A large-scale longitudinal indoor air quality study: is low-cost sensor deployment a viable approach?

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ABSTRACT

To date, the vast majority of indoor air quality studies have relied on repeated visits to dwellings to obtain data derived from short-term monitoring exercises, a time-consuming process that places considerable constraints on personnel, equipment and costs. These studies have focussed on the use of research-grade instrumentation; however, recent developments in the field of consumer-grade indoor air quality sensor technology offers new opportunities. Several studies have reported that these devices provide sufficient accuracy to be utilised in longitudinal studies and collect data via remote transmission. This new development means that it is now possible to collect longer-term data and larger sample sizes than was previously possible. However, additional factors need to be considered that did not represent issues when short-term sampling methodologies were employed. Factors that influence occupant engagement and data transmission need to be considered. With reference to three customer-grade sensors, this current study focusses on reviewing a set of parameters that should be considered for longitudinal studies. .

One customer-grade sensor device was selected for demonstrative purposes and its capability to remotely transmit data was assessed. To date, the device has recorded data for 86 consecutive days from March to June 2019. In addition to compiling summary statistics, it was possible to download all the raw data and analyse indoor environmental quality parameters which exceeded baseline scenarios. The results showed that while the average temperature was 20.4°C; the average hourly temperatures exceeded 24°C for a cumulative time of 1512 hours and exceeded 26°C for a cumulative time of 509 hours over the period. Similarly for CO_2, the average concentration was 546 ppm; however, the hourly average of the CO_2 concentrations exceeded 1000 ppm for 100 hours over the period.

While several factors need to be considered when selecting a device, and it is possible that a single device will not fit all scenarios, preliminary results indicate that customer-grade instruments have the potential for applications in conducting longitudinal based indoor air quality studies. Further work is planned to evaluate the effectiveness of larger-scale deployment within indoor environments for extended periods.

KEYWORDS

- Indoor air quality
- Large scale data collection
- Low-cost sensors
- Indoor built environment

1 INTRODUCTION

The personal exposure of an individual to air pollution has a negative impact on their health (WHO, 2010). Residential exposures to air pollutants are of particular concern, as occupants spend more than half of the time spent in their residence (Klepeis et al., 2001, Broderick et al., 2015), with elderly and children spending up to 100% of their time in dwellings (Torfs et al., 2008). Numerous studies have highlighted that indoor activities contribute to air pollution through combustion events such as smoking, frying, solid fuel fires and use of candles and incense (Broderick et al., 2017, Semple et al., 2012, He et al., 2004, Morawska et al., 2013) and resuspension activities such as cleaning, walking, and vacuuming (Ferro et al., 2004, Boor et al., 2015).

Volatile Organic Compounds (VOCs) are gases emitted from different solid or liquid materials that include a variety of chemicals compounds. VOCs can be generated from a range of sources: furnishings, construction materials, paints, adhesives, cleaners, frying foods, smoking, dry cleaned clothing, deodorisers, showering, moulds and pesticides (Torfs et al., 2008, Hiscock et al., 2012, Brown et al., 2015). In a recent study, Svanes et al. (2018) reported that inhalation exposure to cleaning products could be as harmful as smoking 20 cigarettes per day. The study found that among women who used sprays or other cleaning products at least once per week, there was an associated decline in lung function.

Numerous studies highlight the potential for large spatial variations in pollutant concentrations even within the same dwelling due to the presence of doors and walls (Ferro et al., 2009, Du et al., 2012, McGrath et al., 2014b). These factors have important implications for exposure estimations and factors that influence ventilation controls (temperatures and humidity sensors). Spatial variations can also occur due to different requirements for mechanical ventilation; habitable rooms, kitchen, utility room, bathroom and sanitary accommodation (no bath or shower) can have varying minimum extract rates (DHPLG, 2019, DHPLG, 2009). The temporal variation in indoor air quality, due to building-, occupant- and environment- related factors, has been widely recognised (Tsai, 2018, McGrath et al., 2014a). In a study of seasonal indoor air quality variations, Bekö et al. (2016) noted that while building regulations require a minimum outdoor air supply rate, moisture generation typically will not be constant, and varies significantly with occupant activities. The authors expressed concern about the criteria surrounding a minimum outdoor air supply rate and its ability to account for varying moisture generation. While moisture, CO_2 and temperature can be strongly linked to occupants' activities (cooking, washing clothes, showering) (Yik et al., 2004, Persily, 2015), there is a need to also consider pollutants that can be generated without an occupant, such as radon (McGrath and Byrne, 2019, Collignan et al., 2016).

Reliable estimates of indoor environmental quality require sample sizes with larger datasets due to the complex nature of the indoor built environment (where some of the influencing factors on air quality are building characteristics, occupant behaviour, ventilation type, and ventilation system maintenance). The IEA's Energy in Buildings and Communities Programme established Annex 68 to discuss "*Indoor Air Quality Design and Control in Low Energy Residential Buildings*". As part of this Annex, Cony Renaud Salis et al. (2017) noted that there are very limited data available regarding pollutant concentrations in low-energy residential buildings. The issue is complicated as the data are usually reported only as aggregated pollutant concentrations (average, min, max), which lack detail for an individual building.

The relative cost of research-grade indoor environmental quality (IEQ) instruments has placed considerable constraints on conducting large-scale monitoring campaigns. The vast majority of relevant studies to date have relied on repeated visits to dwellings to obtain data derived from short-term monitoring exercises, a time-consuming process that places constraints on both personnel and equipment resources. However, recent advancements in the development of customer-grade (low-cost) sensors with the capability for remotely transmitting information means that there is now a unique opportunity to gather large-scale monitoring data without the traditional constrictions.

A number of studies show that customer-grade sensors have the potential to reasonably measure indoor air quality. Moreno-Rangel et al. (2018) compared a Foobot FBT0002100 with GrayWolf instruments (GrayWolf Sensing Solution, Shelton, CT, USA), where the GrayWolf probes represented high-grade research equipment. The study reported a significant agreement with temperature (r_s= 0.832–0.871), relative humidity (r_s= 0.935–0.948), *t*VOC (r_s= 0.827–0.869), and $PM_{2.5}$ (r_s= 0.787–0.866) data. However, the Foobot device lacked a specific CO_2 sensor and instead estimated CO_2 based on a percentage of TVOC measurements. Singer and Delp (2018) compared the accuracy of seven low-cost IEQ devices (AirBeam 1, Air Quality Egg, AirVisual Node, Awair, Foobot, Purple Air PA-II, and Speck) with two research-grade optical aerosol monitors (pDR-1500, MetOne BT-645). The study generated fine particulate matter based on common residential sources in laboratory conditions and analysed time-resolved measurements. Four of the devices measured were deemed suitable to have sufficient accuracy and reliability to detect large PM sources within the residential environment; although the devices were not considered suitable for detecting all sources of ultrafine particle emissions (below 0.3 µm diameter).

Developments in low-cost sensor technology, combined with the capability for remotely transmitting information, means that there is now a unique opportunity to gather large-scale monitoring data without the traditional constrictions. Longitudinal studies have the potential to overcome, through continuous monitoring, the traditional uncertainties associated with occupant behaviour and short-term changes in the built environment that are a current limitation in short-term monitoring studies. The objective of this study is to evaluate the conditions under which consumer-grade monitors can optimally perform large-scale data collection.

2 METHODOLOGY

2.1 Review of devices

For the purposes of this study, the focus was not on the accuracy and analysis of the sensors, as earlier studies have already quantified these factors. The current study instead concentrated on parameters that need consideration when conducting a longitudinal-based monitoring study. Several factors need specific attention that would not be necessary during traditional-short-term monitoring exercises.

Occupants' willingness to participate in monitoring studies was deemed the highest priority, and as such, it was felt that off-the-shelf products were designed to be visually more appealing, while custom-made devices are unlikely to achieve the same level of aesthetics. For this reason, custom-made devices controlled by micro-controllers (Arduino, Raspberry Pi, etc.) were not considered in the scope of this review.

This study focussed on factors including: wireless data transmission protocols; continuous recording and transmission of information; occupants' behaviour and willingness to maintain engagement. The use of battery vs mains power supply is a factor which has varying importance depending on the sampling duration, as occupants may or may not be willing to leave devices plugged in for extended periods. The size, mounting option and visual appeal need to be considered to ensure that the occupants do not move the devices during the course of the study.

The strengths of longitudinal-based studies are the ability to collect long-term measurements; therefore, consideration must be given to ensure that the raw data can be obtained over the sampling period. Several devices store the data on a cloud-based server;

however, some devices display the data via a smartphone and the ability to access the raw data via an online-portal needs to be considered.

Three IEQ sensors were identified; uHoo (uHoo Air, Hong Kong, Hong Kong), Airthings Wave Plus (Oslo, Norway) and Foobot (Foobot, Belvaux, Luxembourg). These devices were reviewed based on the factors discussed above.

2.2 Pilot study of a selected device

One sensor, the Airthings WavePlus, was selected for demonstrative purposes to assess the capability and potential application ofthese devices during monitoring campaigns. The device was placed in a naturally-ventilated office (approximate volume 28 $m^{3,}$ and dual occupancy$^{)}$ from March 2019 until June 2019 The device was mounted on the wall, as shown in Figure 1.

Figure 1. A IEQ sensor mounted on the wall in an office.

3 RESULTS

Table 1 summarises some of the characteristics that should be considered when selecting a device for monitoring in a longitudinal based study. Occupants' willingness to maintain engagement with the study becomes a greater challenge the longer the desired sampling period; power consumption, sampling location and position of the sensor are factors that require greater consideration for long term monitoring.

The data transmission protocol is a factor that needs particular care. While some devices operate via a mobile-phone app, this ultimately requires the occupant to login into the app on a regular basis to allow the data to upload to the servers; this can pose challenges in terms of long-term engagement, but also has the potential to introduce bias as the occupant becomes aware of their air quality conditions. While uHoo and Footbot connect directly to a Wi-Fi network, they currently do not support secondary authentication login portals, managed login networks or networks protected by firewalls. While these networks are considered to be less common in the residential environment, they may occur in some localised situations.

Table 1: A summary of key factors for three different customer-grade IEQ sensors.

Parameters	Wave Plus	uHoo	Foobot
Internal storage	Yes		No
Remote data transmission protocols	Only uploads data to cloud via smartphone (Bluetooth connectivity). Alternatively, can connect directly to the cloud via additional hub (Bluetooth connectivity)	Connects to the clould via a private WiFi network	Connects to the clould via a private WiFi network
Monitoring Parameters	Radon, Humidity, TVOCs, Temperature, CO_2 and Air Pressure	Temperature, Humidity, VOC, CO_2, Air Pressure, Particulate Matter (PM2.5), Nitrogen Dioxide, Carbon Monoxide and Ozone	Fine Particles, Total VOC, Carbon Dioxide, Temperature and Humidity
Sampling Resolution	5-minute resolution for Humidity, TVOCs, Temperature, CO2 and air pressure: Hourly for radon	1-minute intervals	5-minute intervals
Power Supply	Battery Operated - 2 AA batteries	Micro USB power adapter and 5V DC external power adapter	AC-DC 5V 0.5A USB power adaptor
Cloud base storage	Cloud-based with iOS and Android mobile applications include online dashboard	Cloud-based with iOS and Android mobile applications	Stores data in a cloud based server
Access to the raw data	Downloadable CSV files	Downloadable CSV files (with Uhoo Pro)	Downloadable
Warranty on the devices	1-year warranty	1-year warranty	1-year warranty
Position / Mounting	Supports wall or ceiling mount	Rests on a horizontal surface	Rests on a horizontal surface
Dimensions	12 cm (diameter) x 3.6 cm (height)	16.5 cm (height) x 85 cm (diameter)	7.1cm (diameter) x 17.2 cm (height)
Weight	219 grams	210 grams	475 grams
Restricted access	Assigned to a smartphone via an app log in.	Assigned to a smartphone via an app log in.	Assigned to a smartphone via an app log in.

Table 2: A summary of the indoor environmental parameters collect by the AirThings WavePlus over an 86 days period.

	Radon (Bq m^{-3})	Temperature (°C)	Relative Humidity (%)	Air Pressure (Pa)	CO_2 (ppm)	VOCs (ppb)
Average	17	20.4	42.7	101,377	546	207
Standard Deviation	9	2.4	6.6	1,119	105	165
Minimum	0	11.2	21.5	97,610	399	0
Maximum	76	29.5	58.0	103,670	1288	659

The IEQ device recorded temperature, humidity, carbon dioxide, TVOCs and air pressure at 5-minute intervals and the radon concentration at hourly intervals. Table 2 summarises the raw data exported from the Airthings dashboard over the entire 86-day period. In total, 125,538 data points were collected over the sampling period.

Figure 2 shows the time-series trends collected by the WavePlus over a month-long period. The figure represents a screenshot of the dashboard taken from the web browser. While the averages are displayed on the left-hand side, the time-series data displayed on the right-hand side provides a more-detailed analysis of the conditions within the room. Pre-defined conditions established by Airthings determined the colour coding on the graphs; for example, the red spikes in the temperature data corresponds to when the temperature exceeds 25°C, while the blue portions indicate where the temperature fell below 18°C.

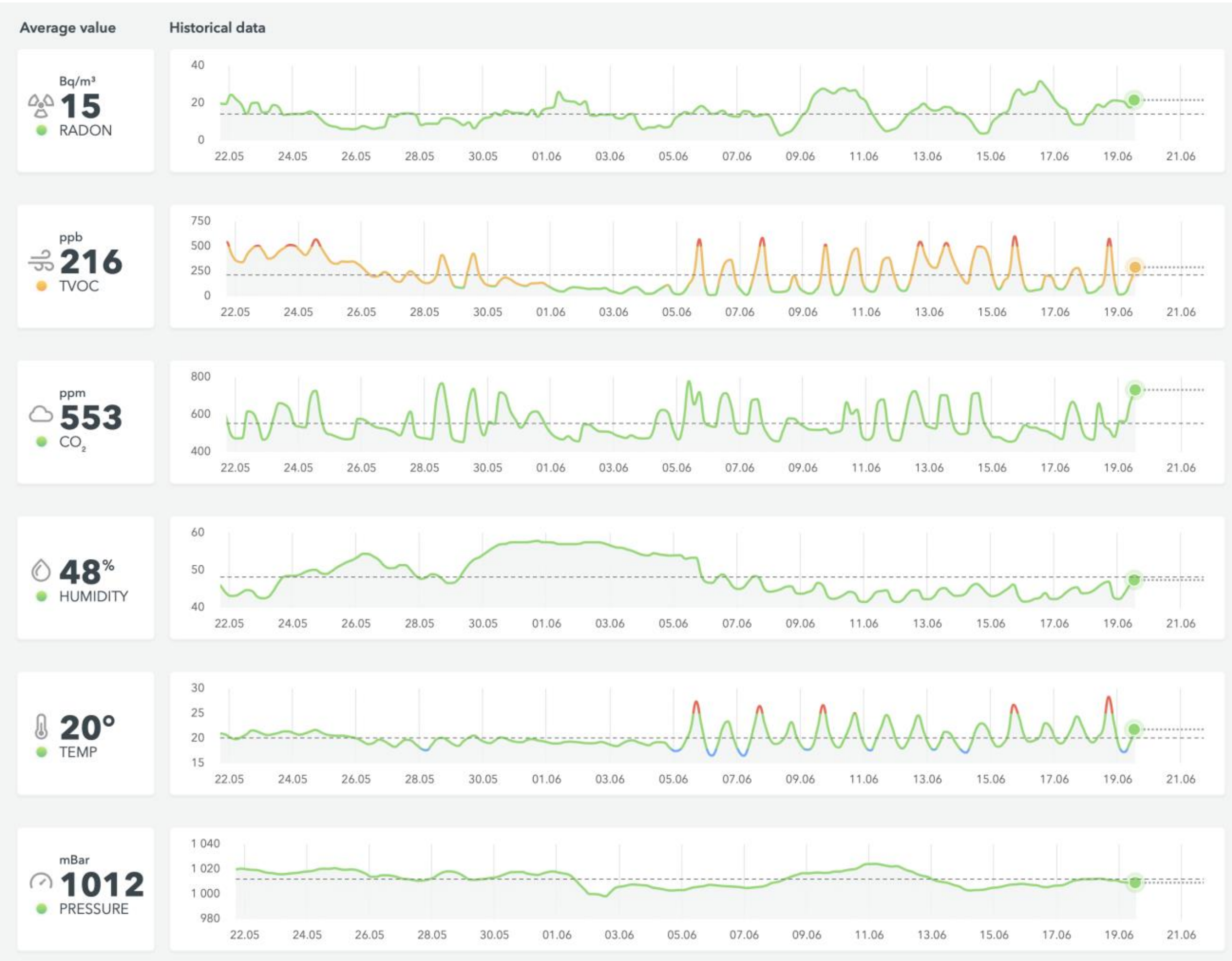

Figure 2: A screenshot showing the dashboard containing the data collected using an AirThings WavePlus. The figure shows data for a month-long period for radon, TVOCs, carbon dioxide, humidity, temperature and air pressure measurements

Based on the quantity of data collected, it was possible to further analyse the raw data. While the average temperature was 20.4°C, further analysis determined that the average hourly temperatures exceeded 24.0°C for a cumulative of 1,512 hours and exceeded 26.0°C for a cumulative of 509 hours over the period. Similarly, the average CO_2 was 546, while the hourly average of the CO_2 concentrations exceeded 1,000 ppm for 100 hours over the period.

4 CONCLUSIONS

The traditional approaches to monitoring indoor air quality in residential environments rely upon repeated visits to dwellings, and this poses considerable constraints on personnel, equipment and costs. These constraints limit the capability of obtaining comprehensive data sets, including the number of houses and the sampling duration. Recent developments in the field of consumer IEQ sensor technology offers the possibility to conduct longitudinal studies. The current study identified factors that need to be considered when using customer-grade sensors for longitudinal studies that are not associated with traditional monitoring using research-grade instrumentation. Three different customer-grade sensors were selected and reviewed in this context. Each device has advantages and disadvantages that facilitate their use in longitudinal studies. The circumstances that surround the monitoring campaign (duration, location, occupants, air quality parameters, Wi-Fi transmission) will influence the device that is selected for the monitoring campaign.

One sensor was selected to assess its potential application in longer-term monitoring. The device recorded six indoor environmental parameters (temperature, humidity, carbon dioxide, TVOCs, radon and air pressure) and collected data in an office environment for 86 days. Average, standard deviation, minimum and maximum values were calculated based on the raw data. In addition, it was possible to identify periods and durations during which environmental conditions were exceeded.

The results show promising trends where customer-grade instruments could be used to conduct longitudinal based indoor air quality studies; these have been significantly constrained to date. The next stage of the current project is to deploy the sensors in 10 residential environments and assess the ability to remotely collect and analyse the data from these dwellings. The longitudinal approach will capture changes in occupants' behaviour, seasonal variations, meteorology conditions and varying spatial variation within a dwelling.

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