Indoor Air Quality Monitoring 2.0 – Seeing the invisible

In China, the new battle is for clean air and to keep the ubiquitous pollution at bay. Therefore, China is plenty of opportunity for professionals in the IAQ industry having the world's highest levels of public awareness of indoor air quality combined with incredible growth in built environments. As the market has matured, one of the fastest trends has been the continuous monitoring to track and validate indoor environmental quality. Yet, for all the interest, there are still many questions about how to select and use monitors.

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Practitioner's perspective

The perspective of a consulting and engineering firm is providing IAQ consulting, ventilation system design, implementation of systems and their monitoring. This article is aimed at the practitioner and operator.

Four years ago, a client requested the ability to continuously monitor their air quality after we had installed an office-wide filtration system. After a market search failed to yield suitable systems that could measure PM2.5 levels and report over the internet, we had no choice but to create our own monitor, one of the first of its type for non-industrial use in China. Less than a month after we installed the monitors, Shanghai experienced some of the highest levels of pollution ever recorded locally (over 1800% higher than the WHO 24-hour health standard). The monitoring system showed that despite the high outdoor levels, the filtration system achieved 93% average reduction with a healthy level inside. Instead of having to respond to employees' panic and absenteeism, our client won staff trust and scored a PR coup for employees' care and wellness. Since then, we have sought to integrate monitoring into schools, offices, and buildings, and currently oversee more than 3000 monitors streaming live data over a cloud monitoring network.

Why monitor?

China is an ideal proving ground to acid test sensors and monitors. The frequent high levels of pollution outdoors paired with a cultural preference for natural ventilation provide challenging requirements. We often find that sensors created in North America or Europe fail quickly in China, and perhaps, not unsurprisingly, most of our preferred technology is domestically produced. Against this backdrop, we have seen very fast growth in the adoption of monitors for a number of reasons.

1. **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 was a problem. However, today, continuous monitors make it possible to quickly, inexpensively, and meaningfully depict the health performance of a space.
2. **Moore's Law – sensors have come way down in price while increasing in performance**. There are superior monitors today at, approximately, one third of the cost compared to those provided only two years ago.
3. **There is 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. Visitors entering elevators in the popular SOHO

office complexes have a full colour display showing outdoor versus indoor air quality readings. With the easy availability of inexpensive consumer grade monitors (as low as ~USD40), 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, facilities managers, or operations teams. This can either be a PR nightmare or, as in the case of our first monitoring client, a marketing, selling or recruiting point.

4. **Monitoring data enables self-auditing and green building certification performance validation.** Most sophisticated clients want to show the Return of Investments (ROI) on projects to justify their investment. 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 factors that impact air quality after commissioning. An unnoticed side effect of air quality monitoring is a mind shift in involving the facilities managers 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 view cause and effect.
5. **Monitoring enables automation**. In the past, we used to design and implement solutions for clients. We, then, would train teams on how and when to operate the systems. Typically, a unit is only considered successfully commissioned if it achieves over 95% single pass reduction from the outlet vs. inlet readings and either below PM 2.5 of 35 μg/m³ over a 24 hours' average, or greater than 90% ambient room reduction during the same period. However, we found that in reality, once we left, results would often degrade due to:

a. Improper system operations – speed, on/off, filter maintenance
b. Failure to control infiltration of outdoor air, or;
c. Negative pressurization bringing in unfiltered outdoor makeup air

Training helps, but it is very difficult to overcome ingrained habits such as opening the windows for "fresh air" during cleaning or out of habit. Operations staff also frequently turn over, resulting in a new crop of untrained personnel. Experience has shown that the best answer is to take the operator out of the equation, using automation software powered with live readings to govern filtration and ventilation system operation "on-demand" only when needed. Automation systems should generally also have a scheduling system to differentiate between working and non-working (or non-occupied) hours. Not only does this ensure consistent performance, but, such systems can also reduce energy usage up to 90% (compared to continuous operation).

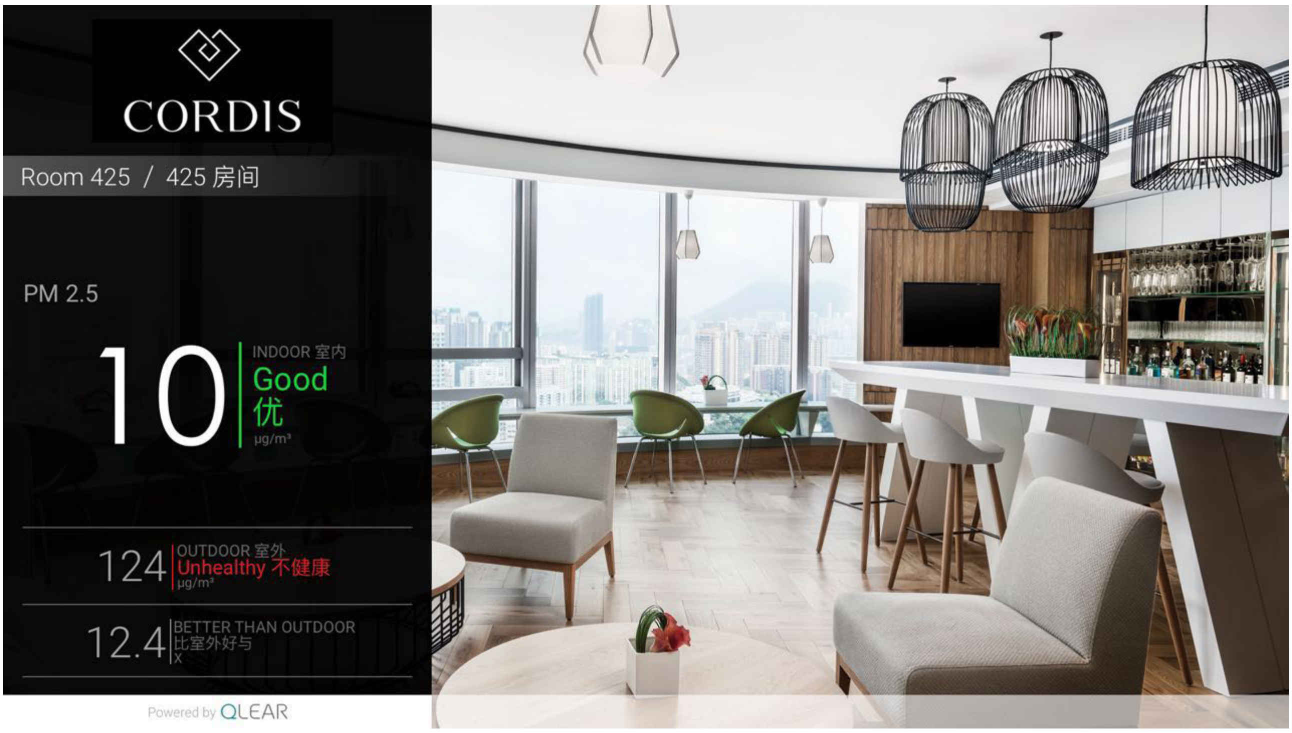

Figure 1. Indoor air quality monitoring data screenshots as displayed in a hotel public spaces.

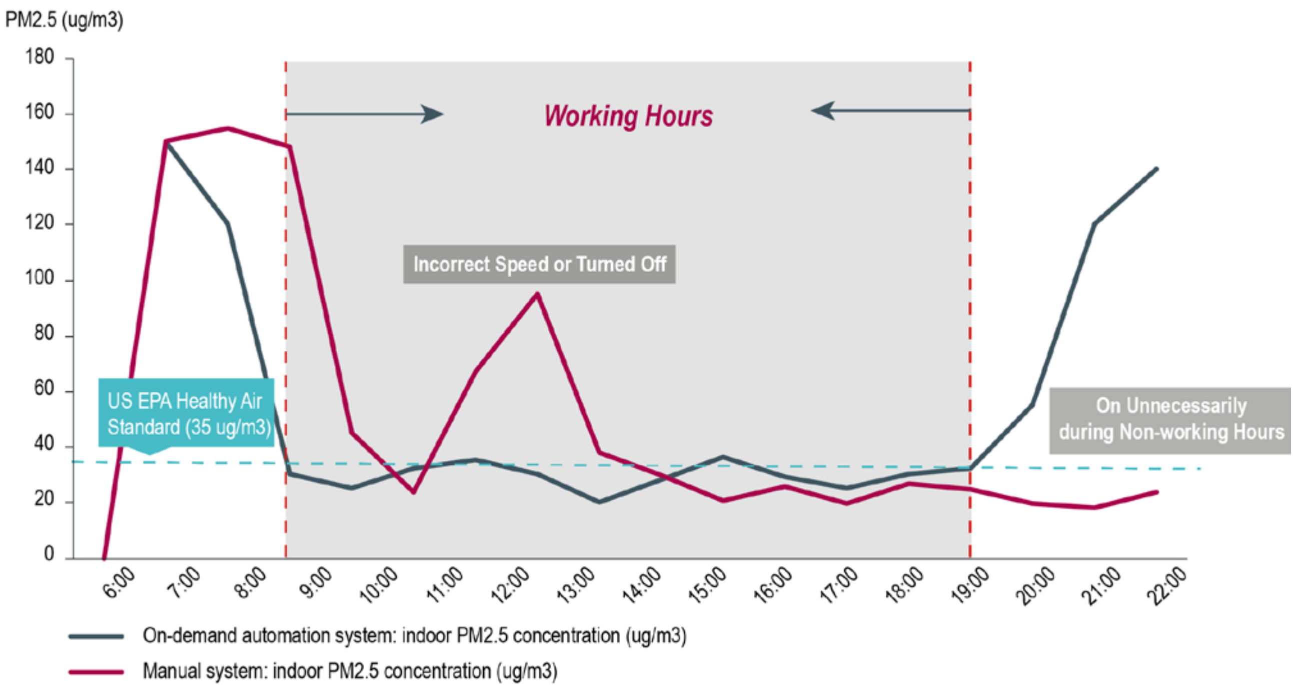

Figure 2. On-demand Automation vs. Manual Operation (µg/m^3 equals µg/m^3). [Source: "Every breath we take–transforming the health of China's office space," JLL & PureLiving Research Report, December 2015.]

All sensors are not created equal

One of the most frequent questions we are asked is "How do I select a monitor?" After all, monitors today may cost between $35 to more than $5000.

Figure 3. Various types of continuous monitoring equipment.

Typically, we guide monitor selection with a few considerations:

1. Pick a monitor based on the sensors needed, the criticality of performance, and how challenging the environment is. The parameters presented in **Table 1** are the most important in IAQ monitoring.
2. "Paper specs" are not a good indicator of performance. Often, sensor capabilities listed in technical or marketing data sheets are used to compare and select sensors, even by inexperienced monitor manufacturers. However, sensors are impacted by design (i.e. sensor proximity on a Printed Circuit Board may lead to elevated temperature readings and premature failure.) Sensors often also vary widely in terms of long-term stability. Therefore, monitors must be either performance tested by the end user's representative over time or by a reputable multi-brand dealer.
3. Realistic expectations of accuracy. Instead of looking for accuracy that is close to the reference source, evaluators should test by batches of at least 4 units and look for repeatability of readings and fit to the reference monitor's response curve. This indicates manufacturing and sensor quality. Accuracy also needs to be evaluated over a wide range, not just a single reading. Cheaper sensors may match a reference method within a common range, but not at low or high ranges.
4. RESET™ monitoring standards are key to identifying the difference between good and poor sensors. Created in China in 2011 and adopted by companies across the world, RESET™ is a healthy building standard for indoor air quality built around continuous monitoring data. In addition to whole building and interiors certifications, RESET™ also certifies monitoring hardware with a set of requirements that categorize monitor quality into three groups: A for calibration-grade, B for commercial-grade, and C for consumer-grade. RESET™ includes requirements that one would not normally consider such as a data buffer so that in case communications fails, data will still be stored.

Table 1. The most important parameters in IAQ monitoring.

IAQ parameter	Common sensor technologies	Recommended measurement range (Grade B)	Selection notes
Particulate Matter (PM)	Optical particle counter (OPC)	0–300 µg/m³	Sensors should be able to provide particle count, not just mass concentration. Critical considerations: humidity compensation, stability, repeatability, accuracy over the ranges likely to be encountered.
Carbon Dioxide (CO_2)	NDIR	0–2000 ppm	CO_2 indicates the "quality" of ventilation and is possibly the most important IAQ parameter. Select sensors that have auto-zeroing features and that can be field-replaceable.
Total Volatile Organic Compounds (TVOC)	Metal Oxide Sensors (MOS) Photoionization Detector (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 inexperienced manufacturers or first generation monitors suffer from inaccuracy due to heat generated from 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.
Formaldehyde	Colormetric, electrochemical; chemical	0.03–0.3 mg/m³	Currently, there are no real-time technologies known to the author that reliably match laboratory HPLC analysis. Avoid.

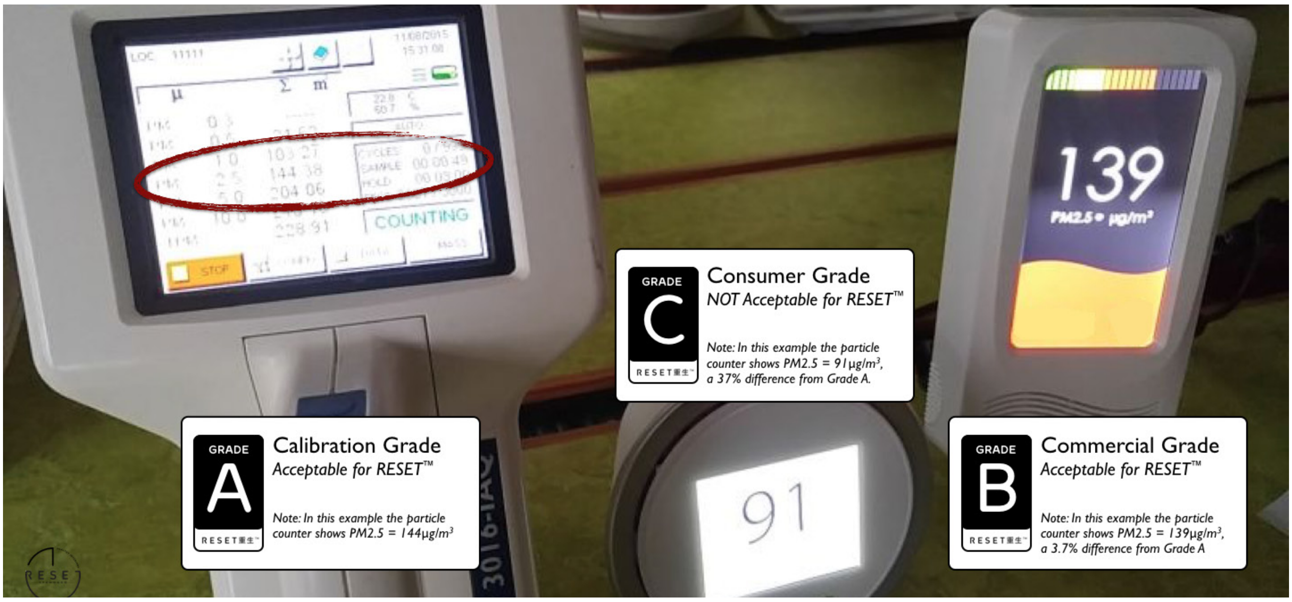

Figure 4. Varying accuracy of three monitors show the difference between monitor quality grades. General rule: if you can't calibrate it, don't buy it. Only Grade A and Grade B monitors are accepted for RESET™. Latest RESET™ standards are here: http://reset.build/resources/RESET_Accredited_Air_Monitor_Requirements

5. Costs

- Initial. Monitors meeting RESET™ standards typically cost about $100–300 for Grade C (Consumer-grade) monitors, about $600–1400 for Grade B (Commercial-grade) monitors, and upwards of $3000 for Grade A (Calibration-grade). Costs vary depending on number of sensors, convenience features, and brand.
- Maintenance. Annual or semi-annual calibration is critical for maintaining accuracy, particularly in polluted environments and is generally mandatory for recertification. Generally, annual calibration and maintenance costs are typically 10-20% of initial cost.
- Software. Most professional software is on a subscription basis and can be paired with different hardware. Annual costs may be free for limited basic versions or $100–300 per monitor per year depending on total number of monitors and the sophistication of the software.
- Hosting and connectivity. If privacy is a concern, local hosts and networking may be required, but in most cases, monitors simply need to connect to the internet. Initial installation can be done by third parties or DIY.
- Leasing options. Increasingly, service providers are offering "pay-as-you-go" monitoring packages that include hardware, calibration, cloud-ware, and support on an annual basis. This way, hassle is minimized and technology is future-proofed.

Deployment Tips:

Deployment location, choice of communications protocols, power supplies, should be carefully planned to ensure representative data – or data at all – is received for analysis.

1. **Connectivity**. The ability for the monitor to transmit data is a major source of problems if not carefully considered when monitors are selected and deployed. IT departments must be involved early on or can pose challenges later (see **Table 2**).
2. **How many monitors are needed?** Monitors read only the nearby air quality. Therefore, the appropriate number of monitors depends on how many representative environments are in a space. A small 500 m² office with staff area, conference rooms, canteen, and lab, for instance, may need four monitors, while a 2000 m² factory floor with the same equipment and ventilation system may only need two. In a mixed-use office environment, **the general rule of thumb is about one per 500 m².** Building standards and certification programs such as RESET™ may have their own requirements. Also, sensitive populations may expect monitoring around them. Generally, focus on staff areas.
3. **Location and placement**
    - Height. Generally, in the breathing zone – 1–2 m high above the floor is ideal. However, if there are children (i.e. school) or theft/interference is an issue, mounting monitors above head height or in lockable boxes are options.
    - What to avoid. Monitors should not be located near windows or areas of outdoor air intrusion, near HVAC supply ducts (unless the supply air is being monitored), or any sources of unusual IAQ pollutants. If possible, a site survey taking handheld readings to check the representativeness of planned monitoring locations should be done ahead of time.
    - Tables vs wall mounted. If possible, wall mounted is preferable, as occupants are major sources of IAQ pollution and can particularly impact CO_2 and VOC readings. Wall mounts do require some installation (see photos) but also are less likely to be disrupted, unplugged, or moved. For new construction, be aware that newly painted walls can impact TVOC readings.
    - Ducts. Generally, we are most interested in measuring the actual ambient air that occupants are breathing and place the monitors in the breathing zone. However, if our purpose is to measure the building's own ventilation system or filtration systems before the occupants' behaviour or indoor sources filter or contaminate this air, we want to measure the air being supplied by the ducts. The use of a duct box that penetrates the duct as well as secures the monitor, can achieve this. Tip: monitoring outdoor air supply ducts is a convenient way to measure outdoor air quality without needing an outdoor "hardened" monitor to be exposed to the elements.
    - Documentation. It is very important to create – and maintain – the location of monitors on a floorplan or BIM (building information management) system plan. Monitors have a way of moving and accountability can be a problem over time, especially with staff turnover.
4. **Power options.** Corded power packs, while convenient, are likely to be unplugged, so DC from within the walls is preferred. If power cords must be used, select outlets that are less utilized, and mark the power plugs with signs saying, "Do not unplug", etc. Some monitors have a battery option, which can be convenient for validation or calibration against fresh air.
5. **Validation.** Monitors must be checked against reference machines, preferably before deployment and then once again on-site. Documentation should be kept in case of challenge. Outdoor air may be used as a field expedient check for CO_2 and TVOC. Be careful about comparing spot PM readings against published PM readings, which are typically hourly averages and, also, not co-located. If many monitors are being deployed (typically more than 10), it is often advisable to also deploy a high quality handheld reference machine or an "alpha class" monitor that can be used as a comparison.
6. **Signage.** As previously mentioned, occupants may often impact monitoring, either by moving the monitors, unplugging them, breathing on them, doing construction work near them, or even stealing them. If the monitors cannot be deployed in a secure manner or out of reach, clear dual language signage that says, "Ongoing monitoring, please do not touch or unplug" is necessary.
7. **Renovation or other indoor sources.** If possible, monitors should not be installed until just before occupation. Since monitors can be a useful tool in gauging the readiness of indoor air for move-in, they can be set up before, but never should be exposed to construction activity such as painting, which can damage or destroy sensitive sensors. If they must be installed during construction, they should be bagged up in airtight bags and secured to avoid loss.

Table 2. The pros and cons of different communications types.

Communications type	Pros	Cons
Bluetooth	Useful for portable hand-carried or wearable monitors, but not fixed ones; useful if application requires frequent communications with mobile phones	Very limited range; pairing problems; Bluetooth is still not a universal standard
Wifi	Ubiquitous in most places; if not many monitors, easy to set up a dedicated "hotspot" style Wi-Fi router. Mainly useful in residential or small business and non-critical sites	Can be unstable; routers settings or passwords often changed due to business process; some monitor chipsets cannot handle 5.0 GHz bands; most monitors cannot handle username login systems that businesses often use
GPRS (mobile SIM card)	Can be used anywhere there is mobile signal; can be used to augment gaps; separate GPRS modem may be more acceptable to some security requirements than piggybacking on inter/intranet	Cell coverage can be spotty and change over time; must remember to keep subscription paid; cost of GPRS modem; must check compatibility of network with monitor's SIM card module
Zigbee	Longer distance than Wi-Fi, penetrates walls and solid materials better	Requires "hub and spoke" setup; ZigBee router is cost prohibitive if just several monitors; not very popular with monitor suppliers
LAN (RJ-45)	Very stable; fewest chances of connectivity problems	Some IT departments and business rules don't allow third party devices to get on network; physical cabling needed
Coax/analog	Similar to LAN; very stable; good for hotels or buildings; inexpensive	Generally, only available during construction (or requires opening up walls); less common

Cloud-ware and analysis

Sensor data is of little value, especially to non-experts. Data needs to be aggregated, made visually meaningful, and interpreted to drive action. In the old days, software was like cleanroom software – unattractive, purpose-built, not flexible, and local to the building. Today, the software is built on the cloud to provide remote access, be interoperable, create easier interoperability, allow benchmarking and trend analysis, and enable automation. However, privacy issues may impact this decision. Although the focus is currently on air, software platforms are enabling us to increasingly include other environmental parameters, such as light and sound.

Due to space constraints, software, visualization, and data analysis will be the subject of a follow-on article.

Conclusions & takeaways

Continuous air quality monitoring is a critical component of effective IAQ systems, from assessing the baseline condition to optimizing settings to maintenance. The monitoring hardware industry is growing rapidly, but "soft knowledge" – selecting the right hardware, deploying monitors correctly, and getting maximum value out of the data with a cloud analysis platform and automation software – will need attention in order to actually achieve results. ■