A Study of Lighting Energy Consumption Model for Office Buildings

Ren Xiaoxin[1,*], Yan Da[2], Zhou Xin[3]
[1,2,3]Department of Building Science, Tsinghua University, Beijing 100084, China

ABSTRACT

The paper focuses on a survey of several single offices in office buildings, where occupants' movement, light-control behavior, lighting energy consumption and indoor illumination are measured. It reveals the key factors of lighting energy consumption in office buildings like the illuminance level, occupancy patterns and occupant behaviors, and how the factors work. The quantitative model of a typical person by moving and control behaviors is set out on the base of the analysis result of the survey. When it is expanded to more occupants, the different characteristics of lighting energy consumption among different scales office buildings due to the crowding effect can be simulated, which means that more occupants in the office (building) will result in a more regular schedule, a longer light open time and less influence by different behaviors.

KEYWORDS

Lighting system use, office building, energy consumption, occupant behavior, computation model

1 Introduction

Office buildings, as an important part of commercial buildings, arouse attention both on characteristics of energy consumption and energy saving projects. The energy consumption of an office building includes lighting, equipment, AC, elevator, ventilation and drainage. Lighting takes up 10%—25% of the whole according to the breakdown of several buildings. Therefore, a study of the lighting energy consumption model of office buildings makes fundamental sense of the study on the total building energy consumption.

According to abundance survey results, there's a remarkable difference between the energy consumption of small-scale office buildings and the large ones. A series of primary researches reveals that, as Figure 1 and Figure 2 show, lighting open status varies a lot from single to multiply offices. In the single office, the schedule randomizes from time to time, lighting opens less, and the energy consumption is lower; while in the multiply office, the schedule is more steady, lighting opens more, and the energy consumption is higher.

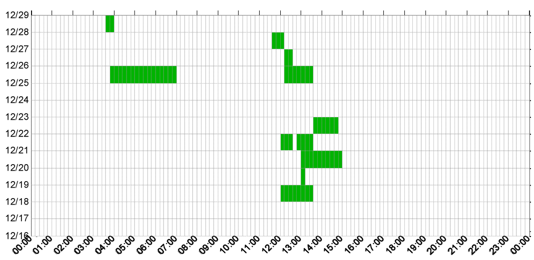


Figure 1 Lighting open schedule in a single office

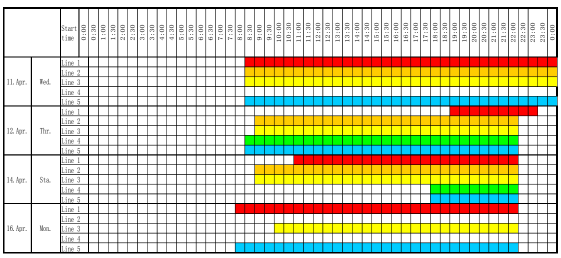


Figure 2 Lighting open schedule in a multiply office

Many existing studies have been focused on these phenomena. It is showed that lighting energy consumption is affected mainly by external illumination and occupants' behavior. Some studies believe that lighting use is quite interrelated with external illumination. When it is brighter outside, occupants tend to use sunshine, which results in less open time of artificial lighting[1][2][3][4][5]. On the other hand, some other studies argue that occupants' behavior has significant influence. The results indicate that the use of lighting in multiply offices has no statistical relationship with external illumination, but is more related with room occupation and human

* Corresponding author email: rxx12@tsinghua.edu.cn

behavior, and is also widely related with the point-in-time in a day[6][7][8][9]. Basing on the above, some probabilistic lighting models for small-scale office buildings and residence have been set up [10][11][12]. However, there is no specific conclusion on the key effecting elements about lighting energy consumption, and also no studies have explained clearly why the different research results are both exist.

Considering the above, for the purpose of quantificationally describing and calculating the difference of lighting energy consumption in different buildings, and explaining the phenomenon, this paper chooses a series of single offices for a further follow-up survey, and a model based on the result is preliminary founded. In this way, the main factors of lighting energy consumption and how they affect can be found clearly.

2 Field research

The experiment site:

Five single offices of a department building in an university in Beijing, with different orientations (north and south), are choosen to do the follow-up survey. The location of the office is showed in Figure 3.

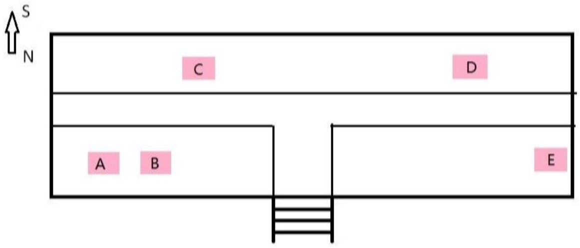


Figure 3 The sketch map of measured single offices

Experimental period:

2012.5.28—2012.6.3 (last for a week).

Experimental method:

Power meters are used for measuring lighting energy consumption in every minute, illuminance meters for vertical and horizontal illumination, surveillance videos for personnel movement, and questionnaires for lighting use habit.

Experimental result:

Take single-office A (Figure 4) and C (Figure 5) for examples, showed from the results, the light in office A is completely close during the survey period. The illumination in the office is generally above 200lux, except a short time below 40lux, however the light is still close. Office C’s light opens twice during the test, once for 1.5h, the other for 1h, both at about 18:00.

Summarizing the survey results of office A, B, C, D and E as Table 1, it shows a great diversity among different single offices both in the level of energy consumption and in the degree of dispersion.

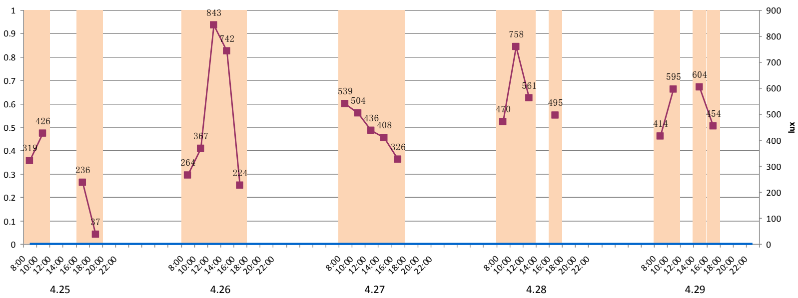


Figure 4 Occupancy, illumination and lighting situation of single office A (towards north)

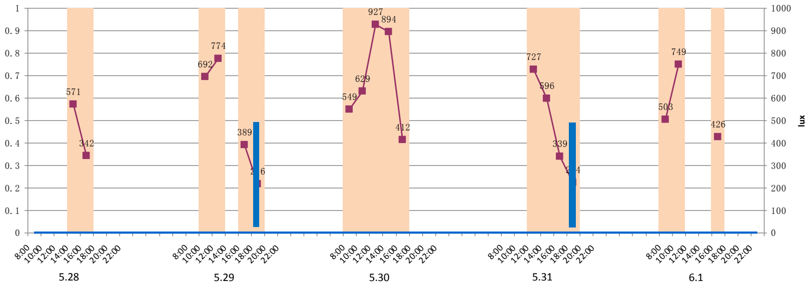


Figure 5 Occupancy, illumination and lighting situation of single office C (towards south)

Table 1 The results of lighting energy consumption survey in single offices

Measured Offices	Average day lighting open time (h)	Average day lighting energy consumption (kWh)	Day lighting energy consumption SD(kWh)
Office A	0	0	0
Office B	0.7	0.063	0.0128
Office C	0.5	0.045	0.0236
Office D	1.4	0.126	0.0632
Office E	2.3	0.207	0.0816

Through the fundamental survey of single offices, a typical person's key factors of lighting-control behavior and the way they work are mainly revealed, which can be taken as a part of groundwork for deeper research.

3 Lighting model of a single person

3.1 The personnel-movement model

According to the method of calculating personnel-movement through Markov chain mentioned by C. Wang[13], the model can be applied to the lighting model by a simplified edition, which only entering and exiting the measured building (office) are considered.

Take the event of going to work as an example, a matrix is needed in the Markov method.

$$P_{go\_office} = \begin{matrix} & \begin{matrix} 0 & 1 \end{matrix} \\ \begin{matrix} 0 \\ 1 \end{matrix} & \begin{bmatrix} p_{00} & p_{01} \\ 0 & 1 \end{bmatrix} \end{matrix}$$

In the matrix, number 0 means outside and 1 means inside the building (office). The matrix means that at a given time, there's a possibility matrix P∞ for a given person to stay outside and a possibility matrix P01=1-P∞ to arrive at the office; once he comes to work, he stays in the office not leaving before noonbreak.

Based on the characteristics of geometric distribution, the matrix can be completed, so that the personnel-movement during starting work time is able to simulated. The situation during ending work time is similar but contrary. What's more, the personnel-movement during lunch beginning and ending time are also calculalble.

in this way, the personnel-movement during a weekday in an office building can be discribed by the eight paremeters of stated starting work time, earliest starting work time, stated ending work time, latest ending work time, stated starting noon break time, earliest starting noon break time, stated ending noon break time and latest ending noon break time.

3.2 The lighting-control model

Concluded from the survey results of measured single offices, paying close attention to the effecting factors to open and close lights, we can see that there's a great difference in lighting control behavior between different occupants, which lead to the obvious gap of lighting energy consumption. However, different behaviors can be put into the same frame to be discussed, which needs to summarize several feature parameters standing for the lighting-control model of a single person.

The factors' effects on opening and closing lights are showed as, which follows two main lines, influenced by personnel-movement as well as illumination. When a person come to work in the morning, he will have a judgment whether to open the light; when he leaves at noon, another judgment whether to close the light; coming back in the afternoon whether to open the light if closed then; leaving the office whether to close the light or leave it on. At the same time comes the effect of illumination, when it drops to a certain level there's a probability to open the light, and rises to a certain level to close it. There's a different possibility array of a different person, then shows a different lighting control behavior.

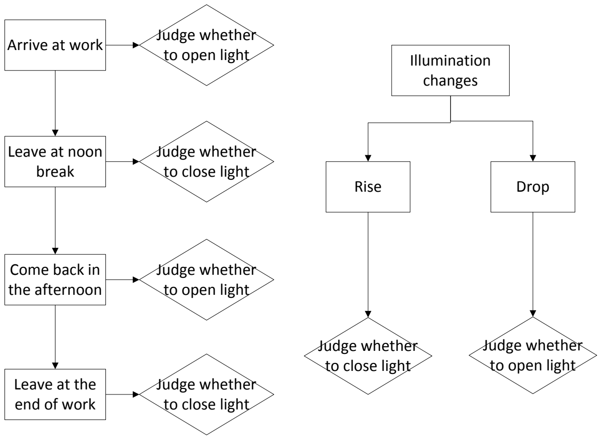


Figure 6 The block diagram of opening and closing lights

After making a statistical analysis based on the survey results, we try to use a quantitative method to describe how the key factors affect lighting energy consumption.

First, a certain probability array is used to describe the influence on lighting open situation by human behavior, as showed in Table 2.

Table 2 The probability array of lighting-control related by personnel-movement

The probability to open light when coming (including morning and afternoon)	P_1
The probability to close light when leaving at noon	P_2
The probability to close light when leaving at the end of work	P_3

On the other hand, the influence of illumination can be described by a series of probability curve: like the probability to open the light is larger and larger as the dropping of inner illumination; for a different person with an unique behavior there will be an unique curve to describe, so the illumination when the probability to open the light is 50% (L1) can be a character parameter to define it. The method can also used in the description of closing light, which comes out with a parameter L2. If the experiment can be expanded in both quality and time in the next step, a more accurate curve can be sure to be expected.

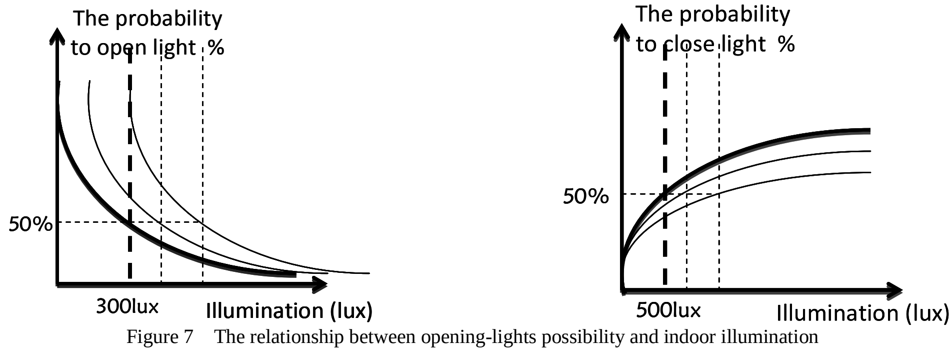


Figure 7 The relationship between opening-lights possibility and indoor illumination

4 The verify of the lighting model

For verify the reliability of the calculation method, a single-office C is taken as an example to simulate, and a comparison with the actual measurement are conducted. As the personnel-movement model is quote from the Markov model, so in this verification we check only the opening and closing light model by input the real personnel-movement to the calculate model.

The input parameters of the single-office C lighting model is showed in Table 3.

Table 3 The input parameters of single-office C model

Input parameters	Value	Input parameters	Value
The probability to open light when coming P_1	0.2	The character illumination when opening light L1 (lux)	200
The probability to close light when leaving at noon P_2	0.6	The character illumination when closing light L2 (lux)	450
The probability to close light when leaving at night P_3	0.9	Lighting installed power W_0 (W)	45

A simulation result is showed in Figure 8 (the red line stands for calculation result and the blue line stands for actual measurement), in which the simulation is relatively agree with the real situation. Because the model is calculated based on a random process, so repeating the simulation to get an 'expect lighting energy consumption', comparing with the real situation as Table 4. We can find that the model describes the real situation quite well, even in a single calculation of a series repeating simulation, which proves the effectiveness of the lighting model of a single person.

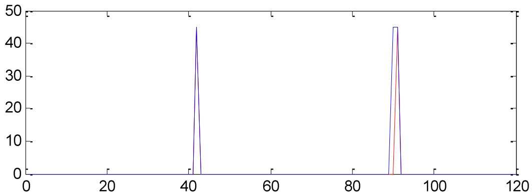


Figure 8 The simulation result of single-office C

Table 4 The repeating simulation result of single-office C (100 times)

Average day lighting energy consumption in simulation (kWh)	Average day lighting energy consumption in actual measurement (kWh)	Standard Deviation (kWh)
0.048	0.045	0.0082

5 Application of the lighting model

5.1 expansion from single-model to multiply-model

In order to apply the single-model, it's important to expand it into a multiply one properly,and the calculation process is designed as Figure 9.

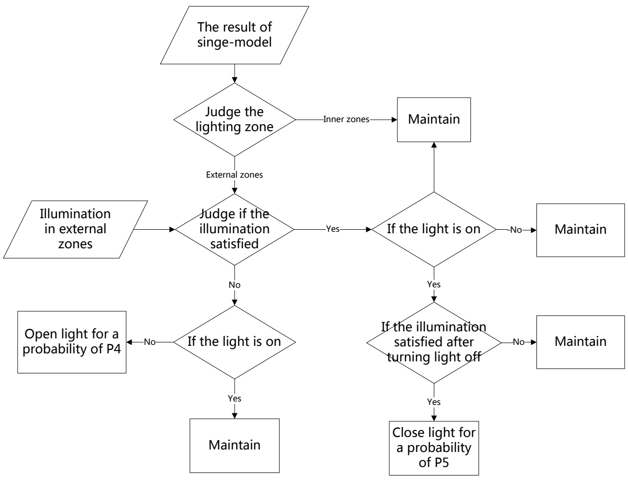


Figure 9 The block diagram of an extending lighting model from a single person to multiply

5.2 The impact of crowding effect

The crowding effect is usually showed in multiply-offices and a whole office building, when occupants gather to a degree, there will be an influence to the light energy consumption, which makes the lighting schedule more regular, and the light open ratio is larger bringing higher energy consumption.

Coefficient of variability is used as an important value to describe the stability of lighting energy consumption level. CV=SD/mean (SD means standard deviation), so that the influence of different scales is removed to describe the randomness in different conditions exactly. The smaller CV is the more concentrate the data is, with less randomness; from the view of physics, it means the schedule is more regular, and the energy consumption level is more concentrate and stable.

Set up a lighting model of a multiply-office, where five independent switches are used to control light. The occupants' behavior is showed as Table 5. With the rising of occupant number, from 1 to 5, then to 20, we can see the result of crowding effect in multiply-office based on increasing occupants through comparison.

A single simulation result is showed in Figure 10, from which we can preliminarily see that with the increasing of the occupant number, light open time increases, and when it comes to W=20, the light is on nearly the whole working time. By repeating the calculation, we can get the average day lighting energy consumption with different numbers of occupants, and the compare result is showed as Figure 11. As a conclusion, we can find that in the same office, when the number of occupants increases, the mutual influence will lead to a longer lighting open time and a higher level of energy consumption; on the other hand, considering the CV in Table 6 when the numbers of occupants changes, when the number of occupants increases, CV decreases, randomness gets weaken, lighting schedule gets more regular, and energy consumption comes to a steady level. Conclude from above, it shows the influence result of crowding effect when occupants get more and more.

Table 5 Characteristic parameters of a typical lighting-control behavior

The probability to open light when coming immediately	The illumination when the probability to open light is 50%	The probability to close light when leaving at noon	The probability to close light when leaving at the end of work	The illumination when the probability to close light is 50%
0.5	300lux	0.3	0.6	550lux

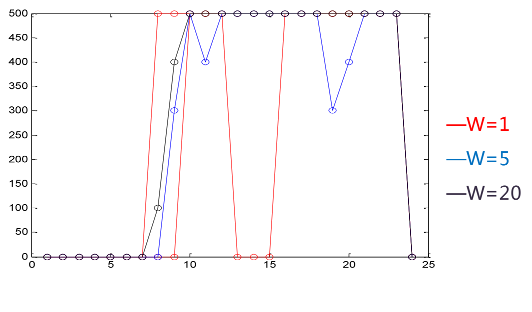


Figure 10 The simulation results of lighting energy consumption with different numbers of occupants

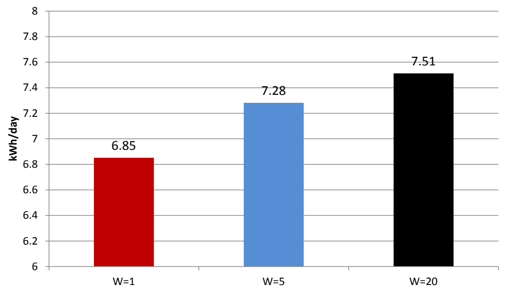


Figure 11 A compare of different level of energy consumption leaded by different occupant numbers

Table 6 The influence of crowding effect leaded by different occupant numbers

Numbers of occupants	W=1	W=5	W=20
Calculating average day Lighting energy consumption (kWh/day)	6.85	7.28	7.51
Standard deviation（kWh）	3.557	0.838	0.253
Coefficient of variability	0.5192	0.1151	0.0337

If going on with using the same method to calculate other cases with different numbers of occupants, we can get a series of CVs changing as Figure 12 shows. From the figure, CV seriously decreases with the increasing of occupant number; when the number comes up to more than 5, CV is small enough and doesn't change much, which means that in this case the crowding effect is quite obvious.

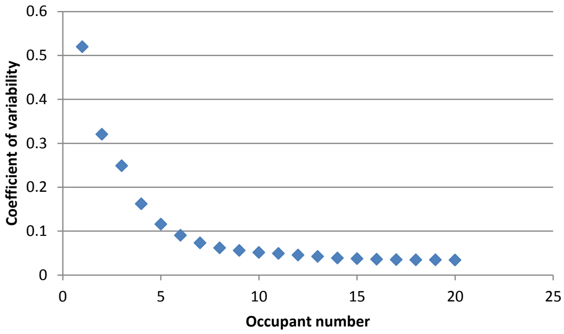


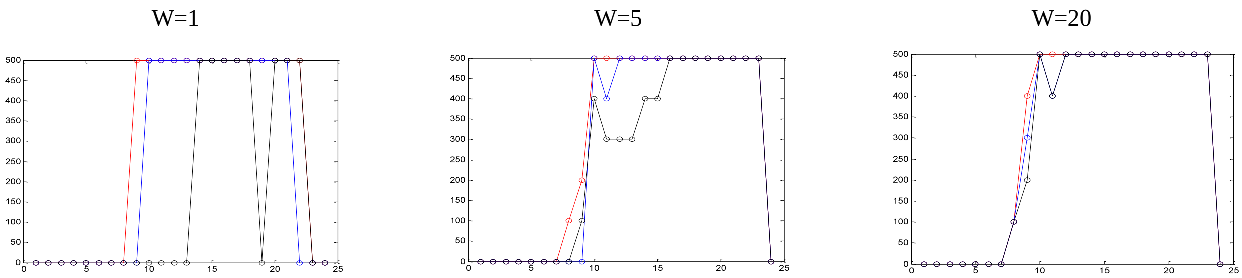
Figure 12 Coefficient of variability changes with occupant numbers

5.3 The effect of different occupants' behavior

In reality, occupant's behavior varies from person to person. In order to explore the influence of different lighting-control behaviors, three types of typical occupants are set, with the characteristic parameters shown Table 7. Still consider the three cases with different numbers of occupants (W=1, 5, 20) for example, and change the occupants' behaviors in each case, so that we can get the simulation result as Figure 13 shows.

Table 7 Characteristic parameters of different lighting-control behaviors

Type	The probability to open light when coming immediately	The illumination when the probability to open light is 50%	The probability to close light when leaving at noon	The probability to close light when leaving at the end of work	The illumination when the probability to close light is 50%
A	0.8	400lux	0	0.3	650lux
B	0.5	300lux	0.3	0.6	550lux
C	0.2	200lux	0.6	0.9	450lux



The red line means type A, the blue line means type B, the black line means type C

Figure 13 The simulation result of different numbers of occupants with different behaviors

From the figure, we can see that increasing with the occupancy number, the schedule is more and more regular, the difference among three types of typical occupants is smaller and smaller. In the W=20 case, the influence of a single person behavior is not so notable, so that the results of the three groups are quite similar and regular.

6 Conclusion

The study focuses on the lighting use in small-scale office buildings, based on a series of follow-up survey in single-offices. After meticulously measuring the indoor illumination, personnel movement, lighting energy consumption, and detailed lighting use behavior questionnaire, we have got conclusions below:

1. A statistical quantitative bottom-up lighting energy consumption model based on human behaviors for office buildings is set up;

The model reflect quantificationally the key factors of lighting energy consumption and how they exactly work;

2. Starting from a single-person model, the research explains the difference in lighting energy consumption among office buildings with different scales;
3. According to crowding effect, more occupants in the office (building) will result in a more regular schedule, a longer light open time and the less influence by different behaviors.

ACKNOWLEDGEMENTS

This project is supported by Swire Properties. Field survey and measured data of the buildings of Swire Properties are cooperated and technically supported by its Technology Support and Sustainable Department (TSSD) and Maintenance and Operation department (MO).

REFERENCES

[1] C.F. Reinhart, K. Voss. Monitoring manual control of electric lighting and blinds. Lighting Research and Technology 35 (2003) 243–260.

[2] Danny H.W.Li, Tony N.T.Lam, S.L.Wong. Lighting and energy performance for an office using high frequency dimming controls[J]. Energy Conversion and Management, June 2006, 1133-1145.

[3] Galasiu,A, Atif,M. Applicability of daylighting computer modeling in real case studies: comparison between measured and simulated daylight availability and lighting consumption[C]. IEA Task 21/Annex 29 Official Report, 1998-10-06.

[4] Danny H.W.Li, Joseph C.Lam, Evaluation of lighting performance in office buildings with daylighting controls[J]. Energy and buildings, Oct 2001, 793-803.

[5] V.K.Maitreya. Daytime artificial lighting in office buildings in India[J]. Building and Environment. 1977, 159-163.

[6] Geun Young Yun, Hyo Joo Kong, Hyoin Kim, Jeong Tai Kim. A field survey of visual comfort and lighting energy consumption in open plan offices[J]. Energy and Buildings, Mar 2012, 146-151.

[7] Geun Young Yun, Hyoin Kim. Jeong Tai Kim. Effects of occupancy and lighting use patterns on lighting energy consumption[J]. Energy and Buildings, Mar 2012, 152-158.

[8] J.A. Love, Manual switching patterns observed in private offices[J], Lighting Research and Technology 30 (1998) 45–50.

[9] D. Lindelöf, N. Morel, A field investigation of the intermediate light switching by users[J], Energy and Buildings 38 (2006) 790–801.

[10] Hunt, D. 1979. The use of artificial lighting in relation to daylight levels and occupancy[J]. Building and Environment, 14, p.21-33.

[11] C.F. Reinhart, Lightswitch 2002: a model for manual control of electric lighting and blinds[J], Solar Energy 77 (1) (2004) 15–28.

[12] Joakim Widen, Annica M.Nilsson, Ewa Wackelgard. A combined Markov-chain and bottom-up approach to modelling of domestic lighting demand[J]. Energy and Buildings, Oct 2009, 1001-1012.

[13] Chuang Wang, Da Yan, Yi Jiang. A novel approach for building occupancy simulation[J]. Building Simulation, Vol 4,No 2, 2011, 149-167.