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Integrated analysis of energy, indoor environment, and occupant satisfaction in green buildings using real-time monitoring data and on-site investigation

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ARTICLE INFO

Keywords:
Green building
Energy consumption
Indoor environmental quality
Occupant satisfaction
Integrated analysis
Multiple linear regression

ABSTRACT

Recently, a growing literature pay attention to the green buildings, and most of them focuses on design, energy simulation, and post-occupancy evaluation but rarely involves the integration analysis of energy consumption, indoor environmental quality, and occupant satisfaction in the operational stage. In this paper, the authors propose a comprehensive quantitative study based on energy-environment-satisfaction (EES) and take a three-star green building in Shanghai as an example. Through the use of real-time monitoring data, the study analyses the distribution characteristics of the parameters of EES. Meanwhile, this study discusses the differences between operational energy consumption and design parameters and also quantifies the exponential relationship between per floor personnel density and building energy consumption. Moreover, combined with the user satisfaction survey, some improvements are suggested. Furthermore, the relationship between daily energy consumption and the environmental parameters of daily energy consumption, PM2.5, CO2, temperature, relative humidity, and illumination is fitted, and the results indicate that there is a multivariate linear relationship with a correlation of 0.876. Through the sensitivity analysis, we found that the relative humidity affects 1.4 times as much as CO2. Therefore, its control value is critical to reduce energy consumption in the operation of green buildings.

1. Introduction

Green building design is considered to be an effective way to decrease energy consumption, and the green building evaluation standard is an important basis for the implementation of green building design, but the actual benefits of green building design during the operational stage is not clear. However, the goal of green building design is to use energy efficiently and to provide a level of Indoor Environmental Quality (IEQ) for their occupants. In China, the first version of the Green Building Evaluation Standard (GBES) [1] was published in 2006. The Ministry of Housing and Urban Rural Development of China formally started the Chinese Green Building Label (CGBL) certification in April 2008. The GBES has been revised twice, in 2014 and in 2019 [2, 3].

In recent years, the development of CGBL projects has accelerated in China. However, only 5% of CGBL projects have obtained an Operation Label, while most of CGBL projects have obtained a Design Label [4]. At present, there are few studies on the operational performance analysis of CGBL projects in China. The operational post evaluation standard for green buildings has recently been launched in July 10, 2019, but most of the CGBL projects are not verified the green technical implementation effect in terms of the operational phase [5]. Therefore, a comprehensive analysis of the operation of green buildings is considered important. Building performance includes energy consumption, IEQ, including thermal, indoor air quality, lighting and acoustics, and user satisfaction. Energy performance often affects IEQ parameters [6], and the relationship diagram between energy and IEQ is only proposed. Peixian L. et al. [7] presents different post-occupancy evaluation (POE) methods, which include the occupant survey, interview, walkthrough, IEQ in-site measurements, and energy audit. Fowler K M. et al. [8] provide a detailed post evaluation of 22 buildings. Nilashi M. et al. [9] propose a knowledge-based expert system based on the analytic hierarchy process and fuzzy logic to assess the performance of green buildings.

Currently, research is focused on energy use, IEQ, and occupant satisfaction of green buildings. Table 1 summarizes the current studies
on green buildings.

From Table 1, we can see the human factors play an important role in the relationship of EES especially the occupant satisfaction. When the IEQ conditions are not comfortable, the corresponding adjustable IEQ factors can be adjusted or controlled by the occupant. Therefore, the objective IEQ and occupant satisfaction interact with each other. For example, when the high CO$_2$ concentration causes the dizziness and other symptoms of office workers, people will take the initiative to ask for the adjustment of fresh air volume.

Energy Consumption. Aly M. Elharidi et al. [11] observed energy consumption increases centrally serviced buildings, and also assessed the relative thermal comfort and environmental conditions. Borong Lin et al. [15] found that the average EUI of mechanically conditioned buildings was 23% lower than the constraint value in the Hot-Summer Cold-Winter zone. Agha-Hossein M et al. [20] compared user satisfaction in a previous building to that of current headquarters, and found that users were more satisfied with their work environment in their new building than previous office. John H. Scofield [23] compared 21 Leadership in Energy and Environmental Design (LEED) buildings with 953 large New York office buildings, and the results showed that the LEED buildings consume the same energy as other office buildings.

IEQ. Ding Yong et al. [10] analyzed the IEQ of CGBL in summer in Chongqing, and found that questionnaire survey and objective measurement of physical indicators are important in POE. Z.F. Pei et al. [16] surveyed 10 green buildings in China, and the results revealed that CGBL buildings have a higher satisfaction level than common buildings. Young S. Lee et al. [25] studied the thermal, indoor air quality (IAQ), and the lighting environment in 5 typical LEED office buildings and found that improved IAQ enhanced workplace performance.

Occupant satisfaction. Occupant satisfaction research is also crucial in assessing the performance of green buildings. Some researchers have shown that green buildings improve occupant satisfaction, while others have found the opposite. Stefano Schiavona [17] showed that impact factors unrelated to IEQ significantly affected user satisfaction. Ruey-Lung Hwang et al. [18] surveyed and compared IEQ and satisfaction of green and common buildings, and found that the overall IEQ satisfaction was higher in the green buildings than in the common ones. In contrast, Sergio Altomonte et al. [11] suggested the Building Research Establishment Environmental Assessment Method (BREEAM) certification did not influence user satisfaction. Schiavon S and Altomonte S [19] pointed out users in LEED-buildings reported the same overall building and workspace satisfaction as users in non-LEED buildings.

The previous research literature is mainly focus on energy use, IEQ and occupant satisfaction of operating performance in green buildings were separately. Several studies compared the energy use index (EUI) of green buildings with non-green buildings, and benchmark and simulate energy consumption. In the DSEE PB, personnel density is an important correction factor of office building energy consumption. Regression models between energy use and outdoor air temperature throughout the whole year can be classified into six models, namely 1P Model, 2P Model, 3P Model, 4P Model, 5P Model [27]. In terms of indoor environment, researches focused on current situation and improvement measures. Some studies also revealed green buildings had a higher occupant satisfaction level than for common buildings. On the contrary, some researchers hold negative attitudes.

However, there is no quantitative relationship between energy consumption and indoor parameters.

The review reference [28] started to emphasize the importance of combination analysis of energy use, IEQ and occupant satisfaction and points out such problems should be the focus of future research.

Firstly, the quantitative relationship between energy use, IEQ and occupant satisfaction is very complex. The quantitative impact of IEQ on energy consumption is still unknown. For green building, different building has different green technology, such as facility or system, different operating schedules or modes, different energy efficiencies. Moreover, there are many influencing factors, and the mutual influence is complex. The difference of users’ individual needs for comfort [29] and the indoor environment control level [30] will cause great fluctuation of energy consumption. Secondly, energy consumption real-time data and indoor environment real-time data need to be synchronous, collaborative and continuous, and to ensure the quality of data. If the real-time monitoring data is interrupted, regression models and quantitative relationships are not available.

The main aims of this paper are: (1) to comprehensive analyse energy consumption, environment, satisfaction in green building; and (2) to conduct quantitative relationship between energy consumption and indoor environment parameters. In this paper, an integrated analysis of energy-environment-satisfaction (EES) was undertaken through detailed site investigation and IEQ measurements for a green office building in Shanghai. This paper is composed of five sections. In Section 2, the research framework of EES on green buildings is presented. Section 3 outlines the results of the analysis of a three-star green office building in Shanghai. In Section 4, the results of this paper are discussed. Finally, Section 5 provides the main conclusions.
Table 1

| Country          | Year | Building number | IEQ parameter | Method                                      | Reference                                      |
|------------------|------|-----------------|---------------|---------------------------------------------|------------------------------------------------|
| China            | 2018 | 10              | -             | -                                           | -                                              |
| United Kingdom   | 2017 | 4               | -             | -                                           | -                                              |
| Egypt            | 2017 | 59              | -             | -                                           | -                                              |
| United States of America (USA) | 2016 | 31              | -             | -                                           | -                                              |
| China            | 2015 | 10              | -             | -                                           | -                                              |
| USA              | 2014 | 144             | -             | -                                           | -                                              |
| Taiwan           | 2013 | 5               | -             | -                                           | -                                              |
| USA              | 2013 | 144             | -             | -                                           | -                                              |
| Australia        | 2013 | 15              | Not mentioned | Not mentioned                              | Not mentioned                                  |
| China            | 2012 | 21              | -             | -                                           | -                                              |
| Australia        | 2012 | 21              | -             | -                                           | -                                              |
| China            | 2010 | 5               | -             | -                                           | -                                              |

2. Methodology

2.1. EES research framework

In this research, detailed investigation and analysis of the energy consumption, IEQ, and occupant satisfaction was undertaken for a green office building. The research framework includes three main steps: planning preparation, data collection, and data analysis [31]. See Fig. 1 for the research framework.

In this paper, we obtained quantitative and qualitative data through questionnaire surveys, field surveys, and indoor environmental monitoring. The detailed survey information is shown in Table 2.

2.2. Data collection

Green building design data were sourced from the consultant and the building owner. Energy consumption data are derived from energy bill, monitoring platform and long-term monitoring of the indoor environment by the researchers. User satisfaction results were obtained through the researcher’s questionnaire survey.

2.2.1. Basic information

Building design information, such as the green measurements for energy and standards used for IEQ, were obtained from the design documents.

2.2.2. Operational data

2.2.2.1. Energy consumption. Monthly electricity and gas use were recorded in energy bills. Realtime monitoring data was from the city energy consumption monitoring platform system (ECMPS) which records hourly energy use. ECMPS can measure air conditioning, lighting and plug, power, and other special energy consumption continuously.

2.2.2.2. On-site environmental data. The IEQ monitoring include five sensors for measuring five essential indoor environmental parameters, such as air temperatures, relative humidity (RH), CO₂, PM2.5, and horizontal illumination level. IEQ monitors were installed in representative office zones, open office zones, at 0.75 m height, with a frequency of at least 10 min interval in summer, and winter for more than one month. Instrument accuracy met the testing requirements. Meanwhile, a questionnaire survey was undertaken, including a satisfaction survey of users. Table 3 shows the main real-time monitoring parameters and reference standards.

2.2.2.3. Occupant survey. Previous studies from the Centre for the Built Environment (CBE) database indicated that LEED buildings had higher satisfaction ratings (Huizenga et al., 2003; 2005 [32,33]). A questionnaire was designed based on the research literature [34], and included basic information of users, IEQ, indoor environmental concern and control, and building service performance, and was designed to align with the corresponding interpretation indicators. The post-occupancy evaluation of the indoor environment of the case office building was evaluated by comparing the results of the office site monitoring and the user’s subjective evaluation questionnaire. The survey questionnaire design is shown in Table 4.

For recent work in occupant satisfaction area, see for instance Han-His liang, Sergio Altamonte [18,19], the votes of “very satisfied” (+3), “dissatisfied” (−2), and “slightly dissatisfied” (−1) were pooled into a single category of “uncomfortable” while those of “very satisfied” (+3), “satisfied” (+2), and “slightly satisfied” (+1) into the category of “comfortable”, the “seven-degree scale method” was used for evaluation of IEQ and building service performance. In this study, “seven-degree scale method” will be used in the evaluation of IEQ and Occupant satisfaction.
3. Case study

3.1. Building information

Approximately two-thirds of the CGBL projects were in the hot summer and cold winter zone in China [35]. A detailed field survey was carried out for the CHT building in Shanghai, China. To investigate energy consumption, IEQ, and occupant satisfaction. The selected office building (Fig. 2) was awarded the three-star CGBL for Design Label in 2010 and Operation Label in 2016. The CHT building is an office building in the hot summer and cold winter zone. The CHT building has five floors above the ground and one floor underground, with a total floor area of 21994 m$^2$ and useful office area of 13295 m$^2$.

The main functions of the CHT building include office, meeting, catering, underground parking, and property management office. In initial design, the number of occupants was 2275, but the actual number is only 181. The CHT building mainly uses the combination of ground source heat pump and auxiliary cooling tower for cooling. The underground staff dining room, hall on the first floor, report hall on the second floor and other large spaces adopt constant air volume system from the air handling unit (AHU). Fan coil and fresh air system is used in office area and conference rooms. Most of the fresh air systems are pre-cooled or pre-heated by using the energy discharged after full heat recovery. Two full heat recovery machines with air volume of 9000 m$^3$/h are selected, with heat recovery efficiency of 70%. And other 24-h air-conditioned rooms, such as fire control room, duty room, weak current center, use split air conditioners; High efficiency fluorescent lamps and energy-saving lamps are used in the building. The power density values of all rooms and places are lower than the target values in the standard for lighting design of buildings (GB 50034–2004). The lighting of stairwell is controlled by acousto-optic control delay switch. The lighting of office, meeting room and underground garage is controlled by group switch. The lighting can be turned on or off according to the actual needs. The energy-saving design is based on the Design Standard for Energy Saving of Public Buildings (DSEEPB) (GB 50189–2005).

3.2. Results

3.2.1. Energy consumption

The GBES includes the application of energy-saving technologies. Reducing energy consumption by adopting energy-saving technology is one of the most important concerns in the design of green buildings. Electricity is the main energy source in the CHT building and is used for HVAC, lighting and sucker, equipment, and others. The annual EUI distribution of this building is shown in Fig. 3. The monthly EUI for six years and the average EUI is shown in Fig. 4.

3.2.1.1. Energy use index. According to the Standard for Energy Consumption of Buildings (SECB) in China [36], the CHT building is mechanically conditioned. The average EUI over six years is 99 kWh/(m$^2$. a), and the results of the comparison with energy consumption in similar buildings are shown in Table 5.

From Table 5, the EUI of the CHT building is 10% and 37% lower than the upper limit for the Chinese standards. EUI is lower than the
same type of office buildings in Shanghai Hongqiao. In the CHT building, the actual operational EUI complies with the requirements of the two standards and is close to the recommended value.

Based on the monthly EUI and outdoor air temperature from 2013 to 2018, a fitted relationship can be obtained, which can be seen in Fig. 5. As shown in Fig. 5, monthly EUI increases as outdoor air temperature rise in summer from June to September. However, the operation of heating system from December to March, air outdoor temperatures in January and February are between 5 and 8 °C and during this period the New year day holiday and Spring Festival holiday reduce monthly EUI. This is also the reason why monthly EUI in Fig. 5 decreases with the decrease of temperature. On this basis, the owners of the CHT building can improve energy efficiency based on the weather data.

### 3.2.1.2. Energy breakdown

The GBES requires that new green buildings should install an energy consumption sub-metering monitoring platform. The results of energy consumption sub item can be seen in Table 6. Table 6 shows that lighting and plug takes up 32% of the annual EUI is lower than the non-green office building. In contrast, other three other energy such as HVAC, Power plant and other auxiliary system energy use are higher the non-green office building. Throughout the whole year, lighting and plug, power plant, other auxiliary systems take up 32%, 14%, and 16% of the annual EUI is higher than the non-green ones. HVAC system consumes the remaining 38% energy.

### 3.2.2. Impact of the number of people

In the operation stage, the performance parameters of the enclosure structure have been determined. The actual operation energy consumption is mainly affected by indoor environment and occupant-related parameters. The per capita floor area (PCFA), and IEQ parameters, such as indoor temperature, RH, illumination, CO\(_2\), and PM2.5, influence the energy consumption of the building.

The actual number of people in the building and the relevant standards for design reference are shown in Table 7.

The Chinese SECB gives a formula for EUI calculation for office buildings (1) to (3):

\[
E_{\text{oc}} = E_s \cdot \gamma_1 \cdot \gamma_2
\]  
(1)

\[
\gamma_1 = 0.3 + 0.7 \frac{T_s}{T}
\]  
(2)

\[
\gamma_2 = 0.7 + 0.3 \frac{S}{S_0}
\]  
(3)

Where, \(E_{\text{oc}}\) is the revised value of the measured value of EUI for office buildings; \(E_s\) is the measured EUI for office buildings; \(\gamma_1\) is the correction factor for temperature.

### Table 2

Parameters and data source for green office buildings.

| No. | Parameters | Unit | Data Source |
|-----|------------|------|-------------|
| 1   | Building age | years | Property manager |
| 2   | Certification levels | | Design document |
| 3   | Rating standard | | Green Building Label Evaluation System 2006/2014/2019 |
| 4   | Internal floor area (IFA) | m\(^2\) | Design drawings and design schematics |
| 5   | Floors/Height | | Design schematics & on-site observation |
| 6   | Building envelope | | Design schematics & on-site observation |
| 7   | Operating hours per day | hour | Time schedule |
| 8   | Occupancy number | | Property manager |
| 9   | Annual energy consumption | kWh | Monthly electricity and gas bills |
| 10  | Cooling Period/Heating Period | Month | Property manager |
| 11  | Window to wall ratio | | Design schematics & on-site observation |
| 12  | Wall and window types, shading type | | Design schematics & on-site observation |
| 13  | Cooling source, Cooling capacity | | Design drawings |
| 14  | Cooling terminals | | Design drawings |
| 15  | Heating source, Heating capacity | | Design drawings |
| 16  | Heating terminals | | Design drawings |
| 17  | Energy efficiency technology | | Green building Consultation Report |
| 18  | IEQ technology | | Green building Consultation Report |
| 19  | Heating, ventilation, and air conditioning (HVAC) system & control description | | Schematics, BMS, on-site measurement |
| 20  | HVAC system energy consumption | kWh | Sub-metering records |
| 21  | Lighting and plug energy consumption | kWh | Sub-metering records |
| 22  | Pump and drainage, Vertical transport energy consumption | kWh | Sub-metering records |
| 23  | Special equipment energy consumption | kWh | Sub-metering records |
| 24  | IEQ acoustics environment (sound insulation), lighting environment (visible light transmission and glare reduction), thermal environment (temperature/humidity), IAQ [ventilation, carbon dioxide (CO\(_2\))/volatile organic carbons (VOCs)] | | On-site measurement |
| 25  | Occupant survey - overall perception of the IEQ | | On-site survey |

### Table 3

Green office building indoor environment real-time monitoring parameters and requirement of standards.

| IEQ | Objective indicators | IEQ parameter range of office buildings | Standard |
|-----|----------------------|----------------------------------------|----------|
| Thermal environment | Temperature (°C) | Cooling season: Level 1 Comfort Zone:24-26 °C, 40-60%, Level 2 Comfort Zone:26-28 °C, ≤70% Heating season: Level 1 Comfort Zone:22-24 °C, ≥30%, Level 2 Comfort Zone:18-22 °C, | Code for design of heating, ventilation and air conditioning of civil buildings GB 50736-2016 |
| | RH (%) | | |
| Illumination environment | Illumination (lux) | Limited value: 0.75 m, 300 lux | Standard for lighting design of buildings GB 50034-2013 |
| IAQ | PM2.5(μg/m\(^3\)) | Daily average concentration: <37.5 | Assessment standard for healthy building T/AS CO2-2016 |
| | CO\(_2\)(ppm) | Daily average:1000 | Indoor air quality standards GB/T18883-2002 |
factor of the use time for office buildings; \( \gamma_2 \) is the correction coefficient of PCFA for office buildings; \( T \) is the actual operation hours of office buildings (h/a); \( s \) is the actual PCFA, which is the ratio of the building area used to the actual number of personnel (m\(^2\)/person). \( T_s \) is the standard annual operation time, 2500 h/a, and \( S_s \) is standard PCFA, 10 m\(^2\)/person.

According to formula (1) to (3), the EUI can be calculated from Table 7. Based on the above data of EUI and PCFA, we got the

![Fig. 2. The CHT building.](image)

![Fig. 3. Annual EUI](image)

![Fig. 4. Monthly EUI](image)

Table 5

| Region/Standard | EUI (kWh/(m\(^2\).a)) |
|-----------------|------------------------|
| Energy Consumption Standards for Civil Buildings GB/T51161-2016 \[41\] | Upper limit is 110 kWh/(m\(^2\).a); Guidance value is 80 kWh/(m\(^2\).a) |
| Rational Use of Building Energy Guide for Comprehensive Building DB 31/T795-2014 \[37\] | Upper limit is 156 kWh/(m\(^2\).a); Advanced value is 110 kWh/(m\(^2\).a) |
| 46 commercial office buildings in Shanghai (2019) \[38\] | 112 kWh/(m\(^2\).a) |
| 8 CGBL office buildings in Shanghai (2014) \[39\] | 110 kWh/(m\(^2\).a) |
| 18 green buildings in hot-summer cold-winter zone (2015) \[40\] | 85 kWh/(m\(^2\).a) |

Table 4

| Description | Property |
|-------------|----------|
| Gender | Male, female |
| Age | <30; 31–40; 41-50; 51–60; >60 |
| How long you have been working in this building | Less than 3 m; 3 m-1 y; less than 5 y; 6-10 y; more than 10 y |
| How much time do you spend in the office every week | <10 h; 11–20 h; 21–40 h; >40 h |
| Please indicate your work room number and floor number | Very dissatisfied; slightly dissatisfied; neutral; slightly satisfied; satisfied; very satisfied |
| EQ | Temperature; humidity; airflow; air quality; light environment; sound environment; All items are concerned; no concern |
| The ability to control your own indoor environment | Often; sometimes; occasionally; |
| Do you actively control and adjust the indoor environment of the building? (such as adjusting air conditioning temperature, opening and closing windows, drawing curtains, etc.) | |
| Building service performance | |
| Work efficiency | |
| Work layout and space around you | |
| Provision of comfortable furniture | |
| Cleanliness of your work environment | |
| Overall operation and maintenance of the building | |

Note: the studied case in Shanghai is 99 kWh/(m\(^2\).a).
exponential relationship between per floor personnel density and building energy consumption with the high correlation value is 0.9822. The fitted relationship is shown in Fig. 6.

3.2.3. Indoor environmental quality

For the CHT building, the monitoring area focused on the most frequently used offices. The five key parameters were measured using selected continuous monitoring instruments. The 6 measurement positions were located in four typical office areas: Property Independent Office on the first floor (1FIO, East), open office space on the second floor (2FOO, Inner zone), small office on the third floor (3FSO, west north), open office space on the third floor (3FOO, Inner zone), front desk on the fourth floor (4FFR, South), and small independent office on the fourth floor (4FIO, South).

The indoor environment data were continuously monitored in the office area during the operational period in summer, winter, and the transition seasons, from July 22, 2017 to August 21, 2017, from January 22, 2018 to February 22, 2018, and from April 2, 2018 to April 23, 2018, respectively. The environmental monitoring data were downloaded during working hours from 9:00 a.m. to 17:00 p.m. The monitoring results were analyzed to obtain a box plot. Fig. 7 indicates the thermal environment in the main office area in summer and winter.

Fig. 7 shows the characteristics of the thermal environment in the main office area during working hours from 9:00 to 17:00. From the results of long-term thermal monitoring, the indoor air temperature in summer ranges from 23 to 31 °C while RH ranges from 40% to 85%. The first floor of the building consists of a hall, meeting rooms, and property offices. 1FIO is a Property Management Office, and users of this office will frequently go out for equipment management and maintenance work. Thus, air conditioning of this room is not stable. 1FIO has an RH of more than 80%. The environment of the other rooms is in a comfortable range most of the working time. 2FOO is above the meeting room, and the IEQ is not as favourable as the similar room, 3FOO. As the 3FSO room faces west and experiences occasional high temperatures due to solar radiation on summer afternoons, shade curtains should be used in the afternoon.

Fig. 8 shows a boxplot of CO₂ concentrations in the monitored rooms in winter, summer, and the transition season. The average CO₂ concentration in the rooms is below the standard requirement of 1000 ppm, as shown in Table 3. However, there is still a certain percentage of time that the CO₂ concentration is above 1000 ppm, especially in 3FOO, 4FFR, 1FIO rooms in the transition season and in winter. In a word, the average CO₂ concentration in 3FOO and 4FFR is 838 and 871, respectively, which is higher than other rooms. 4FFR is the front desk on the 4th floor and is located in front of the elevator lobby. A print-copy room next to the 3FOO measurement point causes high CO₂ concentrations in 3FOO. As the 3FSO room faces west and experiences occasional high temperatures due to solar radiation on summer afternoons, shade curtains should be used in the afternoon.

Fig. 9 shows the PM2.5 boxplot in the monitored rooms in winter, summer, and the transition season. The average PM2.5 concentration in the rooms is below 505 ppm in summer. 3FOO and 4FFR both have two different average values in winter.

Table 6

| End-use system     | Case study (average for six years) | Energy consumption monitoring platform in Shanghai [41] |
|--------------------|-----------------------------------|-------------------------------------------------|
| HVAC               | 38%                               | 30%                                             |
| Lighting and plug  | 32%                               | 52%                                             |
| Power plant        | 14%                               | 10%                                             |
| Other auxiliary    | 16%                               | 9%                                              |
| system             |                                   |                                                 |

Table 7

Parameters of PCFA.

| PCFA (m²/per capita) | PCFA measured in design | PCFA measured | DSEEPB | Green Building Performance Calculation Standard | SECB |
|----------------------|-------------------------|---------------|--------|------------------------------------------|------|
|                      | 4                       | 51            | 8      | 8                                        | 10   |

Fig. 6. Distribution of building energy consumption in different PCFA.
time points in the measurement results of 4FFR and 1FIO exceed the standard value. These PM2.5 are too high, caused by someone smoking.

Fig. 10 displays the illumination value boxplot at desk height in the monitored rooms in winter, summer, and the transition season. In general, the average illuminance near the window can meet the standard requirements, while the illuminance in the internal area such as 2FOO and 3FOO is lower than 300 lux, so the illuminance level needs to be improved.

3.2.4. Occupant satisfaction

The questionnaire was aimed at the user satisfaction related to the indoor environment parameters of the building. Based on the index system, the questionnaire focused on the assessment of the current performance of the building by the users in terms of the acoustic environment, light environment, thermal environment, IAQ, as well as the main causes of dissatisfaction. Forty-three questionnaires were distributed, completed, and collected. See Fig. 11 for the basic information of the participants.

The seven degrees scale of 1–3–5 was used to evaluate satisfaction. The result of occupant satisfaction for the CHT building is presented in Fig. 12.

Fig. 12 shows the median, and first and third quartiles, of the occupant satisfaction with five IEQ parameters and the building overall. The mean overall indoor environment is 1.07, and could be considered “slightly satisfied”. The mean values of occupant satisfaction with the five environment parameters (T, RH, IAQ, Illumination and Acoustic environment) in the CHT buildings are as follows: 1.14, 1.05, 0.88, 1.07 and 0.98.

Satisfaction rate is the proportion of the satisfaction value that is greater than 0. The statistical results of IEQ satisfaction is shown in Fig. 13. As shown in Fig. 13, the highest satisfaction of the overall indoor environment was 93%, which is higher than the other five aspects (T, RH, IAQ, Illumination and Acoustic environment) due to the user’s tolerance for green building. The lowest satisfaction was 86%, which is
consistent with the low levels of lighting measured.

Table 8 below presents the type of work of 1F–4F occupants. Further analysis was undertaken on the satisfaction results of 1F–4F participants. The statistical results are shown in Fig. 14. As 1F comprises the main property office and meeting room and has outdoor interference, the participants’ satisfaction with the temperature is only 0.5. The satisfaction of respondents from 2F–4F is greater than 1. In general, the occupant satisfaction of 3F office area is lower than 2F and 4F. The reason is that 3F has the influence of printing room and weak current room.

3.2.5. Relationship between DEC and IEQ

When the indoor environmental parameters change, the building daily energy consumption (DEC) will also change. For example, under cooling conditions in summer, lower indoor air temperature and RH means higher energy consumption through the air conditioning system;
under the same conditions, with more fresh air, the CO\textsubscript{2} concentration is lower, and there will be higher energy consumption. The higher the illumination value, the higher the energy consumption, and the smaller the PM2.5, the higher the energy consumption. The author assumes that there is a relationship between DEC and daily average IEQ parameters. See Table 9 for the normalization method of indoor environmental parameters. Therefore, a linear equation can be formulated as follows:

\[ Y = aX_1 + bX_2 + cX_3 + dX_4 + eX_5 + \varepsilon \]  \hspace{1cm} (4)

The regression analysis was performed with the Statistical Package for the Social Sciences (SPSS), and the R of the regression model is 0.876, and sig is 0.002. The results indicated the multiple-parameter regression equation, as follows:

\[ Y = 804.963X_1 + 919.590X_2 + 692.768X_3 - 654.241X_4 + 704.155X_5 + 5600.873 \]  \hspace{1cm} (5)

Based on Eq. (5), Predicted DEC can be gained. Fig. 15 shows measured DEC and Predicted DEC. It has high fitting degree and the error is within 7%.

4. Discussion

4.1. Operational energy use compared with design goal

The CHT building was designed in accordance with the DSEEPB (GB 50189–2005). During the design, the objectives for energy saving rate for HVAC and lighting systems were specified. The actual operating energy use of the CHT building was compared with the design objectives, and the results are shown in Table 10.

Table 10 shows the total measured energy consumption is 16% higher than the initial design specification. Table 6 presents the results that the measured energy use for HVAC and lighting is 6% and 9% lower than the DSEEPB reference building energy-saving standard. The heating difference of the measured and the design is due to the air tightness of doors and windows, which leads to the infiltration of outdoor air in winter and the excessive energy consumption of actual heating. However, there are 2275 persons at the design in the energy simulation model, and in fact, there are only 181 persons. Some offices are unoccupied.

4.2. Sensitivity analysis: key indoor environmental factors for the energy performance

There are many researches on sensitivity analysis in building energy analysis [43]. The sensitivity analysis methods can be divided into local and global sensitivity analysis. Local sensitivity analysis belongs to the class of the one-factor-at-a-time methods. Sensitivity measures are often calculated when one factor is changed and all other factors are fixed. As
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Fig. 14. Satisfaction results box plot of 1F–4F participants.

Fig. 15. Measured DEC and predicted DEC

Table 9
Calculation of IEQ parameters.

| Symbol | Parameters                          | Calculation method                                                                 |
|--------|------------------------------------|------------------------------------------------------------------------------------|
| Y      | DEC                                |                                                                                    |
| X1     | Normalized value of difference     | $X_{1k} = \frac{(T_{ik} - T_{ok})}{\max(T_{ik} - T_{ok})}$                         |
|        | between indoor air temperature and  |                                                                                    |
|        | outdoor temperature                |                                                                                    |
| X2     | Normalized value of the difference | $X_{2k} = \frac{(R_{i,k} - R_{o,k})}{\max(R_{i,k} - R_{o,k})}$                     |
|        | between indoor humidity and outdoor |                                                                                    |
|        | RH                                 |                                                                                    |
| X3     | Normalized value of PM2.5          | $X_{3k} = \frac{\min(P_{i,k})}{\max(P_{i,k})}$                                    |
| X4     | Normalized value of CO2 concentration | $X_{4k} = \frac{\max(C_{i,k})}{\min(C_{i,k})}$                                    |
| X5     | Normalized value of illuminance    | $X_{5k} = \frac{L_{i,k}}{\max(L_{i,k})}$                                          |

Table 9 Calculation of IEQ parameters.

a result, the choice of base case is very important in local sensitivity analysis method. This method is easily applied to identify the key variables affecting building energy use.

In this paper, Local sensitivity analysis of five indoor environmental factors is judged by the change rate of building daily energy consumption. Combined with local sensitivity analysis, the value of building daily energy consumption is calculated. Eq. (5) is used to calculate the daily energy consumption of different case.

The sensitivity of five indoor environmental factors is judged by the change of daily energy consumption rate (DECR). Combined with the local sensitivity analysis, only one factor is changed in each calculation, and other sensitive factors are fixed to calculate the building daily energy consumption value. The value of DECR is given by:

$$DECR = \frac{(Y_{1,act} - Y_{1,po}) \times X_{1,act}}{Y_{1,act} \times (X_{1,po} - X_{1,act})}$$

Where, $X_{1,act}$ is the base case ($J = 1$) of the five indoor environmental factors, $Y_{1,act}$ is the base case ($J = 1$) of DEC, $X_{1,po}$ is the different case ($J = 2, \ldots, 8$) of the five indoor environmental factors; $Y_{1,po}$ is the DEC value of the different case ($J = 2, \ldots, 8$).

The parameters and results of the local sensitivity analysis method are shown in Table 11.
Table 10
Energy use in a CGBL-certified office building in hot-summer cold-winter zone.

| Energy use | Reference building refer to DSEEPB standard (1) | Design specification (2) | Measured energy use (3) | Difference (3)–(1) % | Difference (3)–(2) % |
|------------|-----------------------------------------------|--------------------------|------------------------|----------------------|----------------------|
| Heating    | 155555                                        | 95535                    | 212954                 | 37%                  | 123%                 |
| Air conditioning | 352070                                    | 296805                   | 264156                 | –25%                | –11%                 |
| HVAC       | 507625                                        | 392340                   | 477110                 | –6%                 | 22%                  |
| Lighting   | 397922                                        | 331734                   | 361737                 | –9%                 | 9%                   |
| Total      | 904717                                        | 724073                   | 838847                 | –7%                 | 16%                  |

Table 11
The sensitivity factors and results of the local sensitivity analysis.

| J | Ti | X1, X2 | DEC1 | DEC2 | DEC3 | DEC4 | DEC5 | DEC6 | DEC7 | DEC8 |
|---|----|--------|------|------|------|------|------|------|------|------|
| 1 | 24 | 25     | 26   | 27   | 28   | 29   | 30   | 31   |      |      |
| 2 |    | 0.91   | 0.82 | 0.73 | 0.64 | 0.55 | 0.45 | 0.36 |      |      |
| 3 |    | 0.0996 | 0.0997| 0.0997| 0.0997| 0.0997| 0.0997| 0.0998|      |      |
| 4 |    | 0.9640 | 0.9500| 0.9050| 0.8400| 0.7460| 0.6390| 0.5370|      |      |
| 5 |    | 0.8400 | 0.7500| 0.6600| 0.5700| 0.4900| 0.4100| 0.3400|      |      |
| 6 |    | 0.9640 | 0.9500| 0.9050| 0.8400| 0.7460| 0.6390| 0.5370|      |      |
| 7 |    | 0.0996 | 0.0997| 0.0997| 0.0997| 0.0997| 0.0997| 0.0998|      |      |
| 8 |    | 0.0996 | 0.0997| 0.0997| 0.0997| 0.0997| 0.0997| 0.0998|      |      |

When considering the influence of single factors, DEC value is calculated in accordance with this scenario case. The relationship between the DEC and each indoor environment parameters. These three sensitivity factors (T, RH and CO₂) have a linear relationship with daily energy consumption. The relationship between PM2.5 and daily energy consumption is logarithmic.

The sensitivity results of five indoor environmental factors to DEC are shown in Fig. 17. The sensitivity order was RH, T, illumination, PM2.5 and CO₂ concentration. The sensitivity of RH is the highest, which is 1.4 times of CO₂ concentration factor.

4.3. Recommendations

The illumination range should be 1500–3000 lux, according to the relationship curve between the illumination and optical environment satisfaction given by the International Commission on Illumination (CIE). Domestic research [44] also shows that in non-green office buildings in Shanghài, Beijng, the optimal level of illumination is 1000–1200 lux. In the CHT building in this paper, the illumination at the height of 0.75 m was 300–600 lux, which meets the building lighting design standard GB 50034–2013. However, there was a lower satisfaction rate, and the level of illumination of 2FOO and 3FOO must be improved to enhance user satisfaction.

In response to public health events, air conditioning must be operated by managers. Due to the recent occurrence and spread of a new coronavirus in China, in the more concentrated office buildings, the HVAC system operating strategy should be adapted according to the type of air-conditioning system. (1) It is advisable to increase ventilation with fresh air. (2) The large space of the first-floor hall and the second-floor reporting hall is a closed air system. The return valve should be closed, and the new air valve and the exhaust valve should be opened. (3) The office and meeting rooms use a fan coil unit with a fresh air system. In the open office area, where the air is delivered by multiple fan coils, the fan coil unit should be deactivated, and the fresh air system should be activated. The fan coil can be switched on if it serves a separate office.

5. Conclusions

This paper focused on a quantitative study based on energy-environment-satisfaction, which the energy consumption and environmental parameters are integrated. The main conclusions are as follows:

(1) The study takes a three-star green building in Shanghai as an example. According to the real-time monitoring data, the study analyses the distribution characteristics of parameters energy consumption and environments. Then the relationship between daily energy consumption and the environmental parameters of temperature, relative humidity, PM2.5, CO₂ and illumination is fitted based monitoring data, and the results indicate that there is a multivariate linear relationship with a correlation of 0.876.

(2) Through sensitivity analysis, the sensitivity results of five indoor environmental factors to DEC were RH, T, illumination, PM2.5 and CO₂ concentration. The sensitivity of RH is the highest, which is 1.4 times of CO₂ concentration factor. Therefore, its control value is critical to reduce energy consumption in the operation of green buildings.

(3) Operational energy use compared with design goal presents the results that the measured energy use for HVAC and lighting is 6% and 9% lower than the DSEEPB reference building energy-saving standard. The difference is due to the air tightness of doors and windows and there are 2275 persons at the design, and in fact, there are only 181 persons.

(4) This paper quantifies the exponential relationship between per floor personnel density and building energy consumption, and the high correlation value is 0.9822. Moreover, combined with the user satisfaction survey, some improvements are suggested.

It should be emphasized that in ESS method, the relationship between DEC and IQE should be further studied. The 5 parameters have different degrees of influence on energy consumption. As a next step, sensitivity analysis and weighting of the factors should be studied. Future research should aim to achieve an optimal indoor environment with minimal energy consumption.
Declaration of competing interest

The authors declared that they have no conflicts of interest to this work.

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Acknowledgments

This research is supported by the China National key research and development program (Grant No. 2016YFC0700100). Great thanks to the owners and managers of the building in survey who supported for this research.

References

[1] GB/T, Green Building Evaluation Standard. GB/T 50378-2006, Ministry of Housing and Urban Rural Development of the People’s Republic of China, Beijing, 2006 (in Chinese).
