Establishment of Key Performance Indicators for Green Building Operations Monitoring—An Application to China Case Study

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Abstract: Released green building evaluation standards for operation stage include a huge number of indicators, which are very comprehensive and systematic. However, the indicators of these standards are very complicated and a large amount of time and manpower are consumed for their evaluation. To evaluate the operational performance of green buildings more practically and efficiently, some studies collect the operational data for part of the indicators (mainly focusing on building energy performance, indoor environmental quality or occupant satisfaction), which are too rough to evaluate the performance of green building. This paper proposed a total of 27 key performance indicators (KPIs) for green building operations monitoring. The number of proposed indicators is much fewer than the evaluation standards, as well as suitable for long-term monitoring, which can dramatically reduce evaluation time and cost. On the other hand, the indicators involving Outdoor environmental quality, Indoor environmental quality, HVAC system, P&D system, Renewable energy system, Total resource consumption and User behavior, which are more comprehensive and systematic than the conventional monitoring studies for operational performance of green building. Firstly, an indicators library for operations monitoring of green building was established based on relevant standards and literature review in this field. Secondly, “SMART” principle and Delphi method were adopted to select the key performance indicators for green building operations monitoring. Different background experts regarding green building industry were chosen to screen the most relevant, accessible and measurable indicators. Subsequently, two projects in China were selected for case study of key performance indicators proposed in this paper for green building operations monitoring to validate the feasibility and advancement.

Keywords: green building; operations monitoring; key performance indicators; SMART principle; user behavior

1. Introduction

Green buildings, which are environmentally responsible and resource-efficient, have witnessed tremendous growth in these years [1,2]. In spite of the rapid development of green buildings worldwide, more and more researchers have found that numerous green buildings underperform compared with their design phase specifications. Newsham et al. [3] found that 28%–35% of the buildings with LEED certification showed more energy consumption than non-green buildings. Research by Scofield reported that the buildings with LEED certification did not save energy compared with their conventional counterparts [4]. Davies et al. [5] concluded that the indoor
environmental qualities of certain green buildings in the UK were below expectations. To explore the performance gap, it is necessary to conduct green building data collection of operational performance. A set of indicators is an important means to evaluate the operational performance [6].

Some countries have released green building evaluation standards for the operation stage including a quantity of indicators, and Table 1 lists the type and number of indicators proposed by typical green building evaluation standards for this stage [7–11].

Table 1. The summary of type and number of indicators proposed by typical green building evaluation standards for operation stage.

| Ref. | Name of Green Building Evaluation Standard | Released Country (Abbr.) | Type of Indicators                                                                 | Number of Indicators |
|------|------------------------------------------|-------------------------|-----------------------------------------------------------------------------------|----------------------|
| [7]  | LEED v4 OM&EM                            | USA                     | Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality | 46                   |
| [8]  | BREEAM In-Use International 2015          | UK                      | Management, Health and Wellbeing, Energy, Transport, Water, Materials, Waste, Land Use and Ecology, Pollution | 89                   |
| [9]  | CASBEE for Existing Buildings v2014       | JPN                     | Indoor Environmental Quality, Service Performance, Outdoor Environmental Quality, Energy Consumption, Water Consumption, Pollution | 102                  |
| [10] | Assessment standard for green building   | CHN                     | Outdoor Environmental Quality, Energy Consumption, Water Consumption, Materials and Resources, Indoor Environmental Quality, Construction, Operational Management | 140                  |
| [11] | Green Building Inspection Technical Standard | CHN                       | Outdoor Environmental Quality, Indoor Environmental Quality, Artificial Lighting and Electrical system, Building Envelope, HVAC System, Plumbing and Drainage System, Renewable Energy System | 57                   |

On the one hand, the indicators proposed in the evaluation standard are very comprehensive and systematic. On the other hand, huge amounts of indicators proposed in the evaluation standard are very complicated and a large amount of time and manpower were consumed for their evaluation, and additionally, they are not suitable for long-term monitoring [12]. To evaluate the operational performance of green buildings more practically and efficiently, some studies collect the operational data for part of the indicators, Table 2 lists the type and number of indicators utilized to evaluate operational performance of green buildings in some typical studies. In terms of the type of evaluated indicators, [13] and [14] mainly focus on energy performance. [15] and [16] mainly focus on Indoor Environmental Quality (IEQ). Reference [17] mainly focuses on occupant satisfaction. Other studies [18–20] evaluated combinations of the three aspects. The number of indicators is much fewer than the standards, which is more practical and cost-saving. As the communication and network technologies developed rapidly, the process of collecting operational data has become more efficient and less expensive [21,22], making it possible to collect more data for other types of indicators in the long term, such as outdoor environmental quality, water usage, renewable energy usage [12]. Furthermore, building energy usage, indoor environmental quality and user satisfaction are merely the operational results, it is more important to monitor the indicators that influence these operational results. For example, the operational efficiency of an HVAC system affects the energy consumption [23]. Similarly, the users’ behaviors can impact the building energy consumption [24] and IEQ significantly [25].
Table 2. The summary of type and number of indicators utilized by typical studies to evaluate the operational performance of green buildings.

| Ref. | Building Type                  | Type of Indicators                              | Number of Indicators |
|------|--------------------------------|-------------------------------------------------|----------------------|
| [13] | Office building                | Energy use and COP of chiller system            | 6                    |
| [14] | commercial building            | Energy performance                              | 4                    |
| [15] | Town hall                      | Indoor environmental quality and control status of HVAC system | 5                    |
| [16] | Office building                | Indoor environmental quality                    | 5                    |
| [17] | Various buildings              | Occupant satisfaction                           | 17                   |
| [18] | Office building                | Energy use and indoor environmental quality      | 8                    |
| [19] | Office building                | Energy use and indoor environmental quality      | 8                    |
| [20] | Residential building           | Energy behaviors and occupant satisfaction       | 4                    |

Key performance indicators (KPIs) are widely used as target-based quantitative management indicators in performance management systems for different industries, for example the manufacturing industry [26], business industry [27] and academia [28]. In terms of the method of establishment of key performance indicators, existing studies do not adequately illustrate the establishing process for operational performance indicators of green building industry. However, method studies regarding establishing key performance indicators for other industries still can be referred. For the selection method of KPIs, the “SMART” principle is generally used to screen and distinguish the key indicators [29], and the application of this principle was proved to be effective and practical [30]. For the execution of selection of KPIs, the Delphi method has been proved to be effective in achieving consensus when there is uncertain information or lack of empirical evidence for different industries [31].

This paper aims to propose a set of key performance indicators (KPIs) for green building operations monitoring, that is more practical and efficient than the evaluation standards, and also more comprehensive and systematic than the conventional monitoring studies for operational performance of green building. These proposed KPIs can be used to identify the whole picture of operational performance of green building, and provide foundation for further specific diagnosis.

2. Methodology

Firstly, an indicators library for operations monitoring of green building was established based on relevant standards and literature review in this field. Secondly, “SMART” principle and Delphi method were adopted to select the key performance indicators for green building operations monitoring. Subsequently, two projects in China were selected for case study of key performance indicators for green building operations monitoring to validate the feasibility and advancement. See Figure 1 for an illustration of the research process undertaken.
2.1. Establishment of Green Building Operations Monitoring Indicators Library

2.1.1. Initial Proposal of Indicators by Incorporation of Standards and Regulations

To establish an authoritative and comprehensive library of operations monitoring indicators for green buildings in China, relevant standards and regulations were researched initially. Upon searching the current Chinese standards for green buildings at the national public service platform for standards information of China, 547 standards and related regulations were obtained and researched. However, no standard or regulation appeared to have been released specifically for operations monitoring of green building.

Among the researched green building standards and regulations, the most authoritative and widely used national standard in the field of green buildings in China is GB/T 50378-2014 “Assessment standard for green building” [10]. Other local, industrial, or association assessment standards of green buildings have been established by referring to this national standard. Although this assessment standard does not specify the green building dynamic operations monitoring system, some credit requirements of the standard involve several quantitative performance evaluation indicators that could be used for long-term dynamic monitoring during the operational stage of a building, such as cooling and heating source system efficiency, non-potable water source utilization rate, and renewable energy utilization rate. The association standard of China CSUS/GBC 05-2014 “Green Building Inspection Technical Standards” [11] has the same goal as the green building dynamic monitoring, which is used to verify the actual performance of the green building after its operationalization. The framework of the inspection is comprehensive and systematic. Although the “inspection” is a static verification rather than dynamic monitoring, this standard still has great relevance for research on the establishment of green building operations monitoring indicators library. Therefor these two standards were shortlisted for a deeper study for the initial proposal for green building inspection or assessment indicators. The indicator framework of CSUS/GBC 05-2014 is more similar to the monitoring system proposed in this study, which included seven primary indicators and 32 secondary indicators. According to GB/T 50378-2014 [10], 22 quantitative indicators can be extracted from the credit requirements, which can be integrated with the secondary indicators of CSUS/GBC 05-2014. Thus, the initially proposed primary indicators were inspired by the “Green Building Inspection Technical Standards (CSUS/GBC 05-2014)”, while the secondary indicators were inspired by both the standards, GB/T 50378-2014 and CSUS/GBC 05-2014.

2.1.2. Elimination of Indicators
Based on the initially proposed green building operations inspection or assessment indicators inspired by the aforementioned standards and regulations, an elimination of less relevant indicators was conducted following two principles:

(1) Firstly, certain inspection indicators are relevant at the time of site selection stage, construction stage, or completion acceptance stage, which are not really related to the long-term operation of the building. For example, the indicator related to sewage discharge from the construction sites is relevant during the construction stage only. Similarly, the indicator related to electromagnetic radiation around buildings and soil radon concentration needs to be inspected during the site selection stage to make sure that the project site is suitable for construction and use.

(2) Secondly, certain inspection indicators are relevant only at the beginning of the building operations. The operational performance of these indicators will nearly not vary during the operations stage unless a retrofitting takes place, and there is no need for long-term monitoring of such indicators. Examples include natural daylight environment, lighting power density, thermal performance of the building envelope, etc.

2.1.3. Supplementary Indicators

After the elimination of the irrelevant indicators, the remaining indicators could be preliminarily considered for long-term monitoring during the operational stage of the green building. To establish a comprehensive monitoring indicators library, the method of literature assimilation was used to develop supplementary indicators, in which the standards and regulations were not involved.

According to the purpose of this study, the keywords “green building”, “operating performance”, “operation monitoring” and “post-occupancy evaluation” were used for the literature search for the past five years. Search engines including Web of Science [32] and Scopus [33] were chosen to find relevant literatures which were considered as frequently-used for research. A total of 625 relevant articles were found as the initial literature database. After creating the initial database of articles, the further selection principles are from three aspects:

(1) Only articles from international journals with high citations were included.
(2) Only articles with specific operational data of green buildings were included.
(3) Articles without significance test were excluded for further review.

Thus 86 articles were identified for further analysis. On the basis of purpose of the literature review, these 86 most relevant articles on green building operational performance monitoring could be summarized in two categories. One category was with regard to monitoring or investigating the building energy or water consumption and comparing the data with design objectives. The other category was related to the IEQ performances of green buildings by objective monitoring or subjective survey. As for the subjective survey, since China is still a developing country, the credit system is not complete, and also because of the tolerance culture, the results of occupant survey are not reliable enough. The indicators concerned with IEQ were already included in the library. Indicators concerned with building energy and water consumption were added as supplementary to the library.

Moreover, the users’ behaviors can impact the building energy consumption [24] and IEQ [25] significantly. Monitoring users’ behaviors can improve the efficiency of Heating, Ventilation, and Air-Conditioning (HVAC) systems [34] and indoor environment quality [35]. Therefore, the indicators in terms of users’ behaviors were also added to the library. After adding the indicators, the green building operations monitoring indicators library was established, which consisted of some primary and some secondary indicators.

2.2. Selection of Key Performance Indicators for Green Building Operations Monitoring

In this study, KPIs are used to evaluate the key performance of the green building operations and reflect the actual effect of green building operations intuitively and comprehensively. The primary criterion for selecting the KPIs is that they should play a key role in saving resources and improving the environmental quality during the operations.
Referring to the studies of other industries, “SMART” principle was introduced for the selection of the KPIs for the green building operations monitoring indicators library. The “SMART” principle was interpreted as follows: S stands for ‘specific’. These KPIs can be used for monitoring all types of green buildings during the operations phase. To maintain flexibility, reduce monitoring costs, and improve implementation, the KPIs can be appropriately reduced according to the specific conditions of the project. M stands for ‘measurability’ and indicates long-term accuracy, layout difficulty, and remote transmission capability of the monitoring equipment installed. A stands for ‘accessibility’ and indicates the ease of obtaining the data related to the indicator parameters and whether it has the possibility of installing the monitoring equipment. R stands for ‘relevance’ and indicates the degree of correlation and irreplaceability of indicators with green building operations monitoring targets. T stands for ‘time bounded’ and indicates the sampling frequency requirements of the indicators monitoring. This study selected each indicator of the library based on the three principles, namely relevance, accessibility, and measurability (RAM) of the SMART principle. The T and S (‘time bounded’ and ‘specific’) principles were applied for the KPI implementation and not for the KPI selection.

Each secondary indicator was evaluated from the aforementioned three aspects (RAM) and was scored on a scale of 1 to 5 integer points for every aspect to reflect its degree. For example, 1 point for relevance means the indicator only weakly reflects the operational performance of the green building, whereas 5 points means the indicator has strong correlation with the operational performance of the green building. The total score for each secondary indicator was the sum of the scores on the three aspects. The formula is as follows:

\[ S_t = S_r + S_a + S_m \]

where \( S_t \) – Total score for each secondary indicator; \( S_r \) – Score of relevance; \( S_a \) – Score of accessibility; and \( S_m \) – Score of measurability.

The Delphi method was used to score the indicators reasonably and select the final candidates. Twenty green building experts were asked to score each secondary indicator from the three aspects, i.e., RAM, using the 1–5 scale according to their knowledge and experience. The characteristics of experts are shown in Table 3. After each indicator was assigned the scores, the average scores for the three aspects from the scores of the experts for each indicator were calculated and rounded to the nearest integer. Then, the scores for each secondary indicator were added. If the total score was greater than 9 points (which indicates a scoring rate more than 60%), the indicator was retained; otherwise, the indicator was eliminated. Thus, the KPIs for the green building operations monitoring were finalized.

| Background                  | Number of Experts | Title             | Experience (Number of Years) | Affiliation          |
|-----------------------------|-------------------|-------------------|------------------------------|----------------------|
| Research of green building  | 5                 | Professor         | More than 10                 | Academia             |
| Design of green building    | 2                 | Senior Architect  | More than 10                 | Design institute     |
| Design of green building    | 3                 | Senior Engineer   | More than 10                 | Design institute     |
| Consulting of green building| 5                 | Senior Engineer   | More than 10                 | Consulting institute |
| Monitoring of green building| 2                 | Senior Engineer   | More than 5                  | Industry             |
| Management of green building| 3                 | Senior Manager    | More than 10                 | Property management agency |
2.3. Case Study of KPIs for Green Building Operations Monitoring

Two projects were selected for case study of key performance indicators proposed in this paper for green building operations monitoring to validate the feasibility and advancement. The two case projects are all in Liangjiang New District, Chongqing city, located in Southwest China and belongs to the Hot-Summer-Cold-Winter region. The projects are all certified green office buildings by China Green Building Label and named as YL, LJ respectively in this paper. The specifications of the two projects are described in Table 4.

| Specification        | YL                          | LJ                          |
|----------------------|-----------------------------|-----------------------------|
| Number of Floors     | Five                        | Seven                       |
| Building Areas (m²)  | 36,372                      | 111,101                     |
| HVAC System          | Cooling: Centrifugal Chiller + screw chiller. Heating: Gas Boiler | Cooling: Centrifugal Chiller Heating: Gas Boiler |
| P&D System           | Municipal potable water + Rain water harvesting system | Municipal potable water + Rain water harvesting system |
| Renewable Energy     | Air source heat pump for domestic hot water | Not applicable |
| System               |                             |                             |

The typical floor plan of project YL is shown in Figure 2. and the typical floor plan of project LJ is shown in Figure 3. The rooms marked with room number represent placement of indoor environmental quality monitoring device in the room.

![Figure 2. Typical floor plan of project YL.](image)

![Figure 3. Typical floor plan of project LJ.](image)
For outdoor environmental quality monitoring, an integrated outdoor environment monitoring device called CESMS with multi-functional sensors was used which can collect outdoor temperature and relative humidity, wind speed, wind direction, SO₂, NO₂, PM₂.₅, noise with 5 min sensing intervals. The outdoor environment monitoring device were installed on the lighting poles of site boundaries at a height of about 2.5 m. The measured range and accuracy of CESMS sensors are listed in Table 5. For indoor environmental quality monitoring, an integrated indoor environment monitoring device called IBEM with multi-functional sensors was used which can collect indoor temperature and relative humidity, CO₂, PM₂.₅, and illuminance data in 5 min sensing intervals. The indoor environment monitoring devices were installed on the central desks of offices. The measured range and accuracy of IBEM sensors are listed in Table 6.

Table 5. The measured range and accuracy of CESMS sensors.

| Measured Parameter | Range       | Accuracy  |
|--------------------|-------------|-----------|
| Temperature        | −40–80 °C   | ± 0.3 °C  |
| Relative Humidity  | 0–99.9%     | ± 2%      |
| PM₂.₅              | 0–1000 μg/m³| ± 10%     |
| SO₂                | 1–500 ppm   | ± 3%      |
| NO₂                | 1–500 ppm   | ± 3%      |
| Wind Direction     | 0–360°      | ± 1°      |
| Wind speed         | 0–70 m/s    | ± 0.3 m/s |
| Noise              | 20–130 dB   | ± 1.5 dB  |

Table 6. The measured range and accuracy of IBEM sensors.

| Measured Parameter | Range       | Accuracy  |
|--------------------|-------------|-----------|
| Temperature        | −40–80 °C   | ± 0.5 °C  |
| Relative Humidity  | 0–99%       | ± 5%      |
| PM₂.₅              | 0–1000 μg/m³| ± 10%     |
| CO₂                | 0–500 ppm   | ± 75 ppm  |
| Illuminance        | 0–5000 lux  | ± 5%      |

The CESMS and IBEM sensors have been calibrated and examined by China National Institute of Metrology and the reliability for long-term monitoring can be guaranteed according to the corresponding national standards of China. For other indicators monitoring such as HVAC, P&D, Renewable energy system, and User behavior, the conventional remote transmission meters and sensors were installed and will not be further described in this paper. Since the two projects have been put into use, according to the “S” (Specific) in the SMART principle, and the actual situation of the projects, the dynamic monitoring data for part of green KPIs were collected and listed in Table 7.

Table 7. The KPI obtained of two projects for case study.

| No. | KPI                                           | Project YL | Project LJ |
|-----|----------------------------------------------|------------|------------|
| 1   | Outdoor air quality                          | ●          | ●          |
| 2   | Outdoor acoustic environment quality          | ●          | ●          |
| 3   | Heat island indicators                        | ●          | ●          |
| 4   | Indoor light environment quality              | ●          | ●          |
| 5   | Indoor thermal environment quality            | ●          | ●          |
| 6   | Indoor air quality                            | ●          | ●          |
| 7   | Cooling source system energy efficiency       | ●          | ●          |
|     | coefficient (SCOP)                            | ●          | ●          |
| 8   | Pump power consumption cooling (heat) load    | ●          | ●          |
|     | ratio                                         | ●          | ●          |
| 9   | Non-potable water source utilization rate     | — —        | ●          |
| 10  | Occupancy status                              | ●          | ●          |
This paper takes the monitoring data of the typical working week of two office buildings in the cooling season (July 31, 2017 to August 4, 2017) as an example, the KPI monitoring data involved in the two projects are comparatively analyzed, and also compared with the values of national standards.

3. Results

3.1. Establishment of Green Building Operations Monitoring Indicators Library

3.1.1. Initial Proposal of Indicators by Standards and Regulation Induction

According to the method of standards and regulation incorporation, seven primary indicators and 36 secondary indicators were introduced based on two standards, CSUS/GBC 05-2014 (“Green Building Inspection Technical Standards”) and GB/T 50378-2014 (“Assessment standard for green building”). The indicators are listed in Table 8.

| Primary Indicators | Secondary Indicators |
|--------------------|----------------------|
| Outdoor environmental quality | Soil radon concentration |
| | Electromagnetic radiation around buildings |
| | Sewage discharge from construction site |
| | Outdoor lighting pollution |
| | Outdoor air quality |
| | Outdoor acoustic environment quality |
| | Heat island index |
| | Outdoor wind environment quality |
| Indoor environmental quality | Indoor light environment quality |
| | Indoor acoustic environment quality |
| | Indoor thermal environment quality |
| | Indoor air quality |
| | Indoor natural light environmental quality |
| Artificial lighting and electrical system | Lighting power density |
| | Lighting glare |
| | Submetering verification |
| Building envelope | Thermal performance of building envelope |
| | Air tightness of window |
| HVAC system | Water-cooled chiller coefficient of performance (COP) |
| | Cooling source system energy efficiency coefficient (SCOP) |
| | Chilled water system supply and return temperature difference |

Note: “●” means the data of indicator was monitored.
Because of this, the two principles proposed in Section 2.1.2, 10 secondary indicators were eliminated. Because all the secondary indicators of “artificial lighting and electrical system” and “building envelope” were eliminated, these two primary indicators were also eliminated. The eliminated indicators are listed in Table 9.

**Table 9. Estimated indicators based on the two principles proposed in the section 2.1.2.**

| Primary Indicators                           | Eliminated Secondary Indicators                                      |
|---------------------------------------------|---------------------------------------------------------------------|
| Outdoor environmental quality               | Soil radon concentration                                              |
| Indoor environmental quality                | Electromagnetic radiation around buildings                           |
| Artificial lighting and electrical system   | Sewage discharge from construction site                              |
| Building envelope                           | Indoor natural light environmental quality                           |
| Plumbing and drainage system                | Lighting power density                                               |
|                                             | Lighting glare                                                      |
|                                             | Submetering verification                                             |
|                                             | Thermal performance of building envelope                            |
|                                             | Air tightness of window                                              |
|                                             | Terminal water pressure                                             |

3.1.3. Supplementary Indicators

Based on a literature research using the key words “green building”, “operating performance”, “post-occupancy evaluation”, and “operation monitoring”, the most researched aspects appeared to be building energy consumption and indoor environmental quality. The indicators in terms of IEQ were proposed in the initially established library of this study. For building performance evaluation, energy saving is considered one of the most important aspects and the initial driving factor for the development of green buildings. Energy-saving designs are involved largest credits in nearly all evaluation standards of green building. The total building energy consumption monitored or collected mainly includes electricity [36], water [37], and gas [38]. Thus, the indicators of “Electricity consumption”, “Water consumption”, and “Gas consumption” were added to the library.

With the rapid development of China’s green buildings, more and more researchers have investigated the green buildings’ actual energy consumption in China. Apart from monitoring the total energy consumption, Jing et al. [13] analyzed the energy breakdown of 30 Hong Kong office buildings and concluded that, HVAC systems consumed 68% of the total energy consumption,
lighting systems consumed 14%, and 18% for other systems. Therefore, more attention needs to be paid to the energy consumption of HVAC and artificial lighting systems to save more energy specifically. Thus, the indicators of “HVAC system power consumption” and “Lighting system power consumption” were added to the library.

According to the analysis presented in Section 2.1.3, the users’ behaviors have very significant impact on the building energy consumption and the indoor environmental quality. The users’ behaviors during the operation of the building mainly include the occupancy status [39], air conditioners [40], lamps [41], control behavior of the doors and windows [42], and curtains [43].

After supplementing the indicators related to the building energy consumption and user behavior, this study proposed a finalized green building operations monitoring indicators library. This library includes seven primary indicators and 38 secondary indicators of green building operations monitoring. The library and its monitoring parameters are shown in Table 10.

| Primary Indicators                        | Secondary Indicators                                      | Monitoring Parameters                                                                 |
|-------------------------------------------|----------------------------------------------------------|----------------------------------------------------------------------------------------|
| Outdoor environmental quality             | Outdoor air quality                                       | Outdoor SO₂, NO₂, PM₂.₅ concentration                                                 |
|                                           | Outdoor acoustic environment quality                      | Outdoor noise                                                                          |
|                                           | Heat island index                                         | Outdoor temperature                                                                    |
|                                           | Outdoor wind environment quality                         | Outdoor pedestrian zone wind speed                                                     |
| Indoor environmental quality              | Indoor light environment quality                          | Indoor illumination                                                                    |
|                                           | Indoor acoustic environment quality                       | Indoor noise                                                                           |
|                                           | Indoor thermal environment quality                        | Indoor temperature and humidity                                                        |
|                                           | Indoor air quality                                        | Indoor formaldehyde, TVOC, PM₂.₅, CO₂ concentration                                     |
|                                           | Water-cooled chiller coefficient of performance (COP)     | Chilled water supply and return temperature, Chilled water flow rate, input power     |
|                                           | Cooling source system energy efficiency coefficient (SCOP) | Condensing water pump input power, cooling tower input power, chiller input power, chiller input power, chilled water supply and return temperature, chilled water flow rate |
|                                           | Chilled water system supply and return temperature difference | Chilled water system main pipe supply temperature, return temperature              |
| HVAC system                               | Pump efficiency                                          | Pump inlet and outlet pressure, flow rate, input power                                 |
|                                           | AC system total air volume                                | Air handling, fresh air unit total air volume                                           |
|                                           | Branch air volume                                         | Air volume of each branch of air handling and fresh air system                        |
|                                           | Air system balance                                       | Air volume of each branch of air handling and fresh air system                        |
|                                           | Fan power consumption per air volume                      | Fan input power, air volume                                                            |
|                                           | Fresh air volume                                         | Air volume of unit                                                                     |
|                                           | Boiler thermal efficiency                                 | Fuel consumption, hot water flow rate, supply and return water temperature             |
|                                           | Pump power consumption cooling (heat) load ratio          | System cooling (heat) load and pump input power                                       |
|                                           | Heat recovery efficiency of PAU                           | Fresh air in/out air dry and wet bulb temperature, exhaust air dry and wet bulb temperature |
|                                           | Annual average energy comprehensive utilization           | Annual total heat of waste heat supply, annual total cooling of waste heat supply, annual net output electricity and fuel consumption |
| Plumbing and drainage system | Building pipeline leakage rate | Total water intake, water consumption of each branch |
|-----------------------------|-------------------------------|--------------------------------------------------|
| Non-potable water source utilization rate | Non-potable water source consumption, potable water total water intake quantity |
| Water quality | Supply water, drainage water, and non-potable water |

| Renewable energy system | Renewable energy utilization rate |
|-------------------------|----------------------------------|
| Solar water heating system: total heat supply, solar hot water tank for heat |
| Photovoltaic power generation system: total electricity production, building electricity consumption |
| Ground source heat pump system: total cooling (heating) supply, ground source heat pump unit cooling (heating) supply |
| Air source heat pump system: total heat supply for domestic hot water, heat supply for air source heat pump unit |

| Total resource consumption | Electricity consumption | Total electricity consumption per building area |
|---------------------------|------------------------|-------------------------------------------------|
| Water consumption | Total water consumption per building area |
| Gas consumption | Total gas consumption per building area |
| Lighting system power consumption | Total power consumption of the lighting system per building area |
| HVAC system power consumption | Total power consumption of HVAC system per building area |

| User behavior | Occupancy status | Whether the staff is in the room |
|---------------|------------------|---------------------------------|
| Window open status | Whether the window is open |
| Door open status | Whether the door is open |
| Lighting status | Whether the lighting is turned on |
| Sunshade status | Whether the sunshade is closed |
| AC terminal status | Whether the AC terminal is turned on |
| AC terminal room temperature setting | AC terminal temperature setting |
| AC terminal air speed setting | High, medium and low setting |

3.2. Selection of KPIs for Green Building Operations Monitoring

Twenty experts of green building industry were asked to score each secondary indicator from three aspects (relevance, accessibility, and measurability) using a scale of 1 to 5. The average scores for the three aspects of each indicator were calculated, and rounded to the nearest integer. Then the total score for each secondary indicator was summed up, and the results are listed in Table 11.

According to the scores obtained for each secondary indicator by the Delphi method, the total scores of 27 indicators were greater than nine points, while 11 indicators had scores equal to or less than nine points. The finalized green building operation monitoring KPIs, comprising seven primary indicators and 27 secondary indicators, are shown in Figure 4.
Table 11. Average score results (round to the nearest integer) of each aspect and total scores for secondary indicators according to twenty green building experts’ knowledge and experiences.

| Primary Indicators        | Secondary Indicators                               | Average Score of Relevance | Average Score of Accessibility | Average Score of Measurability | Total Score |
|---------------------------|----------------------------------------------------|----------------------------|--------------------------------|--------------------------------|-------------|
| Outdoor environmental quality | Outdoor air quality                               | 3                          | 5                              | 3                              | 11          |
|                           | Outdoor acoustic environment quality               | 3                          | 5                              | 5                              | 13          |
|                           | Heat island index                                 | 3                          | 3                              | 5                              | 11          |
|                           | Outdoor wind environment quality                  | 3                          | 2                              | 5                              | 10          |
| Indoor environmental quality | Indoor light environment quality                  | 4                          | 4                              | 4                              | 12          |
|                           | Indoor acoustic environment quality               | 4                          | 5                              | 4                              | 13          |
|                           | Indoor thermal environment quality                | 5                          | 5                              | 5                              | 15          |
|                           | Indoor air quality                                | 5                          | 4                              | 3                              | 12          |
| HVAC system               | Water-cooled chiller coefficient of performance (COP) | 3                          | 3                              | 3                              | 9           |
|                           | Cooling source system energy efficiency coefficient (SCOP) | 4                          | 4                              | 3                              | 11          |
|                           | Chilled water system supply and return temperature difference | 1                          | 4                              | 4                              | 9           |
|                           | Pump efficiency                                   | 3                          | 3                              | 2                              | 8           |
|                           | AC system total air volume                        | 1                          | 2                              | 2                              | 5           |
|                           | Branch air volume                                 | 2                          | 2                              | 2                              | 6           |
|                           | Air system balance                                | 2                          | 2                              | 1                              | 5           |
|                           | Fan power consumption per air volume              | 4                          | 2                              | 1                              | 7           |
|                           | Fresh air volume                                  | 4                          | 3                              | 2                              | 9           |
|                           | Boiler thermal efficiency                         | 5                          | 3                              | 3                              | 11          |
|                           | Pump power consumption cooling (heat) load ratio  | 4                          | 3                              | 3                              | 10          |
|                           | Heat recovery efficiency of PAU                   | 4                          | 3                              | 3                              | 10          |
|                           | Annual average energy comprehensive               | 3                          | 3                              | 4                              | 10          |
utilization efficiency of combined heat and power cooling system

| Plumbing and drainage system | | | |
|-----------------------------|---|---|---|
| Building pipeline leakage rate | 4 | 3 | 3 | 10 |
| Non-potable water source utilization rate | 4 | 4 | 4 | 12 |
| Water quality | 5 | 1 | 1 | 7 |

| Renewable energy system | | | |
|-------------------------|---|---|---|
| Renewable energy utilization rate | 4 | 4 | 3 | 11 |

| Total resource consumption | | | |
|----------------------------|---|---|---|
| Electricity consumption | 5 | 5 | 5 | 15 |
| Water consumption | 4 | 5 | 5 | 14 |
| Gas consumption | 5 | 2 | 3 | 10 |
| Lighting system power consumption | 4 | 5 | 5 | 14 |
| HVAC system power consumption | 5 | 5 | 5 | 15 |

| User behavior | | | |
|---------------|---|---|---|
| Occupancy status | 4 | 4 | 5 | 13 |
| Window open status | 4 | 3 | 3 | 10 |
| Door open status | 4 | 3 | 3 | 10 |
| Lighting status | 4 | 1 | 3 | 8 |
| Sunshade status | 2 | 1 | 3 | 6 |
| AC terminal status | 3 | 4 | 3 | 10 |
| AC terminal room temperature setting | 4 | 3 | 3 | 10 |

| AC terminal air speed setting | 4 | 3 | 3 | 10 |

**Figure 4.** Key Performance Indicators (KPIs) for green building operations monitoring.

### 3.3. Case study of KPIs for green Building Operations Monitoring

#### 3.3.1. Evaluation Results Using Monitoring Data of Conventional Indicators

The conventional indicators mainly include energy performance and IEQ [12], the monitoring data of the two projects during the week of cooling season (July 31, 2017 to August 4, 2017) was firstly compared regarding conventional indicators. The evaluation results are listed in Table 12.
Table 12. The monitoring data of conventional indicators for two case projects.

| Primary Indicators | Secondary Indicators | Monitoring Parameters | Project YL | Project LJ | Unit | Difference Ratio |
|--------------------|----------------------|-----------------------|------------|------------|------|------------------|
| Total Resource Consumption | Electricity consumption per building area | Total electricity consumption per building area | 1.348 | 1.413 | kWh/m² | 4.8% |
| | Lighting system power consumption per building area | Lighting system power consumption per building area | 0.096 | 0.098 | kWh/m² | 2.1% |
| | Air conditioning system power consumption per building area | Air conditioning system power consumption per building area | 1.059 | 1.086 | kWh/m² | 2.5% |
| Indoor Environmental Quality | Indoor light environment quality | Average value of indoor illumination level | 220 | 211 | Lux | 4.1% |
| | | Average value of outdoor NO₂ concentration | 82 | 60 | µg/m³ | 26.8% |
| | | Average value of outdoor SO₂ concentration | 74 | 56 | µg/m³ | 24.3% |
| | | Average value of outdoor PM₂.₅ concentration | 59 | 54 | µg/m³ | 8.5% |

3.3.2. Evaluation Results Using Monitoring Data of Key Performance Indicators in This Paper

Apart from the indicators of Total Resource Consumption and Indoor Environmental Quality, monitoring data of other key performance indicators such as Outdoor Environmental Quality, HVAC system, User behavior also collected and compared, the results are listed in Table 13.

Table 13. The monitoring data of other key performance indicators for two case projects.

| Primary Indicators | Secondary Indicators | Monitoring Parameters | Project YL | Project LJ | Unit | Difference Ratio |
|--------------------|----------------------|-----------------------|------------|------------|------|------------------|
| Outdoor Environmental Quality | Outdoor air quality | Average value of outdoor NO₂ | 82 | 60 | µg/m³ | 26.8% |
| | | Average value of outdoor SO₂ | 74 | 56 | µg/m³ | 24.3% |
| | | Average value of outdoor PM₂.₅ | 59 | 54 | µg/m³ | 8.5% |
| | Outdoor acoustic environment quality | Average value of outdoor noise level | 56 | 48 | dB | 14.3% |
| Heat island indicators | Average value of outdoor temperature | 37 | 36 | °C | 2.7% |
|------------------------|-------------------------------------|----|----|----|------|
| Cooling source system  | Average value of SCOP               | 3.73 | 3.36 | — | 9.9% |
| HVAC system            |                                     |     |     |    |      |
| Pump power consumption | Average value of Pump power         | 0.045 | 0.061 | — | 35.6% |
| cooling (heat) load    | consumption cooling (heat) load     |     |     |    |      |
| ratio                  | ratio                               |     |     |    |      |
| Occupancy status       | Average value of occupancy rate     | 82 | 64 | % | 22.0% |
| User behavior          | Window open status                  | 38 | 27 | % | 28.9% |
|                        | Average value of window opening rate|     |     |    |      |
| Door open status       | Average value of door opening rate  | 85 | 65 | % | 23.5% |

3.3.3. Analysis of Evaluation Results

As it is shown in Table 12, if the evaluation was conducted only using conventional indicators (Total Resource Consumption and Indoor Environmental Quality), the operational performance of the two projects would be considered very close, because the difference ratios for the two projects in terms of the conventional indicators are no more than 5%. However, if more key performance indicators such as Outdoor Environmental Quality, HVAC system, User behavior introduced for evaluation, the conclusion would be contradictory, because most of the difference ratios for the two projects in terms of the other key performance indicators are significant in [13. For example, although the indoor environmental quality of YL is slightly better than LJ, the outdoor environmental quality of YL is worse than LJ for 8.5%–26.8%. The average value of occupancy rate, window opening rate and door opening rate of YL are all significantly larger than LJ, which means much more cooling load will be generated from the offices in YL, whereas the air conditioning system power consumption per building area of YL is lower than LJ, which can be inferred that the operational performance of air conditioning system of LJ needs to be optimized more urgently. The monitoring data of HVAC system for the two projects also can prove the inference. Therefore, it is necessary to apply a set of key performance indicators (KPIs) for green building operations monitoring, that is more comprehensive and systematic than the conventional monitoring studies, and will provide a whole picture for operational performance of green building.

4. Discussion

4.1. Universality of the Methodology

Although this study initially established an indicators library for operations monitoring of green building based on Chinese green building standards. The method of proposal and elimination of
indicators by standards and regulations induction can be applied to other areas around the world. Firstly, the researcher should select the most relevant local standards and regulations in terms of operation stage for green building. The method of incorporation of standards and regulation can be used to initially propose a local indicators library. Secondly, the two principles proposed in section 2.1.2 in this paper can be introduced to eliminate the less relevant indicators for green building operations monitoring.

As for the supplementary indicators, as discussed in the above section, the indicator in terms of occupant satisfaction is not adapted to China’s national conditions at the present stage. However, it is suggested to supplement the indicator of occupant satisfaction to the key performance indicators of green buildings for the developed regions, such as North America, Europe and Japan.

In terms of selection of KPIs for green building operations monitoring, local experts with different background (include but not limit to research, design, consulting, monitoring and management of green building) should be carefully chosen. Based on the SMART principle proposed in section 2.2 of this paper, the local experts can screen the key performance indicators most adapted to local development conditions of green building.

4.2. Limitations and Future Works

This study mainly focused on the establishment process of key performance indicators for green building operations monitoring. The methodology can be used for other researchers to propose KPIs according to local development situation and preference of green building. However, there are still some limitations of this work.

Firstly, how to utilize the key performance indicators proposed in this study for overall assessment of green building operation should be studied in the future. For example, the assessment method of the LEED [7] and BREEAM [8] standard is assigning the credits different scores, and accumulating the scores directly for an overall evaluation score. While the assessment method of the Assessment standard for green building in China [10] is accumulating the scores with different weights. The assessment method of CASBEE standard [9] is relatively complex, the overall evaluation result defined as Built Environment Efficiency (BEE). The value of BEE is calculated from the Environmental Quality of Building (Q) score divided by the Environmental Load of Building (LR) score. Accordingly, the indicators of CASBEE have been incorporated into two categories, which are Q and LR. There are strengths and weakness for different methods. Method selection for overall evaluation of KPIs for green building operations monitoring needs to be further studied in the future. Subsequently, to obtain an overall evaluation result, the weight (or specific score) for each key performance indicator needs to assign reasonably. According to the SMART principle, it is strongly recommended that the management team of building to specifically assign weights for KPIs considering the building operations condition and user demands.

Secondly, the indicators in terms of user behaviors cannot be used for evaluating the building operations performance directly. However, the conjoint analysis method between monitoring data of user behaviors and other indicators (building energy performance, HVAC system, IEQ, etc.) could be further studied to further reveal the practical values of indicators regarding user behaviors. For example, several typical behavior patterns can be classified, such as “energy efficient behavior pattern”, “normal behavior pattern”, “energy wasting behavior pattern”, to explore the detailed relationship behind monitoring data of user behavior and building energy performance. Moreover, the relationship between window (door)-opening behaviors and indoor air quality and thermal comfort might be adverse. The window or door kept opening may improve the indoor air quality, yet would make the indoor temperature and humidity rather difficult to be controlled in a comfortable range. How to take advantage of monitoring data of user behavior indicators to improve the indoor environmental quality comprehensively should be studied in the future.

5. Conclusions

This study established an indicators library for operations monitoring of green building based on relevant standards and literature review in this field. “SMART” principle and the Delphi method
were adopted to select and propose a more comprehensive and systematic KPIs more practical and efficient than the evaluation standards, and also more comprehensive and systematic than the conventional monitoring studies for operational performance of green building. Subsequently, two projects in China were selected for case study of key performance indicators for green building operations monitoring to validate the feasibility and advancement. Based on the analyses, the following conclusions may be drawn:

1. The KPIs for green building operations monitoring proposed in this study give consideration to both integrity and flexibility, and can be applied to different green buildings. They can contribute to intuitive understanding of green building operation status for the building owner, management team, and especially, the building users.
2. The monitoring data of the KPIs can be utilized for preliminary evaluation of the building performance, which can provide foundation for further specific diagnosis.
3. The KPIs can provide some enlightenment and reference for systematic evaluation of the “green degree” of green building operations and improvement of the green building operations performance.

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