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Augmenting Audits: Exploring the Role of Sensor Toolkits in Sustainable Buildings Management

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Audits are commonly carried out by facilities managers (FMs) to quantify the sustainability and performance of the buildings they manage, informing improvements to infrastructure for resource and cost savings, and assessing compliance with standards and legislation. The scope for what can be audited is limited by available infrastructure. In this article, we investigate the utility of a flexible sensor toolkit to enhance existing energy auditing practices. We present findings from a qualitative study with FM and student auditor participants from 3 organisations. Our study covers how these toolkits were used and integrated into auditing practices within these organisations, and the opportunities and issues for resource management that arose as a result. We conclude with design implications for toolkits to support sensor-augmented audits, make recommendations towards a deployment protocol for sensor toolkits used in this context, and develop broader considerations for how future standards and policies might be adapted to leverage this potential.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)** → Empirical studies in HCI

KEYWORDS

Energy; Audits; Building Management; Sustainability; Sensor Toolkits; Data; Practices; Professionals

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1 INTRODUCTION

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 (UK). Energy audits seek to identify inefficiencies in building design and operation to reduce running costs and ensure standards-compliance [1]. *Sensor toolkits* have emerged as a key tool to support audits, however, their roles in this are yet to be reported in academic literature. In this article, we seek to understand *the design of sensor toolkits for effective building management.* We investigate how sensor toolkits are used by FMs to augment their existing audit

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practices with additional data. We study the application of an environmental sensor toolkit, *BuildAX*[1], which 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 our study.

Sensor toolkits are distinct from static systems such as Building Management Systems (which control HVAC and capture limited environmental data). We consider sensor toolkits 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. [31]) 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 Building Management Systems (BMS), in managing their organisation's energy consumption. However, we found that 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. We present our findings on a deployment of our 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. We 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 [43]. 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 [1]. 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.

Sustainability and energy auditing are fundamentally interconnected: commercial premises in the UK consumed 50,264 GWh of natural gas and 74,453 GWh of electricity [15] in 2015, making facilities management a domain of huge potential for sustainability research. Measuring and verification protocols (e.g. the International Performance Measurement and Verification Protocol, or "IPMVP" [29]) 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. [3, 19, 28, 31]). In *Sustainable Interaction Design* [6], Blevis 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 [35].

In this article, we contribute to this agenda by investigating the utility of flexible sensor toolkits to support sustainability through existing energy auditing practices. We examine the context of internal audits in this 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 our study are therefore all facilities managers, energy managers

[1] Documentation for the open-source BuildAX system may be found at http://buildax.co.uk/

(specialised facilities managers), and students performing audits with a facilities department for professional development or as part of a taught module.

2 RELATED WORK

In our examination of sensor toolkits in the context of energy auditing, we review current research on the development of sensors and their uses in citizen science and sustainability, and HCI perspectives on buildings management and auditing. The limitations and challenges of these studies inform the framing of our findings and discussion.

2.1 Sensor Toolkits

Pervasive sensing has been heavily investigated in Ubicomp and HCI literature from several viewpoints, developing understandings of where and how sensing technologies can be applied to enable desired outcomes. In 2010, DiSalvo et al. [17] 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*. Yet, these 'amateurs' may be 'local experts' in their own right as in [40], exploring the depths and utility of data that engineers or researchers might otherwise miss.

Though not all of these sensor systems are positioned as toolkits, they are often designed with a particular set of users in mind. In contrast, a sensor toolkit as we define it here may be used by different groups of people to investigate various concerns. In an example study, Aoki et al. attached air quality monitoring sensors to vehicles in [3], to explore how such sensors can provoke community action about air quality. We highlight this study in particular because it provided a community with the tools to capture air quality and the legitimacy to enact change.

Other sensor platforms are designed for gathering and exploiting data to infer the experience of cyclists [19] and drivers [27], enabling these users to investigate the health implications of air pollution. The process by which people interact with data, rather than the data collection process itself, is relevant to the buildings management context we examine in this work. Recent work in this field [12] has examined the role of such data in negotiations between office occupants and facilities managers, and how this might democratise thermal comfort and energy-use in the workplace.

The legibility and indexicality of data is explored by Tolmie et al. [45], describing how participants in the domestic context articulate understandings of their everyday interactions as captured through sensor data, challenging often-cited privacy concerns in big data capture by finding that context was removed to the extent that the data became illegible. Physikit [28] challenges the often *'black-box'* or opaque nature of this data, and assists users to make sense of it through the application of tangible interfaces. Ambient and situated visualisations may also be aesthetically pleasing [4, 9, 34] with filtered and processed data being presented in an exploratory fashion. In our study, however, we consider the utility of sensor data in augmenting the work of FMs, as opposed to using it as a tool for engagement or persuasion.

The progression towards low-cost and widely available sensing technologies allows the collection of diverse data streams, as in [24, 25]. In [31], Jahn et al. 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 [33] studied how occupancy estimations might be used to identify potential energy savings in HVAC system usage. Sensor toolkits lend themselves well to application in research, and are often repurposed for different studies and combined with other data collection methods (e.g. ethnography) when used within Ubicomp and HCI. This has enabled research into specialist practices [22], home energy [5, 41] and urban contexts [14] among others, demonstrating how sensor toolkits have been used in a variety of settings to achieve diverse research outcomes.

Other literature has explored how users interact with the data generated by sensors (not necessarily sensor *toolkits* per se, but systems for data collection). Visualising eco-feedback data has been explored in novel ways [23], to motivate behaviour change [17], though such approaches risk alienating users by treating them as "micro-resource managers" [44]. The behaviour change approach may additionally be problematic in that its modernist philosophical underpinnings engender a reductionist approach to sustainability which incorrectly positions technology as a solution to complex issues, as considered by Brynjarsdóttir [8]. In this research, we consider how sensor toolkits can be adopted into and influence the existing practices of facilities managers, following one approach suggested by that work: to move *beyond persuasion*, shifting from a narrow focus on end-user behaviours to a consideration of energy in the wider organisational context of its use.

2.2 Auditing and Buildings Management

Buildings management and energy auditing are tightly interrelated, and are often viewed as an application area for sensor technologies: an opportunity for tighter building controls through the collection of fine-grained data [20, 32]. Success may be measured in, for example, meeting the compliance requirements of standards for thermal comfort such as ASHRAE 55:2004 [2]. However, experience has shown that thermal comfort of occupants is not guaranteed by standards adherence: comfort is subjective and influenced by many factors. As shown by Clear et al. in [10, 13], designing Ubicomp technologies with occupant adaptation in mind can be a more sustainable option by "*steer[ing] inhabitants away from non-adaptive interactions such as routine reliance on mechanical heating*". This builds on the earlier notion of sustainable standards for thermal comfort introduced by Humphries & Nicol [38].

While tight regulation may not be helpful as it diminishes the responsibility of the building occupant in their use of energy-reliant systems [11], it does raise opportunities for building management policies and technologies to recognise the subjectivity of thermal comfort [36] by allowing for adaptive actions for personal thermal control. Building occupants are themselves actors in this process: work by Schwartz et al. [42] 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.

Recent work in HCI has examined the use of novel technologies in auditing, such as automated aerial thermography [37] to assist in understanding heat loss from building structures. In the residential sector, the use of sensor toolkits to assist the work practices of energy advisors has been examined by Fischer et al. [22], who demonstrate how making sense of collected data only occurs through the *interaction* between the client (who has specialised knowledge of the practices and processes of their home) and the energy advisor. Energy management conducted by amateurs has been examined by Hasselqvist et al. in [26], which identifies potential for work which "*link[s] energy data to energy action*". There is therefore scope to connect Ubicomp and HCI research to sustainable policy and standards, and auditing practices may be considered a starting point for change. Standards such as ISO 50001 [30] enable building managers to save money and resources, and tackle climate change, and are used by organisations and governments worldwide. In this article we connect to Dourish's considerations of work at different scales [18] by considering the implications of high granularity sensor data for such standards.

3 METHODOLOGY

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

Our deployments with postgraduate students were similarly exploratory in nature. The FMs who participated in this study recommended we make contact with 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 contacted us following this, seeking to use sensor toolkits as part of their auditing projects, working closely with the professional facilities managers we had spoken with previously. We 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. This enabled us to understand 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 where deployments varied in length from 2 weeks to ongoing, semi-permanent installations lasting from 6 months to a year. Several deployment settings were examined as part of this work: 4 buildings within our own university campus, and 3 external buildings including a school, an office building, and an office at another university. 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 subjected to thematic analysis, detailed in [7], with our 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 article.

3.1 Participants

The participants in our interview study were facilities managers of educational institutions in the north of England. We interviewed the Sustainability and Energy Managers at our own university as part of our initial exploration of the space, which helped to finalise a research direction for this project. We then interviewed individual facilities managers who had approached us, and had performed audits using our 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 one of our sensor toolkits. *FM3* is the estates team manager at another university. *FM4* is the head of estates at a secondary school.

Table 1. Facilities Managers: Participant Information

Participant	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

FMs explored our 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 our 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.

Our student participants *S1* and *S2* performed data collection towards their Masters dissertations using our 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 our request for interview from the group of 11 focus group participants.

Table 2. Masters Student Auditors: Participant Information

Participant	Reason	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

All our 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 this analysis as their work was not auditing related.

3.2 Our Sensor Toolkit

The sensor toolkits distributed to FMs and students consisted of a base unit logger (see Fig. 1) 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[2]. The sensors were 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

Fig. 1. BuildAX Environmental Sensor Toolkit: including logger, sensor nodes and supplied cables

[2] 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.

does not cope well with high resolution data, but does afford analysis capability to auditors without a background using statistical software packages. Additionally, we developed a simple online tool to generate PDF reports from uploaded sensor data files, to allow visual analysis of trends over time.

The process of physically deploying a sensor toolkit involves distributing the sensor nodes within the space, setting up the base-unit, and (in a number of deployments) accessing this from the network to retrieve data in real time. In our larger researcher-led deployments, we 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.

4 FINDINGS

Through analysis of our study data, we developed understandings of how the auditors we spoke to engage with existing systems and practices, detailed in the section **Potential in Existing Audit Practices**. We examine the approaches, methodologies and tacit knowledge leveraged by auditors when addressing a task in which the collection of data is necessary, and the sense-making practices they employ in interrogating sensor data to ask questions of the built environment, in **Questions and Answers**. Finally, the **Tensions and Challenges** encountered throughout the auditing process are dealt with in the final section, including instances where the realities of sensor toolkit use did not correlate with expectations.

4.1 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: our SAs had 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. In this section we examine how existing sociotechnical systems and practices were affected by the introduction of sensor toolkits, how these technologies informed ongoing audits, and provided the data FMs needed to generate understandings of the building fabric.

4.1.1 Change Through Understanding

Auditing is employed by FMs as a tool for questioning and informing change. Our 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 [21].

However, FM1 tells us that *"... with ESOS' research regulations, you have to do energy audits every 4 years unless, you are exempt if 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 [29]). 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.

4.1.2 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 our conversations with the FMs and SAs, it became apparent that the kind of data collected by our 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.

4.1.3 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 users: *"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 the facilities managers we spoke to as they can enable or strengthen ongoing continual improvement.

4.2 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 our second theme examine how FMs and students we interviewed approach and answer these kinds of questions, and how the functionalities and affordances of a sensor toolkit influence their approach to designing sensor deployments.

4.2.1 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 our FMs and students: why they wanted to collect data using sensor toolkits, and how they planned to use that data. The professional facilities managers in our study had clearly targeted intentions for how our 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 users' 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.

4.2.2 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 settings we observed. 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.

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 our discussion we address how such tacit knowledge might be leveraged in the deployment of a sensor toolkit, by outlining a protocol for augmented audits. We also consider how the target audience of sensor toolkits might be widened as a result, and what this would enable.

4.2.3 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 at our institution 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.

4.2.4 Analytic Ability

In this finding, we show that sensor toolkits in the form we deployed them were well suited for professionals, and document 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 backgrounds were not uncommon for the facilities managers we spoke to. 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 we spoke to 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).*

As we had provided a set of reporting tools (see Fig. 2) for SAs to use, we used this to generate 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).*

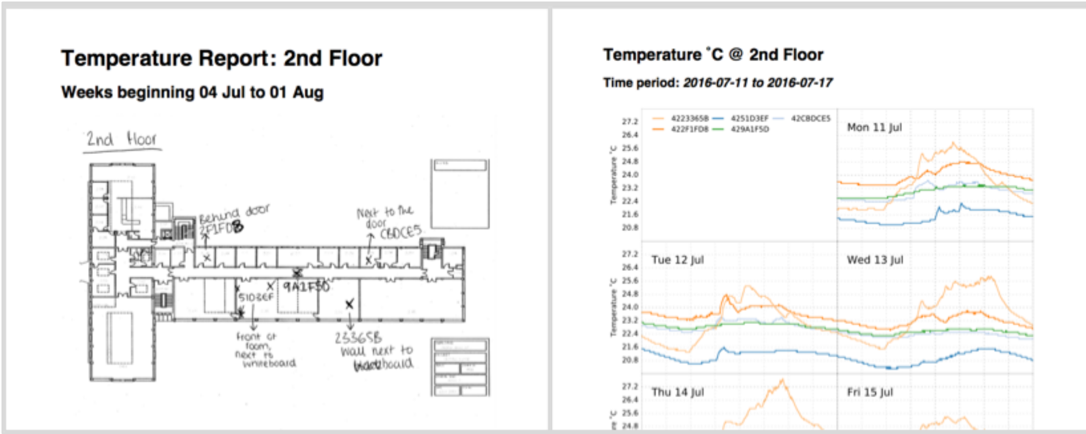

Fig. 2. The BuildAX report generation toolkit generates PDF reports for visual analysis of sensor data

We find that in order to move from data to action, 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 our discussion, we examine how these skills might be made portable through sensor toolkit design.

4.3 Tensions and Challenges

The final section of our findings 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. We include examples of limitations, where FMs and SAs found that the toolkits did not function in accordance with their expectations.

4.3.1 Understanding Building "End Users"

A factor which we have yet to examine is how building occupants or "end users" are considered 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).* Building users' 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 the building users 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 building users: *"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 users 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).* We revisit how this tension of consent against the imposition of monitoring tools might be problematic in our 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.

4.3.2 Temporal Challenges

Many of the challenges discussed by our participants were related to sensor deployments, rather than with processing of collected data. Firstly, the deployment contexts which often occurred during the course of our 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 our 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 we 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 our discussion, we 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.

4.3.3 Usability Challenges

Another challenge we encountered related to users' ability to deploy sensor toolkits. When asked about her experience of deploying the toolkit, S2 noted that the presence of a researcher, an expert voice on sensor toolkit deployment, was an advantageous 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).*

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 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. So 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).* This provokes a discussion of where the experience of using toolkits could be improved. 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 we elaborate on in our discussion.

5 DISCUSSION

Our findings have highlighted how the application of sensor toolkits to existing practices demonstrates the tacit knowledge and sense-making practices of FMs and SAs. In this section, we 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.

5.1 (Re)designing Sensor Toolkits

First, we consider what we learned about sensor toolkit design. Our 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/user power dynamic. Instances where there is an obvious financial or sustainable gain in using data to critique the concerns of building users, (such as where FM4 was able to argue against the installation of air conditioning through the data provided by our 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 [16] 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 our SAs found, a sensor toolkit may also be used to infer the actions of building users. Tolmie et al. [45] 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, we consider that 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 users 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: we assert that current procedure does not involve building users in the building management process, other than through complaints. Though there is an obvious role for democratisation technologies such as e-voting (e.g. [46]), another approach might be to redesign sensor toolkits to make them accessible for the novice user. How then, might we distil and incorporate expert knowledge 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', such as those in [3].

Though a toolkit (as we define it) is inherently *repurposeable,* by no means does this disqualify us from designing in these 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: we hold that 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 [26]. 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.

5.2 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. We provide guidelines based on our 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, given the findings of this article we 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 our 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 users 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 building users also reduces the possibility that gathered data will misrepresent the actuality: users might be empowered to annotate or otherwise comment on specific features that FMs identify.

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 our 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 our design constraint that sensor toolkits should be *redeployable*, we hold 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 our protocol recommendations relates to the *tacit knowledge* of experts, which new auditors (including amateurs) deploying sensor toolkits may not have access to. Our 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. Primarily, this is because 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. More interestingly, 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 building users have a vested interest in a successful outcome. By engaging with users, 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.

5.3 Standards and Practices

Standards are constantly under revision. At the time of writing, ISO 50001 (as used by facilities managers in our study) is under review. 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. We have found that, through their use, sensor toolkits bring into focus the standards and practices they were used to support.

This raises two questions for Ubicomp and HCI researchers in future work: how do we *better support such standards*, and how can we *build technologies that question the standards and policies themselves*? Dourish [18] 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 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 Ubicomp and HCI to support and inform existing practices 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), we as researchers 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 [39] 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.

5.4 Limitations

We recognise and foreground some limitations of our study into the use of sensor toolkits by facilities managers and student auditors, that future work might build on these. We first reflect on the role of our student auditors as early-career auditors: by approaching the auditing task with limited experience, they revealed certain knowledge and skill assumptions we make about potential users of a sensor toolkit for sustainable buildings management. Though we consider our student auditors as early-career auditors, for many this was the first real audit they had performed and as such was a learning experience, in which we would expect some parallels 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 us to develop accompanying analysis tools for early-career auditors whose background did not include statistics training. Some also displayed commendable dedication (the work forms part of their dissertations), and were more exploratory in their deployments with fewer preconceived notions of auditing processes.

In terms of the generalisability of our findings, while we do see some generalisable value in our results this is not our only contribution. This work 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 us but also to our participants. This kind of auditing, enabled by technology and HCI is relatively new to the facilities management industry. Hence, our findings 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. We expect the practical and mental work (and interaction design required to support this) will be similar and transferable, and an important subject for future research. But, we also expect 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.

6 CONCLUSION

We presented a 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. Our reflections 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. Our contribution relates 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 practices.

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