Research on Indoor Environmental Performance of Green Office Buildings in Shanghai Based on Field Investigation

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Abstract. In order to understand the indoor environmental performance of green buildings after operation, 12 green buildings in Shanghai were selected to carry out long-term continuous monitoring and field collection study, data was comparative analysed with relevant national standards. Results show that the indoor environmental compliance rate of the building is more than 75%, and the comfort zone of the temperature and humidity are wider than the standard. The compliance rate of the light environment is generally good. At the same time, similar research results of other cities in China were compared, and the causes of the results were analysed. Finally, based on the measured data, the optimized standard limits of some parameters were proposed.

1. Introduction
The requirements for green building have been changed along with the great progress since 1992, when China began to make green buildings the development direction of the construction industry. From the initial principle of "four conservation and one environmental protection", now more and more attention has been paid to the performance of green buildings. The indoor environmental performance of a building is a comprehensive expression of the indoor thermal and humid environment, air quality, acoustic environment and light environment. It is also the best reflection of the impact and comfort of the indoor environment on building users after the green building is put into operation. In this paper, the indoor environmental performance of green buildings in Shanghai is studied through the analysis of indoor environmental measurement. The reference baselines of relevant parameters are given based on a large scale of data, which can provide reference for the evaluation of green building operation in the future.

2. Literature review
By the end of December 2016, there were 7,235 construction projects in China that had obtained green building label, with a total construction area of up to 800 million square meters[1]. Nevertheless, only a small fraction of them were operate label. The main cause of this phenomenon is during the design phase of green buildings, the designer usually focuses on what technologies should be adopted in green buildings and the expected performance of various technologies in the application process. However, the design concept of the building cannot represent the actual operation effect. At the same time, the evaluation of operation identification is often made on the level of a single technical performance index, ignoring the coupling effect between various technologies, as well as the interference factors in actual use. All the causes above lead to the discrepancies between actual implementation effect and the original design goal. Moreover, some studies found the actual operation effect of some green buildings is not as good as that of traditional buildings.
Tham K W et al.[2] compared green buildings and non-green buildings in Singapore, and found that compared with green buildings, the indoor temperature of non-green buildings is lower, the illumination is smaller, and the ventilation efficiency is 2.5-3 times that of green buildings. Davies M et al.[3] found that the indoor environmental quality of some green buildings in the UK is not good, as these buildings usually use high-density envelope structure to achieve energy conservation, which result in a poor indoor air quality and greater risk of overheating in transition season.

The rapid development of green buildings has exposed many problems, studies from different aspects of green building have been conducted. Yang G et al.[4] sorted out the research results on energy consumption, indoor environment quality (IEQ) and user satisfaction of green buildings in recent years in and abroad, and found that the USA, China, the UK, Italy and Australia were listed as the five countries with the largest contributions to green building research. Among the 106 literatures investigated, the research focuses can be roughly divided into two aspects. One is to study the actual energy consumption level of green buildings and whether the performance meet the expectation. The other is to study the actual indoor environmental quality of green buildings by means of parameter measurement or subjective satisfaction survey. The objective measurement of IEQ focus on parameters such as indoor temperature ($T$), relative humidity ($R_h$), global temperature ($T_g$), air speed ($v$), CO$_2$ concentration, PM2.5, formaldehyde, VOCs, lux and noise level (dB(A)). Subjective surveys usually involve thermal comfort, air quality, illumination, acoustic, and other non-physical factors.

The evaluation standards for green buildings emphasizes four aspects that need to be paid attention to improve indoor environmental quality, including thermal environmental quality, acoustic, visual quality and IAQ[5][6][7].

As a diagnostic tool, the method of post occupancy evaluation (POE) has been widely used in IAQ control. However, after many times of adjustment and correction, the existing research mainly adopts the method of one-time data collection, which cannot fully represent the feedback from users throughout a building's operation [8]. With the improvement of sensing technology, POE is now increasingly using indoor environmental monitoring equipment to overcome the previous difficulties in data collection. Zhe W et al.[9] studied the indoor air quality of 8 major large hub airport terminals in China. They placed continuous monitoring equipment in key areas of the airport to monitor the temperature and humidity of the room and air supply at intervals of 10 minutes. Meanwhile, illumination, noise intensity, and CO$_2$ concentration were also recorded. Liang et al. [10] placed indoor environment monitoring equipment in a green building and a commercial building on a moving carrier to investigate staff satisfaction. The moving carrier is at the same level with workers’ respiratory exposure area, which is 1.1 meters above the ground. Data of indoor temperature, global temperature, relative humidity, air velocity, noise level, CO2 concentration, VOCs were gathered continuously every 20 minutes.

### 3. Relevant standard

In recent years, with the in-depth popularization of people-oriented concept, national standards and industrial standards have made normative provisions for different parts of indoor environmental performance of buildings, and the emphasis of each standard is diverse for different stages of the whole life cycle of buildings.

The whole life cycle of buildings was divided into three stages, which are design, construction, and operation. Different standards applied to each stage were summarized as table 1.

| No | Standard | Stage of building |
|----|----------|------------------|
| A  | Code for thermal design of civil building | √ |
| B  | Design code for heating ventilation and air conditioning of civil buildings (GB50736-2012) | √ |
| C  | Standard for lighting design of buildings (GB50034-2013) | √ |
The applicable stage of each standard is a general situation. However, there may be special circumstances, such as a provision in the standard can be applicable to the design and operation stage both. Therefore, in the following text the application of different parameters may not be strictly consistent with table 1.

3.1 Limit of indoor thermal environment

There is not much difference between the standards in indoor thermal environment of the building,

Table 2. Limit of indoor thermal environment in different standards.

| Stage       | No  | Winter Temperature (°C) | Winter Humidity (%) | Summer Temperature (°C) | Summer Humidity (%) |
|-------------|-----|-------------------------|---------------------|-------------------------|---------------------|
| Design      | A   | 18                      | 30-60               | 26                      | 60                  |
|             | B   | 22-24                   | 18-22               | 24-26                   | 26-28               | 40-60               | ≤70                  |
|             | E   | ≥18                     | -                   | ≤29                     | ≤70                  |
| Construction| H   | Allowable deviation of -2~+1|                   | Allowable deviation of -2~+1 |                   |
| Operation   | I   | 16-24                   | 30-60               | 22-29                   | 40-80               |
|             | J   | 20-24                   | 30-70               | 23-26                   | 30-70               |
|             | K   | 22-24                   | 18-22               | 24-26                   | 26-28               | 40-60               | ≤70                  |
|             | L   | Area ratio of main function room which is satisfied with overall thermal environment evaluation level II |
|             | M   | Overall evaluation and Local percentage dissatisfied caused by thermal environment (LPD) |

In the architectural design stage, standard No.B makes detailed requirements on the design temperature and relative humidity of comfort air conditioning. There are few standards applied to construction stage. Only standard No.H stipulates the allowable indoor temperature and relative humidity deviation. Many standards are appliable to the operation stage, among which, standard No.L and standard No.M only provide the necessary indexes and reference range, rather than give specific
3.2 Limit of indoor air quality

In 8 standards applicable to design age, only standard No.F stipulates the grading of daily indoor design concentrations of PM2.5, TVOC and formaldehyde. Standard No.E and No.G stipulates the TVOC and formaldehyde concentration of civil building during construction stage.

There are many indoor air quality provisions applicable to operation stage, however the difference is diverse. On the basis of standard No.I, several standards have integrated and improved the parameter limits of indoor air quality. Standard No.I was compiled before 2002, which may be unable to adapt to recent changes in the atmosphere. As a consequence of greenhouse effect, the concentration of CO2 has increased a lot, usually around 400ppm, sometimes reaching more than 450ppm. Based on this, ISO17772.1 requires the limit of CO2 concentration must take the outdoor atmosphere into account, which avoids the influence brought by the outdoor atmospheric change. Same method was accepted by standard No.K.

| Stage | No | PM2.5 (μg/m³) | CO2 (ppm) | TVOC (mg/m³) | Formaldehyde (mg/m³) |
|-------|----|---------------|-----------|--------------|----------------------|
| Design| F  | Daily design concentration (25/35/50/75 corresponding to level 1~4) | — | 0.3^c | 0.03~0.05^c |
| Construction| E | — | — | 0.5^c | 0.08^c |
| | G | — | — | 0.6^c | 0.12^c |
| Operation| I | — | daily avg≤1000 (8-hour avg) | 0.60 (time-avg) | 0.10 |
| | K | 25^a/75^b (daily avg) 15^a/35^b (annual avg) | Outdoor atmospheric concentration +550^a/800^b | 0.5^a/0.6^b (time-avg) | 0.08^a/0.1^b (time-avg) |
| | L | annual avg≤25 | — | — | — |
| | M | annual avg≤35 daily avg≤37.5 (18-day not guaranteed throughout the year) | daily avg≤900 | — | — |

^a Level I.
^b Level II.
^c Civil construction type II: buildings except hospital, nursing home, kindergarten and school.

3.3 Limit of indoor lighting environment

In the design phase of the building, GB 50034-2013 (standard No.C), Standard for lighting design of buildings, specifies the standard lighting values of all kinds of public buildings in detail. For office buildings, illumination value of general office is 300lx, and the limit value of high-grade office is 500lx. According to GB 50033-2013 (standard No.D) of Standard for daylighting design of buildings, indoor natural lighting illumination value of offices and meeting rooms with side lighting is 450lx.

The evaluation of the lighting environment in the building operation stage is more comprehensive. In addition to the basic illumination value, it also increases the area proportion when the lighting coefficient of different areas inside the building meets the lighting requirements, as well as the minimum
number of hours that the illumination value of the area proportion meets the standards. See table 4 for details.

| Stage  | No | Illuminance (lx)/Index                  |
|--------|----|----------------------------------------|
| Design | C  | 300(open office)/ 500(private office)  |
|        | D  | 450                                    |
| Operation | L | 300lx, number of satisfied hour, area proportion |
|         | M | 300lx, number of satisfied hour, area proportion |

4. Methods
Driven by computer technology, the two most prominent achievements in the field of POE method are IEQ car for indoor environmental quality measurement and online questionnaire survey for user survey. Among them, IEQ trolley is a wheelbarrow and a mobile integrated tool for measuring indoor environmental quality [11]. For green office buildings, the distribution of indoor environment is basically stable. Therefore, the method of fixed-point measurement can be adopted to fix the integrated indoor environment monitoring equipment in several typical positions, namely, the desk at the edge and the middle of the office area, which can truly reflect the overall indoor environment of the area.

4.1 Equipment
In this study, iBEM intelligent environment instrument was used for indoor environment test. This device can simultaneously monitor indoor air temperature, relative humidity, illumination, CO2 and PM2.5 concentration, and upload the data to the cloud in real time. Users can download the data after preliminary screening from the cloud. The test range and uncertainty of each parameter sensor are shown in table 5 below.

| Parameters   | Measuring range | Precision            |
|--------------|-----------------|----------------------|
| Temperature  | -40~80°C        | ±0.5°C               |
| Humidity     | 0~99%RH         | ±5%                  |
| PM2.5        | 0~1000μg/m3     | ±10@20~500μg/m3      |
| CO2          | 0~5000ppm       | ±75ppm               |
| Illumination | 0~50000lux      | ±5%                  |

4.2 Data acquisition
The field study were conducted in 12 3-star green office buildings in Shanghai. The actual measurement includes two parts: continuous data monitoring and field data collection. The indoor environment of the building was continuously monitored in winter and summer, and the testing period of each season was at least 2 working weeks.

Continuous data monitoring instruments were placed in typical work area, such as private offices, opening offices and meeting rooms. The measuring point was located on the working plane (1.1m above the ground), avoiding the tuyere, shade and sun. Data collected can be a real reaction of the building environment performance. Continuous monitoring interval is 15 minutes.

Meanwhile, field data (formaldehyde and TVOC concentration) were also collected every 1 hour. Five groups of data are recorded.

5. Results and discussion
5.1 Principles of data analysis
Based on the existing standards, different standards are adopted for different parameters. The detailed criteria are as follows.
Table 6. Principles of data analysis.

| Building environment | Standard                  | Parameters       | Winter  | Summer |
|----------------------|---------------------------|------------------|---------|--------|
| Thermal              | GB 50736-2012(B)          | Temperature (°C) | 18-24   | 24-28  |
|                      |                           | Humidity (%)     | 0-60    | 40-70  |
| Air quality          | T/ASC 02-2016(M)          | PM2.5 (μg/m³)   | 37.5    |        |
|                      | GB/T 18883-2002(I)        | CO₂ (ppm)       | 1000    |        |
|                      |                           | Formaldehyde (mg/m³) | 0.1    |        |
|                      |                           | TVOC (mg/m³)    | 0.6     |        |
| Lighting             | GB50034-2013(C)           | Illumination (lx)| 300     |        |

Among them, for the indoor thermal environment (air temperature and relative humidity), two calibration methods are adopted.

The first method is to compare two parameters and calculate the respective compliance rate. For example, if the temperature of a measuring point in winter is between 18 °C and 24°C, then it is recorded as reaching the standard. Otherwise, it is recorded as failing to reach the standard. The satisfaction rate of temperature is the percentage of the number reaching the standard in the total number. The calculation method of the humidity compliance rate is identical.

The other method is to take temperature and humidity as a set of thermal environment parameters and calculate the overall thermal environment compliance rate. Only when the temperature and humidity of a measuring point reach the standard at the same time can it be recorded as a measuring point. For example, if the winter temperature at a certain point is 17.5°C and the humidity is 33.5%, which is outside 18-24°C, the measurement point is recorded as substandard measurement point. The calculation method of the compliance rate is the same as above.

5.2 Analysis of indoor environmental performance

5.2.1 Winter condition. The compliance rate of temperature and humidity of winter condition is shown in figure 1.

![Figure 1. Compliance rate of temperature and humidity (winter).](image)

From figure 1, there is a big difference in indoor temperature compliance rate of green office buildings in winter. Only four buildings had a temperature compliance rate of more than 75%. The relative humidity compliance rate is good, and only two are less than 75%.

In order to explore the relationship between the single parameter compliance rate and the overall compliance rate of the thermal environment, the indoor temperature and humidity data of each building under test were plotted in a box, and the scatter plot of the thermal environment compliance rate was
also plotted, as shown in figure 2.

Figure 2 shows only 3 buildings have a thermal environment compliance rate of more than 75%. For the 12 buildings tested, the influence of indoor temperature on the compliance rate of thermal environment in winter is greater than that of relative humidity. For example, in building 8, the compliance rate of relative humidity, indoor temperature thermal environment is 100%, 6%, 5% respectively. As can be seen from the box diagram, the indoor temperature in winter is higher than the upper limit of 24℃, resulting in a low overall compliance rate.

5.2.2 Summer condition. The compliance rate of temperature and humidity of summer condition is shown in figure 3.

![Figure 3. Compliance rate of temperature and humidity (summer).](image)

Figure 3 shows a big difference in indoor temperature compliance rate of green office buildings in summer. The temperature compliance rate of two buildings did not reach 75%. Five buildings failed to achieve the relative humidity standard of 75%.

Figure 4 is the combination figure of thermal compliance rate, temperature, humidity of summer condition. Only four buildings have a thermal environment compliance rate of more than 75%. The influence of relative humidity on the thermal environment compliance rate in summer is greater than that of indoor temperature. For example, in building 5, the indoor temperature compliance rate in summer is 99%, the relative humidity compliance rate is 20%, and the thermal environment compliance rate is only 21%. As can be seen from the box diagram, indoor relative humidity in summer tends to be in the high humidity area, which is higher than the upper humidity limit of 70℃, resulting in a low overall standard achieving rate of the thermal and humid environment.

5.2.3 Similar studies comparison. Test results in our study show that the indoor temperature is high in winter and the indoor relative humidity is low in summer.

In reference[12], the indoor thermal environment of six office buildings in Guangzhou were tested. It was found that the indoor temperature range of in summer was 24.8 ℃ ~ 26.7 ℃, the average temperature was 25.55 ℃. The relative humidity range was 75.9% ~ 87.9%, and the average relative humidity was 81.11%. Compared with national standard, the indoor temperature and relative humidity of green buildings investigated were low in summer, which reflects the same problems as in this paper.

Literature[13] to invested 10 green buildings in Chongqing and found out that in summer, 60% of the thermal environment measuring point belonged to the thermal comfort level I area. About 30% of the measuring point belongs to the thermal comfort level II area, which was slightly higher than reference [12]. Obvious problem showed up, such as cold, hot, wet and dry. The satisfaction percentage was below 10%, but the subjective satisfaction of the staff was good.

Results above show that the indoor thermal environment of green buildings is easily affected by outdoor conditions, and there will be differences between climate regions. The low compliance rate may
correspond to high satisfaction, due to people's adaptability or other psychological factors.

5.3 Analysis of lighting
The compliance rate of lighting is shown in figure 5.

In winter, compliance rate of lighting varied greatly, and 6 failed to reach 75%. Summer illuminance reached standard circumstance best, be in above 75%.

As can be seen from the quartile map, indoor illuminance values are relatively dispersed under the two working conditions. Under the same compliance for example, different buildings may have different I distributed, like building 10 and 11.

Other studies have also found that, in the indoor environmental performance of green buildings, the regional difference in illumination is small, but illumination value between buildings is pretty different. Literature [13] found that the average illuminance of office buildings in Chongqing was higher than the standard requirements, but about 20.5% of the office areas failed to meet the illuminance value requirements in standard. Besides, some buildings had high illuminance value, and the illuminance difference between each building was large. Literature[14] investigated the indoor environment of 7 green buildings and conventional buildings in Beijing, and found that the indoor illumination of some green buildings was relatively dispersed, and sub-standard conditions existed.

In relevant standards, the requirement of indoor illumination is a low threshold, which is the lowest level that the lighting environment needs to reach. Therefore, this project screened the invested buildings with the measured illumination rate of more than 75%. After comparing the quartile value of the remaining cases, it turned out the lowest value of indoor illumination is 320lx, which can be used as a baseline for the green building with high-performance. In other words, the indoor illumination of this kind of building should be at least 320lx.

5.4 Analysis of indoor air quality
The mean value of PM2.5 and CO2 concentration was calculated and benchmarked by means of section 5.1. Results were drawn into histogram figures 6 and 8.

Formaldehyde and TVOV concentration are instantaneous values collected on site, so data was classified by working conditions, and results were drawn in box figure 9 and figure 10.

5.4.1 Compliance rate of PM2.5. For green office buildings, when the windows are opened or the filtering capacity of air processing equipment is not sufficient, some PM2.5 from outdoor air will be brought into the room. Therefore, indoor PM2.5 mainly comes from outdoors, and different areas are affected in different degrees. Take Beijing and Shanghai for example.
In 2018, the PM2.5 concentration in Beijing stood at 51 μg/m³, 37% lower than 2015. The air quality in Shanghai was relatively good. In 2018, the average concentration was 36 μg/m³, 7.7% lower than 2017 and 41.9% lower than 2013. The PM2.5 measured in this paper meet the requirement in summer, and the compliance rate was above 90%. In winter, the compliance was poor, especially, the compliance rate of building 10 was 66%, lower than 75%.

The indoor pollutants required by other relevant standards for green buildings are upper limits, indicating that indoor pollutants in buildings should be below this concentration. In this study, after calculating the upper quartiles of data collected, the maximum value was 37μg/m³. Therefore, for green buildings with high-performance in Shanghai, indoor PM2.5 concentration should be below 37 μg/m³.

5.4.2 Compliance rate of CO₂. For the internal environment of the building, CO₂ is related to the respiration of people and plants, and is also affected by other factors (such as outdoor air penetration).
Indoor CO₂ concentration shows obvious accumulation phenomenon, as shown in figure 7(a). However, the research results show that the indoor CO₂ concentration of buildings can basically reach the requirements of 1000ppm in GB/T 18883-2002 [13]. The indoor CO₂ volume fraction of some surveyed buildings was distributed centrally between (350–500) PPM, with an average value of 480 ppm[14], as in figure 7(b). In this paper, CO₂ in two conditions is good. The upper quartile value of each group was calculated respectively, and the result was 703ppm. This value can be used as a reference to make higher requirements for the indoor CO₂ concentration of green office buildings in Shanghai.

5.4.3 Compliance rate of TVOC and Formaldehyde. Compared to winter, the compliance rate of TVOC in summer is lower and have a wider distribution range.

In winter, the formaldehyde concentration collected from the site was basically below 0.10mg/m³, with a compliance rate above 98%. In summer, some measurement points did not reach the standard, but the overall compliance was good.

6. Conclusion
In this paper, the indoor environmental performance of 12 green office buildings in Shanghai was studied, and the indoor air temperature, relative humidity, illumination and air quality parameters of the buildings were monitored on site for a long time. A comprehensive benchmarking analysis was carried out on the collected data and the results were compared with the same domestic studies. The results can reflect the actual situation of the indoor environmental performance of green office buildings in Shanghai in a real and comprehensive way. The main conclusions are as follows:

For similar green office buildings, the compliance rate of indoor thermal environment varies greatly. Indoor temperature in winter has a great influence on the thermal environment compliance rate, and the indoor air temperature in winter is lower than the standard comfort zone. In summer, the relative humidity has a greater influence on the compliance rate of the hot and humid environment, which is
reflected in the fact that the indoor relative humidity of green office buildings in Shanghai tends to be high in summer, resulting in the low compliance rate of some of them.

Green building indoor thermal environment are easily affected by the outdoor climate condition, differences existed in different regions. In high outdoor humidity areas, such as Shanghai, Guangzhou, studies show the same problem.

The measured compliance rate of lighting environment varies greatly under two working conditions. Summer illuminance standard condition is better. The measured quartile value under the illumination is 320lx, which can be used as the recommended illumination limit under the 75% compliance rate in the lighting environment.

In terms of indoor air quality, PM2.5 standards in summer are relatively good, all of which are above 90%. The maximum value of upper quartiles of measured data is 37 μg/m³, which can be used as the recommended upper limit concentration of PM2.5. The CO2 compliance rate is generally high, exceeding 97%. The value of the upper quartile of the measured data is 703ppm, which can be used as the recommended upper limit concentration of CO2. Under the three working conditions, the compliance rates of formaldehyde and TVOC concentrations were all good, but some measurement points still failed to reach the standard.

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