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An Intelligent IEQ Monitoring and Feedback System: Development and Applications

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ABSTRACT

Indoor environmental quality (IEQ) significantly affects human health and wellbeing. Therefore, continuous IEQ monitoring and feedback is of great concern in both the industrial and academic communities. However, most existing studies only focus on developing sensors that cost-effectively promote IEQ measurement while ignoring interactions between the human side and IEQ monitoring. In this study, an intelligent IEQ monitoring and feedback system—the Intelligent Built Enviroment (IBEM)—is developed. Firstly, the IBEM hardware instrument integrates air temperature, relative humidity, CO_2, particulate matter with an aerodynamic diameter no greater than 2.5 μm ($PM_{2.5}$), and illuminance sensors within a small device. The accuracy of this integrated device was tested through a co-location experiment with reference sensors; the device exhibited a strong correlation with the reference sensors, with a slight deviation (R^2 > 0.97 and slopes between 1.01 and 1.05). Secondly, a wireless data transmission module, a cloud storage module, and graphical user interfaces (i.e., a web platform and mobile interface) were built to establish a pathway for dataflow and interactive feedback with the occupants of the indoor environments. Thus, the IEQ parameters can be continuously monitored with a high spatiotemporal resolution, interactive feedback can be induced, and synchronous data collection on occupant satisfaction and objective environmental parameters can be realized. IBEM has been widely applied in 131 buildings in 18 cities/areas in China, with 1188 sample locations. Among these applications, we report on the targeted IEQ diagnoses of two individual buildings and the exploration of relationships between subjective and objective IEQ data in detail here. This work demonstrates the great value of IBEM in both industrial and academic research.

1. Introduction

People spend nearly 90% of their lifetime indoors [1]. Thus, indoor environmental quality (IEQ) directly affects human health and social wellbeing [2–4]. For example, long-term exposure to a raised indoor temperature and humidity level can result in more severe sick building syndrome (SBS) symptoms [5]. The intensity of SBS symptoms increase and working productivity decreases when the indoor air becomes stuffier [6]. Logue and Price [7] from the Lawrence Berkeley National Lab studied the chronic health impact of indoor air pollutants in residences in the United States. They found that indoor air pollutants caused an annual loss of 400–1100 disability-adjusted life years (DALYs) per 100 000 persons, and that particulate matter with an aerodynamic diameter no greater than 2.5 μm ($PM_{2.5}$) contributed most to the DALYs lost in this analysis. Another study by Xiang et al. [8] estimated that 5.7 billion and 190.1 billion USD losses were respectively attributable to short- and long-term indoor exposure to $PM_{2.5}$ of outdoor origin in urban China. These health and economic losses caused by poor IEQ have aroused significant concern and deep thinking on IEQ monitoring and control.

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Practical tools are needed in order to undertake measurements of IEQ efficiently and robustly. The traditional IEQ monitoring protocol consists of a large number of independent environmental sensors [9–11] for measurements such as air temperature, humidity, carbon dioxide (CO_2), particulate matter (PM), air pollutants, illuminance, noise, and so forth. However, the total cost of these sensors is often overly high. Furthermore, their assembly is intensely invasive in real-life scenarios [12,13], which dramatically limits the popularity of IEQ measurements in the spatial dimension. In addition, these sensors only support local data storage, so IEQ measurement must be conducted on the spot or in the short term [14–16]. Thus, traditional IEQ measurement tools are deficient in terms of spatiotemporal scale and data resolution. As a result, the previous understanding of IEQ characteristics has been partial and inaccurate.

With the rise of the Internet of Things (IoT) and big data technologies in recent decades, considerable progress has been made on IEQ monitoring tools [17]. New technologies, such as sensor integration, wireless data transmission, and cloud service, are being introduced into the development of IEQ monitoring tools [18–20]. Ali et al. [21] developed an open-source platform for the integration of various IEQ sensors. This platform can support a flexible synchronization of massive and long-term IEQ measurements at a low cost. Kelly et al. [22] applied the IoT to establish an IEQ monitoring system in residential buildings that implements the wireless interconnection of sensors via ZigBee and Internet Protocol version 6 (IPv6). Parkinson et al. [23,24] developed a continuous IEQ monitoring system, SAMBA, based on a wireless sensor network. SAMBA provides a more comprehensive solution for understanding the performance of indoor environments, consisting of both a low-cost suite of sensors and a web platform for IEQ rating and analysis. These new tools have significantly enhanced the efficiency of IEQ measurement. More importantly, they provide the opportunity for IEQ data collection on a broader spatiotemporal scale and with more satisfactory resolution.

However, objective IEQ monitoring alone is not enough to achieve an excellent indoor environment. It is also necessary to open up a path for IEQ information interaction with occupants. The occupants of an indoor environment often desire to know the objective IEQ conditions in their surrounding areas [25]; furthermore, researchers in the field need to listen to the opinions of occupants in order to create a better indoor environment [26]. Unfortunately, although many researchers have conducted objective measurements and subjective surveys of IEQ in their studies, it is difficult to synchronize objective and subjective data within a broad spatiotemporal scale [27–30]. In other words, the actual IEQ conditions at the exact time and location the survey occurred are unknown, and people are surveyed without understanding objective IEQ results. This defect makes further studies on the correlation between IEQ parameters and occupant satisfaction in real-life scenarios impossible. In sum, the existing tools cannot achieve the simultaneous data collection of objective IEQ data and occupant opinions, nor do they permit information interaction between indoor environmental data and occupants.

Therefore, the primary goal of this study was to develop an IEQ monitoring device that consists of multiple sensors with low cost, high accuracy, and remote transmission. Based on the hardware of this IEQ device, we also aimed to build an intelligent IEQ system software that includes a cloud database and platform. The proposed system is expected to not only achieve long-term continuous IEQ monitoring but also support simultaneous information interaction and occupant feedback.

The remainder of this paper is organized as follows:

- Section 2 provides a detailed description of the technology from both the software and hardware sides.
- Section 3 examines the sensor performance based on a field experiment.
- Section 4 presents the technology application with a few examples.
- Section 5 discusses a comparison with other counterparts and the limitations of this study.

2. Development of the intelligent built environment monitor

Our group has been developing the Intelligent Built Environment Monitor (IBEM) since 2014. Thus far, IBEM is still undergoing continuous improvement and upgrading. This section introduces the whole architecture of IBEM, including both hardware and software.

As shown in Fig. 1, IBEM comprises five parts—an integrated sensor, a cloud server, a database, a web platform, and a mobile interface—that are connected and finally evolve into a pathway for dataflow. IEQ data (i.e., air temperature (temp), relative humidity (RH), CO_2, $PM_{2.5}$, and illuminance) are collected by the integrated sensor and transmitted to the cloud server through the third-generation mobile communication technology (3G), 4G, or Wi-Fi. After receiving the data, the cloud server saves it into the database. Then, the server transfers the data to the web platform and mobile interface for tracking, visualization, and analysis when needed. On the web platform, people can examine the running status of IBEM, see historical IEQ data, and download data for further analyses. On the mobile interface, the IEQ information is provided to occupants more directly, such as in the form of an objective value and assessment score of the real-time IEQ conditions and optimization suggestions to address poor IEQ factors.

Meanwhile, people can express their opinions and provide satisfaction ratings on the mobile interface regarding thermal comfort, air quality, lighting, acoustic quality, and overall environment. These subjective votes are uploaded to the cloud server and immediately fused with the corresponding objective IEQ data that was recorded at the same time the ratings were provided. This is the key to achieving the synchronous collection of objective and subjective IEQ data.

Based on IBEM, multiple IEQ parameters can be monitored using only one instrument, which helps solve the spatiotemporal sampling problem at a low cost. More importantly, this system connects the indoor environment with its occupants and breaks the information asymmetry between them. The following two subsections introduce the detailed technical information of IBEM.

2.1. Hardware

The IBEM hardware mainly comprises environmental parameter sensors, which are the foundation of IEQ data collection. In order to reduce the cost and improve the convenience of environmental monitoring, a sensor integration design is adopted in this study. However, considering the cost and size, it is impractical to include all IEQ sensors in one instrument. Therefore, after deliberations on the importance of each IEQ parameter and the need for long-term monitoring, five sensors were eventually chosen: temp, RH, CO_2, $PM_{2.5}$, and illuminance. Table 1 lists the selected sensors' information (i.e., supplier, measurement principle, range, and accuracy). The manufacturer certification periods of all sensors are more than three years.

Two caveats need to be explained:

(1) Sensors of chemical pollutants, such as formaldehyde or total volatile organic compounds (TVOCs), were not integrated into the IBEM. Although the costs of these sensors are relatively small, low-cost TVOC sensors lack specificity and formaldehyde sensors lack accuracy at appropriate levels, limiting their applicability in

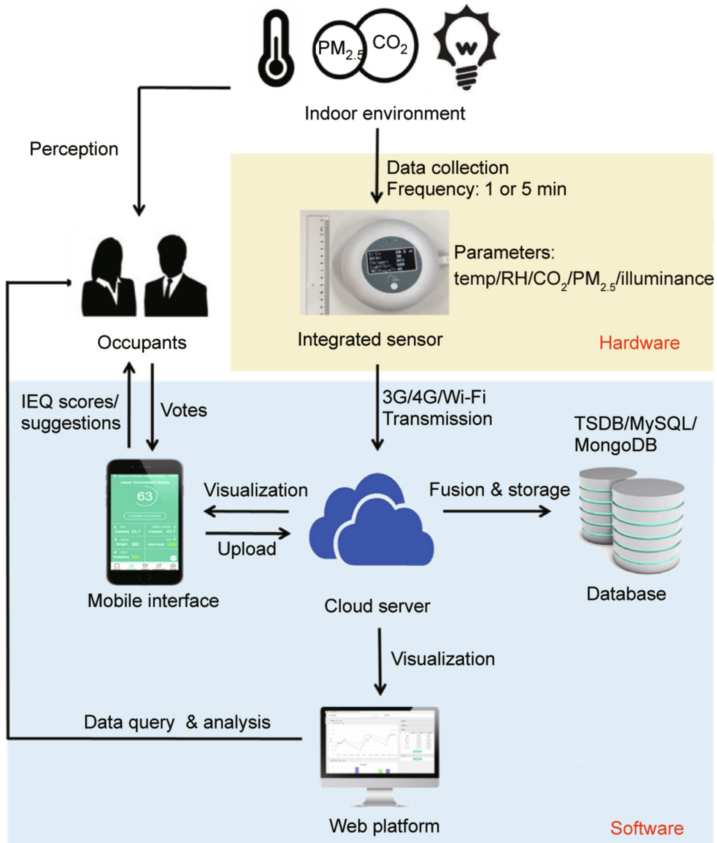


Fig. 1. The system architecture of IBEM. TSDB: time-series database. TSPB: time-series database.

Table 1
Information on the IEQ sensors.

Parameter	Product number	Sensor supplier	Principle	Range	Accuracy
Temp, RH	SHT30	Sensirion AG (Switzerland)	Complementary metal–oxidesemiconductor (CMOS) sensing	Temp: −40–80 °C RH: 0–99%	Temp: ±0.5 °C RH: ±5%
CO_2	S8-0053	SenseAir (Sweden)	Non-dispersive infrared ray (NDIR)	0–5000 parts per million (ppm)	±75 ppm
$PM_{2.5}$	PMSA003-A	Plantower (China)	Laser light scattering	0–1000 $\mu g \cdot m^{-3}$	±10% @ 20–500 $\mu g \cdot m^{-3}$
Illuminance	BH1750FVI	ROHM Semi (Japan)	Photovoltaic effect sensing	0–50 000 lx	±5%

this study. Furthermore, the need for long-term continuous monitoring of chemical pollutants is not specially required in Chinese standards [31–33]. The standard measurement protocol is a sampling test under certain conditions rather than long-term monitoring.

(2) Noise level was not included, even though acoustics have an impact on human perceptions of IEQ. This is one of the defects in our hardware development, but we still have two considerations: Firstly, noise standards [34–36] focus more on background noise and less on speech. For example, according to the Chinese national standard on noise [36], a room's acoustic performance should be assessed when the outdoor noise is at its maximum. Furthermore, the room should be unoccupied, the heating, ventilation, and air conditioning (HVAC) system should be running, and the windows should be closed during the noise measurement. Therefore, there are no continuous sampling requirements for noise level over timeframes [24], and a one-time noise test under the most adverse conditions is adequate in many cases. Secondly, unlike other IEQ parameters, there are nearly no immediate control means or technologies for the acoustic environment in most buildings. Therefore, although we could obtain the real-time noise level, the value of these data for improving the operating acoustic performance is negligible. From this perspective, the continuous monitoring of noise levels seems less valuable in comparison with other parameters.

In addition to sensors, the hardware includes other functional modules: a data transmission module, a data storage module (backup), a power module, and a display module. All of these are integrated into one device, as shown in Fig. 2. After years of research, the integrated device has gone through several upgrades and renovations. As a result, the latest version of the device is a palm-sized round box with a diameter of 125 mm and a height of 40 mm, which can be placed on desks in real-life measurement scenarios.

The data transmission module can upload IEQ data to the cloud via 3G, 4G, or Wi-Fi at predefined intervals (e.g., every 1 or 5 min). 3G or 4G transmission is automatically achieved by the subscriber identity module (SIM) card pre-embedded inside the device,

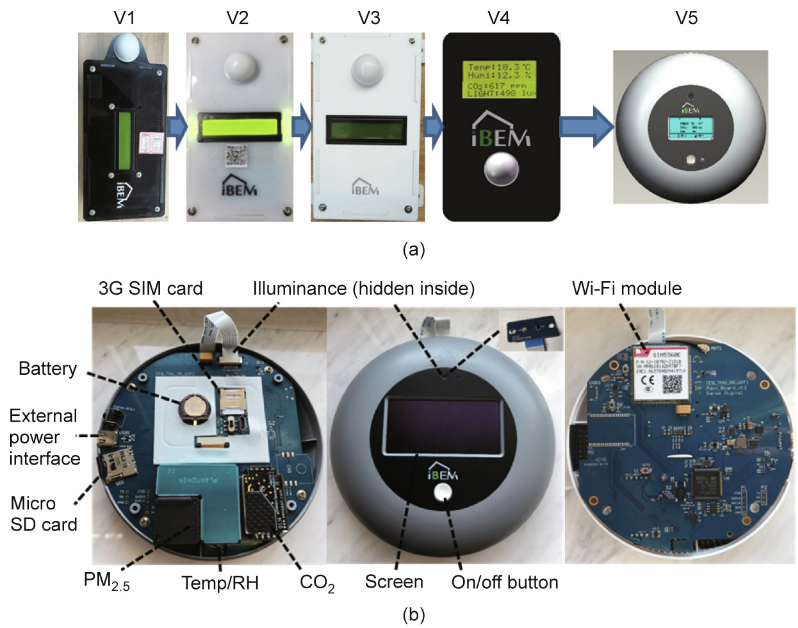


Fig. 2. (a) The entire development process of IBEM with different versions; (b) the internal structure of the IBEM device, including sensors, data transmission module, data storage module, power module, and display module. SIM: subscriber identity module; SD: secure digital.

without any additional operations on site. Alternatively, Wi-Fi transmission requires users to connect the device to existing Wi-Fi in several steps that take less than 2 min. These two signals can be used as double insurance to guarantee wireless data transmission in most cases. Furthermore, the data transmission module has a self-recovery function that recovers the connection automatically after a temporary network interruption. This function significantly improves the data transmission reliability in long-term monitoring.

The data storage module mainly provides a backup of data storage for cases in which wireless data transmission cannot be achieved. IEQ data can be stored locally in a micro secure digital (microSD) card, which generally accommodates the amount of data from more than one year of continuous monitoring.

The power module includes an external power interface (universal serial bus (USB) Type C) and one button battery for backup. The designed electrical parameters are 5 V direct current (DC) and 2 A as input. Typically, the device is powered by external electricity. However, when the external power supply shuts down temporarily, the button battery can be used as a short-term power supply that can generally provide continuous power for one week.

The display module is designed for the visualization of real-time IEQ data and the status of network connections. An light emitting diode (LED) screen is installed on the front of the device, which can be turned on by pressing the button and automatically goes off after 15 s to conserve energy.

Given its many sensors and modules, it is a major challenge to minimize interference for the integrated device—especially the influence of heat dissipation on the measurement accuracy of the air temperature and relative humidity sensors. Solutions were considered from three aspects and adopted to solve this problem. Firstly, air temperature and relative humidity sensors are installed at the windward position (i.e., the edge of the mainboard closest to the external environment), so the airflow passes through them first. Secondly, the rated power of each module is controlled at below 1 W to reduce heat dissipation. Thirdly, the distance between the primary heat sources and the sensors has been designed to be as far as possible. For example, the Wi-Fi module is placed on the opposite side of the mainboard at the farthest distance from the air temperature and relative humidity sensors. Based on the above considerations, the measurement accuracy of IBEM is ensured. The performance test and validation results are further presented in Section 3.

2.2. Software

The software design of IBEM consists of two main parts: ① data transmission and storage (i.e., the cloud server and database) and ② data presentation and human–computer interaction (i.e., the web platform and mobile interface).

Data transmission and storage: The whole architecture is developed based on the software-as-a-service (SaaS) concept, as shown in Fig. 3. Firstly, Nginx load-balancing technology is applied to access the multi-source data. Secondly, the Apache Tomcat 8.0 server and Linux operating system are adopted. JavaEE Spring is used as the server programming framework. The servers use the same application programming interface (API) under the unified standard to make it convenient to find data. Thirdly, different databases store different data types to ensure efficient reading and writing; these databases include a time-series database (TSDB) for dynamic IEQ data, MySQL database for static information data, and MongoDB database for subjective survey data. In addition, a master–slave backup work mode is adopted in all databases, and all the data are synchronized through the intranet to ensure data security.

Data presentation and human–computer interaction: Both the web platform and the mobile interface were developed to establish an information "bridge" or pathway between the indoor environment and its occupants, as shown in Fig. 4. The web platform is open to professionals and data analysts for data visualization and downloads, while the mobile interface is mainly designed for the building occupants to assess the IEQ conditions and rate their opinions. People can easily access the mobile interface by using their smartphones to scan the quick response (QR) code attached to the IBEM monitoring device placed nearest to them. Fig. 4(b) shows several primary functions of the mobile interface, which are further illustrated below.

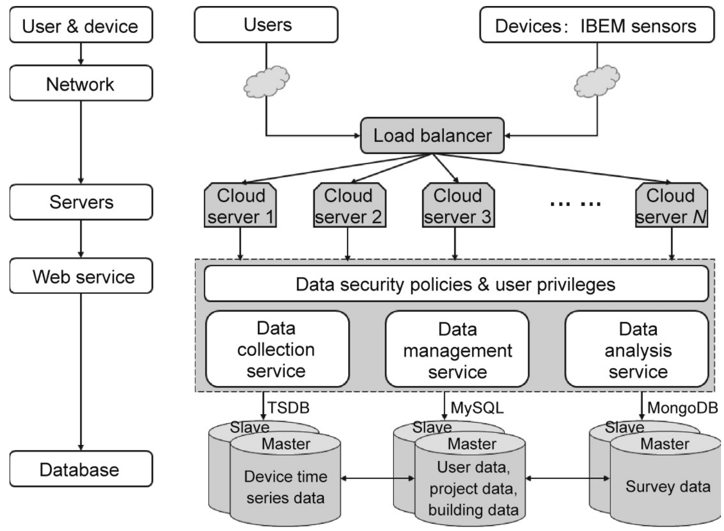


Fig. 3. The framework of data transmission and storage.

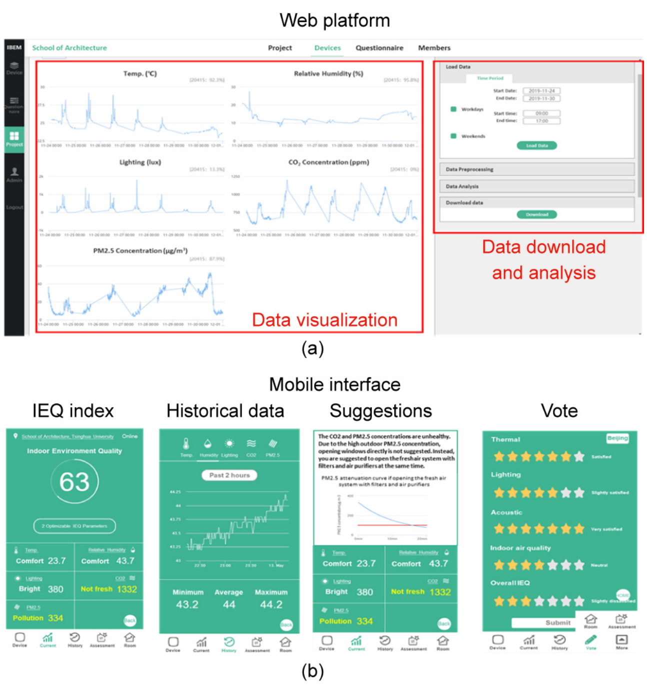


Fig. 4. Data presentation and human–computer interaction.

Occupants can see the real-time IEQ parameters and their ratings. The rating represents an assessment of the criterion-based compliance performance of the IEQ parameter. The measurement results of specific parameters are checked against the compliance criteria drawn from the relevant national or international standards (Table 2) [33,36–39] to determine the ratings. When calculating the real-time rating of one IEQ parameter, the IBEM measurements within the past 1 h period are considered. That is, the rating is calculated based on the percent of measurement results within the compliance range in the last hour: The rating *X* represents *X*% of the measurement results in compliance.

Finally, the overall IEQ index with a centesimal grade is calculated based on the weighting scheme (Table 3). For thermal comfort, the weight is set to 0.30 (0.18 for temperature and 0.12 for humidity), which is generally consistent with the previous settings [12]. A higher weight (0.40) is put on indoor air quality (IAQ), compared with other studies (0.14–0.36), because Chinese people usually pay more attention to IAQ, and their satisfaction with IAQ is relatively low, according to our previous study [40]. More specifically, we set the weight of CO_2 to 0.24 and the weight of $PM_{2.5}$ to 0.16. The weight value for CO_2 concentration is higher because this measurement can reflect the overall ventilation performance and is often used as a comprehensive indicator for IAQ evaluation. For lighting, the weight is set to 0.15, which is slightly lower than in other studies (0.16–0.29). This is because the indoor lighting environment generally reaches the standard, according to a large-scale measurement of green buildings in China [41]. Thus, we lowered the weight of illuminance to make the differentiation of the IEQ index more prominent and to reflect the problems of other IEQ factors to a greater extent. In regard to acoustics, although IBEM cannot measure noise level yet, the weight of acoustics is still kept in order to ensure the integrity of the IEQ evaluation; however, its weight is lowered to 0.15, compared with other studies (0.18–0.39). At present, we assume a maximum score for acoustics. In the future, when a noise sensor is added to the IBEM device, the weight of noise level will be adjusted, and the score for acoustics will vary according to the measured data. Finally, it should be mentioned that the weighting scheme given in this paper is just an example, and it will be revised as the research goes further.

Table 2
The compliance range for each IEQ parameter.

Parameter	Compliance range	Source
Temp	24–28 °C (summer); 18–24 °C (winter)	GB 50736–2012 [37]
RH	$\leq$ 70% (summer); no requirement (winter)	GB 50736–2012 [37]
CO_2	$\leq$ 1000 ppm	ANSI/ASHRAE 62.1–2019 [38]
$PM_{2.5}$	$\leq$ 35 $\mu g \cdot m^{-3}$	T/ASC02–2016 [33]
Illuminance	$\geq$ 300 lx (office)	GB 50034–2013 [39]
A-weighted sound level	$\leq$ 45 dB (office)	GB 50118–2010 [36]

Historical IEQ data is also available on the IBEM mobile interface. However, unlike the corresponding function on the web platform, a historical data query on the mobile interface will only support a recent short period (less than one day). The purpose of this design is to reduce the interface's response time and ensure a good user experience.

Table 3
The weighting scheme for IEQ index calculation.

Thermal comfort		Air quality		Lighting	Acoustics
Temp	RH	CO_2	$PM_{2.5}$	Illuminance	–
0.18	0.12	0.24	0.16	0.15	0.15

For IEQ factors with poor performance, the mobile interface provides specific suggestions to help occupants make appropriate adjustments. For example, the interface suggests that the occupants turn on air purifiers when the IAQ is very bad. More importantly, a voting module is developed based on the mobile interface. People can submit their perceptions or level of satisfaction with each IEQ factor after learning about the actual IEQ parameters. These votes are matched with the objective IEQ parameters monitored by the IBEM device for that particular time period and place, and the combined data is uploaded and saved in the database. In this way, subjective and objective IEQ data can be collected simultaneously, thereby overcoming the disadvantage in traditional retrospective surveys of blindness to objective IEQ conditions. That is, it is possible to know how different IEQ conditions affect people's perceptions in actual buildings. This result can help researchers identify the most satisfactory IEQ conditions for a certain space. Such information is the key to the on-demand provisioning of environmental control. Another feature of this vote collection method is that it can accept ratings from building occupants passively, instead of conducting surveys actively (which may make people annoyed). However, this approach may also cause a bias toward dissatisfaction because people are more likely to vote (i.e., complain) when they feel uncomfortable, rather than voting when the IEQ performance is satisfactory. This issue needs to be addressed, although more analyses are required for verification. In this paper, we will not discuss the issue of possible bias further.

3. Performance test based on a limited field evaluation

Before use, the IBEM devices are first calibrated in a testing chamber by the National Institute of Metrology (see Section S1 in Appendix A). In order to describe the IBEM performance after authoritative calibration, this section presents a limited field evaluation in a controlled office. The performance and accuracy of the IBEM monitoring devices were tested based on the co-location strategy with several commercial sensors (i.e., reference sensors). More information on the reference sensors is provided in Table 4 [42]. These reference sensors were chosen for comparison because they were widely used in both industry and academic researches [43,44]. All the reference sensors were within the manufacturer certification period, ensuring adequate accuracy.

Co-location of both IBEM devices and their commercial equivalents was done in five locations in an office with two floors. These five locations were selected to collect data from very different environments, which ensured that the parameter range during the test was as wide as possible. Data collection occurred at 5 min intervals over two days for both the commercial and IBEM devices. The averaging time was 10 min for each measurement. Fig. 5 shows the office floor plan and the placement of devices for co-location testing. All devices were placed on desks at a height of 0.75 m.

In the office space, a variable refrigerant volume air conditioning system and humidifier were used for thermal environment (i.e., air temperature and RH) control. Electric shading blinds and LED lights with adjustable luminous flux and color temperature were used for lighting control. Mechanical ventilation equipment with high-efficiency filters (the minimum efficiency reporting value (MERV) of the filters was 15) was used to provide outdoor air for CO_2 concentration control, and air purifiers were used for $PM_{2.5}$ concentration control. Furthermore, to create conditions with high CO_2 and $PM_{2.5}$ concentrations during the test, dry ice and incense were used as the respective sources of CO_2 and $PM_{2.5}$. During the experiment, the room was unoccupied, and we created considerably different IEQ conditions with an air temperature varying from 15 to 27 °C, RH varying from 20% to 60%, illuminance varying from 0 to 700 lx, CO_2 concentration varying from 400 to 2000 parts per million (ppm), and $PM_{2.5}$ concentration varying from 10 to 200 $\mu g \cdot m^{-3}$. As a result, the IEQ conditions were broad enough to simulate most scenarios in actual buildings.

IEQ monitoring data from the IBEM devices and their commercial counterparts were compared, and linear correlations are shown in Fig. 6. The IBEM and HOBO data loggers revealed strong correlations for temperature and RH readings throughout the test (Figs. 6(a) and (b); $R^2 > 0.99$ and slopes between 1.01 and 1.02). The average deviation was 0.3 °C for temperature and 0.9% for RH. CO_2 and $PM_{2.5}$ concentration measurements were also strongly correlated between the IBEM devices and their counterparts (Figs. 6(c) and (d); $R^2 > 0.97$ and slopes between 1.01 and 1.05), albeit with some scatter. The average deviation was only 25 ppm for CO_2 concentration and 7 $\mu g \cdot m^{-3}$ for $PM_{2.5}$ concentration. For illuminance, the IBEM devices showed strong correlations with the TESTO sensors (Fig. 6(e); $R^2 > 0.98$ and slope = 1.01), and the average deviation was less than 11 lx. These test results validate the measurement accuracy of the IBEM devices.

It should be noted that the above experiment tested the short-term performance of IBEM under different IEQ conditions. In terms of long-term performance, IBEM can perform self-calibration for CO_2 concentration and illuminance in most buildings because the baseline values of these measurements are roughly constant over time. For example, the baseline of CO_2 concentration is 400 ppm (outdoor value). If a room is unoccupied and well-ventilated for a long time, the indoor CO_2 concentration should decrease to 400 ppm. Similarly, the baseline of illuminance is 0 lx (totally dark). If the room is unoccupied at night and all lights are off, the indoor illuminance should be 0 lx. The self-calibration algorithm automatically compares the minimum measured value in a certain period with the baseline value and then removes the offset. However, if a building has no long periods of non-occupancy, it is difficult to determine the IEQ parameter baseline. Under such circumstances, the self-calibration method is not valid, and it is necessary to call back the monitoring devices for manual calibration.

Table 4
Information on the reference sensors.

Parameter	Reference sensor	Range	Accuracy
Temp, RH	HOBO MX1102 (Onset Computer Corporation, USA)	Temp: 0–50 °C RH: 1%–90%	Temp: ±0.21 °C @ 0–50 °C RH: ±2% @ 20%–80%
CO_2	HOBO MX1102 (Onset Computer Corporation, USA)	0–5000 ppm	±50 ppm
$PM_{2.5}$	TONGDY G03-PM2.5 (Tongdy Sensing Technology Corporation, China)	0–600 $\mu g \cdot m^{-3}$	±10 μg + 5% of the reading
Illuminance	TESTO 545 (Testo SE & Co. KGaA, Germany)	0–100 000 lx	Class C according to DIN 5032-7 [42]

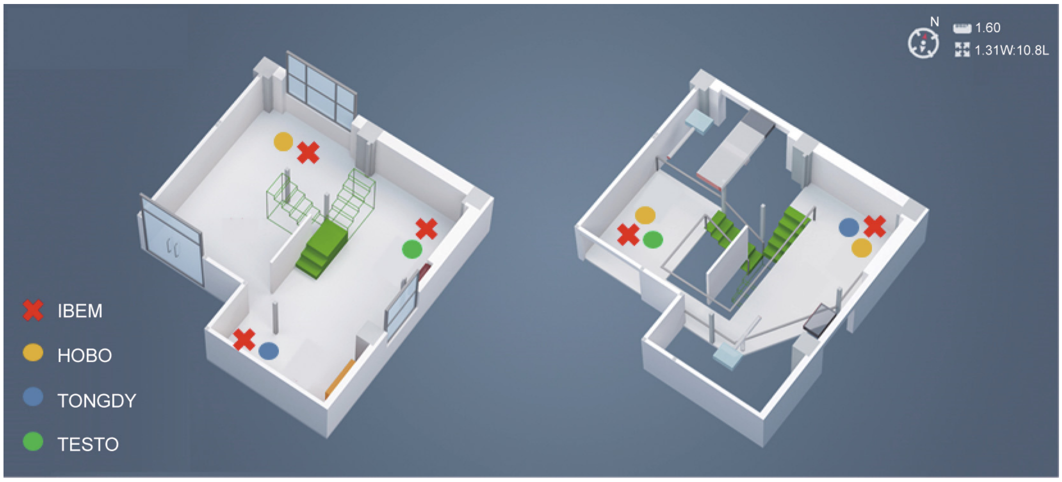


Fig. 5. Placement of IBEM and commercial devices for co-location testing.

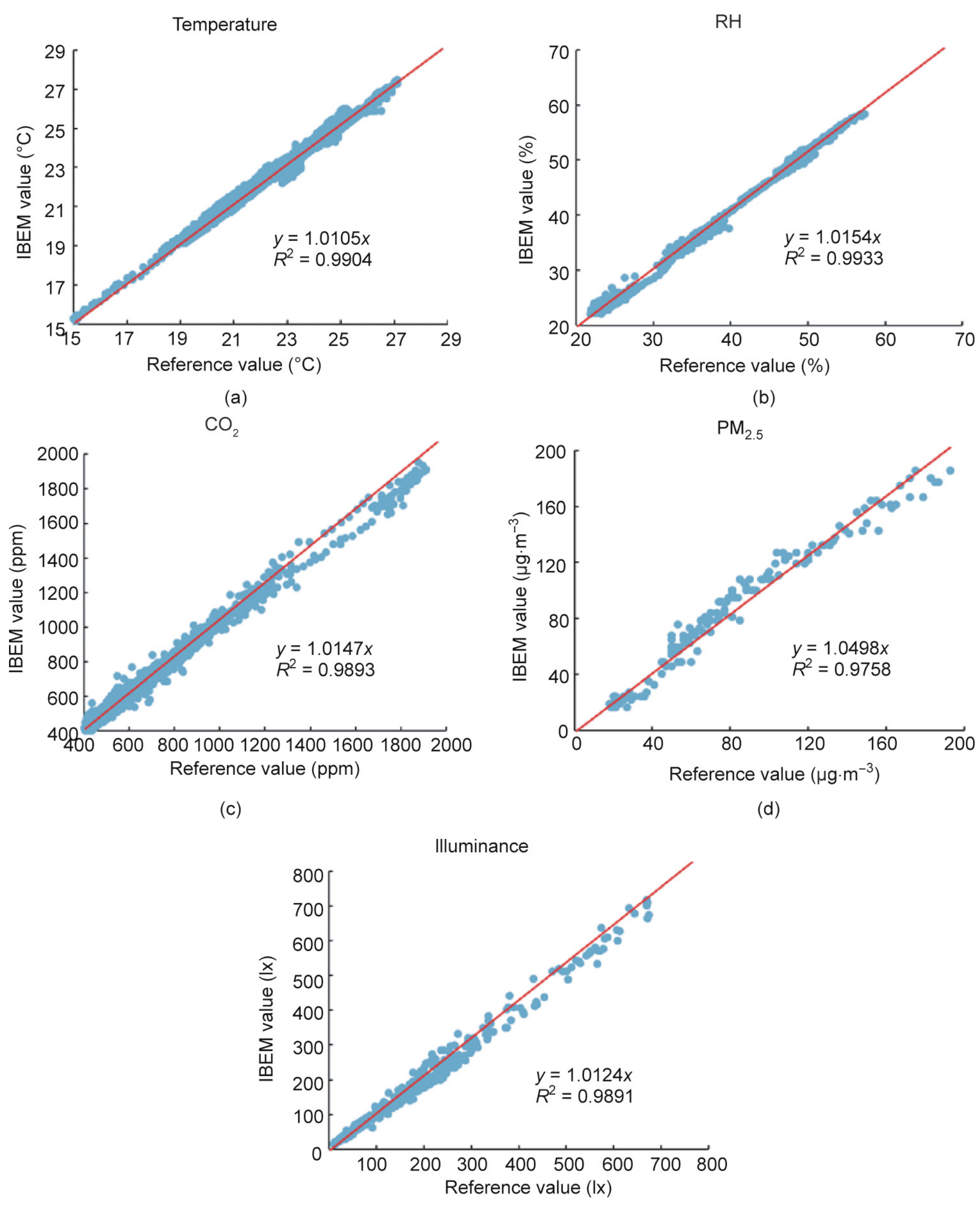


Fig. 6. Comparisons between IBEM devices and their commercial counterparts: (a)–(c) HOBO; (d) TONGDY; and (e) TESTO.

The baselines for temperature, RH, and $PM_{2.5}$ concentration are not constant over time due to the influence of outdoor weather and other factors. Thus, the calibrations for these measurements over the long term must generally be manual. Our study calls back each monitoring device for manual calibration and maintenance at least once a year. Furthermore, we entrusted a third-party detection institution to conduct high-frequency data acquisition tests under an extreme environment, demonstrating the long-term operational reliability of IBEM.

4. Applications and results

The IBEM is being applied in many actual buildings in China. By the end of 2020, the devices and systems had been deployed in 131 buildings in 18 cities/area, covering four climate zones, including severe cold, cold, hot-summer–cold-winter (HSCW), and hot-summer-warm-winter (HSWW) zone. The measured buildings also included a variety of types, such as office (48%), shopping mall (13%), school (9%), hospital (8%), hotel (6%), residence (11%), and others (5%). Fig. 7 shows the distribution of geographic locations and types of monitored buildings.

The selection principle for the number and location of sensors in each building is illustrated in Section S2 in Appendix A, which considers the building types, areas, floors, room types, orientations, and other factors. Thus far, a total of 1188 sensor locations have been accumulated.

At each sample location, IEQ parameters are continuously monitored for a whole year or for at least two weeks in each season, with a data collection interval of 1 or 5 min. The average online rate is nearly 90%, except for artificially unplugged devices. In addition, occupant feedback from the area near each sample location is collected via the mobile interface of IBEM. As a result, an IEQ database with a broad spatiotemporal scale and relatively fine resolution has been established. The data amount exceeds 1.09 TB, including more than three billion records of IEQ parameters and 2425 building occupant votes fused with objective IEQ data from the same time period and location.

Based on such a large-scale IEQ database, many analyses have been conducted. Firstly, the macro characteristics of IEQ in Chinese buildings were revealed, and overall poor IEQ performances were observed. For example, the imbalance between supply and demand in thermal environment control was a significant problem. During winter, overheating in the cold zone (i.e., "supply" > "demand") was common, while heating was insufficient (i.e., "supply" < "demand") in the HSCW zone. This work has been published in *Building and Environment* [41]. Secondly, detailed analyses and targeted diagnoses of IEQ performance in certain individual buildings were carried out according to the spatiotemporal and dynamic features of IEQ. This work can help building operators to improve IEQ practically. Thirdly, correlations between subjective and objective IEQ data were studied, providing assistance to researchers in determining what IEQ parameters are most satisfactory and what occupants' actual demands are for IEQ control.

Since a report on the first application has already been published, the first application will not be discussed further here. Instead, the following sections provide a few examples of the second and third applications.

4.1. Targeted IEQ diagnosis of individual buildings

Based on long-term continuous IEQ monitoring in multiple spaces within one building, we conducted targeted IEQ diagnosis, which can tell building operators when and where IEQ performances are inadequate. Here, we present two examples of IEQ diagnosis with the help of IBEM, one in an office and the other in a hospital.

4.1.1. Case 1: Thermal environment diagnosis in an office building

The selected office building is located in Tianjin (a cold zone). It has five floors, and the total floor area is 5700 m^2. We deployed a total of ten IBEM devices on the ground floor, intermediate floor,

Climate zone	City or area
Severe cold	Harbin
	Shenyang
	Ngari Prefecture
Cold	Dalian
	Beijing
	Tianjin
Hot-summer–cold-winter	Shanghai
	Suzhou
	Changzhou
	Nanjing
	Hangzhou
	Hefei
	Wuhan
	Chongqing
	Chengdu
Hot-summer–warm-winter	Guangzhou
	Shenzhen
	Zhuhai

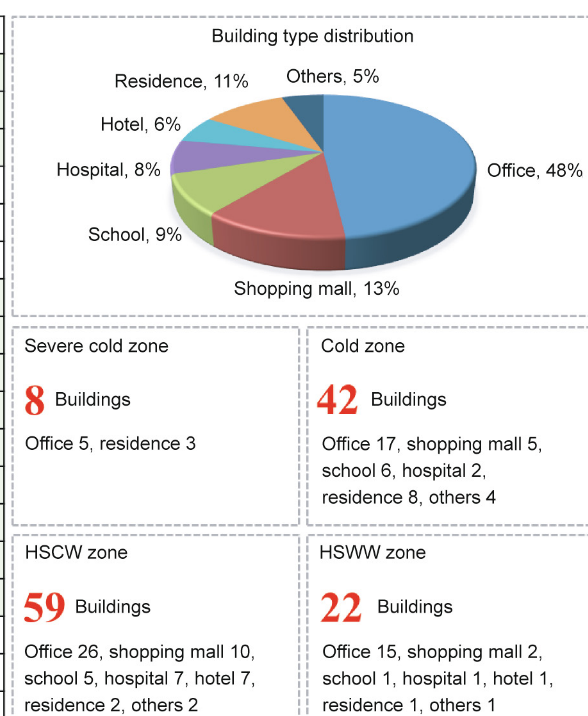


Fig. 7. Distribution of geographic locations and types of monitored buildings.

and top floor. Open-plan offices and private offices with various orientations were chosen as the main measured spaces. Continuous monitoring lasted for a whole year. Data from July, 2017 are chosen here to diagnose the indoor thermal performance in summer, as shown in Fig. 8.

For each space, all data within the same hour from all workdays in July were gathered. These data were then classified into different temperature range partitions, and the monthly average proportion of each partition within the same hour was calculated. Finally, the daily variation of the temperature partition proportion within each hour was presented in a stacking bar chart. In this way, the results represent the comprehensive indoor thermal environment characteristics over a whole month, instead of randomly selecting one day for analysis. Furthermore, this method allows the variation and distribution features to be seen clearly, rather than providing a single index on average.

As shown in Fig. 8, the private office in the east and the open-plan office in the south had a good thermal performance. However, the indoor air temperatures in the open-plan office in the north and the private office in the west were often above the comfort zone (> 28 °C) during the daytime. For the private office in the west, the thermal problem was much worse in the afternoon due to intense sunlight from the setting sun coming through the glass curtain wall. In addition, the lobby entrance hall was always hot during the daytime even though the air conditioning system was working, due to frequent openings of the front door. These results from the thermal environment diagnosis were fed back to the building operators, and the corresponding retrofits were put underway to enhance the occupants' thermal comfort.

4.1.2. Case 2: Indoor air quality diagnosis in a hospital building

During the coronavirus disease 2019 (COVID-19) epidemic, IBEM was used in hospital buildings for real-time IEQ diagnosis and early warning of indoor environmental risks. CO_2 and $PM_{2.5}$ concentrations were the critical parameters of concern: ① CO_2 concentration reflects the ventilation performance; and ② $PM_{2.5}$ concentration reflects indoor air cleanliness and the purification effect of the filtration system.

One hospital from Wuhan (in the HSCW zone) is selected here to show the IAQ diagnosis results based on IBEM. The floor area of the building is 22 154 m^2. A total of 24 IBEM devices were deployed in almost all types of rooms with different functions, including inpatient wards, emergency treatment rooms, consulting rooms, pharmacies, offices, nurse stations, locker rooms, lounges, and aisles. Continuous IEQ monitoring at 5 min intervals began on 14 March and continued to 29 April 2020. Due to the high spatiotemporal resolution of the data collection, an IAQ dynamic field at each moment was obtained based on the spatial interpolation method. This study used triangulation with linear interpolation to assign values to the empty areas between sample locations.

Fig. 9 shows the IAQ dynamic field of the hospital within one typical day. Screenshots of the field are only shown for times when poor air quality was found during the daytime. It was found that inadequate ventilation (high CO_2 concentrations) mainly occurred in the inpatient wards. However, the problem of insufficient air purification (high $PM_{2.5}$ concentrations) could occur in almost every space, such as in contaminated zones (i.e., inpatient wards, etc.), semi-contaminated zones (i.e., treatment rooms, aisles, etc.), and clean zones (i.e., locker rooms, offices, etc.).

According to the diagnosis results for the IAQ in the hospital, it is possible to pinpoint where and when the problems arise and thus improve the corresponding ventilation and purification strategy in a timely manner. Therefore, IBEM provides technical support for preventing and controlling infection risks from indoor air aerosols in hospitals.

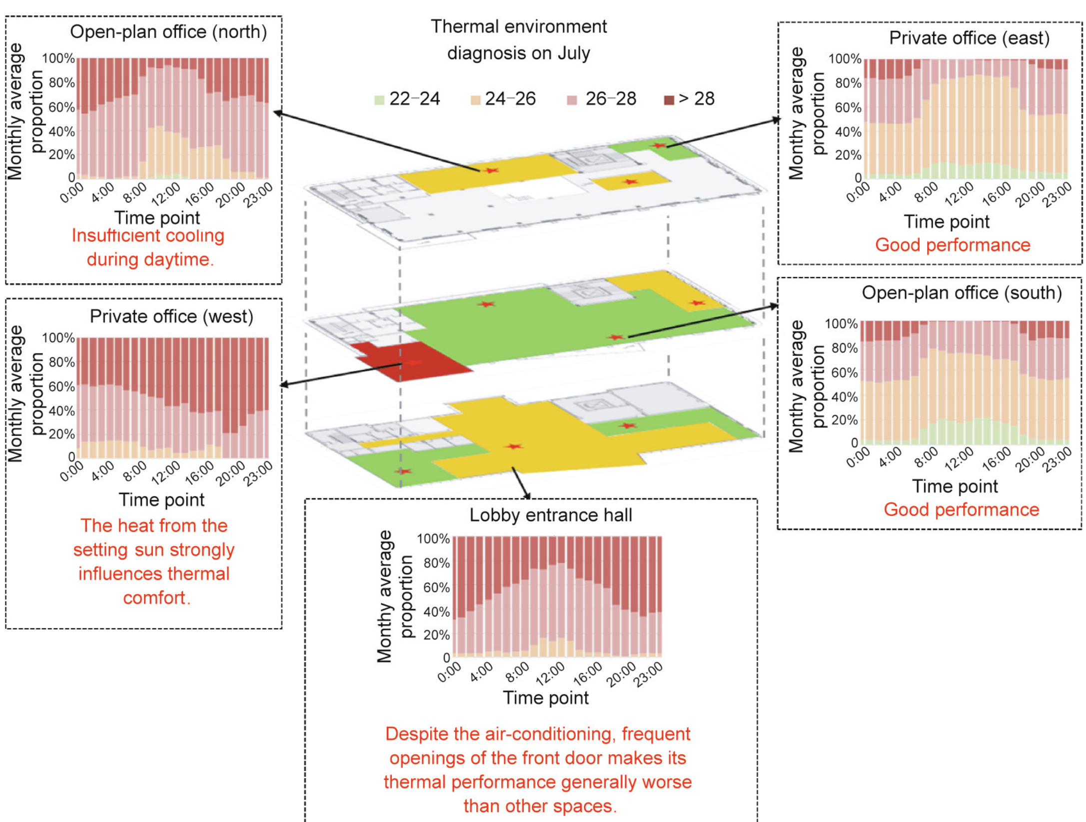


Fig. 8. Targeted thermal environment diagnosis for an office building.

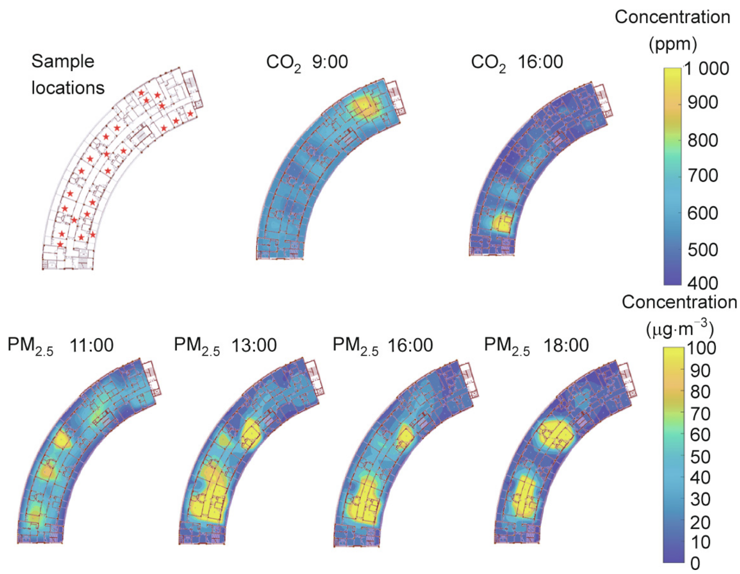


Fig. 9. A dynamic diagnosis of the IAQ field of a hospital building (because graphic interchange format (GIF) animation cannot be displayed in this figure, the measurements from one day and a few screenshots of certain moments were selected for examples).

4.2. Correlations between subjective and objective IEQ data

Previous studies have explored human perceptions of and responses to IEQ parameters through a series of experiments in climate chambers or simulated spaces [45]. However, the relationship between subjective perceptions and objective parameters in real-life scenarios is often different from that in climate chambers or simulated spaces because people's activities and behaviors are not controlled in actual buildings. Thus, it is necessary to study building occupants' satisfaction and demands on IEQ parameters under natural conditions.

Based on IBEM and its function of information interaction and feedback via the mobile interface, we have collected 2425 building occupants' satisfaction votes on IEQ, which were matched with the environmental parameters at the relevant times and locations. Occupant votes use a seven-point scale with "+3" indicating "very satisfied" and "–3" indicating "very dissatisfied." Distributions of occupant satisfaction under different IEQ conditions were analyzed and compared. The findings presented below show how indoor air temperature and CO_2 concentration each affect occupant satisfaction.

4.2.1. How does indoor air temperature affect thermal satisfaction?

Differences in climate and HVAC systems between northern and southern China can influence thermal experiences and preferences. Thus, the collected occupant votes were split into two parts: Occupants from the severe cold and cold zones were gathered to represent the northern group, while occupants from the HSCW and HSWW zones represented the southern group.

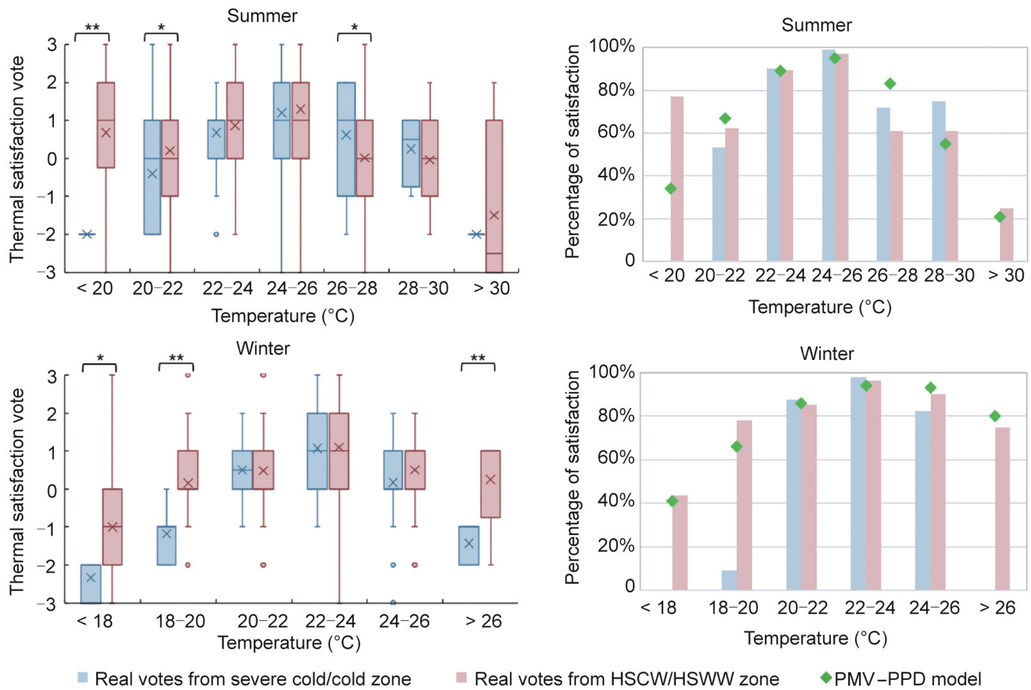
The thermal satisfaction votes of these two groups under different indoor air temperature conditions during summer and winter were compared, as shown in Fig. 10. A statistical test (the Wilcoxon–Mann–Whitney test) was conducted, and the P values between the two data groups were calculated. If the difference was statistically significant, it was marked with an asterisk ($P < 0.05$) or two asterisks ($P < 0.01$). Furthermore, the percentage of satisfied occupants (i.e., votes from "0" to "+3") was calculated at each temperature partition and compared with the predicted result according to the predicted mean vote (PMV)–predicted percentage dissatisfied (PPD) model for thermal comfort [46]. The predicted percentage of satisfied occupants was calculated based on several assumptions: ① The mean radiant temperature equaled the air temperature; ② the airspeed was below 0.2 $m \cdot s^{-1}$; ③ the metabolic rate of the occupants was 1.0 Met (1 Met = 58.2 $W \cdot m^{-2}$); and ④ the clothing insulation in summer and winter was 0.5 and 1.0 Clo (1 Clo = 0.155 $m^2 \cdot K \cdot W^{-1}$), respectively.

During summer, 24–26 °C was the most satisfactory thermal condition for both the northern and southern groups. However, the northern group had a weaker acceptance of cooler conditions than the southern group. When the indoor air temperature was below 22 °C, the thermal satisfaction of the northern group dropped more sharply than that of the southern group ($P < 0.05$ when the temperature was within 20–22 °C; $P < 0.01$ when the temperature was below 20 °C). Compared with the PMV–PPD model, the percentage of satisfied occupants in the northern group was below the model-based prediction when the air temperature went below 22 °C. This result indicates that buildings in northern China should avoid the overcooling problem in summer for thermal environment control. Otherwise, occupant satisfaction will decrease dramatically, along with the problem of energy waste.

In winter, thermal satisfaction from the southern group varied more smoothly with air temperature, and their relationship was consistent with the PMV–PPD model. However, due to living in an environment with central heating for years, occupants from northern China were pickier about thermal conditions in winter. As long as the air temperature was not within the range of 20–26 °C, the actual thermal satisfaction from the northern group would decrease significantly—a result that was much lower than that of the southern counterpart and the PMV–PPD prediction results under the same conditions ($P < 0.05$ when the temperature was below 18 °C; $P < 0.01$ when the temperature was within 18–20 °C and above 26 °C). Such a result indicates that building occupants in northern China have a narrower range of adaptation to the thermal environment in winter. Therefore, it is challenging to achieve high satisfaction in temperature control among northern Chinese occupants during the winter.

4.2.2. How does indoor CO_2 concentration affect air quality satisfaction?

Before studying the relationship between CO_2 concentration and occupant satisfaction with air quality, it is first necessary to distinguish how buildings are ventilated. Buildings in China



Data group in summer	< 20 °C		20–22 °C		22–24 °C		24–26 °C		26–28 °C		28–30 °C		> 30 °C	
	North	South	North	South	North	South	North	South	North	South	North	South	North	South
The number of samples *N*	5	42	87	128	90	116	236	342	78	90	20	45	4	19

Data group in winter	< 18 °C		18–20 °C		20–22 °C		22–24 °C		24–26 °C		> 26 °C	
	North	South	North	South	North	South	North	South	North	South	North	South
The number of samples *N*	16	44	18	51	82	151	280	323	58	68	12	20

Fig. 10. Relationship between indoor air temperature and occupant thermal satisfaction. Blue represents the Northern group (severe cold/cold zone), red represents the southern group (HSCW/HSWW zone), and green represents the predicted result of the PMV–PPD model; significance test: *$P < 0.05$ and **$P < 0.01$.

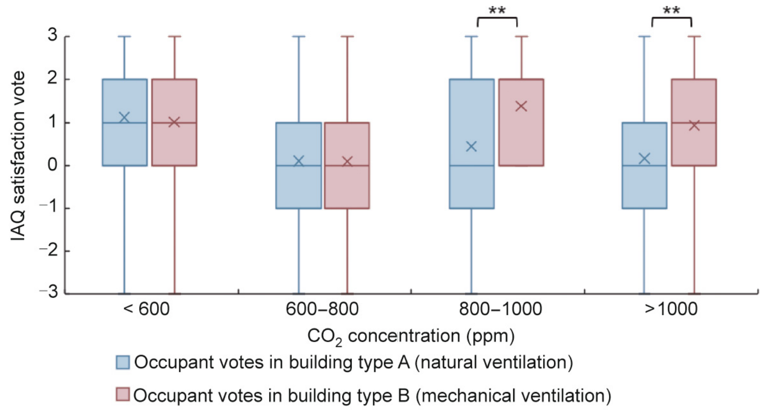
are generally categorized into types A and B, according to different ventilation types. Type A refers to buildings whose windows can be opened for natural ventilation, while type B refers to buildings that use mechanical ventilation throughout the year.

Fig. 11 shows the occupant votes for indoor air satisfaction at different CO_2 concentrations and gives a comparison between building types A and B, tested with the Wilcoxon–Mann–Whitney test. It was found that the average IAQ satisfaction at different levels of CO_2 concentration varied within a small range, regardless of whether the occupants were in building type A or B. The average satisfaction score was always above zero at any level of CO_2 concentration. However, the votes extended to "–3" for all data groups, which suggested that a substantial minority always considered the air quality unacceptable, regardless of the objective IAQ performance. This result indicates that people are not very sensitive to CO_2 concentration, and it is difficult to increase their subjective satisfaction by improving the objective performance. From the perspective of energy conservation, it is unnecessary to maintain CO_2 concentration at a very low level, as long as the limit of 1000 ppm is not exceeded. However, the occupants in building type A seemed to have a lower acceptance for relatively high CO_2 concentrations than the occupants in building type B. When the CO_2 concentration was above 800 ppm, the occupant satisfaction with air quality in building type A was significantly lower than that in building type B ($P < 0.01$).

5. Discussion

The large-scale applications and results from the case studies provided above have demonstrated that IBEM can be used efficiently for IEQ monitoring, feedback, diagnosis, and improvement. However, similar IEQ monitoring tools and systems can be found in other studies. In order to clearly show the advantages and disadvantages of different systems, this section compares their performance in five aspects: diversity of sensors, integration, extendibility, data platform, and feedback and interaction, as shown in Table 5 [19–21,23,24,47–52].

- **Diversity of sensors:** In this aspect, IBEM does not perform well, as it only includes sensors for air temperature, RH, CO_2, $PM_{2.5}$, and illuminance, without acoustics and other air quality parameters. Some other systems selected more sensors for more comprehensive IEQ monitoring. For example, SAMBA [23,24] also measures globe temperature, airspeed, sound pressure level, CO, formaldehyde, and TVOCs, besides the above five parameters in IBEM. More extensively, the IEQ system introduced by Liu et al. [51] and Dai et al. [52] even monitors occupants' actions in terms of opening/closing windows and operating the parameters of the mechanical ventilation system, both of which have significant influences on IEQ.
- **Integration:** Except for a small minority of studies [51,52] that directly use multiple individual market devices for IEQ monitoring, most systems—including the IBEM—have developed a



Data group	< 600 ppm		600–800 ppm		800–1000 ppm		> 1000 ppm	
	Type A	Type B	Type A	Type B	Type A	Type B	Type A	Type B
The number of samples *N*	593	282	462	334	258	257	131	108

Fig. 11. Relationship between indoor CO_2 concentration and occupant air quality satisfaction. Blue represents occupant votes from building type A, and red represents occupant votes from building type B; significance test: $^{**}P < 0.01$.

Table 5
Comparison between IBEM and other intelligent IEQ monitoring tools and systems.

System	Country	Diversity of sensors	Integration	Extendibility	Data platform	Feedback and interaction
Ali et al. [21]	USA	≥ 6	√	√	×	×
Ali et al. [47]	USA	≥ 7	√	√	√	×
Karami et al. [19]	USA	9	√	×	×	×
Sun et al. [48]	Spain	12	√	√	×	×
Arroyo et al. [49]	Spain	4	√	√	×	×
Perez et al. [20]	Germany	3	√	×	√	×
Parkinson et al. [23,24]	Australia	10	√	√	√	×
Moreno-Rangel et al. [50]	UK	5	√	×	√	×
Liu et al. [51]/Dai et al. [52]	China	4	×	×	√	×
IBEM	China	5	√	×	√	√

"√" means that the system has or supports the specific function; "×" means that the system does not have or support the specific function.

hardware solution that integrates a suite of sensors into a single "box" for low-cost and high-efficiency IEQ measurement. This development of integration is also suitable for large-scale production and application.

- **Extendibility:** IBEM does not support sensor customization, and its functions are not flexible for different scenarios. Some other IEQ monitoring systems perform better. For example, OSBSS [21] is designed and constructed using open-source hardware and software based on the Arduino platform. All its sensors are customizable, which allows for more flexibility in cost-effectively synchronizing a larger number of IEQ measurements. The IEQ system developed by Sun et al. [48] is another example with high-level extendibility. It consists of multiple modularized sensors, and users can freely choose different sensors by means of a simple plug-in.
- **Data platform**: This aspect is well presented in IBEM and in many other systems [20,23,24,47,50–52]. With the development of communication and web service technology, an increasing number studies are providing a software layer where end-users can access data, receive suggestions, and evaluate the performance of their built environment.
- **Feedback and interaction**: This aspect is an essential advantage of IBEM in comparison with the other tools and systems. Most systems can only show the measured IEQ performance to users and cannot "listen" to users; thus, they do not sufficiently build a pathway for information interaction between the occupants and their environment. However, IBEM presents real-time IEQ conditions to building occupants immediately and collects their subjective feedback at the same time. This feedback is essential for demand control, which can be used to achieve a high level of occupant satisfaction and low energy consumption. Furthermore, bidirectional data flow on IEQ creates new research opportunities and more value in the field of the built environment. For example, Zhuang et al. [53,54] found that interactive feedback transformed building occupants' style of IEQ control from a habit-driven mode to a deliberate thinking mode and induced more positive behaviors toward energy conservation, such as setting thermostats with higher temperatures in summer.

According to these comparison results, IBEM performs better on the integration and data platform level, especially in regard to feedback and interaction, but worse in terms of the diversity of sensors and extendibility.

This study has other limitations that need to be improved in future works. Firstly, a scientific and simplified deployment scheme for IBEM has not been proposed. Although IBEM enables cost-effective built environment measurements, it is still necessary to deploy many onsite devices—a task that mainly relies on manual experience. Based on the measured big data from buildings with different scenarios, it is expected to identify the coupling relationships for IEQ data between different sample locations, which can reduce unnecessary devices. At that time, we will be able to achieve the whole-field monitoring of IEQ based on a limited number of devices and transform the IBEM deployment methodology from an experience-based model to a data-driven model. Secondly, IBEM is not automatically linked with the environmental control system, which limits its IEQ optimization application. We are still working on integrating the real-time IEQ monitoring records and occupant satisfaction ratings with the intelligent control system.

6. Conclusions

This study introduced an intelligent IEQ monitoring and feedback system (IBEM) and presented its field validation and several application cases. The IBEM hardware instrument integrates air temperature, RH, CO_2, $PM_{2.5}$, and illuminance sensors into a small device, significantly reducing the cost and improving deployment efficiency. The performance and accuracy of this integrated IEQ monitoring device have been tested through co-location experiments with reference sensors. The IBEM device strongly correlated with its counterparts, with slight deviation (R^2 > 0.97 and slopes between 1.01 and 1.05). In terms of software design, IBEM can achieve wireless data transmission and cloud storage. More importantly, two types of graphical user interfaces (i.e., a web platform and a mobile interface) are built for data visualization and interactive feedback. Therefore, IBEM can continuously monitor IEQ parameters with a high spatiotemporal resolution, induce interactive feedback with building occupants, and realize the synchronous data collection of occupant satisfaction and objective environmental parameters at the same time and location.

To date, IBEM has been widely applied in 131 buildings from 18 cities/areas in China, and an extensive IEQ database with a total of 1188 sample locations and more than 1.09 TB of data has been established. Furthermore, based on IBEM, we have conducted targeted IEQ diagnoses of individual buildings and explored the correlations between subjective and objective IEQ data in real-world scenarios. This work demonstrates the great value of IBEM in both industrial and academic research.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2021.09.017.

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