Implementation of energy conservation in a commercial building using BEM and sub-metering technology

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Abstract. In the whole life cycle of buildings, proper building energy management is important to achieve energy efficiency. In this research, Building Energy Model (BEM) was used to analyze the energy consumption of a hotel building. The BEM of the building with information of the HVAC system was established to simulate the energy consumption. The performance of the HVAC system was measured using the sub-metering technology. The comparison between the simulation results and the measured performance revealed several problems of the HVAC system in operation, including unreasonable setpoint temperature of the chilled water and a small temperature difference between the supplied and returned chilled water. The BEM was adjusted to take into account the real operational load. Finally, an optimal setpoint temperature schedule of the chilled water was proposed to reduce the operational energy consumption of the HVAC system.

1. Introduction
With the increase of numbers of commercial buildings, the phenomena of the unreasonable energy consumption become more and more serious. Therefore, it is of great significance to reduce inappropriate energy consumption in the operation management. The methods for significant savings in building energy consumption are typically guided by analysis through building energy simulation. However, due to the lack of field measured data, the building energy simulation model may not be accurate enough. It is important to calibrate the parameters before applying them in simulation (Yuan et al. 2017). Chen et al. (2018) claimed that some well-accepted simulation methods had high uncertainty, and the key variables of simulation should be monitored by sub-metering to continuously improve the building energy performance. Li et al. (2014) used the energy sub-metering platform for energy conservation in public buildings. In order to improve the fidelity in evaluating the performance of energy conservation optimization, Yang et al. (2016) used the Particle Swarm Optimization to calibrate building energy model. There is no doubt that establishing an accurate building energy model is a key step for the analysis of energy consumption. Tian et al. (2016) obtained the simulated energy consumption for the purpose of finding the optimal method in design stage, using EnergyPlus and Dakota. This paper proposes a method to calibrate building energy model by using sub-metering technology. And then the adjusted model is used for simulation in operation stage with the integration of EnergyPlus and Dakota.
2. Materials and methods

2.1. Experimental architecture
A certain hotel building, which is located in Yangzhou, Jiangsu Province (32°23′ N, 119°25′ E), has a building area of 45402.56 m² and a story number of 14 above and 1 below. This commercial building mainly undertakes the tasks of accommodation, meeting and banquet, and the details of the room function in each floor are shown in table 1 below.

| Floor | Room function                                      |
|-------|---------------------------------------------------|
| -1F   | Dining hall, bathroom, switching room, air-conditioning control room |
| 1F    | Lobby, dining hall, meeting room                  |
| 2F    | Dining hall, VIP room, kitchen                    |
| 3F    | Chinese restaurant, fitness room, swimming pool   |
| 4F    | Offices                                           |
| 5F-14F| Guest rooms                                       |

Table 1. The room function in each floor.

Yangzhou experiences four distinct seasons, with hot summers and cold winters. Data from the Chinese Standard Weather Data show that in summer, the outdoor calculation dry bulb temperature is 32.8°C, and wet bulb temperature is 28.5°C. The air-conditioning system of experimental architecture is river water source heat pump system. The system contains two water source heat pump units, and through field research, only one of them is used every time.

2.2. Building energy model (BEM)
The SketchUp was used to draw the three-dimensional model of the experimental architecture. The accuracy of this model is fairly high. However, it need not be such accurate in the energy consumption simulation. The model can be simplified by only reserving the key information such as floor, interior wall, exterior wall, roof and shading, while deleting other irrelevant information. Figure 1(a) shows the architectural rendering of the hotel building, and figure 1(b) demonstrates three-dimensional model diagram of the target building.

![Figure 1](image1.png)

Figure 1. Diagrams of the experimental architecture: (a) architectural rendering; (b) three-dimensional model diagram.

Then, the three-dimensional model was imported into the software OpenStudio. In the OpenStudio, the elements of the building, such as building materials and systems were defined, and the rooms with the similar thermal status (similar temperature and humidity) were grouped into the same thermal zone. After establishing the thermal zones, the occupant density and the equipment power were input into the model. The operation schedule is also a critical part, and it contains personal activity schedule, equipment operation schedule, refrigeration operation schedule, and heating operation schedule.

Finally, the software OpenStudio called the engine EnergyPlus for energy consumption calculation. The information, such as total annual electricity/gas consumption, peak electricity consumption, and
the power of electrical appliance were obtained. At this moment, the Building Energy Model (BEM) was finished.

2.3. Data collection using sub-metering technology
Ten types of operating parameters were selected as the measured objects: electric voltage, electric current, electric power, electricity consumption, the supply/return temperature of the chilled/cooling water, and the flow of chilled/cooling water. The information of the electricity was measured by installing data collectors on the experimental architecture’s power distribution cabinet. The temperature and the flow of the chilled/cooling water were collected by temperature sensor and flow sensor, respectively. Then, all these data were stored into the database which was set up by MySQL. The data would be displayed on a website which had already been built by Javascript. In fact, there are various kinds of data which are measured by sub-metering technology, and this paper only discusses ten types of data mentioned above.

2.4. Adjustments of BEM
As there is often a difference between the actual operating condition and the design condition, the BEM needs an appropriate adjustment for the purpose of conducting a more accurate energy consumption analysis. The parameters, such as materials of building envelope, building height and building area, are fixed and need no adjustments. However, the parameters, such as occupant density and operation schedule, need adjustments to match the actual condition. The coincidence factor was used to calibrate the occupant density (table 2) and the operating schedule was replaced with the actual one. According to the field research, the coincidence factor for room I (VIP room, guest room, meeting room, office) and room II (dining room, fitness room, corridor) was depend on the room usage rate and area usage rate, respectively.

Table 2. Occupant density before/after adjustment of different rooms.

| Room function | Occupant density before adjustment (people/m²) | Coincidence factor | Occupant density after adjustment (people/m²) |
|---------------|-----------------------------------------------|--------------------|---------------------------------------------|
| VIP room      | 0.2                                           | 20%                | 0.04                                        |
| Guest room    | 0.08                                          | 20%                | 0.016                                       |
| Meeting room  | 0.5                                           | 20%                | 0.1                                         |
| Office        | 0.1                                           | 60%                | 0.06                                        |
| Dining hall   | 0.5                                           | 20%                | 0.1                                         |
| Fitness room  | 0.7                                           | 40%                | 0.28                                        |
| Corridor      | 0.1                                           | 30%                | 0.03                                        |

Figure 2. Value difference: (a) before adjustment; (b) after adjustment.
The electricity consumption was used to verify the accuracy of the adjustment. Figure 2(a) shows the value difference between simulated and measured data before adjustment, and figure 2(b) shows the value difference after adjustment. After adjustments, the total simulated electricity consumption (Jan-Aug, 2017) ES is 2781041 kWh, and the total measured electricity consumption (Jan-Aug, 2017) EM is 2534037 kWh. The relative error $\varepsilon$ is:

$$\varepsilon = \frac{(E_S - E_M)}{E_M}$$  \hspace{1cm} (1)

The relative error $\varepsilon$ is 9.7%, less than 10% and the adjustment for the parameters of BEM could be thought rational.

2.5. Simulation for energy consumption

The adjusted BEM was used for simulation to obtain the optimal setpoint temperature schedule of the chilled water. The integrated computation based on Dakota and EnergyPlus and Evolutionary Algorithms were used for the simulation. The objective function was established based on the operating cost $M$ and the thermal comfort $PMV$ (-3~+3), as shown in equations (2)-(5) below:

$$F = \min \left( M + w_{PMV} \cdot \sum_{t=1}^{24} PMV^2 \right)$$  \hspace{1cm} (2)

$$M = \sum_{t=1}^{24} \left( P_{ch,t} + P_{eb,t} + P_{cb,t} + P_{ee,t} \right) \times m_t$$  \hspace{1cm} (3)

$$w_{PMV} = \frac{\max(M_1,M_2,...,M_{24}) - \min(M_1,M_2,...,M_{24})}{R_{max} - R_{min}}$$  \hspace{1cm} (4)

$$R = \{PMV^2\}, \ i=1,2,...,24$$  \hspace{1cm} (5)

where $P_{ch,t}$ is the power of water source heat pump unit, kW; $P_{eb,t}$ is the power of chilled water pump, kW; $P_{cb,t}$ is the power of cooling water pump, kW; $P_{ee,t}$ is the power of air conditioning terminal, kW; $m_t$ is the time-of-use electricity price, 0.882 yuan/kWh (08:00-24:00), 0.394 yuan/kWh (00:00-08:00); $w_{PMV}$ is the correction factor.

The supply temperature of the chilled water was selected as the variable. Then, divide a day into several time periods, and define a supply temperature of chilled water in each period of time (table 3).

| Time  | 0~6 | 6~8 | 8~10 | 10~12 | 12~14 | 14~16 | 16~18 | 18~23 | 23~24 |
|-------|-----|-----|------|-------|-------|-------|-------|-------|-------|
| $T_0$ (℃) | 13  | 12  | 11   | 11    | 11    | 11    | 11    | 11    | 13    |
| $T_i$ (℃) | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ |

where the constraint condition of variable $x_i$ is:

$$7 \leq x_i \leq 13, \ i=1,2,...,9$$  \hspace{1cm} (6)

3. Results

3.1. Non-heating energy consumption index

As the experimental architecture is located in a hot summer and cold winter area, the non-heating energy consumption index is 240 kWh/(m²•a) (constraint value), according to Standards for Energy Consumption of Building (China 2016). Due to the fact that the measured electricity consumption (Jan-Aug, 2017) was 2534037 kWh, the total annual electricity consumption was estimated to be 3801056 kWh. Table 4 shows the non-heating energy consumption index of the target building.

| Building area | Total annual electricity consumption (estimated) | Non-heating energy consumption index | Constraint value |
|---------------|-------------------------------------------------|-------------------------------------|------------------|
| 45402.56 m²   | 3801056 kWh                                     | 83.7 kWh/(m²•a)                     | 240 kWh/(m²•a)   |
It is clear that the non-heating energy consumption index is far less than the constraint value. This is mainly due to the low utilization rate of the target building, which is about 30%-40%, according to the field research.

3.2. Supply/return temperature of the chilled/cooling water

Take the temperature of chilled/cooling water (August 5, 2017) as an example. Figure 3(a) shows the measured supply/return and simulated supply/return temperature of the chilled water. It was observed that the simulated supply/return temperature of chilled water were lower than the measured supply/return temperature from 00:00 to 08:00, while were close to the measured ones from 08:00 to 24:00. In addition, the temperature difference between the supply and return of chilled water was lower from 00:00 to 08:00, compared to that from 08:00 to 24:00.

Figure 3(b) shows the measured supply/return and simulated supply/return temperature of the cooling water. It was observed that the trend of the simulated temperature of cooling water was consistent of the measured ones. However, the measured supply/return temperature of cooling water were obviously higher than the simulated value, because the heat exchange from the cooling side of the units were not efficient.

![Graph](image_url)

Figure 3. The comparison between measured value and simulated value (August 5, 2017): (a) chilled water; (b) cooling water.

3.3. Optimal setpoint temperature schedule of chilled water

A typical day (August 5, 2017) was selected for energy consumption analysis after simulation. Table 5 demonstrates the optimal setpoint temperature schedule of chilled water after simulation.

| Time     | 0–6 | 6–8 | 8–10 | 10–12 | 12–14 | 14–16 | 16–18 | 18–23 | 23–24 |
|----------|-----|-----|------|-------|-------|-------|-------|-------|-------|
| T_i (℃)  | 8   | 12  | 12   | 8     | 12    | 10    | 10    | 12    | 8     |

In the typical day, the total energy consumption and total operating cost before and after optimization are shown in table 6.

| Energy consumption (kWh) | Total cost (yuan) |
|--------------------------|-------------------|
| Unit                     |                   |
| Chilled water pump       |                   |
| Cooling water pump       |                   |
| Air-conditioning terminal|                   |
| Total                    |                   |
| Before                   | 11657.2           |
| After                    | 11587.7           |
| Variation                | -69.5             |
After optimization, the energy consumption of units increased, while the energy consumption of chilled/cooling water pumps and air-conditioning terminals decreased. On the whole, the total energy consumption and total operating cost all reduced.

4. Discussion
As mentioned above, there was a lower temperature difference between the supply and return of the chilled water from 00:00 to 08:00, when the setpoint temperature of the supplied chilled water was 13℃ during this period. The high setpoint temperature of the supplied chilled water might reduce the energy consumption of the unit, however, according to the measured data, it might also cause the lower temperature difference between the supplied and returned chilled water, which resulted in the increasing flow of water pumps. This would increase the energy consumption of water pumps, and might not decrease the energy consumption of the whole system, when considering the combination of the units, pumps and the air-conditioning terminals.

In fact, considering the time-of-use electricity price, the operating cost was not very high from 00:00 to 08:00. During this period, the supply temperature of the chilled water could be set low, which would decrease the energy consumption of water pumps, or even total energy consumption. Also, this method was benefit for the thermal comfort, as it could be considered as a pre-cooling way.

This paper just took the supply temperature of the chilled water as the variable for optimization. Indeed, in the future, with the integration of EnergyPlus and Dakota, other parameters, such as building thermal parameters, room setting temperature and supply temperature of the domestic hot water (DHW), could be chosen as the variable for building energy saving simulation.

5. Conclusion
In this study, a certain hotel building in Yangzhou was selected as the experimental architecture. The software SketchUp was used to draw the three-dimensional diagram of the target building. And the model was imported to the software OpenStudio to input building information and define thermal zones. The engine EnergyPlus was called by OpenStudio for energy consumption calculation to obtain the information of the target building’s energy consumption. Sub-metering technology was used to measure various kinds of data, which could be stored in the database set up by MySQL and displayed on the website built up by Javascript. Ten types of operating parameters were selected for discussion in this paper. Then, with the use of sub-metering technology, the coincidence factor was used to adjust the occupant density and operating schedule was replaced with the actual one to make an adjustment of the BEM. With the integration of EnergyPlus and Dakota, the adjusted BEM was applied to the energy conservation operation to obtain the optimal setpoint temperature schedule of the chilled water.

The results show that the experimental architecture had a low utilization rate. The simulated supply/return temperature of chilled water were lower than the measured supply/return temperature from 00:00 to 08:00, while were close to the measured ones from 08:00 to 24:00. The measured supply/return temperature of cooling water were obviously higher than the simulated value, because the heat exchange from the cooling side of the units were not efficient. And after the simulation for energy management, an optimal setpoint temperature of the chilled water was obtained, which could decrease the total energy consumption and total operating cost. In addition, the method of this paper could be duplicated in other projects.

References
[1] Chen Z, Freihaut J, Lin B and Wang D 2018 Inverse energy model development via high-dimensional data analysis and sub-metering priority in building data monitoring ENERG BUILDINGS 172 116-24
[2] Li W, Xu P, Zhang H and Chen Y 2014 Energy saving audit method based on energy sub-metering platform of public buildings Adv. Mater. Res. 962-965 1627-30
[3] Tian Z, Chen W, Shi X and Si B 2016 Method and case analysis of integrated EnergyPlus and Dakota optimization of building energy consumption Building Technique Development 43
73-76

[4] Yuan J, Nian Y, Su B and Meng Q 2017 A simultaneous calibration and parameter ranking method for building energy models *APPL ENERG* **206** 657-66

[5] Yang T, Pan Y, Mao J, Wang Y and Huang Z 2016 An automated optimization method for calibrating building energy simulation models with measured data: Orientation and a case study *APPL ENERG* **179** 1220-31

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