Continuous IEQ Monitoring System: context and development

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Abstract

Addressing two common challenges for building performance – reducing the carbon footprint attached to the provision of comfortable indoor environments, and improving the health and wellbeing of occupants – requires a more comprehensive understanding of how the indoor environments of buildings are operated. This paper introduces SAMBA, a state-of-the-art monitoring station for continuous, real-time measurements of indoor environmental quality (IEQ) parameters from occupants' work desks. It combines a hardware solution that integrates a low-cost suite of sensors with a software platform designed to automatically analyse and visualize data for quick interpretation of IEQ performance by non-scientist. In addition to feeding a massive IEQ database for research, the resulting data may be used to better inform the metrological requirements for popular international IEQ rating schemes. This new era of indoor environmental monitoring based upon systems such as SAMBA affords a fundamentally new approach to built environmental field research that holds significant promise to improve building performance and indoor environmental quality and occupant satisfaction, health, wellbeing and performance.

Keywords

Indoor environmental quality; continuous monitoring; building performance; sensors; analytics; measurement

Highlights

- Discusses the technological innovations that have led to activity in IEQ monitoring systems
- Outlines the market drivers for low-cost continuous IEQ monitoring in offices
- Introduces a low-cost IEQ monitoring system for use in office buildings
- Details the sensor hardware and cloud software platform for data analysis and visualisation
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1. Introduction

The 1/9/90 rule-of-thumb on service sector enterprise operating costs suggests that 1% is attributable to energy costs, 9% to building rental costs, and the remaining 90% is attributable to payroll for personnel (WGBC, 2014). These simplistic generalisations are broadly applicable to the over 25 million square metres of commercial office floor space in Australia (PCA, 2017), explaining why occupant health, comfort, wellbeing and productivity sit at the top of the list of facility management performance criteria. Companies aspiring to sustainability leadership are now compelled to include management strategies for workplace Indoor Environmental Quality (IEQ). This has resulted in a marked increase in uptake of IEQ rating systems requiring monitoring of physical indoor environmental conditions for input to IEQ performance metrics (ASHRAE, 2009), but undertaking these measurements of IEQ in an efficient and robust manner has proven difficult (Heinzerling et al., 2013).

The principal aim of this work is to describe the development and performance of a low-cost, pervasive indoor environmental quality (IEQ) monitoring system intended for use in commercial office buildings. The present paper introduces a hardware solution for autonomous IEQ data acquisition and the cloud software platform for data transformation, synthesis, storage and visualisation. The following paper will assess the performance of the SAMBA system and place it within the context of measurement requirements and sampling protocols of relevant IEQ standards.

2. Technological context

The concept of a comprehensive array of sensors for automated IEQ monitoring is not new, with perhaps the earliest attempt being the analog *thermal comfort meter* described by Korsgaard & Madsen (1971) that measured and then integrated the requisite individual thermal environmental parameters into the Predicted Mean Vote (PMV) comfort index (Fanger, 1970). Nicol & Humphreys (1973) developed a similar research-specific comfort logger, and a commercially available, integrated scientific comfort assessment system was used in lab studies by Olesen (1982). Heinzerling et al. (2013) offer a thorough summary of a number of mobile, integrated systems developed for thermal comfort field studies from the 1990's. Typical of that era is the

'Sputnik' thermal comfort cart developed for detailed thermal comfort field studies that would go on to form part of the ASHRAE RP-884 database (de Dear, 1998), from which the first adaptive thermal comfort standard (de Dear & Brager, 1998; ASHRAE 2004) was derived. 'Sputnik', like other systems in its class, consisted of an assembly of off-the-shelf, laboratory-grade transducers mounted onto a mobile platform, typically a cart of some sort, and connected to a centralised data acquisition and storage device.

Since 'sputnik', the technological context in this area of indoor environmental monitoring has shifted dramatically following the availability of very low-cost hardware and open-source software targeted initially at the hobbyist market. Popular single-board microcontrollers like *Arduino©* or *Raspberry Pi©* have been readily adopted for the development of IEQ monitoring systems (e.g. Ali et al., 2016; Carre et al., 2016; Edirisinghe et al., 2012; Habibi, 2016; Mui et al., 2016; Salamone et al., 2015), effectively removing the limitation of carts requiring colocation of sensors through the use of autonomous, wireless technologies. But these systems appear to be proof-of-concept or project-specific tools, and therefore limited in scale.

The present section describes three technological innovations that have prompted a flurry of activity in IEQ monitoring systems, including the development of the SAMBA indoor environmental monitoring system under discussion. It is our belief that this new era of indoor environmental monitoring based upon systems such as SAMBA affords a fundamentally new approach to built environmental field research, due to the following factors.

2.1 Internet of Things

Whilst the term has been overused and quickly become passé, the underlying concept of the Internet of Things (stylized as IoT) represents the overarching framework of the technological revolution unfolding over the past 20 years. Coined by Kevin Ashton at the turn of the century, the term IoT generally refers to the proliferation of network-addressable devices embedded in everyday objects, allowing them to invisibly interact and cooperate to reach common goals (Chen et al., 2012; de Maruo et al., 2015; Gubbi et al., 2013; Mainetti et al., 2011). IoT is also used interchangeably with

ubiquitous computing (Weiser, 1993), although UbiComp doesn't necessarily imply coordination between devices.

The digitisation and 'datafication' of previously unquantified events and processes is made possible by the 'things' being pervasive in presence and context-aware. Gartner (2016) forecast the number of connected devices to reach over 20 billion 'things' by 2020. Whilst these devices are capable of generating prodigious volumes of data, bringing a unique set of challenges in itself (Gibson, 2010), they present opportunities to gain novel insights through innovative applications and analysis, particularly in the built environment. Prominent examples include the smart energy grid (Bui et al., 2012) or next-generation building management systems (Hong et al., 2012; Jang et al., 2008; Kazmi et al, 2014; Schor et al., 2009; Wu & Noy, 2010).

2.2 Wireless Sensor Networks

Whilst the IoT may be considered the conceptual framework to describe the connected world, the enabling technology is the wireless sensor network (WSN). A wireless sensor network normally has a large number of wireless sensing devices (often referred to as nodes) placed in and around the phenomena of interest (Akyildiz et al., 2002) to measure and disseminate useful information. Nodes are equipped with a sensor to measure their immediate environment, a microprocessor to convert the raw signal of the sensor into useable data, and then a transmitter to send the data packet. Such devices have been made possible by the prevalence of configurable, multifunction integrated circuits (IC) at low price points permitting dense distribution of sensing devices. And whilst there is significant potential for microelectro-mechanical systems (MEMS) (Sohraby et al., 2007) due to their small size, low power requirements and modest unit cost, more traditional sensing technologies will continue to be shoehorned into WSN nodes until MEMS technology matures.

In most WSN architectures the sensor nodes are not designed for computationally intensive tasks, but instead wirelessly transmit only the required, partially-processed data to a central collection and storage point (Akyildiz et al., 2002). This is often achieved through a mesh network configuration in which each sensor node communicates with peer nodes to relay data packets to the end-point (Jang et al.,

2008). The centralised infrastructure forms the middleware layer of the system and is responsible for coordination between the different ends of the network as well as data fusion, storage, analysis and visualization. Because the server is often located remotely, data transmission from the local network of nodes to the final repository may be performed by a gateway device. This logical network topology allows for the efficient capture of high-resolution, contextualised data from many different and often diverse environments (Chen et al., 2012) that can be analysed using cloud computing resources to generate significant insight for the end-user through a web service.

In order to realise the promise of the IoT paradigm, there is a need to deploy large-scale WSN using technologies that are platform, protocol, and device agnostic (Gubbi et al., 2013). Continued development of open wireless technologies like Wi-Fi, Bluetooth, and RFID has overseen the growth of IoT uptake and WSN implementation, but the major obstacle remains the harmonization of non-interoperable information and communication technologies and proprietary protocols. As a workaround, most machine to machine (M2M) interactions employ IP-based networking and web services as a *de facto* standard due to ease of development and a lack of a more universally endorsed or open alternative.

2.3 Big Data

Defining 'big data' is difficult considering the term's misuse and voguish nature in popular media. But the term is used here in reference to datasets so large and complex that they present a unique set of management challenges for contemporary technologies. Under the Internet of Things framework, wireless sensor networks have rendered data ubiquitous and cheap, with the rate of data produced growing at around 40% each year (Fan & Bifet, 2013). Laney (2001) characterised this as a three-dimensional expansion; volume, velocity, and variety of data. The ease with which data can now be generated has largely outpaced useful applications for it. There are persistent computational challenges around storage, analysis and visualisation, particularly considering that much of it is likely to be of little or no interest to anyone for the foreseeable future. But if effectively managed and filtered into robotically resolvable formats, there is potential for machine learning methods to efficiently analyse datasets to provide valuable insight (Wu et al., 2014).

Despite high levels of interest from academia over the last 20 years, most developments within the realm of big data analytics have come from industry, leading to the development of Business Intelligence and Analytics (BIA) tools to improve operational efficiency and automate strategic decision-making (Chen et al., 2012; Labrinidis & Jagadish, 2012; Lavale et al., 2010; Lohr, 2012; Wu et al., 2014). Leading technology companies continue to innovate in the area of artificial intelligence, machine learning, and data mining, representing an industry estimated at US$100 billion and currently growing at twice the rate of the software industry as a whole (Gibson, 2010). Most popular BIA platforms provide powerful data visualisation tools that democratise analytics for non-experts through easy-to-use web tools and dashboards.

In much the same way that accurate measurement of phenomena heralded significant advances in modern science, big data may represent yet another step in the evolution of scientific practice. The popularity of Chris Andersen's (2008) piece on the potential of big data to upend the scientific method lead to a lively and wide-ranging debate within the academic community (de Maruo et al., 2015; Labrinidis & Jagadish, 2012; Mazzocchi, 2015). The basis of Andersen's argument is that the accumulation of vast amounts of data on a given phenomenon supersedes the need for testable hypotheses. Instead, advanced data mining techniques that efficiently sift through large datasets find patterns and relationships relating to something of interest, and the interpretation is developed *post hoc*. In other words, correlations arising from data-driven research overtakes hypothetico-deductive reasoning in knowledge production. It is our belief, much like Mazzocchi (2015), that inductive inferences steering scientific progress should be closely scrutinised, and that big data science should be regarded as just another, albeit powerful heuristic tool. Even with the rise of technology-based empiricism, the fundamental role of science remains the ascription of meaning to phenomena, not simply observing occurrences. This caveat applies equally to built environmental research as it does to other domains. In IEQ, there will always be a place for subjective evaluations of indoor environments by their occupants. Objective, instrumental measures, regardless of spatio-temporal resolution, are not in themselves sufficient to characterise indoor environmental quality. Nonetheless, big data science

has the potential to profoundly augment existing research methods aimed at understanding indoor environmental perceptions of building occupants.

3. The built environment context

The built environment offers broad scope to implement new technologies for optimisation and improvement of IEQ and energy efficiency, with the significant co-benefits of increased occupant health, comfort, wellbeing and performance, along with reduced environmental and climate impacts. The latest IPCC estimates (2014) indicate that 32% of global final energy use and 19% of energy-related greenhouse gas emissions are attributable to buildings. The majority of this energy expenditure occurs during the operational phase, with end-use largely related to the provision of IEQ. In Australia, it is common for commercial office tenancy agreements to include clauses requiring narrow control (±1°C) around indoor setpoint temperatures that are significantly lower than recommended in the authoritative international thermal comfort standards such as ASHRAE 55-2010 (Roussac & Bright, 2012). Whilst several studies have demonstrated that every 1K widening of the heating and cooling setpoint temperature deadband in the right direction results in up to 10% savings in HVAC energy (e.g. Yang et al., 2014), building operators may be reluctant to relax control in fear of breaching their tenancy agreement.

The technological paradigm outlined in this paper are not groundbreaking in many domains, but uptake in the buildings sector remains relatively slow. Roussac & Bright (2012) offer compelling explanations for tardy adoption of new technologies, including the extended lifecycle of buildings, legacy infrastructure, and inflexible long-term lease agreements with detailed specifications on building operation like the temperature set-point example given earlier. Most importantly, the "net rent" basis of common leasing arrangements in Australia, the UK, and the USA, see the tenant paying for energy costs, providing no incentive for landlords to make capital investments to improve building services beyond what is delivered. These aspects of lease management conspire against to create arrangements where the provision of IEQ remains the purview of building owners, and largely out of the control of the tenants who actually occupy the space (Wong & Mui, 2009). Despite these constraints, the Global Real Estate Sustainability Benchmark Report (GRESB, 2015) found

Australian and New Zealand property companies outperformed their overseas counterparts in key environmental, social and governance indicators. This demonstrates a willingness on the part of the top-tiered commercial property owners to differentiate themselves from "the rest" and deliver demonstrably superior space to their tenants, particularly in terms of sustainability, and more recently, indoor environmental quality (IEQ) and "building wellness."

3.1 Indoor Environmental Quality

Over the past five years there has been phenomenal growth in the interest in IEQ issues throughout the Australian commercial building sector, driven largely by a deepening faith in the causal connection between indoor environment and the productivity and performance of office workforces (Al horr et al., 2016; Leaman & Bordass, 1999; Leaman & Bordass, 2007; Thomas, 2010). Although scientific evidence supporting the IEQ-productivity nexus is highly contentious due to the complications surrounding dependent variables like cognitive performance (e.g. de Dear et al., 2013; Altomonte & Schiavon, 2013), there seems little doubt that more satisfied building occupants with higher levels of wellbeing generally translate into better outcomes for the organizations leasing the building (Newsham et al., 2008; Sakhare & Ralegaonkar, 2014). Nowhere has the growth in IEQ interest been more obvious than in the sector's aggressive pursuit of certification from IEQ accreditation schemes and rating tools. The two dominant national building sustainability rating tools in Australia are the National Australian Built Environment Rating System "Indoor Environment" (NABERS, 2015) and the Green Buildings Council Australia's "Green Star - Performance" (GBCA, 2015). International certification programmes include the US Green Building Council's Leadership in Energy & Environmental Design (USGBC, 2013) and the International WELL Building Institute's WELL Building Standard, which has swept through the Australian commercial property sector in recent years. These rating schemes have served as powerful market drivers and motivators for building owners and operators to meet or, in the case of the premium grade offices, to exceed performance guidelines (Malmqvist, 2008).

Appraisal of IEQ normally employs two data acquisition strategies: occupant surveys and instrumental measurements of indoor environmental parameters. The former,

often referred to as Post-Occupancy Evaluation (POE), collects qualitative data on occupants' subjective evaluations of the indoor environment of their workplace (Nicol & Roaf, 2005). Although there is no universally standardised POE protocol, mostly online tools have been developed (see Peretti & Schiavon, 2011) to automatically deploy surveys and collect responses to questions ranging from individual ratings of thermal comfort to overall satisfaction with the indoor environment. The most prominent of these are the Building Use Studies (BUS) methodology developed in the UK (Leaman and Bordass, 2001), and the US equivalent by the Centre for the Built Environment (Zagareus et al., 2004). More recently in Australia, the Building Occupant Survey System Australia (Candido et al., 2016) has become the *de facto* national POE tool. Whilst web-based POE surveys have evolved as a pathway to amassing databases of subjective building evaluations, there remain problems around the opportunity costs of having more than half the building's population of occupants spend more between 30 to 60 minutes filling in a questionnaire. There are also problems around contextualising responses and extracting meaningful insights from occupant feedback. Confounding factors such as industrial relations climate in the workplace, staff morale, and myriad personal issues all potentially exert influence over how an office population rates their workplace environment (Frontczak & Wargocki, 2011; Levin, 1996). For these reasons, subjective assessments are often fused with instrumental measurements of environmental parameters. These objective data are considered a "ground-truth" or "reality check" on the subjective responses gained through POE, and will therefore remain a valuable requirement for the valid assessment of building IEQ for the foreseeable future (Heinzerling, 2012).

Objective measures of IEQ are generally grouped into four distinct categories: thermal comfort, lighting, indoor air quality and acoustical quality (Bluyseen, 2010; Loonen et al., 2015; Wei et al., 2016). Compartmentalisation of IEQ categories is reflected in the different standards pertaining to relevant areas of expertise; for example ASHRAE Standard 55 for thermal comfort (2013) and ASHRAE Standard 62.1 (2016) for ventilation and indoor air quality. Investigations of the effects of environmental conditions on occupant comfort traditionally isolate or control individual parameters in simplified experimental designs rather than considering the complex multi-modal interactions that impact occupants in actual office buildings (Levin, 1996; Mui & Chan, 2005; Olesen & Seelen, 1993). As a workaround, findings

are often integrated into IEQ 'models' or indices (e.g. Rohles et al., 1989; Mendell, 2003; Olesen & Seelen, 1993) that combine the effects of the constituent areas by applying weighting coefficients to them according to their assumed relative impact on overall occupant satisfaction. The output is a single, summative IEQ evaluation. For example, a meta-analysis by Frontczak & Wargocki (2011) found occupants considered thermal comfort to be the most important IEQ factor, followed by acoustic comfort. The same ranking was confirmed in their follow-up analysis of the CBE database (Frontczak et al., 2012). Several criticisms have been levelled at these and other IEQ models due to the presumed linearity in relationships between IEQ factors (Kim & de Dear, 2012), completely ignoring interaction effects (Heinzerling et al., 2013), and a lack of standardised measurement protocols (Kim & Haberl, 2012a,b).

Pressure from industry on the IEQ research community to develop a single, summative index of building IEQ performance for the purposes of benchmarking is only expected to increase in the near future. Paramount to this objective is the establishment of a standardised measurement protocol, as well as clear articulation of how the data is used to appraise IEQ performance. The suggestion by Heinzerling et al. (2013) for simple compliance or noncompliance measures seems sensible in light of the uncertainty around other methods. Simply ratcheting up the operational targets towards 'better' performance in the form of tighter temperature controls or lower pollutant concentrations seems certain to drive practices that lead to excessive energy use for no discernible improvement in occupant comfort, health or wellbeing. For IEQ models to advance there needs to be a clearer understanding of which environmental indicators are valid proxies for occupant satisfaction, and a stronger appreciation for the metrological issues surrounding those measures.

3.2 IEQ monitoring

The accurate characterisation of indoor environmental conditions inside a building comes down to a spatio-temporal sampling problem. Most physical parameters commonly used in IEQ appraisals exhibit significant variability over a plethora of time and space scales, and accurately hitting a moving target with instrumentation poses several technical and logistical challenges. The spatial variance of IEQ is evident between floors, as well as across a single floorplate at the HVAC zone level -

perimeter versus core zones, east versus west zones in morning and afternoon, north versus south zones in summer versus winter. Some IEQ parameters demonstrate variances at the scale of personal microclimates of individual occupants. For example, air speed is known to vary significantly over very short distances (tens of centimetres) due to fluid dynamics produced by air-supply vents and the often-complex flow patterns occurring within a furnished and occupied room with diverse heat sources and cold surfaces scattered unevenly throughout. Even specific indoor air pollution concentrations such as Total Volatile Organic Compounds (TVOC) demonstrate sharp spatial gradients and variations, depending on proximity to emission sources such as cleaning agents, particular pieces of furniture, or even some fit-out materials such as drapes.

The temporal dimension of IEQ parameters within buildings is characterised by gradients, cycles and variations across multiple timescales. These range from second-to-second turbulence, through diurnal cycles, up to synoptic-scale changes in the daily weather conditions outside the building, up to seasonal-scale variations in solar position, external shading, and general outdoor meteorological environment. Time-series data of air temperature and relative humidity within office buildings demonstrate complex ebbs and flows as HVAC systems start-up, respond to changing thermal loads, and then switch-off at the end of "occupied hours". IAQ bellwether parameters such as CO_2 concentrations, widely used as a proxy for ventilation rates (Seppanen et al., 1999) and occupant density (Ke & Mumma, 1997), also reflect the tidal flows of building occupants at the start, middle and end of the working day. The mix of daylight to artificial lighting inside a building responds to the sun path arc from one side of a building to the other through the course of a day, while the background noise level inside a contemporary sealed-façade office building is overwhelmingly dominated by occupant density fluctuations throughout the working day.

The central tenet of the present paper is that the wave of innovation in pervasive sensor technologies, wireless communication protocols, and data mining analytics dissolves these spatio-temporal sampling problems and opens up hitherto inaccessible avenues for new IEQ research. A new generation of building management and control systems (BMCS) utilising an IoT framework by deploying dense WSNs for

environmental monitoring and building operations (Menzel et al., 2008) are capable of generating unprecedented insight into commercial office building IEQ performance. These networks, comprised of easy-to-deploy, cost-effective sensors, replace or augment traditional hard-wired systems that are often heterogeneous in implementation (Mainetti et al., 2011) and too coarse in resolution (Gubbi et al., 2013) to properly capture the variability of IEQ inside a building. Highly localised environmental sensors capable of monitoring the micro-environments to which individual occupants are exposed for the duration of their working day are of much more use than wall-mounted sensors currently deployed for fixed-infrastructure control system networks. This kind of innovation represents a quantum leap in IEQ monitoring that holds significant promise to improve building performance and indoor environmental quality and occupant satisfaction, health, wellbeing and performance.

4. SAMBA - A wireless IEQ sensor network

The IEQ Lab at The University of Sydney has developed SAMBA, an indicative monitoring solution to comprehensively measure IEQ in commercial office buildings. Conceived in 2012, the project involved the development of a patented hardware solution (Aus Patent No. 2015101659) for continuous IEQ measurement, as well as a patented software solution (Aus Patent No. 2015101660) for the automated processing and visualisation of the instrumental data. SAMBA, the 'backronym' for which is Sentient Ambient Monitoring of Buildings in Australia, integrates a low-cost suite of sensors and modest data-processing capabilities to autonomously measure key IEQ indicators (see figure 1). Permanent placement within the occupied zone enables both spatial sampling across the building's floor plate (cross-sectional measurements) and longitudinal measurements through time (all occupied hours for weeks, months, seasons or even years) to fairly characterise the environmental conditions experienced by occupants of office buildings. Resultant data are wirelessly communicated to a centralised web service, known as IEQAnalytics, where a dashboard presents a real-time visualisation of all measured IEQ parameters and calculated indices in an intelligible and actionable format for building owners, facility managers, tenants and occupants. Data are presented alongside the relevant IEQ standards or operational guidelines for the purposes of compliance time calculations.
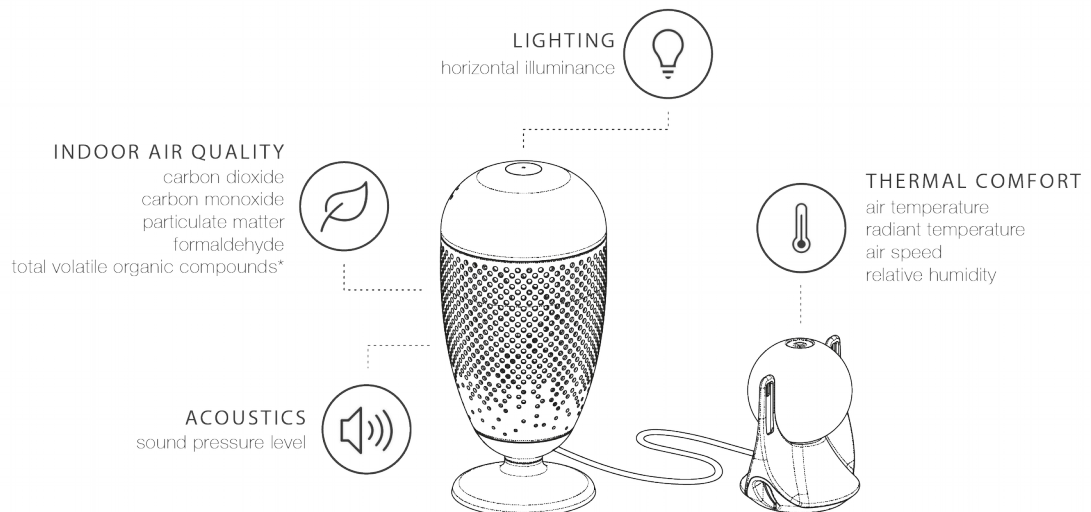
Figure 1. Diagrammatic representation of the SAMBA device, and its measurement capabilities.

The IEQAnalytics platform was designed first and foremost as a research tool, but manifold practical end-uses and benefits of an IEQ performance monitoring system have been identified for the commercial building sector:

- Building owners or building portfolio managers looking towards occupant-centric indices of building performance seeking market advantage in the highly competitive commercial property sector.
- Commercial building tenants seeking to ensure that the building they are leasing is providing an indoor environment at the quality grade specified in their lease.
- Specialist service providers and consultants to the sector who wish to offer evidence of demonstrable quality improvements, such as building services engineering, architects, interior design, and office fit-out firms.
- Relevant government and regulatory bodies who require a cost-effective means of collecting truly representative IEQ performance data.

The remainder of this paper will detail the key design decisions and technical specifications of the SAMBA monitoring systems (section 4) and the associated IEQAnalytics web-service (section 5).

4.1 Housing design

Significant attention was given to the aesthetics of the housing encasing the electronic components because the intention was to have SAMBA placed on desks in the occupied zone of premium-grade commercial offices (see figure 2), often populated by highly paid and quite discerning employees who may be wary of the intrusion of such technology into their immediate workspace. While performance of the sensors was the main design consideration, it was recognised that enclosing an array of devices designed to measure the ambient indoor environmental conditions would involve compromises. The original prototype had all sensors co-located inside a single housing unit. Internal testing showed that there was significant biasing of temperature-sensitive devices by waste heat from other components such as the power-conditioning circuit and other sensors, and this was confirmed by a computational fluid dynamics (CFD) analysis, prompting a decision to 'break-out' all temperature sensitive transducers to a satellite device. A common Ethernet cable that relays power to the satellite device and transmits data back to the processor on the main board using serial communication connects the base and satellite enclosures. Choice of materials for the housing was specifically made to avoid off-gassing of chemical compounds that would interfere with the indoor air quality sensors.
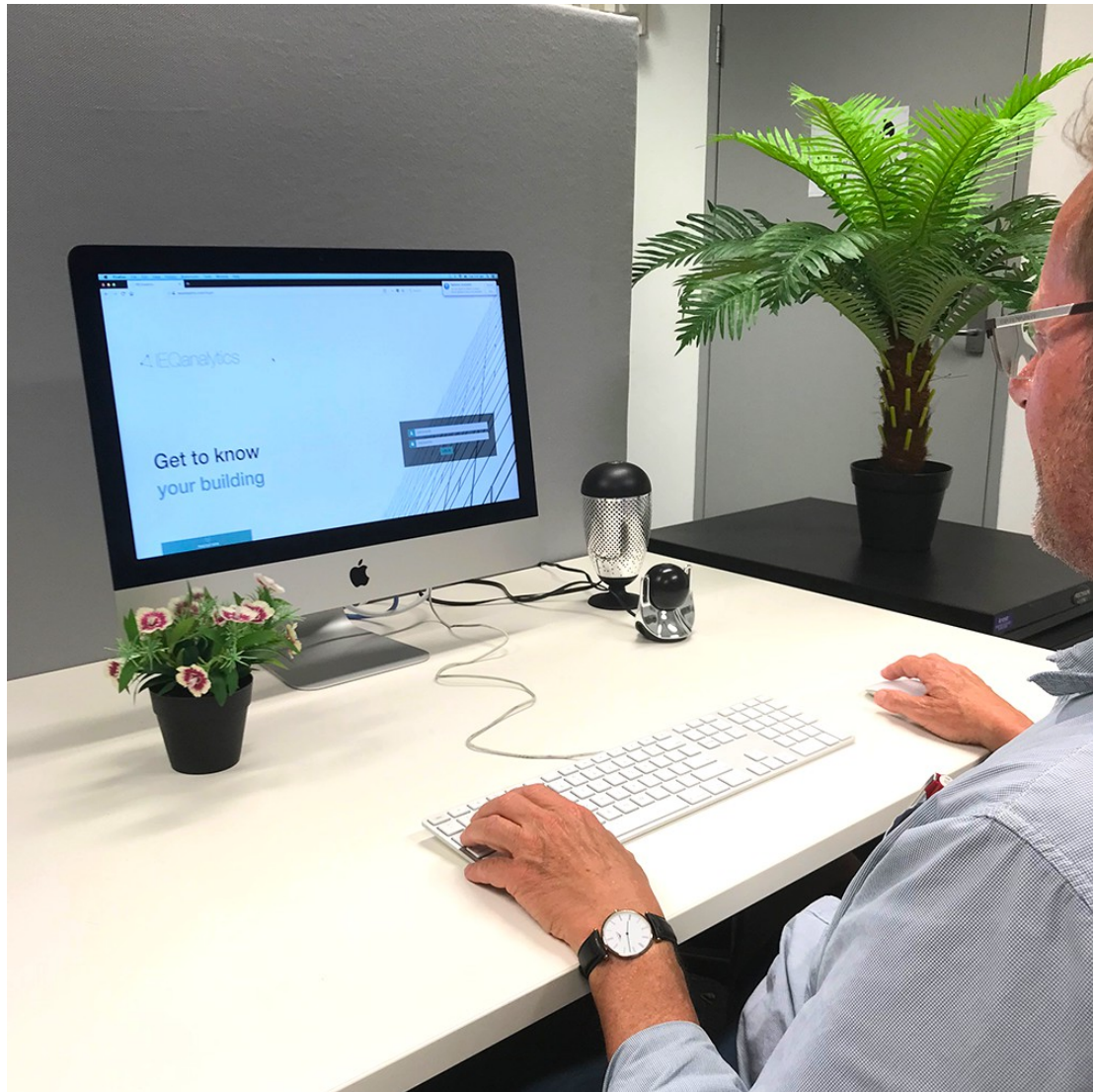
Figure 2. A SAMBA placed in the occupied zone at a desk. The main unit measures 190mm (h) x 90mm (d), and the satellite unit measures 95mm (h) x 95mm (w) x 95mm (d).

4.2 Sensor selection and hardware design

The original prototype device consisted of a selection of off-the-shelf sensor breakout boards attached to an Arduino Uno microcontroller. Open-source software libraries accelerated the sensor selection process by lowering development barriers to initial testing. The decision to move from the open-source Arduino development environment to an embedded system design with bespoke printed circuit board assemblies (PCBA) was made to reduce component costs and permit scalable manufacture and assembly of the devices (see figure 3). Although there was substantial development overhead of switching system architecture from the Arduino AVR to the ARM® Cortex®, the additional functionality and improved performance

of the latter microcontroller unit (MCU) was dictated by the more complex measurement procedures required of parameters such as sound pressure level on the A-weighted decibel scale.
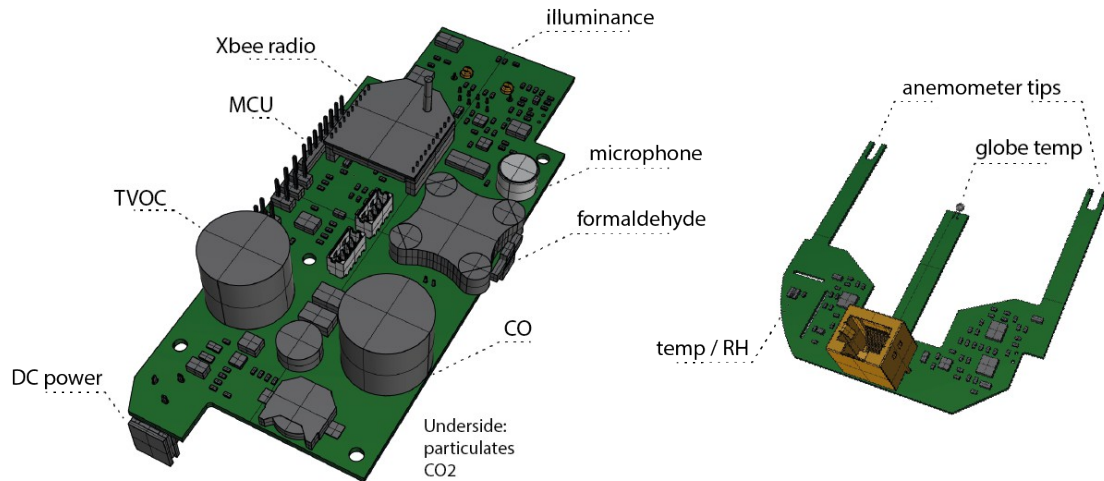

Figure 3. 3D render of the PCBAs inside the main unit (left) and the satellite unit (right). Placement of sensors and important components are shown.

Rather than focusing on laboratory-grade measurement practices appropriate to diagnostic and forensic applications, the sensor performance requirements of SAMBA were scaled to the application – 'good-enough' big data, thus allowing substantial reductions in both hardware costs and end-use operational costs (technical personnel not being required for IEQ data acquisition). This is in line with the suggestion by Heinzerling et al. (2013) and Malmqvist (2008) that the focus should be on inexpensive but accurate and readily available devices that balance cost against scientific relevance for high performance building applications. Apart from cost, other considerations in sensor selections for SAMBA were performance (accuracy, range, sensitivity, resolution, calibration drift), power requirements (supply voltage, supply current), output type (analog, digital), interface protocol (I^2C, SPI), and form factor (through-hole, surface mount, OEM module). IEQ parameters targeted by SAMBA were decided by the requirements for Australia's NABERS Indoor Environment rating scheme. Table 1 lists the measured parameters and the NABERS requirements; further information on sensor performance is given in part 2 of this series Where possible the sensors connect with the PCB using plugs or sockets for modularity, allowing the sensing capabilities to be tailored to the application and thus saving on component

costs. PCB breakouts of power supply and general purpose input/output (GPIO) pins offer a method for expanding sensing capabilities in subsequent revisions to the SAMBA design without requiring PCB modifications.

Table 1. List of sensors included in SAMBA, and their performance specifications

Parameter	Sensor Type	Range	Resolution
Air temperature	NTC thermistor	0 to 50°C	0.1°C
Relative humidity	Capacitive	5 to 95%	0.1%
Globe temperature	NTC thermistor	0 to 50°C	0.1°C
Air speed	Bi-directional thermal anemometer	0 to 1 m/s	0.01m/s
Sound pressure level	Electret microphone	40 to 90 dBA	0.1 dBA
Illuminance	Broadband photodiode	0 to 20,000 lx	1 lx
Carbon dioxide (CO_2)	Nondispersive infrared	0 to 5000 ppm	1 ppm
Carbon monoxide (CO)	Electrochemical	0 to 50 ppm	0.1 ppm
Formaldehyde (HCHO)	Electrochemical	0 to 2 ppm	0.01 ppm
Total volatile organic compounds (TVOC)	Photoionisation	10 to 2000 ppb	10 ppb

Components supporting essential data acquisition capabilities like flash memory, real-time clock (RTC), radio communications, and power were chosen to suit the application requirements of long-term, continuous and autonomous indoor environmental monitoring. On-board data storage and RTC provide the requisite feature set for continuous data sampling and storage if connectivity with the wireless personal area network (WPAN) is lost or intermittent. Xbee radio modules provide a convenient solution to implementation of an *ad-hoc* wireless network based on Zigbee, a low-power communication specification based on IEEE 802.15.4 that is widely used in building automation systems. This ensures that SAMBA could operate effectively without requiring access to the host organisation's (building tenant's) data network. In addition to supporting Zigbee Pro wireless mesh networks, the proprietary firmware for the Xbee module coordinates the self-organising network with features like self-healing, route optimisation, and data redundancy.

On-site SAMBA installation was designed to be a simple plug-and-play procedure with no prior knowledge of the system required. The power conditioning circuit is designed for 12VDC 1A input (typical power consumption of 3.5 W) via a

transformer plugged into a general power outlet. Use of a generic transformer allows for internationalisation by sourcing a suitable power pack in the dominant AC power voltages (90-264 VAC 50/60 Hz) and socket type of a given country. The longitudinal measurement agenda and universal availability of power plugs in commercial offices meant portability and battery-operation were not key design requirements.

4.3 Firmware

The SAMBA firmware is written in C/C++ using the Atmel Studio integrated design environment (IDE). The codebase is comprised of individual libraries for low-level configuration of components and sensors, and the main process responsible for the coordination of time-keeping, sensor outputs, and data processing, storage, packetisation, and communication. Upon powering on the SAMBA device there is an initial warm-up period of 10 minutes to allow for sensor stabilisation, network formation, RTC synchronisation, and flash memory initialisation. Timekeeping is performed on the network gateway device, but is resynchronised with a network time protocol (NTP) server every hour and propagated through the network periodically to prevent significant drift. Once the 10-minute warm-up period has elapsed the device waits until the next 5-minute time-step (e.g. 09:00hrs or 09:05hrs or 09:10hrs) before entering the sampling routine to ensure harmonisation of measurements between SAMBA devices.

The firmware contains two distinct modes of operation that employ different sampling and data processing procedures. The first is a 'factory' or 'calibration' mode that is entered by issuing a command over the wireless network only during the warm-up phase. Under calibration mode the device simply polls each sensor once every 5 seconds and outputs time-stamped measurements via serial for collation downstream, with no error checking or data processing. The second, known as 'production' mode, is entered by default after warm-up. Production mode contains a much more robust sampling routine. Sensors are polled at different frequencies depending on the dynamism and variance of the physical environmental quantity they are targeting. This ranges from 16 kHz in order to properly characterise sound pressure level (SPL) in the audible range, down to 0.2 Hz for air temperature due to its relative stability. Measurements are entered into a buffer only if they pass basic quality-assurance

checks. When detected, spurious measurements in the data stream are discarded and attempts to reinitialise the sensor are made.

The sampling loop runs for 270 seconds, after which the average for each parameter is calculated and saved to SAMBA's flash memory. The remaining 30 seconds of the 5-minute time-step is allocated solely to data communications. The SAMBA alerts the gateway device (see section 4.4) that it has a data packet ready for transmission. If present, the gateway acknowledges the transmission request and confirms receipt so that data packet can be erased from memory, and the device then holds until it re-enters the sampling routine. If the gateway device is not reachable, the SAMBA continually attempts to re-establish a connection but will return to sampling at the completion of the 30-second communication window. On-board memory was sized to accommodate up to a year of data should the SAMBA be offline, and multiple packets can be sent during the communication window if the SAMBA was unable to transmit them for whatever reason. This approach ensures the integrity of the SAMBA time-series data even if the WPAN collapses momentarily.

4.4 Network topology

The Xbee RF modules in SAMBA are configured to use the Zigbee Pro mesh networking capabilities. Under this network topology (see figure 4) the SAMBAs act as 'nodes' that cooperate with other nodes to optimise data relay routes to the coordinating device, known as a gateway. In this application the gateway is equipped with cellular data communication capabilities so it can bridge the WPAN with the wider area network (WAN) for data transfer of collated time-series SAMBA data to a remote centralised server using mobile telecommunications technologies such as LTE. A single gateway is configured to coordinate all SAMBAs within a building, assuming the single mesh network provides coverage for all SAMBAs. There are three distinct advantages of this network topology in the present application. First, creating an *ad-hoc* wireless network does not require access to, interfere with, or disrupt any of the host building's existing services or information/communication networks. Second, cellular communication capabilities are required only at the gateway device and not each individual node, thus reducing complexity and cost. Third, direct connection between each node device and the gateway is not necessary

as they can relay data between themselves, thus allowing nodes (SAMBAs) to be widely distributed across the building's entire floorplate, provided there are other proximal nodes capable of relaying data to the gateway. This is ideal for commercial offices with complex fit outs, or if building operators choose to collocate communication devices inside service conduits that may attenuate radio signals.
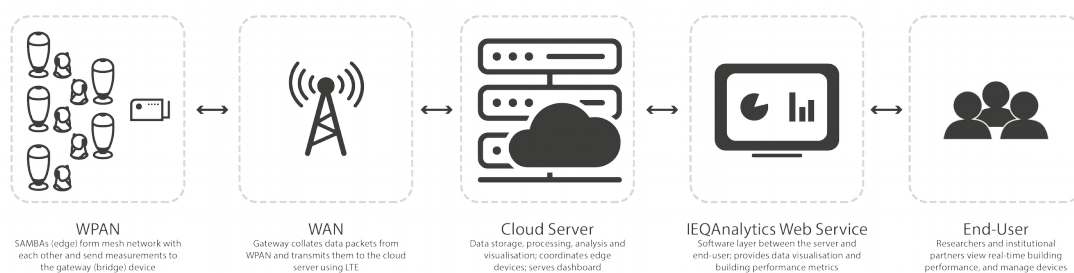

Figure 4. A diagrammatic representation of the network topology underpinning the IEQAnalytics platform.

In addition to acting as a coordinator on the WPAN and a bridge to the WAN, the gateway device is responsible for processing sensor data before uploading to the central server. This, and additional computing tasks are achieved using the native Python environment. The gateways determine their geographic coordinates using reverse-IP lookups and trilateration methods, allowing them to retrieve the 6AM outdoor air temperature for their nearest capital city from the central server in order to estimate clothing insulation using the dynamic method proposed by Schiavon & Lee (2013) and endorsed by ASHRAE 55-2017. Gateways also provide basic diagnostic tools, remote access to WPAN, and over-the-air updates of SAMBA firmware.

5. IEQAnalytics web service

The edge devices (SAMBAs) and bridge devices (gateways) are coordinated by a central 'cloud' server known as the IEQAnalytics web service, which provides the infrastructure for data quality-assurance, transformation, analysis, and visualisation. Perhaps most importantly it provides the software layer for the dashboard where end-users can access the data, calculated indices and criterion-based performance evaluations of their building. The following section details the key functionalities of the IEQAnalytics web service.

5.1 System architecture

The IEQAnalytics web service utilizes the Amazon Web Services (AWS) platform to provide highly available and scalable web infrastructure. Backend data storage is performed by an AWS relational database service MySQL instance. The servers handling requests run Amazon Linux which is a Linux distribution designed and optimised specifically for use within the AWS ecosystem. The server-side logic is implemented in PHP 5 and served to clients by the Apache 2 web server software. Incoming requests from both dashboard users and SAMBA gateway devices are directed to a load balancer to distribute requests evenly across a pool of available servers. Employing the use of a load balancer affords scalability to the IEQAnalytics web service; new server instances are automatically started as demand increases to handle the influx of requests and then stopped when demand decreases.

Tables in the relational database (MySQL) are structured by the types of data stored, which includes raw SAMBA measurements, building metadata (general descriptors of the building and it's services), tenant organisation information, external meteorological data (retrieved from the Australian Government's national provider for weather services (Bureau of Meteorology), along with sundry outdoor air quality observations from the relevant state environmental authorities' online resources. Also included in the cloud web service is the repository of calibration coefficients for each sensor inside each SAMBA device on the IEA Analytics register. Along with their unique identifier, SAMBAs transmit raw sensor outputs to the cloud server. Calibration coefficients are then applied to incoming data before being saved to the measurements table. There are several advantages of this approach; first, it provides a layer of data encryption and security because any data intercepted between the SAMBA device and the cloud server is meaningless without the unique calibration coefficients. Second, there is no need for custom firmware containing device-specific information. Third, any systematic biasing of sensors identified during field measurements may be automatically corrected and updated remotely without the need for equipment to be returned to base.

Once the calibration coefficients have been applied to the raw data, additional synthetic indices such as Predicted Mean Vote (PMV) and the associated Predicted Percentage Dissatisfied (PPD) (Fanger, 1970) are calculated using the relevant

environmental measurements from SAMBA. This includes mean radiant temperature (ASHRAE, 2001), which is calculated from SAMBA's globe temperature, air temperature, and air speed. In addition to clothing level, PMV also requires estimates of metabolic rate of the occupants as inputs. Metabolic rate is assumed to be a constant, 1.1met units, as per the ASHRAE 55-2013 recommended value for standard office work.

A SAMBA device is unaware of its location; the server assigns incoming data packets to a 'zone' according to instructions established within the dashboard. This allows SAMBAs to be moved between zones without requiring significant changes to the database. Multiple zones may exist on a 'floor' level, and multiple floors are attached to a 'building' level. The top structural tier is 'organisation' which may have multiple buildings associated with it. User accounts may be given access privileges at any tier, allowing them to view data for all levels underneath it. For example, a user with 'floor' access may view the SAMBA data associated for all devices in the zones attached to that particular floor, but not for all devices within the building. These user privileges also provide access to the RESTful application programming interface (API) for M2M telemetry of 15-minute data averages for partner organisations to integrate into their own bespoke data management platforms.

5.2 Dashboard design

Successfully synthesising data and generating insight from complex sensing environments at various spatial and temporal resolutions is inherently difficult. For example, there is little research exploring how many longitudinal IEQ measurements are required for the resulting dataset to be deemed representative of the variance of indoor environments for a particular building. Furthermore, continuous time-series data presents challenges around how the data is broken down and analysed for the purpose of IEQ evaluations. These challenges were highlighted by Kim & Haberl (2014) in their preliminary analysis of complex IEQ data using novel methods beyond time-series or frequency analyses. This remains an important area of research if the application of big data to building performance is ever to achieve widespread uptake.

The frontend of the IEQAnalytics web service is a real-time dashboard which serves as the portal for users to view their IEQ measurements and calculated building performance metrics (see figure 5). The dashboard is built primarily using PHP and Javascript to accommodate dynamic content. This was considered a necessary requirement for real-time updates to encourage user interaction and engagement, with many research studies showing that timely feedback of performance helps improve building operations (Darby, 2006; Roussac & de Dear, 2012). For this reason, the data visualisation methods displayed on the dashboard were chosen to appeal to non-experts (i.e. building operators, sustainability mangers and others) as they are the primary end-users of the dashboard. Only the most recent 3-months of measurements are available through the dashboard, in order to ensure good performance on modest computing infrastructure. Archival data is stored on the server and made available to partner institutions as a database dump upon request. Weekly reports that summarise the building performance over the four IEQ domains of thermal comfort, lighting, acoustics and indoor air quality are automatically generated and emailed to users early every Monday morning. These contain compliance statistics, total number of alerts (exceedances beyond the operational targets), and highlights of problem areas to encourage more detailed follow-up diagnostics.

Figure 5. A mock-up of the IEQAnalytics dashboard, as seen by end-users of the service. Devices on different floors of the building may be selected through the left-

hand navigation pane, and hourly averages over the past 3-months are shown by clicking the bar on the right-hand side of the dashboard.

The main dashboard view is comprised of five distinct panels (see Figure 5): real-time averages, compliance times, recent histories, alerts, and noncompliant parameters. The real-time averages display the latest 5-minute measurements averaged over all the SAMBAs present on the selected floor of the building. The colour of the text changes to indicate a noncompliant result. Compliance times for the selected floor for each of the four IEQ domains are displayed as dials spanning user-selectable timeframes, ranging from last three hours to month, to give users performance trends over recent history. The recent history chart is a time-series of the last 9-hours of measurements for all zones of the selected floor. A mouse over popup allows the user to view the numeric value of the measurement and the time it was recorded. Noncompliant measurements over the past three hours are flagged in the alerts panel. Each entry indicates the zone and the exact time at which the exceedance occurred, as well as a link to view the associated measurements. These are totalised over a 3-month period and presented as a pie-chart indicating the sources of noncompliance by each of the four IEQ domains. Hourly averages over the past 3-months are available through the side bar on the right-hand side of the dashboard.

5.3 Compliance calculations and IEQ rating

The IEQAnalytics dashboard also presents a summative performance index referred to as 'IEQ Rating'. The IEQ rating represents an assessment of the criterion based compliance performance of the indoor space based on SAMBA measurements; that is, the SAMBA measurements in the database in the previous 3-months for that space are considered when calculating the IEQ rating. The rating is based on the hourly averages of SAMBA measurements, and is generated floor-by-floor for a building. Averages are calculated for specific parameters as measured by all SAMBAs on a given floor and then checked against compliance criteria drawn from the relevant national and international standards to determine a summative IEQ Rating (see table 2). For this reason, the greater the number of SAMBAs monitoring a floor, the more fair and representative the IEQ Rating will be. Currently the minimum recommended

SAMBA density is five devices per floor, or one per air conditioning zone, whichever is higher.

Table 2. Compliance thresholds for the four IEQ categories. Units of measurement have been converted from mg/m^3 to ppm using known molecular weights (isobutylene for TVOC).

IEQ Category	Parameter	Threshold	Source
Thermal Comfort	PMV	± 0.5	ASHRAE 55-2013
Acoustics	SPL	45 dBA (unoccupied)	AS/NZS 2107
Lighting	Illuminance	160 lux	AS/NZS 1680.2.2
Indoor Air Quality	CO2	1000 ppm	ASHRAE 62.1
	PM10	0.05mg/m^3	WHO, 2005
	CO	8 ppm	WHO, 2010
	HCHO*	0.1 mg/m^3	WHO, 2010
	TVOC*	200 ppb	USGBC LEED v4

* HCHO and TVOC only have suggested thresholds because there are currently no national or international guidelines for these parameters. These thresholds are indicative only and are excluded from compliance calculations, but alerts are raised when measurements exceed these values.

There are three rating levels: Good (green), Fair (yellow), and Poor (red). These ratings are given based on the total number of time spent within compliance ranges: Good is applied to more than 80% of assessment hours spent in compliance; Fair is between 60-80% of assessment hours spent in compliance; Poor is less than 60% compliance. The four constituent categories of IEQ are weighted in the summative IEQ rating following the precedent set by the NABERS IE rating tool (NABERS, 2015). Thermal Comfort compliance and Indoor Air Quality each contribute 0.35 to the final rating, and Lighting and Acoustics contributing 0.15 each. The heavier weighting accorded to thermal comfort and IAQ are an acknowledgement of the greater number of parameters included in those domain measurements. There are multiple parameters comprising the IAQ category, so if one parameter exceeds the relevant threshold then that hour is deemed noncompliant, regardless of the performance on the other IAQ parameters. Each IEQ category is assessed differently. Thermal comfort, lighting, and IAQ compliance are assessed only during occupied hours (8AM – 6PM); acoustic compliance on the other hand is only assessed during unoccupied hours (7PM – 7AM) but after the air conditioning system has started (in

effect the acoustics measure is an index of HVAC system-generated background noise that is audible within the occupied zone). There are two 'fringe' hours (7-8AM and 7-8PM) where compliance is not checked – this is because occupancy during these times is ambiguous and changes depending on organization and industry. Weekends and public holidays are excluded from all compliance metrics.

6. Conclusion

As described in this paper, SAMBA provides a strategy for efficient data acquisition of IEQ parameters *en masse* within office buildings. Apart from providing timely and actionable IEQ data to building operators and facility managers, it opens up rich new possibilities for building science research. First and foremost, SAMBA will feed the world's largest research database of commercial building IEQ performance. This database can provide a suitable resource for benchmarking of individual building's performance; in effect, a normative performance approach (e.g. building x achieves thermal comfort performance that is better than 90% of comparable office buildings in the IEQAnalytics database). Such an extensive database of IEQ measurements will allow for a range of scientific investigations through data-mining, particularly when paired with subjective IEQ measurements (questionnaires) from the actual building occupants themselves. Exploration of the multimodal interaction effects for different IEQ vectors within commercial buildings would also be feasible with this new data resource. This research topic is underdeveloped due to the methodological and logistical difficulties in collecting field data like this using conventional strategies. Moreover, the research scope is not limited to IEQ inside commercial office buildings; SAMBA can easily be deployed in residential settings, health-care facilities, retail facilities, or learning environments, providing appropriate adjustments are made to the assumed metabolic and clothing insulation patterns of occupants in these different building typologies.

The second paper will evaluate the performance of SAMBA IEQ monitoring stations against reference devices used in calibration procedures and position its performance within the requirements outlined in relevant international standards.

Acknowledgements

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