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Defining and demonstrating a smart technology configuration to improve energy performance and occupant comfort in existing buildings: a conceptual framework

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Abstract

Purpose – To achieve the building and property by 2050, decarbonisation goals will now require a significant increase in the rate of improvement in the energy performance of buildings. Occupant behaviour is crucial. This study seeks to guide the application of smart building technology in existing building stock to support improved building energy performance and occupant comfort.

Design/methodology/approach – This study follows a logical partitioning approach to the development of a schema for building energy performance and occupant comfort. A review of the literature is presented to identify the characteristics that label and structure the problem elements. A smart building technology framework is overlaid on the schema. The framework is then applied to configure and demonstrate an actual technology implementation for existing building stock.

Findings – The developed schema represents the key components and relationships of building energy performance when combined with occupant comfort. This schema provides a basis for the definition of a smart building technologies framework for existing building stock. The study demonstrates a viable configuration of available smart building technologies that couple building energy performance with occupant comfort in the existing building stock. Technical limitations (such as relatively simple building management control regimes) and pragmatic limitations (such as change management issues) are noted for consideration.

Originality/value – This is the first development of a schema to represent how building energy performance can be coupled with occupant comfort in existing building stock using smart building technologies. The demonstration study applies one of many possible technology configurations currently available, and promotes the use of open source applications with push-pull functionality. The schema provides a common basis and guide for future studies.

Keywords Building energy performance, Post occupancy evaluation, Indoor environmental quality, Internet of Things, Smart buildings

Paper type Research paper

Introduction

Continuous global population growth has driven a significant increase (around 2.5% annually over the past decade) in the gross floor area of our built environment. This is set to double again by 2050 (UNEP, 2020). By comparison, over the past decade, energy efficiency measures in the built environment have reduced the delivery energy usage per m^2 by around just 1% per year overall. More extreme weather events and a growing demand for energy services in our buildings has lifted energy consumption in the built environment to 36% of global energy use (IEA, 2020). With rising population, more extreme weather and greater focus on occupant comfort, the control of internal temperature is now the fastest-growing use of energy in buildings (Bezerra *et al.*, 2021). Electricity consumption in building operations represents nearly 55% of electricity consumption worldwide (UNEP, 2020). Progress in the building and property sector

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towards its 2050 decarbonisation goals, incuding the World Green Building Council, Net Zero Carbon Buildings Commitment (World Green Building Council, 2021), is losing momentum. It is estimated that a 5-fold increase in the rate of decarbonisation is now required, if the 2050 goals are to be achieved (UNEP, 2020).

Occupant behaviour is known to play a crucial role in the reduction of energy consumption in a building (Paone and Bacher, 2018). The most successful driver of effective behavioural change in reducing energy consumption, requires a combination of building performance monitoring coupled with appropriate feedback to the occupants (OECD, 2017). However, despite a significant technical improvement in the field of smart building management systems (smart BMSs), for high-end new developments and sustainability retrofits, the majority of existing building stock is still unable to monitor or manage building performance with sufficient sophistication (Jia *et al.*, 2019). The BMS is a computer-based system that monitors and controls mechanical and electrical equipment of the building, including heating, ventilation, air-conditioning (HVAC), fire and security systems (Brooks *et al.*, 2018). Effective performance feedback to the occupant is then also problematic, because there is insufficient data granularity (Dong *et al.*, 2019). When data is available, typically it is aggregated across an entire building, floor or building management zone. Building performance data is rarely localised to an individual room or occupant (Sayed and Gabbar, 2018). This especially reflects the majority of existing BMSs, which still depend on relatively simple, zoned set-point control regimes to manage the building energy services (Jia *et al.*, 2019).

It is long recognised that people experience the environmental factors that drive occupant comfort (temperature, air quality, noise, etc.) differently (Asadi *et al.*, 2017). It is also known that individual microclimates can vary significantly within the same building, between immediately adjacent spaces serviced by the same building-conditioning infrastructure, and even within the same contained space (Pérez Galaso *et al.*, 2016). Consequently, building energy management systems struggle to optimise energy use whilst still providing a satisfactory level of comfort to all occupants across all environmental factors (Minoli *et al.*, 2017). This common failure to provide a satisfactory level of individual comfort is especially important because environmental comfort is a key driver of staff productivity and general well-being (Al Horr *et al.*, 2016).

The notion of smart building infrastructure involves the live capture of performance data using a network of digital sensor and monitoring devices to better manage the building and its occupants (Brilakis *et al.*, 2020). Over time, the performance data can be used to model and simulate the interaction between buildings, the external environment and people, and thereby improve overall energy use and/or occupant comfort (Khajavi *et al.*, 2019). However, despite the increasing deployment of building performance sensors and the development of ever more intelligent BMSs, the density of data points achieved still tends to be inadequate to register or control differences across the microclimates of individual building occupants (Gao *et al.*, 2021). The sensors being deployed also tend to focus on limited environmental factors (Humphreys, 2005). Further, legacy BMSs often lack the sophistication or infrastructure to control building performance with the required fidelity (Minoli *et al.*, 2017). Occupants are generally left out of the information feedback flow (Delzendeh *et al.*, 2017), and post-occupancy building evaluation is infrequent, perception-based and aggregated at best (Hassanain and Iftikhar, 2015).

This study follows a logical partitioning approach to the development of a schema for building energy performance and occupant comfort. The schema is used to define a smart building technology framework for existing building stock, which is then applied to configure and demonstrate an actual technology implementation. First, a review of the literature is presented in order to identify the problem characteristics. There have been a number of very recent and systematic reviews of the relevant topics, and therefore the literature review for this study leverages and draws directly on the findings of those reviews. Second, based on the findings of the literature review, a schema is developed for building energy management and occupant comfort. This schema labels and structures the problem elements. Third, a smart building technology framework is overlaid on the schema. This framework represents how smart building technology can be applied to each of the key problem elements. Fourth, the smart building technology framework is used to identify and configure a feasible demonstration of available smart technology for the existing building stock.

Methodology

This study aims to define a framework and demonstrate a configuration of smart technology to improve building energy performance and occupant comfort in existing building stock. A schema of building energy performance and occupant comfort in existing building stock is developed as the basis for the technology framework. A schema is broadly defined as an organising structure of knowledge about a concept that guides the processing of new information (Fiske and Taylor, 1991). The notion of a schema has origins largely in cognitive psychology, where it is typically used to characterise how generic concepts are stored in memory as data structures (Rumelhart, 1975). Learning theory leveraged this notion as the basis for a transactional approach to teaching and learning (McVee *et al.*, 2005). More recently, the schema has been formalised as a powerful representation of knowledge in machine learning and for logical data structures in database design (Tillmann, 2017).

In the particular setting of research, the notion of a schema has been adapted and applied to reduce the data complexity and ambiguity associated with a problem – what Balogun and Johnson (2004) describe as a process of "sensemaking". For example, Hunt (2010) pioneered the use of a schema in the development of marketing theory, applying schema as the primary organisational mechanism to enable more systematic investigation and theory development. In smart building applications Balaji *et al.* (2018) applied the concept of a schema to represent energy management, but in that case the schema is used more literally as a database design specification. This study adopts the schema in the same sense as Jimenez *et al.* (2013), as a "logical partitioning" that structures the problem for investigation and understanding. The logical partitioning approach requires the phenomenon in question to be specified through a process of definition and labelling. Definition comes from a review of the problem literature, to identify the relevant problem characteristics. These characteristics are then labelled and arranged in logical relationship to one another to form the schema (Jimenez *et al.*, 2013).

The logical partitioning schema approach is appropriate to building energy performance and occupant comfort because extensive research already exists on all key aspects of those phenomena in isolation, and the contained application domain of smart building technology in existing building stock limits the number of options for which competing schemas might make sense. The developed schema then provides an important instrument for future research, as it offers a point of reference against which to draw conclusions about potentially missing problem characteristics, and to challenge ineffective or poorly evidenced labelling. The more immediate purpose of the schema in this study is to enable a smart building technology framework to be formulated across each of the schema elements. A technology framework is a set of elements presented in a normative architecture, to aid understanding and study (Traoré, 2017). Based on the proposed framework, an actual smart building technology configuration for existing building stock can be demonstrated.

Literature review

Multiple previous studies have presented effective improvements to building performance using next generation smart building technologies (Minoli *et al.*, 2017). Smart building technologies integrate physical building components with a network of digital sensors commonly referred to collectively as an Internet of Things (IoT), creating a Cyber Physical System (CPS) or Digital Twin (Verma *et al.*, 2019). Sensors, actuators and controllers (which collectively operationalise building digital twin systems) have become increasingly resilient, smart, multi-factored and affordable (USDeptEnergy, 2020). However, a systematic review of smart building features, functions and technologies highlighted that the retrofit of existing building stock is a particularly significant challenge, with critical research gaps around the inclusion of external parameters (such as climatic conditions) and occupant needs as key performance indicators (Dakheel *et al.*, 2020). An in-depth state-of-the-art review of research particular to IoT applications for smart buildings also identified a number of key challenges, including: the need to verify proposed technology configurations through practical applications; the adoption of standard/open communication protocols; and the effective integration of data acquired in multiple formats for multiple purposes (Jia *et al.*, 2019). A state-of-the-art review of digital twin applications to the construction industry found no common definition of digital twin in that context, and concluded that future research should focus on barriers to the successful implementation of digital twin technologies (Opoku *et al.*, 2021). The same review highlighted a significant research gap particularly focussing on the operational and decommissioning phases of a building (Opoku *et al.*, 2021).

The particular challenge of applying smart building technologies to existing building stock is also highlighted in several reviews of research studies focussed on operational energy cost and/or consumption. Schmidt and Åhlund (2018) concluded that only a minority of such studies addressed the integration of existing BMSs or included external weather conditions, and none described a general methodology for turning existing building stock into closed-loop CPS/smart building systems. Dong *et al.* (2019) included the management of energy along with visual comfort and indoor air quality in a comprehensive review of sensor technologies. The Building Energy Management System (BEMS) is a complement to the BMS which monitors and controls the building energy consumption more specifically (Beucker *et al.*, 2015). A review of more than 40 case studies published between 2005 and 2018 by Dong *et al.* (2019), highlighted the extent of the potential energy savings possible with occupancy-based sensors at up to 70% of HVAC energy consumption and 40% of light energy consumption. However, the same review identified a critical future research challenge to be the combination of visual, thermal, air quality and acoustic comfort monitoring to satisfy individual occupant preferences.

The review of adaptive-predictive control strategies (APCS) for HVAC systems in smart buildings by Gholamzadehmir *et al.* (2020) focussed more on advanced control strategies than on the traditional BEMS capabilities found in much existing building stock. A traditional BEMS is often restricted to set-point controls that operate to maintain building services within set functional limits, based perhaps on seasons, days of the week, operational hours, or other basic environmental measures. The capacity of a traditional BEMS to control the microclimate environments of individual occupants is also limited, controlling services at best to the level of building zones of multiple spaces, and/or to multiple occupants as aggregates. However, even the advanced HVAC control capabilities reviewed by Gholamzadehmir *et al.* (2020) identified the monitoring, modelling and promotion of effective occupant behaviour to be a key research challenge. The review concluded that this challenge can only be addressed partially through the use of sensors, and requires more direct engagement with occupants through more frequent feedback on active comfort perceptions and provision of building performance measures. This "human-in-the-loop" issue is the particular focus of a critical review by Lee and Karava (2020), which recommends far greater attention be given to how valid occupant feedback responses can be collected, as such data is core to the learning methods that underpin APCS models.

Closely allied to research on the application of smart building technologies is the integration of IoT in building information modelling (BIM) (Hosseini *et al.*, 2018). A review of BIM integration for existing buildings by Mohamed *et al.* (2020) found that BIM applications are significantly hampered by the lack of quality BIM models for most existing buildings, and the data exchange barriers that remain between BIM, BEMS and other facility management systems. Insufficient software interoperability, along with the general lack of actual BIM applications in the operational phase of a building were also identified as a critical research gap in the review by Yang *et al.* (2021). A comprehensive critical review of BIM applications in smart buildings by Panteli *et al.* (2020) had a particular focus on the operational/post-construction phase application of BIM. Once again, the review revealed major interoperability challenges still facing the proposed combination of BIM with real time building performance data in existing buildings. A finding echoed by the survey of facilities management professionals was reported by Dixit *et al.* (2019). Studies such as Rogage *et al.* (2020), Valinejadshoubi *et al.* (2021) and Hilal *et al.* (2019), demonstrate that BIM does have potential application in the future for the operational phase of a building. Overall, the research on BIM integration with other smart building technologies at the operational phase of a building is still at an early stage of development, and is largely theoretical in substance at this time (Panteli *et al.*, 2020).

Beyond the technical aspects of smart building technologies, there is increasing public awareness, and concern, with the effects that poor indoor environments can have on occupant comfort, health and productivity (Hong *et al.*, 2017). Studies show that occupant comfort is primarily dependent on the immediate temperature, humidity, air quality, noise and lighting levels (Al Horr *et al.*, 2016). Each of these factors has been studied extensively to determine acceptable comfort levels for occupants of buildings. For example, the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) are widely used in design guides and standards as aggregated targets for thermal comfort (Martell *et al.*, 2020). The significance of interaction between environmental parameters has been recognised (Clausen and Wyon, 2008), noting that the perception of comfort is a composite response across several key factors (Huang *et al.*, 2012). Further, as a comprehensive review of the occupant behaviour literature by Delzendeh *et al.* (2017) indicates, the perception of comfort also depends on multiple contextual factors. The factors identified by Delzendeh *et al.* (2017), and broadly confirmed by (Day *et al.*, 2020a), include the following: the sense of agency (capacity to adjust conditions by such actions as opening/closing blinds, wearing more or less clothing, moving location, etc.); physiology (people have very different physical sensitivities to a given level of environmental factors); emotion (moods and temperaments impact perceptions); and psychology (herd mentality and peer pressure, for example, can influence behaviour and perceptions). International standards do seek to draw this myriad of occupant comfort factors together, to provide a single, comprehensive index for each key factor (for example, ANSI/ASHRAE Standard 55–2020 for thermal conditions). However, whilst the use of stochastic representations is showing some promise (Paone and Bacher, 2018), a single, combined measure across multiple key factors is not considered feasible at this time (Humphreys, 2005).

In summary, a review of a series of recent systematic literature reviews consistently concludes that a particular research gap exists for practical applications of smart building technologies to the operational phase of a building, and specifically to the existing building stock. This study addresses that gap. The literature review also highlights the need for developed systems to demonstrate that internal, occupant and external performance metrics can be integrated effectively within a coherent data ecosystem. This study is structured around internal space, occupant experience and external environment factors. Whilst BIM offers potential to provide a coherent data ecosystem in theory, practical BIM integration at the operational phase of a building remains only a future possibility. Given the aim of this study is to identify and then demonstrate the practical realisation of a smart technology configuration using technology already available for existing building stock, BIM technology does not feature in this particular configuration beyond noting its future potential.

A building energy performance and occupant comfort schema

The schema representation of a typical BEMS is presented in Figure 1. For most practical purposes the energy performance of a building is traditionally considered down to the level of a zone. A single zone might represent an entire building level, a large space with multiple occupants, or a cluster of multiple smaller spaces with either individual or multiple occupants in each. Effectively, each zone has discrete infrastructure to deliver building services (such as heating, cooling, lighting, air-conditioning, etc.), and discrete BEMS controls to manage the energy consumption of those services (including automatic or manual thermostats, light switches, automated dampers, etc.). Each zone of a building is then separately managed by the BEMS within an overall control strategy established by the building facility manager. The control strategy will be informed by occupant feedback on their experience of comfort in the space, but formal occupancy evaluation is typically infrequent and occupant feedback on their comfort is largely anecdotal (Hassanain and Iftikhar, 2015). Alternatively, the control strategy may be configured to provide environmental conditions based on generalised comfort standards and guidelines, such as ANSI/ASHRAE Standard 55–2017: Thermal Environmental Conditions for Human Occupancy. Operationally, the BEMS control strategy responds to the feedback it receives from the various sensors that monitor the performance of the BEMS infrastructure in delivering the intended spatial settings. The BEMS sensor data and occupant feedback are, in turn, often supplemented by external environmental data feeds and systems reporting on factors such as local climate conditions, occupancy rosters, energy tariffs, etc (Sayed and Gabbar, 2018). The external environment can also mitigate the impact of external factors such as climate on a given zone, due to effects such as overshadowing and shielding.

Some emerging smart buildings do have capacity to monitor and control the internal environmental conditions down to the microclimate of an individual occupant (Kim *et al.*, 2019). However, typical BEMS, and certainly the majority of those deployed in existing building stock, are rarely able to manage environmental conditions separately for individual building occupants. Rather, occupants in a single BEMS zone will be treated as an aggregate, and individuals will experience potentially quite different microclimates of air quality, levels of lighting, etc. to other occupants, even occupants of that same zone. Each zone will be monitored by a limited number of sensors (possibly only a single sensor) which makes microclimate variations indiscernible. Each zone will be serviced as if it were a single regime, even though all manner of local factors (ducting, orientation, layout, overshadowing, occupancy, etc.) can significantly influence the microclimates created within a zone (Sayed and Gabbar, 2018).

The proposed schema representing the BEMS and how an individual occupant experiences comfort is presented in Figure 2. Any human experience is a complex of cognitive, emotional, physiological and behavioural processes (Yetton *et al.*, 2019). That is, according to the prevailing

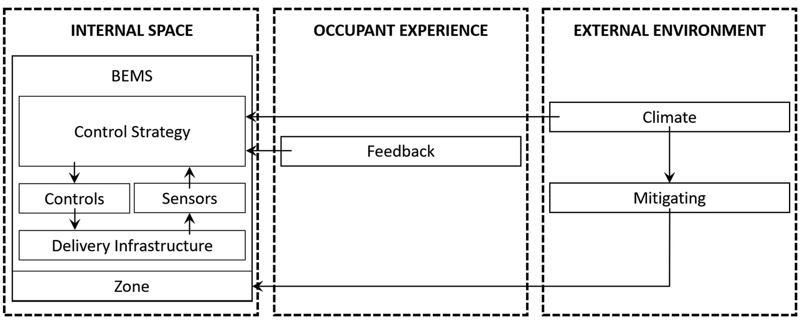

Figure 1.
The schema representation of a typical BEMS

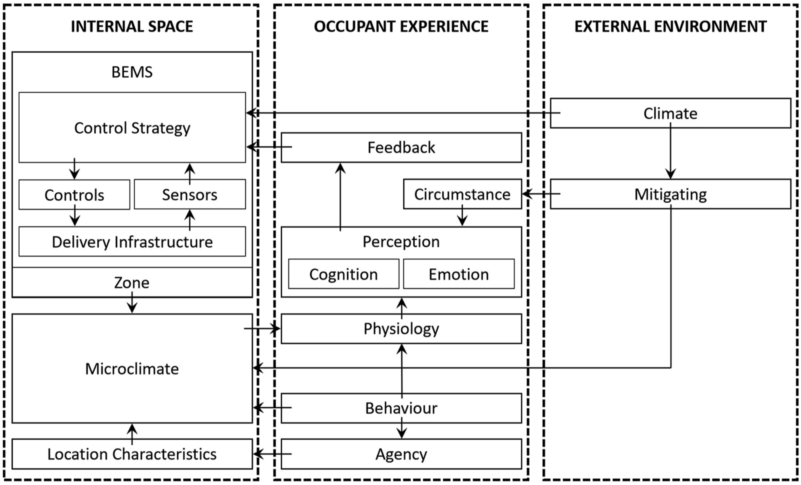

Figure 2.
The combined schema for BEMS and occupant comfort

transactional theories (Lazarus and Folkman, 1987), experience comprises an actual physiological arousal and behavioural response in combination with (given personal meaning by) a perceptive appraisal of those sensed conditions. An experience must be sensed and perceived (Langdon and Sawang, 2018). The sensed physical conditions are those of the immediate microclimate, driven primarily by the building services delivered to that location by the BEMS and as influenced by external environmental factors (weather, position of the sun, etc.), and the physical characteristics of the location (orientation, layout, density of occupants, etc.) (IEA, 2017). The microclimate conditions are also influenced by the adaptive behaviour of occupants (opening/closing windows or doors, opening/closing window blinds, turning on/off artificial lights, moving locations, etc.), and changing the characteristics of the location (use of discrete heaters or fans, wearing more or less clothes, etc.), where this is possible. Non-adaptive behaviour (reporting/ignoring any discomfort, etc.) and the overall sense of personal agency can also impact the capacity for adaptive behaviour to influence location characteristics. Further, even under the same microclimate conditions, any two occupants may respond differently, based on their individual physiology, emotional characteristics and other personal circumstances. Thus, the same individual may experience comfort differently in exactly the same microclimate conditions, but at different times, when their personal physiology, behaviour and/or emotional circumstances might vary (Al Horr *et al.*, 2016).

Occupants experience comfort as a dynamic response to the combination of a physical microclimate environment (influenced directly by the BEMS, the external environment, and immediate physical location characteristics), adaptive behaviour (clothing, window shades, etc.), non-adaptive behaviour, and the physical and emotional circumstances of the individual. Because all of these factors and how they interrelate will be complex and variable, the dynamic occupant experience of comfort needs to be monitored continuously, with a high frequency of measurements and over time (longitudinally).

A smart building technology framework for existing building stock

To effectively apply smart technology to improve building energy performance and occupant comfort, all elements of the combined BEMS and occupant comfort schema need to be replicated within a network of digital sensor and monitoring devices. Figure 3 provides a simplified framework of available smart digital technologies which overlay each of the

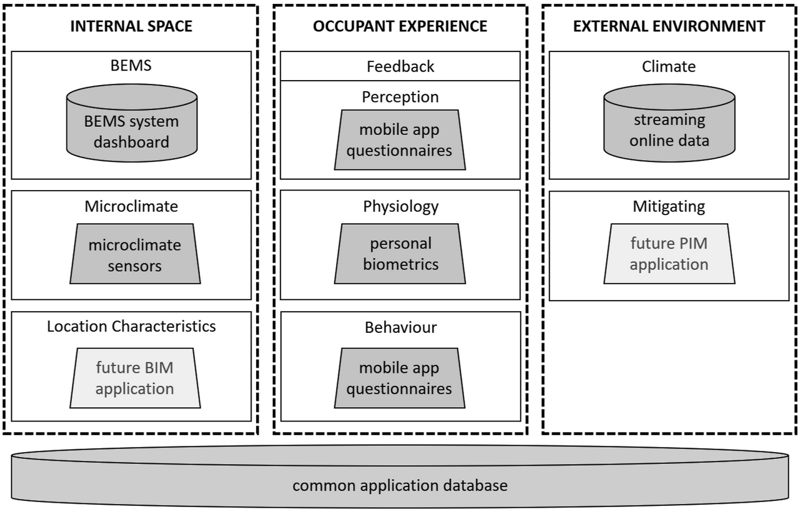

Figure 3.
The smart building technology schema

significant elements contained in the combined schema. BEMS software applications themselves typically provide an online dashboard-type interface to the live and historical performance data of a building. This information is used by the building facility manager to review and manage the control regimes applied by the BEMS system (Beucker *et al.*, 2015). Many of the various systems that constitute a BEMS currently operate proprietary data networks and formats. However, as the problems of maintaining and managing multiple discrete systems grow, and market competition increases, the move to open source and common data standards is accelerating (Minoli *et al.*, 2017). In any event, various digital exchange protocols already exist (such as API's) to enable a common application database to interface with many third-party BEMS dashboards and their respective databases.

The performance parameters of an individual microclimate can be monitored using a combination of individual sensors (temperature, humidity, noise, air quality, etc.). However, there are also now devices available that contain multiple sensors to measure multiple parameters using a single device. Current sensors have various levels of accuracy, costs, network capabilities, data access provisions and sizes. However, affordable, consumer-grade devices are readily available that can be deployed unobtrusively to monitor individual microclimates and provide live data feeds across all key environmental comfort parameters. Data can variously be stored in the device for later download, and/or be networked using several alternative technologies. For example, many IoT devices are currently able to utilise cellular network solutions such as NB-IoT, LoRa or Cat-M1, satellite, Bluetooth and/or Wi-Fi connectivity.

Location characteristics are significant, but relatively stable over time. A key potential for the future application of BIM at the operational stage of a building is to provide a digital record of individual location characteristics – the geometry, layout, components, maintenance and other details (Becerik-Gerber *et al.*, 2011). At this time, where a relevant BIM model is unavailable, an inspection record of the location characteristics can be maintained in a simple spreadsheet or other data management system used in general building facility management.

Changing focus from the internal space to the occupant experience of comfort, the conventional approach to monitoring experiences is to use psychometric instruments (questionnaires, interviews and the like) to obtain occupant perceptions of their comfort and well-being (Coulacoglou and Saklofske, 2017). This approach provides an important source of data, but can only access the perceived reflections of an individual – a relatively narrow window into how an occupant is experiencing a space in comfort terms. Further, is the infrequency with which psychometric instruments can be administered, and the importance of follow-up surveys to check reporting consistency. Online survey technologies are readily available, and these can make administration easier with potentially increased frequency and greater participation. Also, it is increasingly common for online survey capabilities to be incorporated into mobile applications which can then both push and pull information to participants. For example, an application running on a mobile device might pull information as to when an occupant enters a particular geo-space/location, or is in close proximity to a particular sensor device of known location. Such information might then be used by the mobile application to only push prompts to complete a questionnaire when the occupant is in a particular location – such as the personal workspace. The push function can also be used to prompt a participant to complete a questionnaire at more frequent intervals, or in particular circumstances (such as when the occupant has been in a specific location for a specific length of time, or when the environmental parameters of a specific microclimate exceed certain values). Push also allows the system to provide certain information to the occupant, such as air quality alerts, daily summaries of building performance, aggregated comfort reports, etc. This can be significant in supporting and promoting the sense of personal agency, which can positively influence the comfort behaviour of an occupant (Day *et al.*, 2020b). The pull function can then be used to collect questionnaire responses and other feedback.

Given careful ethical consideration, the physiology of an occupant can be monitored using various forms of biometric sensor, from personal health and activity trackers (for example, heart rates), to medical grade wristbands (for example, electrodermal activity), to mobile electroencephalogram (EEG) devices (for example, brain activity). Physiology is of interest because the physical response itself contributes directly to the experience of comfort. However, studies also demonstrate that the same sub-conscious processes that trigger many physiological responses are deeply implicated in emotional states (Yetton *et al.*, 2019). For example, certain variations in electrodermal activity directly indicate heightened emotional arousal. Thus, the data from selected biometric devices can also be used empirically to measure perception (cognitive and emotional) responses, including the level of stress and other drivers of how comfort is experienced (Samson and Koh, 2020).

Monitoring occupant behaviour can also raise some difficult ethical and privacy issues. Psychometric instruments are a common solution as these make the study process more transparent, but they also share many of the same difficulties as discussed previously for occupant perceptions more specifically. Again, mobile application questionnaires can improve the frequency of responses and number of participants in a study. Camera-based technologies that use live video streams and machine learning to monitor behaviour are beginning to appear in construction more generally (Huang *et al.*, 2021). Seghezzi *et al.* (2021) present an evaluation of such a camera-based technology to monitor building occupant behaviour in the specific context of better space management and cleaning, but this is a preliminary evaluation only. The use of mobile application questionnaires best represents immediate smart technology capabilities.

External environmental factors such as climate can be incorporated into a smart technology framework as a special case of the microclimate monitoring, using the same microclimate sensors to monitor external conditions as were previously described for internal spaces. However, a range of online streaming data services are readily available that provide accurate, if somewhat more aggregated, readings of external temperature, humidity, etc. The benefit of these online services is that they typically have extensive historical data available that can also be used to inform the BEMS control strategies.

In a similar way to the locations characteristics previously described, the factors that mitigate the external environment are also relatively stable over time. The equivalent BIM functionalities that potentially provide a digital record of individual location characteristics are now being developed and implemented at the precinct scale to combine multiple BIM models and associated geographic information system (GIS) data into a single, consolidated model (Plume *et al.*, 2017). Like BIM, however, precinct information modelling (PIM) is not widely implemented or readily available for operational buildings.

Arguably, the most critical component of a smart technology framework that couples building energy performance with occupant comfort is the common application database. This data exchange hub acts to provide a common point of contact between the BEMS, the microclimate and biometric sensors, streaming data and the mobile application. BEMS control strategies can then draw more directly (and potentially in real time), on the microclimate performance, external climate conditions and occupant comfort feedback. Occupant comfort perceptions can be influenced by empirical data on overall building performance settings, external environment factors, individual microclimate performance across a range of environmental parameters, and comparative measures of occupant comfort over time and between occupants. The BEMS can be made more responsive to the comfort of actual occupants in a particular space at any given time. Occupants can also exercise more agency in response to their actual microclimate conditions. Data collected in the common application database over time can be analysed to identify issues and opportunities to improve building performance relative to occupant comfort. Data collected over time can also form the basis of models with the potential to predict changes in occupant comfort and optimise BEMS control strategies accordingly.

A demonstration smart building technology configuration for existing building stock

The intention of a technology framework is to generalise a set of elements that can be realised in a variety of ways. A significant consideration for any framework is also the practicality with which it can be realised (Traoré, 2017). To demonstrate the potential of the proposed technology framework for existing building stock in practice, an integrated, effective and affordable implementation has been trialled successfully for a commercial building in Australia.

Core elements of the framework demonstration are shown in Figure 4.

The trial demonstration is implemented in an existing commercial building that combines teaching and office/administration functions on a major university campus in Australia. The trial demonstration is part of an ongoing longitudinal study of building performance and occupant comfort optimisation at the university. The building comprises a single basement level car park, with 6 above ground levels of combined teaching and office space, and a gross floor area approaching 30,000 m^2. Completed in 2015, the building has undergone several minor refurbishments to upgrade facilities and general building services. Various sensor technologies have been added piecemeal to the BEMS for monitoring and control purposes, but management and control is still based on defined zones that cover multiple spaces.

The BEMS used in this building is common across all buildings on the immediate campus. It is operated using a typical BEMS (Environmental Automation, 2021) and supporting monitoring system (Optergy, 2021). The BEMS harvests data from, and interacts with, multiple bespoke building services systems (for energy, water, heating, etc.). It also ingests relevant data from external sources including online streaming data services (local weather, utility tariffs, etc.), and other business administration services (room booking systems, maintenance schedules, etc.). With appropriate access permissions, the same data being incorporated into the BEMS can also be shared with other software systems using standard Application Programming Interfaces (API's). This includes the common application database

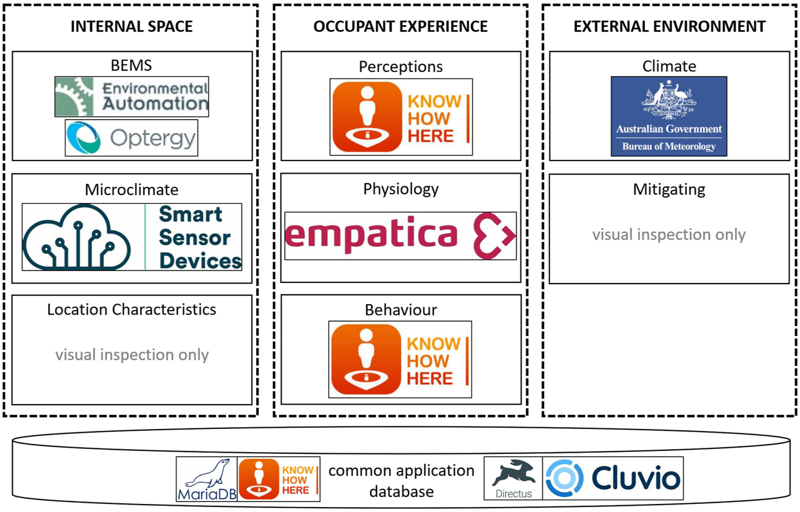

Figure 4.
Smart digital technology demonstration configuration (images sourced from various websites, as referenced in the following text)

at the core of the current framework demonstration. Whilst direct data exchange using API's is entirely possible, for the purposes of this trial, selected data has been exported and transferred as standard CSV format files. Access to online streaming data services (such as the Australian Government Bureau of Meteorology, 2021) is managed directly using standard API protocols by the common application database.

The current building BEMS implementation does not incorporate individual occupant biometrics or microclimate performance data. There is, however, a range of consumer and medical grade wearable devices capable of monitoring personal biometrics, including heart rate, blood volume and electrodermal activity. This trial implementation used a medical-grade wristband (Empatica, 2021) to monitor individual blood volume pulse, beat interval, electrodermal activity and peripheral skin temperature. Collectively, these biometrics enable heightened emotional responses to external environmental factors (such as comfort) to be synchronised in time and analysed. Data is collected every few seconds, and can either be stored on the device for later download, or streamed to a database of choice. For the purposes of this trial, data from each device is downloaded for analysis as standard CSV format files.

Sensor technology is developing at a rapid rate. For the purposes of this trial a single personal air quality monitor (PAQM) device (Smart Sensor Devices, 2021) has been used to monitor the microclimate of individual occupants. This PAQM is a compact and affordable wireless device that records localised temperature, humidity, lighting and ambient pressure, along with the standard Air Quality Index (AQI) and particulate matter (PM.10, PM2.5). The sensors used have the following tolerance ratings:

(1) Temperature, range: $-20\ldots65$ °C. Accuracy: $\pm$ 1 °C

(2) Humidity, range: $0\ldots100\%$ rH. Accuracy: $\pm$ 3% rH.

(3) Ambient light: 1…128 kLux. Resolution: 100mLux

(4) Pressure, range: 300…1,100 hPa. Accuracy: $\pm$ 0.6 hPa

(5) Particulate matter (PM1.0 & PM 2.5): resolution 0.3 μg/m^3. Max Error: $\pm$ 10%

Data from the PAQM was streamed directly to the common application database using a combination of Wi-Fi and Bluetooth technologies. A separate PAQM device was deployed to the work desk of each participant, and the environmental parameters of the immediate microclimate were recorded continuously at 2–3 min intervals.

A specially commissioned mobile application built on a commercial platform (KnowHowHere, 2021) was used to pull occupant comfort perceptions from participants using a customised occupant comfort survey instrument. The common application database for this trial demonstration project was also part of the mobile application platform. Survey responses were automatically added to the common application database. To improve the frequency of participation in the survey, the push functionality of the mobile application enabled regular reminders, alerts and summary data to be sent to individual participants whenever they were in the immediate vicinity of their allocated PAQM device (work space).

The common application database was built around an open-source data management system (MariaDB, 2021) as part of the mobile application platform. The common database ingests data from multiple sources using standard API's and equivalent communication protocols. It is administered using an open-source headless content management system (Directus, 2021). In this way, data streams from otherwise discrete applications were integrated into a single data representation. To then process and render the common data for display and use by the mobile application, interactive dashboards and analytics reports were generated using customised R scripts on top of SQL queries (Cluvio, 2021). Thus, the mobile application platform, with its associated database management systems, provides the all-important data coupling between BEMS and occupant comfort.

The common application database is a central repository for all data harvested from the BEMS system, external streaming data online, personal biometrics, microclimate sensors and mobile application questionnaires (occupant perceptions). The mobile application platform then manages the ingestion of the data sources, along with the presentation of data and its analysis to inform participating occupants and the building facility manager on the operational performance of both the building services and occupant comfort. Over time, this coupled data will be used for further analysis and simulation model development, where the resulting models can be used to predict and optimise building performance with occupant comfort (Sun and Hong, 2017).

Discussion

The built environment offers a critical site for potential energy savings to combat global warming, and for improved occupant comfort to enhance well-being and increase productivity. Emerging smart building technologies are enabling these benefits to be realised increasingly in high-end new build and sustainability retrofits. However, the substantive proportion of buildings globally still operate using relatively simple BEMS control regimes, which fail to engage building occupants in the behavioural change that is so critical to delivered energy use reduction. There is an immediate and pressing need to improve the building energy performance and the comfort of occupants in existing building stock. This study seeks to develop and apply a schema for BEMS and user comfort requirements to create and demonstrate a smart building technologies framework to make available key smart technology benefits to existing building facility managers.

At the core of the developed technology framework is a common application database that couples the management of building energy performance directly with the actual and perceived comfort of individual occupants. The opportunity for this comes from recent developments in IoT sensor and communication technologies that enable largely open source and affordable integration of building, occupant and the broader external environment digital twins (Bécue *et al.*, 2020). However, by no means do these technologies currently represent all aspects of buildings, occupants and the environment. The availability of affordable sensors does not guarantee they are entirely accurate. Despite impressive performance at the price point (currently US$275 per device), the sensors used in this trial are patently inferior to the most accurate sensors available. The PAQM sensor used also has various connectivity limitations (2.4 GHz Wi-Fi only, Bluetooth 4.2), power (Micro USB only) and other current restrictions. Realistically, these are teething issues not fundamental challenges. The capabilities of IoT sensor technologies are advancing rapidly, costs are falling, and devices are becoming increasingly reliable, portable and more discrete (Arup, 2019).

The choice of biometric sensor for this study is a relatively expensive, medical-grade device, where various consumer-grade (and more affordable) devices are now becoming available with comparable capabilities. There are also restrictions placed on the range of personal mobile devices able to run any given mobile application by the app stores that deploy such applications (Google Play and Apple App Store, for example). Specifically, the app stores restrict any new mobile applications to versions that only run on the most recent generations of Android and IoS operating systems. In addition, not all BEMS and third party systems allow API connectivity, meaning that not all existing building stock will qualify immediately for the version of the technology configuration demonstrated in this study. However, despite the various device limitations identified for this study, the underlying schema does usefully apply already to a significant proportion of existing building and occupant situations, and that proportion is growing rapidly as the technical limitations are addressed.

More generally, as with any system involving human interaction, there are potentially more pragmatic issues to consider. For example, implementation of the demonstration system has taken several months to achieve because of increased security concerns (and hurdles) associated with any Wi-Fi enabled connectivity to business systems. In this case, a university-wide DeviceNet Wi-Fi network configuration has been created, separate to the standard Wi-Fi network supporting regular student and staff network access. The DeviceNet operates over the same infrastructure as the regular Wi-Fi, but employs a restricted protocol that enables IoT devices to exchange data and connect to the internet without compromising the security of the information technology infrastructure overall. Practically, however, the proposed technology framework does require an appropriate network system available to connect the sensor devices throughout a building.

In addition to cyber security issues, there are also likely to be individual and business concerns associated with data security relating to the performance of buildings and the behaviour and performance of occupants. Energy consumption, occupant productivity and other measures potentially included in the common application database may well have commercial and ethical sensitivities. Particular care is required when building and managing the common application database to ensure the likes of access permissions, data governance and the provenance of data are adequately protected (Loukids *et al.*, 2018). This is standard, good operational practice, and generally will simply conform to existing policy and procedural guidelines.

More subtly perhaps, but no less a potential issue, is the common resistance to operational change of any sort (Goncalves, 2007). Building facility managers may not welcome the potential for greater scrutiny and focus on the performance of a building at the microclimate level (not to say, the potential for increased agency on behalf of occupants). Occupants may not welcome the potential for increased monitoring of their behaviour (actually or perceived). It is incumbent upon the leaders of such change to address potential resistance by highlighting the opportunity to increase energy savings, improve occupant wellbeing, and/or promote productivity gains, for example. The effective adoption and application of the proposed schema, like any organisational change, demands careful management.

Another significant challenge facing the implementation of the proposed schema, and highlighted in the particular situation of this demonstration study, is where the technical limitations of a BEMS are unable to effect the necessary environmental changes at every microclimate level. If the BEMS system, like most extant systems and BMS infrastructure, is unable to control individual microclimates separately (because they can only operate across zones, for example), there is the recipe for occupant disappointment and increased dissatisfaction with comfort. However, even where there is only an aggregated setting possible across a zone, that setting can be better managed when there is data available on actual occupancy, and/or the collective preferences of that particular group of occupants is better known. Each individual may not end up with their exact environmental preferences, but the overall level of comfort can certainly be improved and optimised against energy use. For example, in the demonstration study the temperature setting and control for a row of offices along an external wall was controlled by a single sensor device (thermostat) placed in a small internal space used to house a bank of photocopiers. When there is a run on photocopies, the temperature of that room increases significantly, the BEMS seeks to cool the space, and all of the associated offices are cooled unnecessarily, and often to the considerable discomfort of connected office occupants. When each microclimate is being independently monitored, at the very least, the BEMS response can be more measured across the microclimate conditions of the entire zone.

Against benefits such as the increased agency of occupants, more accessible and timely data, improved user comfort, etc., overall building performance optimisation must also factor in the energy usage and costs (Alesky and Bauer, 2020). A BEMS that is constantly starting and stopping based on dynamic changes to multiple occupant comfort levels, is unlikely to be running efficiently. Not every building facility manager would support increased awareness of actual microclimate environmental values, especially if the BEMS is unable to respond and adjust accordingly. There are many genuine practical issues including cost and data proprietary to consider before enacting the proposed smart building technology framework in full. Nevertheless, with increasing concern over health and wellbeing in the built environment, the potential for significant productivity gains, and the possibility of reducing overall energy consumption, any more direct coupling of building energy performance and occupant comfort has to be considered. This potential coupling, of course, is the same promise offered by smart buildings more generally. The proposed schema shows that many of the same benefits now being realised in new builds and sustainable retrofits, are also possible for existing building stock.

Conclusion

The study develops a schema for BEMS and occupant comfort. This schema is overlaid with a framework for smart building technologies. The framework is implemented using available smart technologies. The technologies comprise the BEMS system dashboard, streaming data online, personal biometrics, microclimate sensors and mobile application questionnaires. The BEMS and occupant comfort coupling is achieved through a common application database which operates as a data exchange hub combining internal space, occupant experience and external environment parameters. The practical viability of a smart building technologies ecosystem is demonstrated for an existing commercial building.

Technical limitations of the study are discussed. These relate to the relatively simple extant BEMS control regimes, accuracy of the sensor devices, and other various current biometric and connectivity technical limitations. However, the demonstration study shows that the proposed schema does usefully apply already to a significant proportion of existing building and occupant situations, and that proportion is growing rapidly as the various technical limitations are addressed.

Pragmatic limitations of the study are also discussed. These largely equate with the regular issues associated with any digital technology change management: cyber security and working through legacy systems; business and individual data sensitivities; resistance to change; and the like. With careful management, the opportunities to increase energy savings, improve occupant well-being, and promote productivity gains are real and achievable.

More generally, the schema is presented as a basis for future research through which the various components, relationships and labels can be examined in more depth, challenged and improved. Similarly, the particular smart building technologies used in the demonstration of the technology framework are only a single instance of many possible options and alternative combinations of technology. Future studies will usefully demonstrate the relative strengths and weaknesses of other and new options as they emerge.

Finally, this study has developed and demonstrated the viability of a smart building technology configuration for existing building stock. The broader utility of the underlying schema and proposed technology framework has been argued here. However, future studies will be required to realise that utility empirically through the deployment and operation of actual implementations over time. Only then will the potential benefits to energy use and occupant wellbeing be empirically monitored, recorded, analysed and fully evidenced.

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