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Calibrated building energy simulation and its application in a high-rise commercial building in Shanghai

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Abstract

The method of calibrated computer simulation is summarized on the basis of related literatures and guidelines. It is used to analyze the energy performance of a high-rise commercial building in Shanghai, China. DOE-2 energy model is built up with the detailed data of building and system that are collected on as-built drawings, specifications, operating records and site surveys. Model calibration is conducted on the comparison between simulation output and measured energy use. Energy model is adjusted until statistics indices are met in compliance to applicable standards and guidelines. Calibrated model is used in the performance analysis for energy conservation measures (ECMs) that are about to be implemented in the retrofitting project of the high-rise, including using variable speed chilled water pumps instead of constant variable speed ones, using free cooling during winter and mild seasons, decreasing lighting power densities. Energy saving performance is simulated and calculated to find out which ECM is the best option for the building.

Keywords: Calibrated simulation; Energy consumption; ECM

1. Introduction

Building energy simulation has been playing an increasingly significant role not only in building design, but also in operation, diagnostics, commissioning and evaluation of buildings in the last two decades. It can help designers compare various design options and lead them to energy-efficient designs in manner of cost-effectiveness. Building energy simulation can also help facility managers and engineers identify energy saving potentials and evaluate the energy performance and cost-effectiveness of ECMs (energy saving measures) to be implemented. There are many building energy simulation software available nowadays. Some are simplified energy analysis tools that only provide a quick analysis of annual energy use of buildings, but some use more detailed models and run on hourly basis that provide detailed hour-by-hour energy analysis of buildings [1]. No matter which software is used, calibration of simulation models is necessary and crucial for the accuracy and usability of energy simulation. The calibration process compares the results of the simulation with measured data and tunes the simulation until its results closely match the measured data. A number of researchers have made progress in this topic. Chimack [2] used the calibrated DOE-2 model to determine the peak cooling loads and do energy assessment of a 107-year-old science museum; Pedrini et al. [3] employed the method of simulation and calibration to model more than 15 office buildings in Brazil; Norford et al. [4] discussed the major sources of the wide discrepancy between predicted and actual energy use and in the process of simulation and calibration, they formulated calibration guidelines and developed insights that may be of use to others. Yoon et al. [5] developed a systematic method using a ‘‘base load analysis approach’’ to calibrate a building energy performance model with a combination of monthly utility billing data and sub-metered data in large buildings in Korea.

This paper introduces the method of calibrated energy simulation and presents one case study in that the method is used in analyzing the energy consumption of a high-rise commercial building in Shanghai.

2. Calibrated simulation approach

Calibrated simulation approach is defined in three standards or guidelines—ASHRAE Guideline 14-2002 [6]: Measurement

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of Energy and Demand savings, M&V Guidelines: Measurement and Verification of Federal Energy Projects (FEMP) [7], International Performance Measurement and Verification Protocol (IPMVP) [8]. Calibrated simulation is an appropriate method to measure and determine energy and demand savings of ECMs under the conditions, e.g., when whole-building metered electrical data are not available or when savings cannot be determined by measurements or when measures interact with other building systems but it is difficult to isolate the savings, etc. Calibrated simulation is also very useful, facility professionals who can benefit from the availability of a model to explore energy saving potentials as well as ECM impacts. However, calibrated simulation cannot be used under the conditions, e.g., when measures can be analyzed without simulation, or when buildings or HVAC systems cannot be readily simulated, or when the resources are not sufficient and so on.

2.1. Calibrated simulation steps

The calibrated simulation approach has the following steps.

2.1.1. Produce a calibrated simulation plan

In the preparation of a calibrated simulation plan, the baseline scenario and post-retrofit scenario have to be specified, the simulation software has to be selected, and the tolerances of calibration indices have to be checked.

2.1.2. Collect data

The data include building plans (building geometry and construction materials), operating schedules, historical utility data (a minimum 12 months, hourly data if available), information of building system components (lighting systems, plug loads, HVAC systems, building envelope and thermal mass, building occupants, other major energy-using loads) and weather data (a typical year and a specific year). On-site surveys, interviews, spot and short-term measurements, etc. could be appropriate methods to collect these data and information.

2.1.3. Input data and run model

The best guide for inputting data into a model is the manual of the simulation software selected by the simulator. In order to minimize the simulation error, the following data should be checked as input or output:

(a) Building orientation.
(b) HVAC system zoning.
(c) External surface characteristics.
(d) Lighting and plug load power densities and operating schedules.
(e) HVAC system characteristics and operating schedules.
(f) Plant equipment characteristics.

2.1.4. Calibration of simulation model

One of the following three approaches must be selected for calibration:

(a) Comparing model monthly usage predictions to monthly utility bill data.
(b) Comparing model monthly usage predictions to monthly utility bill data in combination with comparing model sub-system usage predictions to measured hourly data.
(c) Comparing model hourly usage predictions to hourly utility bill data.

2.1.5. Refine model

If the statistical indices calculated during the previous step indicate that the model is not sufficiently calibrated, revise the model inputs, run the model, and compare its prediction to the measured data again.

2.1.6. Calculate energy and demand savings

Both baseline model and post-retrofit model are run to calculate the energy and demand savings of each ECM.

2.2. Model calibration criteria

Considering the availability of utility data, the first calibration approach – calibrating with monthly utility data – is employed in this paper. For this approach, the three guidelines previous mentioned in the paper specify the acceptable tolerances for the calibration of simulation [6–8] (Table 1).

Table 1
Acceptable tolerance for monthly data calibration

Index	ASHRAE 14 (%)	IPMVP (%)	FEMP (%)
ERR_{month}	±5	±20	±15
ERR_{year}	–	–	±10
CV ($RMSE_{month}$)	±15	±5	±10

ERR: mean bias error; CV (RMSE): coefficient of variation of the root-mean-squared error.

Table 2
Characteristics of envelope

Envelope	Characteristics
External wall	U^a = 0.441 W/(m² °C)
Internal wall	U = 2.196 W/(m² °C)
Roof	U = 0.416 W/(m² °C)
Door	U = 2.675 W/(m² °C); VT^b = 0.13; SC^c = 0.22
Floor	
Ground	U = 0.143W/(m² °C)
Internal	U = 1.034W/(m² °C)
Ceiling	U = 4.229W/(m² °C)
Window	
GL-1	U = 2.675 W/(m² °C); VT = 0.13; SC = 0.22
GL-2	U = 2.675 W/(m² °C); VT = 0.35; SC = 0.44
Skylight	U = 2.677 W/(m² °C); VT = 0.08; SC = 0.13

[a] U: heat transfer coefficient.
[b] SC: shading coefficient.
[c] VT: visible transmittance.

The combination of ERR and CV (RMSE) can determine how well the model predicts whole-building energy usage. The lower the ERR and CV (RMSE), the better the calibration.

3. Building description

The building is located in Lujiazui, the CBD in Pudong New Area in Shanghai. The total building area is approximately 300,000 m^2. The tower has 88 floors above ground, with floors 3–50 consisting of office space and floors 53–87 consisting of hotel. The building was constructed in 1999. In addition, the building includes a six-story podium located adjacent to the main tower. The podium contains hotel ballrooms, an auditorium, a hotel nightclub, entertainment centers, and retail shopping areas. There are also three underground levels that contain various building support areas, e.g., food court, hotel service facilities, offices, miscellaneous equipment rooms, plant rooms, retail facilities, parking garages and so on. Miscellaneous service areas are located throughout the building. Levels 51 and 52 are mechanical equipment floors. Level 88 is a large indoor observation deck. The four penthouse levels above the 88th floor also contain mechanical equipment.

4. Model development and calibration

The model is built using visualDOE4.0 [9], which uses DOE2.1e as the simulation engine. DOE2.1e is the current version of DOE-2, a world-widely accepted detailed hour-by-hour simulation engine currently in use.

4.1. Data input and model development

The data of weather, envelop, internal loads, HVAC system, non-HVAC systems, etc. are input into the model.

4.1.1. Weather data

The typical meteorological year (TMY) data of Shanghai developed by DOE is used in the initial model running.

Table 3
Internal loads

Space	Lighting (W/m^2)		Plug (W/m^2)		Occupant (m^2/person)
	Before calibration	After calibration	Before calibration	After calibration	
Office[a]	20	12	30	15	9.2
Hotel[a]	10	15	15	5	23.23
Restaurant[a]	20	30	12	10	1.4
Lobby of office[a]	30	10	15	1	5
Lobby of hotel[a]	30	30	15	1	5
Department[a]	30	30	15	10	4.6
Auditorium[a]	10	15	10	5	5
Garage[b]	10	8	10	1	1000
Warehouse[b]	10	8	10	1	1000
Plant room[b]	20	8	30	1	1000

[a] Air-conditioned spaces with the set temperature in summer of 24 °C and that in winter of 22 °C.
[b] Non-air-conditioned spaces.

Table 4
HVAC system input data

Components	Characteristics	
	Before calibration	After calibration
Terminal system	Podium and office: fan power box system (FPB) Hotel: four pipe fan coil unit system (FCU)	
Cooling set point	24 ± 2 °C	
Heating set point	22 ± 2 °C	
Chiller	One centrifugal chiller, autosized, COP = 5.5	Eight centrifugal chillers (6 × 4220 kW: COP = 4.89, 2 × 1408 kW: COP = 4.28)
Leaving chilled water temperature	5.6 °C	6.5 °C
Cooling tower	One tower, one-speed fan, autosized	Six towers, each: 90 kW, water flow rate = 1814.4 l/s, two-speed fan, efficiency of motor = 0.9
Cooling water temperature	29.5 °C/35.1 °C	32.2 °C/37.8 °C
Chilled water secondary pump	Constant speed, H = 490 kPa, η = 0.8 (motor efficiency = 0.9)	
Gas boiler	One gas boiler, autosized, η = 0.7	η = 0.85
Hot water temperature	70 °C/53.3 °C	55 °C/45 °C
Hot water pump	Constant speed, H = 400 kPa, η = 0.8 (motor efficiency = 0.9)	

4.1.2. Envelop

Table 2 lists the characteristics data of envelope.

4.1.3. Internal loads

The internal loads including lighting, plug and occupancy and the operating schedules are specified based on the design data in the initial model (see Table 3: before calibration).

4.1.4. HVAC system and zoning

The HVAC system is input into the initial model as presented in Table 4 (before calibration). The HVAC system is shut down during non-working period (18:00–7:00) in office. The standard office space is divided into one internal zone and four perimeter zones facing south, east, north and west with the depth of 4.2 m from the external wall. Reheating coils are provided with FPBs servicing perimeter zones but are not with those servicing internal zones.

4.1.5. Outdoor air flow rate and infiltration rate

Outdoor air flow rate is set as 9.5l/s person (34.2 m^3/h person). The infiltration rate is set as 0.2 ACH when air-conditioning system operating and 0 ACH when air-conditioning system off in all spaces.

4.1.6. Non-HVAC systems

Non-HVAC systems include lighting system, office equipment, lifts and elevators, cooking facilities, laundry, swimming pool, domestic hot water, etc. Among those, the energy consumption of lighting system and office equipment is calculated using visualDOE4.0, while the others are estimated in compliance to design and site-measured data.

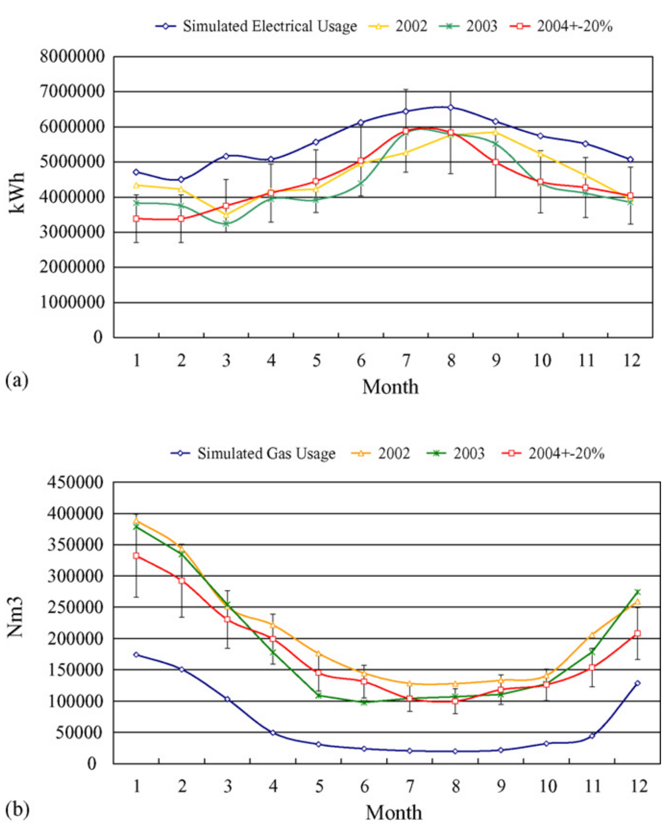

Fig. 1. (a) Electrical usages from the initial model vs. real 2002, 2003, 2004 electrical usages (±20%); (b) gas usages from the initial model vs. real 2002, 2003, 2004 gas usages (±20%).

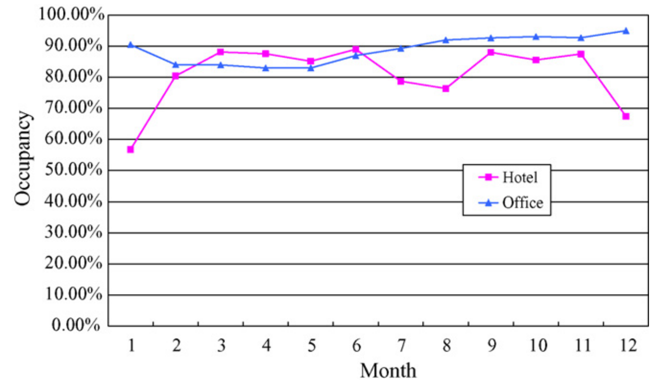

Fig. 2. Monthly average occupancy percentages of hotel and office.

4.1.7. Initial simulation results

The simulated energy consumption of HVAC system and lighting system and office equipment and the estimated energy consumption of the other building systems are summed up to the total simulated monthly energy consumption. Fig. 1 presents the initial simulation results from the running of the initial model together with the real consumption of electricity and gas in 2002, 2003 and 2004. The monthly errors are very high, mostly larger than 20%.

4.2. Model calibration

The inputs of weather data, internal loads, HVAC system, infiltration, non-HVAC systems are revised and refined for the purpose of model calibration.

4.2.1. Weather data

A real meteorological year data of the latest year (2004) instead of TMY data is used in running the calibrated model. Authors of this article have developed the actual meteorological

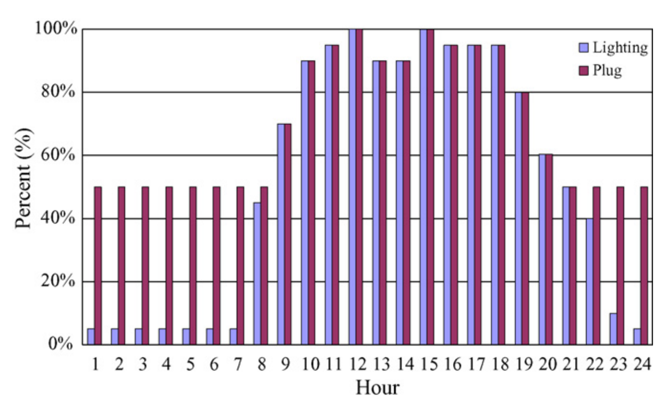

Fig. 3. Schedule of lighting and plug power densities in week days in office.

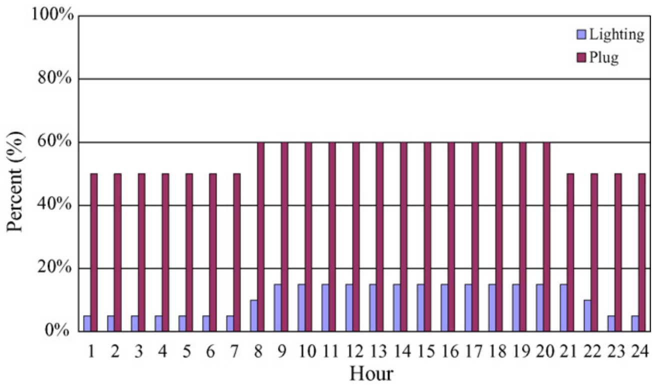

Fig. 4. Schedule of lighting and plug power densities in weekend and holidays in office.

year data of 2004 using the software they developed on themselves [10].

4.2.2. Internal loads

By analyzing the results of hour-by-hour site measurement of end-users for 24 h in 1 workday, the lighting and plug densities are tuned as listed in Table 3 (after calibration). The lighting densities in the spaces like restaurant, lobby of hotel and department are relatively high because incandescent lamps are used in these spaces due to the good color rendering property. The internal loads (lighting, plug and occupancy) fluctuate month by month according to the statistics of the facility managers (Fig. 2). Figs. 3–5 present the hourly schedule of lighting and plug power densities of office and hotel, which are also based on the 24 h recording in 1 workday. From which we can know that the lighting and plug loads during off-time are still relatively high.

4.2.3. HVAC system

The inputs are tuned for HVAC system according to the actual specifications and site measurement of system components as listed in Table 4. Moreover, based on the information obtained by surveying and discussion with facility managers, the cooling system is turned off from December 16 to April 1 and the heating system is off from May 15 to December 1. The gas consumption for humidification in winter (December,

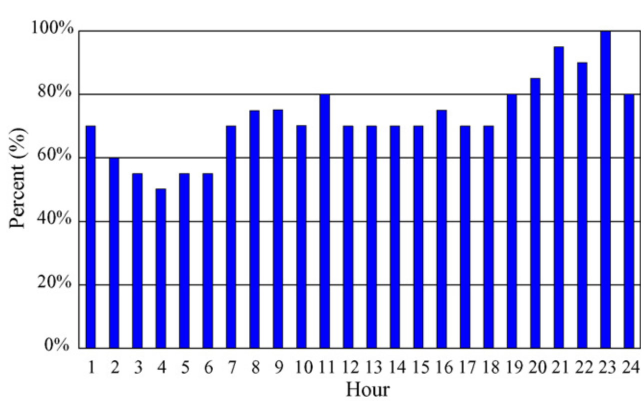

Fig. 5. Schedule of lighting and plug power densities in hotel.

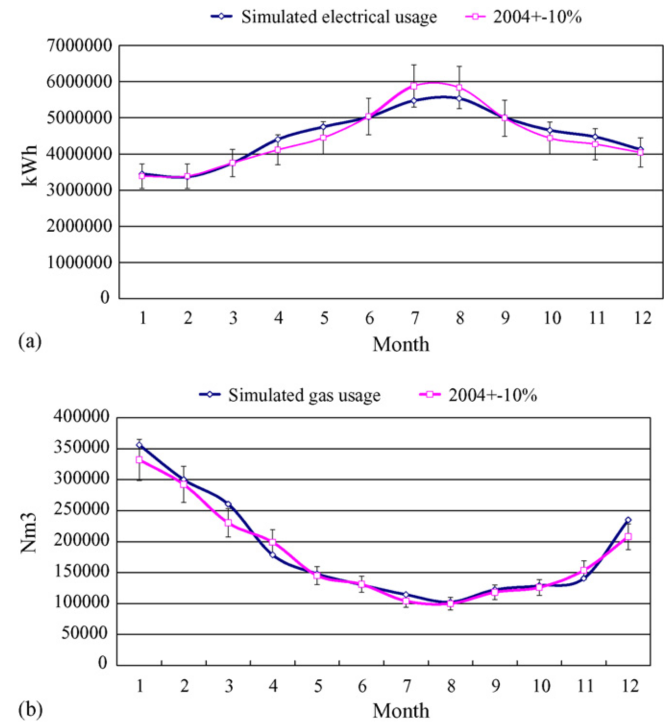

Fig. 6. (a) Electrical usages from the fourth calibrated model vs. real 2004 electrical usages (±10%); (b) natural gas usages from the fourth calibrated model vs. real 2004 gas usages (±10%).

January and February) is calculated according to the air humidity difference between indoor and outdoors.

4.2.4. Infiltration rate

Due to the good hermetical characteristic of the envelope, the infiltration rate is changed into 0ACH in the internal zones and 0.1ACH in the perimeter zones. The infiltration rate in lobbies is set as 0.2ACH.

4.2.5. Results of calibrated model

Fig. 6 shows that the simulation results of the calibrated model match well with the real 2004 energy usages.

Table 5 presents the indices of calibration, among which, the indices for electricity are completely within the acceptable tolerances specified by all of the three guidelines, while those for gas are only within the acceptable tolerances specified by FEMP but not by ASHRAE 14 and IPMVP. Table 5 also gives the indices of the initial model for comparison.

Table 5
Calibration results

Index	Electricity		Gas	
	Before calibration (%)	After calibration (%)	Before calibration (%)	After calibration (%)
ERR_{month}	±39	±7.1	±82	±13.1
ERR_{year}	±25.7	±1.2	±67.8	±3.1
CV ($RMSE_{month}$)	±24.9	±4.71	±64.4	±8.92

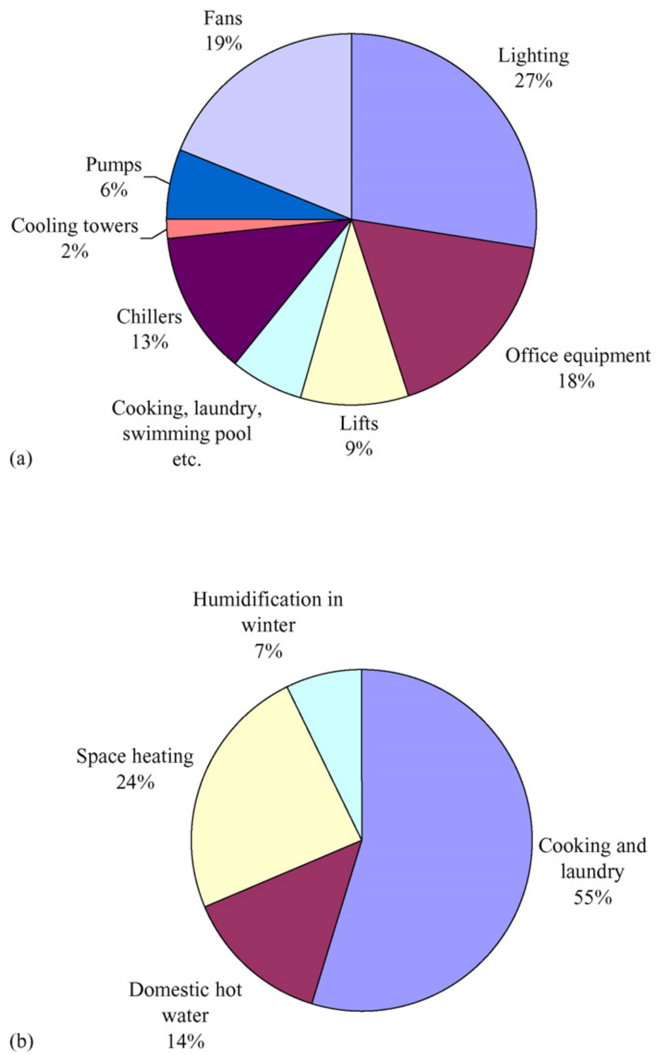

Fig. 7. (a) Annual electricity end-use breakdowns; (b) annual gas end-use breakdowns.

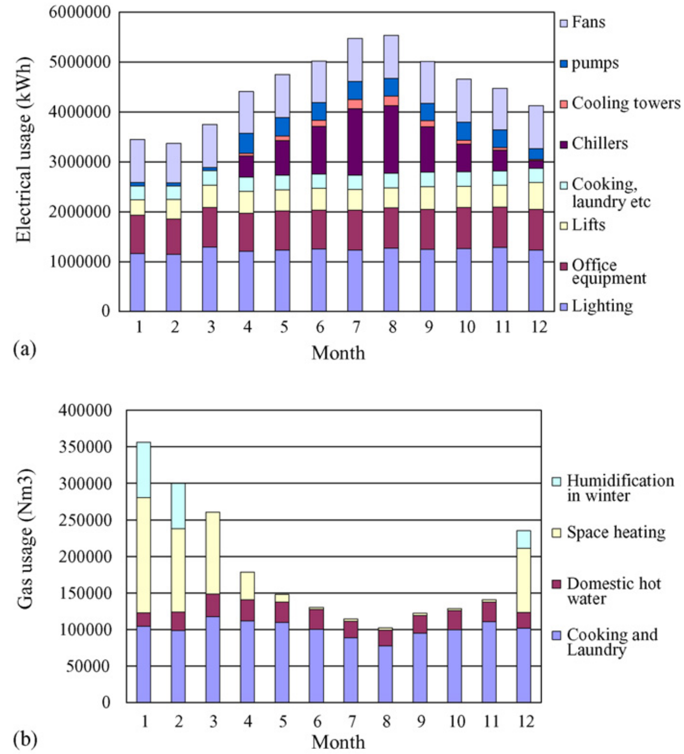

Fig. 8. (a) Monthly electricity end-use breakdowns; (b) monthly gas end-use breakdowns.

4.2.6. Error analysis

Although the simulated results can match the measured ones very well, the differences and errors exist between them. The main reasons for these errors can be analyzed as followed:

- The actual randomicity of the operating schedule of internal loads cannot be simulated exactly in the model, e.g., there will be a big increase of the occupancy in hotel if a big delegation settles down 1 day.
- Although the gas boilers supply not only domestic hot water (DHW) and space heating but also laundry and humidification, the software can only simulate the gas consumed by DHW and space heating so that consumed by laundry and humidification has to be estimated. Therefore, the gas boilers are set as "autosized" but not inputting the actual specification. This is also the main reason why the gas usage is outside acceptable tolerances specified by ASHRAE and IPMVP.
- The HVAC system components, e.g., chillers, cooling towers, pumps, fans, AHUs and FPBs are specified in the model with the design data or rated data, except for those site-testing having been taken by facility managers. However, the actual operating condition is always not the same as design or rated condition.
- Since it is very difficult to find the part-load performance characteristics of cooling towers, pumps and fans, the default values and part-load curves in DOE-2 are used in simulation.
- The chilled water of the entire building is supplied by one system in the model, while the actual building is divided into high level zone and low level zone, which are served by separate chilled water system, respectively. This may be one of the reasons why the simulated electrical usage deviates more significantly from the real electrical usage during the summer months (June and July) than the other months.

4.3. Energy end-use breakdown

With the sufficiently calibrated model, the energy end-uses are individually calculated for lighting, office equipment, cooling (chillers, cooling towers, pumps and fans), heating, humidification, domestic hot water, lifts, etc. (see Fig. 7). The largest portion of the electrical usage is space cooling, which accounts for 40% of the total energy use; the second largest portion is lighting, accounting for 27%, followed by office equipment, accounting for 18% of the total energy use. Gas end-use contains cooking and laundry (55%), space heating, humidification (31%), and domestic hot water (14%).

Fig. 8 shows that the energy end-use of lighting, office equipment, lifts, cooking and laundry facilities, domestic hot

Table 6
Energy saving of ECMs

	Electricity (kWH/m^2)			Gas (Nm^3/m^2)			Primary Energy (mJ/m^2)		
	Usage	Saving	Percent	Usage	Saving	Percent	Usage	Saving	Percent
Base case	180			7.39			1955		
ECM1	172	8	4.4	7.39	0	0	1879	76	3.9
ECM2	180	0	0	7.39	0	0	1955	0	0
ECM3	177	3	1.7	7.43	−0.04	−0.5	1927	28	1.4

water and even fans changes little month by month, which can be regarded as the fixed part of the energy end-use. The energy usage of chillers, cooling towers, pumps, space heating and humidification accounts for the flexible part of the energy end-use.

4.4. ECMs evaluation

Three ECMs are individually simulated with calibrated base case model. They are:

(1) Changing the secondary chilled water pumps and hot water pumps from constant speed into variable speed.
(2) Using free cooling in winter and mild seasons.
(3) Decreasing the lighting power density from 12 to 9.31 W/m^2 by increasing the efficiency of lighting system without sacrificing the illumination level in office (500 lx).

Energy savings of the three ECMs as shown in Table 6 are very limited. Especially ECM2 (free cooling) saves little energy due to the normally high relative humidity of outdoor air in Shanghai.

5. Conclusions

This paper has summarized the calibrated simulation as one of building energy analysis methods and employed it to simulate and analyze the energy usages of a high-rise commercial building in Shanghai. Necessary data and information of the building have been collected and measured on site as the input of models. The model has been repeatedly modified to comply with the calibration requirement. After several steps of calibration, energy model can accurately predict the actual energy usage of specific buildings.

With calibrated model, energy end-use breakdown of the building has been analyzed and displayed. Such breakdown could hardly be extracted from utility bills without necessary meters.

The calibrated model has also been used to simulate and calculate the energy savings of three possible ECMs, among which, ECM 1–changing the secondary chilled water pumps and hot water pumps from constant speed into variable speed–is the best. The results make sense with the specific characteristics of the building.

6. Nomenclature

$$\mathrm{ERR}_{\mathrm{month}}\,(\%) = \left[\frac{(M-S)_{\mathrm{month}}}{M_{\mathrm{month}}}\right] \times 100\% \quad (1)$$

$$\mathrm{ERR}_{\mathrm{year}}\,(\%) = \sum\nolimits_{\mathrm{year}}\left[\frac{\mathrm{ERR}_{\mathrm{month}}}{N_{\mathrm{month}}}\right] \quad (2)$$

where M: measured electricity (kWh) or fuel consumption; S: simulated electricity (kWh) or fuel consumption; N_{month}: number of utility bills in the year.

$$\mathrm{CV}\,(\mathrm{RSME}_{\mathrm{month}})\,(\%) = \left[\frac{\mathrm{RSME}_{\mathrm{month}}}{A_{\mathrm{month}}}\right] \times 100\%$$

$$\mathrm{RSME}_{\mathrm{month}} = \left\{\frac{\left[\sum_{\mathrm{month}}(M-S)^2_{\mathrm{month}}\right]}{N_{\mathrm{month}}}\right\}^{1/2}$$

$$A_{\mathrm{month}} = \left[\frac{\sum(M_{\mathrm{month}})}{N_{\mathrm{month}}}\right]$$

where RMSE: root-mean-squared monthly error; A_{month}: mean of the monthly utility bills.

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