79 Drive Towards Real-Time Reasoning of Building Performance: Development of a Live, Cloud-Based System

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Abstract

Post-occupancy evaluation data on both building performance and occupant comfort can be useful for facility operation and management, and for workspace design but are rarely used in practice due to challenges and research gaps in data collection and analysis. We argue that with the growth of mobile and pervasive computing capabilities, future space design and building management will be based on real-time feedback loops of building performance data—qualitative and quantitative—available through the cloud, at stakeholders' fingertips. We have developed a live, cloud-based system to begin contextualizing fragmented big data sets as evidence to support improvement of workspace management and design, and this paper presents the development process. The proposed system has three functions: data collection, processing, and reporting. A wireless sensor network collects physical environmental data which are then posted to a cloud-hosted server. A smart device-administered survey collects occupants' perception data. Thermal comfort principles, as well as HCI (human–computer interaction) development guidelines and design principles, were followed during development of the app, which was then rigorously tested. The time-stamped survey data are synchronized with environmental data captured by relevant sensors. Pilot data collection is ongoing, as is the correlation analysis of the two data sets used to validate the process. The real-time reasoning and report generation features, supplemented with additional data, will be beneficial to space design, and to facility operation and management. This holistic system is expected to provide a powerful and practical tool for both designers and facility managers.

Keywords

Real time data • Building performance • POE • IEQ mobile app

79.1 Introduction

Post-occupancy evaluation (POE) is the process of evaluating buildings in a systematic and rigorous manner at some point after they have been occupied. The evaluation is intended to discover differences between performance criteria and actual building performance, thus providing insights into the consequences of past design decisions, as well as into the building's actual performance. This knowledge could eventually form a sound basis for creating better buildings in the future, influencing codes, standards and design choices [16].

POEs have typically focused on technical evaluations, such as of HVAC systems or building materials, but the effects of technical performance on occupant health, safety, and physical and psychological comfort need to be considered. In general, POE is a useful technique for assessing how well buildings perform, and its main focus is on building occupants' environmental satisfaction. Indoor environment quality (IEQ) has been measured as a major aspect of POE, and both physical condition monitoring and occupant surveys have been conducted in order to understand building performance, as well as to ensure the validity of other measurements taken. Conventional IEQ assessment approaches have been used to assess building

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I. Mutis and T. Hartmann (eds.), *Advances in Informatics and Computing in Civil and Construction Engineering*,
https://doi.org/10.1007/978-3-030-00220-6_79

performance through feedback on occupants' perceptions of and satisfaction with the environment. IEQ assessment has also been conducted as part of the assessment process for green building certification (e.g., LEED and Green Star) and building performance ratings (e.g., NABERS). The focus of POE was initially on energy and environmental performance, with the intention being to identify successes and failures of green design strategies and technologies. Later, the focus shifted towards building occupants (who are the primary users of buildings) in order to identify opportunities for improvements that would increase productivity in green buildings. As a result, not only buildings' technical capabilities or energy and environmental performance have been assessed, but also feedback provided by occupants to ensure high performance; there is overwhelming evidence of a link between better quality indoor environments and increased occupant health and comfort, which contributes to productivity [9, 12–14, 20].

A large evidence base has been generated concerning elements of workspace design that support the comfort of building occupants [21]. Although POE data can be useful for facility operation and management, they seem to be rarely referred to in building management practice, partly due to the nature of conventional, manual intervention-based data collection. These collection methods continue to be favored, even though the world is moving into the era of mobile and pervasive computing. In addition, systematic correlation of quantitative building performance data and qualitative occupancy evaluation data represents not only a gap in the research, but also in practice.

In this vacuum, the objectives of the present, ongoing research project are three-fold: (i) to develop a live, smart technologies-based platform composed of wireless sensor networks, mobile computing and cloud server for real-time data collection on building performance, representing both quantitative and qualitative data; (ii) to systematically correlate these performance and POE data, and validate the survey for repeated use; and (iii) to develop an analytical algorithm to derive intelligent condition assessment reasoning, alerts and facility management decisions, and provide feedback on workplace preferences and space needs to designers.

As the first step of contextualizing the fragmented big data sets to provide an evidence base for improving workspace design, we developed a cloud-passed wireless sensor network and a POE app to capture building evaluation data in real time. This paper reports on that development process.

79.2 Literature Review

A post-occupancy evaluation (POE) can be conducted using either objective or subjective methods, or a combination of these. Objective methods include physical measurements and utility audits in a numerical format, and subjective methods include occupant surveys, interviews and walk-through inspections. Occupant surveys, either standardized or customized, seem to be the most commonly used method in recent POE projects [7]. Surveys, in the form of self-administered or web-based questionnaires, make large samples feasible, and thus can be useful in describing the characteristics of a large population [2]. They also increase the likelihood of honest responses compared to formats involving interaction with another person, such as a face-to-face or telephone interview [11].

Research has shown that even when physical building conditions satisfy applicable standards or regulations, building occupants often evaluate their indoor environment negatively [8, 17]. This is due not only to their individual preferences, but also to the combined effects of the physical conditions [11, 15, 16, 18].

As a response to this, protocols have been developed in building-related disciplines with which to conduct occupant surveys on indoor conditions. The current protocols use a standardized survey as a subjective method, and numerous sensors and equipment as an objective method. Standardized survey methods have been developed—from a paper-based and face-to-face questionnaire, to a web-based survey—mostly asking questions about occupants' perception of, and satisfaction with, their environment. An apparently typical recent protocol is a web-based occupant survey, with indoor condition measurements taken using a portable monitoring cart (e.g., CBE's Occupant IEQ Survey, the Building Occupant Survey System Australia, or BOSSA). This approach is designed to capture the environmental satisfaction of building occupants as well as the indoor conditions, and usually matches the subjective responses of the building occupants with contemporaneous, objective IEQ measurements. Despite the development of these current techniques and tool kits, the IEQ assessment results seem almost never to have been used in building management practice. Anecdotal evidence suggests that this may be partly due to the manual and intensive nature and practical limitations of these data collection methods, as well as to a lack of knowledge of the best use of such data. These are major challenges for building maintenance and operations professionals.

Yong et al. [23], for their Intelligent Pervasive Spaces approach, envisaged monitoring objective building performance data in real time using wireless sensor networks. Internet access and mobile devices have changed the nature and ways of collecting both subjective and objective data. According to the Australian Bureau of Statistics [1], the number of households with access to the internet increased from 66.6% in 2007–2008 to 86% in 2014–2015. This allows access to a wide range of information, and also provides a crucial means of communication for individuals, communities, businesses and governments. Accordingly, a range of devices, such as desktop or laptop computers, mobile or smart phones, and tablets, are used to access the internet.

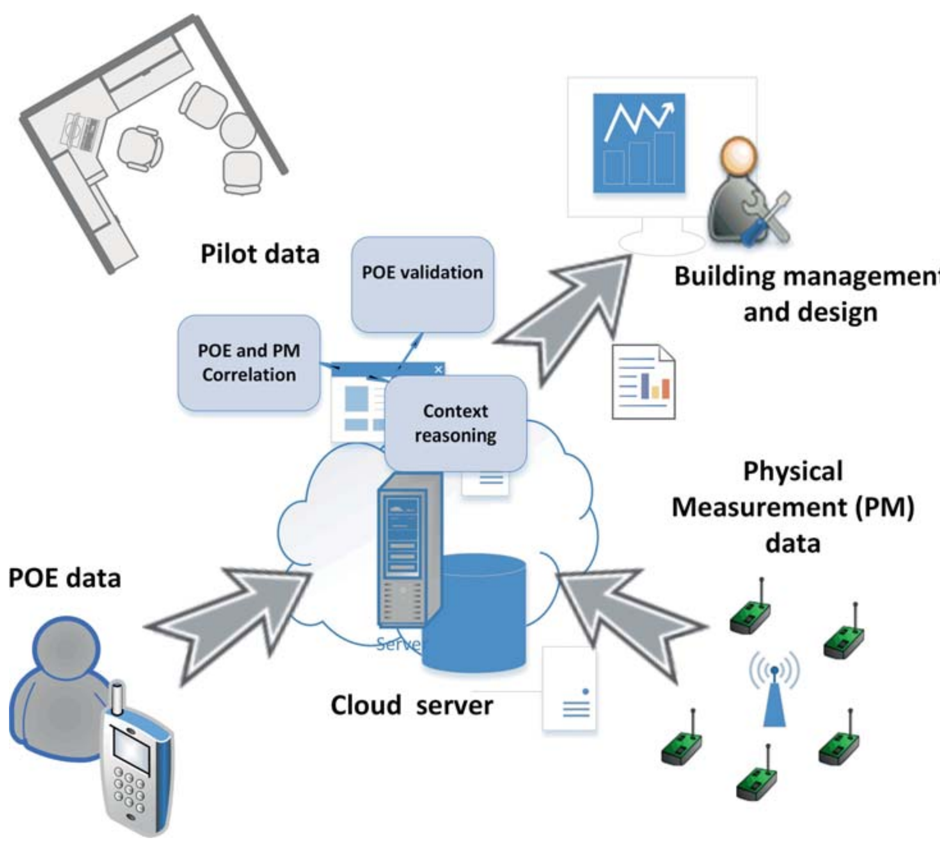
However, gaps exist in data analysis. Data on building occupants' 'functional comfort' have generated a large amount of evidence on both supportive and non-supportive elements of workspace design [21]. A meaningful correlation of the qualitative and quantitative data sets, which is yet to be undertaken, has the potential to bolster this existing knowledge. In addition, analysis and reporting based on the current techniques uses a 'benchmark', a mean score, in order to compare the performance of individual buildings. Although benchmarks can provide an overall indication of building performance, it is unrealistic to expect such a score to be used as a diagnostic or building management tool, due to its lack of generalizability. Real-time data collection and analysis can capture the unique features of each building, which allows the gap between current IEQ assessments and the variability within each building to be filled. Real-time data collection can also enhance building performance, and improve communication between building users and building managers. Cloud computing, integrated wirelessly, has allowed data storage and processing to become cost-effective, and facilitates real-time feedback.

A rigorously validated POE survey systematically correlated with—and supported by—objective building performance data makes effective use of occupancy data. Such quantitative and qualitative data sets (currently fragmented in practice) have the potential to be used again and again to improve serviceability and decision making in facility management, and also as a feedback loop to improve workspaces.

79.3 The Live Platform

The proposed live platform is composed of data collection, data analysis and reporting systems. The system architecture is shown in Fig. 79.1. The system consists of (i) data collection, (ii) data processing, and (iii) browser-based reporting components.

Fig. 79.1 System architecture



The real-time data collection components are: (i) a wireless sensor network to collect physical measurements (quantitative data); and (ii) a smart phone app to collect data on occupants' perceptions (qualitative data). Both components are cloud–connected, and update the data repository in real time. Pilot data are collected to correlate the qualitative and quantitative data sets and to validate the POE survey for repeated use. The use of a cloud server enables real-time context reasoning based on the findings from the validation. This context reasoning generates real-time web browser-based reports, and aids building management and workspace design-related decision making. The web server used in this project is Amazon Web Server (AWS). Other components of the system are discussed below.

79.3.1 Sensor Network

The sensor network used to collect data in the current version of the system is based on the TelosB platform. A TelosB mote has an IEEE 802.15.4 radio with an integrated antenna, a low power MCU, and a 250 kbps data rate. The mote has an embedded 8 MHz TI MSP430 microcontroller with 10 kB RAM. The mote runs the TinyOS operating system, as shown in Fig. 79.2. The mesh network configuration is illustrated in Fig. 79.3. The network is composed of six TelosB motes, including one mote that acts as the central coordinator of the sensor network.

Fig. 79.2 TelosB mote

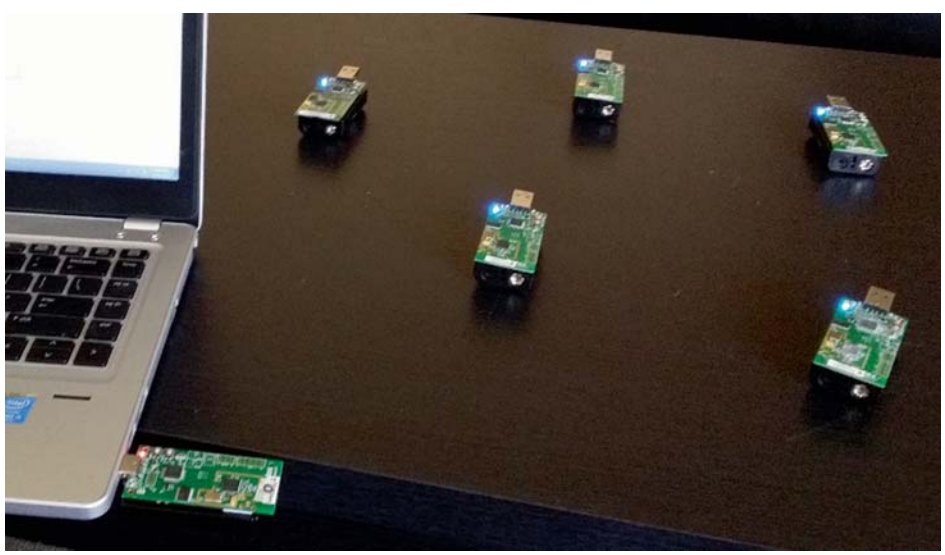


Fig. 79.3 TelosB mesh network

The coordinator of the network (NODE 0) is connected to a central server using a Universal Serial BUS (USB) connection. The coordinator communicates with the server via a C# program. The other nodes (NODEs 1–5) report temperature and humidity values to the coordinator. The coordinator updates the values from all nodes to the cloud server, together with the time stamp and node ID, every 5 s (this was the trial frequency, but others can be set as needed).

79.4 Mobile App

79.4.1 POE Design Principles

To develop an app to capture subjective occupant evaluation data, three parameters on perceived indoor conditions, corresponding with physical parameters, including temperature, humidity and air freshness, were selected. The aim was to achieve a high response rate, so a quick survey was designed, rather than one that would bore or tire recipients. A five-point semantic differential scale using two adjectives with a neutral point (e.g., 1 = hot, 3 = comfortable, 5 = cold) was selected to quantify the occupants' perception of indoor conditions. For thermal sensation, a neutral state means 'comfortable' or 'acceptable', indicating an absence of discomfort due to heat or cold. Participants were also asked to rate their overall satisfaction with thermal conditions. For this overall satisfaction level, a four-point Likert scale was chosen (e.g., 1 = very dissatisfied and 4 = very satisfied). Neuman [12] argues that more specific responses yield more information, but on the other hand, requests for too many specifics can create confusion in the context of a questionnaire.

79.4.2 Human–Computer Interaction (HCI) Design Principles

Human–computer interaction development guidelines and design principles were also followed during the mobile app development process. Initial discussion with POE and facility management experts revealed their needs in terms of the app's practical uses. The top priorities for the app were that it should be simple, easy for occupants to use, and interactive. The fundamentals of successful user-centered design [5] were also considered. Given that the POE design principles recommended that information provided in the app be simple, it was easy to adopt this 'simplicity' as an observational technique, as recommended by Dix [5]. Navigation design elements and global structure [5] were also carefully thought through based on the target users and application areas. We decided upon a maximum of two panels for primary information display, and to include an option button for settings. Direct manipulation [5] was another aspect considered, features of which include: the visibility of objects of interest; the actions used directly manipulate visible objects; and incremental actions within the interface. Dix [5] also argues that it is vital that users experience engagement and fun. The design therefore uses minimal text, and encourages users to enter their perception by means of symbols representing their feelings. For example comfortable conditions are represented by symbols for positive emotions, and uncomfortable conditions by symbols for negative ones. In addition interactive color schemes were used in the design—e.g., hot and dry conditions in red and cold and humid in blue, stale air in red and fresh in green—to: (i) clearly distinguish each option that the user selects, which minimizes errors due to ambiguity, improving the survey's construct validity [10]; and (ii) indicate the measurement being collected.

79.4.3 App Development

The app supports the collection of perception data through (i) a wall-mounted Android device, and (ii) a hand-held smart phone device. Data are then posted to the Amazon Web Server. The first version of the app was developed for Android tablets. Both Android and iOS apps were developed so that the app was compatible with the vast majority of smart phones. The phone apps were built using SDK version 16 (supports Jelly Bean 4.1 and above) for Android, and for iOS version 8.0 or above. The android tab version is SDK version 15 (supports Ice Cream Sandwich 4.00 and above) The Android studio (in Java programming language) and XCode (Objective C programming language) platforms were used for coding and compiling. Adobe Photoshop and Adobe Illustrator (AI) were used as the design tools.

The app's graphical user interface (GUI) is shown in Fig. 79.4. As shown in Fig. 79.4a, the app's settings enable selection of a specific sensor and location. The user is then surveyed about the temperature, humidity and air freshness, as per Fig. 79.4b, and their overall satisfaction, as per Fig. 79.4c. The time stamped perception data are then posted to the AWS. These data are synchronized with environmental data captured through the relevant wireless sensor, based on the initial configuration (physical location and sensor number) and time.

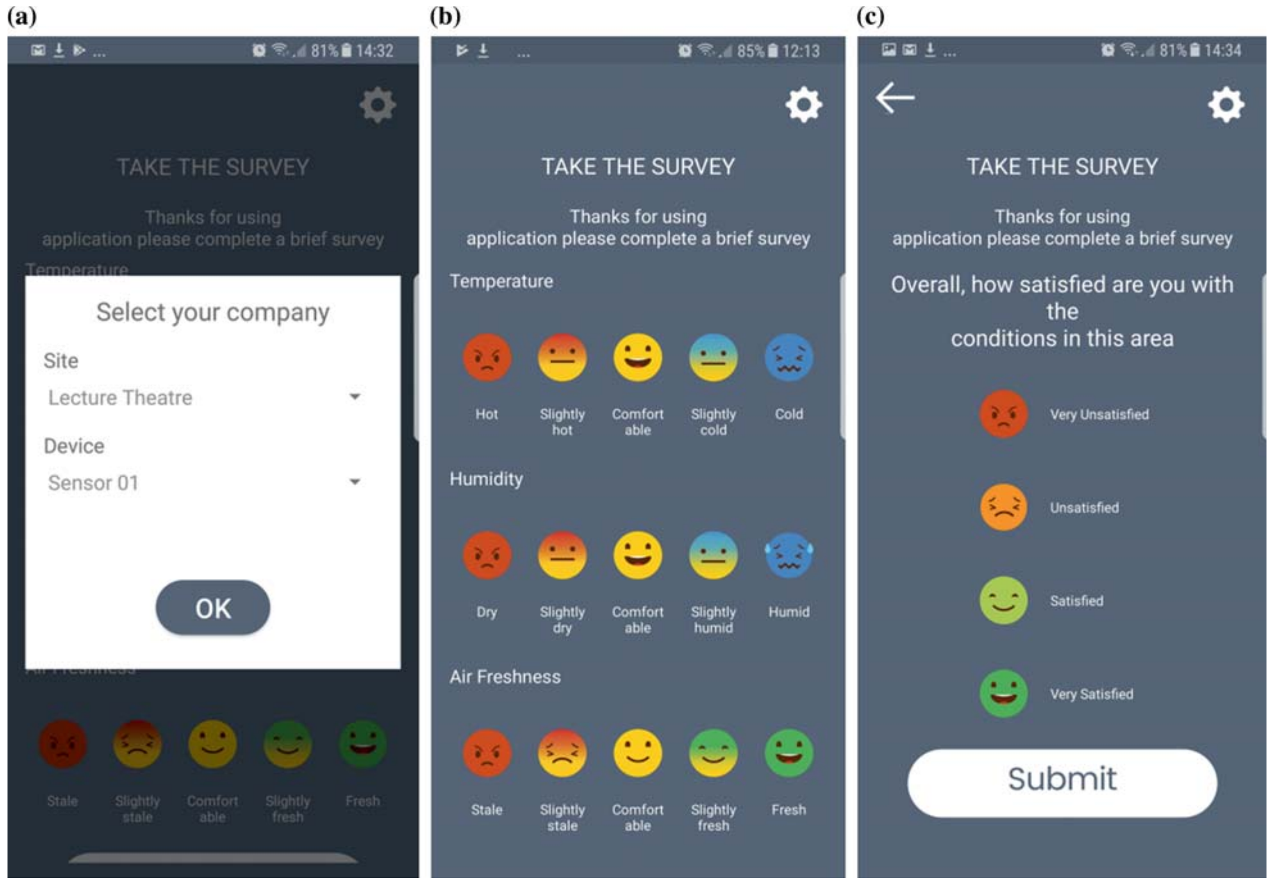


Fig. 79.4 Mobile app GUI

79.5 Testing and Initial Data Collection

The Android tablet app was tested on Samsung Galaxy Tab 4 and Tab A. The Android mobile phone version of the app was tested on Samsung galaxy S8, S7, S6, S5, S4, J7 and J5 phones. The iOS app was tested on iPhone 5, 6, 6s, 7 and 8.

An initial trial data collection using this system will be conducted to capture data in lecture theaters in a tertiary institution. The sensor network will be placed inside the theatre, and students will report their perceptions about the indoor conditions. This proposed trial data collection will also provide anonymous data about space utilization. The app (in its Android and iOS versions) will be hosted publicly during the trial. The University's Human Research Ethics Committee has granted approval for this data collection activity, and the trial is planned to occur in 2018. The lecture theater floor area is 166.33 m^2 with a balcony of 147.12 m^2 and it has the room capacity for 160. The layout of the lecture theatre and sensor placement is shown in Fig. 79.5.

The two types of data is statistically analyzed to investigate whether the two set of data are correlated. Theoretically, within the comfort boundaries of physical conditions, the occupant perceptions of the indoor conditions will remain a comfortable state. If the physical conditions go outside the comfort boundaries, the occupant perceptions will reach a state of discomfort. During this analysis process both quantitative and qualitative data can validate each other.

The data can identify zones that do not meet the set points in physical measurements (standards for indoor conditions); and the occupant perceptions (discomfort/dissatisfaction), which can be directly connected to building management systems to rectify the issues or help building managers to investigate the issues. Additional details about this pilot data collection, data correlation, data analysis and results are reported elsewhere [22].

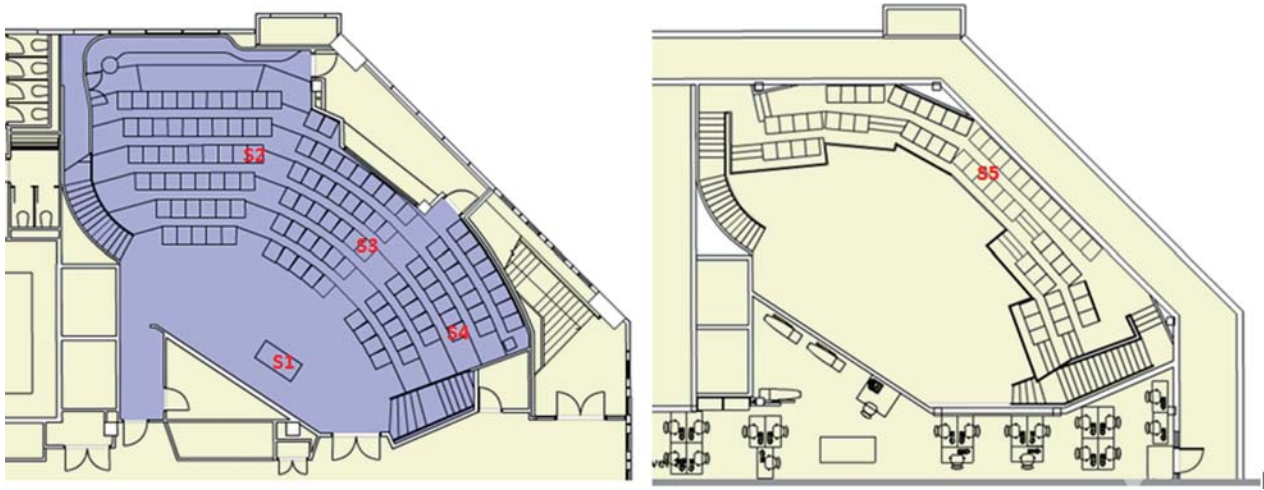


Fig. 79.5 Sensor placement in the lecture theatre

79.6 Conclusions

To fill the gaps in the POE research domain, we propose a holistic system. This system is also expected to provide a practical and powerful tool for both space designers and facility managers. This paper has discussed the development of a live, cloud-based, system for collection of both qualitative data on physical environments, and qualitative data on occupants' perception of building performance. Verification and validation of the survey will be undertaken as part of ongoing work on the project. This cloud-based system will also be extended to include context awareness and reasoning by correlating the qualitative and quantitative data sets. This real-time reasoning feature will be beneficial for space design, as well as for facility operation and management.

Future work will also include expanding the types of environmental sensor to include light sensors, digital microphones, CO_2 sensors, and object/IR (Infra-red) temperature sensors that can provide context-rich information about the use of the space. Given the growing interest in and use of building information modelling (BIM) in facility management, we also envisage linking this system with BIM. The resulting fully functional live system is expected to facilitate a BIM ecosystem integrated with other operational systems [6], and thus collaboration between parties, including planners, designers and facility managers, through live data collection, data analytics and visualization.

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