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THE APPLICATION OF BUILDING ENERGY SIMULATION AND CALIBRATION IN TWO HIGH-RISE COMMERCIAL BUILDINGS IN SHANGHAI

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ABSTRACT

The method of calibrated computer simulation is summarized and introduced based on related literatures and guidelines, which is used to analyze the energy consumption of two high-rise commercial buildings in Shanghai, China. The detailed data of the buildings and systems are collected and input to build up models with DOE-2, then the output of simulation is compared to the measured energy consumption data to refine and calibrate the models. Several energy conservation measures (ECMs) are analyzed based on the calibrated models, including using variable speed chilled water pumps instead of constant variable speed ones, using free cooling during winter and mild seasons, replacing old low efficiency cooling towers with new high efficiency ones, decreasing lighting power densities. Energy saving performance is simulated and calculated to find out which ECM is the best option for each building.

INTRODUCTION

Building energy simulation plays a bigger role not only in building design, but also in the operation, diagnostics, commissioning and evaluation of buildings in the last two decades. Building energy simulation can help the designers compare various design options and lead them to more optimal and energy saving designs. Building energy simulation can also help the managers and engineers define the energy saving potentials and evaluate the energy saving effects of ECMs (energy conservation measures). There are many building energy simulation software available nowadays, among which, some are simplified energy analysis model, which can only provide a quick analysis of annual energy use of buildings, some are hourly simulation models, which can provide detailed hour-by-hour energy analysis of buildings; some are only text-based programs, some have user-friendly interfaces (P. Jacobs, 2002). No matter which software is used, the calibration of the simulation model is necessary and important 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. Michael J. Chimack et al (2001) used the calibrated DOE-2 model to determine the peak cooling loads and do energy assessment of a 107-year-old science museum; A. Pedrini, et al (2002) employed the method of simulation and calibration to model more than 15 office buildings in Brazil; L. K. Norford, et al (1994) 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. Jongho Yoon et al (2003) 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 then uses it to analyze the energy consumption of two high-rise commercial buildings in Shanghai.

CALIBRATED SIMULATION APPROCH

Calibrated simulation approach is defined in three standards or guidelines – ASHRAE Guideline 14-2002: Measure of energy and demand savings (ASHRAE Standards Committee, 2002), M&V Guidelines: Measurement and verification of federal energy projects (FEMP) (U.S. DOE, 2000), IPMVP (International Performance Measurement and Verification Protocol) (IPMVP, 2002).

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, through which the facility professionals can benefit from the availability of a model to explore the energy saving potentials as well as their impacts. However Calibrated simulation can not be used under the conditions, e.g., when measures can be analyzed without simulation, or when buildings or HVAC systems can not be readily simulated, or when the resources are not sufficient and so on.

Calibrated Simulation Steps

The calibrated simulation approach has the following steps (U.S. DOE, 2000):

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. *Collect data*

The data includes building plans (building geometry and construction materials), 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 and etc could be appropriate methods to collect these data and information.

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

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.

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.

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.

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.

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

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.

BUILDING A

Building Description

Building A is located in Lujiazui, the commercial center in Pudong New Area in Shanghai. The total building area is 300000m^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 6-story podium building located adjacent to the main tower. The podium building 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.

Model Development and Calibration

The model is built with visualDOE4.0 (Architectural Energy Corporation, 2004), which is based on DOE2.1e. DOE2.1e is the current version of DOE-2, which is a detailed hour-by-hour simulation program and also the most popular whole building energy analysis tool currently in use.

Data Input and Model Development

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

1. *Weather Data*

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

2. *Envelop*

Table 2 lists the characteristics data of envelope of Building A.

Table 2 Characteristics of envelope of Building A

ENVELOPE		CHARACTERISTICS
External wall		U*=0.441 W/m^2 ^{o}C
Internal wall		U=2.196W/m^2 ^{o}C
Roof		U=0.416W/m^2 ^{o}C
Door		U=2.675W/m^2 ^{o}C VT**=0.13 SC***=0.22
Floor	Ground	U=0.143W/m^2 ^{o}C
	Internal	U=1.034W/m^2 ^{o}C
Ceiling		U=4.229W/m^2 ^{o}C
Window	GL-1	U=2.675 W/m^2 ^{o}C VT=0.13 SC=0.22
	GL-2	U=2.675 W/m^2 ^{o}C VT=0.35 SC=0.44
Skylight		U=2.677 W/m^2 ^{o}C VT=0.08 SC=0.13

*U: Heat transfer coefficient
**SC: Shading Coefficient;
***VT: Visible Transmittance

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. *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 office spaces are divided into internal zones and perimeter zones at 4.2m distance from the external wall, FPBs with reheating coils being used in perimeter zones.

Table 3 Internal loads of Building A

SPACE	LIGHTING (W/m^2)		PLUG (W/m^2)		OCCU-PANCY (m^2/PERSON)
	Before calibra-tion	After calibra-tion	Before calibra-tion	After calibra-tion	
Office*	20	12	30	15	9.2
Hotel*	10	15	15	5	23.23
Restaurant*	20	30	12	10	1.4
Lobby of office*	30	10	15	1	5
Lobby of hotel*	30	30	15	1	5
Department*	30	30	15	10	4.6
Auditorium*	10	15	10	5	5
Garage**	10	8	10	1	1000
Warehouse**	10	8	10	1	1000
Plant room**	20	8	30	1	1000

*Air conditioned spaces with the set temperature in summer of 24^{o}C and that in winter of 22^{o}C
* Non-air-conditioned spaces

5. *Outdoor Air Flow Rate and Infiltration Rate*

Outdoor air flow rate is set as 9.5l/s·person (34.2m^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.

6. *Non-HVAC Systems*

Non-HVAC systems include lighting system, office equipment, lifts and elevators, cooking facilities, laundry, swimming pool, domestic hot water, and etc. Among which, the energy consumption of lighting system and office equipment can be calculated by the software, while the others are estimated based on the design data and site measurement.

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 of Building A. Figure 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%.

Table 4 HVAC System Input Data of Building A

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℃	
Heating set point	22±2℃	
Chiller	1 centrifugal chiller, autosized, COP=5.5	8 centrifugal chillers (6*4220kW: COP=4.89, 2*1408kW: COP=4.28)
Leaving chilled water temperature	5.6°C	6.5°C
Cooling tower	1 tower, one-speed fan, autosized	6 towers, each: 90kW, water flow rate=1814.4l/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=490kPa, η=0.8 (Motor efficiency=0.9)	
Gas boiler	1 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=400kPa, η=0.8 (Motor efficiency=0.9)	

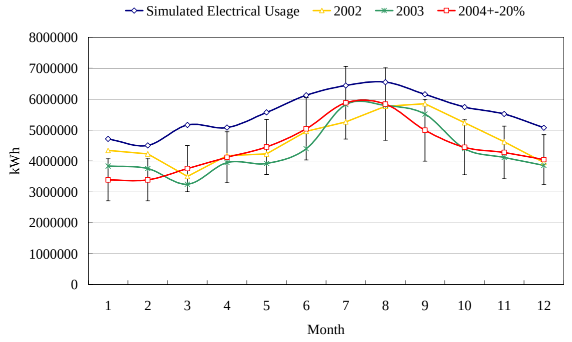

Figure 1(a) Electrical usages from the initial model vs. real 2002, 2003, 2004 electrical usages (±20%) in Building A

Model Calibration

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

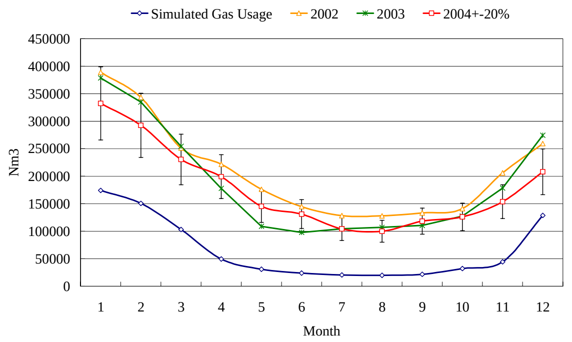

Figure 1(b) Gas usages from the initial model vs. real 2002, 2003, 2004 gas usages (±20%) in Building A

1. Weather Data

A real meteorological year data of the latest year (2004) in stead of TMY data is used in running the calibrated model. The real meteorological year data of 2004 is made by the authors with the software developed by themselves.(Zhizhong Huang, Yiqun Pan, 2006).

2. Internal loads

By analyzing the results of hour-by-hour site measurement of end-users for 24hours in one 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 (Figure 2). Figures 3 to 5 present the hourly schedule of lighting and plug power densities of office and hotel, which are also based on the 24 hour recording in one workday. From which we can know that the lighting and plug loads during off-time are still relatively high in Building A.

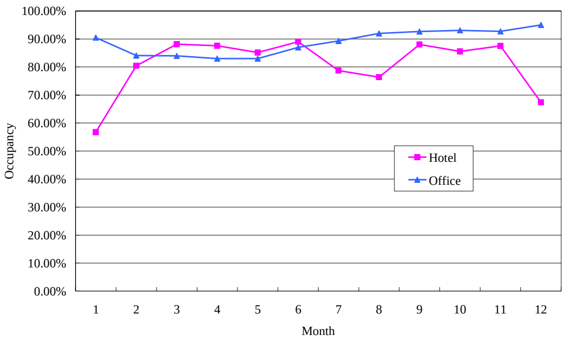

Figure 2 Monthly average occupancy percentages of hotel and office

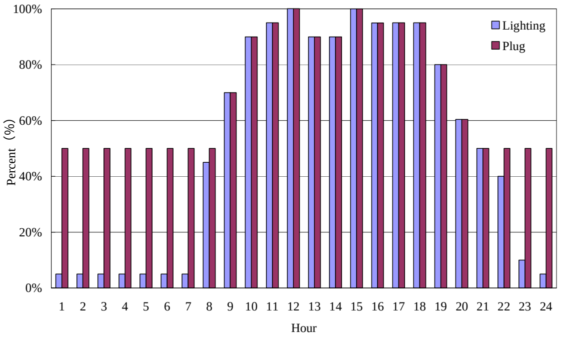

Figure 3 Schedule of lighting and plug power densities in week days in office

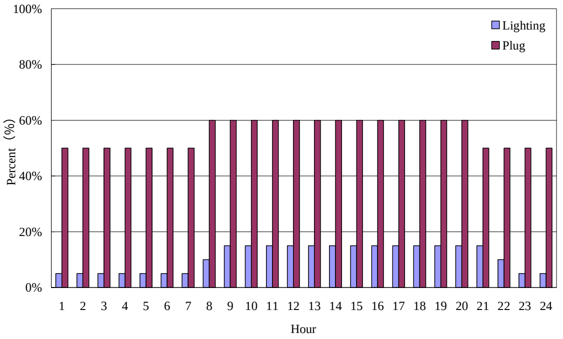

Figure 4 Schedule of lighting and plug power densities in weekend and holidays in office

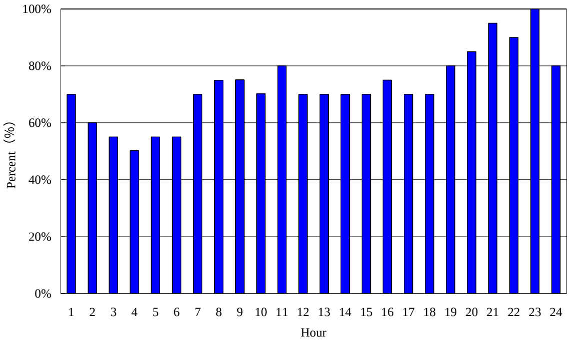

Figure 5 Schedule of lighting and plug power densities in hotel

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 Dec 16th to Apr 1st and the heating system is off from May 15th to Dec 1st. The gas consumption for humidification in winter (Dec, Jan and Feb) is calculated according to the air humidity difference between indoor and outdoors.

4. *Infiltration Rate*

Due to the good hermetical characteristic of the envelope of Building A, 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 0.2h-1.

5. *Results of Calibrated Model*

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

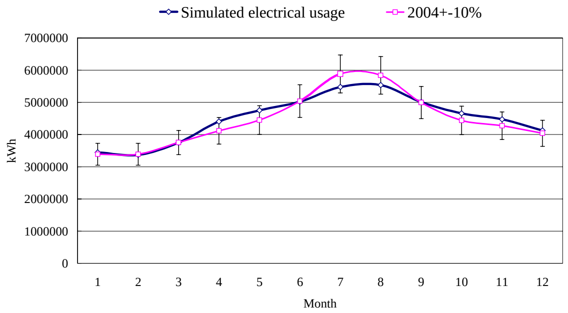

Figure 6(a) Electrical usages from the fourth calibrated model vs. real 2004 electrical usages(±10%) in Building A

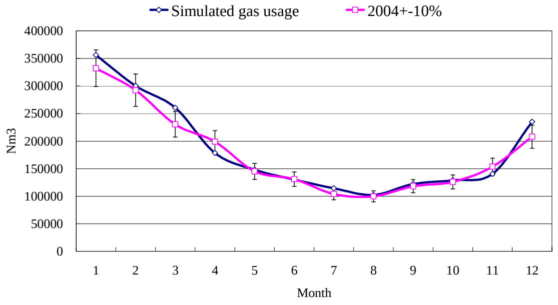

Figure 6(b) Natural gas usages from the fourth calibrated model vs. real 2004 gas usages (±10%) in Building A

Table 5 presents the indices of calibration, among which, the indices for electricity are totally within the acceptable tolerances specified by 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.

Table5 Calibration results for Building A

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%

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 can not 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 one 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.

Energy end-use breakdown

With the sufficiently calibrated model, the energy end-uses are calculated respectively for lighting, office equipment, cooling (chillers, cooling towers, pumps and fans), heating, humidification, domestic hot water, lifts, and etc. (see Figures 7-10). The biggest part of the electrical usage is space cooling, which accounts for 40%; the second biggest part is lighting, accounting for 27%, and the third is office equipment, accounting for 18%. The three gas end-use is cooking and laundry (55%), space heating and humidification (31%) and domestic hot water (14%).

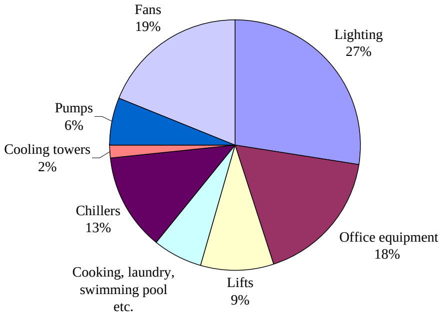

Figure 7 Annual electricity end-use breakdowns for Building A

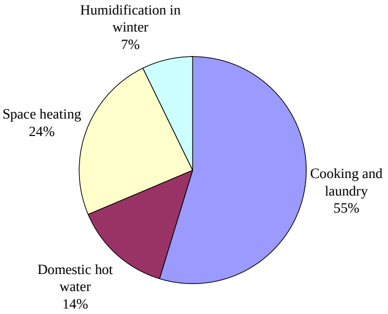

Figure 8 Annual gas end-use breakdowns for Building A

Figures 9 and 10 show that the energy end-use of lighting, office equipment, lifts, cooking and laundry facilities, domestic hot water and even fans changes little month by month, which can be regarded as the fixed part of the energy end-use of Building A. The energy usage of chillers, cooling towers, pumps, space heating and humidification accounts for the flexible part of the energy end-use of Building A.

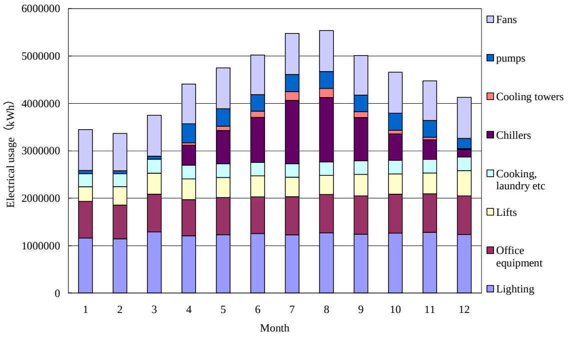

Figure 9 Monthly Electricity end-use breakdowns for Building A

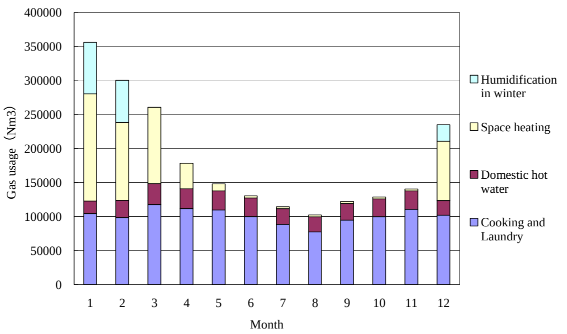

Figure 10 Monthly gas end-use breakdowns for Building A

ECMs Evaluation

Three ECMs are 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 12W/m^2 into 9.31W/m^2 by increasing the efficiency of lighting system without sacrificing the illumination level in office (500lux).

Table 6 gives the simulated the energy savings of the three ECMs, which are very limited. Especially ECM2 (free cooling) has almost no saving due to the high outdoor humidity normally in Shanghai

Table 6 Energy saving of ECMs for Building A

ELECTRICITY (kWh/m^2)	**USAGE (kWh/m^2)**	**SAVING (kWh/m^2)**	**PERCENT (%)**
Base Case	180		
ECM1	172	8	4.4%
ECM2	180	0	0
ECM3	177	3	1.7%
GAS (Nm^3/m^2)	**USAGE (Nm^3/m^2)**	**SAVING (Nm^3/m^2)**	**PERCENT (%)**
Base Case	7.39		
ECM1	7.39	0	0
ECM2	7.39	0	0
ECM3	7.43	-0.04	-0.5%
PRIMARY ENERGY(MJ/m^2)	**USAGE (MJ/m^2)**	**SAVING (MJ/m^2)**	**PERCENT (%)**
Base Case (MJ/m^2)	1955		
ECM1	1879	76	3.9%
ECM2	1955	0	0
ECM3	1927	28	1.4%

BUILDING B

Basic Information

Building B is located in Xujiahui, the other commercial center in the southwest of Shanghai. The total building area is 67000m^2. The building has 41 floors above ground, one floor underground, including an 8-story podium. The building was constructed in 1996. The first three levels of the building mainly contain banks, restaurants, sauna facilities and departments. The levels above 3 are mainly offices, with only two floors as language learning classrooms. Levels 9, 23 and 41 are mechanical equipment floors.

Model Development and Calibration

The model is built with eQUEST (Quick Energy Simulation Tool), which is based on DOE2.2. DOE2.2 is built on DOE2.1 but includes a number of upgrades and changes (James J. Hirsch, 2003). This freeware tool also allows the user to do detailed hour-by-hour analysis on energy usage.

Data Input and Model Development

1. Weather Data

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

2. Envelop

Table 7 lists the characteristics data of envelope of Building B.

Table 7 Characteristics of envelope of Building B

ENVELOPE		**CHARACTERISTICS**
External wall		U*=3.05 W/m^2 ^{o}C
Internal wall		U=2.28 W/m^2 ^{o}C
Roof		U=2.91 W/m^2 ^{o}C
Floor	Ground	U=0.47 W/m^2 ^{o}C
	Internal	U=2.27 W/m^2 ^{o}C
Ceiling		U=2.05 W/m^2 ^{o}C
Window	1	U=6.17 W/m^2 ^{o}C SC=0.95 SHGC*=0.81
	2	U=6.12 W/m^2 ^{o}C SC=0.53 SHGC=0.46

*SHGC: Solar heat gain coefficient

Compared with the envelope of Building A, the envelope of Building B has much lower heat insulation performance. (Table 2 vs. Table 7)

3. Internal Loads

The internal loads listed in Table 8 are based on the design data. The lighting densities in the spaces with the same functions (e.g. office) of Building B are higher that those of Building A (e.g. office), because Building B is relatively older and relatively lower efficient lighting system was installed in the building.

Table 8 Internal loads of Building B

SPACE	LIGHTING (W/m^2)	PLUG (W/m^2)	OCCUPANT (m^2/PERSON)
Office	15	15	18
Classroom	20	25	3
Bank	15	25	4
Restaurant	40	10	6
Sauna	25	—	20
Department	25	10	5
Lobby	40	—	5
Garage*	5	—	500
Corridor	10	—	35

* Non-air-conditioned spaces

4. *HVAC System and Zoning*

Table 9 lists main data of HVAC system after calibration. The standard office space is divided into one internal zone (corridor) and four perimeter zones facing south, east, north and west.

Table 9 HVAC System Input Data of Building B

COMPONENTS	CHARACTERISTICS
Terminal system	Podium: Constant air volume system (CAV) Office: two pipe fan coil unit system (FCU)
Cooling set point*	24±2℃
Heating set point*	22±2℃
Chiller	3 centrifugal chillers (2*900RT, 1*400RT), COP=4.5
Chilled water temperature	6℃/10.5℃
Oil boiler	3*4.5MW, η=60%

* The HVAC system is shut down during non-working period in all various spaces, e.g., 17:30-8:00 in office.

5. *Outdoor Air Flow Rate and Infiltration Rate*

Outdoor air flow rate is set as 30m^3/h·person. The infiltration rate is 0ACH in the internal zones and 0.2ACH in perimeter zones.

6. *Initial Simulation Results*

Table 10 gives the simulation results of the initial model of Building B (before calibration).

<u>Model Calibration</u>

The inputs of weather data, internal loads and operating schedule of HVAC system are revised for the purpose of model calibration.

1. *Weather Data*

A real meteorological year data in stead of typical meteorological year (TMY) data is also used in running the model of Building B.

2. *Internal Loads*

According to the site measurement, the lighting densities of the following spaces are revised:

- Lobby: 26.4 W/m^2
- Garage: 3.1 W/m^2
- Corridor: 6 W/m^2

3. *Schedule of HVAC System*

According to the surveying and discussion with facility managers in Building B, the schedule of HVAC system is refined. In detail, the cooling supply period is changed from May 1st – Oct 31st to Apr 20th – Nov 11th, during which, from June 16th to Sep 15th the cooling is supplied three hours longer than normal; the heating supply period is from Jan 1st to Apr 4th and from Nov 30th to Dec 31st.

4. *Results of Calibrated Model*

Figure 11 illustrates he simulated result of the calibrated model as well as the real energy consumption in 2004, which shows that the simulation results of the calibrated model meet very well with the real 2004 electrical usages.

Table 10 presents the indices of calibration, which are totally within the acceptable tolerances specified by the FEMP, except for ERR_{month} not meeting the requirement of ASHRAE 14 and CV($RMSE_{month}$) not meeting the requirement of IPMVP.

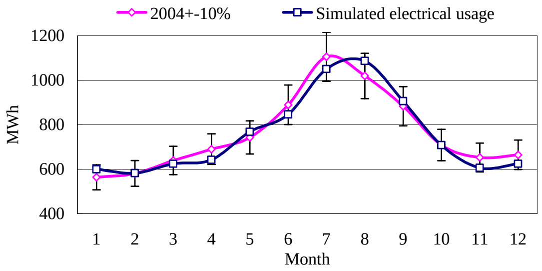

Figure 11 Electrical usages from the third calibrated model vs. real 2004 electrical usages(±10%) in Building B

Table10 Calibration results for Building B

INDEX	ELECTRICITY	
	Before Calibration	After Calibration
ERR_{month}	±22.24%	±10.01 %
ERR_{year}	±6.76%	±2.37 %
CV($RMSE_{month}$)	±8.65%	±5.70 %

<u>Error Analysis</u>

- The actual randomicity of the operating schedule of internal loads can not be simulated exactly in the model.
- Since there is no building automation in Building B, the HVAC system is controlled by hand, which may not always operates as the schedules set in the model.
- The detailed information of the envelope

construction can not be found, which may cause error in the simulation of the heat gain through the envelope.

Energy end-use breakdown

Figures 12 and 13 present annual and monthly electricity end-use breakdowns of Building B, which is different from those of Building A. The biggest part of the electrical usage is equipment (including office equipment, lifts, etc), which accounts for 45.8%; the second biggest part is lighting, accounting for 32.8%, and the third is space cooling (including chillers, cooling towers, pumps and fans), accounting for 21.4%.

ECMs Evaluation

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

1. Changing the pumps serving the high levels from constant speed into variable speed.
2. Replacing the old low efficient cooling towers with high efficient two-speed-fan cooling towers.
3. Decreasing the lighting power density from 15W/m^2 into 10W/m^2 by increasing the efficiency of lighting system without sacrificing the illumination level in office (400lux~450lux).

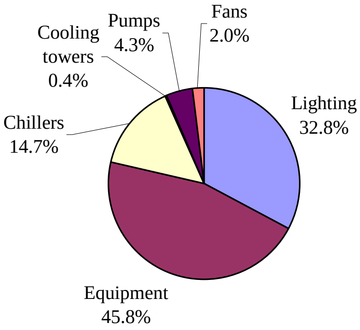

Figure 12 Annual electricity end-use breakdowns for Building B

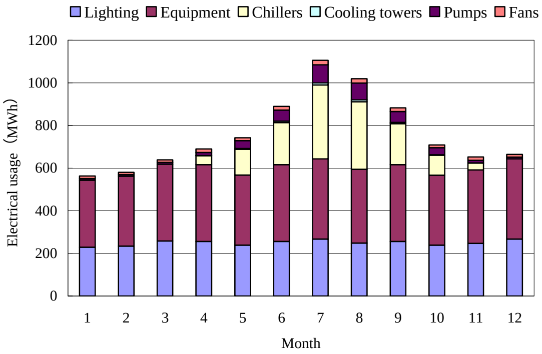

Figure 13 Monthly Electricity end-use breakdowns for Building B

Table 11 gives the simulated the energy savings of the three ECMs, among which, ECM3 (improving lighting system) has the highest energy saving.

Table 11 Energy saving of ECMs for Building B

ELECTRICITY (KWH/M^2)	**USAGE (KWH/M^2)**	**SAVING (KWH/M^2)**	**PERCENT (%)**
Base Case	157.4		
ECM1	155.9	1.5	0.95
ECM2	156.5	0.9	0.57
ECM3	147.3	10.1	6.4
OIL (MJ/M^2)	**USAGE (MJ/M^2)**	**SAVING (MJ/M^2)**	**PERCENT (%)**
Base Case	166.1		
ECM1	167.6	-1.5	-0.9%
ECM2	166.1	0	0
ECM3	179.3	-13.2	-7.9%
PRIMARY ENERGY (MJ/M^2)	**USAGE (MJ/M^2)**	**SAVING (MJ/M^2)**	**PERCENT (%)**
Base Case	1657		
ECM1	1645	12	0.7%
ECM2	1649	8	0.5%
ECM3	1575	82	5.2%

CONCLUSIONS

This paper has summarized the calibrated simulation as one building energy analysis method and employed it to simulate and analyze the energy usages of two high-rise commercial buildings in Shanghai. Necessary data and information of the two buildings have been collected and measured on site as the input of models. The models have been refined to comply with the calibration. The calibration processes and refined input data are described in detail. After calibration, the model can predict the real energy usage very well.

With calibrated model, energy end-use of the two buildings has been calculated and analyzed, which is very difficult to break down from the utility bills.

The calibrated models have also been used to simulate and calculate the energy savings of possible ECMs for the two buildings. For Building A, ECM 1 – changing the secondary chilled water pumps and hot water pumps from constant speed into variable speed – is the best among the three options; For Building B, ECM 3 – decreasing the lighting power density from 15W/m^2 into 10W/m^2 by increasing the efficiency of lighting system without sacrificing the illumination level in office (400lux~450lux) – is the best among the three options.

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NOMENCLATURE

$$ERR_{month}(\%) = \left[\frac{(M-S)_{month}}{M_{month}} \right] \times 100\% \tag{1}$$

$$ERR_{year}(\%) = \sum_{year} \left[\frac{ERR_{month}}{N_{month}} \right] \tag{2}$$

Where,

M: measured electricity (kWh) or fuel consumption

S: simulated electricity (kWh) or fuel consumption

N_{month}: number of utility bills in the year

$$CV(RSME_{month})(\%) = \left[\frac{RSME_{month}}{A_{month}} \right] \times 100\%$$

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

$$A_{month} = \left[\frac{\sum (M_{month})}{N_{month}} \right] \tag{3}$$

Where,

RMSE: root-mean-squared monthly error

A_{month}: mean of the monthly utility bills