was used throughout the coding process to apply codes and generate a searchable code set. I produced different code-sets for the occupant and managerial interviews, with 40 codes shared between both corpora summarised in Table 3.

Theme	Summary
Social	The social environment of the office which participants exist within, and how it acts on them (and they act on it)
Probe Effects	Effects of the ThermoKiosk Probe on the office, including how it did (or did not) influence participants
Thermal Comfort	Relating to participant accounts of thermal comfort
Knowledge and Understandings	Participant lay understandings, reports, opinions, and expectations of systems (including HVAC and other technical systems)
Environment	Reports and accounts of the thermal environment of the office
Organisation	Relating to the wider organisation of the university, its policies and its processes.

Table 4: Seven themes produced in the thematic analysis of the interviews.

Extant thematic codes were synthesised into six distinct themes, which are summarised in Table 4. Codes of low weight (i.e. that occurred infrequently) were only included if they strongly fit into an existing theme. These themes informed the synthesis of the findings, which are presented in the next section.

5.3 Findings

This section presents six findings identified from the themes produced in the analysis of the ThermoKiosk study, with considerations for environmental data and digital technologies in the context of collective experience and shared understandings of office thermal comfort.

5.3.1 *Occupant Accounts Make Subjective/Objective Data Meaningful*

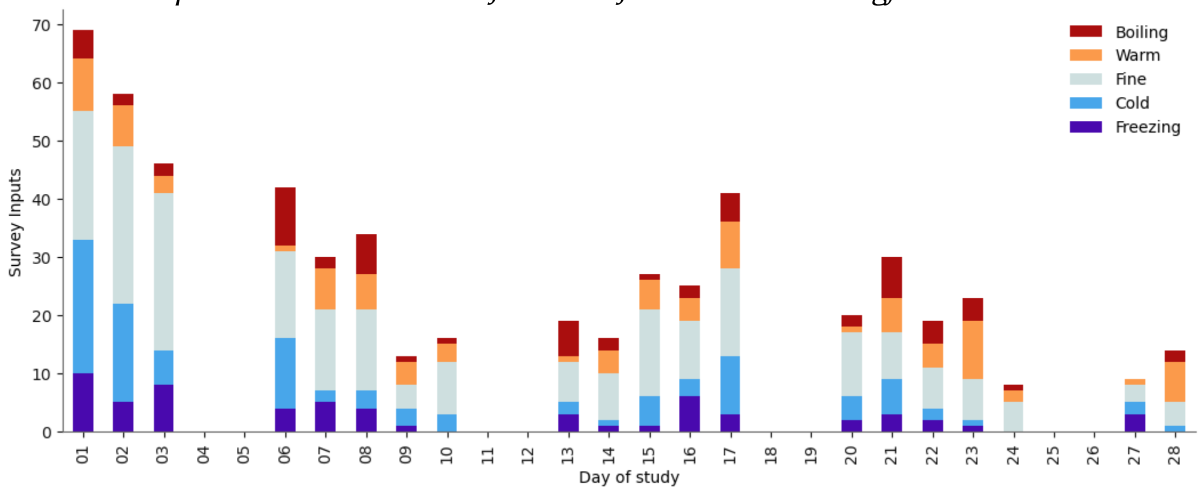

Figure 14: Engagement with the survey devices across the study period

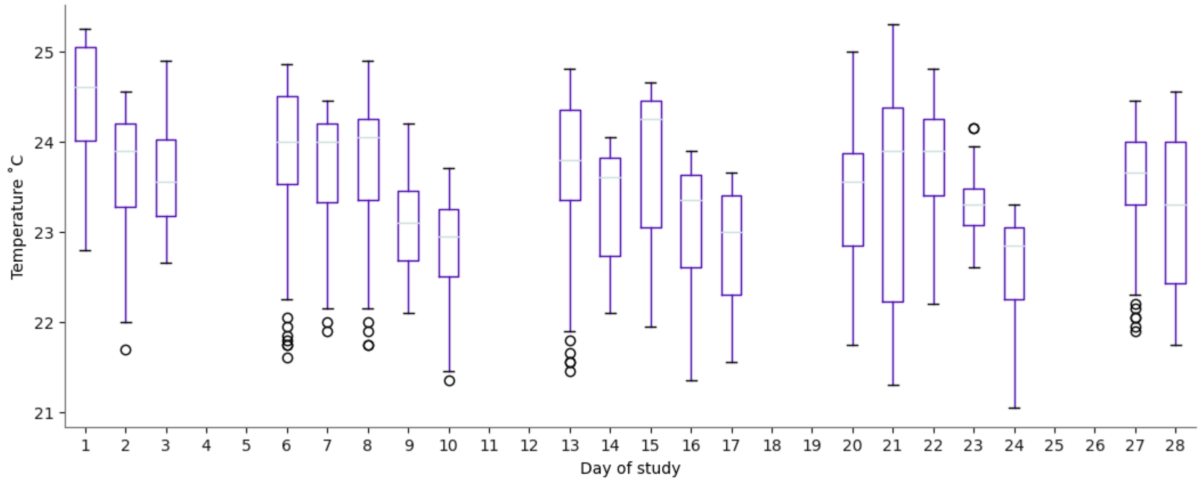

Figure 15: Box plot for temperature range (8am-6pm) in the office during the study period (weekend values removed, as there were no ThermoKiosk inputs)

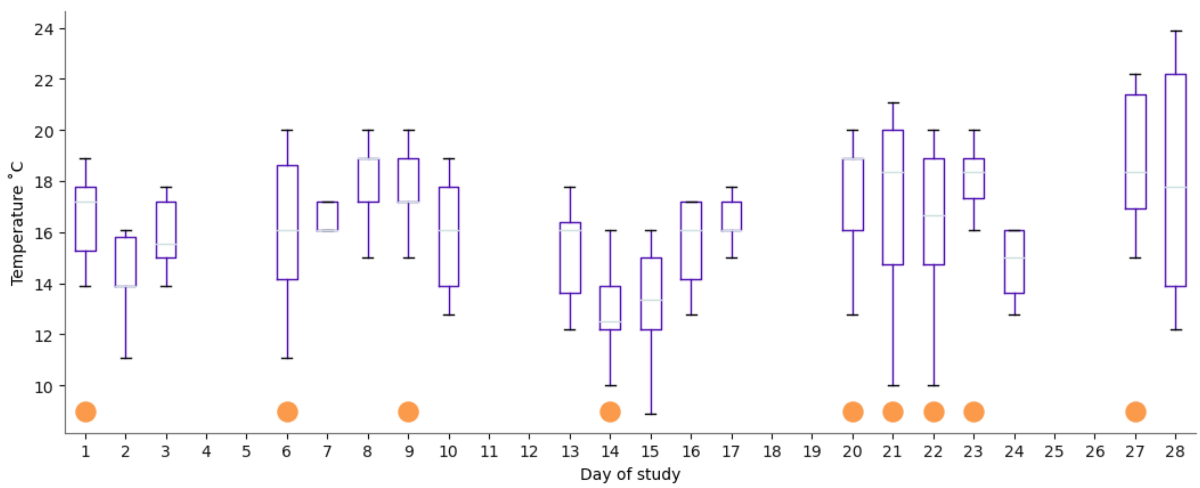

Figure 16: Box plot for outdoor temperature (8am-6pm) during the study period. Sun icons indicate fair weather conditions, thus likely solar gain in the office

Occupant accounts in the interview data revealed meaning in the patterns visible through the sensor data and subjective inputs, aiding in their analysis. But, while relating accounts of subjective experiences to this data can explain these patterns, this does not ameliorate occupants' discomfort.

Patterns in the Objective Sensor Data

A total of 559 button presses were recorded during the study, following a filtering step to remove erroneous values from the data[25]. An initially high level of interaction (likely due to novelty effects) tapers off linearly, reaching a low at day 9 of the study. Interaction then again increases reaching a second peak on the 17th day, with a gradual tailing-off towards the end of the study. While there is no definitive explanation for the increase in interaction towards the end of week 3 (days 13-17), one possible hypothesis arises from the temperature data: week 3 shows an inverse correlation between indoor temperature (decreasing, Figure 14) and average outdoor temperature[26] (increasing, Figure 16). This could indicate higher use of the air-conditioning unit, though for reasons expanded on in 5.3.2 this is not evident in the data. There is also an apparent correlation between outdoor temperature and interaction in the 3rd and 4th weeks which would support this hypothesis. That said, this is not conclusive and it is possible that other social factors, for example conversations around temperature, comfort and the ThermoKiosk probe also played a role in this second peak.

Relating the environmental conditions in the office (Figure 15) to the subjective inputs (Figure 14) does not reveal any other immediately obvious patterns. For example, Fridays (days 10, 17, and 24) are all very similar in terms of the temperature conditions, but show completely different levels of interaction with the ThermoKiosk probe. This could be due to unknown social factors which were not revealed in the interview data. It would be difficult for anyone, facilities manager or occupant, interpreting the interaction data alone to draw conclusions or adjust the automated control system accordingly. While the warmer temperatures might account for participants inputting 'hot' or 'boiling' values into the

[25] A fault with the survey devices caused them to occasionally register all inputs simultaneously (to the microsecond), which was easy to filter out in the data and would not have biased the results in any way.

[26] Data source: weather.com historic weather API. As the study office is located in the inner city, and the weather station feeding this API is located at the airport, the real air temperatures were likely 1-2 degrees higher than this feed. Local temperature data is available from the Urban Observatory at https://newcastle.urbanobservatory.ac.uk/archive/graphs/2016/8/variable/40/?agg=&sensors=1568, but due to an outage unfortunately data is missing for July 30th through August 4th 2016.

probe system, there are a significant number of 'cold' or 'freezing' inputs which cannot be explained by the temperature plot where the minimum value is around 21˚C. To investigate this further, I examined the data more closely on the day-to-day level.

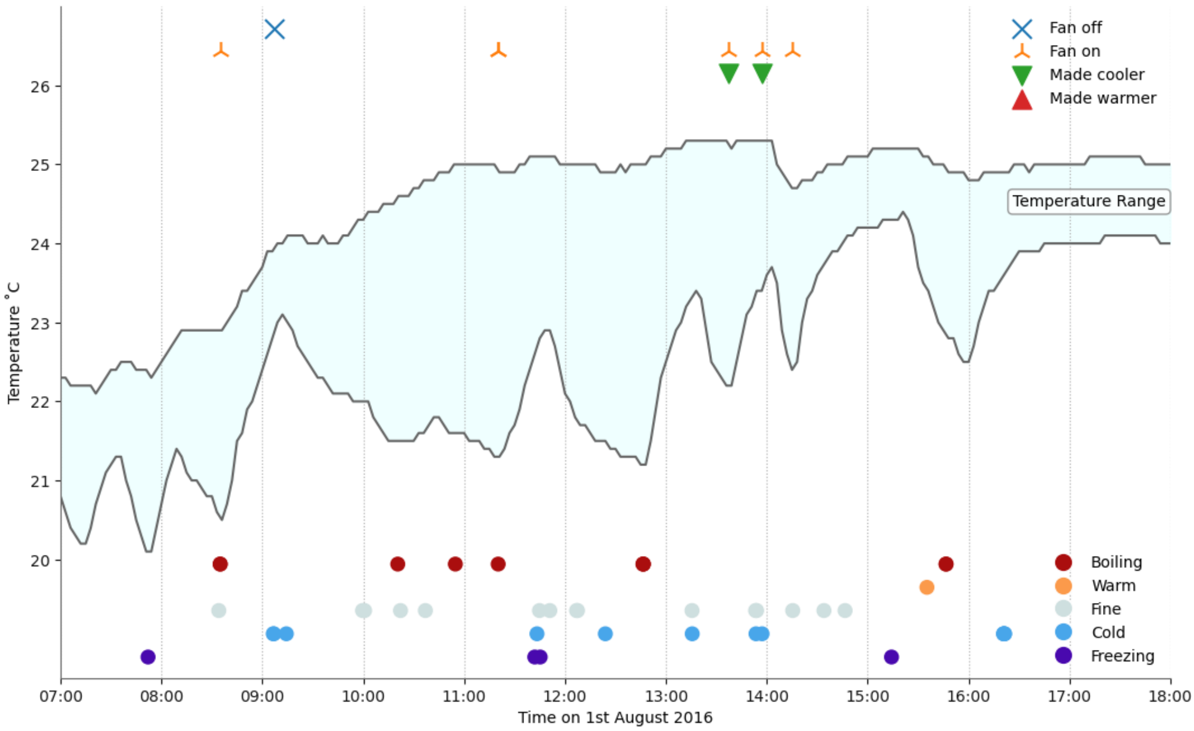

Figure 17: Temperature range plot for 1st August 2016, showing survey inputs and occupant reports of adjustments to the HVAC system

Figure 17 shows a sample of the data collected during working hours on day 6 of the study, 1st August 2016. Along the top of the graph can be seen the HVAC changes recorded by occupants on the tablet interface, and along the bottom occupants' ThermoKiosk inputs. The two lines plotted on the graph do not correspond to any single sensor, but show the minimum and maximum temperature conditions for the whole office. The largest temperature range observed was at 12:50pm, an almost 4˚C differential. Of particular interest are the inputs for 'freezing' (at 11:45am and 15:10pm) which at first glance do not obviously correlate with the conditions: indeed, if anything they seem to counter-intuitively correspond with the high peaks of the lower-bound temperature curve.

A further statistical analysis might of course prove or disprove correlations between these data sets, but the primary purpose of the data presented in this section is to support accounts from the qualitative interview data. And, accordingly, the reason for these 'freezing' inputs are revealed in the qualitative data, where several participants discuss the effects of the cold air flow from the HVAC inflow grilles positioned above them: "*...that* *tends to be because the fans above us, as soon as they kick in it is cold air blasting straight on us*" (P11). The explanation seems to be that the occupants who pressed 'freezing' are experiencing a cold temperature as a result of chilled airflow from the HVAC vents positioned above them, and declare their subjective 'freezing' experience shortly after these are activated.

The Relationship of Data to Thermal Comfort

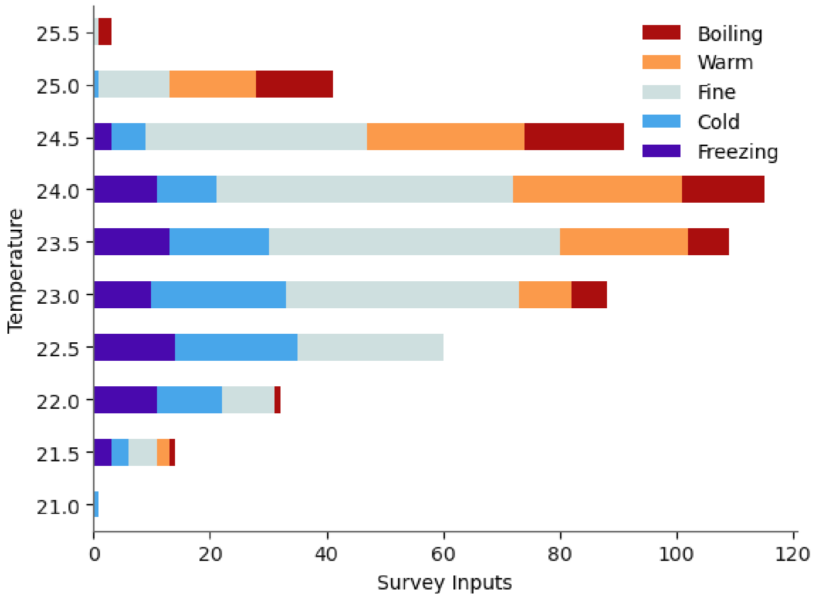

Figure 18: Inputs to the survey devices indexed by room temperature

This is further supported by Figure 18, which shows the normal distribution for ThermoKiosk inputs indexed by mean room temperature. While there is a slight weighting towards higher temperatures for the 'hot' survey responses and towards lower temperatures for the 'cold' options, the overlap in this graph is significant, with participants reporting their comfort at the median temperature of 23.5˚C being split almost evenly between too hot and too cold. Demonstrating that the chilling effect of the HVAC airflow is invisible in the data, FM2 expresses surprise at this: "*25 votes for 'freezing' when it's between 24 and 24½ degrees?!*" (FM2). Yet, the range of temperatures within the office, albeit generally higher than the outdoor conditions, mainly falls within the conditions considered to be reasonable by facilities management. FM1, from his examination of the data, notes that these "*are not extreme temperatures, 21 and 24. If it was 16˚C and 15 ˚C, then fair enough. But, it is not extreme. Twenty-one to twenty-four, that is probably ideal for an office*" (FM1). This, of course, would be of little solace to the occupants of the office, who are chronically uncomfortable and likely would not find this organisationally mandated temperature range to be of much relevance to their personal experience of thermal comfort in the office: "*I mean, at 23 degrees it feels Baltic, when we press this it feels Baltic in there, it doesn't feel like 23 degrees, from what the sensor says it is.*" (P3). While it is well known that temperature is not the sole determinant of comfort, and standards include variables for multiple other determinants (ANSI/ASHRAE, 2010, sec. 5.1), this is not especially useful for occupants who just want the discomfort issues to be 'sorted out'.

In summary, quantitative data may illustrate the conditions of the studied office, but is of little utility without occupant accounts to contextualise it, once again extending the findings of Tolmie *et al.* (2016) to the non-domestic context. Yet, through this, some patterns of engagement with the probe are revealed which would not be obvious from the qualitative data alone. It is clear that occupants' subjective inputs did not directly track temperature, as might be assumed (for example by FM2 above) and that while there is strong evidence from the qualitative interviews that air velocity is a significant discomfort factor for occupants[27], further investigation is necessary to uncover the underlying causes. Further, there was evidence to suggest that novelty effects in the study may to some extent have been mitigated by discomfort, prompting ongoing interaction with the probe.

5.3.2 *Occupant Modes of Interaction with ThermoKiosk Introduce Bias*

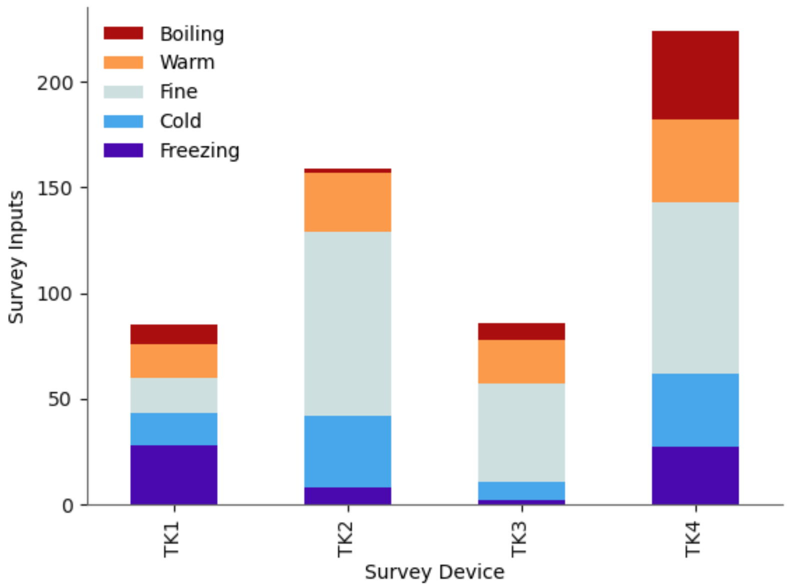

Figure 19: Stacked bar chart showing the number of inputs per survey device

[27] In fact, air velocity was investigated by engineers and found to be performing correctly: see finding 5.3.5.

Interaction varied between the four deployed survey devices (Figure 19), with all devices recording wide variation and an almost even distribution between 'boiling' (n=61) and 'freezing' (n=65), and 'warm' (n=104) and 'cold' (n=93). The locations of the survey devices in the office are shown in Figure 13 above. This represents a broad set of thermal experiences within the space, which is strongly backed up by the interview data.

ThermoKiosk Survey Interaction Practices

While a significant number of "I'm fine" votes (n=231, 41.7%) were also recorded, it is still the case that people who regularly interact are the ones who are not 'fine' (n=323, 58.3%). TK1 saw the largest proportion of 'not fine' votes, which FM2 views as more of a possible cause for concern than the others: "*using this data, if I was presented with this, would I make any changes to […] the heating?* […] *I would say, based on 0, 3 and 4, probably not. […] But Number 1, you have a look at that and you would maybe think, 'Yes […] it might need looking at.*'" (FM2). Per Figure 13, TK1 was located on a thoroughfare and next to the HVAC controller for the more populated half of the room, which could explain this result, as occupants would press it in passing or when they got up to change the HVAC controller: "*Everyone was just pressing them as they walked by*" (P7) "*I know a lot of people use the one by the controlling thing, usually when they go up, they'll press whatever they feel, and then change what temperature they want it to be, or whatever it is.*" (P6).

Other occupants interacted with the probe on a more regular time-based basis, "*I've had, 'I'll vote at these times,' or when I suddenly remember I'll try and vote at midday or around about that time*" (P13). For some, their discomfort prompted an interaction, and they would not interact if they did not have a specific reason to: "*I don't think about pressing it. It's only if I'm too hot or too cold that I tend to press it, really, I think it doesn't enter your head, if you're fine, you know, you're getting on with your work and you're fine, and you don't think, 'Oh, I'd better go and press the button because I'm fine.'*" (P3) This could begin to explain why fewer 'fine' inputs were recorded than others. Observations of others and office conversations could also prompt input: "*someone would say, like, 'Oh, are you really hot?' Or, like, someone would put a coat on and be like, 'I'm absolutely freezing.' Then that made me think, 'Oh, I'm quite alright as I am' and then I'd vote.*" (P14). Further, individuals who are less comfortable are likely to create more inputs to the survey device: "*Where [P12] sits he gets far too hot, so he was using it a lot. People in those kinds of extremes were the people who were using it a lot*" (P7). This suggests a set of complex social biases present in the subjective inputs represented in Figure 19, which should perhaps warn against the use of this data as an input to any automated thermo-regulation algorithm.

HVAC Tablet Display Use and Usefulness

While the ThermoKiosk input devices themselves were well-used, the design of the tablet displays, which included buttons for an occupant to report how they had adjusted the HVAC controller, saw less frequent interaction: "*I keep forgetting to do that one as well. Usually, I just hit it and then change it*" (P12), with some participants disregarding it altogether "*I noticed some people looking at the thing on the wall, but I've never ever looked at the thing on the wall, never*" (P10). It is likely that the physicality of the survey device was more successful in terms of promoting interaction than the displays. This is also visible in Figure 17, where there are marked changes in minimum room temperature which do not have a corresponding HVAC action associated with them.

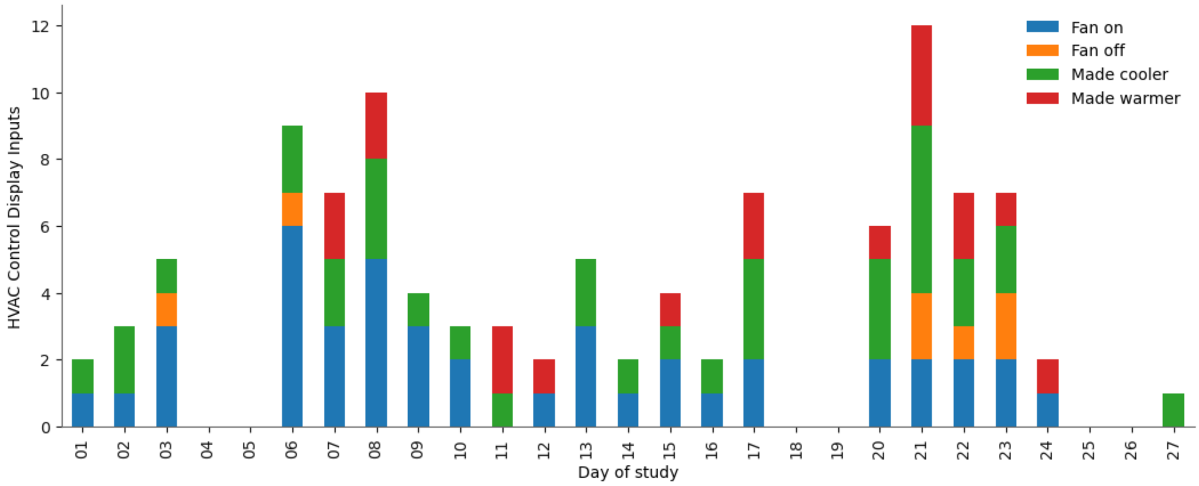

Figure 20: Engagement with the tablet displays over the study period

Interestingly, interaction with the tablet displays (Figure 20) did not display the same pattern of novelty effect as the ThermoKiosk devices (Figure 14), with interaction ebbing and flowing over the study period, and even capturing some evidence of weekend working (days 11,12) where the survey devices did not. This relates also to the lack of engagement of some participants with the HVAC controller in general: 5 of the 14 office participants stated that they did not use the controller at all: "*... the staff at one end of the room do kind of go up and use it, but I never have*" (P2). Further, the meaning of the HVAC control feedback buttons was unclear to some participants, with P11 feeding back that "*on that display I find it a bit confusing, because it says, 'Fan on but made cooler.' I'm not sure. I guess I need to understand the controls more to be able to answer those questions* " (P11). How knowledge of the HVAC system influenced occupant perceptions is further expanded on in finding 5.3.6. Further, some assumptions made about how people used the HVAC controller which factored into the design of the tool didn't necessarily pan out, to some extent limiting the usefulness of this HVAC feedback data. In addition, the controller could be set to auto or manual mode, something which regularly came up in participant interviews, a button for which was entirely missing from the tablet display. FM1 also expressed that the sensor data would not be useful for the purpose of optimising the HVAC system, as "*you cannot really get anything off these because you do not know what has happened in the room, you don't know what mode it is in, do you?*" (FM1).

As such, data inputs to the ThermoKiosk and display represented a broad and interacting set of subjective experiences, the capture of which were influenced by occupants' office practices. As different occupants interacted in different ways with the probe, it is important not to take its output as directly representative of the experiences of people in the office, but instead as an additional data source which retains the same biases as comfort complaints, which are known for being overly representative of vocal minorities. Understandings of the HVAC system also limited the usefulness of user-reported interaction with its interface, suggesting that there are better ways to gather this data.

5.3.3 Anti-Adaptive Building Design Limits Thermal Comfort

The adaptive model of thermal comfort posits that "*building occupants are not simply passive recipients of their building's internal thermal environment, like climate chamber experimental subjects, but rather, they play an active role in creating their own thermal preferences.*" (De Dear and Brager, 2001). Following the hand-over of control of the HVAC system by facilities management in the study office, occupants in this study played an active role in determining the operation of this system, but were to a certain extent thwarted by the very design of the building itself. In other words, the building had never been designed to effectively enable the kind of control which occupants desired.

The Limits of Adaptive Actions

In many ways, handing over manual control of the HVAC system was a compromise and action of last resort for the facilities management team, with FM1 pointing out that the air conditioning "*is the only thing we have got with that building and the way it has been designed. It does work, but for the users they cannot do anything. They cannot turn a radiator off, you cannot open a window, you have not got that facility. That is why we have given them* *control over the unit*" (FM1). The thermal design of the office centres around the HVAC system, meaning that other adaptive possibilities are deliberately limited by its architects: in an air-conditioned room, such actions are viewed as unsustainable, energy-wasting and disruptive to the operation of the HVAC system.

Several occupants did hold that the situation in the office had improved since both the handing-over of manual control, and the installation of a second HVAC control panel which separated the system between the two ends of the office: "*it is not as big of an issue as it was before, where it was just always hot. It was really bad*" (P11). Yet, it was still necessary for occupants to take adaptive actions to manage their individual comfort. Clothing was one of the primary methods for this, especially for occupants in the cooler half of the office: "*I always wear a cardy anyway, but I know a few months back, not necessarily in this last two weeks, that I was bringing in one of those poncho wrap things because I was really cold, yes"* (P6), although it was also pointed out by multiple participants that being too cold in the office is easier to deal with in this manner: "*I think it will be easier for them to have put a jumper on than for us to take off more layers of clothing and stuff.*" (P11). Other participants dealt with discomfort simply by leaving the space, and finding a more comfortable location in which to work: "*the way I sometimes deal with it is, I'll take myself off to another- like a quiet room and sit somewhere cooler, if I've got a piece of work to do that needs attention and I can't focus because I'm too hot"* (P12).

Yet, there were still multiple ways in which the adaptive actions that occupants were able to take were limited by the design of the building. As well as the lack of openable windows to achieve air flow "*we don't have any windows we can open, either*" (P6), the doors were also alarmed for security and fire-safety reasons: "*if you have them open too long, the alarms start to go off*" (P2). Personal desk fans were reported as essential where it was possible to get them: "*people have to ask for them and I think it's sometimes a little difficult to get one but I've got one for now and I'd struggle to manage without it*" (P12). Further, organisational policy also worked to reduce adaptive opportunities, as participants reported being admonished with regards to their fans: "*I thought that was a bit stupid. I know there were regulations and things, but it is like, 'We are hot up here. We have told you we are hot. We want desk fans'*" (P11). As such, maintaining one's own comfort via local means becomes an almost activist act, subverting policy to manage one's comfort. P2 also notes the psychological effects of having little control over her surroundings: "*yes, you can feel a little bit trapped almost.*" (P2)

Manual Control Considered Harmful?

While the manual control of the air conditioning system was a product of a successful negotiation with facilities management, and was linked to reports of increased comfort in the office, in some ways this proved counterproductive because the building and its systems were never designed for this form of control. P2 expresses this worry, "*I don't know whether or not it's counter-productive if [...] we are all going and changing it ourselves. I don't know if that's better or worse, really...*" (P2). Unfortunately for the office occupants, the quantitative data (Figure 17, above, for example) does support the idea that manual control provides a less constant environment than automated control. As FM2 remarks, "*that would explain why you're getting such broad ranges, throughout the day. Because if, like you said, people are manually changing it themselves and chopping and changing between settings or what-have-you, you can see there that zigzag, I would assume, is essentially your range in temperatures there. Which is why, when people aren't in at the weekend, you're not getting people faffing with the controller, you're not going to get such a fluctuation in temperature*" (FM2). However, it is also possible that the automated control function exacerbates comfort issues for occupants positioned directly under the vents: "*I know one of the girls who'd been sitting next to the controller, she really feels the cold when they put the cold on. [...] It does, sort of, maybe blast us first before it spreads out a bit, maybe"* (P6). While conditions in the office generally had improved with the installation of the second HVAC controller, significant discomfort remained with cold airflow in their area of the office.

This presents a real 'catch-22' situation: occupants at one end of the office feel hot, and turn on the air conditioning. Occupants at the other end instantly feel very cold as a result of the cold inflow vent over their desk, and complain to their colleagues, resulting in the air conditioning being turned off again. The room temperature is never reduced to the temperature setpoint as a result, leading to further discomfort. Yet, as a result of this, there was a strong understanding from participants that making everyone in the office comfortable was impossible: "*unless we have every single person in their own little bubble, we are not going to get something that suits everybody.*" (P1) "*This is the design of the building at the end of the day, I think.*" (P10). While occupants in the study hoped for an eventual solution, they did recognise that other people experienced comfort differently. Further, it is likely that their discomfort (and difficulty in managing it) is a result of the design of the building itself. FM1 sums up the situation: "*it is just the way that that building has been designed [...] It is a fan coil unit. That is the way it is.*" (FM1). The building's automated features, when used in a mode which enables occupant agency, do not support occupants' thermal comfort goals.

5.3.4 Effects on Social Fabric and how Occupants Advertise Comfort

The introduction of the ThermoKiosk probe influenced the social fabric of the office in complex ways, resulting in a range of positive (and possibly some negative) effects. To illustrate these effects, some background is required of the social environment in which the occupants of the office had existed for some time.

ThermoKiosk Allowed for Constructive Dialogue

Although the original automated control of the HVAC system was widely agreed to be intolerable, several participants felt that the social conditions of the office, and their relationships with their colleagues, had in fact deteriorated significantly with the introduction of manual control, in a situation which might be colloquially referred to as the 'air-con wars'. "*It wasn't like every day we were fighting with them [... But] when we were changing it to cool, they were waiting until we'd go away and then they would change it back to auto.*" (P11). Another voice, from the opposite side of the room, and the opposite side of the argument, complained about the HVAC being set to 'cool': "*they'll put it onto the freezing, the lowest one they can possibly get, we can feel a draft, a breeze coming down from a vent or something like that*" (P8). As P4 reports, it "*bred a bit of anger in the office*" (P4), though feeling of animosity this had seemed to pass some participants by: "*as far as I'm aware, there has never been any arguments or anything really heavy with regards to it.*" (P13). The politics of this arrangement were also influenced by existing power structures: while facilities had 'handed over' control of the HVAC panel to the occupants, the manager of one of the groups in the office had soon taken over de-facto control of it, presumably in an attempt to prevent these arguments: P3 had been "*told by the people down the opposite end that their manager said we haven't got to touch it*" (P3). Two factors were reported by participants to have improved this situation at the time of the interviews: the decision to split the HVAC control between the two ends of the office and install a new control panel at the far end of the room, and the introduction of the ThermoKiosk probe.

The split controls meant that occupants reduced the discomfort that they put their colleagues into when adjusting the HVAC for their own comfort: "*we probably feel a little more comfortable changing the temperature because we know it doesn't affect the bottom end*" (P9). The ThermoKiosk probe and study also seemed to have had a positive effect on the social fabric of the office, promoting empathy, conscientiousness, and dialogue. "*I genuinely do think that having this study in place has actually improved relations a bit. [...] People empathise with each other a bit more about how hot or cold they are*" (P9). This sentiment was echoed by others, such as P4 "*I think people are more thoughtful about what the general feeling is in the room*" (P4), and P10 "*I think they are a little bit calmer with the whole thing*" (P10). The probe opened up conversations on thermal comfort, promoting an active dialogue which many occupants were able to engage in without fear of reprisal: "*I think that's what's improved most [...] is people talking about it quite openly.*" (P4). To some extent, this may have been due to novelty effects, which promoted a kind of fun office banter around the probe: "*there was this whole thing, 'How are you feeling?' 'I'm feeling fine.' 'How are you feeling?' 'I'm too hot.' All that kind of little bit of banter*" (P7); and a new context for conversations: "*It's just an additional context for the conversations. Now we have the buttons, so we talk about the buttons"* (P9). In general, occupants reported more (and more positive) conversations about thermal comfort following the introduction of the probe.

Advertising Comfort

The ability to advertise one's comfort (or discomfort) non-verbally was also seen as a positive aspect of the probe, allowing participants to see that they weren't alone in their feeling: "*I think sometimes maybe it is useful to see, like, if someone else has voted that they're hot and you're hot then that way you know that you're not the only one without having to ask everybody else*" (P14). ThermoKiosk, and in particular the public display, also promoted an awareness of the differing perceived temperatures of other participants: "*where I have thought I'm fine, other people have put they are boiling, so it is quite interesting to see that. I guess it is down to the individual as well"* (P11). As well as an understanding that other individuals have both differing internal temperatures, there was also an understanding of the difference in temperature across the room, and the 'microclimates' that others were subjected to: "*I think they're realising that everybody has a different microclimate, depending where they are, and that's not them just complaining*" (P5) and, "*it's not just because they're a little bit soft or they can take the cold more. It's actually because there's quite a difference in the actual room temperature"* (P9). A more communal form of comfort emerged from these experiences, with occupants reporting a heightened awareness and better understanding of others' comfort. It appears that ThermoKiosk reduced the social barriers to control of the air conditioning through its visualisation of consensus, making it more socially acceptable for occupants to change the setting: "*they feel more comfortable at changing it because they* *think, 'I'm not the only one who is feeling too hot or too cold'"* (P13). Further, where the preferences of one occupant might increase the discomfort of others in the office, the visualised information prompted consideration before making the change: "*it would prompt me to think about it and consider what it is*" (P4).

However, the non-anonymous nature of the ThermoKiosk interaction, and its placement in public areas of the office, meant that users were able to observe others' interactions with the device. While this had positive effects for some users in the office, particularly on promoting dialogue: "*if you can see people are pressing the buttons it's like, 'Oh, are you getting a bit hot?' The questions are being asked now, as opposed to people just being quiet before*" (P11), for other occupants, this visibility (and the questioning that accompanied it) was considered a negative: "*I think what developed was, people had a reluctance to go and press the button. [...] there were some people who just didn't want to go and press it in case anybody said anything*" (P5). Yet, other occupants still found this visibility empowering, a form of dissent perhaps encouraged by the past adversariality in the office, and a strike back against the underlying social conditions which prevented P5 from feeling believed and listened to: "*I did actually deliberately find myself pressing one just to annoy another colleague by going, 'Yes, actually, I am cold and my temperature is real, just as yours is.'"* (P5). Yet, ThermoKiosk presented a relatively harmless way of declaring this thermal difference to colleagues, "*so, even if two people have got completely different temperatures and putting different things into the machine, I still think it would probably be construed as a bit of banter. Like, I don't think it would ever be in anyway conflicting, or aggressive, or anything*" (P1). As ThermoKiosk treated all opinions (represented by survey device inputs) as equal the acceptability of dissenting opinions was raised, being represented visually on the tablet display alongside all other inputs. Despite P5's dislike of being questioned on her temperature input by others in the office, other colleagues thought that this ability to start conversations was one of the positive aspects of the probe: "*I think if it was on a website it becomes anonymous, and we can't see people getting up and pressing, so we wouldn't then ask people how they were feeling. I guess it would take away that communication element of it"* (P11). As such, the physicality of the ThermoKiosk became both a positive and a negative for different participants.

In summary, the introduction of the probe raised awareness of others' thermal comfort, opening up conversations and allowed constructive dissent between occupants on the thermal conditions of the office. This was situated within a complex and challenging social environment where occupants often disagreed on the temperature, and had historically experienced a degree of adversariality. Yet, as the next finding demonstrates, these agreements and disagreements translated into tensions for the negotiation of thermal comfort within and beyond the office.

5.3.5 New Routes for Negotiation and Representation in the Office

Negotiations occurred between occupants and the facilities management team responsible for the maintenance of the HVAC system, but also between each other within the office.

The Trouble with Negotiations

These intra-office negotiations had historically been troubled by the 'air-con wars,' a lack of open discussion on the temperature, and difficulties in understanding how others were feeling, as discussed in 5.3.4 above. Yet, negotiations with management had also been troubled, and FM1 expressed frustration at the situation: "*there is something about this room where we have tried everything possible and people still are not comfortable*" (FM1). Something of the difficulty was also understood by P6, who agreed that "*they've been in numerous times from what I can remember, having a look at it, and I don't think they understand either.*" (P6) Yet, the facilities management team were still willing to investigate, and while they did not see an immediate use for the subjective data gathered in the study, they were willing to try: FM2 promised to "*take this and show [the rest of the team] and we'll definitely discuss it, because it does make some really interesting viewing. Sorry that I can't tell you how we would factor this information in straight away*" (FM2).

Despite this, there was a concern voiced by some staff that their concerns hadn't been listened to, expressing frustration at the temperature bounds considered acceptable by facilities management: "*It's alright them [saying], 'Well, it's 23 degrees in there,' and we're saying, 'Well, no, we're freezing cold! Why are we freezing when it says it's 23?' When, say if you were outside, you wouldn't think it was freezing cold if it was 23, would you?"* (P3) Similarly, P5 discussed what they considered an apparent use of legislation as a way of dismissing the thermal discomfort reported by occupants: *"'Well, actually, under-,' what is it, the Health and Safety Executive? Or whatever that directive is where you've got to meet the minimum and maximum. They go, 'oh, there isn't a problem'"* (P5). Yet, facilities management staff in the interviews did seem engaged, and had attempted to address the thermal comfort problems in the office in the past: "*we have had BSRIA*[28] *out, we had a full check done and a full report done from them to see if it was working correctly, which it was. They measured the [air] velocities and everything.*" (FM1). There was also a real consensus from both facilities staff and occupants that it was important to try, and to demonstrate to occupants that their concerns were not being dismissed. FM1 described his prior experience with the use of sensors with staff experiencing discomfort: "*I think you need to show people that you actually are doing something…*" (FM1)

Likewise, while a range of dissenting opinions and thermal preferences were evident in the interview data, participants, generally held that even though it wouldn't be possible to please everyone, the important thing was that facilities try to address the extremes: "*There is not a one-size-fits-all solution to it, but as long as you are trying to remove the extremes or at least deliver something for the majority, I think at least there is an understanding that there is being an attempt made*" (P1). Despite this understanding, it is clear that occupants of the office do not speak with one voice. Some participants felt that the office was extremely cold, others extremely hot, and others still were even satisfied with the thermal environment. In the past, a staff member had assumed responsibility for engaging with facilities management, and the availability of a representative was described as a positive by P12: "*she'd, like, pass on the information. That was a really useful channel. […] They were, sort of, passing her comments to one person who, kind of, kept that conversation going*" (P12). The process of collation and sense-making by an individual situated in the room may not have 'solved' the thermal comfort problems of the office, but it did lead to a greater sense of inclusion.

ThermoKiosk was a Feedback and Engagement Opportunity

Yet, even the ThermoKiosk study itself to some extent demonstrated to participants that their concerns were being heard: "*Even knowing that they are trying to find a resolution, it's good to know. It's when we felt that they weren't doing anything, then you could see people quite disgruntled. At least now, we know that something is attempting to be done*" (P8). There was a strongly expressed desire that facilities engage with staff in the office, and a perception that engagement would be better if they knew what it was really like to work there. It was also important to P9 that this was done by a human: "*if someone from*

[28] BSRIA: the Building Services Research and Information Association, is a non-profit organisation providing consultancy, research, testing and compliance services to the UK building services industry.

[facilities] was willing to come down and just sit with people for 45 minutes or an hour – no more than that, really – and just get their views. And they can better communicate to us directly about what they plan to do then." (P9). That said, colleagues engaging with the ThermoKiosk devices often cited their motivation as a desire to feed back their feelings on comfort to the facilities service, without having to raise a complaint: "*the point of it is to let estates know how we are feeling. I guess it is a way of doing that without having to complain. [...] We want to tell them, so that was the main reason for the vote."* (P11), perhaps in the eventual hope that their input would lead to new understandings which could provide a 'fix': "*I think everyone is quite keen to get the heating, the temperature sorted out*" (P2). In this respect, ThermoKiosk provided a lower barrier to engagement with facilities than a complaint, and the ability to give feedback on an ongoing basis. Further, P1 considered that the process of the deployment and study was more positive than complaints as an interaction modality: "*I think consultation is good [...] because then you kind of give people a bit of ownership. So, rather than them moaning about it, you will actually have them trying to be part of the solution*" (P1). In this way, there is a case to be made for greater transparency and engagement in facilities management practice, particularly in situations such as the studied office, and ThermoKiosk represents one way of achieving this.

ThermoKiosk raised the voices of participants in the office, providing a platform for their discomfort concerns: "*It almost gives you like a little voice, doesn't it? It is like having an MP"* (P1). Further, P12 considered the probe "*a means for people to give feedback. Often, I think, sometimes, you know, people pass comments on and nothing happens, they think they've not been listened to and they get really a bit dejected about it, I suppose.*" (P12) This feeling of inclusion was much needed by some participants, such as P5 who thought that their colleagues "*feel like they're actively being listened to. So, it's quite timely. I didn't know if it was planned but it was, like, 'ooh!' (Laughs)"* (P5). P4 agrees with this, emphasising the importance of listening "*It's also been nice in the way it shows we are being listened to as well because it can get really uncomfortable*" (P4). Yet, there were also negatives voiced regarding the expectations set by the study and probe, as given existing understandings of the thermal environment of the office a 'fix' seemed unlikely, and P1 notes that it would be best to avoid giving false hope: "*You don't want to open a can of worms. So, you don't want people thinking that, actually, this is going to lead to the environment being absolutely in tune to every single person's body climate or whatever"* (P1). Further, there was an observed possibility that ThermoKiosk functioned to some extent as a 'placebo button': a button which when pressed does nothing, but may flash and acknowledge the user's input (just as ThermoKiosk does). "*I think now they are a bit more content because they have something they can go and press, their feelings of discomfort, that gives them a bit of satisfaction. They can vote and then that is fine, they can go back to their desk.*" (P10). While ThermoKiosk was not designed with any such false affordances (Gaver, 1991) and all subjective survey inputs were collected and passed on to facilities management, there is precedent for the use of placebo buttons in relation to office temperature control (Sandberg, 2003) and the design pattern is well-known (Lockton, Harrison and Stanton, 2010; Lockton *et al.*, 2011), regardless of the ethical implications of implementing it.

In summary, ThermoKiosk smoothed intra-office negotiations over comfort, and also has a role to play in greater transparency and engagement in extra-office facilities management processes. Despite the challenges of discomfort within the office, it provided a platform and single point of engagement around comfort concerns, similarly in some respects to how a representative or advocate might. Yet, it is important to note that ThermoKiosk does not collect qualitative accounts of discomfort within the office, and bearing in mind the finding on meaningful data presented in section 5.3.1 above, it does not and should not replace face-to-face negotiations with facilities staff. However, it may have a role to play in collating occupants' varying and dissonant negotiating positions, in order for participants to 'speak with one voice' and feel a greater sense of inclusion around their comfort needs.

5.3.6 The Limits of Local and Institutional Knowledge and Understandings

Having examined occupants' negotiations within and beyond the office (in section 5.3.5), it is of interest to further investigate how they interacted with existing building systems, and how sense-making practices around the functioning of the air conditioning guides this. While these understandings were not captured by the ThermoKiosk probe itself, the interview conversations around it surfaced occupant accounts of them.

HVAC Sense-making and Lay understandings

Occupants recounted their lay understandings of how the HVAC system operates to provide a cooling or heating service, although they also recognised that their knowledge was often limited in this respect: "*I don't know how the system works*" (P11). P1 explains that: "*the air conditioning will track as and when rooms get to a certain temperature, which would suggest that the temperature should always be consistent, but I don't think that is the case*" (P1). Similar expressions of confusion were made by other participants, as evidently the HVAC was not performing in-line with their expectations: "*I thought there was meant to be a cap on what the temperature couldn't go above, but it seems that for some reason, it does go above what it is supposed to go. I thought there was a minimum and maximum"* (P8). Conversations with facilities management, on the other hand, demonstrated that occupant expectations of comfort in relation to achieving a static temperature setpoint were inaccurate: "*I know from experience that it's very difficult [...to] ever get to that 21[˚C] set-point*" (FM2), especially in some of the older buildings on campus.

Occupant knowledge of the air-conditioning system should therefore be considered to be partial and incomplete, and this was recognised by the participants themselves. These factors were also likely exacerbated by the changes made to the system over the past two years, with new and returning staff being especially out-of-the-loop: "*I was always informed that it [...] was managed centrally [...] Maybe that's changed, to be honest [...] I've only been back in post about three weeks*" (P2). In attempting to address this knowledge-gap, occupants engaged in peer knowledge-exchange conversations around the controller: *"they would all be standing round a little control going, 'Well, I think this button does this'"* (P10). Concordantly, P3 suggested that perhaps a little more explanation of how the system works is required: "*maybe we need a little list of what, or explain this auto cool, fan, auto this and that*" (P3) although it seems that this had already been attempted in the past: "*that is why we got those little signs made up for them as well, so they knew what each mode did*" (FM1). It was unclear whether these signs were still present in the office, or if they had gotten lost or been removed.

Lack of knowledge and understanding about the operation of the system also appeared to be the cause or at least some of the complaints in the office. Multiple participants voiced concern regarding the 'air vents' or HVAC inflow grilles mounted in the dropped ceiling of the office, for example, "*I think that's just the venting system because some of them don't work and so the system must be still pushing out the same power, or whatever you do with air conditioning, and it's just not coming out of all the outlets, so it's coming out in lumps in different bits."* (P5), leading to a perception that this was the cause of discomfort: "*their vents aren't working, and they end up getting quite warm"* (P13). However, it was pointed out by FM1 that the perception that this represented a malfunctioning system was incorrect: "*they were pointing at grilles which were actually extract grilles. So, they were saying they were getting a draught from this grille, but it was actually an extract grille"* (FM1). In this way, a lack of understanding of the HVAC system increased complaint volumes in two ways:

reports that the system is not functioning resulting from a misunderstanding of the system, and real discomfort resulting from incorrect operation of the HVAC system.

Opportunities for Experimentation and Knowledge Sharing

Other practices around HVAC control resulted from occupant experimentation with the system, such as P12 who had discovered that he could set the mode of the controller in the evening before leaving, in order to achieve a comfortable environment the next morning: "*I, kind of, discovered beforehand if it's left on auto, just before it goes off, it means when it comes on in the morning, it seems to go back on to the auto setting. So, when people arrive, it's- the room has, kind of, regulated itself. [...] I think it picks up from that point in the morning*" (P12). The 'manual' control of the system really was that: there was no possibility for the controller to resume a comfortable setting in the morning without being set in advance. However, this also interacted with other occupants' comfort: "*it's always freezing when they come in, in the morning. They say, 'Oh sorry, I left it on cold last night'*" (P11). As a result, occupants with a greater understanding of the functioning of the system were able to achieve comfort at the expense of their colleagues. This manual control also had the side effect of removing knowledge from FMs, which would otherwise have been a useful part of the process of sense-making of causal relationships between the room conditions and the HVAC: "*because they have got control of the mode we cannot say what it is going to do. They could leave it in heating mode, it would not do anything because it will be too hot in the room, but it will be sitting at 24/25˚C*" (FM1). Further, facilities do not have knowledge of occupants' hyperlocal (e.g. bodily) environment, which will directly influence comfort: "*Are they freezing? What sort of clothes have they got on?*" (FM1). ThermoKiosk was not designed to capture this kind of ancillary information, and as discussed in finding 5.3.2, the HVAC mode information captured by the display did not fully represent reality.

Occupant accounts of discomfort went beyond what was apparent from the ThermoKiosk data. As previously discussed (finding 5.3.4), there was considerable temperature stratification across the study office, which participants often referred to in their interview accounts: "*It does get considerably warmer, to the point we actually ask people to come over to be able to tell the difference*" (P4). Participants were able to identify situations where better information about the causes of this disparity might lead to better opportunities for adaptation: "*[it's] hot over that side. Is it more than just the suntrap? [...] Because then if we were told, 'oh, it's because of the sun' we could close the blinds the night before...*" (P11). FM2 also discusses the solar gain in the office, adding that *"the only time you would expect a big fluctuation is if the sun comes round. If there is quite a lot of solar gain in the room, you would see it shoot up as the sun passes around, to keep it at a relatively higher temperature, and then it would drop off again as the sun passes back over" (FM2).* There are evidently opportunities here for knowledge transfer between facilities management and office occupants, though there is an open question here regarding how this might best be facilitated. While facilities management already have a strong awareness of the levels of dissatisfaction in the office ("*I suppose if we can log these votes and use it as evidence for that, then we'd have to look into it. But, particularly with the Maintenance Officers, it's nothing that they don't already know."* (FM2)), it is clear that this does not necessarily translate into solutions, and the embodied experiences of occupants in the space should not be discounted in working towards a holistic picture of discomfort.

Despite the ThermoKiosk deployment, which captured subjective data on occupants' comfort, the question remains as to how best these might be integrated into facilities management processes. In designing democratic processes for office management, the limits of occupant knowledge are of key concern. Facilities managers also have intimate knowledge of the functionality of systems that occupants simply don't, leading to disparity in expectations and the possibility of solutions, especially where occupant understandings of these systems may in cases be incorrect.

5.4 Discussion

The findings revealed a number of office tensions identified through the introduction of the ThermoKiosk probe. But how might these be integrated into the management of comfort in the workplace? And, returning to the research question RQ2, what are the implications for collective experience and shared understandings for office occupants? The findings point towards opportunities for technology within office social fabrics that can be adversarial and dissenting, and for intra- and extra-office comfort negotiations within this landscape, ThermoKiosk interacted with the social fabric of the office workplace in varied and complex ways, with implications for how subjective data might be interpreted and used towards achieving 'comfort', and how practices and understandings around HVAC systems influence this.

5.4.1 From Passive Occupants to Active Inhabitants

The context for this case study was a conventionally provisioned modern office building, but where some manual control had been turned over to occupants: as such, one might expect occupants' perception of control to be elevated (Luo *et al.*, 2016). Yet, a large degree of discomfort remained, which may be due to a number of factors: a lack of understanding of the air conditioning system (not knowing how to get it to perform as desired), removal of control due to the social environment and office politics, and distanced engagement with facilities management. ThermoKiosk did not (and was never designed to) 'solve' this discomfort, but highlighted that the underlying reasons for it were less to do with the operation of the HVAC system, and more to do with the social environment in which participants existed.

Cole *et al.* (2008) draw a distinction between the language of 'occupants', who they classify as passive recipients of a provided climate, and 'inhabitants', who "*play an active role in the maintenance and performance of their buildings.*" As such, I have intentionally used the term 'occupants' in this chapter: while participants in the study had negotiated manual control over their office HVAC system, the extent to which they have control is limited by the design of the building (5.3.3), so regardless of whether the thermal environment in the office lies within standardized bounds, occupants have not had sufficient agency to create their own desired comfort conditions within the office. They are not involved in comfort provision at any higher level, or indeed in the choice of the temperature setpoint which the HVAC system tries to achieve, which remained set at the organisationally mandated 21˚C.

In their review of the philosophies and paradigms of comfort, Chappells and Shove (2004) point out that the idea of an 'optimal' indoor environment is marketing spiel forwarded by the manufacturers of HVAC equipment[29], and based on western notions of comfort. In reality, expectations of comfort are socially maintained and differ worldwide: the authors note that "*comfort is a matter of social and collective negotiation,*" and that standards which encode it within tight bounds are unsustainable. As Clear *et al.* (Clear *et al.*, 2014) rightly point out, there is a significant challenge in shifting these expectations and norms. Yet, within the study office, expectations around comfort had to some extent already changed: as in finding 5.3.3, there was something of an acceptance that the HVAC system would be

[29] Who, of course, are well integrated into the boards of professional and standards organisations.

unlikely to please everyone in the office at all times. On the other hand, many occupants still viewed the system as broken (which it was not) and hoped for an eventual fix (5.3.5), so engaging with ThermoKiosk was perceived as a way to help contribute to this. One route to negotiating this tension might involve occupants developing better understandings of the possibilities and limitations of air conditioning, yet historically, the lack of occupant knowledge (as expounded in 5.3.6) has been dealt with by cutting them out of the investigation process entirely. In this respect, the technology probe served as a conduit for negotiations between occupants and facilities management where communication had previously broken down.

There remain barriers to upskilling occupants into active inhabitants. There is significant work within the domestic and smart home fields which addresses this (Jakobi and Schwartz, 2012; Hasselqvist *et al.*, 2015), but very little in the workplace. Yet, as discussed in finding 5.3.4, it does seem that ThermoKiosk did lead to better understandings of other occupants' comfort, which factored into intra-office negotiations. There remains a challenge in expanding these understandings beyond the office, and in promoting communication and knowledge-sharing between facilities management and occupant groups in order to up-skill them into active inhabitants.

5.4.2 Towards Collective Comfort

One possible route by which to respond to this challenge lies in collective comfort. Two issues exist within this: firstly, that with greater occupant knowledge and understandings (as individual occupants become active inhabitants) there might be individual shifts as people become empowered, but no corresponding community shift, which might result in more discomfort for those left behind. It is of note that this split fell along gendered lines, with P9, 12 and 14 (all men) being more comfortable with interacting with the HVAC controller: a reflection of our society in which men are socialised (Stockard, 2006) to experiment, engage with and break systems to a greater extent than women. This relates to 5.3.6, in which some occupants were more empowered than others in terms of their understandings and interactions with the HVAC controller, allowing them to achieve their own comfort goals at the expense of others in the office. Secondly, if comfort is a matter of social and collective negotiation (Chappells and Shove, 2004) there needs to be some negotiation within the community: even if there is no consensus on the best way to manage individual comfort, participants were able to come to understand others' differing temperature sensations (5.3.4*)*. Perhaps communities can be comfortable even if members are not, so long as there is a general understanding of others' comfort. Inversely, it follows that collective comfort cannot be unified with individual comfort without these shared understandings. Occupants becoming inhabitants individually results in comfort being held in tension. Engagement and participation in collective comfort management is the key to moving from individuals to communities.

Both shared understandings and active inhabitants are required for collective comfort. A community approach to comfort holds promise in involving office stakeholders in a closer way. There is precedent within work which discusses energy usage within communities, such as (Bedwell *et al.*, 2014) which demonstrates that attributing energy usage (and therefore responsibility) to small-to-medium groups, just like the one examined in this case study, holds the most promise for energy use reduction, particularly when staff already identify with those groups. Studies of amateur energy communities (Hasselqvist *et al.*, 2015) also suggest that linking data to action at the community level can promote a kind of "*collaborative awareness"* of energy usage. The same may hold true for collective understandings of comfort, and ThermoKiosk was certainly successful at linking subjective comfort data to HVAC controller action. Yet, shared understandings and collective experience alone also do not solve this problem due to a fundamental lack of agency: occupants must, to some extent, act within the bounds and limits of the organisation.

The final necessary part of the puzzle for collective comfort is an engaged facilities management team. The issues inherent in the sole use of complaints as an engagement method hint towards the need for new mechanisms through which occupants can engage, and through which FMs can learn how occupants experience the environment which they are a stakeholder in providing (Hasselqvist and Eriksson, 2018). While FMs may know a great deal about the operation of the HVAC system, and are aware of complaints (and, often of complainants!) this is not a substitute for the embodied experiences of occupants within the office. In 5.3.5, participants believed that if only management knew what the conditions were like in the room, they would be more motivated to explore solutions. Management, for their part, believed that there was nothing more to learn. This is clearly not a negotiable position, and it is compounded by existing standards and practices which encourage perceptions of building users as occupants rather than inhabitants.

Further, as seen in 5.3.4, achieving consensus within a group is hard. Political dynamics in the office meant that the 'communities' which formed around the discomfort issues tended to be localised: the 'cold end' and the 'hot end' having conflicting interests which had in the past led to some animosity. By visualising all these interests as equal and promoting constructive dissent, ThermoKiosk led to greater understanding of others' viewpoints. Negotiation is not just intra- or extra-office; it is social and collective. While facilities management in the office were positioned externally to the occupant community, the findings of (Hasselqvist and Eriksson, 2018) suggest that a greater level of integration is necessary to achieve this. While technologies like ThermoKiosk can assist in starting these conversations, collective comfort means moving from an occupant community to an inhabitant community, and importantly, individuals also need to be socially enabled to achieve this.

5.4.3 Opportunities for Technology within Adversarial Office Social Fabrics

So, how can data and digital technologies foster collective experience and shared understandings in the workplace? As is apparent from the findings of this study, there is a role for technology in making the experiences of occupants visible. That said, collective experience does not mean that everyone has the same experience: dissonance in these conversations is a sign of their health! The visualisation of data provided by ThermoKiosk was of low bandwidth, and while the feedback it provided to occupants in the office was used in the generation of conversations as a route to shared understandings, it was not a replacement for discussion as a mechanism for managing comfort. Further, due to the biases inherent in occupant interaction with the probe (5.3.2), it does not give an accurate picture of collective comfort within the office. In fact, the voices (and inputs) of vocal minorities are just as likely to be reflected in the subjective data as in the conversations. This has the potential to further exacerbate factors like gender bias by providing data that can be pointed to as evidence in a negotiation. Yet, that does not mean that subjective data is without worth. There is a challenge, similar to that raised by Aoki *et al.* (Aoki *et al.*, 2009) in raising the legitimacy of amateurs' data such that it is recognised as valid by professionals. Raising the legitimacy of subjective data must meet a higher barrier still (5.3.6).

Yet, the importance of experience is one factor which the results of the ThermoKiosk study do strongly advocate for. Due to the subjective nature of comfort, temperature setpoints are barely useful in relation to conversations around it, even assuming that these are realistic to achieve (5.3.6). Individual experiences such as 'I'm too cold' are far more accessible to occupants. There is a role for technology in collecting, collating and summarising these experiences, such that they can be of utility in negotiations. By listening and responding to these facilities management teams can demonstrate that they really do 'care' (5.3.5). While this kind of experience exchange can be arranged socially (for example, through regular comfort workshops), technology lowers the barrier to contribution for office occupants. The 'articulation work' done by participants in interpreting and reasoning with this data (Tolmie *et al.*, 2016) adds nuance and context to 'sensor-based accounts', serves as a boundary object (Star and Griesemer, 1989) in opening up these discussions. Further, supporting experiences with missing data (outdoors weather, and HVAC operating parameters, as in 5.3.1) may make it possible to develop deeper understandings of how these variables interact with each other, and assist building occupants in becoming active inhabitants.

The affordances of the HVAC controller also contributed to the difficulty occupants had in regulating their comfort. As demonstrated by finding 5.3.2, the idea that the 'warm mode' makes the room warmer is a false affordance (Norman, 1988). It is entirely possible that occupants would be more successful in managing their comfort if the HVAC was locked on auto, but they were given control over the setpoint. The interface design of the controller was misleading here: even though the temperature setpoint was 21˚C, if the room temperature was above this, the system would do nothing but run the fan if it was set into 'warming' mode. Per (Cole *et al.*, 2008), "*building systems must be readily accessible and comprehensible to building users and clearly accompanied by a willingness to use them.*" This is clearly not the case: the system was neither comprehensible, nor per 5.3.2 were all occupants willing to use it. There is a pressing need in the design of these systems to ensure that occupants have a clear conceptual model of how the heating system responds to their inputs. The lack of this results in confusion and dissatisfaction with the behaviour of the system. It should not be expected that occupants become amateur HVAC engineers, so the design of these interfaces leaves much to be desired. Future work might consider how far novices' mental models of these systems fall from the reality, and make changes to the design of these interfaces as a result.

This finding also raises a point of learning with regards to the design of the ThermoKiosk displays, which as well as suffering from the unclear design of the HVAC controller were also less well-used than the survey devices. A technology which integrates into the BACNet network of the building could capture HVAC mode data more accurately, but faces a higher barrier to development and installation, especially with regards to getting permission to install it from facilities management and the owners of the building. Another option could be to 'shim' the HVAC controller in some way, capturing inputs to it directly in a similar way to how criminal gangs shim banking ATMs with a false front to capture a victim's PIN number. In this respect, research on modern buildings also operates in something of an adversarial environment, and researchers must be able to work around organisationally imposed restrictions.

5.4.4 Civil Disobedience in the Office

One of the features of so-called 'Grade-A' office space in the UK continues to be air conditioning. One would expect that the situation faced by occupants in this study is a relatively common story across the country. Unfortunately, the argument that collectively, with shared understandings, occupants of these buildings can arrive at better and sustainable definitions of comfort, rather than those influenced by the HVAC marketers and encoded into standards, may be flawed. Shared decision-making may lead to less sustainable outcomes: FMs know from experience that the temperature setpoint must be protected, because occupants do not always make sustainable choices even if motivated (Jain *et al.*, 2013), particularly in buildings where the cost of that energy used is not borne by the occupant (Day and O'Brien, 2017). The classic tension between comfort and sustainability emerges here. Participants could enjoy more control and a more dynamic environment through unrestricted use of the HVAC controller, likely resulting in increased energy use. Yet, individual satisfaction due to increased agency (being able to act on feelings of discomfort) improved in this scenario. Within this study, this tension was managed in various ways by occupants and management. But if we accept that thermal comfort and temperature setpoint are not well correlated, and yet allow occupants to adjust the thermostat in response to discomfort, we must also accept that human occupants are not necessarily capable of making the environmentally sustainable decision.

Perhaps there is value in delegating or abdicating responsibility or agency to the benevolent dictatorship of facilities management? The FM, as a service provider (Goulden and Spence, 2015), is essentially the representative for the building's comfort technologies, and the interface for occupants' negotiation efforts. Yet, the standards which dictate the controlled environment of the air-conditioned office also enable the dismissal of comfort complaints if the measured temperature is generally within the prescribed boundaries. This maintains the status quo of disempowered occupants, with thermal conditions imposed upon them rather having agency to maintain their own comfort. Further, one can negotiate with a facilities manager, but not a building: the affordances of a space are generally constrained by how it is designed. It is possible to negotiate with the FM for an additional air conditioning unit, or to open a window, but if the windows in the building cannot be opened this is futile. Yet, direct action against this imposed state with disempowered citizens takes the form of actions which subvert organisational policy (5.3.3), for example bringing in one's own desk fan[30], propping open fire doors, and (in the author's own experience of university halls) opening windows fastened shut with security bolts. These are acts of civil disobedience against rigid and non-negotiable policies: breaking the rules can risk disciplinary action, but this sparks conversations which allow push-back to facilities management, which can lead to increased adaptive opportunity, and ultimately increase occupants' perception of control. There remains a role for FMs in advocating for the environmental consequences of occupants' requests, and a possibility for technology to open up conversations around this to increase perception of control, as ThermoKiosk did.

5.4.5 Limitations

The ThermoKiosk study ran in the summer months, where occupants experienced increased discomfort due to the solar gain present in the office. Therefore, many of the findings of this chapter relate to the conditions they experienced. Further, the discomfort experienced in the study office (which was identified as a 'problem office' by facilities management) was perhaps more severe than other office contexts, which will have influenced the participant accounts, with effects on the findings and discussion presented here. A follow-up study could control for this by introducing the probe into an office without significant levels of discomfort, and contrasting the discussions had with occupants from both environments.

5.5 Summary

The case study presented in this chapter followed a group of office workers during a three-week deployment of ThermoKiosk, a technology probe designed to capture subjective survey inputs on thermal comfort. A data elicitation interview method helped to draw out

[30] In addition, per the findings of (Irwin, 2017a) people undergoing menopause or chemotherapy may use a personal fan at home to maintain their comfort. Some groups benefit more than others in the use of adaptive measures that contravene organisational policy.

occupant experiences of thermal comfort management within the office, discussing their agreements, disagreements and curiosity with regards to the data, and their expectations for what it would show. The findings point towards new understandings of interaction with subjective thermal comfort data, limitations imposed by building design on manually controlled HVAC systems, and effects on social fabrics, negotiation, and occupant/institutional understandings. Critically, the ThermoKiosk intervention promoted negotiation between office occupants and facilities management, where these had previously failed. The discussion elaborates implications for office collective experiences and occupants' shared understandings, arguing that community forms of comfort hold promise in offices where comfort is a result of collective negotiation.

Chapter 6: Case Study 3—Engaging Occupants

Speculation is always more interesting than facts.

Terry Pratchett, "Making Money" (2007)

6.1 Introduction

A growing Human-Building Interaction (HBI) community in HCI is acknowledging that the increased integration of IoT and sensing in buildings will have a significant impact on how occupants experience them and, as such, they *"should be designed and nurtured in a dialogue with their users at the individual as well as social levels"* (Alavi, Lalanne, *et al.*, 2016). A body of HCI literature has focused on automation, on understanding and designing interactions with intelligent, automated systems e.g. (Yang and Newman, 2012; Jensen, Kjeldskov and Skov, 2016), and on understanding the role of the building occupant in this. But, at a recent CHI workshop on HBI, one of the pressing questions that emerged for the community was "*How can smart environments embrace inhabitants' agency?*" (Alavi, Churchill, *et al.*, 2016).

There is an important and recognised need in the construction industry for new ways to evaluate buildings. Office buildings are designed, built, and evaluated according to criteria determined by the construction industry and a relatively small set of stakeholders involved in the procurement process. Although some consultation is often undertaken when commissioning a building project, methods for assessing and evaluating project success are often scoped around the performance of building fabric and systems, with an assumption that the needs of occupants will have been addressed if this is functioning correctly. The longer-term evaluation of buildings is a neglected area, but one which can have a large impact on occupant health and wellbeing, and on the life-cycle costs of the building, which are significantly higher than construction costs. Smart buildings offer new opportunities for better capturing and negotiating building performance and use over the extended life cycle of a building, for and increased occupant agency in the management process, and for designing interactions to integrate this into the normal habitation of the building. Yet, there is surprisingly little cross-over or engagement within HBI with HCI work which addresses hegemony or power imbalances (Keyes, Hoy and Drouhard, 2019), or feminist notions of agency, equity and empowerment (Bardzell, 2010).

Both CS1 and CS2 have provided evidence on the issues inherent in the use of complaints as an engagement method, hinting towards the need for new mechanisms by which a facilities manager can learn about how occupants of their building experience the environment which is provided to them. Environmental data is one mechanism to mediate interactions between building managers and occupants, and I have described how it can leveraged for more inclusive and bottom-up building management, and examined the important role of occupant dialogue and agency to resolve tensions around shared comfort. This chapter continues to develop my focus on participation in building evaluation and management. As discussed in Chapter 2, issues of environmental and social justice are interlinked (Bates, Thomas, Remy, Nathan, *et al.*, 2018) and cannot be approached without consideration of systemic inequities (Dombrowski, Harmon and Fox, 2016). I reviewed work by Bates and Friday (2018) which shows how the normalisation of free next-day delivery has worked to systemically marginalise and exploit gig-economy delivery couriers: the status-quo of the last-mile logistics sector being a barrier to both reduced environmental impact and social justice for the workforce. In a similar vein, this case study engages with students, a group not often considered in terms of workers' rights, but sharing many of the same needs for workspace and built non-domestic infrastructure. Issues of staff underrepresentation and agency have been discussed in the prior chapters, but university students remain an under-considered group. Building on this work, this chapter is concerned with how student perspectives can be included in negotiations about how buildings and their spaces are managed and evaluated in environmentally and sustainably just ways.

Conceptually, building occupants are engaged in the continuous creation (Massey, 1993) and appropriation (Harrison and Dourish, 1996) of places within built spaces. Here I take a step back and ask how student occupants experience and evaluate lived space, and how they conceive of their role within the management and adaptation of it. In this way, I aim to understand how design can support occupants in playing a role in building management, but also in determining the metrics by which spaces should be evaluated. This case study forms an enquiry into the scope for designing new building management practices within the university context, investigating the research question **RQ3**: *how can HBI support occupant agency and participation in the everyday management and adaptation of smart buildings?* In investigating this, I carried out design workshops with student occupants of a smart building. The study was designed around how engagement might be fostered in the management process, with the aim of producing understandings to guide the design of future smart building interactions. To refine and clarify the approach that I take in this chapter, I centre my inquiry around three further sub-research questions:

SRQ1: How do student occupants conceptualise space within the building?
SRQ2: What are students' existing perceptions and expectations of HBI and facilities management, and what is the role of the student occupant in these?
SRQ3: How can we (the HCI/HBI community) design interactions that foster agency and participation for students in their everyday experiences of university smart buildings?

In addressing these questions, this case study contributes new understandings for HBI through an account of the student perspective for design, as well as of how student occupants conceptualise space and how they perceive their role and agency in future smart environments. I explore how HBI might leverage the expertise of student occupants in an ongoing conversation, allowing them to negotiate the terms under which a building should be evaluated (and re-evaluated). Hasselqvist and Eriksson (2018) advocate for combining different stakeholder perspectives and supporting shared responsibility between them: as such, while I engage with multiple stakeholders in this chapter I focus on the perspective of students in my analysis. Other stakeholders are important to understand for a holistic account, but have different practices, experiences and expectations. In answering the sub-research questions above, it is necessary to take a deep dive into students' concerns. As such, the findings presented in this chapter relate to the social fabric of student experience within a smart building, raising the voices of this group and giving an important perspective for appropriate and effective building interaction design within the university context.

6.2 Methods and Participants

The Urban Sciences Building is a newly constructed (2017) smart university building in the UK, intended to be a living lab for sustainability research, and was the site of investigation for this case study. The building is characterised as "smart" because of its highly granular data collection system used by facilities managers to aid in problem diagnosis and to monitor energy efficiency, coupled with a building management system (BMS) which adjusts comfort functions, such as temperature and lighting, accordingly. Its occupants are diverse: office workers (academic and admin staff) and students.

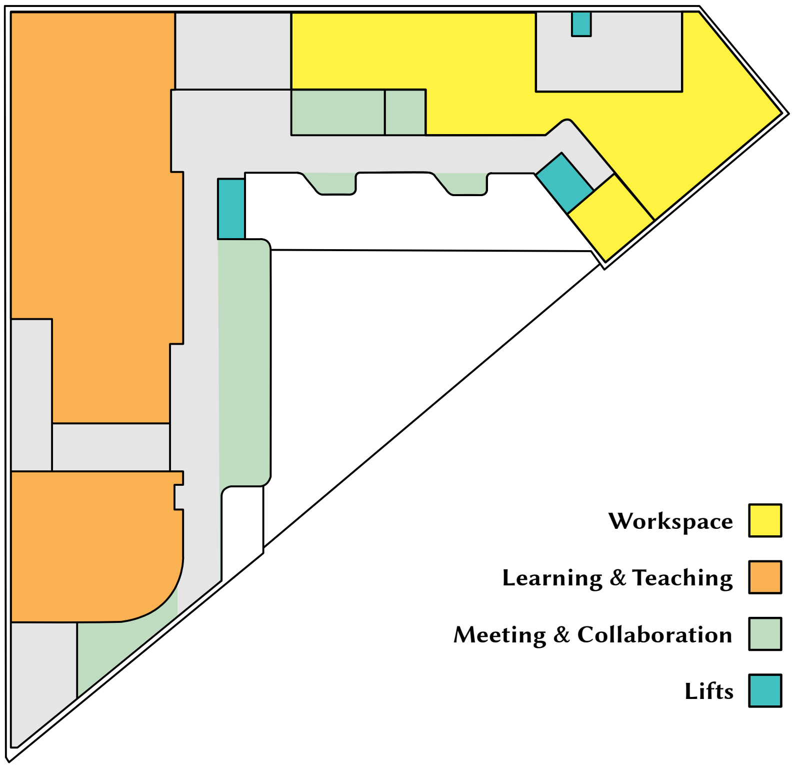

Figure 21: Urban Sciences Building 3rd Floor: a floor plan adapted from the building's architectural drawings, showing the zoned areas on the north (yellow) and west (orange) sides of the building

The north wing of the building is designated as staff workspace, and the west wing is allocated as teaching and learning spaces, including seminar rooms, a lecture theatre, and computer clusters (Figure 21). A central atrium is enclosed by thoroughfares and ad-hoc meeting and collaboration spaces which overlook it.

In scoping this work, I undertook a set of formative interviews with four key building management stakeholders to gain an understanding of the building context, and develop the auditing criteria to be used in student occupant workshops. I sought to understand how managerial staff conceptualise building space and its evaluation, to generate understandings of which aspects of building use should be addressed by the workshops. I chose this stakeholder-interview methodology as co-creation and evaluation of spaces go hand in hand: within an organisational structure, change can only be effected through a carefully managed process involving multiple actors who seek to ensure the building is running according to their set of evaluation criteria.

Staff Role	Interview Length
Deputy Head of Department	21:06
Organisational Manager	19:52
Building Manager	26:47
Senior Estates Manager	19:21

Table 5: Formative study-scoping interviews undertaken with management staff

These stakeholders were involved from an early stage in the design of the building, and were anticipated to have their own unique expectations of its modes of use (as a building and as a living lab) as a result. Managerial interviews were transcribed, and the corpus coded using a lens-based deductive coding approach. The lenses were chosen in response to concerns raised in the literature review of this work, and the results of CS1 and CS2:

- *Existing Practice*: How things are done/happen
- *Space & Place*: Space construction/perception
- *Position & Power*: How occupants (students, staff) are viewed by management

Approximately 600 qualitative codes were produced, revealing themes around *expectations, adversariality, mechanicism and neoliberalism.* These themes are not directly reported on in this chapter, but instead informed the design of the workshops undertaken with student occupants of the building, and fed directly into the diegetic prototypes described below.

6.2.1 Participants

Student occupants were recruited for two design workshops by advertising through a departmental mailing list. The workshops aimed to understand how participants conceptualise spaces within the building, and to engage them in the speculative design of smart building interactions where they have greater agency in the management, operation, and adaptation of the building. The workshops were 2½ hours in length and consisted of two main sections: a building walk and a design task. The building walks were inspired by walking methodologies used previously in the social sciences and in HCI to explore peoples' relationships with place (Crivellaro *et al.*, 2015, 2016; Clarke *et al.*, 2018) as described in Chapter 3. The second half of these workshops made use of speculative design (Dunne and

Raby, 2013) to prompt reflection and discussion on a set of abstract scenarios of future buildings management, and to serve as inspiration for a free design exercise undertaken in the final section of the workshop. With these tasks I sought to bring out the social and cultural assumptions underpinning building interactions and management, and the sociotechnical concerns thereof. The workshop schedule can be found in Appendix D.

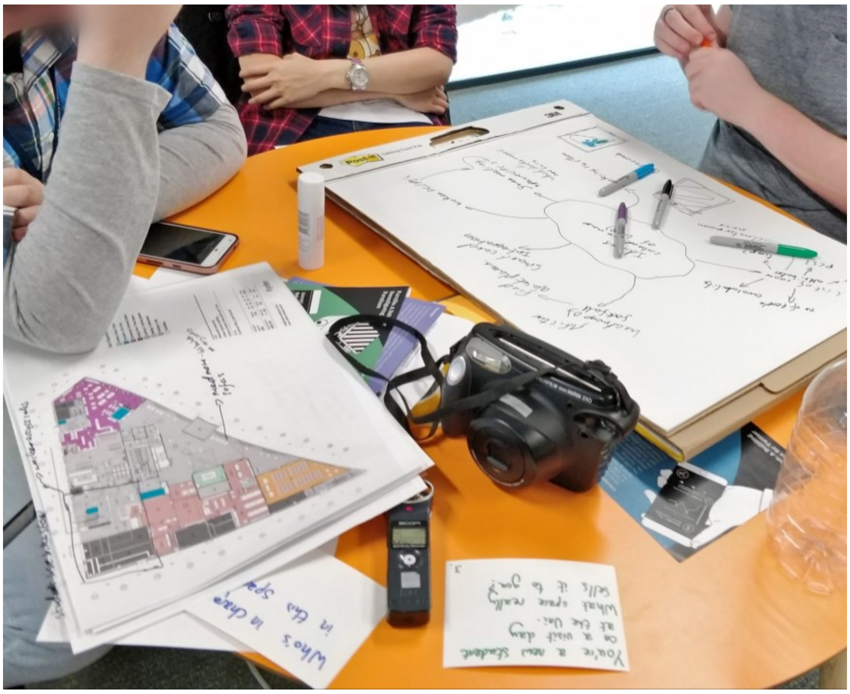

Figure 22: Students participate in the workshop, with materials including polaroid camera, voice recorder, and blueprint flipbook

I recruited 17 students (5F, 11M) to two workshops by advertising through the School of Computing departmental student mailing list. The gender split is indicative of that existing in the department from which students were recruited (no recruited students identified as non-binary or other genders). Participants were incentivised for their participation in the workshop with a £30 voucher.

Demographic	**M**	**F**	**Total**
Undergraduate	8	3	12
Masters	3	2	5
Total	11	5	17

Table 6: Student participant demographics

Workshop activities were run in 3 groups of 3 students (9 participants per workshop total) with a group of two in the second workshop as one participant did not attend. Workshops were undertaken consecutively on a Wednesday afternoon (traditionally a gap in the student teaching schedule) at the start of the summer term. Written informed consent was given by participants and ethical approval for the study was granted as described in Chapter 3, and can be viewed in Appendix B.

6.2.2 Workshops

The workshops were structured broadly into two halves: the first half allowing students to explore the building and relate accounts of their experiences and perceptions of space to a set of question cards produced through the categories identified in the initial interviews; the second half drawing on those experiences to critique a set of diegetic prototypes and produce designs for future ways to address their perceived shortcomings of the building. The workshop structure ran as follows:

1. Ice breaker, greetings, and consent form completion
2. Building walks
    a. Blueprint annotation and walk planning
    b. Walking exercise
    c. Walk feedback
3. Speculative design familiarisation and discussion
4. Free design exercise

Building on prior work on walking practices as a method for exploring spatiality within cities (Crivellaro *et al.*, 2016), it makes sense, as an extension of this, to apply it to the buildings context. Buildings are complex and multimodal, and work on space and place tells us that the meanings which are ascribed to them differ on the individual level. Building walks therefore make sense as a method to investigate this as they allow us to begin to get at the complexity of building use by occupants. Further, it makes sense to combine walking methodologies with speculative design, as both seek to uncover the social and cultural assumptions which underlie the development of technology, challenging and critiquing the technological solutionism often present in HCI design practice. For example, Dourish & Bell (2014) examine Ubicomp literature alongside a selection of British science fiction shows from 1970-2000, demonstrating that the technologies visible in these shows are products of their social and cultural environments, and that researchers might use this to draw attention to the importance of considering sociocultural factors. Similar work (Tanenbaum, Pufal and Tanenbaum, 2016) explores sustainable development in the context of the Mad Max film franchise. It was my intent in combining these methods that this would provide a full grounding in space, place and reality which would be of utility in critiquing the speculative diegetic prototypes presented to participants in the second half of the workshop.

Building walks

Figure 23: A polaroid photo taken by participants to document their building walk

Participant groups were first presented with a *blueprint flip-book* containing floor-plans of the building and asked to annotate them: for example, with routes through the building; where they spend time; the resources they use in those spaces; the people they interact with; and issues they may have encountered. They were then asked to use their blueprint book to plan a route around the building to visit the spaces they had discussed. Participant groups undertook the building walks they had designed unaccompanied by a researcher and were given pre-prepared questions cards to prompt discussion. These included prompts like "What's the purpose of this space– and what do people *really* use it for?", and "Who's in charge in this space?" Participants carried an audio recorder to capture the conversations they had during the walk and were given a Polaroid instant camera to capture snapshots to tell the story of their journey around the building during a follow-up feedback session.

Building walks lasted between 30 and 40 minutes. Following the walk, students were asked to prepare a poster telling the story of their journey around the building, which they then presented to the other two groups and the researcher.

Speculative Design

The walking exercise was designed to encourage participants to think about the present. The second half of the workshops, following **SRQ3**, focused on developing understandings from the walks into questions about what the building might look like in future, and what 'smart' might mean for this. The speculative design task explored how student occupants might view technology, resources, and data as part of the building "fabric" and how they conceive of ideas which would change it, grounding this in their experiences of the building through the walks. Occupants were presented with a set of three illustrated scenarios of fictional future building management technologies, which I refer to as "diegetic prototypes" following (Bosch, 2012; Dunne and Raby, 2013). These prototypes can be considered distinct from design fiction (Blythe, 2014) in that they focused on the technology, rather than the narrative supporting their position in the social fabric of the smart building, as I wanted students to discuss and imagine the wider context for themselves. (Ambe *et al.*, 2019) assert that researchers should include user narratives in the design of fictions, and as such I drew on the formative interviews with building managers to inform the design of the prototypes. This diverts from prior methodologies which have co-designed speculative futures with participants: instead, these were designed by myself drawing on the themes from the guiding research. Feeding this formative stage data into the design of the workshops was a decision made with the intention of grounding the speculative exercise in the concerns of managerial reality, the workshops being a tool to critique this reality and juxtapose it against the concerns of the student population.

Participants were asked to critique these prototypes: they were conversation starters, used to situate the technology ideas within the building space, and to contrast student priorities with the points raised by management in the pilot interview study. Following (Broms, Wangel and Andersson, 2017) the designs were not intended to be serious solutions to problems, but were put forward as provocations (Vines, 2018) to support participants' critical examination of their norms of engagement with the building in daily life. Despite being imagined technologies, they are situated in the real context of the building: the ways in which they interact with this context, as imagined in this exercise, are of interest. The briefing sheets on these diegetic prototypes included a description of the imagined artefact and an illustrative scenario of how participants might interact with it, and are included for reference in Appendix E. The premises for these prototypes are briefly presented in this section. Groups were asked to read all three scenarios, then were assigned one to discuss in more detail and critique using a set of questions asked by the researcher:

1. Where would this be useful?
2. Where would this be disruptive?
3. What effects would this have?
4. What data is collected and used?
5. Who is the user? (And what do they care about?)
6. How would you change the design? (List some areas for improvement.)
7. Does it exclude certain people or groups?
8. How does it get broken?

Finally, at the end of the exercise, groups fed back their answers to these questions to the room, with some facilitation of answers made to probe into responses and get participants to elaborate. Discussions of how they might change the building space, and where they might be effective, ineffective, or disruptive led to a final free design exercise where participants ideated and presented their own interventions.

SpaceBot: A Twitter Bot

The first diegetic prototype involved an autonomous intelligent agent for the building and its management, manifested as a Twitter-based online persona called SpaceBot (**D1**), previously published as a late-breaking work poster at CHI. SpaceBot is an anthropomorphic representation of the building, curious about how people are experiencing it and in developing better understandings of what its sensor data means in terms of occupant experience. SpaceBot, as an online smart agent, captures occupant dialogue *with* and *about* a smart building. It could ask questions around *how people are*, what they *do or do not like*, and what would they like to *change or keep the same*. It tries to engage people in dialogue with others by asking their opinion on others' comments (e.g. by re-tweeting), and how people interpret data points that the building captures.

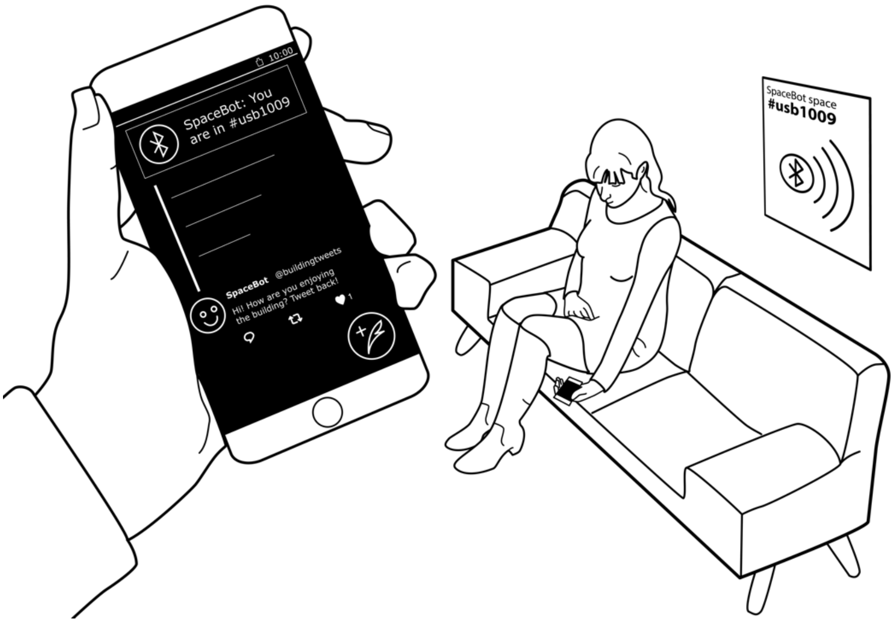

Figure 24: Concept illustration showing a user of the SpaceBot diegetic prototype

Twitter has received wide attention within HCI research: a microblogging platform and source of user-generated content, and a communication channel for organisations. These affordances have also made the platform an engaging feedback mechanism for organisations in the management of their built estate. Twitter 'bots' (autonomously tweeting agents) can be easily developed and deployed, reaching a wide audience. Building on (Wilkie, Michael and Plummer-Fernandez, 2015), who studied how speculative Twitter bots figure in energy use conversations, tweeting buildings present an opportunity to combine agent-based interaction with existing use of the Twitter platform by organisations for feedback and communication.

Questie: A Situated Q&A Platform

The second diegetic prototype, Questie (**D2**) draws on management desire to understand how student occupants perceive and engage with the space. A key theme from my work with building managers to-date is that complaints are often the only way in which the staff who manage non-domestic office buildings find out if there is a problem: this was again reflected in the pilot interview study for this project. **D2** is a top-down solution for gathering ongoing feedback, which can help managers to figure out if there is a problem before it gets bad enough to prompt a complaint.

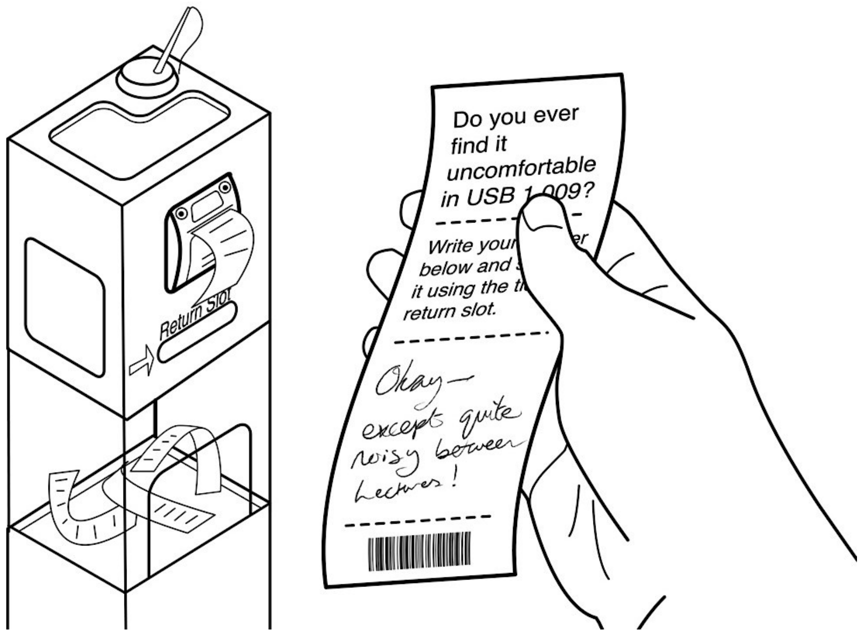

Figure 25: Concept illustration demonstrating the Questie prototype

The physical element of this design is a situated Q&A kiosk, which can be located within spaces of interest in the building, for example the reception. Questie aims to engage people in a process of providing everyday feedback on space use, as a method of supporting user participation in the management of the building. Building managers assign questions to be asked of building occupants, or investigative tasks for them to perform (for example, “how many people are using this space right now?”). When a building occupant walks past Questie, it prints a question or task. The receipt is then scanned in the “returns” slot, and the person can bump their smartcard on the reader to collect points that can be exchanged in the cafe for food and drink. As such, this design also explores how responses might be materially incentivised through integration with existing loyalty schemes.

FurniBa: A Robot for Reconfiguring Furniture

The final diegetic prototype (**D3**) is *FurniBa,* a solution which allows bottom-up reconfiguration of furniture resources within a space. The design played on managerial concerns around furniture use in the building, and was intended to probe students’ thoughts around furniture location and use around the building, and the extent to which they would find it useful to be able to change and adapt building spaces to their needs on-demand. Furniture was identified in the pilot study as something that was easy to change or upgrade, and could be a site of intervention: management staff were interested in creating and curating spaces for students which would be well liked and used.

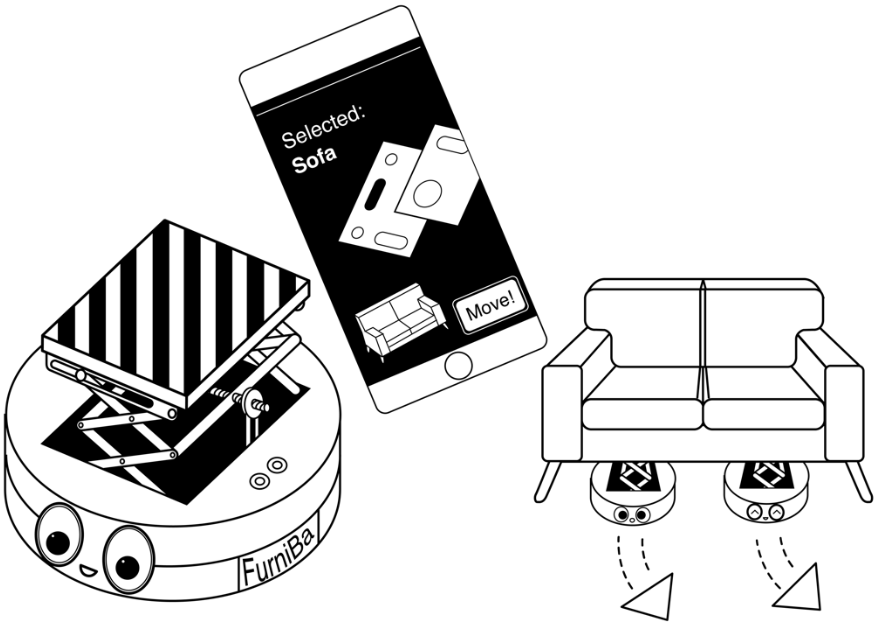

Figure 26: Concept illustration showing how the FurniBa prototype might work

FurniBa envisions a way for furniture resources to be reconfigured within a space from the bottom-up, rather than via the top-down managerially-curated method which is the status quo. The prototype works like a robotic hoover with a powerful lifting jack on its back. It can be called out, via mobile app, to reconfigure the space by moving furniture around. This prototype was intentionally silly (Blythe *et al.*, 2016; Vines, 2018), a reaction to solutionist design intended to probe students' thoughts on furniture location and use around the building, and inter-occupant negotiation in the control and management of this.

6.2.3 Data and Analysis

The workshop exercises were audio recorded (approx. 12 hours audio) and transcribed. The workshops produced a heterogeneous data set comprised of these transcripts, annotated blueprint flipbooks, posters displaying Polaroid photos taken on walks, and participants' design concepts. The thematic analysis of this data corpus was bottom-up, involving iterative open coding of the workshop transcripts: other resources were indexed as they, or the locations they represent, were mentioned. 906 codes were used to label facets of HBI present in sentences, examples including "Comfort", "Responsibility" and "Ownership".

I iteratively affinity diagrammed these codes with oversight from my PhD supervisor to produce three top-level themes from the walks data, and a further three from the speculative design data, with contradictions negotiated by revisiting the transcripts. The purpose of the analysis was to understand common themes from participants relating to human-building interactions (now and in the future) and their experiences of those.

Activity	Total Audio	Transcripts	Codes
Building Walk	7h 15 min	6	545
Design exercise	3 h 57 min	6	361

Table 7: Codes versus activities

6.3 Findings

Participants undertook the building walk and the design exercises in groups. Pseudonyms are used to represent each participant and the group they were part of: *S1G3* indicates student S1 from group 3. The findings are presented in two main sections covering first the situated experiences of human-building interactions, followed by the broader socio-organisational context of these.

6.3.1 Situated Experiences of HBI

Investigation of **SRQ1** led to findings on how students experience spaces in the building, and how they navigate them in terms of access permissions, social hierarchies, and institutional roles. This section describes new understandings which relate to how occupant-management interactions might be designed within the framework of participants' situated experiences with (and within) the smart building.

Securing Space: The Everyday Practices of Nomadic Student-Workers

Student participants in the study were nomadic workers: they had no assigned desk and were required to move around the building to find a workspace. A unique set of practices and building interactions formed around this kind of occupancy, mainly to do with locating workspaces of optimal quality. Space requirements are complex and involve a combination of factors broadly aligned across four categories: comfort, equipment needs, social needs, and spatial constraints.

Comfort needs include thermal comfort, ambient lighting, noise, and distractions: *"I'm quite particular about where I sit, I like a certain amount of light, I like temperature, I don't want my room way too busy…"* (S3G4). Equipment needs are factors such as computer and lab equipment that may be required for some tasks. Social needs include group work: for example, sitting together was deemed desirable, but difficult given the high occupancy of computer workstations: "*if you were with three friends you couldn't sit together, you'd be separated*" (S1G1). Finally, spatial constraints include issues such as resource contention (e.g. rooms being full), access, and the building closing overnight: "*the building wasn't [open] 24 hours[-a-day] so I was there at like 7am, and then couldn't get in, 'cos it's staff only*" (S2G3). It was not always possible to fulfil all these constraints, so some factors had to be prioritised over others: "*There's no natural light, you have no idea of time. The air con's not particularly great. [But] it means you can concentrate if it's really busy downstairs...*" (S2G1). Such priorities vary depending on the task and the individual. For example, participants might turn down a space which would satisfy comfort requirements but wouldn't allow students to sit together for group work.

Participants saw value in a booking system for securing a space to work as this eliminated any compromises that might have to be made. Further, where it was unclear whether students had permission to use spaces within the building, booking supplied a mechanism for reserving the *right* to be there, reducing the risk of being 'kicked out:' "*... you can book some computers in there in case you end up getting kicked out of the labs [...] because of other people's practicals!*" (S2G6). Only some rooms were bookable by taught students, with many being reserved for use by staff: "*unlike the upstairs meeting spaces [...] there isn't an obvious booking system in play.*" (S1G2), and participants felt the system could be improved to open-up more of the building for their use. Even with the existing booking system, finding a workspace often occurred 'on demand'.

Concerns over finding suitable space were reflected in the free design task. Better information provision was one approach considered by G4, making reference to a technology already used in other campus buildings: "*it tells you if it's busy [...] so it will be red at peak times [...] for the library and the gym*" (S1G4). Other groups of participants produced similar designs but focusing on automating requirements management. For example, G1 designed an app that "*best places you in the building for happiness and based on your needs, and then it's also able to improve its recommendations to you...*" (S1G1). A combined recommender system and feedback tool, G1's app was envisioned to provide recommendations based on requirements, and improve those recommendations based on feedback: "*Once you've finished in a space you'll rate how good it is, and that will let the system build up this engine [...] to recommend you better places...*" (S1G1). While these designs provided technological solutions to improving the efficiency of the existing space, the impossible reality of matching everyone's requirements was recognised. In this case, the fall-back would be to rely on existing processes of negotiation with staff: "*it would need to feed that back to the Uni, like, 'you cannot fulfil this requirement"* (S1G3).

Patterns such as commonly busy times do occur and could be captured to improve HBI. But the findings presented here also illustrate important qualities of student practices to consider in new HBIs: the nomadic nature of student habitancy, where work is often done in groups and finding an appropriate workspace involves trying to satisfy complex requirements. Booking systems might be better designed for this, but like other student practices (Clear *et al.*, 2013) there is an element of spontaneity to these (when, where, and with whom) that makes them difficult to plan far in advance.

Negotiating Shared Spaces: 'Structured vs Deliberative' and 'Formal vs Informal' Mechanisms

Analysis of the data corpus uncovered various ways in which building interactions to do with changing the space were approached. Structured interactions (e.g. decision by consensus) were process-based compared to the more *ad lib* deliberative ones. And, formal interactions were operationalised through building managers or other staff in authority, compared to the informal interactions managed by occupants themselves.

Thermal comfort was experienced differently by individuals and was often contested. Consequently, participants felt that an informal or deliberative approach to addressing it would be inappropriate: "*… and you're like the only person constantly saying, 'it's too warm' and everyone just gives you death stares every time you tweet! ((laughter))*" (S1G1). A more suitable approach might be to offer a structured voting mechanism to agree on changes: *S1:* "*How would you change the design…?" S3: "Voting system!*" (S1,3 G4). One participant drew on past experience to support this: "*I've never been in an office where everyone's agreed on the aircon temperature so having a consensus algorithm that was like 'actually 78% of people said it should be colder' would be good.*" In investigating more agency and a greater role for students in building management (**SRQ3**), **D3** focused on furniture as one facet of the building which might be reconfigured on-the-fly by occupants. Participants found it difficult to understand how this might work in practice, possibly as this is strongly tied to social roles and students' distrust in their peers to act responsibly:

> *S1: "This needs to be used responsibly with staff, like IT or lecturers, because this in the hands of a student, they will–"*
> *S3: "Mm, it won't end well. It will last a week or so but that's pretty much it."*
> *(S1,3 G3)*

Yet, participants suggested that a consensus on furniture could indeed be reached: "*I can't actually think of many scenarios where people wouldn't just move it once and then that is in the optimum place for everyone.*" (S1G1)

Pointing to the limitations of consensus-based decision-making, another participant pointed out the difficulty in reaching satisfactory decisions: "*... you can have a voting system [...] but with many things it would be 50-50!*" (S3G1) While resolving conflicts was important to participants, it was recognised that sometimes a structured process might not be sufficient. In another example, not knowing that changing a shared space might negatively affect others was a barrier to interaction: "*how do I know if I move the sofa [that] no one yells at me?!"* (S3G3). These examples might suggest the need for more deliberative approaches; however, participants leaned towards more formal processes of policy and management for resolving them. It was agreed that free reconfiguration could be problematic, and that perhaps there should be limits to what can be moved around: "*It would cause chaos in the area, like, in the building because it might move stuff that's necessary in one place actually.*" (S2G6). Participants preferred modes of reconfiguration closer to existing methods, e.g. via formal negotiation with staff, but it is likely that this is influenced by their familiarity to them.

Yet, more reactive and reconfigurable spaces were not an alien scenario. An existing concept discussed was the use of room dividers to break up a space. Participants envisaged the use of these in practical classes, solving the problem of being 'kicked out': *"when people have a practical and it's a small module, you [...] section off the bit that you need for the module and the rest is free for other people"* (S2G5). This could be viewed as addressing a problem with the design of the building (i.e. holding classes in a large shared space) on which a more participatory management process might facilitate adaptation.

In considering agency and participation for occupants in interactions to do with changing and managing space, it is useful to consider suitability across two dimensions: structured vs deliberative and formal vs informal. These categories serve as a useful tool in thinking about how traditional, centralised forms of buildings management might change in future HBIs to allow for more participatory forms of space management.

How Opaque Space Rules Lead to Unclear Affordances

Participants formed mental models about what spaces were for and their permission to use occupy and use them. Their mental models of these rules in turn informed use of the building. Where spatial rules were unclear, this negatively impacted students' ability to perceive spatial affordances. Participants understood that their role as students affected what spaces they could use in the building, though often the access permissions for a space were unclear. A novel HBI arose relating to this: the use of student smartcards as a proxy for determining permission to use a space.

> *S1: Are we allowed in? What time is it? It should be free. Are we allowed in?*
> *S3: Has anyone got a student card?*
> *<card reader beeps>*
> *S3: That's a no. (laughing)*
> *S1: Ah, once again it beeped, sounding good, and didn't let us in,*
> *(S1,3G2)*

Figure 27: The bike store, which is only accessible to PhD students and staff

Participants discussed how it was unclear if they were allowed to use a given space or resources located in it, though it was assumed that if they could access a given space with their smartcard, they had permission to use it. The bike store is one example which students encountered on their walks, where postgraduates had smartcard access affording the storage of bikes, yet undergraduate students did not:

> *S1: So wait, how did you get the permission for bike, to use the bike rack.*
> *S3: I think if you are a PhD student you start from...*
> *S2: Is there any undergrads that can have it? I don't think the building– the undergrads don't have access to it.*
> *S3: They're too oppressed!*
> *S1: No powers, man!*
> *(S1,2,3G1)*

Yet, students discovered through exploration that space access was actually more permissive than they had assumed: "*I'm seeing that my card actually opens more doors than I thought of it? And all these doors [...] also give you the impression, I guess, the wrong impression that you are not allowed.*" (S1G3). Although for the walking exercise it was not expected that participants would explore areas of the building which they would not normally use, some groups took the opportunity, using the workshop as an excuse to do so.

Another heuristic for determining affordances was the known or implied purpose of a space. While, for some areas, participants had no knowledge of what goes on inside: "*Yeah, so, sort of general research, um– about... um... research about things. Yeah we're not actually sure exactly what goes on there.*" (S2G5), the perception that the space was for 'research' implied that an undergraduate student would not be permitted to use it. Another group complained about the lack of clarity on permission to use whiteboards located in a corridor space: "*These whiteboards. What's the deal with them? 'Cos a lot of times people just write random stuff on it? [...] like– it'd be nice if we get told that we can do that?"* (S1G2). Although the affordances of the whiteboard were well understood (writing, erasing, etc), its location in a thoroughfare muddied the social permissibility of using it, resulting in an unclear spatial rule.

While some spaces have limited affordances in that they are physically inaccessible, there are also social barriers to interactions. G3 took a photo jokingly comparing the staircase from the 4th floor to "*Mount Olympus*", the seat of the Greek gods, and discussed how the top two floors of the building *felt* off-limits to them:

> *S3: Basically I get a kind of, a sense of intimidation, because, you know, that is where most of the lecturers and PhD students reside, and there isn't many rooms for us to access up there. So I don't actually frequent that floor. So what I would say is, that when I look up those stairs, I see an inaccessible floor.*
> *S1: You kind of, it's kind of elitist–*
> *S3: Elitist almost, yes.*
> *(S1,3, G3)*

The floor was not inaccessible in terms of the building's access rules. Yet, participants perceived its affordances according to the socio-physical design of the building, giving the impression that it was off-limits.

Figure 28: The stairway dubbed "Mount Olympus" by the students of G3

Perceived affordances are therefore impacted by understandings of space and how these are communicated. Gaver (1991) points out that culture and experience highlight certain affordances. As such, spatial affordances are also defined and perceived according to the social hierarchy of the organisation. For example, a smartcard-locked door might afford access to research staff, but not to undergraduate students (Gaver defines this as complementarity of action). Yet, student participants also understood space rules as conditional, reliant on social factors which had to be determined before they were *allowed* to use a given space or resource within it. Although S1 jokes "*no powers, man!*", spatial affordances are influenced by and intertwined with the organisation's social hierarchy, which is reproduced and reinforced by the design of HBIs. Acknowledging this can enable better building interaction design for students' mental models and help pursue intended building design outcomes, such as satisfied and included occupants and fostering community and ownership.

6.3.2 Socio-organisational Considerations for HBI

Findings curated in this section illustrate the relationship between a smart building's socio-organisational context and HBI, and how an understanding of this context is essential to sensitively and appropriately design for its occupants.

Mediation is Necessary in Shared Buildings: but Occupants Need to be Better Involved

Interaction with management in the studied building is funnelled through complaints to building managers. This service-oriented interaction modality has advantages, but also disconnects building users from their environment and reduces their agency in the space.

Two of the diegetic prototypes, **D1** and **D2**, were imagined systems for gathering feedback on an ongoing basis instead of waiting for complaints, as an exploration of alternatives to this existing management process. Discussions of these brought up questions of occupant agency and control. Contrary to the expectation that new mechanisms for communication between management and occupants might increase a sense of agency, providing feedback and information without a tangible response actually had a negative impact on perceptions of control: "*... it would be good if you could like not just get the information but request a change*" (S3G4). This relates to experiences of the complaints process. Conversations relating to broken computers and thermal discomfort came up often: e.g. discussing overcrowding and overheating problems in a lecture theatre: "*That lecture room is the worst thing I have ever been in*" (S2G1). While participants emphasised discomfort in these discussions, they noted that it would be rare for people to raise issues with facilities management: "*I know that a lot of the time people won't say anything about the computers being broken.*" (S1G2), because "*I would not bother even telling if I didn't think it was going to change anything*" (S1G1).

Participants noted the self-selection biases inherent in feedback-gathering systems (**D2**), and an awareness that individuals with poorer (particularly thermal) comfort tend to complain the loudest: "*You'd need some sort of consensus [...] rather than one person just being like 'yeah well it's too cold'...*" (S1G1). Furthermore, there was a perception that formal complaints have more weight than ongoing feedback in their power to resolve issues: "*... the issue's not a big enough issue until people complain about it.*" (S1G2) and "*... actual complaints would still be actual complaints... It depends on the effectiveness of the questions.*" (S1G2). It was important that participants should be able to set the agenda, disputing the effectiveness of the targeted feedback prompts from **D2**: "*you could have a general 'is there any feedback?'*

instead of printing a specific question because the person might [...] want to give feedback on something else" (S2G5). Feedback was therefore recognised as important, but issues of agency in raising it and in defining the agenda were seen as possible barriers to participation.

Facilities management are a nebulous group, hugely responsible but disconnected from building users. It is significant that the facilities management team are only ever referred to as "they" in data collected from both the walks and design exercises. "They" are a class of people in charge of the space, who have responsibility for changes made:

> *S3: "Oh look, they've finally installed comfy spaces."*
> *S1: "Oh– I didn't even know **they** were planning on doing that"*
> *(S1,S3G2).*

They also have responsibility for the allocation of resources and organisation of the space and for the maintenance of critical building systems: "*something happened with air conditioning [...] **they** will try to fix it today*" (S1G1). Although this illustrates a distance between facilities management and occupants, and management were in some respects *othered* by participants, accounts from the free design task indicated that they are still seen as an important and necessary part of the organisation to facilitate participants' use of the building. Several groups designed solutions which situated facilities management as the authority with ultimate control over the space provided: "*[If] consistently the system found they can't satisfy students' requirements [...] they will need to put more buildings, more space for this."* (S3G1) and "*... you could look at basically telling that to the university and then someone comes along to that room [and] reorganises it...*" (S1G1). Yet, a process of negotiation was often also envisaged as part of this.

While participants recognised issues with the existing feedback mechanism for reporting issues, they still viewed it as an important channel for more serious problems. In designing for more inclusive buildings, other HBIs are also required, and these must find ways to go beyond information communication and crowdsourcing feedback to enabling occupants participate in shaping agendas.

HBI Must Account for how the Organisation Projects Itself, Within and Beyond the Building

Figure 29: The glass-panelled computer lab photographed by G5, the main working area for many of the student participants

The broader socio-political context of the university influenced student occupants' expectations of the building and the services that they perceived it should provide. Neoliberal perceptions of the university environment were revealed in how students saw the emphasis put on marketing by the institution: "*They sell it good, like, they market themselves good...*" (S1G3). Architectural features such as the glass-panelled windows in the computer labs exacerbated this by making students feel part of that marketing: "*you feel like you're like cattle, being stared at? So like waves of people come in and like stare at you, and it's really frustrating*" (S3G3).

There was a sense that the building had been paid for by student tuition fees, and that problems with it therefore represented a lack of value-for-money: "*I just think, 15 million pounds or whatever it was for this building! And the aircon can't manage to last three weeks...*" (S2G1). Tuition fees are a contextual factor through which the university projects its socio-political orientation. In the design exercise, participants rejected that it was their responsibility to solve these problems:

> *"It shouldn't really be the customer's responsibility to come up with the idea. Like they're offering us a service so we can tell them what we need and then*

> *they can try and do it and feed-back if they can't"*
> *(S2G3)*

This illustrates a two-way influence of the socio-political context on HBI: building design decisions have knock-on effects, such as feelings of being 'marketed' being amplified and reproduced by the building fabric, and buildings and their processes are experienced and understood within and as part of this broader context. HBI cannot be separated from this context, but can potentially mitigate and challenge it. For example, HBI might enable spaces to offer different kinds of value to occupants, e.g. through facilitating different relationships with staff to that of a customer.

The Janus Face of Smart Building Data: Powerful Resource, or Resource for Power?

Smart buildings, as exemplified by the building chosen for this case study, have the ability to collect, analyse, and act on data. Yet, while data can enable novel forms of interaction with the built environment, student participants considered it Janus-faced, highlighting a range of associated concerns. Discussions about data generally occurred in relation to **D1** and **D2**, which encouraged participants to think more broadly about how this data might be used or annotated. Participants were aware that the building was logging large amounts of environmental data: "*we know that the [building] is supposed to be taking in a lot of data and that's kind of like its gimmick*" (S1G2). Among the range of issues extant in the data were concerns about invasions of privacy through tracking emerged in conversations around the collection and use of data as a result: "*Big Brother, innit, being tracked*" (S3G4). Language used also highlighted considerations of ownership of data: "*I really do like the idea of being able to interact with the building that's apparently taking all of our data as well"* (S1G2), the use of the word 'our' raising the question of how data might be more equitably or transparently collected given the perception of ownership by building occupants.

Yet, benefits of data collection were strongly present in the final free design task, where participants ideated on how data might be used, for example in enabling 24 hour access to the building: "*... and the university would be able to actually know who is in what, and this would help with the 24 hours control...*" (S1G3); in visualising busy areas to aid in selection of a workspace "*We've got a heat map down there which [...] can show the busy areas*" (S1G2); and solving thermal comfort issues "*if you got the right consensus algorithm [...] that would have a really good effect on working conditions...*" (S1G1). One group also asked whether staff and students working within the building might have the ability to create their own solutions if the data set were open: *S3:* "*You can access all of the readings, yeah*" S1: "*Like open data, just plug into the API [...], you should be able to query all of it.*" (S1,3G1). Though there was a perhaps technologically-solutionist tendency within the designs produced, they often also offered potential interaction improvements, arising from issues identified through occupants' experience of the building and their participation in the walking activity: "*It would be useful if it told you the aircon was currently on [...] because a lot of the time, like now, the aircon in here won't be on because that [smart] window's open*" (S1G1).

Students also debated the subversion of collected data: from more direct interference with existing systems "*People breathing on the sensors!*" (S3G4) to sabotage sensor equipment; to ways in which the diegetic prototypes might be exploited, for example relating to **D1**: "*it's pretty dodgy I think. [...] It could maybe force you out of a place if it knew you had a general passiveness for not liking hot rooms– it could make the room hotter and things like that!*" (S1G1). The possibility of abuse of occupant-facing systems prompted alternate design suggestions: "*I'd say just have an API [...] and then there's traceability if someone was completely being a dick or something...*" (S1G1) as students questioned whether they would trust other building users to act responsibly in settings with devolved management of the space. **D2** raised similar concerns that "*a lot of people would exploit it [...] Do you think people would use it... properly?*" (S1G2) and suggestions for design changes "*We also had an idea of moving the whole system to be, like, an online system [...] maybe that would help stop people from trying to exploit it...*" (S1G2). As students of an engineering discipline, participants were keenly aware of the potential uses (and misuses) of data collected by the building.

Considering how HBI might account for ethical issues relating to the use of data, this finding highlights occupants' awareness of these issues and their ability to suggest mitigations. Through transparency and the involvement of occupants in conversations around how their data is used, smart building data can be used in ways which include rather than exclude building occupants. Future smart building HBI may leverage this dialogue as a powerful resource for inclusion.

6.4 Discussion

In the previous section, I have presented findings on how student occupants of a smart building conceptualised and understood the space they work in (**SRQ1**), how this relates to perceptions of HBI and facilities management (**SRQ2**), and how agency and participation might be designed into students' everyday experiences of university smart buildings (**SRQ3**). The socio-organisational considerations for such designs were raised in these findings. In this section, I discuss how technology might grant facilities managers insights into the student experience; new digital ways for occupants to play a role in evaluating their building; and link these to HCI in generating design implications for future HBI and facilities management technologies. While this discussion is positioned for designers and practitioners in HCI and HBI, many of its arguments will also be relevant to facilities managers and university management staff who will be best placed in implementing these in future buildings.

6.4.1 Communicating Agency to Building End-Users

Perception of control was important for providing feedback, with one participant saying that they would not even consider engaging if they "*didn't think it was going to change anything*" (S1G1) as reported on in the finding that *Mediation is Necessary in Shared Buildings*. Learned helplessness is an issue in scenarios with low levels of agency as highlighted by Hellwig (2015), where people stop trying to exercise control if their activities have no effect on the situation. To begin to address this, smart building interactions should ideally include an immediate and visible response to communicate to occupants that their action was effective. With comfort systems this interaction is easily understood, for example, turning on a light or showing that the temperature has been recently adjusted on a display, but for furniture reconfigurations a preliminary date and time for when the work might be carried out could be given.

Facilities managers and automation technologies control occupants' space on their behalf. Agency to make changes and manage the space is locked down, for example by centrally controlled thermostats linked to BMS, or windows which do not open because the space is air-conditioned. Goulden and Spence (2015) identify that responsibility for energy management has been centralised with the facilities manager. In the *buildings-as-a-service* model, changes must be requested through facilities management gatekeepers. While in the smart home context, users have more control over their surroundings (including over their automation technologies (Mennicken, Vermeulen and Huang, 2014)) in an organisation this responsibility is deferred to management. There is potential to use data and technology to create flexible spaces, to give *more* control instead of less: *The Janus Face of Smart Building*

Data hints at how this might be enacted through transparency and involvement of occupants in conversations. This supports the perspective on thermal comfort complaints presented in CS2/Chapter 5, and it is well recognised that an increased *locus of control* is psychologically beneficial to feelings of comfort (Haynes, 2008). Comfort is not the only factor determining the fitness for purpose of a building though, and it appears that designing for perception of control holistically could be approached as a starting point in improving occupant agency.

6.4.2 Ongoing Conversations may Lower the Bar for Feedback

Although techniques such as post-occupancy evaluation (BRE, 2019) exist as a method of directly engaging with building users, they are limited in that they are not used in an ongoing manner over the lifetime of the building. While students are lay-experts on the building as seen in CS1, they have no formal training in facilities management: the perspectives of other building stakeholders will be valuable in order to bolster their knowledge and correct misconceptions (Hasselqvist and Eriksson, 2018). Moreover, although participants were able to describe and discuss the pain-points of their experience (as in the finding on *Negotiating Shared Spaces*) these are difficult to get at for facilities managers through traditional feedback processes such as making a complaint (see CS2). This work suggests that there is potential in designing interactions which engage occupants in an ongoing conversation to ensure that the buildings which they inhabit are, and continue to be, fit for purpose. With its experience of user-centred and participatory design methods, and novel interaction techniques, HCI as a field is well positioned in its ability to respond to this challenge. Previous work has examined civic technologies (Boehner and DiSalvo, 2016), participation in planning (Wilson and Tewdwr-Jones, 2019), including voting technologies (Vlachokyriakos, Comber, *et al.*, 2014), sharing themes with the solutions designed by participants. Such approaches might represent a starting point for beginning to understand how occupants might continuously collaborate with management in solving wider problems in the building.

6.4.3 Designing for Exploration and Spatial Appropriateness

The findings of this research also surfaced forms of interaction by occupants with the studied building which were unexpected: for example, how the testing of smartcard access as a proxy for permission to use a space (see *How Opaque Space Rules lead to Unclear Affordances*) helped students to develop mental models of building permission. HBI might consider exploration when designing smart building interactions. Similarly, the *SpaceBot* diegetic prototype (**D1**) depicted a novel interface operated through the Twitter platform. While this received criticism for its susceptibility to abuse, it is necessary to keep in mind that criticism is a resource for design (Vines, 2018) which can be harnessed for creativity. While such interfaces allow for exploratory interaction, technologies of this kind differ in the extent to which the interaction is public or private. Twitter was understood as highly public and therefore not spatially appropriate. Local interfaces, or conversational agents such as Amazon's *Alexa* and Apple's *Siri,* have recently garnered attention from the CHI community (Vtyurina and Fourney, 2018) and may be better suited to this context as they allow spoken interaction. Furthermore, certain types of interactions (such as comfort complaints) may not be suited to a technology where they can be overheard, requiring more discreet forms of interaction, similar to the red/green LED display of the smartcard reader when granting or denying access to a space.

Booking was another form of interaction referred to by students, who viewed it as a way of guaranteeing access to appropriate workspace which met their requirements. Better access to information might alleviate the need for booking, which (as in the finding on *Securing Space*) may be at odds with the spontaneity inherent in the practice of finding a place to work. Participants suggested in the design activity that mobile apps may be a way to accomplish this, giving an easy way to access data on resource contention. Sensor-augmented smart buildings (even retrofitted ones, such as in CS1) offer a unique advantage in this regard as analytics can be performed to create occupancy data (Khan *et al.*, 2014). A solution as simple as visualising and feeding back expected occupancy levels would to allow planning for a future 24-hour period. Situated public displays offer another mechanism for accessing this information, and could enable more complex forms of interaction and negotiation (Johnson *et al.*, 2016), though these should be carefully designed and positioned (Parker, Tomitsch and Kay, 2018) to allow for meaningful engagement. In short, both the technologies deployed within a space, and the interactions and processes designed for them, must be spatially appropriate and account for the social context.

6.4.4 HBI's Role in Supporting (or Challenging) the Status Quo

While buildings management often seeks ways of managing that maintain the *status quo*, this might change in future. In the home, Mennicken *et al.*'s (2014)'s provocation that "*smart homes will collaborate with their inhabitants instead of only being controlled by them*" is pertinent for non-domestic smart buildings too. Taylor *et al.* (2007) identified that the home should support the smartness (meaning intelligence) of its occupants, though in the workplace 'smartness' will have different meanings, including e.g. fostering social interactions (Brown *et al.*, 2014). By shifting the rhetoric of smartness away from automation back towards the human, smart buildings might be made smart for occupants, too, not just building managers.

Feminist HCI, particularly when an intersectional approach is taken (Schlesinger, Edwards and Grinter, 2017; Rankin, Thomas and Joseph, 2020), offers one lens to examine and challenge inequitable social structures and existing processes which marginalise different socioeconomic groups based on race, class, gender, (dis)ability, and so on. Bardzell (2010) offers one critical framework for feminist HCI work, but this is not well adopted (Chivukula and Gray, 2020) despite wide citation of the work, perhaps due to its prescriptiveness about what Feminist HCI can be. Yet, attentiveness to how different groups of people are represented in management decisions within an organisation is important and there is a role for HCI (and indeed HBI) in identifying and disrupting hegemonic structures. Within this case study, students formed an underrepresented group within buildings management processes, but future studies might look at this with more granularity: prior research would indicate that people of colour, LGBTQ+ people, and/or disabled people are further marginalised within this group due to the intersection of these identities. It is critical to include these groups of people to achieve environmental and social justice within buildings management. Technology can help to shift attitudes and build community relationships to this end (Strohmayer, Clamen and Laing, 2019), as long as HCI/HBI practitioners remain wary that designing solutions for complex issues is a technologically solutionist trap.

Buildings management involves making trade-offs and coming to a consensus with differing opinions (per CS2). Perhaps a change in the culture of both managing and occupying buildings needs to occur for more radically reconfigurable buildings to become a reality. As Gray, Stolterman and Siegel (2014) point out, "*professional practice is often shaped by institutional and traditional norms and values that have the potential for improvement through research and practitioner partnerships.*" In this respect, I highlight that *HBI Must Account for How the Organisation Projects Itself, Within and Beyond the Building*. Neoliberal management structures, processes, and cultures are a barrier, but the culture they create results in occupant disengagement: why take responsibility for the space when you're a customer? Although participants rejected having a role in managing the building, they did care about having good space, and this could be better leveraged as stewardship if organisational practices and processes were put in place to enable them to contribute, and to de-centralise and distribute responsibility to more stakeholders. Tackling strongly held perceptions of social roles may be the first step in enabling more democratised forms of management. Directions for HCI/HBI to contribute to this agenda include designing technology to support decentralised responsibility for space management, democratising how decisions are made, and enabling bottom-up provision of resources. Furthermore, there is an open question for us as HBI designers and practitioners: *should HBI be designing to support service-oriented buildings management, or should it be disrupting the space*?

6.4.5 Participatory Auditing

Following the call that I have made that buildings be continually evaluated and reconfigured over their lifetimes, I propose here a technologically mediated approach to engaging building users, tentatively termed '*participatory auditing*' or PA. Specifying a methodology for PA is beyond the scope of this chapter, but from the findings brought forward above I can suggest a manifesto for its central tenets, as follows:

Shift social roles: To reduce occupant reliance on a building-as-a-service model, social roles must be shifted to increase agency, and consequently responsibility. This relies on organisational culture change, as there must be support for this from across the stakeholder spectrum. Technology alone cannot achieve this. Grassroots approaches such as building occupants' unions might play a role here in proposing and achieving such change.

Promote collaboration: Collaboration between occupants and facilities managers is crucial for enabling more radical forms of facilities management; reducing the '*us vs them*' paradigm referred to in the findings. This depends on the aforementioned organisational change. It is likely that more progressive building designers and managers would be at the forefront of adopting new methods for this.

Enable reconfiguration: Occupants are domain experts in the problems they experience, but don't consider it their remit to perform more radical reconfiguration of space or just-in-time adjustments in-person. While the temporal aspect of changes is longer if management needs to be involved to action it, giving timescale estimates and timely up-front approvals or denials can alleviate this. Interaction should be handled by the building itself (for example, perhaps a conversational agent built into the room). No-one should have to send an email to request a change.

Disseminate information: Data should be leveraged as part of collaborative discussions with occupants (as in CS2) to allow informed conversations to take place, and to build expertise in understanding and interpreting data. Technology forms a part of this vision, by enabling novel ways of collecting information on problems, and providing new forums to facilitate their discussion. HCI practitioners can support forerunners in this space, and foster bottom-up solutions to challenge norms.

6.4.6 Limitations

There were limitations to this study. Primarily, I have focused on one kind of non-domestic building, and with one type of occupant: students. This gives one particular perspective of the situation, which I have acknowledged up-front in the methodology section of this chapter. In mitigating this, I recruited across taught undergraduate and postgraduate courses, though some postgraduates worked in staff offices on doctoral training programmes. Yet, future work must attend to other roles: academic staff and PhDs; administrative and support staff; and estates staff including cleaners. Although I conducted pilot interviews with other building stakeholders, those individuals were not included in the workshop to avoid diluting the perspectives of the student occupants. Per Hasselqvist and Eriksson (2018), inclusive buildings management processes should be co-designed with this wider network of stakeholders.

A further limitation arises from the methods used: while the power of speculative methods is (as discussed in Chapter 3) to rehearse the concerns of the present, they do frame participant responses in terms of the technologies of today. This was most visible in the free-design exercise (part 4, §6.2.2), where more than one student group pitched designs for mobile apps which would allow them to book workspaces. Further, when critiquing the diegetic artefacts (particularly **D2** "Questie") it was difficult for students to see how these intentionally 'silly' technologies might fit into their lived reality. A remote framing for these speculation exercises, for example through design fictions describing the smart buildings of a remote sci-fi future, might help student participants to more imaginatively engage with these exercises. This is discussed by Tanenbaum *et al.* (2016) in the context of total environmental collapse: design fiction, being *"uniquely suited to engaging with consequences"* allows us to more radically speculate about the changes required to our existing practices to address the magnitude of the climate challenge. As Tanenbaum *et al.* discuss, the use of values-driven design fiction allows the exploration and critique of values and ethics, "*to force readers to grapple with the ethical issues"* which remained out of sight in the technologies designed by workshop participants.

6.5 Summary

This chapter has presented a case study of student occupants of a smart building, resulting in new understandings of how HCI and HBI practitioners might design interactions that foster agency and participation in facilities management processes. Smart buildings offer an opportunity for better performance and enhanced experience by contextualising services and interactions to the needs and practices of occupants. Yet, this vision is limited by established approaches to building management, delivered top-down through professional facilities management teams, opening up an interaction-gap between occupants and the spaces they inhabit. To address the challenge of how smart buildings might be more inclusively managed, this case study engages with student occupants of a smart building, through design workshops including building walks and speculative futuring. Findings from a qualitative process including a building walk and speculative design workshop point towards new understandings of how student occupants conceptualise and evaluate spaces as they experience them, and of how building management practices might evolve with new sociotechnical systems that better leverage occupant agency. I further outline important directions for the HCI and HBI fields in this nascent research area, including the need for HBI (Human-Building Interaction) design to challenge entrenched roles in building management.

Chapter 7: Discussion

Fitter, happier, more productive.

RADIOHEAD, "FITTER HAPPIER" (1997)

7.1 Introduction

This dissertation has established a critique of the 'modernist' smart building vision, and has argued for both broader consideration of the needs and practices of building occupants, and for the consideration of values, agency and ethics in smart building design. In the introduction to this work, I discussed how smart buildings fall at the centre of a utopian blueprint, their algorithmic intelligence and sensing capability aiming to make them easier to manage and environmentally sustainable. One of the central promises of this vision is that these buildings should be a place where people want to work, creating fitter, happier, more productive occupants. I pointed out that this promise cannot be fulfilled by automation alone, as this technologically solutionist (Morozov, 2013) approach fails to account for how buildings and technologies are used in the real world, and limits the range of possible actions available to a human occupant. There is sufficient evidence in all three case studies to support this, demonstrating significant problems with the assumption that automation always benefits the occupant.

A human-centred smart building might contain automation, but its architectural, sociological, and technological design should still allow for agency on the part of the human occupant. I have therefore argued (in 2.2.2) in favour of a re-framing of the 'smartness' in the 'smart building'. Instead of relying on automation, HBI designers and practitioners can turn to the values, agency and ethics of the third wave of HCI in designing synergistic smart buildings which more fully account for sociotechnical factors and use-in-practice. Correspondingly, the pursuit of a smart building which centres the human has been the focus of the three case studies presented in this work. This motivation runs throughout, looking at existing practices for ways to open up the closed loop of building automation. This chapter therefore reflects on potentials for this which have become apparent through the three case studies. I first revisit, reflect upon and provide answers to the three sub-research questions identified in Chapter 2, as investigated in the three case studies. Secondly, I revist the values and ethics of environmental sustainability and democracy and civics in how they apply to this work. Finally, I propose a set of principles for technology in human-centred smart buildings, with an eye towards how the findings of this dissertation might be implemented in future work.

7.2 Research Results

In Chapter 4, I addressed the research question **RQ1**: "*how can retrofitted sensor data augment facilities management processes, and how might building users be empowered to participate in these?*" The study found that environmental sensor toolkits supported facilities managers in proving compliance with standards, evidencing funding requests, and augmented outdated BMS as an auditing tool. I developed understandings of how these were integrated into projects, and how auditors' knowledge and experience facilitate interpretation of the data. Sensor toolkits are shown to support a kind of second-wave smartness (see 2.2.2) by enabling the human to make smarter decisions: gathering evidence and providing data to factor in. The findings also raised opportunities for using data in negotiations with building end-users, and highlighted sociotechnical tensions and challenges in capturing adequate data for the required purpose. However, questions were also raised about how such tools act to reinforce the manager-occupant power dynamic. I provide a set of recommendations towards a deployment protocol for environmental sensor toolkits, which provide one route by which these tensions might be managed in future deployments. Finally, I highlighted design considerations to address power, privacy and democratic concerns, pointing to how sensor toolkits might be redesigned to empower building occupants to participate in the management process, and note how standards might take this into account.

In Chapter 5, **RQ2** asked: "*how can data and digital technologies foster shared understandings and assist comfort negotiations in the office workplace?*" Through the deployment of a subjective experience survey device, ThermoKiosk, I found that both environmental and subjective data require occupant accounts to be meaningful, and that subjective data reflects complex social factors around interaction practices. Occupants' collective experience of thermal comfort in the study office was often a negative one: the building's design limited occupant adaptation, but ThermoKiosk allowed for constructive dialogue, and smoothed intra-office comfort negotiation with other staff over the room temperature. The limits of occupants' lay knowledge and sense-making practices limited shared understandings in one respect, but also revealed opportunities for experimentation and knowledge sharing. The discussion section pointed to how passive occupants might become active inhabitants of the office space: collective comfort provides one route to this, achieved through social and collective negotiation. An engaged facilities management team remains vital in this, too, advocating for the environmental consequences of occupants' requests. Digital technologies can play a role in opening up conversations and negotiations.

Finally, Chapter 6 investigated **RQ3**: "*how can HBI support occupant agency and participation in the everyday management and adaptation of smart buildings?"* A workshop including a building walk and speculative design revealed student participants' situated and lived experiences with (and within) a university smart building. Occupants' practices in securing space to work were influenced by needs for comfort, equipment, sociality, and spatial constraints, and occupants discussed how they would negotiate changing these spaces to better suit their needs via formal or informal methods. It was also shown that affordances of shared spaces influenced perceptions of use, showing that unclear design of permissions in shared spaces led to a perception that some spaces were off-limits to undergraduate students. A number of socio-organisational factors must be considered in discussions of smart infrastructure, including better involvement of occupants in the management process, accounting for the ways in which organisation projects itself, and the Janus-faced quality of smart building data in how it can both enable novel forms of interaction but also lead to invasions of privacy and concerns about misuse. I discussed in this chapter how agency must be communicated to building end-users if they are to become better involved in the management process, and that ongoing conversations might lower the bar for feedback. Further, I note that HBI as a discipline has a role in supporting (or challenging) the status quo around facilities management, particularly where this is unjust or unsustainable, and social justice approaches can guide us in developing interventions to this end. Finally, I propose a technology-mediated approach to involving participants in discussions on an ongoing basis, with a view to enabling ongoing participation in the everyday management of the smart building.

The remainder of this chapter is dedicated to answering the overarching research question: *what are the roles of data and digital technologies in creating human-centred smart buildings*? I cross-reference the case study data where appropriate to support my argument for a human-centred smart buildings paradigm, with design values and motivations that support occupants rather than automation.

7.3 Human-Centred Smartness

I first re-examine what a human-centred smart building looks like, given the learnings of the three case studies. The question I asked in the introduction was, "*who are smart buildings smart for*?" Several different types of participant have been addressed in this work: amateurs, facilities professionals, office desk workers and nomadic students. With each of these different groups, I have identified different ways that technology can help *them* to be smart. In none of these cases has it been the building itself[31], even in CS3 which was set within a purportedly 'smart' building. It has always been the *people*. Per (Norman, 1993), smartness assists people in the tasks they must accomplish. However, it must do more than this: as I described in section 2.2.2, a third (or fourth) wave smartness is one aware of values, ethics and politics, and takes note of issues which affect individuals, relationships, and societies (Comber, Lampinen and Haapoja, 2019). This dissertation has highlighted how the sociotechnical design of smart building systems can reinforce existing and unjust social structures, and taking a feminist and/or social justice perspective on these (Strohmayer, Clamen and Laing, 2019) can present possibilities for technologies to challenge injustice.

Part of this issue turns on who we view the 'end users' of the smart building to be. While the modernist zeitgeist emphasises the benefits of building automation for individual office workers (generally 'comfort') the *real* end users of the kind of smart building sold by Intel, Microsoft, *et al.* (Microsoft Corporation, 2013; Intel Corporation, 2017) are businesses and their facilities managers. Smarter BMS systems are fantastic if the goal is to track the energy usage of an organisation's built estate (per CS1), but the claim that direct benefits are seen by building occupants appears to be tenuous at best. There is a similar brand of fallacy present here to 'trickle-down' economics. Further, if the sales pitch to buildings for 'comfort' is 'increased productivity', this betrays the neoliberal assumptions underpinning the development of building systems: the core value of the smart building in this paradigm is extracting more labour from workers. HCI and HBI are complicit in supporting this paradigm: as Dourish (2010) argues, the ideological framework of neoliberalism is built into the design of technologies, prioritising the "*rhetoric of individual moral choice*". The notion of 'personalised comfort' (The British Land Company PLC, 2017), a key part of the

[31] I wanted to say, "there is no such thing as a smart brick." Alas, of *course* there is (Engel *et al.*, 2004). In no way do I wish to diminish the achievement of the researchers who created the smart brick, but rather to point out that perhaps our working definitions of smartness differ and need to be refined.

modernist smart building vision, is just another facet of this market focus. This is besides the fact that there is "*no universally accepted definition of office comfort, and there is a clear lack of agreement as to how office comfort should be measured*" (Haynes, 2008). There is evidence to suggest that far more emphasis should be put on designing for adaptation than for tight regulation of the thermal environment (De Dear and Brager, 2001).

Given the realisation that the design of smart buildings technology is not (and cannot be) politically neutral, a larger shift in how we design and consider these is necessary. Centring social justice and feminist perspectives can expand HBI's understanding of how building technologies can reinforce exploitative and unjust social structures. Keyes, Hoy and Drouhard (2019) argue for forms of HCI research which prioritise and maximise autonomy, hold power relationships "*in suspicion,"* and incrementally build towards an alternative moral value system. Such a shift is critical: I have discussed (2.4) how 'smart' environments can limit agency, in effect observing how technologies fail to meet peoples' needs when they are developed with the incorrect assumption that the authors work from a politically neutral perspective. The alternative necessarily requires that HBI/HCI authors "*examine systems of oppression and work to undermine them"* (*ibid.*), and as such it is important for HBI work to challenge the status quo (6.4.4) where this is unjust or unsustainable. Feminist intersectionality (Crenshaw, 1991; Schlesinger, Edwards and Grinter, 2017) provides one framework by which to understand such systems, to "*embrace equity, inclusion and social justice*" (Rankin and Thomas, 2019), and imagine alternative futures (Fox *et al.*, 2017). While this dissertation does not focus on any particular demographic (e.g. black female building occupants) or give insight into their experiences, it does highlight that treating occupants as an homogenous group is unlikely to produce equitable, socially just, or indeed comfortable outcomes (as per 5.4.2).

The facilities-management-as-a-service paradigm is counter-productive in this respect: as seen in CS2 and CS3, the expectation which is set for occupants is that comfortable environments should be provided to them as 'end users' of the building (5.3.6). If time is money, then adjusting the air conditioning is a waste of both. Further, if occupants are students who have paid tuition fees, this further reinforces the customer-provider relationship (6.3.2). There is a challenge in shifting occupant expectations of comfort (Clear *et al.*, 2014), and the perception that one's individual comfort is someone else's responsibility. The question therefore becomes not just "*how can we design to support building users,*" but also "*how can we design to challenge them?"* In moving towards adaptive comfort routines, it will also be necessary to redraw understandings of the role of facilities management away from a manager-user relationship to more inclusive and involved forms of management. Flexible rather than static notions of adaptation are key. Where tighter control can provide ‘personalised comfort’, there is strong evidence to suggest that this can be achieved through adaptive opportunities without requiring integration of personal preferences into HVAC control systems.

Moving beyond comfort, I have further argued that smart buildings should be reframed as collaborative technologies (2.5), as Mennicken *et al.* (2014) argue in the context of the home. In the non-domestic workplace, however, there are a different set of values and meanings at hand. The case studies in this work highlight opportunities for different kinds of collaboration which can be facilitated in a smart building:

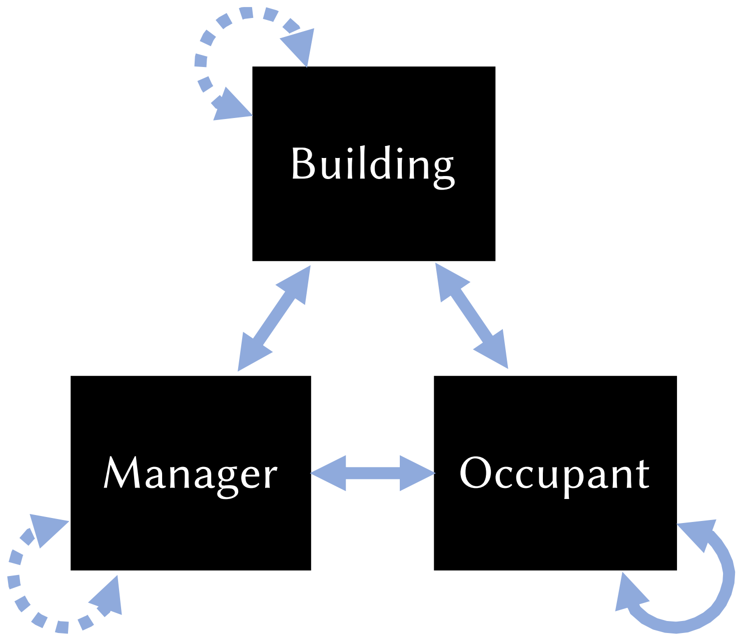

Figure 30: The HBI collaboration triangle. Arrows indicate bi-directional collaboration between agents.

1. *Building-occupant collaboration*: the building assists occupants in their work through its design, for example through clear affordances for space use (6.3.1), or providing opportunities for comfort adaptation (5.3.3). This has implications for how we design buildings, e.g. in the provision of repurposeable space (Brand, 1994).
2. *Building-manager collaboration*: the building assists facilities managers in their work, perhaps by providing useful data in the management of the estate (4.3.1), which may be achieved with retrofittable systems if the building itself does not support it. The

modernist 'smart building vision' does already support this kind of collaboration to some extent, but it is often the only kind which it does.

3. *Occupant-occupant collaboration*: the building and its technologies enable occupants to collaborate with each other. One obvious example of this is the abandoned CSCW concept of Roomware (Streitz, Geißler and Holmer, 1998), but technologies such as ThermoKiosk which act on the social fabric of offices also have a role in fostering this (5.3.4). This also has implications for how occupants might reflect on and consider their comfort.
4. *Occupant-manager collaboration*: the building enables negotiations between occupants and facilities management (5.3.5), and with people further up the stakeholder chain (Parag and Janda, 2014). Data can support these conversations, (4.3.3) albeit with some caveats (5.3.5).

Two further collaboration modalities also exist (indicated by the dotted lines in Figure 30), but are beyond the scope of this dissertation:

5. *Manager-manager collaboration*: networks of facilities managers within and beyond institutions already collaborate to share knowledge and expertise. Although this dissertation did not address collaboration between facilities managers, this may be a point of investigation for future HCI work.
6. *Building-building collaborations* might begin to arise in the smart cities of the future, where smart building systems are linked in a form of civic area network. Buildings could feasibly exchange data on their internal environment, repair condition, user occupation levels and so on to enable new forms of smartness and space allocation.

There are different end-users with different needs, and it follows that each will require a different kind of smartness to facilitate them. However, automation and sensing alone does not clearly contribute to achieving any of these types of collaboration. Building management systems, as the name suggests, facilitate managers. In facilitating occupants, the goal suggested by all three case studies would to be to increase their agency and autonomy, as opposed to ratcheting it down in increasingly tightly regulated environments.

If the evidence points to taking a human-centred approach, it may be useful to connect to the concept of 'fitness for purpose'. The phrase has its roots in consumer protection law (*Sale of Goods Act*, 1979) and sees use in construction contracts where it means that the "*contractor agrees that the design will meet the employer's demands*" (Balchin, 2011). This aligns better with a technical facilities management-centered approach and a quality engineering mindset than notions of human-centredness, and could have utility in achieving industry and organisational uptake of more inclusive management processes. However, it is necessary to identify and define both what the purposes are, and for whom they are 'fit'. New buildings and their instrumentation systems often do already meet the requirements of facilities managers (CS1), but the findings of this dissertation suggest that a smart building should also be fit for the purposes of its occupants in managing both their own comfort and that of the collective (5.4.2) in accomplishing day-to-day tasks, and meeting their spatial and environmental needs (6.3.1). This frames the 'purpose' of the building as a collaborative entity: continually constructed, not static (Brand, 1994), changing over time. However, these purposes can be competing, in tension against one another (5.4.4): comfort versus efficiency and environmental footprint, data collection versus privacy (6.3.2). Collaboration necessitates negotiation. A human-centred smart building facilitates this collaborative environment. Defining the purposes of a building therefore requires an understanding of the socially constructed norms of how buildings are designed, maintained and lived in (CS3), and how these change over time. The only way to do this effectively is to ensure that building occupants are closely involved in the ongoing development of a building as a community of valued stakeholders. The concept of fitness for purpose is useful here, as it requires reflection by management as to how the building can meet these ongoing needs.

Fitness for purpose is not an alien concept to the building industry, and construction firms implement quality assurance standards such as ISO 9001 to "*provide products and services that meet customer and applicable statutory and regulatory requirements*" (ISO, 2015). The case studies presented in this dissertation were undertaken in an organisation which implemented both ISO 14001 and ISO 50001 in the management of its built estate. The WELL Building Standard (International WELL Building Institute PBC and Delos Living LLC, 2016) is an example of a novel standard encoding employee wellness, and includes protocol requirements for adaptable spaces and organisational transparency: ideals this dissertation also supports. There is scope for a new standard to implement a management system reflecting the values and mechanisms for human-centred smart buildings which I have outlined[32]. While ISO standards are proprietary, as pointed out in CS1 (4.4.3) meaning that they are not accessible or affordable to individuals[33], individuals are not the target audience: businesses are. While codifying human-centred buildings in a standard allows for measurement and testing of fitness for purpose (1.2), it does raise an obvious problem: how can we avoid reinforcing the customer-manager dynamic (6.4.4)? The key difference in a human-centred building is that responsibility for ongoing determination of the purposes for which the building is fit is shared between the building owner and community of building occupants. Building occupants must be encouraged to be active inhabitants (Cole *et al.*, 2008), per 5.4.1. A human-centred buildings standard can enforce the setting up of organisational structures and appropriate messaging to communicate agency to building end-users (6.4.1), thereby increasing perception of control to reduce learned helplessness, and providing opportunities for collaboration with facilities management as an equal stakeholder.

There is scope for novel technologies to support the four kinds of collaboration described in this section. Adaptive architecture (Schnädelbach, 2010) holds some promise in this respect by enabling occupant adaptation of spaces, although there is an open remit for future work to: a) scale these experiments up beyond single examples; and b) to explore human-building interaction designs which foster collaboration between various stakeholders. This is not solely a technological problem, as I have described, but CS2 (5.4.3) demonstrates that there are opportunities for technology to facilitate this. The low-hanging fruit here has very much been picked already, for example, space booking apps (Valks, Arkesteijn and Den Heijer, 2019) which are useful for students in securing space to work (6.3.1). However, novel CSCW tools might look towards the building itself (or indeed its occupants) for opportunities to facilitate human-centred smartness.

[32] Though, it may be important to ensure that HVAC equipment manufacturers do not have too much of a presence on the committee for this notional new standard, having a conflict of interest as providers to the air-conditioning market which works against adaptive building design.

[33] At time of writing, an electronic copy of the ISO 50001 standard retails for 138 CHF (around £115 GBP).

7.4 Environmental Sustainability

7.4.1 Energy and Efficiency

Sustainability also factors in fitness for purpose. In CS2 (5.4.4) I wrote that there is a role for facilities management in advocating for the environmental consequences of occupants' requests, a factor also recognised as important by facilities managers in CS1 (4.4.3): "'*we need air conditioning.' [...] I think it's almost a flippant remark, which could cost you a lot in the long run."* (FM4/CS1). By trying to avoid techno-solutionist approaches (as I have within this research) it can sometimes seem that the wider picture of environmental sustainability is clouded in favour of nuance around lived experiences and the effects of technology. This isn't to say that automation can't achieve energy efficiencies: obviously, it can (Moreno, Zamora and Skarmeta, 2014). The argument is that this is not sufficient, and such a framing reduces the human factors to a focus on personal moral choice (Dourish, 2010). Instead, sustainable HCI "*requires locally grounded, socially focused solutions*" (Mankoff, 2012). Further, as Bran Knowles *et al.* posit given the emergency of climate change, "*there is no room for comfortable notions of technological quick fixes, or any kind of intervention that does not in some way address the root cause of climate change*" (Knowles, Bates and Håkansson, 2018). In attempting to understand the design space for human-centred smart buildings, I would assert that nuance around lived experiences, as this dissertation draws out, are essential to design for climate change without resorting to technological solutionism. Further, it raises wider questions around the sustainability of built estates, which I attempt to draw out in this section.

In CS1, facilities managers used the data provided by sensor toolkits in identifying upgrade opportunities for longer term energy savings (4.3.1). In tandem with the data provided by BMS, energy audits can help reduce consumption: not by cumulative optimisations on existing energy inefficient technologies, but by helping to identify the biggest energy draws and targeting interventions accordingly. Measurement is an important part of the picture (Mankoff, 2012), but is still only one part. It is important to remember that looking at sustainability only through the lens of energy consumption is reductive, and that we should "*consider energy in the context of broader sociocultural practices*" (Brynjarsdóttir *et al.*, 2012). There is ample opportunity to also use this data in richer kinds of building user engagement, and the enthusiasm exists within facilities management teams to enable the deployment of new and experimental interventions: "*what I'd like to achieve is very much a* *richer engagement... and a lot of that comes down to technology*" (FM3/CS1) (4.3.2). In CS2 I argued (a little tongue-in-cheek) that the 'benevolent dictatorship' of facilities management may have utility in advocating for the environmental consequences of occupants' requests and actions (5.4.4), yet CS1 showed that building users can be problematised by the processes and policies of an organisation (4.4.1). The goal of richer engagement needs to be designed to take account of this, although there exist privacy issues in the availability of fine-grained data which must be considered within the context of organisational power structures (6.3.2). This demonstrates that although environmental and social justice are linked (Dombrowski, Harmon and Fox, 2016), in the context of HBI there is a tension in upholding these concerns. As I have argued across all case studies, this may be addressed by reconfiguring the positioning of facilities management from a service to end users to a more collaborative endeavour with shared responsibility. Occupants can even be involved in the investigative process, as in both CS1 and (Mauriello *et al.*, 2016).

Still, as HBI pivots towards more socially just and inclusive forms of buildings management it can become difficult to keep the big sustainability issues in focus, while also not oversimplifying them (Brynjarsdóttir *et al.*, 2012). To avoid technosolutionist and reductive approaches to sustainability it is necessary to deeply examine existing sociotechnical systems, as this work has done. Inductive qualitative methodological approaches to data analysis (Braun and Clarke, 2013) are a powerful tool for foregrounding the intricacies of these systems, but can result in an analysis which unearths issues that may be only tangentially related to sustainability. Yet sustainability, as a "wicked problem," is deeply intertwined with these wider social issues, and they are therefore critically important to consider. Advocating for social justice, reimagining participation (in management practices, in this case), confronting the economic models which drive environmental and societal collapse, and thinking in terms of systems rather than people are research approaches that the SHCI community have already embraced (Knowles, Bates and Håkansson, 2018). It therefore makes sense to extend consideration of these to HBI. Further, from a practical perspective, working with and building incrementally on these existing systems may be preferable to making more radical proposals for systems change. This is a tension already well known within the SHCI community (*ibid.*), but one which is particularly salient in buildings management, a business driven by the vested interests of different stakeholders (Goulden and Spence, 2015). Grand proposals for new systems contain inherent risk that presents significant barriers for adoption, but the augmentation of existing systems (CS1) presents a different risk environment which may be a more palatable proposition.

7.4.2 Lifespan and Longevity

Across the three case studies presented in this dissertation, the built estate varied in age: the oldest building examined was constructed in 1955 (CS1), the newest in 2017 (CS3). This presents an interesting point of reflection on building technologies, as technology progresses at a considerably faster pace than the timescale of buildings. Retrofitting of older buildings is known to offer significantly better value over the building's lifecycle than demolition and re-building (UCL Engineering, 2017), and also results in lower carbon emissions. Domestic estate can be expected to have a lifespan of 60-90 years (*ibid.).* Wireless technologies such as the BuildAX toolkit used in CS1 (4.2.2) offer opportunities to collect data with lower embodied emissions (and at far less expense) than gutting and retrofitting buildings, but come at a trade-off in terms of reliability and longevity[34]. In the design of technologies for built environments, HBI practitioners may need to consider the lifespan of their designs, and how they will function over the lifetime of the building. Yet, the service lifetime of these technologies may be long, and their sustainability effects (such as embodied and ongoing emissions) may be so complex that it is difficult for us as human actors to know them (Comber, Lampinen and Haapoja, 2019). Thus, while the aim should lie in maximising the value of a technology over a building's lifetime, how to approach this is a question for future work.

Architecture must adapt. Buildings must continue to grow and change over their lifespans. Stewart Brand writes in "*How Buildings Learn"* that the seeming permanence of architecture is an illusion (Brand, 1994, p. 16): a change in purpose requires adaptation. Adaptability is a key principle in good architecture. The author's own parents live in a 300-year-old cottage of mud/straw wall construction. Its survival is testament to its adaptability. Only the core of the building is original: it has been extended on all sides except the front. On the other hand, Newcastle University's Richardson Road student flats had only a 46 year lifespan: constructed in 1971, demolished and rebuilt in 2017 (Newcastle University Press Office, 2015). Presumably, the university chose demolition and rebuilding over refurbishment

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[34] A caveat exists in that the sensor toolkits themselves have nothing like the longevity of a typical building (in both software and hardware terms) and are themselves not without environmental impact, especially during the production process. These factors need to be balanced in the calculation of harm reduction.

because the brutalist design was dated, and the bespoke nature of the buildings on site made it difficult to adapt them to suit the needs of new generations of students. In avoiding this cycle of demolition and rebuilding, smart buildings should be adaptable. Buckman *et al.*'s (2014) smart building definition referenced in the introduction of this work supports this, placing "*adaptability[...] at the core.*" Yet, smart building design of the modernist variety seems to be monolithic, aiming to produce a building which is so well specified that it will not change. But all buildings age and degrade, their purposes change, and building technologies and materials go in and out of fashion[35]. Brand writes: "*few buildings make it past 60"* (Brand, 1994, p. 38). Will we in 2080 see the Urban Sciences Building (6.2), the setting of CS3, dismantled? One has to wonder if the glass and steel edifice of modern architecture is more or less adaptable than the core red-brick buildings of the university estate, which (while being Grade II listed) have outlasted generations of scholars. Will the data standards and software of its 'smart' BMS succumb to code rot first?

I will leave it to the policy makers, architects, and construction firms to figure out how to make buildings last longer. My point is that while the idea of adaptability over long timescales exists in architecture, there is not yet an existing parallel in HCI/HBI for building technologies. The specification of a building technology is often intrinsically linked up with how a building is designed, and the purpose it is designed for. In CS1, I describe how sensor toolkits can be considered in contrast to hardwired and static systems like BMS: they are repurposeable, redeployable, and retrofittable (4.1). In this respect, they are a breed of adaptive building technologies. Yet, there are limitations too: for technology to adapt and grow it needs support, maintenance, and a community of users. It's not enough to throw a handful of sensors into an older building and call it a day. Software-based interventions and interaction design are also necessary to make these data sources useful, usable, and legible to end users (4.3.2), particularly those with less experience analysing environmental sensor data.

Brand (1994) offers an architectural parallel here, discussing 'high-road' buildings, like stately homes: "*perfection by a combination of good luck and good management"* (*ibid.* p. 84); in contrast with 'low-road' buildings: "*low-visibility, low-rent, no-style, high-turnover*" (*ibid.*

[35] In 1971, chrysotile 'white' asbestos was the miracle material. It was banned in 1999, as its fibres cause lung cancer. More recently, aluminium composite panels (ACP) were the building material *du jour*. Following the 2017 Grenfell Tower disaster, building managers rushed to replace it, often leaving occupants with heavy bills.

p. 62). There are high and low road technologies, too. High-road technologies (like BMS) might stand the test of time, but require a high level of skill (and capital) to commission and operate. Low-road technologies get the job done. If constant revision is the fate of all buildings, then building technologies must be revisable too! But it is easier and cheaper to revise a low-road technology. Consider Streitz *et al.*'s 'Roomware' (Streitz, Geißler and Holmer, 1998): co-operative buildings with the tech built into the furniture and architectural surfaces never actually happened. Although it may have enabled new forms of human-building interaction (and collaboration), it was perhaps a bit *too* high-road a vision, and too much of an investment of time and capital. Another parallel is in the smart home: as I covered in 2.4, Harper (2011) writes that instead of monolithic smart home systems, for the most part we instead experience a 'connected home', with many interlinked, interconnected small devices serving our needs. The connected home is far more adaptable than the smart home: as expected of a 'low-road' technology (or set of technologies). Perhaps this kind of paradigm can be extended to smart non-domestic buildings, too. There is a wealth of possibility for personal devices that move with the 'user' instead of being built into the building, but offer up data to benefit the collaborative whole.

7.4.3 Constructing Comfort

I return here to the issue of comfort. I have called into question the notion that smart buildings can 'solve' comfort: if it is a sociological construct (Chappells and Shove, 2004), then iteratively tighter automation around temperature setpoints cannot effectively ameliorate it. Thermal comfort is notoriously difficult to connect to environmental and physical factors without controlling for outside variables like movement and metabolic rate (Oseland, 1995), and varies by gender[36] (Kingma and Van Marken Lichtenbelt, 2015). There is also a strong psychological component, relating to perceived control (Luo *et al.*, 2016) and learned helplessness (Seligman, cited in Hellwig, 2015, p. 304). Air conditioning technologies (like fan-coil units) regulate temperature, humidity, and CO_2 levels by air and thermal energy exchange with the outdoor environment: just a subset of the factors which enter into comfort calculations like the widely-used PMV/PPD ('predicted mean vote/predicted percentage dissatisfied') (Fanger, 1970), as codified in ISO 7730 (ISO, 2005). If it is not

[36] The Nature Climate Change paper by Kingma and Van Marken Lichtenbelt (2015) garnered a reaction from ASHRAE's Bjarne Olesen (ASHRAE, 2015), a committee member for Standard 55. Olesen criticised the study for its small sample size of 16 women, ascribing their discomfort solely to their level of clothing. However, if comfort is socially constructed, tight regulation cannot satisfy everyone. By Olesen's own admission, "*if the standard is followed the women would be satisfied; but maybe not the men*" (*ibid. p.19).*

possible in practice to accurately account for all these varied and many factors (clothing level and metabolism are usually estimated) then trying to 'solve' comfort by tightly regulating environments seems to be the least energy-efficient approach possible. Perhaps this is why air-conditioned environments, as with the one discussed in CS2, are infamous for discomfort.

This is not a luddite argument: technology does have some power to ameliorate. Erickson and Cerpa (Erickson and Cerpa, 2012) found that their intervention, ThermoVote, achieved energy savings of 10.1%, and that "*some degree of control greatly increases satisfaction and perceived comfort*". On the other hand, their intervention still did not 'solve' collective comfort, finding that "*issues of temperature control can arise if users have diverging opinions for room temperatures.*" The findings of this dissertation support this: in CS2 (5.3.2) some office occupants reported that the conditions in the office were so cold that their colleagues would put their coats back on to cope with it. While this was perceived as a negative, it does demonstrate that people *can and do* adapt to the surroundings for their own comfort: however, given that it was high summer outside the cold was only as a result of the air conditioning. The reality is that air conditioning does not provide individual comfort, and doesn't necessarily provide a static and uniform level of comfort either (5.3.3). While the utopian vision of smart buildings centres on personalised thermal comfort and individualisation, a more realistic (and sustainable) approach could be to shift "*strategies of thermal regulation and socio-cultural expectations*" (Chappells and Shove, 2004).

Expectations of thermally comfortable environments have not always been the norm, and evidence suggests that the invention of air conditioning was responsible for a societal shift in notions of comfort, occurring "*abruptly in the mid-1920s when the primary function of air conditioning shifted from efficient production to human comfort*" (Arsenault, 1984). Earlier reports of thermal comfort show people putting up with discomfort (perhaps out of necessity): Thomas Jefferson, working late one night at his house Monticello in the 1770s "*had to stop writing because his ink had frozen*" (Brand, 1994, p. 103). Further, comfort technologies reinforce notions of comfort, leading to less tolerance over time: "*people today prefer warmer environments, the change being approximately 2.5°C over 25 years*" (Oseland, 1995). While people do feel more comfortable in their own homes than they do at work (*ibid.*), to put up with freezing temperatures is now an indicator of poverty. While it is unlikely that any environment can provide complete comfort to a group of people, there is a role for technology in shifting back expectations of acceptable thermal environments.

Wearing gloves at the keyboard could still become an expectation and a norm again. I write this not to advocate that people should be cold or uncomfortable, but that in acknowledgement that being cold or hot, and needing to adapt one's clothing level accordingly, is not inherently bad. Individual expectations have a role to play in determining comfort, and these are determined socially: residents in traditional Chinese dwellings, for instance, tolerate less comfortable environments than people in modern buildings, and employ a range of adaptive actions to ensure their own comfort (Xu *et al.*, 2018).

This may seem like an individualist argument, of the kind criticised by Brynjarsdóttir *et al.* (2012): individual persuasion in this respect, however, is only one factor in achieving collective comfort. I argued in CS2 (5.4.2) that shared understandings, collective experience, and agency must be considered when designing for collective comfort, but the thermal design of the building also factored considerably in occupants' discomfort (5.3.3). Air conditioning has enabled the glass-and-steel, 21st century, westernised architectural designs that shun adaptation in favour of energy-intensive methods of provisioning comfort, which may ironically be less comfortable. Designing with rather than against nature results in more sustainable outcomes: the desert architecture of Iran, for example, uses thick walls and wind catchers to provide a consistent internal temperature and airflow (Ahmadkhani Maleki, 2011) without the need for air conditioning. Architectural styles vary with the climate across the country, with cold, mountainous areas using high thermal capacity materials and small windows to minimise heat loss (Shahamat, 2014), even aligning with the path of the sun to ensure thermal performance of the building envelope. Free-running, naturally ventilated buildings with opportunity for adaptive actions are thankfully becoming more popular within architectural practice. The Passivhaus standard (Passivhaus Trust, 2010) shows promise in improving energy performance, although there remain challenges in retrofitting older buildings (Dowson *et al.*, 2012). Yet, there is still significant demand from the real-estate sector for so-called 'Grade A' offices, air conditioning being one of the core requirements for this type of space.

Air conditioning is a solution to an artificially created problem: it is not a 'neutral' technology, and its design stands on a set of axioms generated by "*particular bodies, locations, and educational ideals*" (Ford, 2014). Smart 'automated' buildings, and the infrastructure on which they run (Preist, Schien and Shabajee, 2019), use energy. HBI practitioners must consider carefully whether a designed intervention produces a net reduction in energy over leaving well enough alone. However, if technology can enable adaptations within existing uncomfortable environments, without the need for retrofits, this may be one direction by which to question and challenge standards, policies and norms (4.4.3). Further, there is scope to feed into policy directions: the ubiquity of air conditioning to provide comfort at the expense of sustainability is a feedback loop which will only get worse with climate change. I further address issues of democracy, politics and policy in the next section.

7.5 Democracy and Civics

Buildings are not democracies: occupants don't get to choose who runs them. This means that the power structures of organisations (6.3.2) factor strongly in their operation, and that facilities management is oriented top-down as a service to end-users (4.4.1). Now may well be the time for HBI to challenge this paradigm. New work in smart cities, and within the field of digital civics (Vlachokyriakos *et al.*, 2016; Corbett and Le Dantec, 2018) holds promise in achieving some of the recommendations I have made towards openness, transparency and participation in decision-making processes within smart buildings. CHI2020's (Covid-cancelled) HabiTech workshop advocated for the same (Dalton *et al.*, 2020), noting the extant knowledge gap in HCI between the smart home and the smart city.

The smart city has suffered very much the same issues in its conception of 'smartness' as that which I have identified in this work (2.2). Smart city discourse so often functions as a utopian techno-panacea, criticised for its marketing and self-promotion, with "*underlying pro-business and neo-liberal bias*" (Hollands, 2008, p. 4). Hollands argues for the need to shift the balance of power in such cities back to the people who live in them (*ibid.* p. 14). Yet, corporate ICT interests guide this vision, their brand of urban entrepreneurialism rendering the smart city "*a backdrop to corporate advertising and the privatisation of public space.*" (Hollands, 2015, p. 68). Reacting to criticism of this ilk, the corporations have re-framed their smart city rhetoric around civic participation (Cardullo and Kitchin, 2018), but this has further been criticised as a "*re-branding exercise*" (*ibid.*) that obscures an ongoing corporate mission towards "*deregulation, privatisation and more open economies that weakens oversight and enable more efficient capital accumulation*" (Kitchin, 2015). Such a vision for smart cities excludes the people who live and work in them.

Not all is yet lost, however. A small group of researchers within HCI have begun to develop more equitable smart city concepts, often connected to sustainable food system agendas. Heitlinger, Clarke, *et al.* (2019) consider bottom-up initiatives for "*future smart cities beyond corporate visions*", presenting a speculative participatory design method[37] for engaging local people, through which participants considered the positives and negatives of repurposing dilapidated urban backstreets as a site for food growing. Heitlinger, Bryan-Kinns, *et al.* (2019) invoke French philosopher Henri Lefebvre in asking whether citizens have the 'right' to the sustainable smart city, arguing that the hegemony, technofetishism and human exceptionalism entangled in neoliberal smart city visions is nothing less than ecocidal. The authors raise considerations for designing for biocultural diversity, feminist notions of care, and for a common which "*prioritises the collective needs of inhabitants (human and otherwise) over individual property rights*" (*ibid.* p. 9). This argument might be extended to the context of this work: do we also have a right to sustainable smart buildings? Given that smart buildings are almost always privately-owned spaces, it may be more difficult for their occupants to engage in forms of spatial autogestion[38], but this highlights a strong direction for future HBI work.

The digital civics agenda considers how HCI (and interdisciplinary) tools and techniques might foster civic participation and communities, through place-based approaches and dialogue with civic entities (such as local government). Taylor *et al.* (Taylor *et al.*, 2015) challenge the supremacy of 'data' as a problem-solver of all kinds (a notion embraced wholly by the neoliberal 'smart city'), calling instead for an approach which treats data as "*something that multiple parties have a stake in, perhaps even jointly own.*" There are parallels here with the conclusions I have drawn regarding sensor toolkit deployment in CS1 (4.4.1), suggesting that the tensions of imposition and consent which I have identified sit as part of a larger picture about the ethics of data. The design space around e-voting, as explored by Vlachokyriakos *et al.* (2014), offers further opportunities for participation around buildings management within the workplace, although there is danger in disenfranchising contributors if the will of the group is overridden by management. The ThermoKiosk study explored related factors of negotiation over the air conditioning (5.3.5), and it is possible

[37] Speculative participatory design was further utilised as part of a workshop at PDC'18 (Clarke *et al.*, 2018).

[38] Autogestion is a concept rooted in Marxism, typically meaning to "seize the means of production." For the additional nuance in Lefebvre's 'spatial' use, I refer the reader to (Heitlinger, Bryan-Kinns and Comber, 2019).

that had the devices been left in the office for longer, this may have raised questions about why participants were *still* uncomfortable. If we take ‘smarter’ to mean ‘more participatory’, there are roles for data and digital technologies in opening up space for civic participation in non-domestic buildings.

Technologies which enable more dialogic forms of participation and negotiation sit alongside interventions like ThermoKiosk, and may have utility in promoting smarter forms of engagement in building management processes. Situated digital feedback systems have been investigated within digital civics, with interventions including ThoughtCloud (Dow *et al.*, 2016), Viewpoint (Johnson *et al.*, 2016) and JigsAudio (Wilson and Tewdwr-Jones, 2019) exploring the HCI design space around gathering feedback, situated consultation technologies, and participation in urban planning. Yet, while these can still be understood as top-down efforts enabled by engaged community organisations and local government, in engaging communities they address the need to work at different scales (Dourish, 2010) and to think beyond the individual, about organisations, social groups, and governments. There is an untapped opportunity to design smart technologies for civil disobedience (5.4.4) in challenging organisational power structures (and how they are projected, per 6.3.2) in a grassroots manner.

Both this work, and my own, indicates that supporting collaboration between occupants as a community must be a goal for future HBI work. Yet, while the notion of large-scale bottom-up engagement and collaboration is seductive, it could be argued that it is just as naïve in its utopian vision as the corporate smart city. Although people are invested in their environments and do want to negotiate to improve them (5.3.5), their primary focus is their job (or studies, per CS3) and it is entirely understandable that they would just want problems to be ‘sorted out.’ As such, it will be necessary for HBI to challenge such customer-focused notions of responsibility (6.4.4), and technologies which foster collective experience and shared understanding have a role in this. Even adversarial forms of dialogue, as in CS2 when an occupant interacted with the ThermoKiosk just to annoy her colleague (5.3.4), have value in asserting the visibility of one’s opinions beyond the stereotypical passive-aggressive kitchen note. Rather than just collecting feedback, consultation technologies can reproduce the voices of people interacting with them, as in (Wilson and Tewdwr-Jones, 2019), such that nuance can be captured beyond just another vote in a box. By promoting frank discussion and empathy, people can be more accepting of each other and of uncomfortable environmental conditions (5.3.4). We can empathise with other peoples' feelings of (dis)comfort, even if we want our own to be satisfied.

There is a role for the HBI technologies in explicitly facilitating a sense of mutual awareness of the experience of other occupants, and for finding ways to enable dialogue around experiences of the building environment. Technology can be a mediating factor, and can in itself create a sense of community by increasing visibility and bringing awareness through negotiation: these are the tools of collaboration. I have pointed towards the need to conceptualise buildings as supportive and collaborative technologies (2.5), in moving away from modernist rhetoric that forces a reductionist framing of individual responsibility (Brynjarsdóttir *et al.*, 2012). Yet, in addition to designing for collaboration with the building itself, supporting *occupant-occupant collaboration* (as above) is important in establishing a sense of community, and in determining that the building itself is fit for purpose. Reconfigurable digital technologies are one tool to support the development of communities, who are crucial to the realisation of the human-centred smart building.

Other (non-technical) methods of fostering community exist, of course. Community sustainability initiatives such as Green Impact (National Union of Students, 2016), as discussed in CS1 (4.4.3), can provide a setting through which to engage, though still rely on individuals' intrinsic motivations towards sustainable behaviour, despite being supported by the facilities department. Within the domestic sector, housing co-operatives offer a route for social accountability and joint decision-making (Hasselqvist and Eriksson, 2018), though there may be a wider challenge in implementing such a setup in non-domestic office buildings as these are generally provided (or leased) by the employer in a kind of spatial neo-feudalism: a provision of space in return for labour. I have argued that it may be necessary to de-centralise and distribute responsibility to more stakeholders (6.4.4) in challenging neoliberal management structures, and perhaps the opportunity exists for smart building co-operatives in the pursuit of co-operative smart buildings! Occupants in the building become stakeholders, and attend the stakeholder meetings. To my knowledge, this has never been done in the non-domestic sector, and would be hard to get organisational buy-in, but suggests an open direction for future work.

Finally, it would be remiss not to mention forms of workplace beyond the office, particularly given present circumstances (in 2020-21) with the major global event that is the Covid-19 pandemic. Our working lives and relationships have changed significantly, and there has been much discussion of a 'green recovery'. This has not affected the outcomes of this research *per se*, but gives pause for thought with regards to future trajectories and presents a perfect opportunity for radical changes to working cultures and practices within offices. For one thing, working from home has become more common, and may be here to stay for some time: "*COVID-19 has also broken the back of significant business resistance to WFH"* (Beck and Hensher, 2020). Hampton (2017) cautiously indicates that the energy impacts of this shift will be positive, but notes that 'smart' heating systems may well increase energy consumption, reminiscent of the findings of the *Google Nest* study previously discussed in 2.4.2 (Yang and Newman, 2012). There are agendas here which will require future research beyond the remit of this thesis, but the (Sustainable) HCI and HBI research communities can be well positioned to respond to these challenges by understanding values and practices around communities and work.

7.6 Principles for Technology in Human-Centred Smart Buildings

I have described in this chapter my orientation towards the research question "*what are the roles of data and digital technologies in creating human-centred smart buildings*?" Although the 'right' kind of smartness for which I am advocating is a value-judgement, it is one based in inclusion, sustainability, and civic values. I draw from my discussion here to synthesise a set of principles for the design of technology for human-centred smart buildings. These form a manifesto for collaborative HBI which builds on that of Alavi *et al.* (2016) to: a) position the research community and the direction of the field; b) identify useful points of contribution and a framing for future work; and c) recognise structures and assumptions to challenge.

This work has framed HBI as a CSCW topic: buildings are co-operative spaces, and smart buildings are (or ideally should be considered) collaborative technologies. I pointed to the different types of collaboration necessary to support different building end-users in section 7.3. The matrix below shows the types of collaboration alongside the design criteria which address them. These factors were strongly identified within this work, but there will of course exist more and different factors which facilitate each of these kinds of collaboration.

Collaboration	Occupant	Manager
Building	1. Clear affordances, repurposeable space (CS2,3)	2. Useful data, retrofittable sensor systems (CS1)
Occupant	3. Social fabric, shared understandings & experience (CS2)	4. Transparency, data to support negotiation processes (CS1,2,3)

Table 8: Building, occupant and manager collaboration matrix

This leads to the formulation of the first principle, and in turn the others which follow it. While each principle can stand independently, they should also be understood as necessarily interconnected and contributing to one another. While there is of course existing work which tackles some of these principles, they can be taken as directions for innovation, and recommendations for future work in the field:

Principle 1: *Consider buildings as a collaborative technology, to facilitate interaction and collaboration between the building, its occupants, and its manager(s).*

Currently, HBI (as it is represented within the conferences and journals of HCI) only really addresses the first type I have identified: 'building-occupant collaboration'. Yet, this work suggests that the other levels of collaboration require explicit consideration too, from within the field. Different end users have different needs and requirements for building technologies, and the only way to know if a building is fit for purpose is to collaborate with occupants on making it so. The case studies presented in this work have contributed several exemplars for different kinds of collaboration (see Table 8) which may be useful in framing future work. CS3, for example, indicates that occupant-building collaboration may be improved by better communicating affordances and agency, and that occupant-manager collaboration can be fostered through ongoing conversations which treat occupants as local experts on conditions within the space. CS1 demonstrates forms of building-manager collaboration, through data gathering processes which enable investigatory practice, and CS2 provides an example of how occupant-occupant collaboration can be enabled through its technology probe intervention.

Principle 2: *Advocate for the role of the human in smart buildings, considering smartness beyond the technosolutionist vision.*

In this work I have re-framed smartness around collaboration, inclusion, and human decision-making which does not consider occupants a 'problem' to be solved. While there will continue to be a role for automation technologies, authors must be wary of reductive focuses on individuals and energy, and their positives must be carefully weighed against the removal of agency from human actors. There is a role for a 'techno-realism' or 'techno-conservativism' in responding to technosolutionism (Morozov, 2013) and the modernist assertion that technology must progress, taking a step back to understand technology's effects (especially on communities). As is well recognised in HCI, automation may expand rather than eliminate problems (Bainbridge, 1983), as illustrated in CS3 by the unclear affordances experienced by students in the building, and in CS2 where tight temperature regulation produced further discomfort. The principle of function allocation, also known as 'HABA/MABA' or 'Humans-are-better-at / Machines-are-better-at' (Fitt 1951 in De Winter and Dodou, 2014) can also be applied to building technologies: there exist trade-offs between automation and human collaboration and collective control.

Principle 3: *Design for community responsibility, instead of focusing on the individual.*

The hyper-individualist approaches seen in prior work must give way to a more sensitive examination of communities and practices, and devolved forms of responsibility. Per CS2, individual control of building systems can come at the expense of the comfort of the group; personalised comfort can come at the expense of sustainability. Mutual awareness of other building users can begin to address this, and there is a middle ground to follow in designing for buildings and communities of building users. That said, individuals should not be excluded from consideration either, as they can play an important role as representatives for groups. Responsibility must of course be linked to accountability (Hasselqvist and Eriksson, 2018), and there is scope to design new practices and technologies which facilitate this.

Principle 4: *Advance adaptability at the structural, technical, and organisational levels.*

While by necessity some systems will always be hard-wired and limited, others might be designed with adaptation in mind. While there has been limited investigation into adaptive building envelopes e.g. (Schnädelbach *et al.*, 2012), it appears unlikely that massively adaptable building fabrics will become the norm. Therefore, digital systems (supported by organisational practices) might bridge this gap and enhance opportunities for control. Further, there is a distinction to be made between existing technologies and future technologies here: although technologies might be designed that will be inherently adaptable in future, buildings are long-term projects. It will be necessary to design adaptability in ways that take account of existing, inflexible building fabrics and systems. Retrofittable systems such as those seen in CS1 have a role to play here, as they allow on-demand reconfigurability rather than being tightly specified at the construction phase.

Principle 5: *Challenge expectations and the status quo if these are unjust or unsustainable.*

Socio-organisational norms and power structures can limit opportunities for collaboration and adaptation, as can individual expectations (e.g. of provided environments), and these can influence and exacerbate each other. This is most apparent in CS3, and this principle arises directly from the discussion of that chapter. More radical forms of inclusion are possible, but may require shifts in social roles to reduce reliance on facilities management as-a-service and promote collaboration instead. There also appears to be a point to be made here on building automation: the common view is that building technology, if it does not work (e.g. to provide thermal comfort) is insufficient, or plain broken. It may well be necessary to shift expectations back in line with the realities of buildings, that comfort technology shouldn't be expected to 'work' the same for everyone. How we might design technology to facilitate this is an open question for future work.

Principle 6: *Design for negotiation between stakeholders and within groups.*

Negotiation connects people, and is the basis for dialogic forms of participation and inclusion in buildings management processes. Negotiation can also be adversarial and dissenting: direct action (and protest) is a form of negotiation which can challenge rigid and seemingly non-negotiable policies, as seen in CS2. Technology can assist in negotiation with other stakeholders, both within (intra-group) and outside (extra-group) occupant factions, and can provide opportunities for negotiation leading to richer engagements and shared decision-making. Processes of negotiation are also crucial in considering the collective impact of decisions made about the building and the operation of its automated systems (per CS3).

7.7 Future Work

I have made suggestions for future work in this chapter which I summarise, reflect and expand upon here. I suggested in section 7.3 that new collaborative opportunities within smart buildings might arise as an area of interest for CSCW, and in 7.5 I suggested democratic and participatory approaches which might begin to address this gap: the intersection of Digital Civics and HBI remains ripe for future exploration. In 7.4.2, I considered the sustainability trade-off that exists for building technologies in terms of their embodied energy, and suggested that future work might examine how this might be addressed over a building's lifespan. Further, I have also included suggestions for future work within the discussion of each of the three case studies (sections 4.4, 5.4 & 6.4).

There remains an open question in terms of how the impact of this work might be extended to facilities professionals. The reach of academic work is often limited to academics: there has been an ongoing conversation in the HCI community aiming to understand the relationship between research and practice (Gray, Stolterman and Siegel, 2014), and how these might be bridged. One benefit of the work presented in this dissertation is that it has been conducted in collaboration with practitioners. Some of the methods developed are therefore portable to professional practice: CS1, for example, describes the process of deploying sensors with non-experts / novices, ending with a set of recommendations towards a deployment protocol. While such a method could be readily utilised in the investigation of built estate issues, there exists an open remit for future work to explore how to formalise and test such a protocol (per 4.4).

Further, the other methodologies presented in this work might also translate to professional practice (Verma, Alavi and Lalanne, 2017), and therefore further investigation is warranted into the best ways these might be deployed 'in the real world'. For example, the technology probe developed and deployed in CS2 could be of utility in resolving comfort disputes, and it is not beyond imagining that a facilities team might have a stock of similar devices to deploy into 'problem' offices. However, the deployment of a device is unlikely to be useful in isolation: the CS2 study was successful in part because of the engagement that occupants were able to experience with the research team. The data gathering methods I have used in this thesis may therefore be of utility to facilities management personnel in respect to centring the human within their own smart buildings. The data elicitation interview method (examining plots of sensor data with occupants) would be particularly interesting to explore as a tool within professional practice, with a view to asking whether the co-exploration of environmental and comfort feedback data might temper adversarial approaches to comfort inherent in the facilities management-as-a-service model, or indeed disrupt the ‘us vs them’ paradigm observed in CS3. In furthering these goals and improving take-up within industry, award schemes like those discussed in CS1 (4.4.3) are of utility: working towards an ‘Athena Swan’-like framework for inclusive management of buildings could provide a structured route for the identification of inclusion as a problem, and support improvement through best-practice guidelines and awards for their implementation.

With regards to the future trajectory of the field, HBI has become an “*independent design space and topic of interest within HCI,*” just as Alavi *et al.* (2016) set out to achieve within their CHI workshop. HBI researchers have in the intervening years explored a diverse range of topics: environmental factors (Snow, Oakley and Schraefel, 2019); optimisation approaches to space and energy use (Alavi *et al.*, 2018; Konstantakopoulos *et al.*, 2019); ubicomp approaches including interactive materials (Nabil *et al.*, 2017); and the application of HCI methodology to practice (Verma, Alavi and Lalanne, 2017), as discussed above. So, where might the HBI community turn in future? As revealed by this dissertation, there is a deficit of work on the ethical and social issues arising within the context of the built environment, understandings of which could further the goal of developing human-centred smart buildings. While this work begins to broaden the field in terms of HBI’s intersections with social and environmental justice, Sustainable HCI, Feminist HCI, and Digital Civics, obvious gaps in knowledge remain. A turn towards these wider agendas of the third and fourth wave of HCI, and applying established theory from these areas to the HBI context, can help to drive societal impact in the HBI contributions of the future.

Finally, while this work is undertaken and situated within higher education institutions (HEIs), there is applicability beyond the educational sector which can be further explored. Workforce expectations of comfort exist across office work in general (Goulden and Spence, 2015), aligning with the facilities management as-a-service model that has become ubiquitous. Therefore, the conclusions of this dissertation are generalisable to some extent. However, one of the significant benefits to doing this work within the facilities of a higher education provider was the openness of the facilities team, and their willingness to experiment and enact change. This may be a key difference in commercial facilities management, but including commercial facilities management providers as partners on research projects and funding bids may help to open up this sector: the sensors developed in

CS1 were funded partly by an EPSRC project with a commercial facilities management partner. Building and maintaining networks of practitioners and commercial partners open to investigations of this nature will help to generalise the results of work beyond the university. Extending the 'living lab' concept into the wild may be another vehicle for this: it could be argued that for any building to be smart, and to embody the ideal of reconfigurability and continuous change discussed in this chapter, it should support experimentation and learning in the manner of the living lab.

7.8 Summary

This chapter presented a discussion of the outcomes of the three case studies which are the empirical basis for this dissertation, providing answers to the research questions which were developed through the literature review to summarise and contextualise the research results. I have discussed the notion of the human-centred smart building, concluding that understandings of the needs of end-users must be developed and centred within design and discourse in order to ensure that a building is fit for purpose. Further, I outlined four kinds of collaboration which are suggested within the empirical results, noting that HBI to-date has generally focused on only one of these. A discussion of implications for environmental sustainability was presented, advocating for a shift from reductive focuses on individuals and energy to communities and practices; and I have expounded how discourses around democracy and civics can begin to challenge neoliberal paradigms of engagement within the smart building by fostering collaboration and mutual awareness. Finally, I have outlined six principles for technology in human-centred smart buildings, forming a design manifesto which provides directions for future HBI work.

Chapter 8: Conclusion

8.1 Summary

This dissertation addresses through three case studies the role of data and digital technologies in creating human-centred smart buildings. To date, smart buildings have typically been considered from an engineering and systems perspective. While data and algorithms promise reduced energy use and increased value for businesses and occupants, by reviewing the literature in several connected fields I have shown discourse centring on automation to be a reductive and limited framing of smartness which privileges optimisation and efficiency over the needs of human occupants. I looked to understand how a human-centred approach might provide a meaningful contribution to truly 'smart' buildings by conducting three case studies. These examined auditing and measurement processes, community forms of comfort, and lived experiences of a smart building, through which I have made methodological, technical and empirical contributions. From the results of these chapters, I have developed a framework describing the kinds of collaboration which can be considered between stakeholders in the non-domestic building context, and a set of six principles for technology in human-centred smart buildings, functioning as a manifesto for future HBI research.

8.2 Overview of Work

Chapter 1 introduced the work, presenting the problematic nature of the smart building vision, and expounded the basis for this work within human-computer interaction (HCI), computer-supported co-operative work (CSCW), human-building interaction (HBI) and Sustainable HCI. I outlined a basis for the human-centred design of smart buildings, summarised my research approach, and described the structure of this dissertation.

In Chapter 2, I reviewed the literature relating to smartness within built environments, guided by the investigation of the questions: "*what does it mean for a building to be smart?*" and "*what are the underlying assumptions and motivations in 'smart' rhetoric?*" Through this review, I formulate a philosophical position on the meaning of 'smartness' in the smart building, and define research questions for investigation through empirical work.

The first part of this review examined how smart buildings are framed within the context of the first, second and third waves (or 'paradigms') of HCI. I highlighted the values foregrounded by those works, and considered what ‘smart’ might mean if participation and sustainability were core values instead. Further, I examined the literature on smart homes (this being the core area of past research in HCI with regards to smart built environments), dividing my inquiry into the functional, instrumental and socio-technical categories of smart home defined by Wilson *et al.* (2014). Next, in examining smart buildings and the workplace, I looked to the field of CSCW for prior work to understand how technologies and architecture interact with workplace practices and prior work which can be understood as contributing to a smart buildings discourse. Finally, I examine non-domestic buildings work in HCI, noting that the emergent field of HBI offers a framing for research in this nascent area. Concluding this chapter, I defined an overarching research question through the examination of prior discourses in HCI around smart buildings:

What are the roles of data & digital technologies in creating human-centred smart buildings?

This was supported by three sub-research questions, which I investigated within the three corresponding case studies:

RQ1: *How can retrofitted sensor data augment facilities management processes, and how might building users be empowered to participate in these?*

RQ2: *How can data and digital technologies foster shared understandings and assist comfort negotiations in the office workplace?*

RQ3: *How can HBI support occupant agency and participation in the everyday management and adaptation of smart buildings?*

In Chapter 3, I outlined the methodologies employed in the investigation of these research questions, and summarised the research design and my epistemological orientation towards it. I discussed how my qualitative inquiry was supported through the use of quantitative sensor data, and the implications of the social constructivist / interpretivist worldview I employed. I review a range of qualitative methodological frameworks employed in prior HCI work, and through these described the motivations for the methods used in my own work. Further, I described my approach to data collection and analysis, involving focus groups and interviews, which were transcribed with the data corpora being subject to thematic analysis (Braun and Clarke, 2006). Finally, I discussed the case study approach, further explaining processes of data collection within these. The subsequent case study chapters each contained a methodology section that drew on this work with further detail of participants and methods used.

In Chapters 4-6, I described the three case studies I used to investigate the overarching research question. Case study 1 (CS1) “Augmenting Audits” is presented in Chapter 4, case study 2 (CS2) “Negotiating Comfort” in Chapter 5, and case study 3 “Engaging Occupants” in Chapter 6.

Case study 1 (CS1) “Augmenting Audits” addressed the research question **RQ1** through the ways in which novice and professional auditors used retrofitted sensor toolkits to identify problems in buildings, and how they made sense of the data which the sensors provided. Students learning to undertake environmental audits worked with the facilities management team to deploy sensor toolkits. Through workshops and interviews, I explored the experiences of these novice auditors as they learned to interact with the toolkits, began to understand their limitations, and developed skills in using them to audit these buildings. The contributions of this case study relate to understandings of the real-world practices of facilities managers using sensor toolkits; design considerations which address power, privacy and democratic concerns; and recommendations for future work to encourage integration of sensor toolkits into standards and policies.

Investigation of **RQ1** found that retrofitted sensor toolkits can facilitate smarter facilities management processes by supporting managers in proving compliance with standards, evidencing funding requests, and augmenting outdated BMS as an auditing tool. The sociotechnical factors I discovered include a set of tensions and challenges in capturing adequate data, including the knowledge and skills of the auditing party which are utilised in their interpretations of it. Further, I suggest that power, privacy and democratic concerns might be assuaged through design changes to sensor toolkits, to management processes, and to standards and policy.

Case study 2 (CS2) “Negotiating Comfort” investigated **RQ2**, following the experiences of office workers during a three-week deployment of ThermoKiosk, a technology probe designed to capture subjective survey inputs on thermal comfort. A data elicitation interview method helped to draw out occupant experiences of thermal comfort management within the office, discussing their agreements, disagreements and curiosity with regards to the data, and their expectations for what it would show. The findings point towards new understandings of interaction with subjective thermal comfort data, limitations imposed by building design on manually controlled HVAC systems, and effects on social fabrics, comfort negotiation, and occupant/institutional understandings. The discussion elaborates implications for occupants' shared experiences and understandings, arguing that comfort should be treated as a collective experience in offices where comfort is held in tension.

Through **RQ2**, I found that environmental data and digital technologies allowed for constructive dialogue within the office, smoothing intra-office negotiation over the room temperature. Office occupants were able to share understandings of their colleagues' comfort sensations, leading to a more collective experience of comfort. Opportunities for experimentation and knowledge sharing were uncovered with respect to occupants' lay knowledge of the office HVAC systems and the causes of their discomfort, and I suggest that an engaged facilities management team retains a strong role in advocating for the environmental consequences of occupants' requests for changes, while conversations and negotiations around these can be supported by digital technologies.

In Case study 3 (CS3), I explored **RQ3** with student occupants of a university smart building, aiming to understand how HBI can support agency and participation in the everyday management of smart buildings. A speculative design workshop incorporating building walks asked how we might move beyond the scope of the usual complaints process through which occupant feedback is gathered. The findings of the study included new understandings of how student occupants conceptualise and evaluate spaces as they experience them, and of how building management practices might evolve with new sociotechnical systems that better leverage occupant agency. I further outline understandings of how HCI and HBI practitioners might design interactions that foster agency and participation in facilities management processes, and identify a need to challenge entrenched roles in building management.

Tackling **RQ3** resulted in new understandings of how student occupants of a university smart building secure space to work, and how these space-management practices were influenced by needs for comfort, equipment, sociality, and spatial constraints. In addition, it became apparent that the affordances of building space influenced perceptions of students' permission (or lack of such) to use them. I outline a tentative methodology, 'participatory auditing', for engaging building occupants in discussions around the building, and note that collaboration and reconfiguration can be enabled in smarter ways which, although they can be supported by smart infrastructures, rely on changes at the organisational level to enable them.

Finally, Chapter 7 presents a discussion of the outcomes of the three case studies, providing answers to the four research questions originally outlined in Chapter 2. I have developed and outlined my position on the human-centred smart building, concluding that understandings of the needs of end-users must be developed and centred within design and ongoing discourse in order to ensure that a building is fit for purpose. Four kinds of collaboration are identified and discussed alongside the implications for environmental sustainability, and I have identified how work in democracy and civics might provide a route to challenge neoliberal paradigms of engagement within the smart building by fostering collaboration and mutual awareness. Finally, I outlined a framework of six principles for technology in human-centred smart buildings, a manifesto positioning the research community and providing directions for future HBI work.

8.3 Final Comments

Existing smart building visions revolve around modernist interpretations of the role of technology in the built environment, resulting in a narrowed focus on controllable factors such as the building climate, and a tendency to disregard wider ethical and social factors. Participation and inclusion have been overlooked or ignored, resulting in the maintenance of unsustainable status-quos. The purpose of this dissertation has been to robustly challenge this paradigm through the presentation of an alternate vision: the human-centred smart building. This necessitates the questioning of established doctrine, and of asking how the claimed benefits of a technology really impact on people 'on the ground' or work to the detriment of wider sustainability goals. While optimisation and efficiency approaches can constrain the problem (and are therefore attractive) it is essential that claims of sustainable outcomes are substantiated, and to not deny attention to the limiting of agency and negative building-user experiences that automation approaches create. This is a problem which HBI designers and practitioners are uniquely positioned to address.

A human-centred smart building comes in various forms, some of which I have investigated in this thesis. This turns largely on our definition of 'smartness', a subject I cover extensively in Chapter 2, and our orientation towards the values and ethics which are important to consider in such designs. The 'modernist' smart building vision of mainstream discourse is often presented as values-neutral, yet is underpinned by neoliberal assumptions that become visible when the benefits of these buildings are discussed: improved productivity takes centre-stage, and occupant wellbeing is deprioritised. The concept of human-centred smartness is constructed in this work through examination of which stakeholders are empowered by existing processes and regulations (CS1), through collective rather than individual understandings of comfort within the local environment (CS2), and through more inclusive and participatory approaches to the management of the building (CS3). Of course, forms of human-centred smartness other than those unpacked by this thesis do exist, and future work may build on these to understand yet further ways in which our built environment may be made smarter. The framework presented in Chapter 7 functions to guide HBI researchers in this regard: from designing smart buildings as collaborative technologies (*Principle 1*) and advocating for the role of the human within them (*Principle 2*), to challenging unjust or unsustainable approaches both within the field and established professional practice (*Principle 5*).

Within this dissertation, I have explored the role of data and digital technologies in creating human-centred smart buildings. I have devised a novel framework for HBI through three case studies, the outcomes of which represent a substantial and original contribution to the field, and a new direction for design and discourse within this space. Through this, I argue that in future HBI must advocate for the role of the human in the smart building, shifting from a reductive focus on optimisation and energy use to one which accounts for the complexities of organisational structures and practices, re-orienting research and intervention design towards the values and ethics of third-wave HCI. Addressing this paradigm requires a radical re-specification of human-building interaction, requiring researchers and practitioners to look more holistically at the built environment through the lens of environmental and social justice. While there exist tensions between sustainability outcomes and enhancing participation within the smart building, fundamentally rethinking how sustainability gets woven through the design of HBI technologies in participatory ways is key to addressing inequalities in the way that buildings are specified, continually re-specified, and managed on an ongoing basis.

References

ActionAid (2011) *Addicted to tax heavens: The secret life of the FTSE 100.* Available at: https://www.actionaid.org.uk/sites/default/files/doc_lib/addicted_to_tax_havens.pdf.

Ahmadkhani Maleki, B. (2011) 'Traditional Sustainable Solutions in Iranian Desert Architecture to Solve the Energy Problem', *International Journal on "Technical and Physical Problems of Engineering" (IJTPE)*, 3(March), pp. 84–91.

Ahrentzen, S. B. (1992) 'Home as a Workplace in the Lives of Women', in *Place Attachment.* Boston, MA: Springer US, pp. 113–138. doi: 10.1007/978-1-4684-8753-4_6.

Ailon, G. (2008) 'Mirror, Mirror on the Wall: Culture's Consequences in A Value Test of its Own Design', *Academy of Management Review.* Edited by A. Hillman et al. Academy of Management, 33(4), pp. 885–904. doi: 10.5465/amr.2008.34421995.

Ailon, G. (2009) 'A Reply to Geert Hofstede', *The Academy of Management Review.* Edited by A. Hillman et al. Academy of Management, 34(3), pp. 571–573.

Alajmi, A. (2012) 'Energy audit of an educational building in a hot summer climate', *Energy and Buildings.* Elsevier B.V., 47, pp. 122–130. doi: 10.1016/j.enbuild.2011.11.033.

Alavi, H. S., Churchill, E., *et al.* (2016) 'Deconstructing human-building interaction', *Interactions*, 23(6), pp. 60–62. doi: 10.1145/2991897.

Alavi, H. S., Lalanne, D., *et al.* (2016) 'Future of Human-Building Interaction', *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*, pp. 3408–3414. doi: 10.1145/2851581.2856502.

Alavi, H. S. *et al.* (2018) 'The Hide and Seek of Workspace: Towards Human-Centric Sustainable Architecture', in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18.* New York, New York, USA: ACM Press, pp. 1–12. doi: 10.1145/3173574.3173649.

Alavi, H. S., Lalanne, D. and Rogers, Y. (2020) 'The Five Strands of Living Lab', *ACM Transactions on Computer-Human Interaction*, 27(2), pp. 1–26. doi: 10.1145/3380958.

Aldrich, F. K. (2003) 'Smart Homes: Past, Present and Future', in *Inside the Smart Home*. London: Springer-Verlag, pp. 17–39. doi: 10.1007/1-85233-854-7_2.

Allen, B. (1996) 'An integrated approach to Smart House technology for people with disabilities', *Medical Engineering and Physics*, 18(3), pp. 203–206. doi: 10.1016/1350-4533(95)00074-7.

Ambe, A. H. *et al.* (2019) 'The adventures of older authors: Exploring futures through co-design fictions', *Conference on Human Factors in Computing Systems - Proceedings*, pp. 1–16. doi: 10.1145/3290605.3300588.

ANSI/ASHRAE (2010) 'Standard 55-2010: Thermal Environmental Conditions for Human Occupancy', p. 44.

Aoki, P. M. *et al.* (2009) 'A Vehicle for Research: Using Street Sweepers to Explore the Landscape of Environmental Community Action', in *ACM Transactions on Computer-Human Interaction*, pp. 375–384. doi: 10.1145/1518701.1518762.

Arsenault, R. (1984) 'The End of the Long Hot Summer: The Air Conditioner and Southern Culture', *The Journal of Southern History*, 50(4), pp. 597–628. doi: 10.2307/2208474.

ASHRAE (2015) 'Keeping Occupants Comfortable Without Raising Energy Costs', *ASHRAE Twin Tiers Chapter Newsletter*, September, pp. 19–20. Available at: http://twintiers.ashraechapters.org/assets/newsletter/2015.09-TTT.pdf.

Asimakopoulos, S. and Dix, A. (2017) 'Walking: A Grounded Theory of Social Engagement and Experience', *Interacting with Computers*, 29(6), pp. 824–844. doi: 10.1093/iwc/iwx014.

Bainbridge, L. (1983) 'Ironies of automation', *Automatica*, 19(6), pp. 775–779. doi: 10.1016/0005-1098(83)90046-8.

Balchin, A. (2011) *What Does 'Fit For Purpose' Mean?* Available at: https://uk.practicallaw.thomsonreuters.com/8-506-3187 (Accessed: 18 December 2020).

Balta-Ozkan, N. *et al.* (2013) 'Social barriers to the adoption of smart homes', *Energy Policy*. Elsevier Ltd, 63, pp. 363–374. doi: 10.1016/j.enpol.2013.08.043.

Bång, M., Torstensson, C. and Katzeff, C. (2006) 'The PowerHouse: A Persuasive Computer

Game Designed to Raise Awareness of Domestic Energy Consumption', in Wijnand A. IJsselsteijn et al. (eds) *PERSUASIVE 2006. Lecture Notes in Computer Science.* Berlin: Springer-Verlag, pp. 123–132. doi: 10.1007/11755494_33.

Bannon, L. J. (1991) 'From Human Factors to Human Actors: The Role of Psychology and Human-Computer Interaction Studies in System Design', in Greenbaum, J. (ed.) *Design at work: Cooperative Design of Computer Systems.* Lawrence Erlbaum Associates, pp. 24–44. doi: 10.1016/B978-0-08-051574-8.50024-8.

Bardzell, S. (2010) 'Feminist HCI', in *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10.* New York, New York, USA, USA: ACM Press, p. 1301. doi: 10.1145/1753326.1753521.

Bartram, L., Rodgers, J. and Woodbury, R. (2011) 'Smart homes or smart occupants? Supporting aware living in the home', *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 6947 LNCS(PART 2), pp. 52–64. doi: 10.1007/978-3-642-23771-3_5.

Bates, O., Thomas, V., Remy, C., Friday, A., *et al.* (2018) 'Championing Environmental and Social Justice', *Interactions*, pp. 60–63.

Bates, O., Thomas, V., Remy, C., Nathan, L. P., *et al.* (2018) 'The Future of HCI and Sustainability: Championing Environmental and Social Justice', in *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems.* New York, NY, USA: ACM, pp. 1–4. doi: 10.1145/3170427.3185365.

Bates, O. *et al.* (2020) 'Let's start talking the walk: Capturing and reflecting on our limits when working with gig economy workers', in *Proceedings of the 7th International Conference on ICT for Sustainability.* New York, NY, USA: ACM, pp. 227–235. doi: 10.1145/3401335.3401364.

Bates, O. and Friday, A. (2017) 'Beyond Data in the Smart City: Repurposing Existing Campus IoT', *IEEE Pervasive Computing*, 16(2), pp. 54–60. doi: 10.1109/MPRV.2017.30.

Bates, O. and Friday, A. (2018) 'Intangible commodities with free delivery', in *Proceedings of the 2018 Workshop on Computing within Limits.* New York, NY, USA: ACM, pp. 1–8. doi: 10.1145/3232617.3232622.

BBC (1986) *GEM versus Windows - Battle of the GUIs, BBC Archive*. BBC. Available at: https://www.bbc.co.uk/archive/micro_Live_Windows_gem/zm6mjhv (Accessed: 24 August 2020).

Beck, M. J. and Hensher, D. A. (2020) 'What might the changing incidence of Working from Home (WFH) tell us about future transport and land use agendas', *Transport Reviews*, pp. 1–5. doi: 10.1080/01441647.2020.1848141.

Bedwell, B. D. *et al.* (2014) 'Apportioning energy consumption in the workplace: a review of issues in using metering data to motivate staff to save energy', *Technology Analysis & Strategic Management*, 26(10), pp. 1196–1211. doi: 10.1080/09537325.2014.978276.

Bedwell, B. D., Costanza, E. and Jewell, M. (2016) 'Understanding Energy Consumption at Work: Learning from Arrow Hill', in *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing - CSCW '16*. New York, New York, USA: ACM Press, pp. 1335–1346. doi: 10.1145/2818048.2819993.

Bellini, R. *et al.* (2018) 'Feminist HCI: Taking Stock, Moving Forward, and Engaging Community', in *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: ACM, pp. 1–4. doi: 10.1145/3170427.3185370.

Bilandzic, M., Schroeter, R. and Foth, M. (2013) 'Gelatine: making coworking places gel for better collaboration and social learning', in *Proceedings of the 25th Australian Computer-Human Interaction Conference: Augmentation, Application, Innovation, Collaboration (OzCHI '13)*, pp. 427–436. doi: 10.1145/2541016.2541027.

Blevis, E. (2007) 'Sustainable Interaction Design: Invention & Disposal, Renewal & Reuse', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*, pp. 503–512. doi: 10.1145/1240624.1240705.

Blevis, E. *et al.* (2014) 'Billions of interaction designers', *Interactions*. New York, NY, USA: ACM, 21(6), pp. 34–41. doi: 10.1145/2674931.

Blythe, M. (2014) 'Research Through Design Fiction: Narrative in Real and Imaginary Abstracts', *Proceedings of the 32nd Annual ACM Conference on Human factors in Computing Systems (CHI '14)*, p. 10. doi: 10.1145/2556288.2557098.

Blythe, M. *et al.* (2016) 'Anti-Solutionist Strategies: Seriously Silly Design Fiction', *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*, pp. 4968–4978. doi: 10.1145/2858036.2858482.

Bødker, S. (2006) 'When Second Wave HCI meets Third Wave Challenges', in *Proceedings of the 4th Nordic Conference on Human-Computer Interaction: Changing Roles*. Oslo, Norway: ACM, pp. 14–18.

Bødker, S. (2015) 'Third-wave HCI, 10 years later—participation and sharing', *Interactions*. New York, NY, USA, 22(5), pp. 24–31. doi: 10.1145/2804405.

Bødker, S. and Christiansen, E. (2006) 'Computer support for social awareness in flexible work', *Computer Supported Cooperative Work*, 15(1), pp. 1–28. doi: 10.1007/s10606-005-9011-y.

Boehner, K. *et al.* (2007) 'How HCI Interprets the Probes', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*, pp. 1077–1086. doi: 10.1145/1240624.1240789.

Boehner, K. and DiSalvo, C. (2016) 'Data, Design and Civics: An Exploratory Study of Civic Tech', in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*, pp. 2970–2981. doi: 10.1145/2858036.2858326.

Bosch, T. (2012) *Sci-Fi Writer Bruce Sterling Explains the Intriguing New Concept of Design Fiction*, *Slate*. Available at: https://slate.com/technology/2012/03/bruce-sterling-on-design-fictions.html.

Brand, S. (1994) *How Buildings Learn*. New York: Penguin Books.

Braun, V. *et al.* (2019) 'Thematic Analysis', in *Handbook of Research Methods in Health Social Sciences*. Singapore: Springer Singapore, pp. 843–860. doi: 10.1007/978-981-10-5251-4_103.

Braun, V. and Clarke, V. (2006) 'Using thematic analysis in psychology', *Qualitative Research in Psychology*, 3, pp. 77–101. doi: 10.1191/1478088706qp063oa.

Braun, V. and Clarke, V. (2013) *Successful Qualitative Research*. 1st edn. Edited by M. Carmichael. London: SAGE Publications Ltd.

Braun, V. and Clarke, V. (2019) 'Reflecting on reflexive thematic analysis', *Qualitative*

Research in Sport, Exercise and Health. Routledge, 11(4), pp. 589–597. doi: 10.1080/2159676X.2019.1628806.

BRE (2019) *Post-Occupancy Evaluation (POE)*. Available at: https://www.bre.co.uk/page.jsp?id=1793 (Accessed: 1 February 2018).

BRE (2020) *BREEAM: the world's leading sustainability assessment method for masterplanning projects, infrastructure and buildings - BREEAM*. Available at: https://www.breeam.com/ (Accessed: 11 July 2020).

BRE Global Ltd (2016) 'Occupant Satisfaction: Feedback', in *BREEAM In-Use International Technical Manual*, pp. 226–227. Available at: http://files.bregroup.com/breeam/technicalmanuals/SD221_BIU_International_2015_Re-issue_V2.0.pdf.

Briggs, P. *et al.* (2012) 'Invisible design', in *Proceedings of the Designing Interactive Systems Conference on - DIS '12*. New York, New York, USA: ACM Press, p. 534. doi: 10.1145/2317956.2318036.

Broms, L., Wangel, J. and Andersson, C. (2017) 'Sensing energy: Forming stories through speculative design artefacts', *Energy Research and Social Science*, 31(June), pp. 194–204. doi: 10.1016/j.erss.2017.06.025.

Brown, C. *et al.* (2014) 'Tracking Serendipitous Interactions: How Individual Cultures Shape the Office', in *Proceedings of the 17th ACM conference on Computer supported cooperative work & social computing - CSCW '14*. Baltimore, Maryland, USA: ACM Press, pp. 1072–1081. doi: 10.1145/2531602.2531641.

Brulé, E. and Mitchell Finnigan, S. (2020) *Thematic Analysis in HCI*. Available at: https://sociodesign.hypotheses.org/555.

Brush, A. J. J. B. B. *et al.* (2011) 'Home automation in the wild: Challenges and opportunities', *Conference on Human Factors in Computing Systems - Proceedings*, pp. 2115–2124. doi: 10.1145/1978942.1979249.

Brynjarsdóttir, H. *et al.* (2012) 'Sustainably unpersuaded: How Persuasion Narrows Our Vision of Sustainability', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*, p. 947. doi: 10.1145/2207676.2208539.

Buckman, A. H., Mayfield, M. and Beck, S. B. M. (2014) ‘What is a Smart Building?’, *Smart and Sustainable Built Environment*, 3(2), pp. 92–109. doi: 10.1108/SASBE-01-2014-0003.

Cardullo, P. and Kitchin, R. (2018) ‘Being a “citizen” in the smart city: up and down the scaffold of smart citizen participation in Dublin, Ireland’, *GeoJournal*, 84(1), pp. 1–13. doi: 10.1007/s10708-018-9845-8.

Chan, M. *et al.* (2008) ‘A review of smart homes-Present state and future challenges’, *Computer Methods and Programs in Biomedicine*, 91(1), pp. 55–81. doi: 10.1016/j.cmpb.2008.02.001.

Chappells, H. and Shove, E. (2004) ‘COMFORT: A review of philosophies and paradigms’, *Indoor Air*, (March), pp. 1–37.

Chappells, H. and Shove, E. (2005) ‘Debating the future of comfort: Environmental sustainability, energy consumption and the indoor environment’, *Building Research and Information*, 33(1), pp. 32–40. doi: 10.1080/0961321042000322762.

Chivukula, S. S. and Gray, C. M. (2020) ‘Bardzell’s “Feminist HCI” Legacy: Analyzing Citational Patterns’, in *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems.* New York, NY, USA: ACM, pp. 1–8. doi: 10.1145/3334480.3382936.

Clarke, R. *et al.* (2016) ‘Re-configuring participatory media for citizen elders in urban planning’, *Proceedings of the 3rd Conference on Media Architecture Biennale - MAB*, pp. 1–10. doi: 10.1145/2946803.2946815.

Clarke, R. *et al.* (2018) ‘More-than-human urban futures: Speculative Participatory Design to Avoid Ecocidal Smart Cities’, in *Proceedings of the 15th Participatory Design Conference on Short Papers, Situated Actions, Workshops and Tutorial - PDC ’18.* New York, New York, USA: ACM Press, pp. 1–4. doi: 10.1145/3210604.3210641.

Clear, A. K. *et al.* (2013) ‘Domestic Food and Sustainable Design: A Study of University Student Cooking and its Impacts’, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI ’13.* New York, New York, USA: ACM Press, p. 2447. doi: 10.1145/2470654.2481339.

Clear, A. K. *et al.* (2014) ‘Catch my drift?: achieving comfort more sustainably in conventionally heated buildings’, in *Proceedings of the 2014 Conference on Designing*

Interactive Systems (DIS '14), pp. 1015–1024. doi: 10.1145/2598510.2598529.

Clear, A. K., Mitchell Finnigan, S. and Comber, R. (2016) 'Why "automate" shouldn't mean "regulate" for thermal comfort in non-domestic buildings', in *DEMAND Centre Conference*. Lancaster. Available at: http://www.demand.ac.uk/wp-content/uploads/2016/03/DEMAND2016_Full_paper_125-Clear-1.pdf.

Cole, R. J. *et al.* (2008) 'Re-contextualizing the notion of comfort', *Building Research & Information*, 36(4), pp. 323–336. doi: 10.1080/09613210802076328.

Comber, R., Lampinen, A. and Haapoja, J. (2019) 'Towards Post-Interaction Computing: Addressing Immediacy, (un)Intentionality, Instability and Interaction Effects', in *Proceedings of the Halfway to the Future Symposium 2019*. New York, NY, USA: ACM, pp. 1–8. doi: 10.1145/3363384.3363477.

Corbett, E. and Le Dantec, C. A. (2018) 'Exploring trust in digital civics', in *DIS 2018 - Proceedings of the 2018 Designing Interactive Systems Conference*. New York, NY, USA: Association for Computing Machinery, Inc, pp. 9–20. doi: 10.1145/3196709.3196715.

Costanza, E. *et al.* (2016) '"A bit like British Weather, I suppose" Design and Evaluation of the Temperature Calendar', *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*, pp. 4061–4072. doi: 10.1145/2858036.2858367.

Cowan, E. (1973) 'Nixon Asks Householders to Save Heat by Lowering Thermostat 4 Degrees', *The New York Times*, 10 October, p. 33. Available at: https://www.nytimes.com/1973/10/10/archives/nixon-asks-householders-to-save-heat-by-lowering-thermostat-4.html.

Crenshaw, K. (1991) 'Mapping the Margins: Intersectionality, Identity Politics, and Violence against Women of Color', *Stanford Law Review*, 43(6), p. 1241. doi: 10.2307/1229039.

Creswell, J. W. and Creswell, J. D. (2018) *Research design: qualitative, quantitative, and mixed methods approaches*. Fifth Edit. doi: 10.1891/9780826146373.0007.

Crivellaro, C. *et al.* (2015) 'Contesting the City: enacting the Political Through Digitally Supported Urban Walks', in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*, pp. 2853–2862. doi: 10.1145/2702123.2702176.

Crivellaro, C. (2016) *HCI & Re-Making Place*. Newcastle University.

Crivellaro, C. *et al.* (2016) 'Re-Making Places: HCI, "Community Building" and Change', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '16)*. New York, New York, USA: ACM Press, pp. 2958–2969. doi: 10.1145/2858036.2858332.

D'Ignazio, C. and Klein, L. F. (2020) *Data Feminism*. 1st edn, *Data Feminism*. 1st edn. Cambridge, Massachusetts: MIT Press. doi: 10.7551/mitpress/11805.001.0001.

Dalton, N. *et al.* (2012) 'Ar-CHI-Tecture', in *Proceedings of the 2012 ACM annual conference extended abstracts on Human Factors in Computing Systems Extended Abstracts - CHI EA '12*. New York, New York, USA: ACM Press, p. 2743. doi: 10.1145/2212776.2212710.

Dalton, N. *et al.* (2014) 'Interaction and architectural space', in *Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems - CHI EA '14*. New York, New York, USA: ACM Press, pp. 29–32. doi: 10.1145/2559206.2559226.

Dalton, N. S. *et al.* (2016) *Architecture and Interaction*. Edited by N. S. Dalton et al. Cham: Springer International Publishing (Human–Computer Interaction Series). doi: 10.1007/978-3-319-30028-3.

Dalton, R. *et al.* (2020) 'HabiTech: Inhabiting Buildings, Data & Technology', in *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: ACM, pp. 1–8. doi: 10.1145/3334480.3375179.

Day, J. K. and O'Brien, W. (2017) 'Oh behave! Survey stories and lessons learned from building occupants in high-performance buildings', *Energy Research and Social Science*. Elsevier, 31(May), pp. 11–20. doi: 10.1016/j.erss.2017.05.037.

De Dear, R. (2011) 'Revisiting an old hypothesis of human thermal perception : alliesthesia', *Building Research & Information*, 39(2), pp. 108–117. doi: 10.1080/09613218.2011.552269.

De Dear, R. and Brager, G. S. (2001) 'The adaptive model of thermal comfort and energy conservation in the built environment', *International Journal of Biometeorology*, 45(2), pp. 100–108. doi: 10.1007/s004840100093.

Department for Business Energy & Industrial Strategy (2018) *Digest of UK Energy Statistics (DUKES) Chapter 5*. Available at:

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736152/Ch5.pdf.

Desjardins, A., Wakkary, R. and Odom, W. (2015) 'Investigating Genres and Perspectives in HCI Research on the Home', in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*, pp. 3073–3082. doi: 10.1145/2702123.2702540.

Dillahunt, T. and Malone, A. R. (2015) 'The Promise of the Sharing Economy among Disadvantaged Communities', in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*, pp. 2285–2294. doi: 10.1145/2702123.2702189.

Dillahunt, T. and Mankoff, J. (2014) 'Understanding factors of successful engagement around energy consumption between and among households', in *Proceedings of the 17th ACM Conference on Computer Supported Cooperative Work & Social Computing (CSCW '14)*, pp. 1246–1257. doi: 10.1145/2531602.2531626.

Dillahunt, T., Mankoff, J. and Paulos, E. (2010) 'Understanding conflict between landlords and tenants: implications for energy sensing and feedback', in *Proceedings of the 12th ACM international conference on Ubiquitous Computing (Ubicomp '10)*, pp. 149–158. doi: 10.1145/1864349.1864376.

DiSalvo, C., Sengers, P. and Brynjarsdóttir, H. (2010) 'Mapping the landscape of sustainable HCI', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. New York, NY, USA: ACM Press, pp. 1975–1984. doi: 10.1145/1753326.1753625.

Dombrowski, L., Harmon, E. and Fox, S. (2016) 'Social Justice-Oriented Interaction Design', in *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. New York, NY, USA: ACM, pp. 656–671. doi: 10.1145/2901790.2901861.

Dounis, A. I. and Caraiscos, C. (2008) 'Advanced control systems engineering for energy and comfort management in a building environment — A review', *Renewable and Sustainable Energy Reviews*, 13(2009), pp. 1246–1261. doi: 10.1016/j.rser.2008.09.015.

Dourish, P. (2006) 'Re-Space-ing Place : "Place" and "Space" Ten Years On', in *Proceedings of the 2006 20th Anniversary Conference on Computer Supported Cooperative Work - CSCW'06*, pp. 299–308. doi: 10.1145/1180875.1180921.

Dourish, P. (2010) 'HCI and Environmental Sustainability: the Politics of Design and the

Design of Politics', in *Proceedings of the 8th ACM Conference on Designing Interactive Systems (DIS '10)*, pp. 1–10. doi: 10.1145/1858171.1858173.

Dourish, P. and Bell, G. (2014) '"Resistance is futile": Reading science fiction alongside ubiquitous computing', *Personal and Ubiquitous Computing*, 18(4), pp. 769–778. doi: 10.1007/s00779-013-0678-7.

Dow, A. *et al.* (2016) 'ThoughtCloud: Exploring the Role of Feedback Technologies in Care Organisations', in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: ACM, pp. 3625–3636. doi: 10.1145/2858036.2858105.

Dowson, M. *et al.* (2012) 'Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal', *Energy Policy*. Elsevier, 50, pp. 294–305. doi: 10.1016/j.enpol.2012.07.019.

Driscoll Jr., E. B. (2003) *The History of X10*. Available at: http://home.planet.nl/~lhendrix/x10_history.htm (Accessed: 14 May 2020).

Duarte, E. F. and Baranauskas, M. C. C. (2016) 'Revisiting the Three HCI Waves', in *Proceedings of the 15th Brazilian Symposium on Human Factors in Computer Systems - IHC '16*. New York, New York, USA: ACM Press, pp. 1–4. doi: 10.1145/3033701.3033740.

Dunne, A. and Raby, F. (2013) *Speculative Everything*. 1st edn. Cambridge, Massachusetts: MIT Press.

EEVS Insight Ltd (2016) *International Performance Measurement and Verification Protocol*. Available at: http://www.eevs.co.uk/ipmvp.html (Accessed: 11 September 2016).

Eisenman, S. B. *et al.* (2007) 'The BikeNet mobile sensing system for cyclist experience mapping', in *Proceedings of the 5th International Conference on Embedded Networked Sensor Systems (SenSys '07)*, p. 87. doi: 10.1145/1322263.1322273.

Elsden, C. *et al.* (2017) 'On speculative enactments', *Conference on Human Factors in Computing Systems - Proceedings*, 2017-Janua, pp. 5386–5399. doi: 10.1145/3025453.3025503.

Engel, J. M. *et al.* (2004) 'Smart Brick - A Low Cost , Modular Wireless Sensor For Civil Structure Monitoring', in *International Conference on Computing, Communications and Control Technologies (CCCT 2004)*. Austin, Texas, pp. 1–4. Available at:

http://medx.mech.northwestern.edu/publications/papers/124.pdf.

Erickson, V. L. *et al.* (2013) 'ThermoSense: thermal array sensor networks in building management', in *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems (SenSys '13)*, pp. 1–2. doi: 10.1145/2517351.2517437.

Erickson, V. L. and Cerpa, A. E. (2012) 'Thermovote: Participatory Sensing for Efficient Building HVAC Conditioning', in *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings - BuildSys '12*. New York, New York, USA: ACM Press, pp. 9–16. doi: 10.1145/2422531.2422534.

Evans, J. and Jones, P. (2011) 'The walking interview: Methodology, mobility and place', *Applied Geography*. Elsevier Ltd, 31(2), pp. 849–858. doi: 10.1016/j.apgeog.2010.09.005.

Fanger, P. O. (1970) *Thermal comfort. Analysis and applications in environmental engineering.* Copenhagen: Danish Technical Press.

Fischer, J. E. *et al.* (2016) '"Just Whack It on Until It Gets Hot": Working with IoT Data in the Home', in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*, pp. 5933–5944. doi: 10.1145/2858036.2858518.

Fischer, J. E. *et al.* (2017) 'Data Work: How Energy Advisors and Clients Make IoT Data Accountable', *Computer Supported Cooperative Work (CSCW)*. Computer Supported Cooperative Work (CSCW), 26(4–6), pp. 597–626. doi: 10.1007/s10606-017-9293-x.

Fogg, B. (1998) 'Persuasive computers', in *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '98*. New York, New York, USA: ACM Press, pp. 225–232. doi: 10.1145/274644.274677.

Ford, D. (2014) 'The Pneumatic Common: Learning in, with and from the air', *Educational Philosophy and Theory*, 1857(July), pp. 37–41. doi: 10.1080/00131857.2014.930683.

Fox, S. *et al.* (2016) 'Exploring Social Justice, Design, and HCI', in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM, pp. 3293–3300. doi: 10.1145/2851581.2856465.

Fox, S. *et al.* (2017) 'Imagining Intersectional Futures', in *Companion of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing*. New York, NY, USA: ACM, pp. 387–393. doi: 10.1145/3022198.3022665.

Froehlich, J. E. *et al.* (2009) 'HydroSense: Infrastructure-mediated single-point sensing of whole-home water activity', *Proceedings of the 11th international conference on Ubiquitous computing (Ubicomp '09)*, pp. 235–244. doi: 10.1145/1620545.1620581.

Froehlich, J., Findlater, L. and Landay, J. (2010) 'The Design of Eco-Feedback Technology', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*, pp. 1999–2008. doi: 10.1145/1753326.1753629.

Gallacher, S. *et al.* (2015) 'Mood Squeezer', in *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing - CSCW '15*, pp. 891–902. doi: 10.1145/2675133.2675170.

Garg, V. and Bansal, N. K. (1999) 'Smart occupancy sensors to reduce energy consumption', *Energy and Buildings*, 32(1), pp. 81–87. doi: 10.1016/S0378-7788(99)00040-7.

Gaver, W. W. (1991) 'Technology affordances', in *Proceedings of the SIGCHI conference on Human factors in computing systems Reaching through technology - CHI '91*. New York, New York, USA: ACM Press, pp. 79–84. doi: 10.1145/108844.108856.

Gaver, W. W., Beaver, J. and Benford, S. (2003) 'Ambiguity as a resource for design', *Proceedings of the conference on Human factors in computing systems - CHI '03*, p. 233. doi: 10.1145/642611.642653.

Google (2020) *Nest Learning Thermostat, Google Store*. Available at: https://store.google.com/gb/product/nest_learning_thermostat_3rd_gen (Accessed: 29 June 2020).

Goulden, M. and Spence, A. (2015) 'Caught in the middle: The role of the Facilities Manager in organisational energy use', *Energy Policy*. Elsevier, 85, pp. 280–287. doi: 10.1016/j.enpol.2015.06.014.

GOV.UK (2014) *ESOS - Detailed Guidance, Department for Business Energy & Industrial Strategy and Environment Agency*. Available at: https://www.gov.uk/guidance/energy-savings-opportunity-scheme-esos (Accessed: 11 September 2016).

Gray, C. M., Stolterman, E. and Siegel, M. A. (2014) 'Reprioritizing the relationship between

HCI research and practice', in *Proceedings of the 2014 conference on Designing interactive systems*. New York, NY, USA: ACM, pp. 725–734. doi: 10.1145/2598510.2598595.

Gupta, S., Reynolds, M. S. and Patel, S. N. (2010) 'ElectriSense: single-point sensing using EMI for electrical event detection and classification in the home', *Proceedings of the 12th ACM international conference on Ubiquitous computing (Ubicomp '10)*, pp. 139–148. doi: 10.1145/1864349.1864375.

Gustafsson, A. and Bång, M. (2008) 'Evaluation of a pervasive game for domestic energy engagement among teenagers', in *Proceedings of the 2008 International Conference in Advances on Computer Entertainment Technology - ACE '08*. New York, New York, USA: ACM Press, p. 232. doi: 10.1145/1501750.1501804.

Gustafsson, A. and Gyllenswärd, M. (2005) 'The power-aware cord: energy awareness through ambient information display', in *Extended Abstracts on Human Factors in Computing Systems (CHI EA '05)*, pp. 1423–1426. Available at: http://dl.acm.org/citation.cfm?id=1056932 (Accessed: 19 April 2013).

Hameed, P. *et al.* (2014) 'A review on optimized control systems for building energy and comfort management of smart sustainable buildings', *Renewable and Sustainable Energy Reviews*. Elsevier, 34(2014), pp. 409–429. doi: 10.1016/j.rser.2014.03.027.

Hampton, S. (2017) 'An ethnography of energy demand and working from home: Exploring the affective dimensions of social practice in the United Kingdom', *Energy Research and Social Science*. Elsevier Ltd, 28, pp. 1–10. doi: 10.1016/j.erss.2017.03.012.

Hargreaves, T. and Wilson, C. (2013) 'Who uses smart home technologies? Representations of users by the smart home industry', *ECEEE summer study*, pp. 1–14.

Harper, R. (2011) *From Smart Home to Connected Home*, *The Connected Home: The Future of Domestic Life*. London: Springer London. doi: 10.1007/978-0-85729-476-0_1.

Harrison, S. and Dourish, P. (1996) 'Re-Place-ing Space: The Roles of Place and Space in Collaborative Systems', in *Proceedings of the 1996 ACM conference on Computer Supported Cooperative Work (CSCW '96)*, pp. 67–76. doi: 10.1145/240080.240193.

Harrison, S., Tatar, D. and Sengers, P. (2007) 'The Three Paradigms of HCI', in *Alt. CHI Session at the SIGCHI Conference on Human Factors in Computing Systems*. San Jose, California, USA.: ACM, pp. 1–18. doi: 10.1234/12345678.

Hasan, S. S. *et al.* (2018) 'Living Labs: Measuring Human Experience in the Built Environment', pp. 1–8. doi: 10.1145/3170427.3170627 W31,.

Hasselqvist, H. *et al.* (2015) 'Supporting Energy Management as a Cooperative Amateur Activity', *Extended Abstracts of the ACM CHI'15 Conference on Human Factors in Computing Systems*, 2, pp. 1483–1488. doi: 10.1145/2702613.2732724.

Hasselqvist, H., Bogdan, C. and Kis, F. (2016) 'Linking Data to Action: Designing for Amateur Energy Management', in *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS 2016).* Brisbane, QLD, Australia: ACM, pp. 473–483. doi: 10.1145/2901790.2901837.

Hasselqvist, H. and Eriksson, E. (2018) 'Designing for Diverse Stakeholder Engagement in Resource-Intensive Practices', in *Proceedings of the 10th Nordic Conference on Human-Computer Interaction.* ACM, pp. 426–438. doi: 10.1145/3240167.3240193.

Hayes, G. R. (2011) 'The relationship of action research to human-computer interaction', *ACM Transactions on Computer-Human Interaction*, 18(3), pp. 1–20. doi: 10.1145/1993060.1993065.

Haynes, B. P. (2008) 'The impact of office comfort on productivity', *Journal of Facilities Management*, 6(1), pp. 37–51. doi: 10.1108/14725960810847459.

Heitlinger, S. *et al.* (2019) 'Co-Creating "Smart" Sustainable Food Futures with Urban Food Growers', in *Proceedings of the 9th International Conference on Communities & Technologies - Transforming Communities - C&T '19.* New York, New York, USA: ACM Press, pp. 114–120. doi: 10.1145/3328320.3328399.

Heitlinger, S., Bryan-Kinns, N. and Comber, R. (2019) 'The Right to the Sustainable Smart City', in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19.* New York, New York, USA: ACM Press, pp. 1–13. doi: 10.1145/3290605.3300517.

Hellwig, R. T. (2015) 'Perceived control in indoor environments: a conceptual approach', *Building Research & Information*, 43(March 2015), pp. 302–315. doi: 10.1080/09613218.2015.1004150.

Hermstein, W. D. *et al.* (1986) ‘Combined electrical connection unit for power and information connection’. Germany: Bundesrepublik Deutschland. Available at: https://patents.google.com/patent/DE3608910A1/.

Hillier, B. (1996) *Space is the Machine*, *Design Studies*. London: Cambridge University Press. doi: 10.1016/S0142-694X(97)89854-7.

Hirst, A. (2011) ‘Settlers, vagrants and mutual indifference: unintended consequences of hot-desking’, *Journal of Organizational Change Management*, 24(6), pp. 767–788. doi: 10.1108/09534811111175742.

Hoey, J. *et al.* (2011) ‘Rapid specification and automated generation of prompting systems to assist people with dementia’, *Pervasive and Mobile Computing*. Elsevier B.V., 7(3), pp. 299–318. doi: 10.1016/j.pmcj.2010.11.007.

Hofstede, G., Hofstede, G. J. and Minkov, M. (2010) *Culture and Organizations: Software of the Mind*. New York: McGrawHill Education. Available at: https://e-edu.nbu.bg/pluginfile.php/900222/mod_resource/content/1/G.Hofstede_G.J.Hofstede_M.Minkov - Cultures and Organizations - Software of the Mind 3rd_edition 2010.pdf.

Hollands, R. G. (2008) ‘Will the real smart city please stand up? Intelligent, progressive or entrepreneurial?’, *City*, 12(3), pp. 303–320. doi: 10.1080/13604810802479126.

Hollands, R. G. (2015) ‘Critical interventions into the corporate smart city’, *Cambridge Journal of Regions, Economy and Society*, 8(1), pp. 61–77. doi: 10.1093/cjres/rsu011.

Honicky, R. *et al.* (2008) ‘N-SMARTS: Networked Suite of Mobile Atmospheric Real-time Sensors’, in *Proceedings of the Second ACM SIGCOMM workshop on Networked Systems for Developing Regions*, pp. 1–5. doi: 10.1145/1397705.1397713.

Al Horr, Y. *et al.* (2017) ‘Occupant productivity and indoor environment quality: A case of GSAS’, *International Journal of Sustainable Built Environment*. The Gulf Organisation for Research and Development, 6(2), pp. 476–490. doi: 10.1016/j.ijsbe.2017.11.001.

Houben, S. *et al.* (2016) ‘Physikit: Data Engagement Through Physical Ambient Visualizations in the Home’, in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI ’16)*, pp. 1608–1619. doi: 10.1145/2858036.2858059.

Houwelingen, J. H. Van and Raaij, W. F. Van (1989) ‘The effect of goal-setting and daily electronic feedback on in-home energy use’, *Journal of consumer research*, 16, pp. 98–105. Available at: http://www.jstor.org/stable/10.2307/2489305.

HSE (2002) *HSE Operational circular 483/27 “Oil-filled electrical distribution and other switch gear”, Operational Circulars (OCs)*. Available at: https://www.hse.gov.uk/foi/internalops/ocs/400-499/oc483_27.htm (Accessed: 1 June 2020).

Hunt, J. M. *et al.* (1986) ‘Electrical Energy Monitoring and Control System for the Home’, *IEEE Transactions on Consumer Electronics*, C(3), pp. 578–583. Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4071441 (Accessed: 12 December 2012).

Hutchinson, H. *et al.* (2003) ‘Technology probes: inspiring design for and with families’, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’03)*. Ft. Lauderdale, Florida, USA: ACM, pp. 17–24. doi: 10.1145/642611.642616.

Ingold, T. (2004) ‘Culture on the ground: The world perceived through the feet’, *Journal of Material Culture*, 9(3), pp. 315–340. doi: 10.1177/1359183504046896.

Ingold, T. and Vergunst, J. L. (2008) *Ways of Walking: Ethnography and Practice on Foot*. Edited by T. Ingold and J. L. Vergunst. London: Ashgate Publishing, Ltd. Available at: https://books.google.co.uk/books?id=AzYHWx-3FZkC.

Ingram, B. (2009) ‘Learning from architecture’, *Interactions*, 16(6), pp. 64–67. doi: 10.1145/1620693.1620709.

Intel Corporation (2017) *Smart Buildings with Internet of Things Technologies*. Available at: https://www.intel.co.uk/content/www/uk/en/smart-buildings/overview.html (Accessed: 13 December 2018).

International WELL Building Institute PBC and Delos Living LLC (2016) *The WELL Building Standard v1*.

Intille, S. S. (2002) ‘Designing a home of the future’, *IEEE Pervasive Computing*, 1(2), pp. 76–82. doi: 10.1109/MPRV.2002.1012340.

Irwin, G. (2017a) ‘Coping with changing temperatures: Interactions of people facing cancer and menopause with home energy management systems’, *Proceedings of the 31st*

International BCS Human Computer Interaction Conference, British HCI 2017, 2017-July, pp. 1–11. doi: 10.14236/ewic/HCI2017.40.

Irwin, G. (2017b) 'Hot under the collar? Building a perceptive home energy interface for chemotherapy recipients', *SmartObject 2017 - Proceedings of the 2017 ACM Workshop on Interacting with Smart Objects, co-located with IUI 2017*, pp. 31–36. doi: 10.1145/3038450.3038454.

ISO (2005) *ISO 7730:2005 Ergonomics of the thermal environment.* Geneva, Switzerland: International Organization for Standardization. Available at: https://www.iso.org/standard/39155.html.

ISO (2015) *ISO 9001:2015 Quality management systems — Requirements.* Geneva, Switzerland: International Organization for Standardization. Available at: https://www.iso.org/standard/62085.html.

ISO (2018) *ISO 50001:2018 Energy management systems — Requirements with guidance for use.* Geneva, Switzerland: International Organization for Standardization. Available at: https://www.iso.org/standard/69426.html.

Jacovi, M. *et al.* (2006) 'The chasms of CSCW: A citation graph analysis of the CSCW conference', *Proceedings of the ACM Conference on Computer Supported Cooperative Work, CSCW*, pp. 289–298. doi: 10.1145/1180875.1180920.

Jahn, M. *et al.* (2011) 'EnergyPULSE : Tracking Sustainable Behavior in Office Environments', in *e-Energy*. doi: 10.1145/2318716.2318733.

Jain, M. *et al.* (2013) 'We are not in the loop: resource wastage and conservation attitude of employees in indian workplace', in *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing (UbiComp '13)*, pp. 687–696. doi: 10.1145/2493432.2493444.

Jakobi, T. and Schwartz, T. (2012) 'Putting the user in charge: end user development for eco-feedback technologies', *Sustainable Internet and ICT for Sustainability (SustainIT '12)*, p. 4.

Jensen, O. M. (2003) 'Visualisation turns down energy demand', *Danish Building and Urban Research. ECEEE*, pp. 451–454. Available at: http://domo.cust.pdc.nl/9307000/d/q49.pdf (Accessed: 12 December 2012).

Jensen, R. H., Strengers, Y., *et al.* (2018) 'Designing the Desirable Smart Home', pp. 1–14. doi: 10.1145/3173574.3173578.

Jensen, R. H., Raptis, D., *et al.* (2018) 'Washing with the Wind: A Study of Scripting towards Sustainability', in *Proceedings of the 2018 on Designing Interactive Systems Conference 2018 - DIS '18*. New York, New York, USA: ACM Press, pp. 1387–1400. doi: 10.1145/3196709.3196779.

Jensen, R. H., Kjeldskov, J. and Skov, M. B. (2016) 'HeatDial: Beyond User Scheduling in Eco-Interaction', in *Proceedings of the 9th Nordic Conference on Human-Computer Interaction - NordiCHI '16*. New York, New York, USA: ACM Press, pp. 1–10. doi: 10.1145/2971485.2971525.

Jiang, X. *et al.* (2009) 'Experiences with a high-fidelity wireless building energy auditing network', in *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems (SenSys '09)*, pp. 113–126. doi: 10.1145/1644038.1644050.

Johnson, I. G. *et al.* (2016) 'Reflections on Deploying Distributed Consultation Technologies with Community Organisations', in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*, pp. 2945–2957. doi: 10.1145/2858036.2858098.

Kale, S. (2018) 'All you need is loves: the truth about polyamory', *The Guardian*, 25 September. Available at: https://www.theguardian.com/lifeandstyle/2018/sep/25/truth-about-polyamory-monogamy-open-relationships.

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

Keyes, O., Hoy, J. and Drouhard, M. (2019) 'Human-Computer Insurrection', in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*. New York, New York, USA: ACM Press, pp. 1–13. doi: 10.1145/3290605.3300569.

Khan, A. *et al.* (2014) 'Occupancy Monitoring using Environmental & Context Sensors and a Hierarchical Analysis Framework', in *Proceedings of the 1st ACM Conference on Embedded Systems for Energy-Efficient Buildings (BuildSys '14)*. New York, NY, USA: ACM, pp. 90–99. doi: 10.1145/2674061.2674080.

Kidd, C. D. *et al.* (1999) 'The aware home: A living laboratory for ubiquitous computing research', *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 1670, pp. 191–198. doi: 10.1007/10705432_17.

Kientz, J. A. *et al.* (2008) 'The Georgia Tech aware home', in *Proceeding of the twenty-sixth annual CHI conference extended abstracts on Human factors in computing systems - CHI '08.* New York, New York, USA: ACM Press, p. 3675. doi: 10.1145/1358628.1358911.

Kingma, B. and Van Marken Lichtenbelt, W. (2015) 'Energy consumption in buildings and female thermal demand', *Nature Climate Change*, 5(12), pp. 1054–1056. doi: 10.1038/nclimate2741.

Kirman, B., Linehan, C. and Lawson, S. (2010) 'There's a monster in my kitchen: using aversive feedback to motivate behaviour change', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*, pp. 2685–2694. Available at: http://dl.acm.org/citation.cfm?id=1753852 (Accessed: 12 December 2012).

Kitchin, R. (2015) 'Making sense of smart cities: Addressing present shortcomings', *Cambridge Journal of Regions, Economy and Society*, 8(1), pp. 131–136. doi: 10.1093/cjres/rsu027.

Knowles, B. *et al.* (2014) 'Patterns of persuasion for sustainability', in *Proceedings of the 2014 conference on Designing interactive systems - DIS '14.* New York, New York, USA: ACM Press, pp. 1035–1044. doi: 10.1145/2598510.2598536.

Knowles, B. *et al.* (2016) 'Design Patterns, Principles, and Strategies for Sustainable HCI', in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*, pp. 3581–3588. doi: 10.1145/2851581.2856497.

Knowles, B., Bates, O. and Håkansson, M. (2018) 'This Changes Sustainable HCI', in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18.* New York, New York, USA: ACM Press, pp. 1–12. doi: 10.1145/3173574.3174045.

Konstantakopoulos, I. C. *et al.* (2019) 'A deep learning and gamification approach to improving human-building interaction and energy efficiency in smart infrastructure', *Applied Energy*. Elsevier, 237(December 2018), pp. 810–821. doi: 10.1016/j.apenergy.2018.12.065.

Kwek, D. (2003) ‘Decolonizing and Re-Presenting Culture’s Consequences: A Postcolonial Critique of Cross-Cultural Studies in Management’, in Prasad, A. (ed.) *Postcolonial Theory and Organizational Analysis*. New York: Palgrave Macmillan US, pp. 121–146. doi: 10.1057/9781403982292_5.

Launey, R. O. *et al.* (1989) ‘Expandable home automation system’. United States: USPTO.

Lazarova-Molnar, S. and Mohamed, N. (2017) ‘On the Complexity of Smart Buildings Occupant Behavior: Risks and Opportunities’, in *Proceedings of the 8th Balkan Conference in Informatics (BCI ’17)*. New York, New York, USA: ACM Press, pp. 1–4. doi: 10.1145/3136273.3136274.

Leaman, A. (2017) *BUS Methodology Occupant Satisfaction Evaluation*. Available at: https://www.busmethodology.org.uk/ (Accessed: 19 December 2018).

Lee, P. and Zhang, X. (2005) ‘Home entertainment, security, surveillance, and automation control system’. United States: USPTO. Available at: https://www.google.com/patents/US20050267605.

Lindley, J. and Coulton, P. (2015) ‘Back to the future: 10 years of design fiction’, *ACM International Conference Proceeding Series*, pp. 210–211. doi: 10.1145/2783446.2783592.

Liu, L. *et al.* (2016) ‘Smart homes and home health monitoring technologies for older adults: A systematic review’, *International Journal of Medical Informatics*. Elsevier Ireland Ltd, 91, pp. 44–59. doi: 10.1016/j.ijmedinf.2016.04.007.

Lockton, D. *et al.* (2011) ‘Behaviour Change at Work: empowering energy efficiency in the workplace through user-centred design’, *BECC 2011: Behavior, Energy & Climate Change*, pp. 0–15. Available at: http://escholarship.org/uc/item/6ww5h5jm.

Lockton, D. *et al.* (2014) ‘Persuasive technology for sustainable workplaces’, *Interactions*, 21(1), pp. 58–61. doi: 10.1145/2544170.

Lockton, D., Harrison, D. and Stanton, N. A. (2010) *Design with Intent: 101 Patterns for Influencing Behaviour Through Design*. Equifine. Available at: http://www.danlockton.com/dwi/Download_the_cards.

Luo, M. *et al.* (2016) ‘The underlying linkage between personal control and thermal comfort:

Psychological or physical effects?', *Energy and Buildings*. Elsevier B.V., 111(2016), pp. 56–63. doi: 10.1016/j.enbuild.2015.11.004.

De Maat, S. (2015) *On The Symbiosis of People and Building The Perfect Slum*. École Polytechnique Fédérale De Lausanne.

MacFadyen, D. J. *et al.* (1987) 'Communication and energy control system for houses'. United States: USPTO. Available at: http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&p=1&u=/netahtml/PTO/srchnum.html&r=1&f=G&l=50&d=PALL&s1=4899217.PN.

Mankoff, J. (2012) 'HCI and Sustainability: A Tale of Two Motivations', *Interactions*, May, pp. 16–19. doi: 10.1145/2168931.2168937.

Massey, D. (1991) 'A Global Sense of Place', *Marxism Today*, 35(June), pp. 24–29. doi: 10.1016/j.pecs.2007.10.001.

Massey, D. (1993) 'Power Geometry and a Progressive Sense of Place', in Curtis, B. et al. (eds) *Mapping the Futures: Local Cultures, Global Change*. London: Routledge, pp. 56–69. Available at: https://books.google.co.uk/books?id=j4CcmbV0CjIC.

Mauriello, M. L. *et al.* (2016) 'The Future Role of Thermography in Human-Building Interaction', *Future of Human-Building Interaction workshop at the 34rd Annual ACM Conference on Human Factors in Computing Systems*. doi: 10.1136/adc.2009.171629.

Mauriello, M. L., Norooz, L. and Froehlich, J. E. (2015) 'Understanding the Role of Thermography in Energy Auditing: Current Practices and the Potential for Automated Solutions', in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*, pp. 1993–2002. doi: 10.1145/2702123.2702528.

McCarthy, J. and Wright, P. (2004) *Technology as Experience*. Cambridge, Massachusetts: MIT Press.

McCullough, M. (2004) *Digital Ground*. 1st edn. Cambridge, Massachusetts: MIT Press. Available at: https://mitpress.mit.edu/books/digital-ground.

Menezes, A. C. *et al.* (2012) 'Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap', *Applied*

Energy. Elsevier Ltd, 97(2012), pp. 355–364. doi: 10.1016/j.apenergy.2011.11.075.

Mennicken, S., Vermeulen, J. and Huang, E. M. (2014) ‘From today’s augmented houses to tomorrow’s smart homes: New directions for home automation research’, *UbiComp 2014 - Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, pp. 105–115. doi: 10.1145/2632048.2636076.

Microsoft Corporation (2013) *88 Acres*. Available at: https://www.microsoft.com/en-us/stories/88acres/ (Accessed: 19 January 2019).

Moreno, M. V., Zamora, M. A. and Skarmeta, A. F. (2014) ‘User-centric smart buildings for energy sustainable smart cities’, *Transactions on Emerging Telecommunications Technologies*, 25(1), pp. 41–55. doi: 10.1002/ett.2771.

Morgan, E. *et al.* (2018) ‘Co-Designing a Device for Behaviour-Based Energy Reduction in a Large Organisation’, *Proceedings of the ACM on Human-Computer Interaction*, 2(CSCW), pp. 1–23. doi: 10.1145/3274394.

Morozov, E. (2013) *To save everything, click here: Technology, solutionism, and the urge to fix problems that don’t exist*. London: Penguin UK.

Morrissey, K. (2017) *‘I’m a rambler, I’m a gambler, I’m a long way from home’: exploring participation through music and digital design in dementia care School of Applied Psychology Supervisors :* National University of Ireland, Cork.

Moulettes, A. (2007) ‘The absence of women’s voices in Hofstede’s Cultural Consequences’, *Women in Management Review*. Edited by A. Broadbridge. Emerald Group Publishing Limited, 22(6), pp. 443–455. doi: 10.1108/09649420710778682.

Murphy, M. (2006) *Sick Building Syndrome and the Problem of Uncertainty*. Durham and London: Duke University Press.

Nabil, S. *et al.* (2017) ‘Designing future ubiquitous homes with oui interiors: possibilities and challenges’, *Interaction Design and Architecture(s)*, 32, pp. 28–37. Available at: http://www.mifav.uniroma2.it/inevent/events/idea2010/doc/32_2.pdf.

National Union of Students (2016) *NUS Green Impact*. Available at: http://sustainability.nus.org.uk/green-impact/about (Accessed: 21 September 2016).

Neustaedter, C., Brush, A. J. B. B. and Greenberg, S. (2009) 'The Calendar is Crucial: Coordination and Awareness through the Family Calendar', *ACM Transactions on Computer-Human Interaction*, 16(1), pp. 1–48. doi: 10.1145/1502800.1502806.

Newcastle University Press Office (2015) *Richardson Road redevelopment given approval - Press Office - Newcastle University.* Available at: https://www.ncl.ac.uk/press/articles/archive/2015/12/richardsonroad/ (Accessed: 19 December 2020).

Newman, E. A. (1888) 'Thermo-electric apparatus for controlling the temperature of water in pipes'. United States: USPTO.

Nicol, J. F. and Humphreys, M. A. (2002) 'Adaptive thermal comfort and sustainable thermal standards for buildings', *Energy and Buildings*, 34(6), pp. 563–572. doi: 10.1016/S0378-7788(02)00006-3.

Norman, D. A. (1988) *The Design of Everyday Things.* Revised Ed, *Design.* Revised Ed. New York: Basic Books. doi: 10.2307/1423268.

Norman, D. A. (1993) *Things That Make Us Smart.* 1st Editio. Reading, Massachusetts: Addison-Wesley Publishing Company.

Oldenburg, R. (1989) *The Great Good Place: Cafes, Coffee Shops, Bookstores, Bars, Hair Salons, and Other Hangouts at the Heart of a Community.* 1st edn. New York: Marlowe & Company.

Olivier, P. *et al.* (2009) 'Ambient kitchen: Designing situated services using a high fidelity prototyping environment', in *Proceedings of the 2nd International Conference on PErvasive Technologies Related to Assistive Environments - PETRA '09.* New York, New York, USA: ACM Press, pp. 1–7. doi: 10.1145/1579114.1579161.

Oseland, N. A. (1995) 'Predicted and reported thermal sensation in climate chambers, offices and homes', *Energy and Buildings*, 23(2), pp. 105–115. doi: 10.1016/0378-7788(95)00934-5.

Parag, Y. and Janda, K. B. (2014) 'More than filler: Middle actors and socio-technical change in the energy system from the "middle-out"', *Energy Research and Social Science.* Elsevier Ltd, 3(C), pp. 102–112. doi: 10.1016/j.erss.2014.07.011.

Pargman, D. *et al.* (2017) 'The (Un)sustainability of Imagined Future Information Societies', in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17).* New York, New York, USA: ACM, pp. 773–785. doi: 10.1145/3025453.3025858.

Pargman, D. and Raghavan, B. (2014) 'Rethinking sustainability in computing: From buzzword to non-negotiable limits', *Proceedings of the NordiCHI 2014: The 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*, pp. 638–647. doi: 10.1145/2639189.2639228.

Parker, C., Tomitsch, M. and Kay, J. (2018) 'Does the Public Still Look at Public Displays?', *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 2(2), pp. 1–24. doi: 10.1145/3214276.

Passivhaus Trust (2010) *What is Passivhaus?* Available at: https://www.passivhaustrust.org.uk/what_is_passivhaus.php (Accessed: 22 December 2020).

Pham, C. *et al.* (2012) 'The Ambient Kitchen: A Pervasive Sensing Environment for Situated Services', in *Demonstration in the Designing Interactive Systems Conference (DIS 2012).* Newcastle, UK, p. 3.

Pine, K. H. and Liboiron, M. (2015) 'The Politics of Measurement and Action', in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*, pp. 3147–3156. doi: 10.1145/2702123.2702298.

Poltrock, S. and Grudin, J. (1999) 'CSCW, groupware and workflow', in *CHI '99 extended abstracts on Human factors in computer systems - CHI '99.* New York, New York, USA: ACM Press, p. 120. doi: 10.1145/632780.632791.

Preiser, W. F. E. (1995) 'Post-occupancy evaluation: How to make buildings work better', *Facilities*, 13(11), pp. 19–28. doi: 10.1108/02632779510097787.

Preist, C., Schien, D. and Shabajee, P. (2019) 'Evaluating Sustainable Interaction Design of Digital Services: The Case of YouTube', in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems.* New York, NY, USA: ACM, pp. 1–12. doi: 10.1145/3290605.3300627.

Property Industry Alliance (2017) *Property Data Report 2017 Facts and figures about industry to year-end 2016.*

Prost, S., Mattheiss, E. and Tscheligi, M. (2015) 'From Awareness to Empowerment: Using Design Fiction to Explore Paths towards a Sustainable Energy Future', in *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing - CSCW '15*. New York, New York, USA: ACM Press, pp. 1649–1658. doi: 10.1145/2675133.2675281.

Railton, A. R. (1950) 'Push-Button Manor', *Popular Mechanics*, December, pp. 85–87. Available at: http://blog.modernmechanix.com/push-button-manor/#mmGal.

Ramchurn, S. D. *et al.* (2012) 'Putting the "smarts" into the smart grid', *Communications of the ACM*, 55(4), p. 86. doi: 10.1145/2133806.2133825.

Ramsey, A. R. J. (1945) 'The Thermostat or Heat Governor An Outline of its History', *Transactions of the Newcomen Society*. Routledge, 25(1), pp. 53–72. doi: 10.1179/tns.1945.007.

Rankin, Y. A. and Thomas, J. O. (2019) 'Straighten Up and Fly Right: Rethinking Intersectionality in HCI', *Interactions*, 30 October, pp. 64–68. doi: 10.1145/3363033.

Rankin, Y. A., Thomas, J. O. and Joseph, N. M. (2020) 'Intersectionality in HCI: Lost in Translation', *Interactions*, 30 September, pp. 68–71. doi: 10.1145/3416498.

Reddy, S. *et al.* (2010) 'Biketastic: Sensing and Mapping for Better Biking', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*, pp. 1817–1820. doi: 10.1145/1753326.1753598.

Reeves, S. (2012) 'Envisioning ubiquitous computing', in *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*. New York, New York, USA: ACM Press, p. 1573. doi: 10.1145/2207676.2208278.

Riche, Y., Dodge, J. and Metoyer, R. a. (2010) 'Studying always-on electricity feedback in the home', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. New York, NY, USA: ACM Press, pp. 1995–1998. doi: 10.1145/1753326.1753628.

Rodden, T. A. *et al.* (2013) 'At home with agents: Exploring attitudes towards future smart energy infrastructures', *IJCAI International Joint Conference on Artificial Intelligence*, pp. 3057–3061.

Romm, T. and Harwell, D. (2019) 'Microsoft workers call for canceling military contract for technology that could turn warfare into a "video game"', *The Washington Post*, 22 February. Available at: https://www.washingtonpost.com/technology/2019/02/22/microsoft-workers-call-cancelling-military-contract-technology-that-could-turn-warfare-into-video-game/.

Saini, M. K. and Goel, N. (2019) 'How Smart Are Smart Classrooms? A Review of Smart Classroom Technologies', *ACM Computing Surveys*, 52(6), pp. 1–28. doi: 10.1145/3368196.

Sale of Goods Act (1979). c.54. Available at: https://www.legislation.gov.uk/ukpga/1979/54 (Accessed: 18 December 2020).

Sandberg, J. (2003) 'Employees only think they control thermostat', *Wall Street Journal*, pp. 12–14. Available at: http://online.wsj.com/article/SB1042577628591401304.html.

Schlesinger, A., Edwards, W. K. and Grinter, R. E. (2017) 'Intersectional HCI: Engaging Identity through Gender, Race, and Class', in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA, New York, USA: ACM, pp. 5412–5427. doi: 10.1145/3025453.3025766.

Schnädelbach, H. *et al.* (2006) 'Moving Office: Inhabiting a Dynamic Building', in *Proceedings of the 2006 20th Anniversary Conference on Computer Supported Cooperative Work - CSCW'06*. Banff, Alberta, Canada.: ACM, pp. 313–322. doi: 10.1145/1180875.1180924.

Schnädelbach, H. (2010) 'Adaptive Architecture – A Conceptual Framework', in Geelhaar, J. et al. (eds) *MediaCity: Interaction of Architecture, Media and Social Phenomena*, pp. 523–555.

Schnädelbach, H. *et al.* (2012) 'ExoBuilding: Physiologically driven adaptive architecture', *ACM Transactions on Computer-Human Interaction*, 19(4). doi: 10.1145/2395131.2395132.

Schnädelbach, H. *et al.* (2017) 'People, Personal Data and the Built Environment', in *Proceedings of the 2016 ACM Conference Companion Publication on Designing Interactive Systems - DIS '17 Companion*. New York, New York, USA: ACM Press, pp. 360–363. doi: 10.1145/3064857.3064864.

Schwartz, T. *et al.* (2010) 'Sustainable energy practices at work: understanding the role of workers in energy conservation', in *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries*, pp. 452–462. doi: 10.1145/1868914.1868966.

Schwartz, T. *et al.* (2013) 'Cultivating Energy Literacy — Results from a Longitudinal Living

Lab Study of a Home Energy Management System', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13).* Paris, France: ACM. doi: 10.1145/2470654.2466154.

Schwartz, T. *et al.* (2014) 'What People Do with Consumption Feedback: A Long-Term Living Lab Study of a Home Energy Management System', *Interacting with Computers*, 27(6). doi: 10.1093/iwc/iwu009.

Scott, J. *et al.* (2011) 'PreHeat: controlling home heating using occupancy prediction', in *Proceedings of the 13th ACM international conference on Ubiquitous computing (Ubicomp '11).* Available at: http://dl.acm.org/citation.cfm?id=2030151 (Accessed: 31 October 2014).

Seppänen, O. and Fisk, W. (2006) 'Some Quantitative Relations between Indoor Environmental Quality and Work Performance or Health', *HVAC&R Research*, 12(4), pp. 957–973. doi: 10.1080/10789669.2006.10391446.

Shahamat, H. (2014) 'Formal Sustainability in Traditional Architecture of Iran According To Five Principles of Traditional Architecture of Iran', *Journal of Applied Environmental and Biological Sciences*, 4(1), pp. 100–110. Available at: www.textroad.com.

Shapiro, I. (2009) 'Energy audits in large commercial office buildings', *ASHRAE Journal*, 51(1).

Shove, E., Watson, M. and Spurling, N. (2015) 'Conceptualizing connections: Energy demand, infrastructures and social practices', *European Journal of Social Theory*, 18(3), pp. 274–287. doi: 10.1177/1368431015579964.

'Smart' (2017) *Cambridge Academic Content Dictionary.* Cambridge University Press. Available at: https://dictionary.cambridge.org/dictionary/english/smart.

Snow, S., Oakley, M. and Schraefel, M. c. (2019) 'Performance by Design: Supporting Decisions around Indoor Air Quality in Offices', *Proceedings of the 2019 on Designing Interactive Systems Conference - DIS '19*, pp. 99–111. doi: 10.1145/3322276.3322372.

Star, S. L. and Griesemer, J. R. (1989) 'Institutional Ecology, `Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39', *Social Studies of Science*, 19(3), pp. 387–420. doi: 10.1177/030631289019003001.

Steiger, M. *et al.* (2021) 'The Psychological Well-Being of Content Moderators', in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: ACM, pp. 1–14. doi: 10.1145/3411764.3445092.

Sterling, B. (2009) 'Design fiction', *interactions*, 16(3), p. 20. doi: 10.1145/1516016.1516021.

Stockard, J. (2006) 'Gender Socialization', in *Handbook of the Sociology of Gender*. Springer US, pp. 215–227. doi: 10.1007/0-387-36218-5_11.

Streitz, N. A., Geißler, J. and Holmer, T. (1998) 'Roomware for cooperative buildings: Integrated design of architectural spaces and information spaces', *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 1370, pp. 4–18. doi: 10.1007/3-540-69706-3_3.

Strengers, Y. (2011) 'Designing eco-feedback systems for everyday life', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*, pp. 2135–2144. doi: 10.1145/1978942.1979252.

Strengers, Y. (2014) 'Smart energy in everyday life', *interactions*, 21(4), pp. 24–31. doi: 10.1145/2621931.

Strengers, Y. *et al.* (2019) 'Protection, Productivity and Pleasure in the Smart Home', in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*. New York, New York, USA: ACM Press, pp. 1–13. doi: 10.1145/3290605.3300875.

Strohmayer, A. *et al.* (2018) '#CHIversity: Implications for Equality, Diversity, and Inclusion Campaigns', in *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: ACM, pp. 1–10. doi: 10.1145/3170427.3188396.

Strohmayer, A., Clamen, J. and Laing, M. (2019) 'Technologies for Social Justice', in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: ACM, pp. 1–14. doi: 10.1145/3290605.3300882.

Strohmayer, A., Laing, M. and Comber, R. (2017) 'Technologies and Social Justice Outcomes in Sex Work Charities', in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: ACM, pp. 3352–3364. doi: 10.1145/3025453.3025615.

Su, N. M. and Mark, G. (2008) ‘Designing for nomadic work’, in *Proceedings of the 7th ACM conference on Designing interactive systems - DIS ’08*. New York, New York, USA: ACM Press, pp. 305–314. doi: 10.1145/1394445.1394478.

Sundblad, Y. (2011) ‘UTOPIA: Participatory design from scandinavia to the world’, *IFIP Advances in Information and Communication Technology*, 350, pp. 176–186. doi: 10.1007/978-3-642-23315-9_20.

Tanenbaum, J., Pufal, M. and Tanenbaum, K. (2016) ‘The limits of our imagination: Design fiction as a strategy for engaging with dystopian futures’, *Proceedings of the Second Workshop on Computing within Limits - LIMITS ’16*, pp. 1–9. doi: 10.1145/2926676.2926687.

Taylor, A. S. *et al.* (2007) ‘Homes that make us smart’, *Personal and Ubiquitous Computing*, 11(5), pp. 383–393. doi: 10.1007/s00779-006-0076-5.

Taylor, A. S. *et al.* (2015) ‘Data-in-Place: Thinking through the Relations Between Data and Community’, in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI ’15)*, pp. 2863–2872. doi: 10.1145/2702123.2702558.

Taylor, A. S. and Swan, L. (2005) ‘Artful Systems in the Home’, in *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI ’05*. New York, New York, USA: ACM Press, p. 641. doi: 10.1145/1054972.1055060.

The British Land Company PLC (2017) *Smart offices: A 2017 vision for the future*. London. Available at: https://officeagenda.britishland.com/assets/pdfs/smart-offices.pdf.

Thieme, A. *et al.* (2012) ‘“We’ve Bin Watching You” – Designing for Reflection and Social Persuasion to Promote Sustainable Lifestyles’, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’12)*. Austin, Texas, pp. 2337–2346.

Tolmie, P. *et al.* (2016) ‘“This has to be the cats” - personal data legibility in networked sensing systems’, in *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing (CSCW ’16)*. San Francisco, CA, USA: ACM, pp. 491–502. doi: 10.1145/2818048.2819992.

Tseng, E. *et al.* (2020) ‘“We can learn. Why not?”: Designing Technologies to Engender Equity for Home Health Aides’, in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: ACM, pp. 1–14. doi: 10.1145/3313831.3376633.

UCL Engineering (2017) ‘Lifespans & Decisions : Factsheet’. London. Available at: https://www.ucl.ac.uk/engineering-exchange/sites/engineering-exchange/files/fact-sheet-lifespan-and-decisions-social-housing.pdf.

Ur, B. *et al.* (2014) ‘Practical trigger-action programming in the smart home’, in *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI ’14*. New York, New York, USA: ACM Press, pp. 803–812. doi: 10.1145/2556288.2557420.

Valks, B., Arkesteijn, M. and Den Heijer, A. (2019) ‘Smart campus tools 2.0 exploring the use of real-time space use measurement at universities and organizations’, *Facilities*. Emerald Group Publishing Ltd., ahead-of-p(ahead-of-print), pp. 961–980. doi: 10.1108/F-11-2018-0136.

Verma, H., Alavi, H. S. and Lalanne, D. (2017) ‘Studying Space Use: Bringing HCI Tools to Architectural Projects’, in *Proceedings of the 35th Annual ACM Conference on Human Factors in Computing Systems (CHI ’17)*. New York, NY, USA, pp. 3856–3866.

Vines, J. (2018) ‘Playing with Provocations’, in Blythe, M. and Monk, A. (eds) *Funology 2*. Cham: Springer International Publishing (Human–Computer Interaction Series), pp. 111–128. doi: 10.1007/978-3-319-68213-6.

Violet (2009) *Nabaztag, the multipurpose Internet-connected Rabbit*, *violet.net*. Available at: http://web.archive.org/web/20090218165033/http:/www.violet.net/_nabaztag-the-first-rabbit-connected-to-the-internet.html (Accessed: 29 June 2020).

Vlachokyriakos, V., Dunphy, P., *et al.* (2014) ‘BallotShare: An exploration of the design space for digital voting in the workplace’, *Computers in Human Behavior*. Elsevier Ltd, 41(2014), pp. 433–443. doi: 10.1016/j.chb.2014.04.024.

Vlachokyriakos, V., Comber, R., *et al.* (2014) ‘PosterVote: expanding the action repertoire for local political activism’, in *Proceedings of the 2014 Conference on Designing Interactive Systems (DIS ’14)*, pp. 795–804. doi: 10.1145/2598510.2598523.

Vlachokyriakos, V. *et al.* (2016) ‘Digital Civics: Citizen Empowerment With and Through Technology’, in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA ’16*. New York, New York, USA: ACM Press, pp. 1096–1099. doi: 10.1145/2851581.2886436.

Vtyurina, A. and Fourney, A. (2018) ‘Exploring the Role of Conversational Cues in Guided

Task Support with Virtual Assistants', in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. New York, New York, USA: ACM Press, pp. 1–7. doi: 10.1145/3173574.3173782.

Want, R. *et al.* (1992) 'The Active Badge Location System', *ACM Transactions on Information Systems (TOIS)*, 10(1), pp. 91–102. doi: 10.1145/128756.128759.

Way, M. and Bordass, B. (2005) 'Making feedback and post-occupancy evaluation routine 2: Soft Landings - Involving design and building teams in improving performance', *Building Research and Information*, 33(4), pp. 353–360. doi: 10.1080/09613210500162008.

Weiser, M. (1991) 'The Computer For the 21st Century', *Scientific American*, pp. 94–104.

Weiser, M. and Brown, J. S. (2001) 'The Coming Age of Calm Technology', *Distributed Computing*. doi: 10.1.1.129.2275.

Welty, J. (1989) 'Remote control system for control of electrically operable equipment in people occupiable structures'. United States: USPTO. Available at: https://patents.google.com/patent/US5109222A/en.

Wilkie, A., Michael, M. and Plummer-Fernandez, M. (2015) 'Speculative method and Twitter: Bots, energy and three conceptual characters', *Sociological Review*, 63(1), pp. 79–101. doi: 10.1111/1467-954X.12168.

Wilson, A. and Tewdwr-Jones, M. (2019) 'Let's draw and talk about urban change: Deploying digital technology to encourage citizen participation in urban planning', *Environment and Planning B: Urban Analytics and City Science*, pp. 1–17. doi: 10.1177/2399808319831290.

Wilson, C., Hargreaves, T. and Hauxwell-Baldwin, R. (2014) 'Smart homes and their users: a systematic analysis and key challenges', *Personal and Ubiquitous Computing*, 19(2), pp. 463–476. doi: 10.1007/s00779-014-0813-0.

De Winter, J. C. F. and Dodou, D. (2014) 'Why the Fitts list has persisted throughout the history of function allocation', *Cognition, Technology & Work*, 16(1), pp. 1–11. doi: 10.1007/s10111-011-0188-1.

Woodruff, A., Augustin, S. and Foucault, B. (2007) 'Sabbath day home automation: "it's like mixing technology and religion"', *Conference on Human Factors in Computing Systems - Proceedings*, pp. 527–536. doi: 10.1145/1240624.1240710.

Woodruff, A., Hasbrouck, J. and Augustin, S. (2008) 'A bright green perspective on sustainable choices', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*, pp. 313–322. doi: 10.1145/1357054.1357109.

Xu, C. *et al.* (2018) 'Thermal comfort and thermal adaptive behaviours in traditional dwellings: A case study in Nanjing, China', *Building and Environment*. Elsevier, 142(June), pp. 153–170. doi: 10.1016/j.buildenv.2018.06.006.

Yang, R. and Newman, M. W. (2012) 'Living with an intelligent thermostat: Advanced control for heating and cooling systems', in *Proceedings of the 2012 ACM Conference on Ubiquitous Computing - UbiComp '12*. New York, New York, USA: ACM Press, p. 1102. doi: 10.1145/2370216.2370449.

Yang, R. and Newman, M. W. (2013) 'Learning from a learning thermostat: Lessons for intelligent systems for the home', in *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing - UbiComp '13*. New York, New York, USA: ACM Press, p. 93. doi: 10.1145/2493432.2493489.

Zalejska-Jonsson, A. and Wilhelmsson, M. (2013) 'Impact of perceived indoor environment quality on overall satisfaction in Swedish dwellings', *Building and Environment*. Elsevier Ltd, 63, pp. 134–144. doi: 10.1016/j.buildenv.2013.02.005.

Zimmerman, J., Forlizzi, J. and Evenson, S. (2007) 'Research Through Design as a Method for Interaction Design Research in HCI', in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '07*. New York, New York, USA: ACM Press, pp. 493–502. doi: 10.1145/1240624.1240704.

Zimmerman, J., Stolterman, E. and Forlizzi, J. (2010) 'An analysis and critique of Research through Design: towards a formalization of a research approach.', in *Proceedings of the 8th ACM Conference on Designing Interactive Systems (DIS '10)*, pp. 310–319. doi: 10.1145/1858171.1858228.

Appendix A: Example Consent Form and Information Sheet

Consent Form for Participants

I give consent to participate in the study: ***'Investigating Technology-Mediated Sustainable Building Space Use'***, being carried out at Newcastle University.

Please **INITIAL** each box

- I have read and understood the information sheet about taking part. ☐
- A team member has answered any questions that I had / I have no further questions. ☐
- I understand that this workshop is being audio recorded. ☐
- I understand that photgraphs may be taken. If an unwanted photo is taken of me I can inform the study facilitator and it will be destroyed. ☐
- I understand that the data collected for this study will be stored in a secure location in the School of Computing at Newcastle University. ☐
- I understand that the data collected about me will be used only for research purposes. ☐
- I understand that I will not be mentioned by name on any documents or in any presentations about the research. ☐
- I understand that I can withdraw from the study at any time without needing to give a reason. ☐
- Withdrawing from the study will not affect any services that I am currently receiving now or might receive in the future. ☐

Signature of participant..

Name (in capitals) ....Date..........................

Signature of team member..

Name (in capitals) ....Date..........................

Samantha Finnigan

Open Lab, Newcastle University
Email: s.j.finnigan@ncl.ac.uk
Telephone: (0191) 208 4633

Participant Information Sheet

Thank you for your interest in taking part in this study, which examines the provision and use of student workspaces within the Urban Sciences Building at Newcastle University. This sheet provides information about the study and what participation involves. Please read it carefully. If you have any further queries, please contact:

Samantha Finnigan
Open Lab (School of Computing)
Urban Sciences Building, Science Central
Newcastle University
Email: s.j.finnigan@ncl.ac.uk, Tel: (0191) 208 4632

Project Title: Investigating Sensor-mediated Sustainable Building Space Use

This project aims to explore how student study spaces are used in a "smart" university building, developing ideas for how data might be collected and used as part of sensor-driven services positioned to building occupants and managerial staff (for evaluation of the building's design and the development of future space usage policy). This session will be a short interview, with questions around the building and its study spaces, and how the usage of these spaces might evolve in future. It will take about 20-30 minutes.

Participation in this study is **entirely voluntary**: feel free to ask for clarification or information throughout. You may also withdraw at any point prior to, during, and up to two weeks after the interview. You need not give a reason. Any information collected from you will then be destroyed. Before the study commences you will be asked to sign a consent form to confirm that you have received and read this information sheet and that you are willing to take part in the research.

What will happen to the information you provide?

We will treat any information you provide carefully. In accordance with the Data Protection Act 1998, any personal information, such as your name and contact details, held in physical format (e.g., paper) will be stored in a locked filing cabinet on Newcastle University premises. Any personal information stored electronically will be on an encrypted, password protected computer. We will keep your contact details in case we need to get in touch about this research in the future. We will not pass these details to others but we may contact you about further related research; but only if you are happy for us to do so. The interview will be audio-recorded as this helps us to better understand and analyse the information you provide. Dictaphones containing recordings will be stored securely and erased as soon as the recording is transferred to a secure, password protected computer.

Raw recordings and transcripts will be treated with confidentiality and, with the exception of the transcription service, will only be accessible to the research team. Any information that is shared beyond this team will be made as anonymous as possible. This means that your name (and any others you mention) will be removed and pseudonyms used instead. Other particularly identifying features will also be changed. Anonymised information provided by you may then be used in publications, presentations and teaching. This may include quotations from what you say. Fully anonymised transcripts and questionnaire responses will be kept indefinitely to inform future research projects.

What are the possible risks and benefits of taking part?

There is a small risk that those who know you personally very well may be able to *guess* your identity from anonymised accounts, especially if they see you taking part in the research. If so, the impact on you is likely to be negligible as the research does not aim to explore any particularly sensitive topics. If you feel that any aspects of the interview are uncomfortable, you need not provide an answer. You can also withdraw at any point. Although we hope the experience of taking part will be interesting and enjoyable, there may be no immediate benefits from participation. Please note that the interview is part of a wider research project on this topic and you may be invited to participate in other aspects. If so, any further participation will be entirely your choice, and you will be given further information and time to help you make that decision.

Who is conducting this research?

This research forms part of a PhD research project project being carried out at Newcastle University. It is funded by a grant from NIReS (Newcastle University Institute for Sustainability).

Appendix B: Ethical Approval

University Ethics Form Version 2.1

Date submitted
06/03/2016 16:05:05

Applicant Details

Is this approval for a:
Student Project [A2]

What type of degree programme is being studied?
Postgraduate Research (e.g. PhD) [A3]

Name of Principal Researcher:
Sam Mitchell Finnigan

Please enter your email address
s.j.finnigan@ncl.ac.uk

Please select your school / academic unit
School of Computing Science [A6]

Please enter the module code

Please enter your supervisors email:
robert.comber@newcastle.ac.uk

Please select your supervisor's school/unit:
School of Computing Science [A6]

Project Details

Project Title
Understanding social and technical factors in the deployment of pervasive sensing for evidence-based management, services and policy

Project Synopsis
This project aims to understand the social and technical factors in the deployment of environmental pervasive sensing technologies to support evidence-based management, services and sustainable policy in non-domestic buildings. Bringing together a number of case-studies of such systems as deployed in collaboration with facilities managers, office workers, and students, this project aims to provide recommendations for the design of tools for understanding conditions within the local built environment, utilising that understanding in building digital tools to provide new perspectives on environmental complaints (e.g. thermal comfort), and creating evidence-backed policy recommendations towards the sustainable management of buildings and offices. Methods including interviews and focus groups will be used to collect data for three case studies, examining: the use of shared, open plan offices and how personal thermal comfort might be managed through the introduction of sensor platforms and novel displays; how sensor toolkits could be retrofit in organisations and become a part of existing facilities management practice, alongside existing tools such as BMS; and how amateur/novice auditors might leverage sensor kits to evidence their built environment, and how this evidence might influence sustainable policy in an organisation.

Project start date
07/03/2016

Project end date
02/10/2017

Is the project externally funded?
No [A3]

Does your project involve collaborators outside of the University?
No [N]

Existing Ethics, Sponsorship & Responsibility

Has ethical approval to cover this proposal already been obtained?
No [N]

Will anyone be acting as sponsor under the NHS Research Governance Framework for Health and Social Care?
No [N]

Do you have a Newcastle upon Tyne Hospitals (NUTH) reference?
No [N]

Will someone other than you (the principal investigator) or your supervisor (for student projects) be responsible for the conduct, management and design of the research?
No [N]

The Animals (Scientific Procedures) Act defines protected animals as: 'any living vertebrate other than man…in its foetal, larval or embryonic form……from the stage of its development when— (a)in the case of a mammal, bird or reptile, half the gestation or incubation period for the relevant species has elapsed; and (b)in any other case, it becomes capable of independent feeding'. In practice 'Protected' animals are all living vertebrates (other than man), including some immature forms, and cephalopods (e.g. octopus, squid, cuttlefish). Using this definition, does your research involve the observation, capture or manipulation of animals or their tissues?
No [N]

Will the study involve participants recruited by virtue of being NHS patients or service users, their dependents, their carers or human tissues or the use of NHS & Health/Social Care Facilities or otherwise require REC approval?
No [N]

Does the research involve human participants e.g. use of questionnaires, focus groups, observation, surveys or lab-based studies involving human participants?
Yes [Y]

Does the study involve any of the following? [a. The study involves children or other vulnerable groups; as defined in Section 59 of the Safeguarding Vulnerable Adults Act 2006 as those who are relatively or absolutely incapable of protecting their own interests, or those in unequal relationships e.g. participants who are subordinate to the researcher(s) in a context outside the research?]

Does the study involve any of the following? [b. The study requires the co-operation of a gatekeeper (defined as someone who can exert undue influence) for initial access to the groups or individuals to be recruited e.g. students at school, members of a self-help group, or residents of a nursing home? NB. The IoN & School of Psychology volunteer pools are not considered gatekeepers in this case.]

Does the study involve any of the following? [c. It is necessary for participants to take part in the study without their knowledge and consent e.g. covert observation of people in non-public places?.]

Does the study involve any of the following? [d. Deliberately misleading participants in any way?]

Does the study involve any of the following? [e. Discussion of sensitive topics e.g. sexual activity or drug use?]

Does the study involve any of the following? [f. The administration of drugs, placebos or other substances (e.g. food substances, vitamins) to the study participants.]

Does the study involve any of the following? [g. Invasive, intrusive or potentially harmful procedures of any kind?*]

Does the study involve any of the following? [h. Obtaining blood or tissue samples?*]

Does the study involve any of the following? [i. Pain or more than mild discomfort?]

Does the study involve any of the following? [j. Psychological stress, anxiety, harm or negative consequences beyond that encountered in normal life?]

Does the study involve any of the following? [k. Prolonged or repetitive testing i.e. more than 4 hours commitment or attendance on more than two occasions?]

Does the study involve any of the following? [l. Financial inducements (other than reasonable expenses and compensation for time)?]

Does the research involve the viewing, usage or transfer of Sensitive Personal Data as defined by the Data Protection Act 1998 or data governed by statute such as the Official Secrets Act 1989 / Terrorism Act 2006, commercial contract or by convention e.g. client confidentiality? (If you are unsure please tick YES and complete the sub-questions).
No [N]

Will the study cause direct or indirect damage to the environment or emissions outside permissible levels or be conducted in an Area of Special Scientific Interest or which is of cultural significance?
No [N]

Will the research be conducted outside of the European Economic Area (EEA) or will it involve international collaborators outside the EEA?
No [N]

Next Steps

Based on your answers your project has triggered none of the high risk flags. Therefore the University requires no further ethical review before your project progresses. Should your project change you may need to apply for new ethical approval.

Supporting Documentation

Please upload any documents (not uploaded elsewhere in the application) which you think are relevant to the consideration of your application.

filecount - Please upload any documents (not uploaded elsewhere in the application) which you think are relevant to the consideration of your application.
0

Thank you for completing the University's Ethical Review Form. Based on your answers the University is satisfied that your project has met its ethical expectations and that no further review is required before you begin your research. Please be aware that if you make any significant changes to your project then you should complete this form again as further review may be required. Confirmation of this decision will be emailed to you. Please complete the declaration to submit your application. Declaration I certify that: [the information contained within this application is accurate.]
Yes [Y]

Thank you for completing the University's Ethical Review Form. Based on your answers the University is satisfied that your project has met its ethical expectations and that no further review is required before you begin your research. Please be aware that if you make any significant changes to your project then you should complete this form again as further review may be required. Confirmation of this decision will be emailed to you. Please complete the declaration to submit your application. Declaration I certify that: [the research will be undertaken in line with all appropriate, University, legal and local standards and regulations.]
Yes [Y]

Thank you for completing the University's Ethical Review Form. Based on your answers the University is satisfied that your project has met its ethical expectations and that no further review is required before you begin your research. Please be aware that if you make any significant changes to your project then you should complete this form again as further review may be required. Confirmation of this decision will be emailed to you. Please complete the declaration to submit your application. Declaration I certify that: [I have attempted to identify the risks that may arise in conducting this research and acknowledge my obligation to (and rights of) any participants.]
Yes [Y]

Thank you for completing the University's Ethical Review Form. Based on your answers the University is satisfied that your project has met its ethical expectations and that no further review is required before you begin your research. Please be aware that if you make any significant changes to your project then you should complete this form again as further review may be required. Confirmation of this decision will be emailed to you. Please complete the declaration to submit your application. Declaration I certify that: [no work will begin until all appropriate permissions are in place.]
Yes [Y]

University Ethics Form Version 2.1.1 (445487)

Date submitted
24/10/2017 15:23:57

Applicant Details

Is this approval for a:
Student Project [A2]
What type of degree programme is being studied?
Postgraduate Research (e.g. PhD) [A3]
Name of Principal Researcher:
Samantha Mitchell Finnigan
Please enter your email address
s.j.finnigan@ncl.ac.uk
Please select your school / academic unit
School of Computing [A1]
Please enter the module code
Please enter your supervisor's email:
patrick.olivier@ncl.ac.uk
Please select your supervisor's school/unit:
School of Computing [A1]

Project Details

Project Title
Investigating Sensor-mediated Sustainable Building Space Use
Project Synopsis
Modern office buildings often include designed-in data collection capability via their Building Management Systems. This project aims to explore how student study spaces are used in a non- domestic “smart” office building, developing design sensitivities for how this data might be used as part of sensor-driven services positioned to building occupants, and to managers for evaluation of the building’s sustainable architectural design and the development and auditing of future space usage policy. The Urban Sciences Building at Newcastle University is the newly developed home of a number of University departments, billed as a “living laboratory” for sustainability research. Open-plan spaces for student study are available for use during gaps in the teaching schedule. These spaces are interesting to look at as they are highly reconfigurable, lending themselves to intervention in response to quantitative and qualitative data. The empirical basis for this project will be in interviews with building managers and the student population, generating an understanding of which aspects of building use should be addressed by a sensor-driven service. Following this study will be the design and deployment of a technology probe: an intervention considering the relationship between space and the building, integrating feedback from students and staff we interviewed.
Project start date
24/10/2017
Project end date
31/03/2018
Is the project externally funded?
No [A3]

Does your project involve collaborators outside of the University?

No [N]

Existing Ethics, Sponsorship & Responsibility

Has ethical approval to cover this proposal already been obtained?

No [N]

Will anyone be acting as sponsor under the NHS Research Governance Framework for Health and Social Care?

No [N]

Do you have a Newcastle upon Tyne Hospitals (NUTH) reference?

No [N]

Will someone other than you (the principal investigator) or your supervisor (for student projects) be responsible for the conduct, management and design of the research?

No [N]

Animals (I)

The Animals (Scientific Procedures) Act defines protected animals as: 'any living vertebrate other than man…in its foetal, larval or embryonic form……from the stage of its development when— (a)in the case of a mammal, bird or reptile, half the gestation or incubation period for the relevant species has elapsed; and (b)in any other case, it becomes capable of independent feeding'.

In practice 'Protected' animals are all living vertebrates (other than man), including some immature forms, and cephalopods (e.g. octopus, squid, cuttlefish).

Using this definition, does your research involve the observation, capture or manipulation of animals or their tissues?

No [N]

NHS, Health & Social Care: Facilities, Staff & Patients (I)

Will the study involve participants recruited by virtue of being NHS patients or service users, their dependents, their carers or human tissues or the use of NHS & Health/Social Care Facilities or otherwise require REC approval?

No [N]

Human Participants in a Non-Clinical Setting (I)

Does the research involve human participants e.g. use of questionnaires, focus groups, observation, surveys or lab-based studies involving human participants?

Yes [Y]

Does the study involve any of the following? [a. The study involves children or other vulnerable groups; as defined in Section 59 of the Safeguarding Vulnerable Adults Act 2006 as those who are relatively or absolutely incapable of protecting their own interests, or those in unequal relationships e.g. participants who are subordinate to the researcher(s) in a context outside the research?]

Does the study involve any of the following? [b. The study requires the co-operation of a gatekeeper (defined as someone who can exert undue influence) for initial access to the groups or individuals to be recruited e.g. students at school, members of a self-help group, or residents of a nursing home? NB. The IoN & School of Psychology volunteer pools are not considered gatekeepers in this case.]

Does the study involve any of the following? [c. It is necessary for participants to take part in the study without their knowledge and consent e.g. covert observation of people in non-public places?.]

Does the study involve any of the following? [d. Deliberately misleading participants in any way?]

Does the study involve any of the following? [e. Discussion of sensitive topics e.g. sexual activity or drug use?]

Does the study involve any of the following? [f. The administration of drugs, placebos or other substances (e.g. food substances, vitamins) to the study participants.]

Does the study involve any of the following? [g. Invasive, intrusive or potentially harmful procedures of any kind?*]

Does the study involve any of the following? [h. Obtaining blood or tissue samples?*]
Does the study involve any of the following? [i. Pain or more than mild discomfort?]
Does the study involve any of the following? [j. Psychological stress, anxiety, harm or negative consequences beyond that encountered in normal life?]
Does the study involve any of the following? [k. Prolonged or repetitive testing i.e. more than 4 hours commitment or attendance on more than two occasions?]
Does the study involve any of the following? [l. Financial inducements (other than reasonable expenses and compensation for time)?]

Data (I)

Does the research involve the viewing, usage or transfer of Sensitive Personal Data as defined by the Data Protection Act 1998 or data governed by statute such as the Official Secrets Act 1989 / Terrorism Act 2006, commercial contract or by convention e.g. client confidentiality? (If you are unsure please tick YES and complete the sub-questions).
No [N]

Environment (I)

Will the study cause direct or indirect damage to the environment or emissions outside permissible levels or be conducted in an Area of Special Scientific Interest or which is of cultural significance?
No [N]

International Projects (I)

Will the research be conducted outside of the European Economic Area (EEA) or will it involve international collaborators outside the EEA?
No [N]

Next Steps

Based on your answers your project has triggered none of the high risk flags. Therefore the University requires no further ethical review before your project progresses. Should your project change you may need to apply for new ethical approval.

Supporting Documentation

Please upload any documents (not uploaded elsewhere in the application) which you think are relevant to the consideration of your application.
filecount - Please upload any documents (not uploaded elsewhere in the application) which you think are relevant to the consideration of your application.
0
Thank you for completing the University's Ethical Review Form. Based on your answers the University is satisfied that your project has met its ethical expectations and that no further review is required before you begin your research. Please be aware that if you make any significant changes to your project then you should complete this form again as further review may be required. Confirmation of this decision will be emailed to you. Please complete the declaration to submit your application. Declaration I certify that: [the information contained within this application is accurate.]

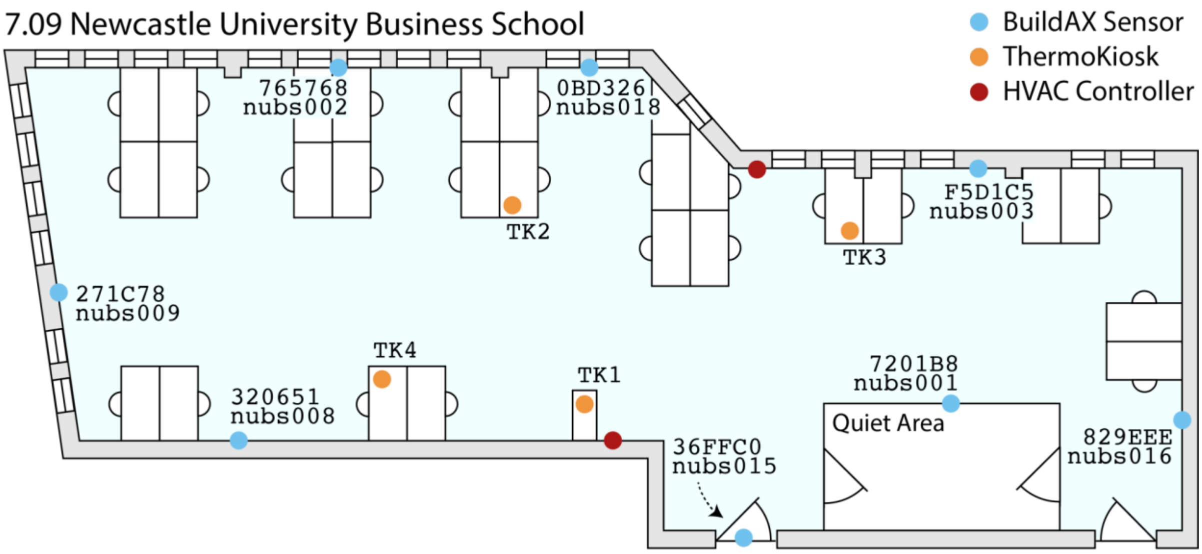
Yes [Y]
Thank you for completing the University's Ethical Review Form. Based on your answers the University is satisfied that your project has met its ethical expectations and that no further review is required before you begin your research. Please be aware that if you make any significant changes to your project then you should complete this form again as further review may be required. Confirmation of this decision will be emailed to you. Please complete the declaration to submit your application. Declaration I certify that: [the research will be undertaken in line with all appropriate, University, legal and local standards and regulations.]
Yes [Y]

Thank you for completing the University's Ethical Review Form. Based on your answers the University is satisfied that your project has met its ethical expectations and that no further review is required before you begin your research. Please be aware that if you make any significant changes to your project then you should complete this form again as further review may be required. Confirmation of this decision will be emailed to you. Please complete the declaration to submit your application. Declaration I certify that: [I have attempted to identify the risks that may arise in conducting this research and acknowledge my obligation to (and rights of) any participants.]
Yes [Y]
Thank you for completing the University's Ethical Review Form. Based on your answers the University is satisfied that your project has met its ethical expectations and that no further review is required before you begin your research. Please be aware that if you make any significant changes to your project then you should complete this form again as further review may be required. Confirmation of this decision will be emailed to you. Please complete the declaration to submit your application. Declaration I certify that: [no work will begin until all appropriate permissions are in place.]
Yes [Y]

Appendix C: Example Sensor Report

Temperature Report: Business School 709

Weeks beginning 25 Jul 2016 to 28 Aug 2016



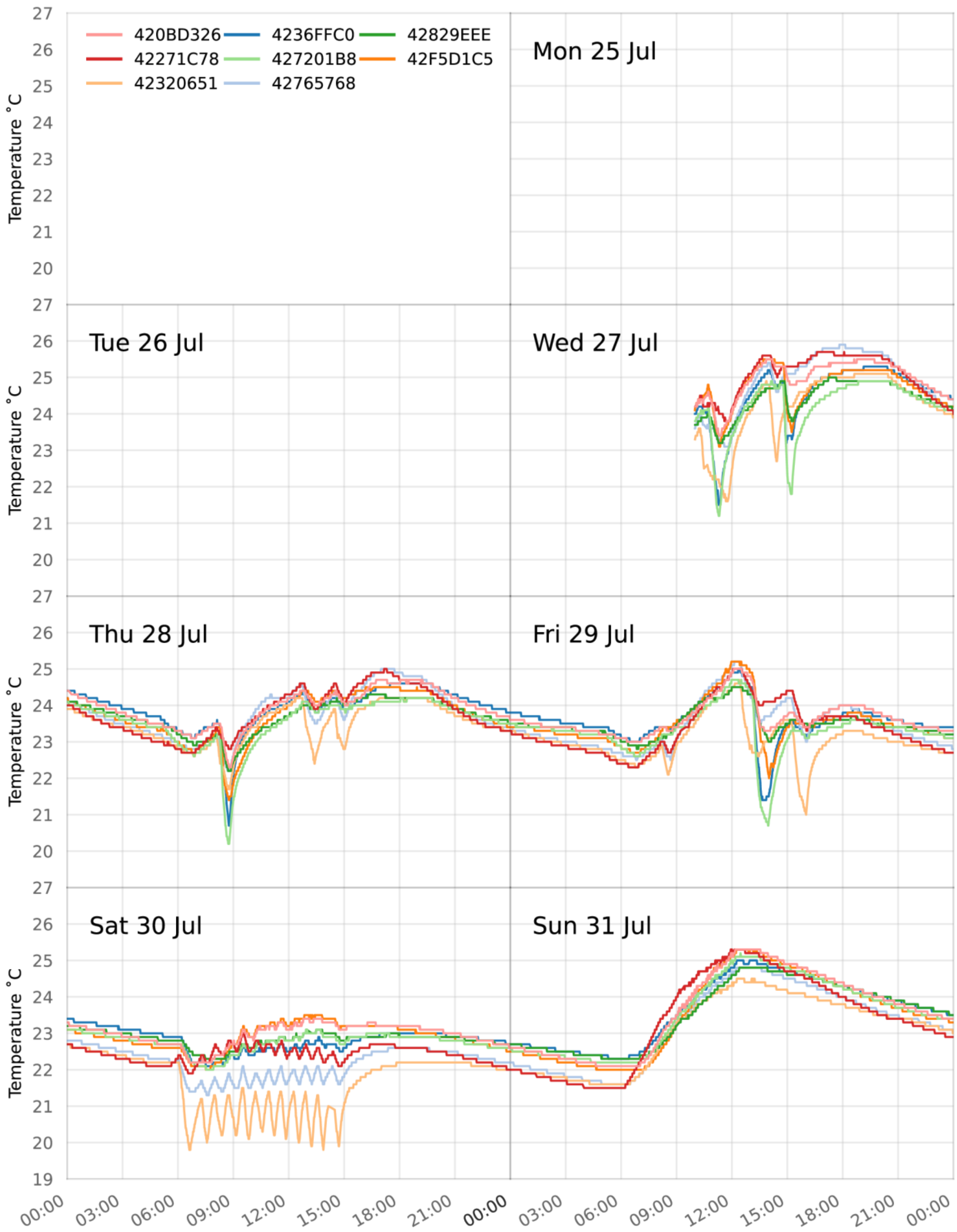
BuildAX data collected during the ThermoKiosk study in room 709 in the Business School

The following sensor IDs have been manually excluded from this report:

- 42071223
- 42B66BCB
- 42B24A84
- 42B3A870
- 42442C78
- 42A141FB
- 42F246DD
- 4284899C
- 42F5B60A
- 4242759B
- 4265A8DB

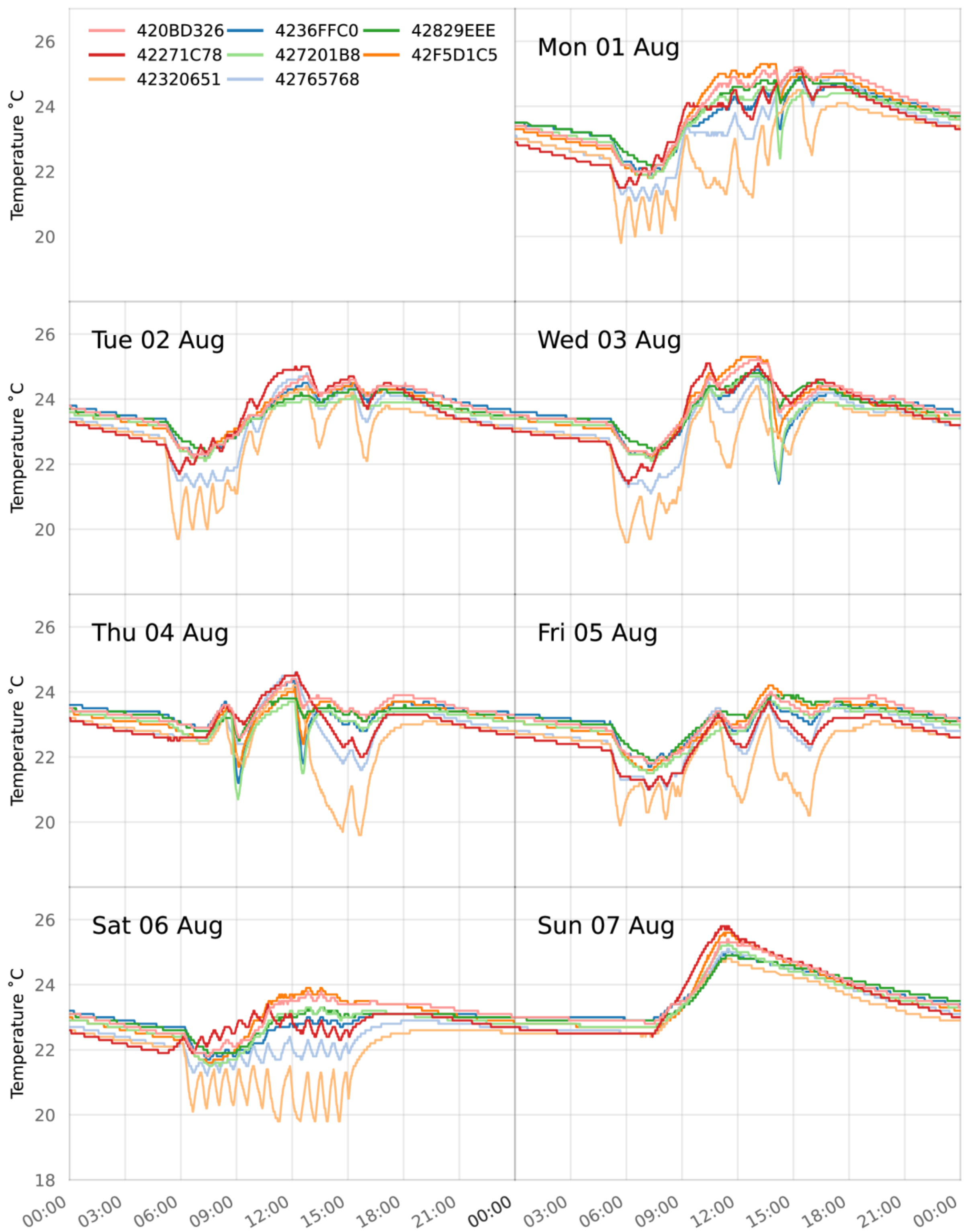
Temperature °C @ Business School 709

Time period: *2016-07-25 to 2016-07-31*



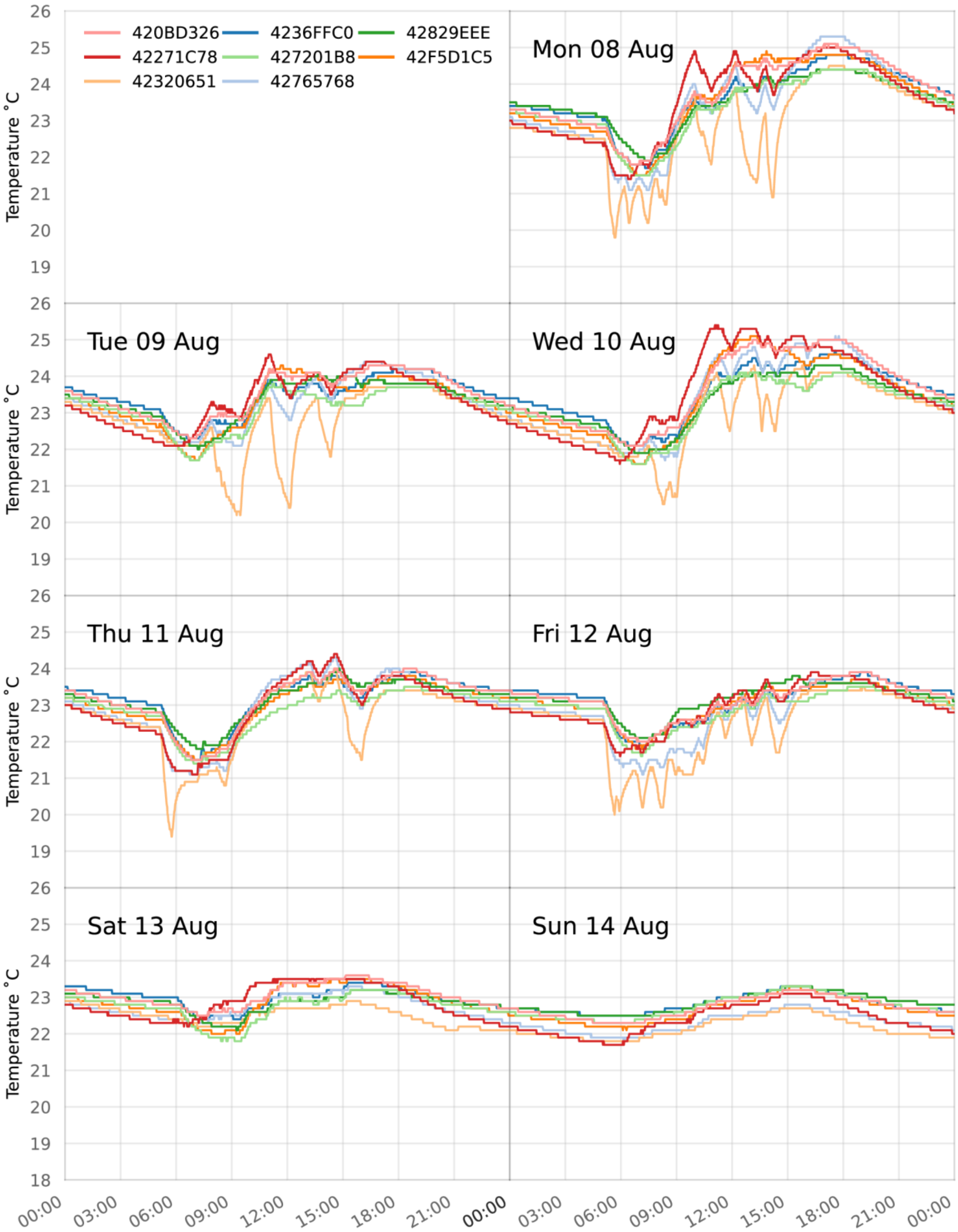
Temperature °C @ Business School 709

Time period: *2016-08-01 to 2016-08-07*



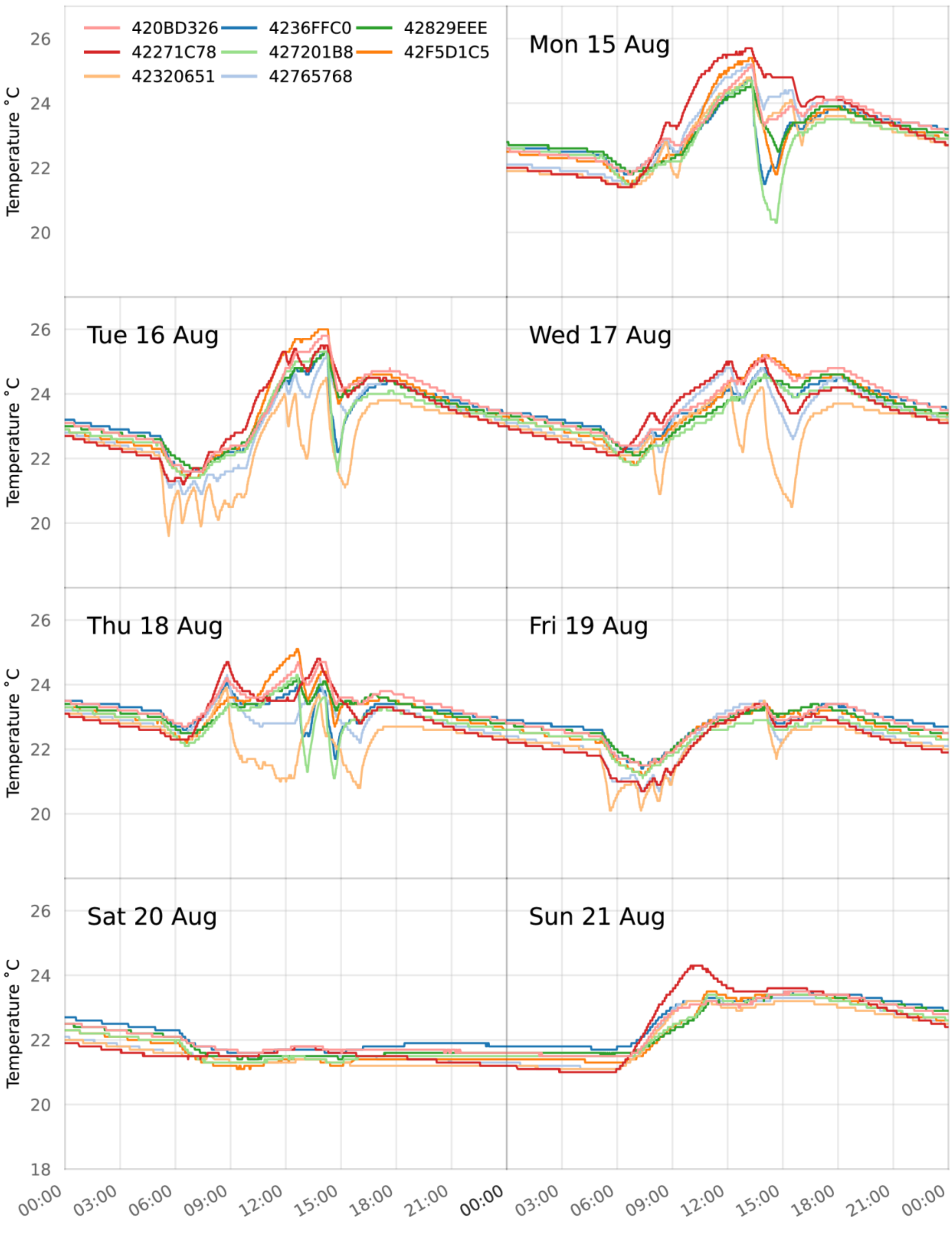
Temperature °C @ Business School 709

Time period: *2016-08-08 to 2016-08-14*



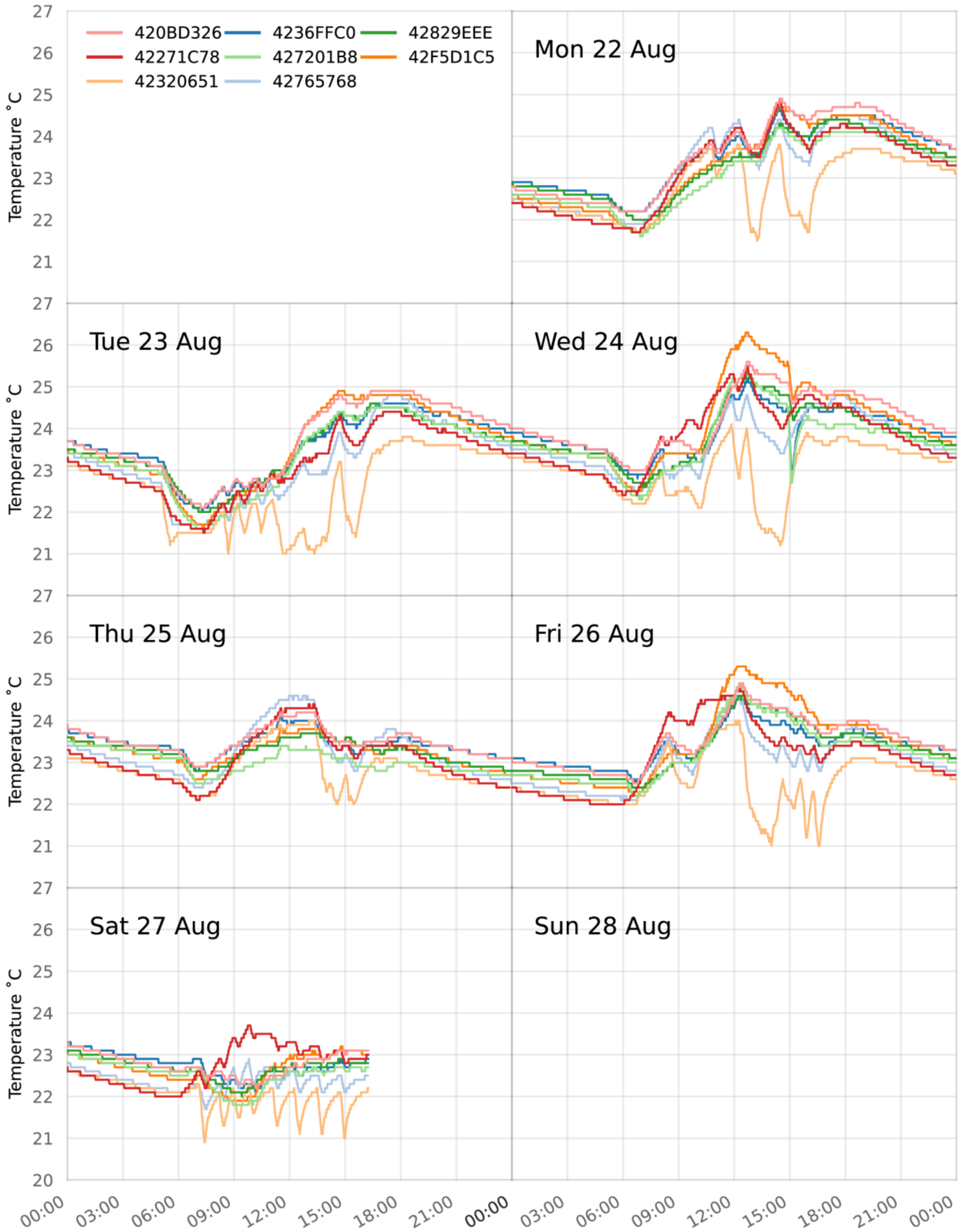
Temperature °C @ Business School 709

Time period: *2016-08-15 to 2016-08-21*



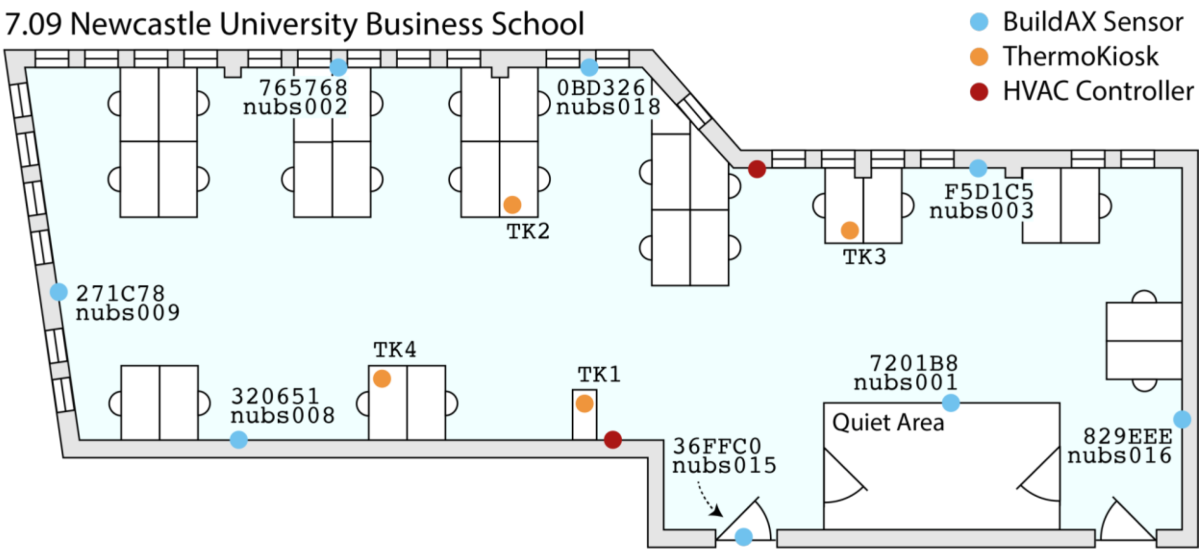
Temperature °C @ Business School 709

Time period: *2016-08-22 to 2016-08-28*



Humidity Report: Business School 709

Weeks beginning 25 Jul 2016 to 28 Aug 2016



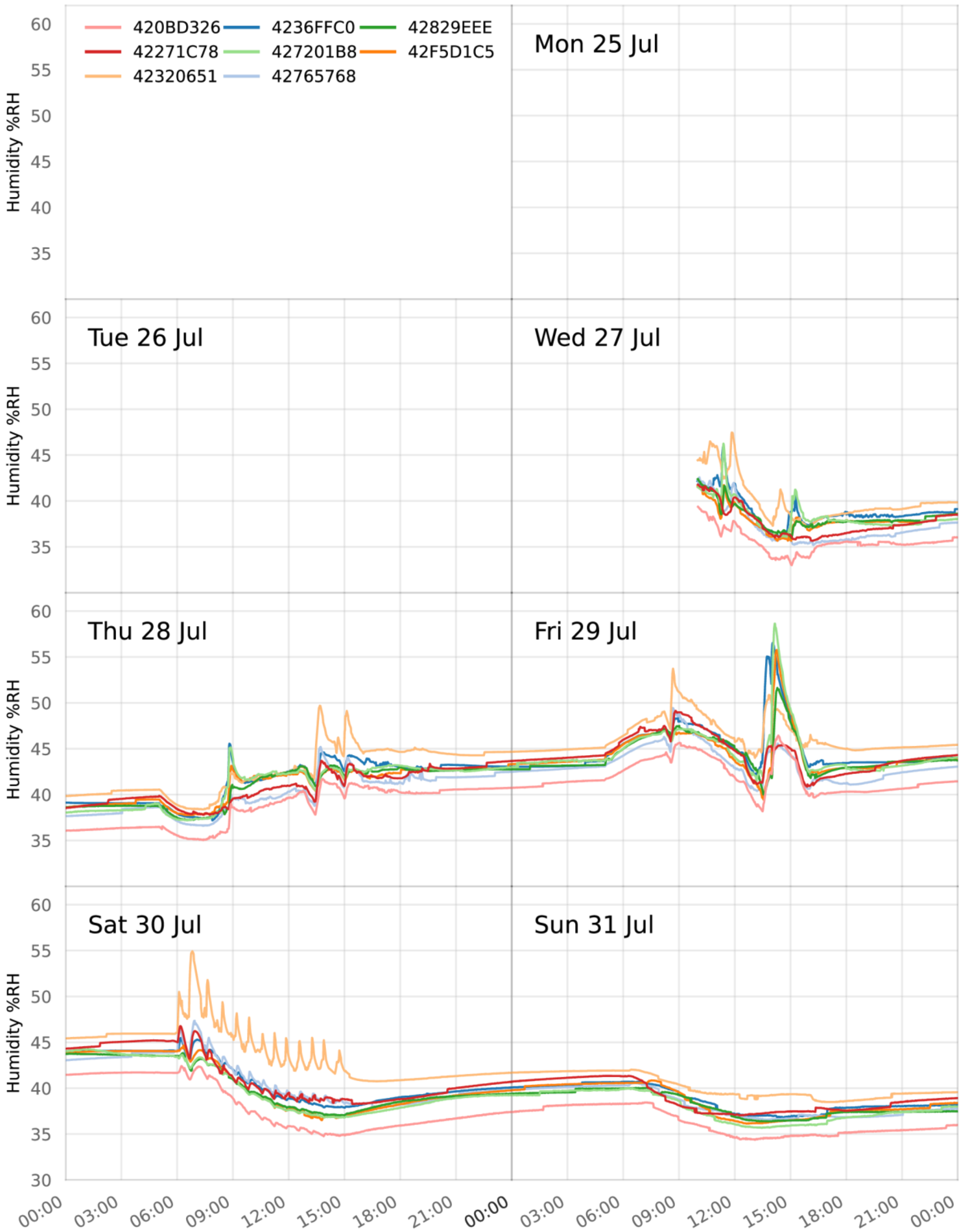
BuildAX data collected during the ThermoKiosk study in room 709 in the Business School

The following sensor IDs have been manually excluded from this report:

- 42071223
- 42B66BCB
- 42B24A84
- 42B3A870
- 42442C78
- 42A141FB
- 42F246DD
- 4284899C
- 42F5B60A
- 4242759B
- 4265A8DB

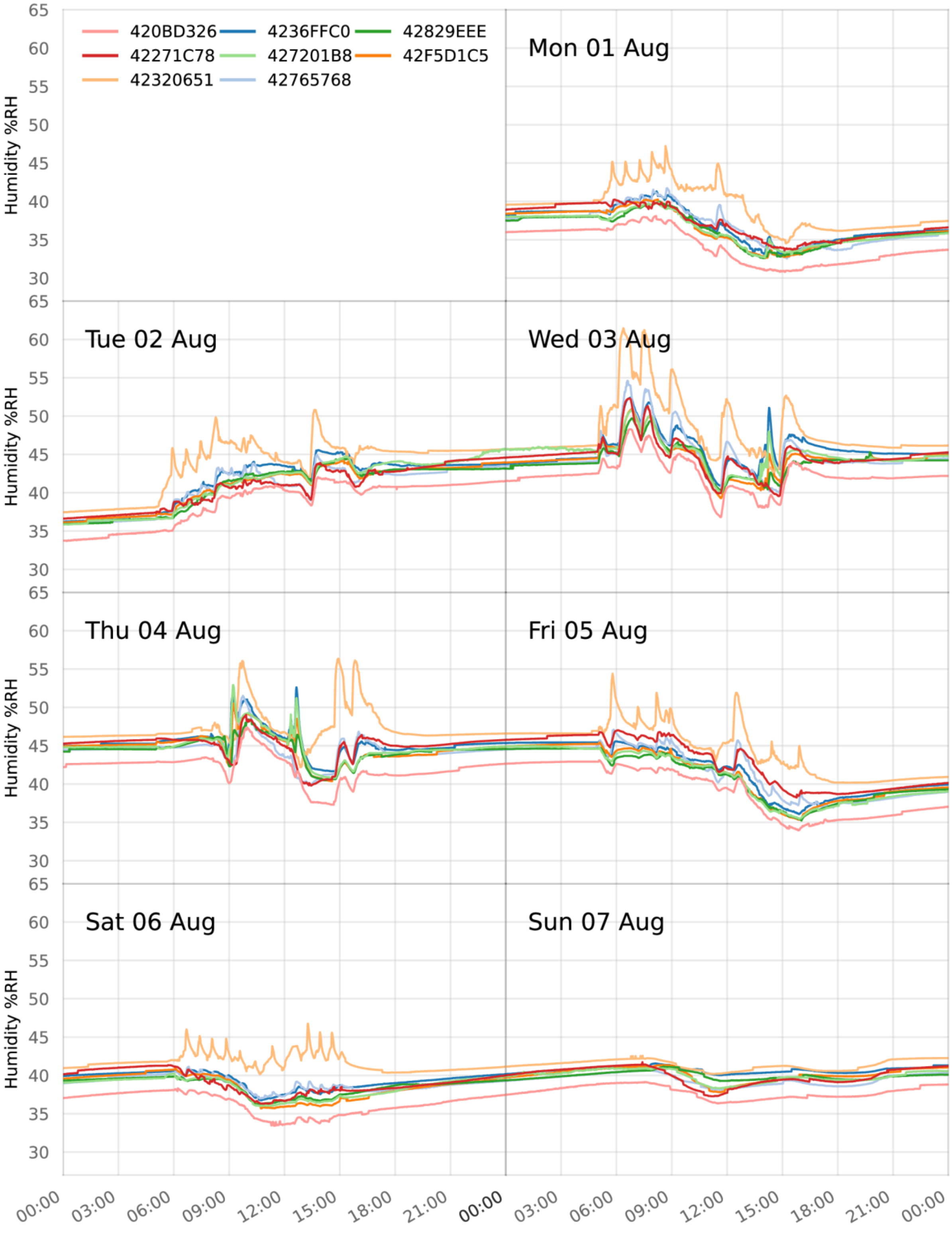
Humidity %RH @ Business School 709

Time period: *2016-07-25 to 2016-07-31*



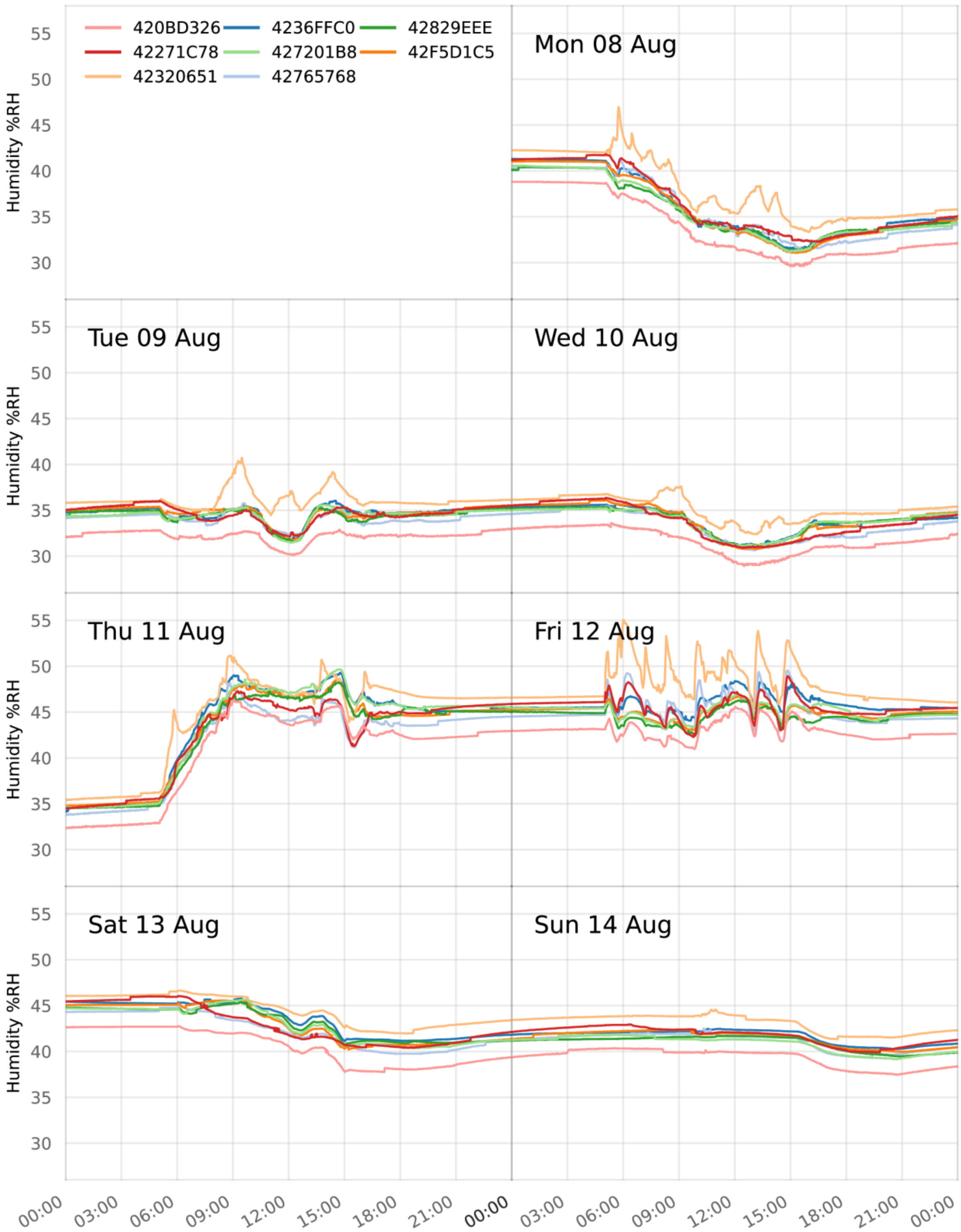
Humidity %RH @ Business School 709

Time period: *2016-08-01 to 2016-08-07*



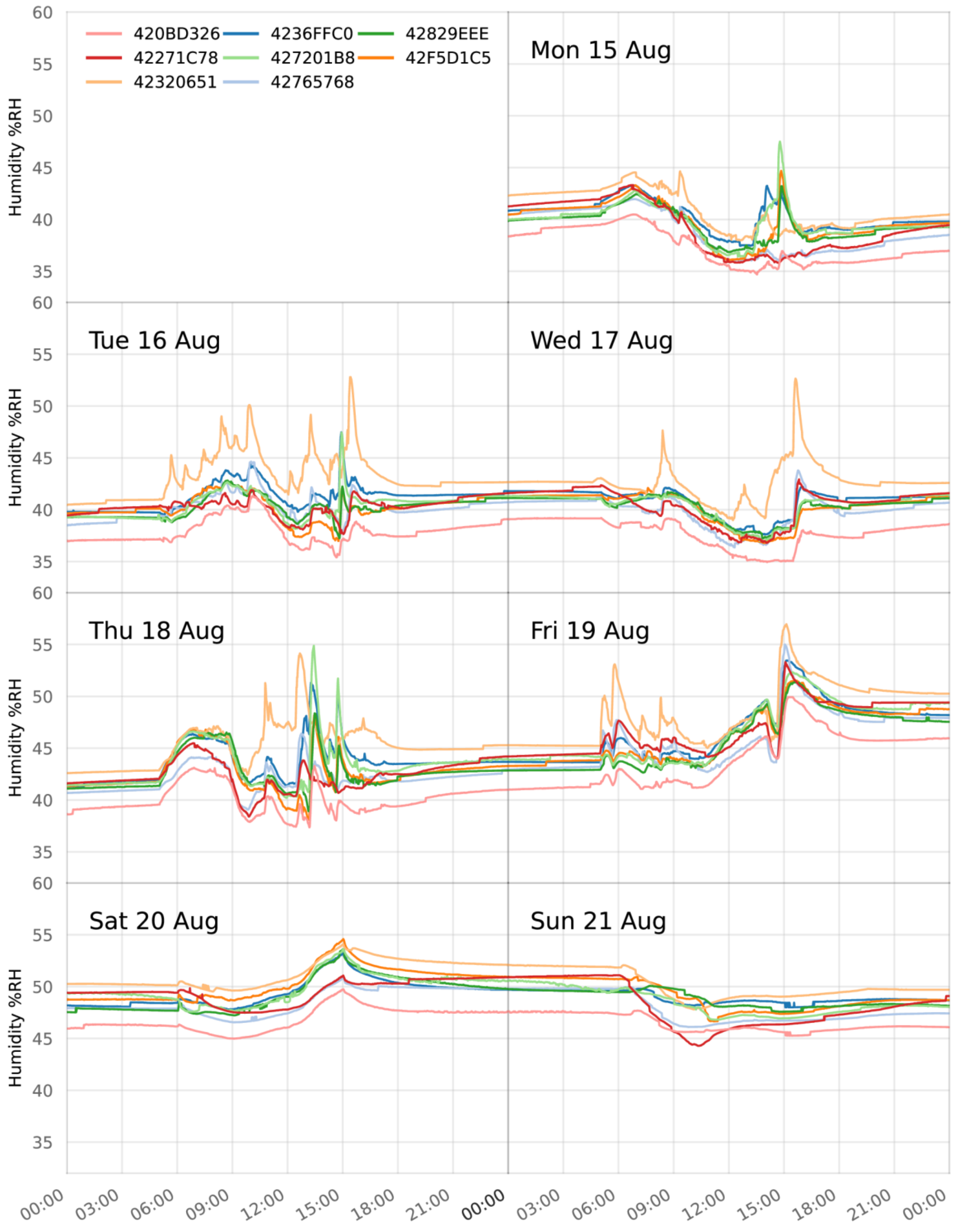
Humidity %RH @ Business School 709

Time period: *2016-08-08 to 2016-08-14*



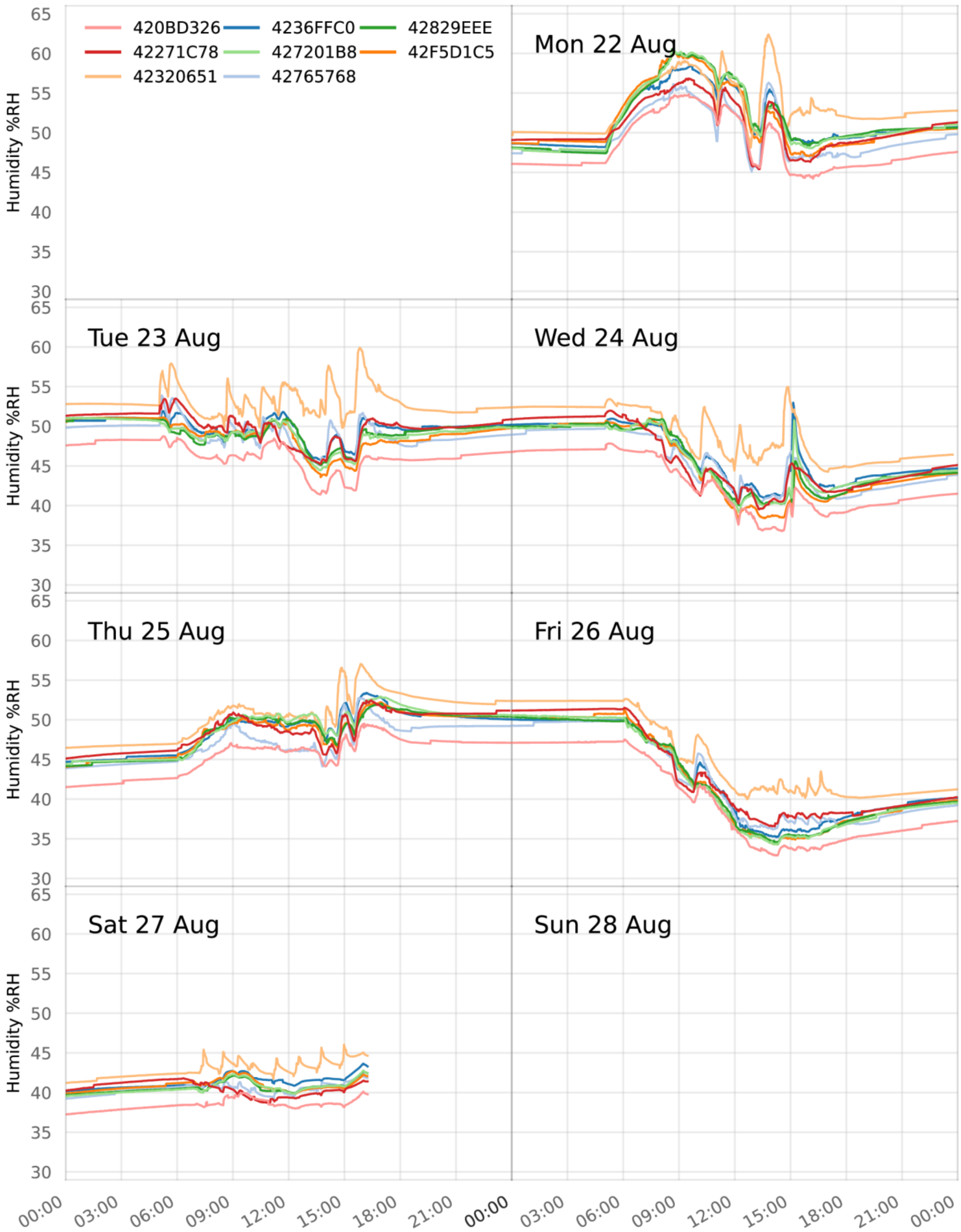
Humidity %RH @ Business School 709

Time period: *2016-08-15 to 2016-08-21*



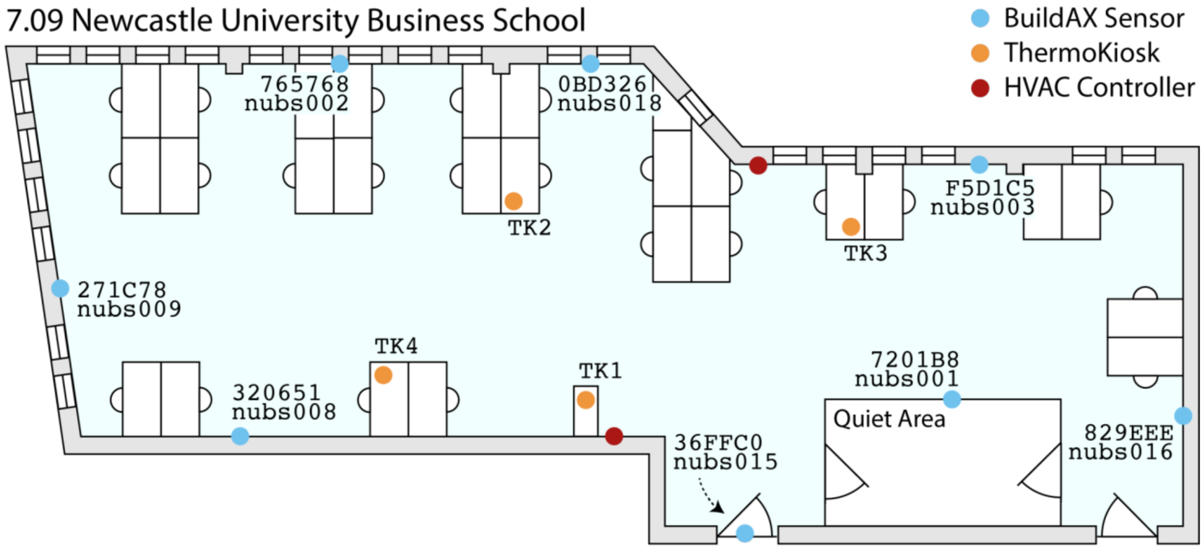
Humidity %RH @ Business School 709

Time period: *2016-08-22 to 2016-08-28*



Light Report: Business School 709

Weeks beginning 25 Jul 2016 to 28 Aug 2016



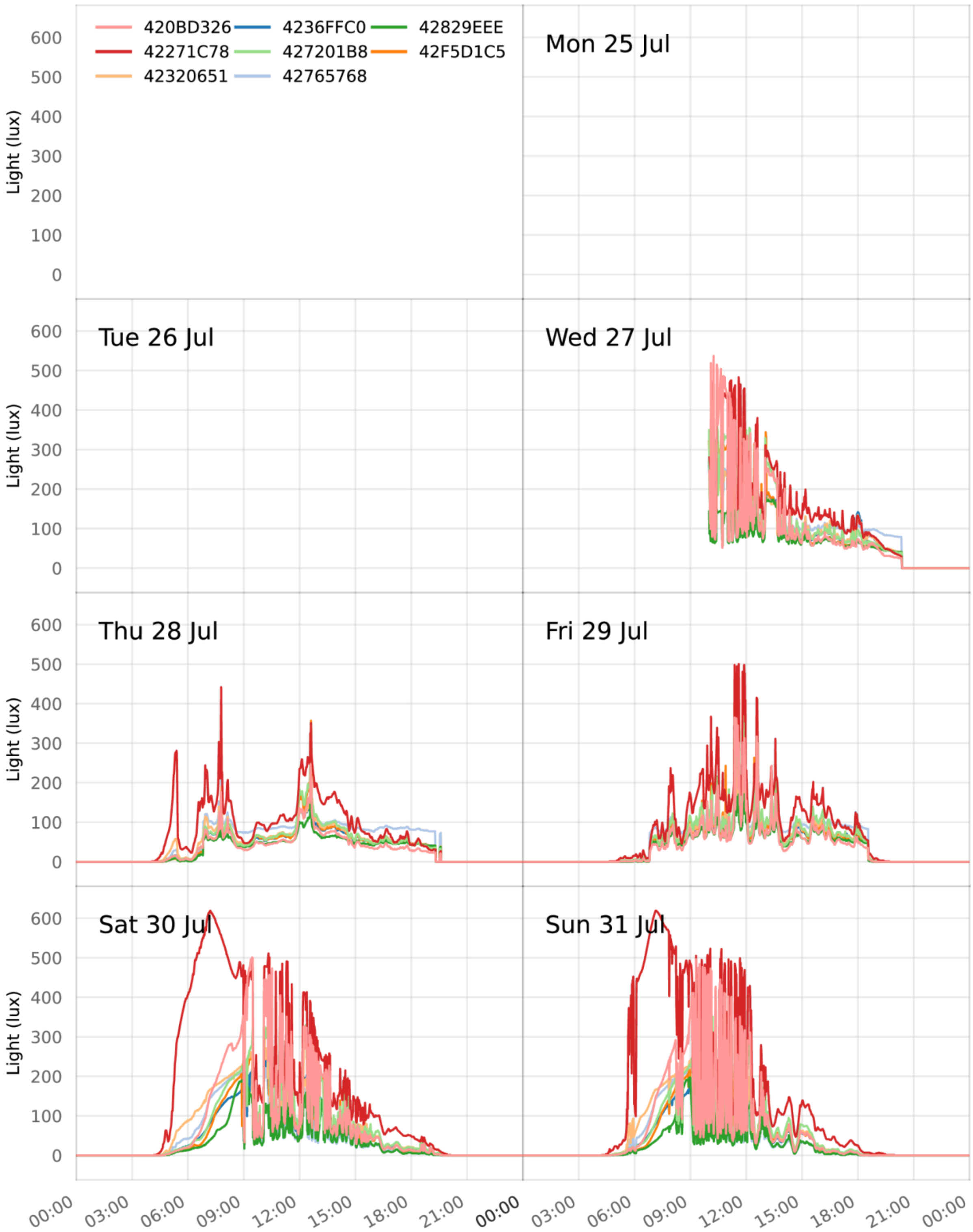
BuildAX data collected during the ThermoKiosk study in room 709 in the Business School

The following sensor IDs have been manually excluded from this report:

- 42071223
- 42B66BCB
- 42B24A84
- 42B3A870
- 42442C78
- 42A141FB
- 42F246DD
- 4284899C
- 42F5B60A
- 4242759B
- 4265A8DB

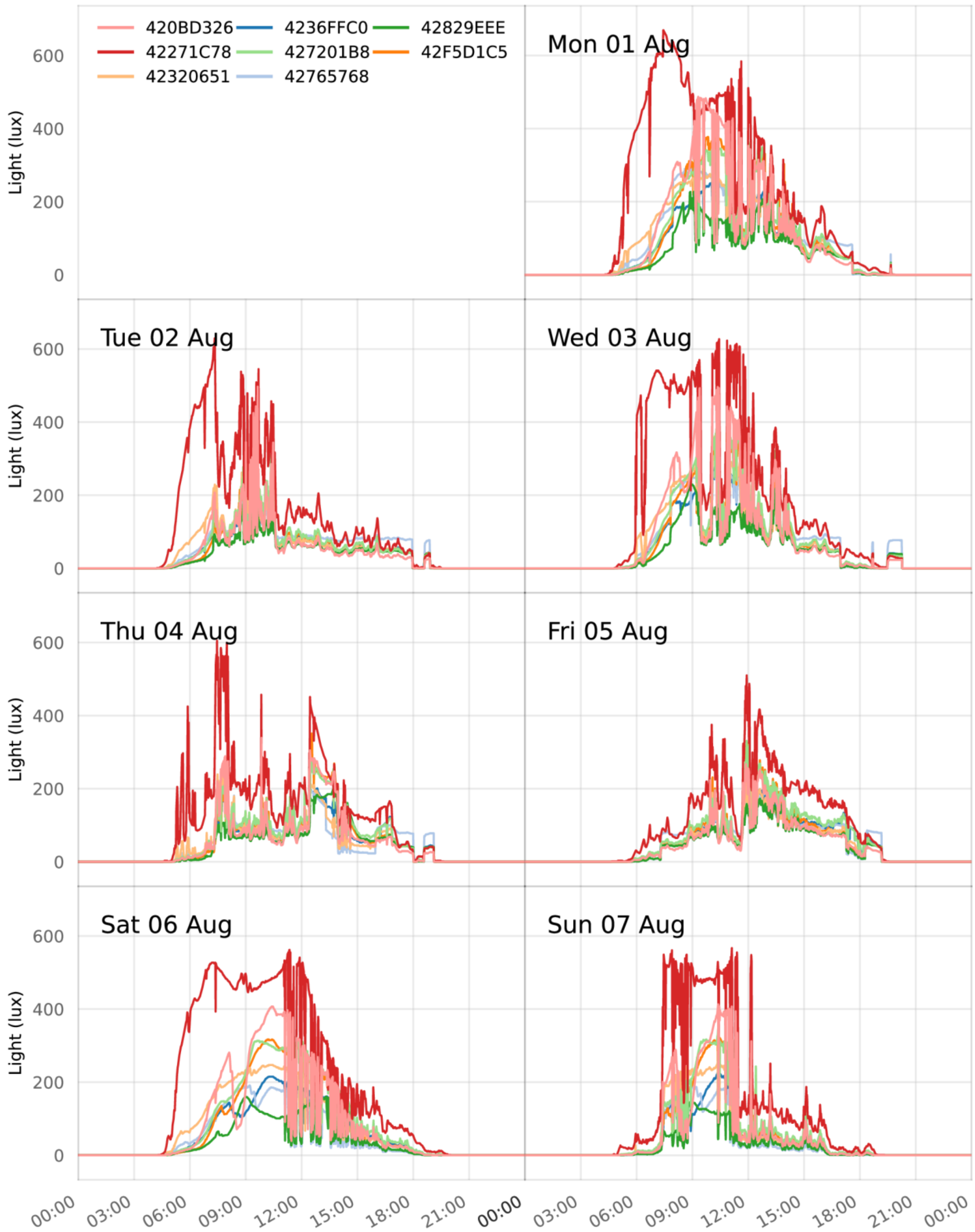
Light (lux) @ Business School 709

Time period: *2016-07-25 to 2016-07-31*



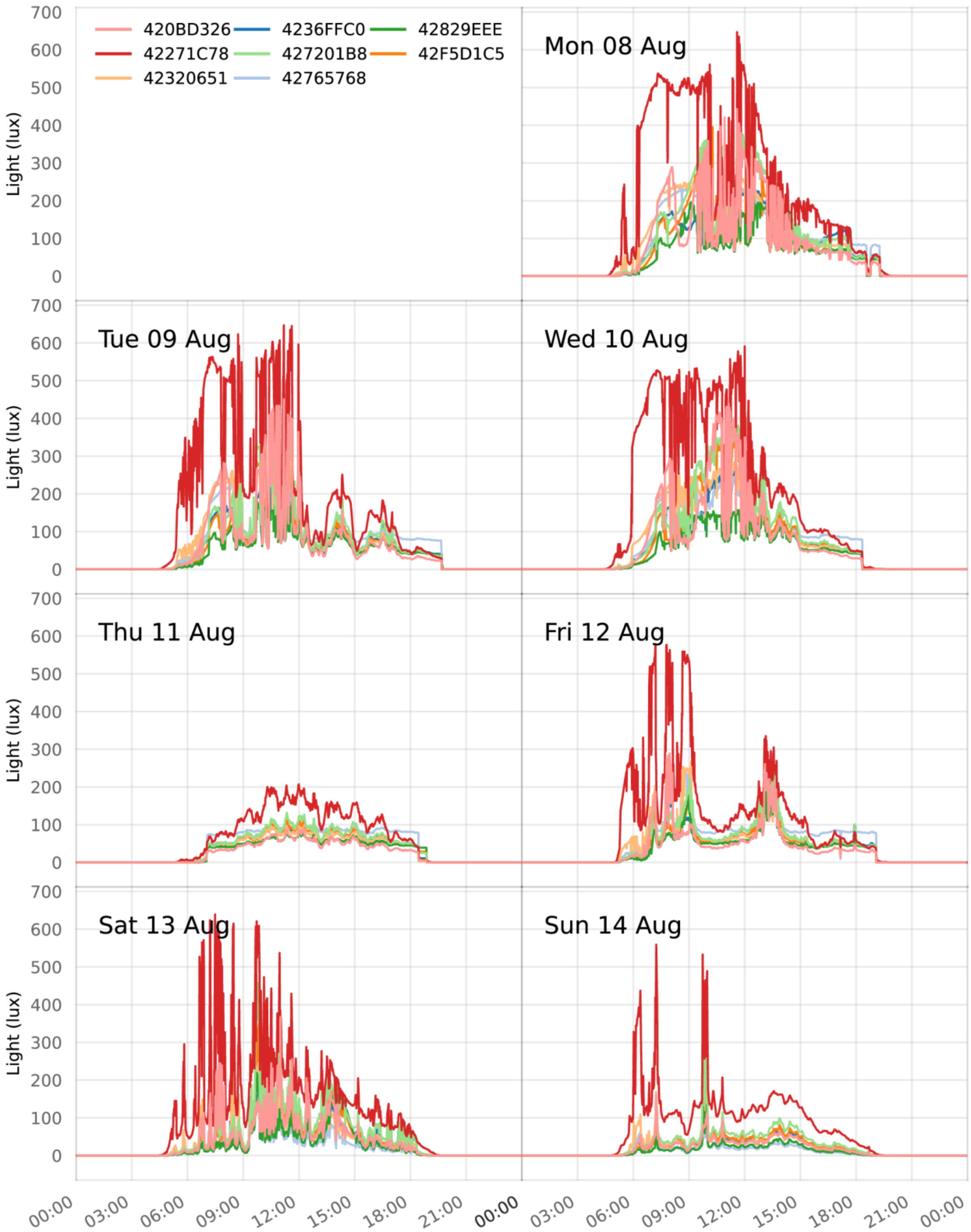
Light (lux) @ Business School 709

Time period: *2016-08-01 to 2016-08-07*



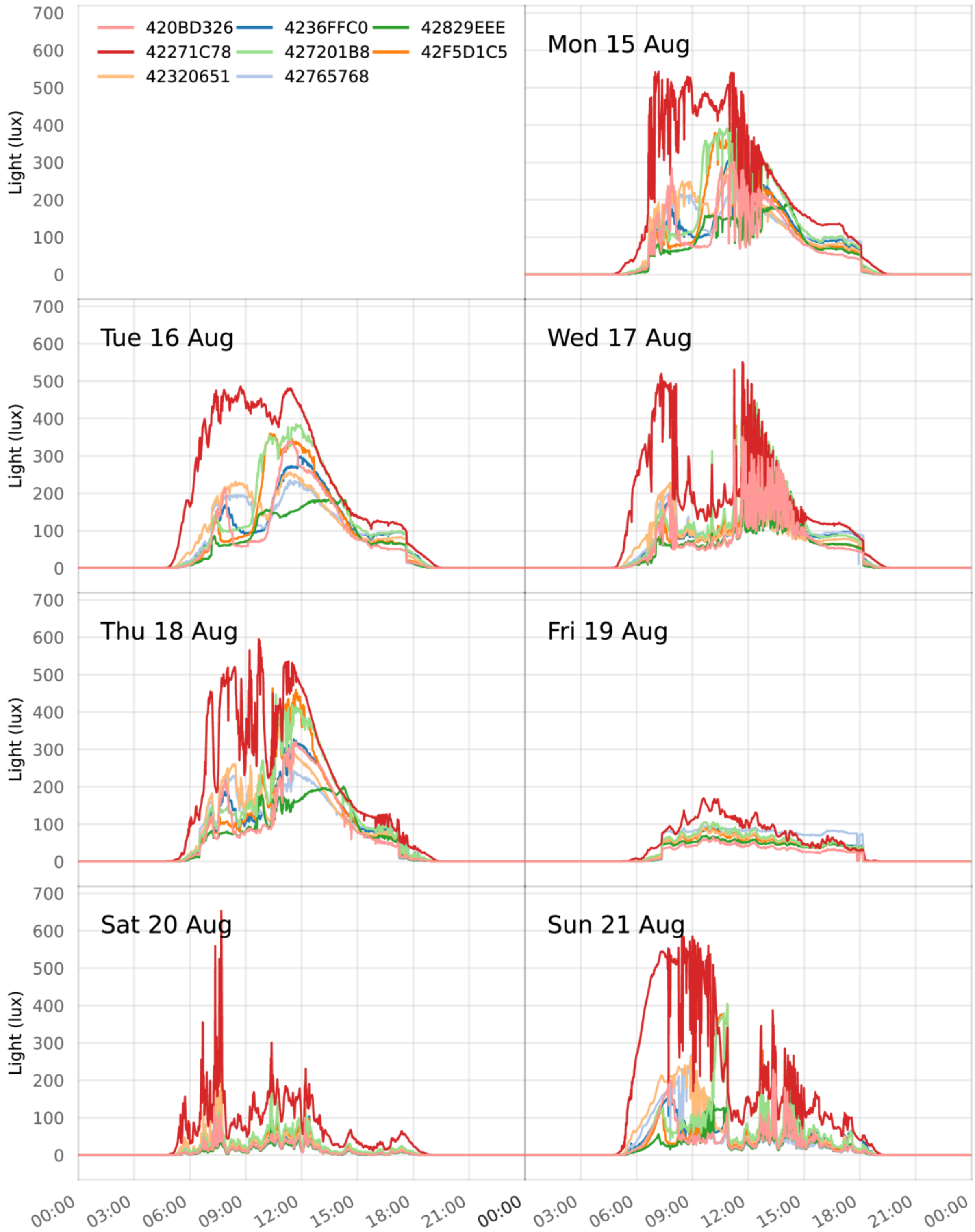
Light (lux) @ Business School 709

Time period: *2016-08-08 to 2016-08-14*



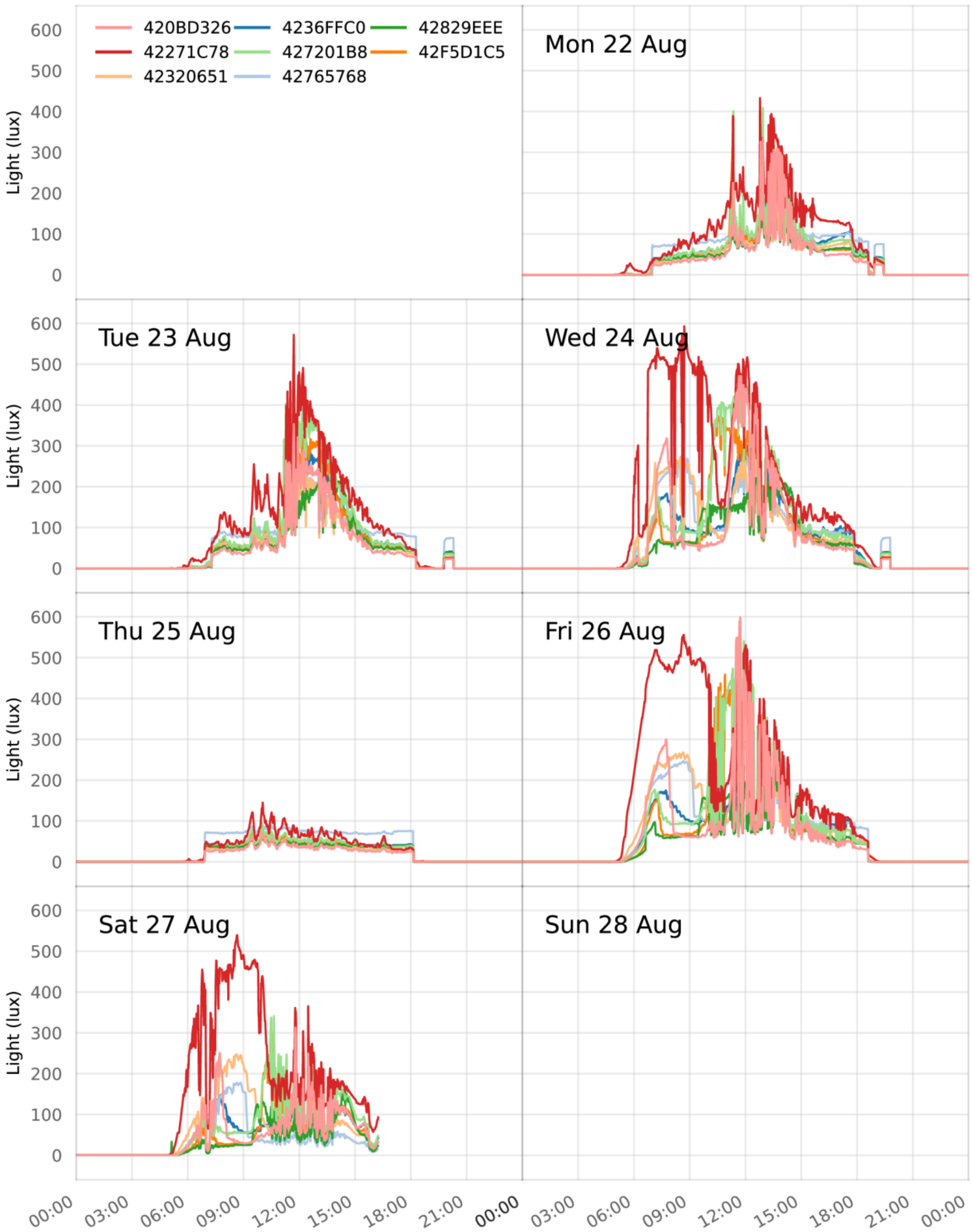
Light (lux) @ Business School 709

Time period: *2016-08-15 to 2016-08-21*



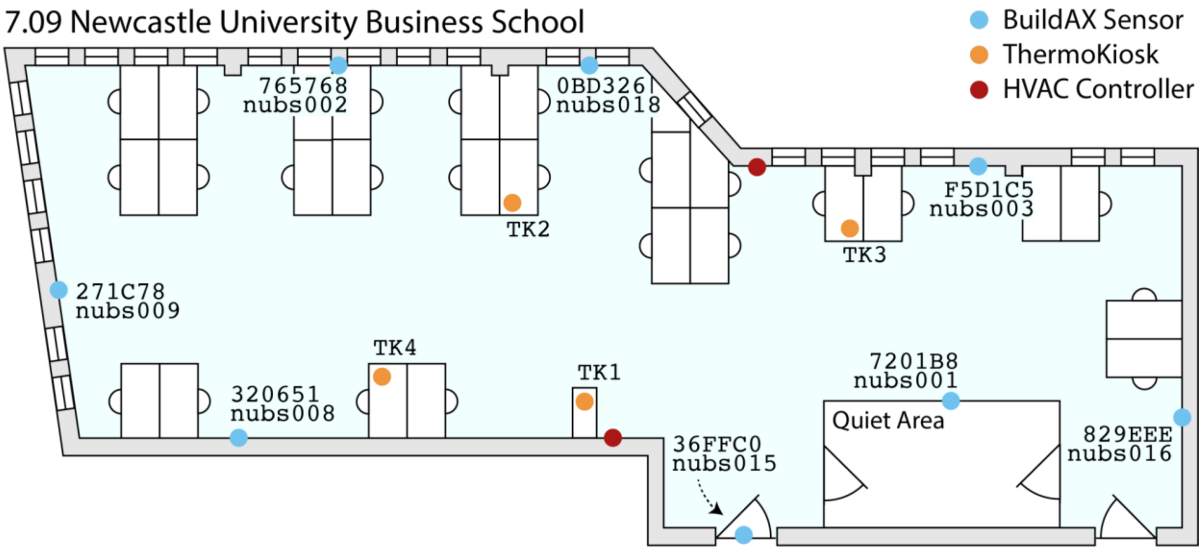
Light (lux) @ Business School 709

Time period: *2016-08-22 to 2016-08-28*



Movement Report: Business School 709

Weeks beginning 25 Jul 2016 to 28 Aug 2016



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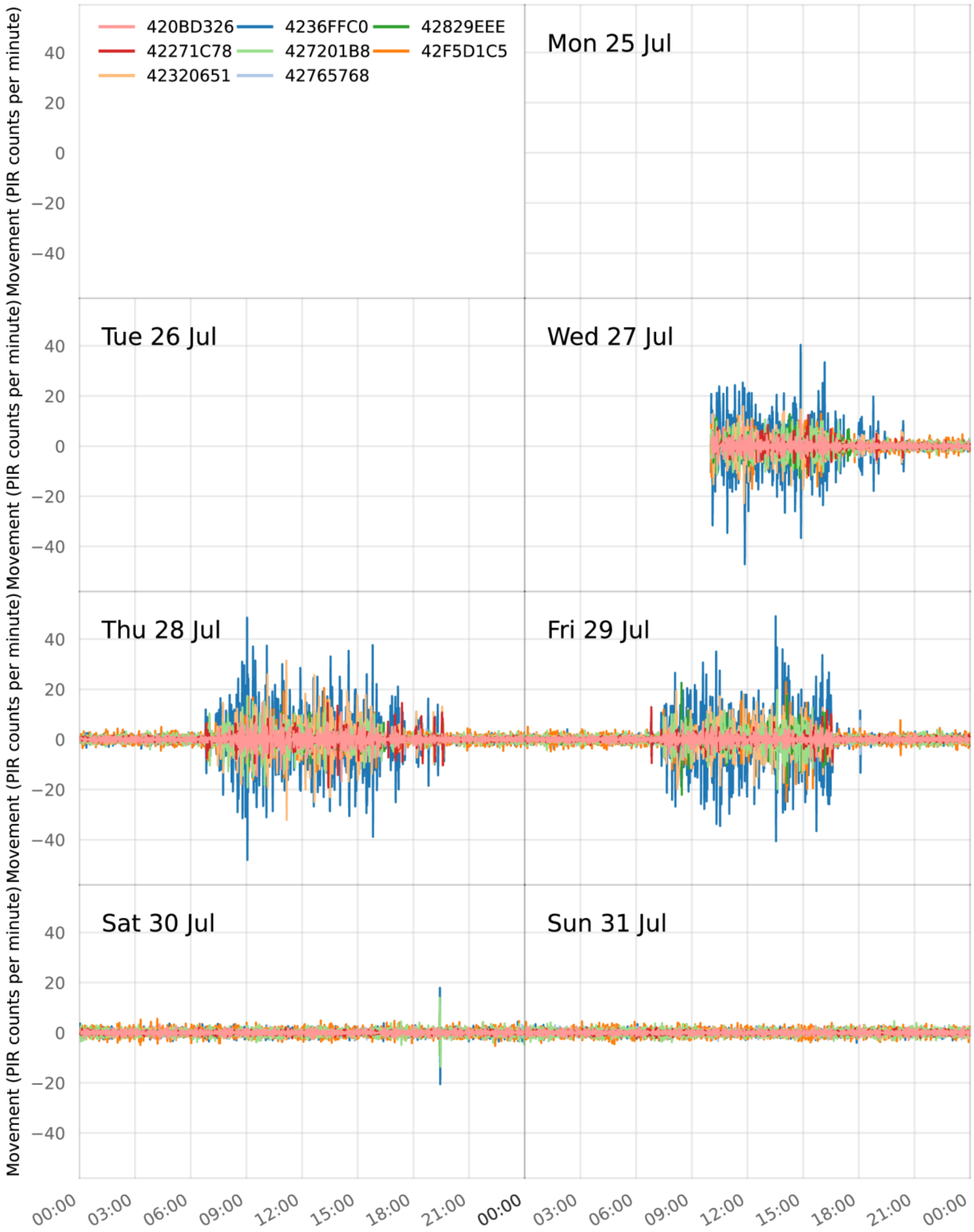
- 4242759B
- 4265A8DB

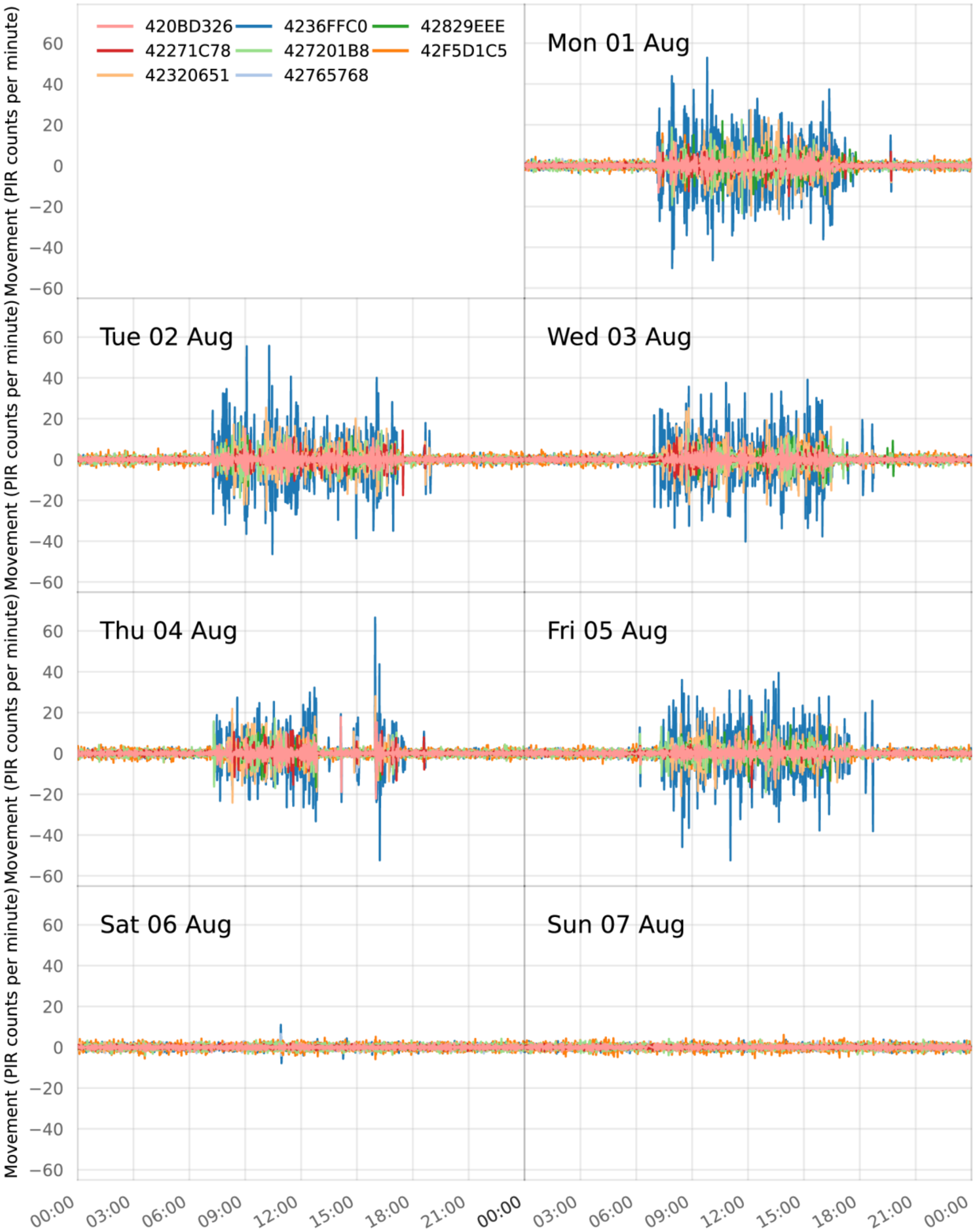
Movement (PIR counts per minute) @ Business School 709

Time period: *2016-07-25 to 2016-07-31*



Movement (PIR counts per minute) @ Business School 709

Time period: *2016-08-01 to 2016-08-07*



Movement (PIR counts per minute) @ Business School 709

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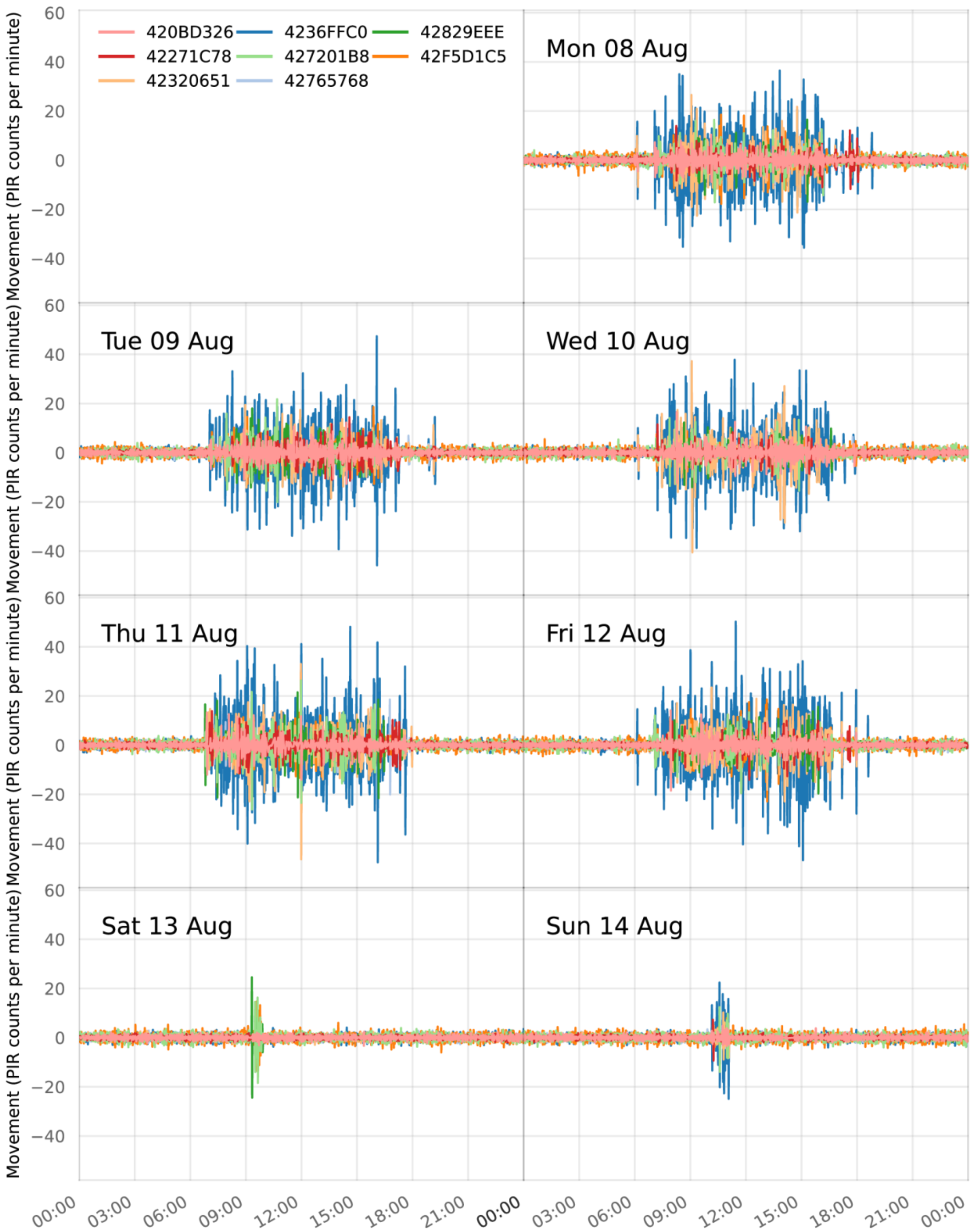
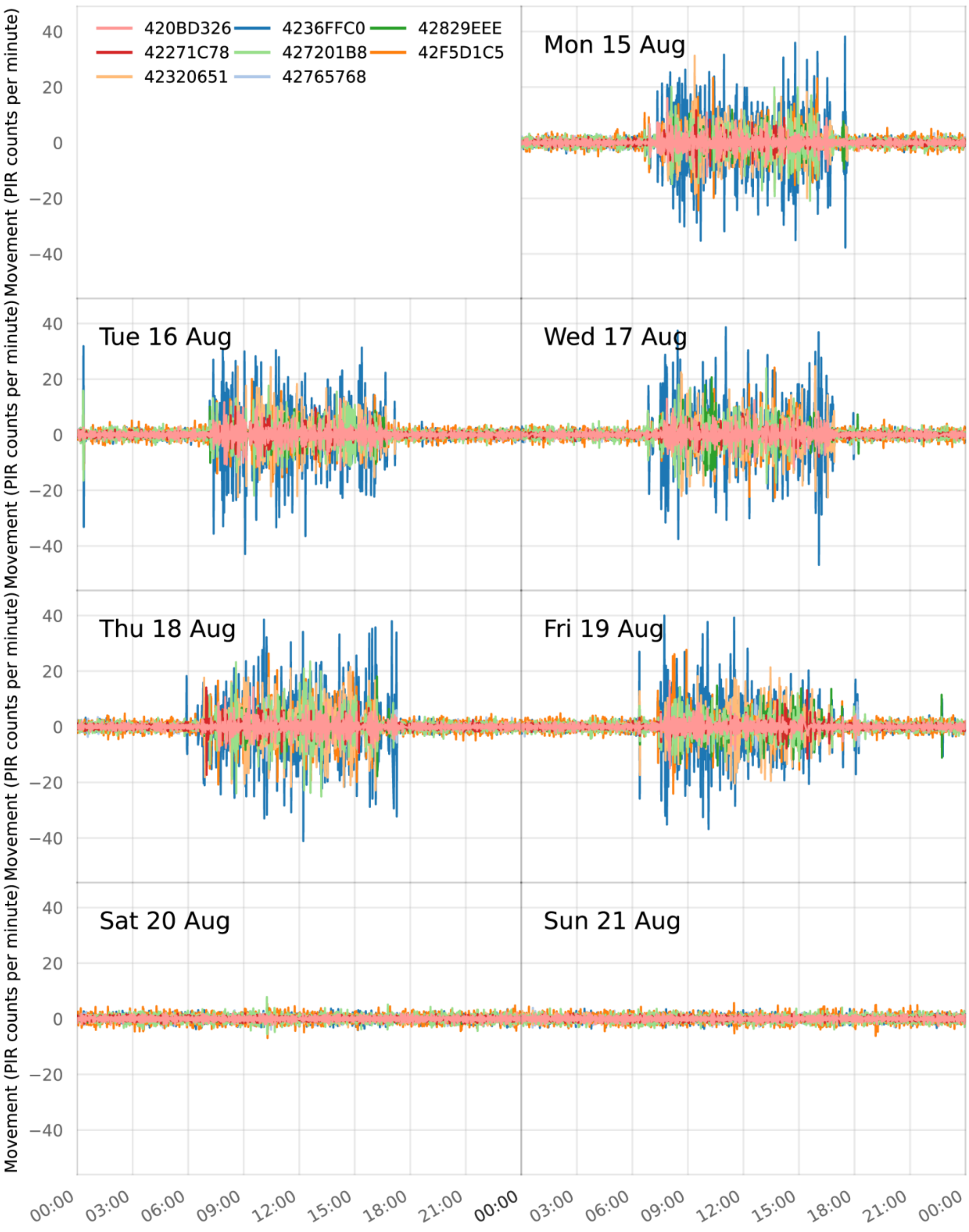


Movement (PIR counts per minute) @ Business School 709

Time period: *2016-08-15 to 2016-08-21*



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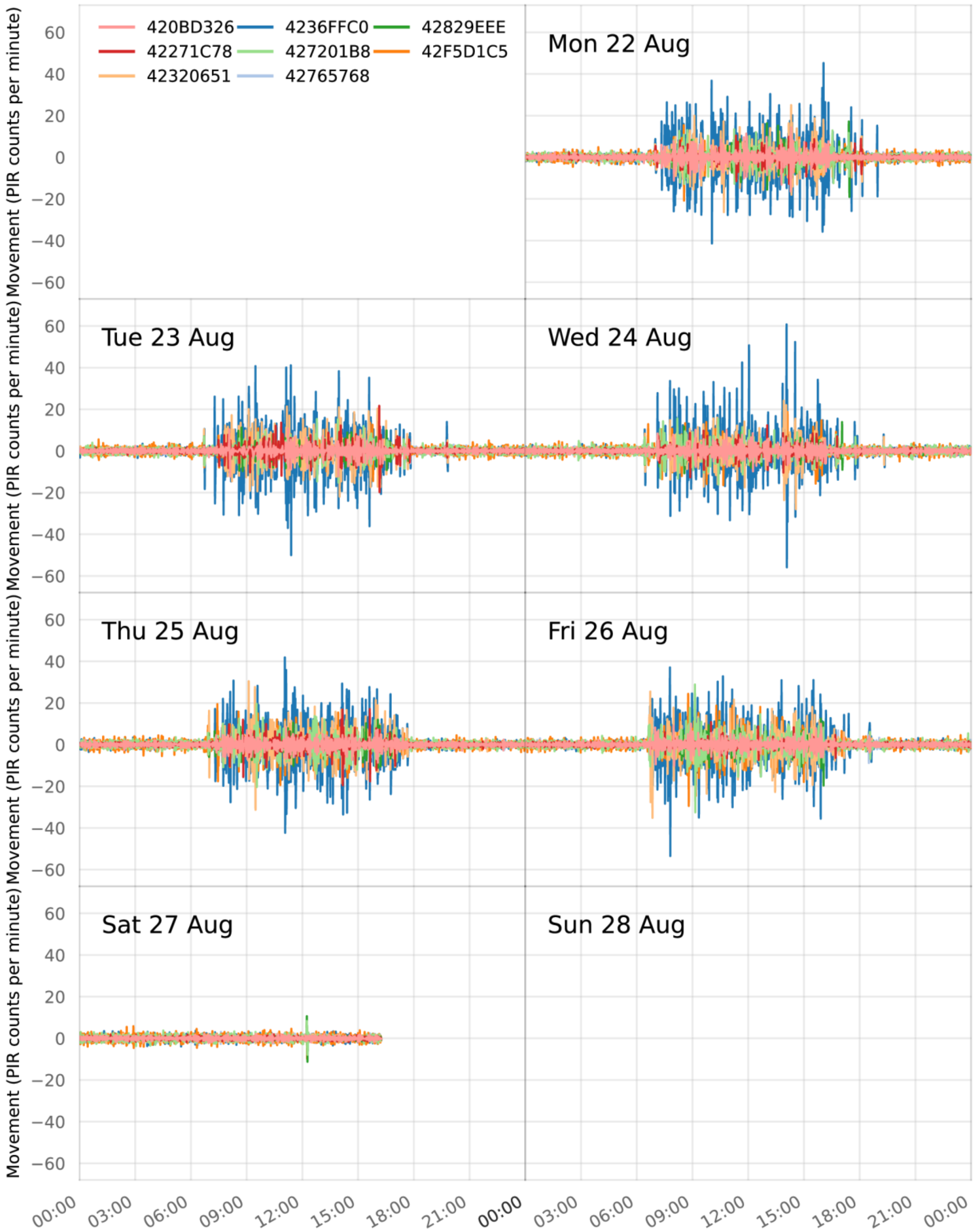


Statistical Aggregates between working hours (9am-5pm)

A note on these stats: values outside of 9am-5pm are not included in the aggregates

Averages:
The mean average is taken for each sensor.
The sensor IDs with the maximum and minimum *averages* (e.g. Warmest & Coldest) are then displayed in the table.
Maximum/Minimum:
Overall Maximum and Minimum (e.g. the warmest and coldest values on record) from any sensor
Ranges:
Ranges are calculated between the overall maximum and minimum (see above)

July 2016

Temperature °C					Humidity %RH				Light (lux)			
Warmest average	**Maximum temperature**	**Coldest average**	**Minimum temperature**	**Temperature range**	**Humidest average**	**Maximum humidity**	**Dryest average**	**Minimum humidity**	**Brightest average**	**Maximum brightness**	**Darkest average**	**Minimum brightness**
420BD326	42765768	42320651	42320651	42320651	42320651	427201B8	420BD326	420BD326	42271C78	420BD326	42829EEE	42829EEE
24.1	25.8	23.1	19.8	5.2	42.8	58.6	37.7	33.0	175.9	537.0	67.1	3.0

August 2016

Temperature °C					Humidity %RH				Light (lux)			
Warmest average	**Maximum temperature**	**Coldest average**	**Minimum temperature**	**Temperature range**	**Humidest average**	**Maximum humidity**	**Dryest average**	**Minimum humidity**	**Brightest average**	**Maximum brightness**	**Darkest average**	**Minimum brightness**
42F5D1C5	42271C78	42320651	42320651	42320651	42320651	42320651	420BD326	420BD326	42271C78	42271C78	42829EEE	420BD326
24.0	25.8	22.6	19.6	5.2	44.1	56.4	38.0	30.8	226.4	627.0	85.4	1.0

August 2016

Temperature °C					Humidity %RH				Light (lux)			
Warmest average	**Maximum temperature**	**Coldest average**	**Minimum temperature**	**Temperature range**	**Humidest average**	**Maximum humidity**	**Dryest average**	**Minimum humidity**	**Brightest average**	**Maximum brightness**	**Darkest average**	**Minimum brightness**
42271C78	42271C78	42320651	42320651	42320651	42320651	42320651	420BD326	420BD326	42271C78	42271C78	42829EEE	42765768
23.7	25.4	22.8	20.2	4.2	41.6	53.9	37.0	28.9	193.6	647.0	72.7	7.0

August 2016

Temperature °C					Humidity %RH				Light (lux)			
Warmest average	**Maximum temperature**	**Coldest average**	**Minimum temperature**	**Temperature range**	**Humidest average**	**Maximum humidity**	**Dryest average**	**Minimum humidity**	**Brightest average**	**Maximum brightness**	**Darkest average**	**Minimum brightness**
42271C78	42F5D1C5	42320651	427201B8	427201B8	42320651	42320651	420BD326	420BD326	42271C78	42271C78	42829EEE	420BD326
23.6	26.0	22.6	20.3	5.0	46.1	57.0	40.9	34.7	204.8	595.0	86.9	0.0

August 2016

Temperature °C					Humidity %RH				Light (lux)			
Warmest average	**Maximum temperature**	**Coldest average**	**Minimum temperature**	**Temperature range**	**Humidest average**	**Maximum humidity**	**Dryest average**	**Minimum humidity**	**Brightest average**	**Maximum brightness**	**Darkest average**	**Minimum brightness**
42F5D1C5	42F5D1C5	42320651	42320651	42F5D1C5	42320651	42320651	420BD326	420BD326	42271C78	420BD326	42829EEE	42765768
23.9	26.3	22.5	21.0	4.4	49.2	62.4	42.8	32.9	192.8	599.0	90.9	7.0

Appendix D: Workshop Schedule (CS3)

Workshop Schedule (2h30 / 150m) | 9 participants per workshop (3x groups of 3) | Wednesday afternoon (no teaching)

Overarching RQ: *How can participatory evaluation of built environments lead to more inclusive, occupant-led management processes in smart-buildings? (understanding experience, preferences, and use/management of resources)*

Task	Description	What it explores (motivation)
Ice Breaker, Paperwork, & General Questions (10 minutes)	Going around the group, everyone gives a short introduction (3 points): • Who they are and what they do, e.g., staff/Undergraduate/PGT/PGR • Why they came to the workshop (even if it was just for the voucher) • Something about themselves About the context: • Discuss University buildings: what do they think the requirements are (from the student perspective) relating to control, access & responsibility? • What do they think the student/occupant role is in managing resources? (and what do they think the resources are?)	Participants' motives for attending the workshop: even if it was just for the voucher, it is interesting to explore their biases. For example, are they particularly concerned about thermal comfort? Have they complained about building conditions before? We want to understand more abstractly their understandings of the university context, occupants' relationship with the organisation and how agreements are reached. Also serves as a slot for filling in the paperwork: consent forms etc.
Building Walks Part I: Blueprint annotation (20 minutes)	Using printed blueprints/floor plans of the USB building, participants draw-on their routes through the building, where they spend time, and annotate them with the resources they use in these spaces. Participants are paired off and we move around the group discussing this. Floor-plans are printed onto transparent A3 Acetate sheets, overlaid with paper in-between and bound. There are several floors in the USB, and this allows us to visualise connections between them. We also can use post-its to annotate the floor-plans with spaces used (e.g. study spaces) resources, people, and issues. Participants will plan how much time they will spend in each space on their route, observing people there and discussing how they interact with the building.	How are spaces used and why? As students are the primary occupants, we need to understand what **purpose** a building like the USB serves for an occupant, (student vs staff or postgraduate). *What does being a student in this building involve?* Explore occupants' perspectives on the following: • How do occupants **experience** spaces (general positive/negative vibe)? • What **tasks** do they carry out? (working, lectures, relaxing, eating, etc) • What **resources/services** do they use within the space? (or not?) • Are the spaces **satisfactory** for what they are used for? (distractions, problems, accessibility, what could be improved?) • How are the important elements of those spaces **controlled**? (provided/self-controlled).
Building Walks Part II (30 minutes)	Choosing a location from those highlighted during the blueprinting exercise, each pair/three go on a walk through the building to that location, where they focus in on the things which they discussed in part I. Participants take photos of the spaces they visit using polaroid instant cameras. **Question cards** are used to elicit images of the space that convey what is important about them, or what story they would like to tell about the	Occupants are challenged to answer questions about the spaces they walk through: they write on the polaroid what they use it for, what resources in the space they use, what makes it a comfortable space for that task, anything else they like/dislike about it: what would you change? The walks are motivated by part (i) of this exercise and further understandings are developed by the walking process in part (ii). By doing the exercise in threes, 3 different routes can be taken and more evidence collected overall, with the route not being dominated by individual personalities.

	space. The photos form a visual record to be used as part of the later design exercise. Our questions relate to our interview findings: [Assumptions, Adversariality, Market Focus, Mechanicism]	
Break (10 mins)	Allow participants to catch up and finish their walks, and provide an opportunity for a break before the 2nd half.	
Building Walks Part III: Feedback (20 minutes)	Participants present the walk they've been on. Using crafting materials (glue, scissors, sharpies, etc) they prepare a poster showing their route and the things they discovered from it. Moving around each group, participants (either as a group, or nominating a speaker) present their posters.	Participants explain in their own words their uses for and understandings of the space. How do students conceptualise this space?
Design Exercise Part I: Design Fictions / Speculative Design **(30 minutes)**	Occupants are presented with a set of three design scenarios which present ideas generated from the themes raised in the initial interviews with managers. The speculative scenarios include a description of the technology and a illustrative scenario/persona of how participants might interact with it. We talk through how these technologies would change the space in general and, using the results from 2.3, how they would affect how participants use those spaces. Are there other spaces that would work for that activity if this was a possibility? What do you think would work well, and what wouldn't? What data is collected and used?	The walking exercise got participants to think about the present. This final exercise introduces a set of design fictions to move understandings developed during the walks towards more abstract questions about what the building might look like in future, and if this is more "smart". We are asking participants to design for alternate scenarios, grounding this in their experiences of the building through the walks. This explores how occupants view technology/resources/data as part of the building "fabric" and how they conceive of ideas which would change it. We are interested in participants' reactions to these scenarios: they are conversation starters. The blueprints from part (i) can be used to situate the technology ideas within the building space, and to discuss where they might be particularly effective or ineffective.
Design Exercise Part II: Free Design (25 minutes)	The final part of this workshop consists of an open-ended design session. Participants brainstorm in their groups and come up with a technology– can be as crazy as you want, doesn't have to be technically possible. They make and present a poster which pitches their concept. Using **discussion prompts** (Themes: Data, control, management, etc) written on a whiteboard, and linking them to their walking experience, participants critique the designs and remix them to propose their own ideas.	Building on part I, this is a more open design session which tries to get participants to think outside the box and come up with new ideas for technologies to change the building or site. We talk through participants' motivations for their ideas and use this to draw insight on what they consider worth changing. How do they evaluate the "success" of their technology?
Conclusion – and vouchers! (5 minutes)	Thank participants for coming, and do the paperwork for vouchers.	

Workshop Preparation: Detailed

Task	Detailed timings, Questions	Data Collection Method	Resources Required
Ice Breaker, Paperwork, & General Questions	10 mins total 5 mins – Introductions & Filling in Consent Forms 5 mins – How does the USB compare to where you were before?	Voice recorder – open discussion	Consent forms Information sheets
Building Walks Part I: Blueprint annotation	20 mins total 5 mins – Task explanation, forming groups 10 mins – In threes, make a list of the places you use in the USB. Find them in the floor plans. Annotate them according to the categories: [**Use, Resources, People, Comfort, Problems**] 5 mins – Walk Planning (in groups): participants write their route down!	3x voice recorders (in groups)	Blueprint books Sharpies Post-its
	Suggest 3-5 locations, where they should spend time observing how it's being used Planning: How long will you be spending in each space?		
Building Walks Part II	30 mins total	Photo elicitation Participants take colour sharpies and write under the polaroids what they represent	Polaroid Cameras Polaroid Film **Question Cards**
	Participants in threes, using their route and timetable planned in (Part I), travel around the building and document their locations with the polaroid cameras. Question cards are used as prompts for things to think about which might be interesting to feed back to the group, but participants have agency here. Question cards: see table 3		
Break	10 mins break		N/A
Building Walks Part III: Feedback	20 mins total 15 mins– groups feed back, showing their photos and describing what they are showing with them. (5 mins each group talking, plus padding for discussion)	Voice recorder	Flipcharts Blueprint Books Sharpies Polaroid Photos from P2
	How did you answer the question cards?		
Design Exercise Part I: Design Fictions / Speculative Design	30 mins total (allowing feedback to overrun if necessary) 5 minutes to read design fictions and discuss with peers 10 mins whole group discussion: follow prompts below 5 minutes in groups: brainstorm a scenario where it doesn't work, breaks, or causes problems (can be wild!). How would you change the design? 10 mins feeding back. 1. Discussion questions / prompts (encourage disagreement!) • Where would this technology be most usefully placed in the building? • Where would this be most *disruptive* within the building? What effects would it have? • What data is collected and used?	Voice recorder	Design Fiction Briefs

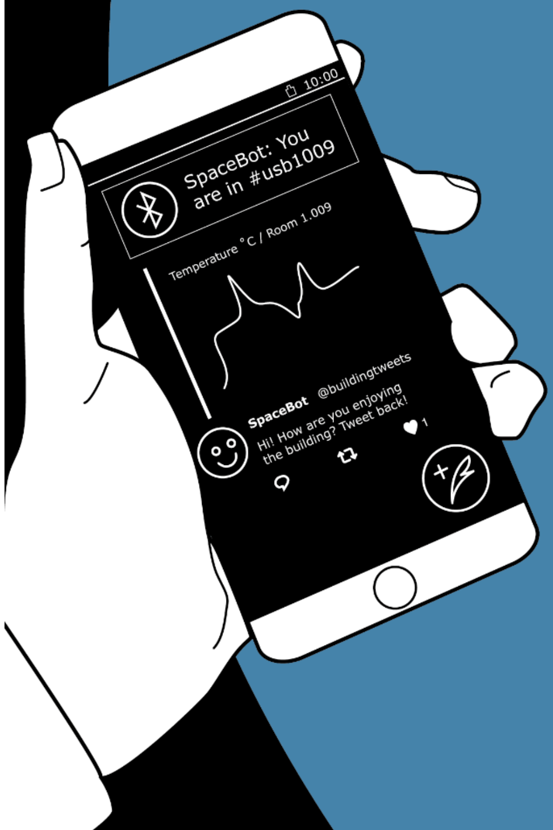
	• Who is the user in this scenario? Who are they? What do they care about? Why might the technology presented here be useful? 2. How would you change the design? • Make a list of reasons why this may not work • Think about the users of this building: does it exclude a certain group? • Tell the story of how it gets broken: who, where, when, why? Can skip to part II if finish early– more time for brainstorming	
Design Exercise Part II	25 mins total 15 mins to develop an idea: example timings: 10 mins brainstorming using post-its and flipcharts 5 mins developing their lightning pitch 10 minutes (3 mins lightning pitch per group) presenting their concept Seed questions for brainstorming: • What do you currently enjoy (or not enjoy) about the USB? • The building isn't finished: what do we build next? • Energy crisis: what if we can only heat the building for 2 hours every day? • Feudalism: what if we bought the student halls next to the USB and had everyone live there for free? • What if the building could be closer to the other end of campus?	Observations & research notes Voice recorder (for pitch)
Conclusion	5 mins total. Voucher distribution and thanks for coming!	Vouchers, pens

Question Cards

[**Resources, People, Comfort, Problems**]
[Assumptions, Adversariality, Market Focus, Mechanicism]

Theme	**Question**
Assumptions / Use	What's the purpose of this space– and what do people *really* use it for?
Adversariality	Who's in charge in this space?
Market focus	You're a new student on a visit day at the Uni. What space really sells it to you?
Mechanicism	Imagine the building is like a machine. What keeps this space running?
Resources	What resources do you use in this space?
People	What are the people who are here right now doing?
Comfort	Do you ever feel uncomfortable here? E.g. Too warm, too cold, or too noisy?
Problems	Tell me about a problem you have (or had) in this space?

Appendix E: Diegetic Prototype Briefs



SpaceBot: A Building Bot for Twitter

Concept

What if your building could Tweet? SpaceBot is a Twitter bot: a mediator for discussion about the USB, backed by data generated by its Building Management System.

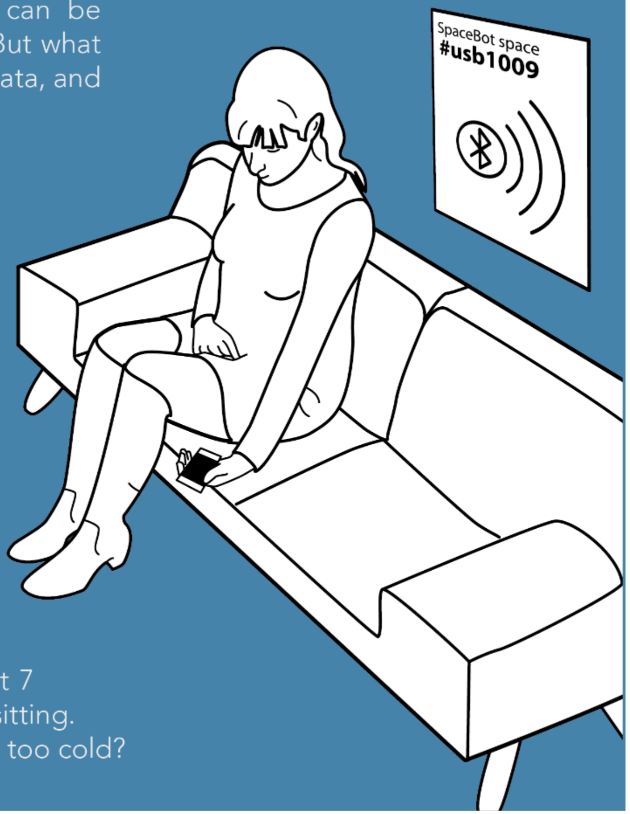
The USB gathers data from sensors installed in the building: it was designed to allow experimentation and data collection. However, we as occupants of the building don't usually get involved in this as the systems can be complex and difficult to interact with. But what if there was an easy way to access this data, and find out how the building "feels"?

Scenario

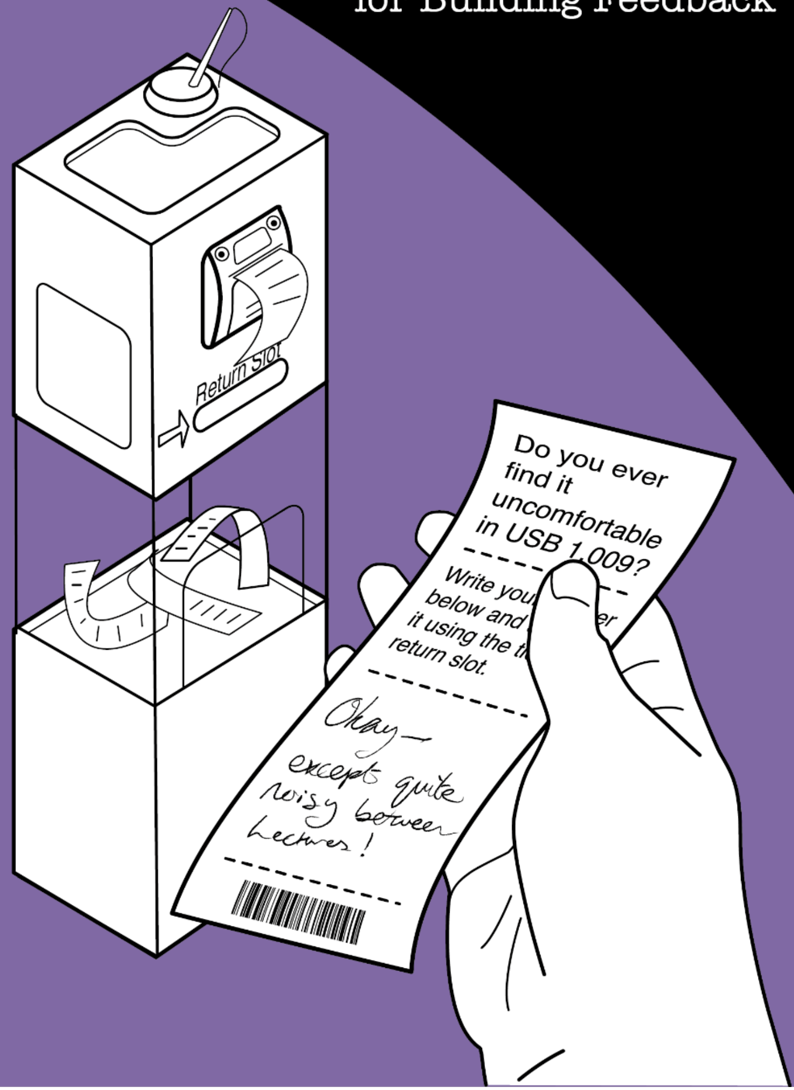
Jane is sitting in the Atrium of the USB when she receives a notification on her phone. She presses it and logs on to Twitter, where she sees a tweet from @SpaceBot: *"In the #USBAtrium right now, it's 23°C. Are you feeling warm or cold?"*

Jane replies to the tweet, saying that it's okay right now but has been too cold in the past. She hashtags the tweet *"#USBAtrium"*. SpaceBot replies with a graph, showing the last 7 days temperature for where she's sitting. Can she pick out the day it was too cold?

"We haven't really got extra resource to look at all this metering data, all this temperature data. […] What we do have– is umpteen interested students, and academics…"
–Manager 3



Questie: A Q&A Machine for Building Feedback



Concept

Complaints are the only way in which the staff who manage the USB can find out if there is a problem with it! Questie is a machine for gathering ongoing feedback, which can help managers to figure out if there is a problem before it gets bad enough to need a complaint.

Questie is motion-activated: when a building occupant walks past, it prints a question or task using its receipt printer. There is a space on the receipt to write-in the answer.

The receipt is then scanned in the *"returns"* slot, and the person can bump their smartcard on the reader to collect points that can be exchanged in the cafe for food and drink.

Scenario

Andy walks past the School of Computing reception on the 2nd floor. There is a *"beep!"* from a machine which stands next to the entrance, and a piece of paper rolls out of a slot.

Curious, Andy tears the paper from the slot and reads it. *"Is there anything we can do to improve our Study Spaces?"* asks the paper. Andy thinks, then grins and writes his answer, resting on the top of the box and using the supplied pen. *"Put an XBox and a screen in the one on the 2nd floor!"*

He then feeds the paper into the return slot, where it is sucked through and the barcode read. He then bumps his smartcard on the reader, looking forward to picking up a sausage roll later on.

"Might as well do what the students want!" –Manager 2

FurniBa: A Robot for Reconfiguring Furniture

Concept

Furniture in the USB is heavy! It's robust and lasts a long time, but if you want to move it around it's difficult: and that limits what you can do with the space. But what if you had a little robot helper which could move it for you?

FurniBa is essentially a Roomba (a robotic hoover) with a powerful lifting jack on its back. It can be called out to reconfigure the space, helping to move furniture around the building.

Students and staff get access to a mobile app which shows a floorplan of the building, and can navigate to the space they're in. They can select the funiture location, and summon a FurniBa to move it around!

Scenario

Alisha is working with her friend in one of the collaborative working spaces on the third floor. She sees that it's sunny outside, and working in this artificially lit space is getting depressing! But look: there's a space over by the window. She'd like to sit over there, but there's no seating!

She pulls out her smartphone and opens the *FurniBa* app. She selects the location, opens the *"add furniture"* menu, and presses *"sofa."* A couple of minutes later, the gentle hum of electric motors can be heard as two robots, working together, maneuver her new furniture to the sunny spot next to the window. They grab their bags and move over to it.

"… a very robust type of furniture, it's heavy– it's like the building, you know. The building's like a heavy, dense building." – Manager 4