Smart monitoring of building performance with IEQ sensor networks

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The recent development of affordable Indoor Environmental Quality (IEQ) sensors has led to a growing interest in continuous indoor climate monitoring. Introduction of advanced IEQ sensor networks will allow us to better analyse building performance. This article addresses a couple of fundamental questions that need to be answered to assure the successful introduction of IEQ sensor networks at a larger scale.

Keywords: Indoor air quality, IAQ, thermal comfort, internet of things, monitoring, performance verification, monitors

To successfully deploy web-based IEQ sensor networks in buildings one needs more than just accurate sensors. It is important to develop an overall view on what to measure, why, where, when and how. A general methodology has to be developed that allows to analyse and present the enormous amount of IEQ data that will be gathered with indoor air quality and temperature sensors in a way that building users and decision makers can relate to. In this article we try to answer some rather essential questions, based upon literature review and the authors' experience with several kinds of IEQ sensor networks. The results presented in this paper can be used to further develop IEQ sensor networks both for academic and more practical purposes, e.g. the application of sensor networks in the context of PPP/DBFMO contracts (Public Private Partnerships / Design, Build, Finance and Maintain-contract).

This article is partly based on a paper that was presented by the first author at the 2018 AIVC conference that was held in Juan-les-Pins (France). It furthermore can be seen as a follow up article of a REHVA journal article on IAQ monitoring (5) that was written by the third author (published in 2017).

Backgrounds

In recent years, air quality sensor technology has improved considerably, resulting in smaller sensors that are more and more reliable, accurate and affordable. Multiple manufacturers for instance offer electronic PM2.5 fine particle sensors the size of a matchbox, or even smaller, of professional quality. Meanwhile, internet of things (IOT) technology has taken off. For IAQ practice this opens a whole new range of possibilities, as ad hoc sensor networks can be built from wireless IEQ monitor devices without much hassle. Today it is possible to monitor the indoor environmental quality of multiple rooms in multiple buildings in real time, from behind the desk, using online monitoring platform that receive test data from the sensor devices, updated every second if you wish. For more background information see e.g. Guyot et al. (2017) [1].

The growing awareness of poor air quality, especially fine particles, as a health threat boosts the call for such monitoring networks. Mainstream electronics manufacturers offer consumer grade devices at rather affordable prices, apparently recognising a market for personal air monitoring. Which helps to boost the interest from building occupants in indoor climate monitoring.

On a professional level, building performance labelling programmes such as WELL require indoor air quality monitoring [2]. Initiated in China, RESET (see www.reset.build) offers a framework for IAQ monitoring that includes standardised practice, technical quality standards for the test equipment, as well as the RESET Accredited Professional training and accreditation programme. There are currently nearly ten types of RESET certified monitoring devices from diverse manufacturers mentioned on the RESET website and over 100 RESET accredited professionals worldwide [3].

Any practitioner who intends to set up an online sensor network will be confronted by a number of issues, each of which has to be solved. This article discusses a number of these considerations, especially the more generic ones. Some of them stem from our own experience (see **Figure 1**), others are the result of a workshop held at the NCEUB Windsor Conference 2018 [4].

Added value

The first question to discuss is: *How to explain to decision makers the added value of measuring with a sensor network compared to old school, short term, handheld measurements?*

Monitors are critical for developing recognition of an indoor air quality (IAQ) problem, which then drives improvement. Traditionally, facility managers or building owners had to commission long and in-depth audits with handheld particle counters to determine whether there is a problem. However, today, continuous monitoring of IEQ allows us to quickly, inexpensively, and meaningfully depict the health performance of a space.

There is a growing recognition that monitoring is critical to validate performance. In China, the phrase "PM2.5" was the fourth most searched term on the internet (per Baidu.com) in 2015. With the easy availability of inexpensive consumer grade monitors (as low as US$40), it is easy and natural for employees and tenants to test out their homes and offices. If they discover problems, they will usually share the information on social media or else challenge their managers, facility managers, or operations teams. This can either be a PR nightmare or a marketing, selling or recruitment opportunity.

Monitoring data enables self-auditing and green building certification, such as BREEAM, LEED and WELL. Most sophisticated clients want to show the Return on Investments (ROI) on projects to justify their investment in a healthy building. They may also want to keep their building or office space performing at a high level over time. The addition of furnishings, increase of headcount density, maintenance, outdoor air infiltration and occupant activity all are actors that impact air quality after commissioning. An unnoticed side effect of air quality monitoring is a mind shift in involving the facility manager and operations team in the "care and feeding" of their indoor environment, because they have a feedback loop now which allows them - and other stakeholders - to observe cause and effect.

Furthermore, monitoring enables climate system optimization and automation. Data informed operation of ventilation, heating and cooling devices can be a very effective way to improve overall building and building system performance.

Figure 1. Sensor network test site, pilot building The Hague (NL).

Parameters to monitor

The second question than is: *What IAQ and thermal parameters should be monitored with the sensor network and at what level of performance?*

For moderate environments (as in most European locations), we consider particulate matter (PM2.5), carbon dioxide CO_2) and temperature (plus possibly also relative humidity) the most important parameters to be monitored indoors. Some monitors include a Total Volatile Organic Compound (TVOC) sensor as well, however our experience is that indoor levels usually stay below detection levels of these sensors. They may be nice to have in specific situations where more significant levels are expected, such as in post-renovations or industrial environments.

Also, monitors with real-time formaldehyde sensors are starting to emerge, though common consensus is that these are not yet reliable enough. As far as nitrogen dioxide sensors are concerned (relevant e.g. at a location with above average outdoor air pollution) also these are not as affordable and reliable yet as e.g. fine particle and carbon dioxide sensors.

PM2.5 sensors should be able to provide particle count, not just mass concentration. Therefore, optical particle counter (OPC) sensors are required with a minimum measurement range of 0-300µg/m³. Critical considerations include: humidity compensation, stability, repeatability and accuracy over the ranges likely to be encountered.

CO_2 sensors should also be of the optical (NDIR) type, with a measuring range of at least 0-2000ppm. Select sensors that have auto-zeroing features and that can be field replaceable.

Temperature sensors can be thermocouples, Resistive Temperature Devices (RTD's) or silicon diodes, with a temperature range up to 50°C. Though measuring temperatures seem straightforward, we find many IEQ monitors to be inaccurate, with an offset up to 2K in off the shelf devices. This may be caused by heat production from other components within the devices, e.g. the driving fans of the air quality sensors.

For those users who may not be sensor professionals, another option for "pre-certified" monitors is to simply look for third-party certified monitors. E.g. RESET is a third-party system that establishes specific criteria for monitoring hardware to reach Grades A (professional), B (building-grade), and C (consumer).

Some manufacturers also have produced monitors that include noise and light sensors. This is something we do not further elaborate upon in this article as the main focus here is on indoor climate monitoring.

Sensor selection

Question nr. 3 is: *How to select the sensors? Taking into account aspects like measurement range, accuracy and self-calibration.*

Sensors must be fit for purpose. Most sensors need periodical calibration, e.g. once a year, whereas other sensors use disposable heads that are periodically replaced. There are numerous devices on the market and it may be hard to choose the right one (best value for money). Which one is the best in a specific situation of course also depends on the accuracy that is needed and e.g. the budget. RESET [3] has tested and approved a limited number of sensor devices that are considered accurate enough / of B-grade (professional, however not lab-grade) quality.

The measurement range is another important issue when selecting sensors. In **Table 1**, recommended measurement ranges are described for sensors meant for non-industrial, indoor use.

Threshold values and outcome visualisation

A further question is: *What threshold values should be applied and how to present measurement outcomes graphically so that e.g. building users understand how (un)healthy/(un)comfortable their indoor climate is?*

The World Health Organization and e.g. the European commission offer limit values for air quality [6, 7]. However, more appropriate values may apply for a specific country, trade or organisation. Furthermore, Occupational Health & Safety standards may have appropriate guidelines for work situations. RESET [3] also has defined specific threshold levels, especially for indoor air quality parameters, see **Table 2**.

RESET has both Regular and High Performance categories of certification. The latter has requirements that are even more stringent for PM2.5 than LEED v4 or e.g. WELL.

Also, some might argue that instead of absolute limit values (concentrations) as threshold values one should evaluate measurement results (esp. air quality) in terms of maximum allowable Indoor-Outdoor (I/O) ratios (measured indoor concentration divided by momentary outdoor concentration).

When presenting the monitoring results, serious health threats should be distinguished from results that may seem alarming at first sight, such as incidental exceedance of a threshold value that was meant as a limit for long term exposure. You want the building occupants to be alarmed only by real hazards.

Representation of (continuous) measurement outcomes (e.g. via a dedicated IEQ platform) normally benefits from intelligent colour coding. That e.g. uses the colour green to indicate non-harmful pollutant levels, red to indicate harmful pollutant levels and orange or yellow when exposure levels are in between the two.

Table 1. *Selection parameters. [5]*

IAQ parameter	Common sensor technology used	Recommended measurement range (Grade B)	Selection notes
Particulate Matter (PM)	Optical particle counters (OPC)	0–300 µg/m³	Sensors should be able to provide particle count, not just mass concentration. Critical considerations: humidity compensation, stability, repeatability, long term accuracy. Measurement of PM 2.5 or PM 1 has preference over measurement of e.g. PM 10, as the smaller particles are more relevant from a health point of view.
Carbon Dioxide (CO_2)	NDIRs	0–2000 ppm	CO_2 is an indicator of the amount of bio-effluents in the air and allows one to assess the effectiveness of the ventilation system. This is usually the most determining parameter for IAQ related symptoms. Select sensors that have auto-zeroing features and that can be field-replaceable.
Total Volatile Organic Compounds (TVOC)	Metal Oxide Sensors (MOS); Photo-ionization Detectors (PID)	0.15–2.00 mg/m³	Both MOS and PID sensors are indicative only and used mainly to show relative change. They will not usually match lab testing. High chemical levels will also require recalibration.
Temperature	Thermocouples; Resistive Temperature Devices (RTDs); Silicon diodes	0–50°C	Many IEQ monitors suffer from inaccuracy due to heat generated by nearby components on same PCB.
Relative Humidity	Capacitive	20–90%	Generally, field-replaceable. Important to measure due to impact of humidity on measurements of other parameters (e.g. PM).
Formaldehyde	Colormetric, electrochemical; chemical	0.03–0.3 mg/m³	Currently, there are no real-time technologies known to the authors that reliably match lab analysis.

Table 2. *Suggested RESET threshold values. [3]*

IAQ parameter	Target level (24 h average)	
	Acceptable	High performance
Particulate Matter (PM 2.5)	< 35 µg/m³	< 12 µg/m³
Total Volatile Organic Compounds (TVOC)	< 500 µg/m³	< 400 µg/m³
Carbon Dioxide (CO_2)	< 1000 ppm	< 600 ppm
Carbon Monoxide (CO)	< 9 ppm	–
Formaldehyde (HCOH)	–*	–*

* no requirements defined yet

Indoor-outdoor relations

Another question that one has to answer before a sensor network can be deployed: *Is it only necessary to measure air quality and temperature at several locations indoors, or also the outdoor air quality and temperature?*

Some areas offer publicly accessible data from sophisticated outdoor measurement stations. This may be an excellent source of outdoor data, e.g. for local PM2.5 concentrations. Often however, outdoor stations don't measure what one needs (e.g. only PM 10 and not PM 2.5). Also, sometime outdoor stations are simply located too far away from the building that is under investigation (more than 10 KM or so). And when a building is located very close to e.g. a severely polluting source like a factory of a busy road local exposure is different anyhow from what the nearby outdoor station of the city or county is measuring.

Therefore, often it does make sense to include an outside air quality and outside temperature sensor when setting up an IEQ sensor network in a building. In that case one can decide to position the outdoor sensors on the roof or so (covered from rain and shielded from direct sunlight), or one places it in the HVAC air inlet.

One considerable advantage of also measuring outdoor levels with the same devices is that one can very accurately calculate the so called Indoor-Outdoor (I/O) ratio for all indoor air quality parameters involved. At the same time, it might make sense to also relate e.g. measured indoor temperatures with the momentary outdoor climate (e.g. daily maximum temperature).

Amount of sensors and location

Furthermore, one could ask: *How many sensors should one use? And where to place the sensors?*

It obviously does not make sense to install one sensor in a building that has e.g. 1000 building occupants. But how does one decide to how many sensors to use as part of an IEQ sensor network? Sensors and monitoring devices are becoming more and more affordable, therefore the deployment of a substantial number becomes more feasible over time. On the other hand: one can overdo it too. For example: applying a monitor / sensor box in all spaces of a building generally speaking is not (cost) effective.

As a general rule one sensor per 500 m² of occupied floor space seems to be adequate (this is in line with the RESET requirements [3]. Plus at least one sensor per representative room type (e.g. office room vs meeting room vs laboratory space).

Also, one has to decide about the location / position of the sensors. Ideally is a location as close to where people are sitting, standing or lying most of the time. In an office building for example this implies that sensors are placed on people's desks, if possible, at breathing zone height (1 to 1,20 m above floor level). If this is not possible, second best is a location on a nearby wall (e.g. next to a wall thermostat). Third best would be a position under the ceiling. Positions within (false) ceiling or e.g. placement inside ventilation ducts should be avoided as this will lead to inadequate estimates of building occupant exposure, unless the purpose is to measure performance of HVAC systems providing air within a building.

Sensor connectivity

An important question is further: *What connectivity solution to select?*

Generally speaking, sensor devices are available with Wi-Fi, ethernet or serial connections for data communication. These may be fine for permanent installations. However, in non-permanent situations where an external party sets up a temporary / ad hoc installation, the client is likely to forbid that the local ethernet or Wi-Fi network is used due to security reasons. In these cases, a dedicated Wi-Fi network is the most straightforward solution, with one internet access point that forwards the collected data from multiple Wi-Fi coupled monitors to the cloud, using the mobile phone network or LoRa. Another option is a decentralised network, where each monitor has its own sim card. However, this technology is not yet wide spread. Whichever connectivity solution is chosen, data is collected on a central server and can be accessed via an online portal where it is stored and can be accessed for analysis.

Other aspects

A last question is: *Are there any other important issues that should be addressed?*

One important aspect that often is forgotten is privacy. Sensor networks should be deployed in such a way that sensitive information is dealt with in accordance with e.g. European General Data Protection Regulation (GDPR). Apart from that, one should recognize that 'technical data' like e.g. measured CO_2 concentrations indoors in fact inform about whether people are present or not (e.g. in a dwelling). Persons with criminal intentions and hacking competences might be very interested in these kinds of data, which is why sensor networks should be designed and operated with not just privacy but also security in mind.

Another often forgotten aspect is interface quality. Data gathered with IEQ sensor networks often are presented via website, smartphones or wall devices in a non-optimal way. Using overcomplex graphs and infographics or even irrelevant ones. One should design the overall system in such a way that data is transformed into information. Explain (graphically) what it means e.g. when the CO_2 concentration is above a certain limit for a considerable amount of time. **Figure 2** provides an example on how to graphically display indoor and outdoor PM2.5 concentrations. In this example chart, the RESET threshold value is indicated, average and peak values are summarized and non-working hours are masked.

Make sure that end-users intuitively understand the information provided and test interfaces with non-technical people before they are launched officially. The last thing we need is high tech sensor networks that measure all kinds of relevant parameters but that produce data that nobody can translate / understand.

One last aspect that often is overseen is overall sensor network robustness. In this context think of questions like: How is the overall system functioning over time? Are all sensors still working after e.g. one year? Is it necessary to exchange components every month or every year or over 5-year period? Are there any alarm signals when there are sensor connectivity issues? Is somebody responsible for periodical maintenance and periodical quality checks?

Conclusions

There are many considerations related to the deployment of IEQ sensor networks. Especially adequate, continuous measurement of indoor air quality parameters is still quite a challenge.

Figure 2. example interface sensor data presentation.

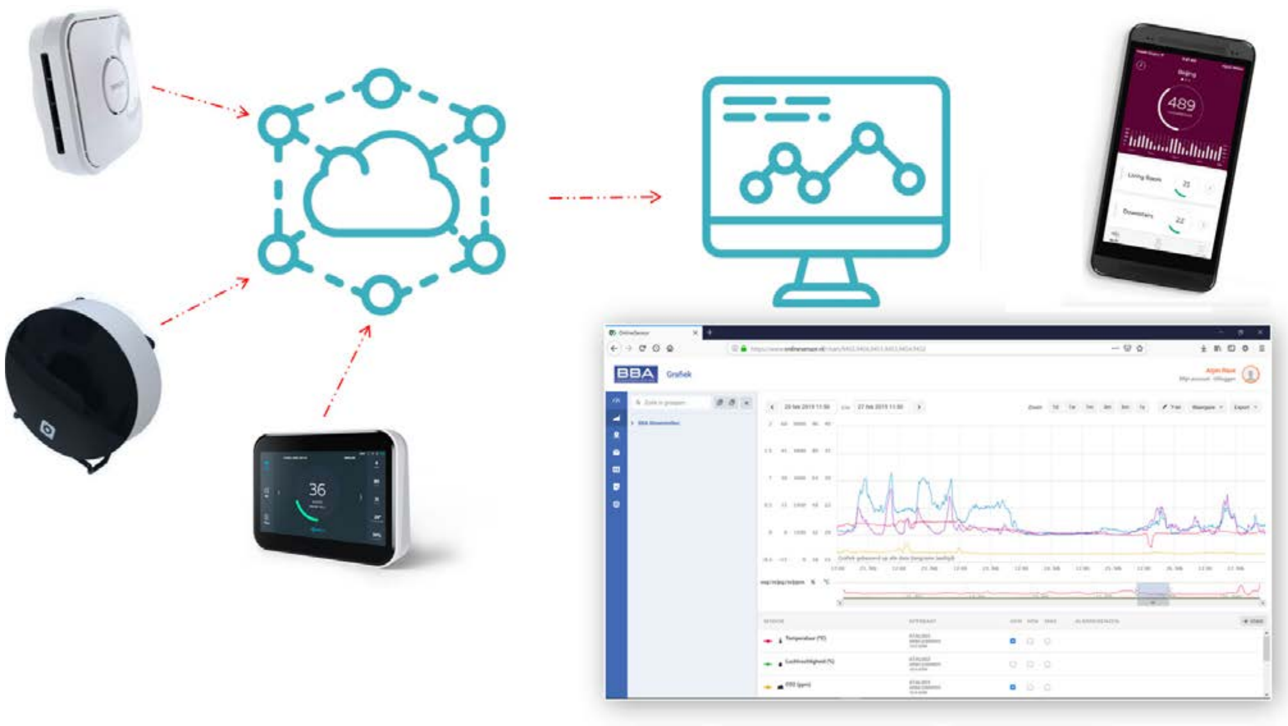

Figure 3. Core elements of an IEQ sensor network.

Several aspects should be considered when designing and operating these sensor networks:

- added value of the network to building occupants (and meaning of the data gathered);
- what parameters to measure (e.g. just CO_2 or also fine particles and volatile organic compounds);
- what threshold values to use and how to present measurement results in relation to these limits;
- simultaneous measurement of (local) outdoor parameters;
- accuracy, measurement range, self-calibration and robustness of sensor components;
- deployment strategy, amount of sensors per floor and location of sensor in rooms;
- connectivity (Wi-Fi vs ethernet etc).

The results presented in this paper can be used to successfully deploy IEQ sensor networks in the field. Which in turn will help to objectify building and building service system performance. ■

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