DATA ANALYSIS AND MODELING OF LIGHTING ENERGY USE IN LARGE OFFICE BUILDINGS

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ABSTRACT
Lighting consumes about 20 to 40% of total electricity use in large office buildings in the U.S. and China. In order to develop better lighting simulation models it is crucial to understand the characteristics of lighting energy use. This paper analyzes the main characteristics of lighting energy use over various time scales, based on the statistical analysis of measured lighting energy use of 17 large office buildings in Beijing and Hong Kong. It was found that the daily 24-hour variations of lighting energy use were mainly driven by the schedule of the building occupants. Outdoor illumination levels have little impact on lighting energy use in large office buildings due to the lack of automatic daylighting controls and relatively small perimeter areas. A stochastic lighting energy use model was developed based on different occupant activities during six time periods throughout a day, and the annual distribution of lighting power across those periods. The model was verified using measured lighting energy use of one selected building. This study demonstrates how statistical analysis and stochastic modeling can be applied to lighting energy use. The developed lighting model can be adopted by building energy modeling programs to improve the simulation accuracy of lighting energy use.

KEYWORDS
building simulation, energy use, lighting, modeling, occupant behavior, office buildings, Poisson distribution

INTRODUCTION
Lighting energy use in large office buildings is as high as 20% to 40% of the building total in both China and the U.S. This has caught the attention of practitioners, researchers, and policy makers. Studies have shown that the two main factors affecting lighting energy use are outdoor illumination and occupant behavior. From other researchers' field studies and simulations, it was concluded that lighting energy use has a correlation with outdoor illumination. When the outdoor illumination is above a certain level, people around perimeter zones with access to natural light are less likely to use artificial electrical lights, and the artificial illumination needed to meet design illuminance levels is lower (Reinhart and Voss 2003, Li et al 2006, Galasiu and Atif 2002, Li and Lam 2001, Maitreya 1997). However, other researchers also found that occupants have a crucial influence on the lighting energy use. Through case studies of actual buildings, Yun et al (2012a) found that in open-plan offices, the usage of lighting was not influenced by outdoor illumination. Instead it had a close relationship with the indoor activities of occupants. Meanwhile, Yong et al (2012b) formulated

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the concept that outdoor illumination has no statistical significance with lighting energy use, and the operation of lighting was strongly correlated to the time of day. Other studies also found that operation of lights by occupants only depended on whether the room is occupied, and is independent of outdoor illumination (Love 1998, Lindelof and Morel 2006).

Currently, most research on lighting energy use is focused on small office and residential buildings. The analysis methods and conclusions from this research provide some hints to help understand the lighting energy use in large office buildings. In China, a common method to predict lighting energy use involves combining lighting power density information with lighting schedules. However, the generation of lighting schedules is too simplified and lacks verification against measured data (Yun and Steemers 2008). This leads to a large discrepancy between simulated and measured lighting energy use (Bluyssen 2009, Norford et al 1994). Furthermore, the annual variation of actual lighting energy use is not captured.More complex lighting energy use models have been reviewed. Hunt (1979) introduced a stochastic model to calculate the probability of turning on lights after the arrival of occupants. He concluded that the probability of occupants turning on artificial lights increases only when the illumination of the working surface is below 100 lux. Newsham (1995) developed the Lightswitch model that followed a stochastic approach and simulated user occupancy at the workplace based on measured field data in an office building in Ottawa, Canada. Reinhart (2004) improved the Lightswitch model to Lightswitch-2002 to calculate the probability of occupants arriving and leaving offices, and the related probability of turning on and off lights. Meanwhile, in Reinhart‘s study, based on the model, the amount of energy savings under different lighting control strategies was evaluated. Joakim Wide ́n et al (2009) used Markov chains to estimate the probability of occupant movement. Then the probability of turning on lights was modeled as a decision based on the lighting level and occupant movement. Since these studies were mainly based on small office buildings (Hunt 1979, Reinhart 2004) and residential buildings (Wide’n et al 2009), there is a strong need to conduct more research on lighting energy use in large office buildings if energy use targets are to be met.

Based on large quantities of measured data from several large office buildings, this paper analyzes the characteristics of total amount and distributions of lighting energy use in large office buildings. Due to the lack of detailed information on the physical characteristics of lighting systems in these buildings, this paper focuses on daily and seasonal lighting energy use patterns. Daily 24-hour lighting curve, annual distribution of lighting power, and main influencing factors of lighting energy use are first identified and discussed through statistical analysis of hourly data. Then a stochastic model is developed which effectively capture random characteristics of lighting energy use. The model accounts for the time-varying nature of lighting energy use, including peaks in usage at certain times of the day. In this study, the general lighting energy use features of large office buildings are analyzed and discussed in depth, and the main influencing factors and distributions of lighting energy use are clarified more distinctly.

RESEARCH METHODS

The research method in this paper is shown in Figure 1. First, the two main factors influencing lighting energy use - outdoor illumination and occupant behavior - are analyzed. To determine the influence of outdoor illumination on lighting energy use, the lighting energy use between different seasons and different building levels (above-grade areas and basements) is compared. The effect of occupant behavior is analyzed by comparing lighting energy used on different types of day

(workdays, weekends, holidays), and by comparing lighting energy use under different occupancy schedules. Then, based on the understanding of main influencing factors of lighting energy use, further discussion about the feature of lighting energy use curve in large office buildings can be gained through the analysis of measured lighting energy use from dozens of large office buildings with energy sub-metering systems. The analysis is mainly focusing on four aspects: 1) annual total energy use; 2) monthly distribution; 3) daily feature; and 4) annual distribution. More in-depth analysis is conducted to decode the annual distribution feature and the time-relevant properties between different time periods. A whole-building lighting energy use model is developed based on the results from the analysis of lighting energy use and lighting profiles at various time scales. The model is then applied to a case study to simulate the lighting energy use, and the simulated results are compared with measured data to verify the model.

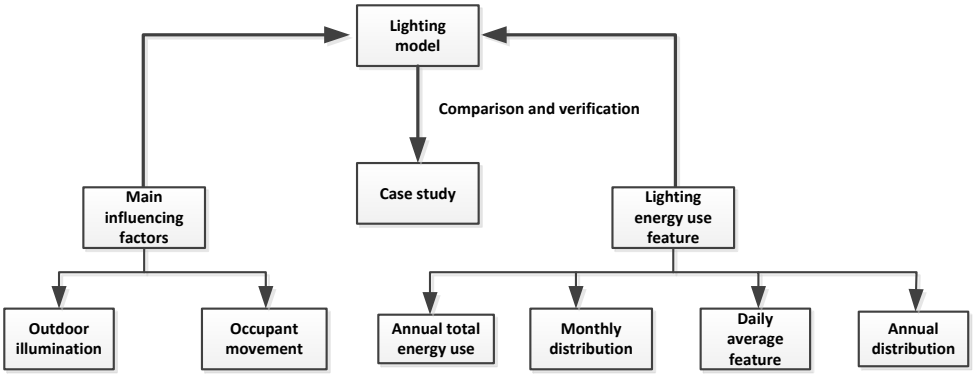


Figure 1 Research route

RESULTS

1 Analysis of influencing factors

1.1 The influence of outdoor illumination

1.1.1 Comparison of lighting energy use between the basement and the above-grade floors

The lighting energy use is shown in Figure 2. The red line in the figure represents the daily mean lighting energy use. The edges of the blue boxes are placed at the 25% and the 75% quartiles. The maximum and minimum data points are also shown. It reveals that the outdoor illumination has no obvious effect on the shape of the average lighting power curves in large office buildings.

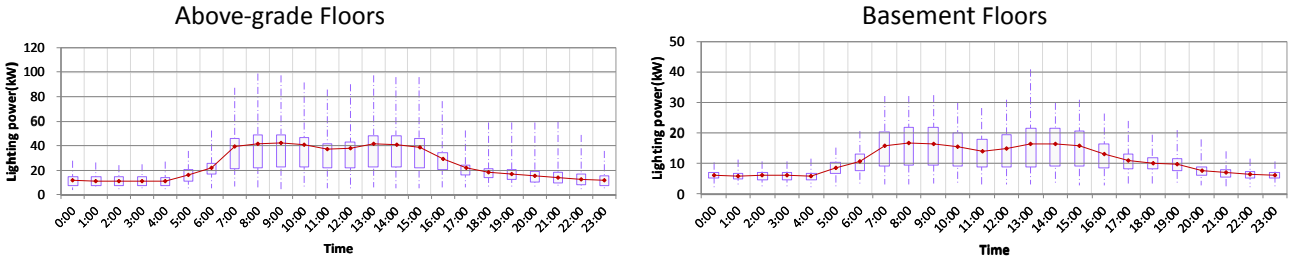


Figure 2 Comparison of lighting energy use between the basements and the above-grade areas

1.1.2 Comparison of lighting energy use between seasons

To further study the influence of outdoor illumination, the lighting energy use between different seasons is compared as shown in Figure 3. It can be concluded that outdoor illumination has no noticeable influence on the total lighting energy use.

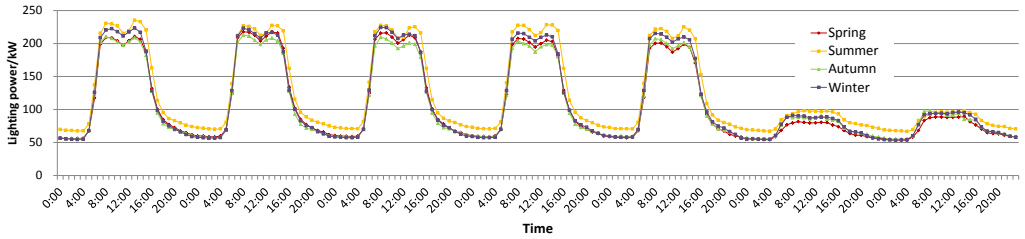


Figure 3 Weekly profiles of average lighting energy use for the four seasons

1.2 The influence of occupant behavior

To assess the influence of occupant behavior on lighting energy use, the power draw between workdays and weekends for the same lighting branch is compared and shown in Figure 4 and Figure 5. As there are many more occupants in the building on workdays, the lighting power on workdays is higher than weekends. Different occupancy events such as arriving at work, going out for lunch, and leaving work can be detected from the workday lighting power curve. While during weekends, the discrete range of lighting energy use is much larger, and a homogeneous lighting schedule cannot be detected due to the uncertainty of overtime work and other events.

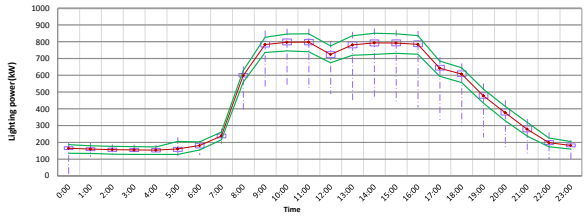


Figure 4 Average lighting power draw on workdays

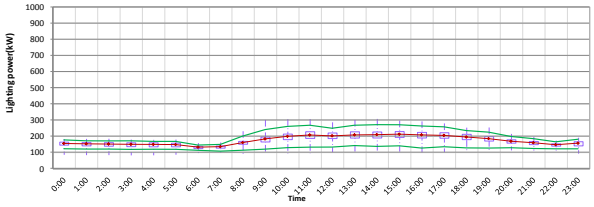


Figure 5 Average lighting power draw on weekends

Note: the red lines are the hourly averages; the green lines represent data at 5% and 95% probability; the blue boxes show the first and third quartiles; the vertical dashed blue lines show the range

2 General characteristics of lighting energy use

Based on measured data of 17 large office buildings in Beijing and Hong Kong, general characteristics of the lighting energy use are analyzed.

2.1 Annual lighting energy use

The electricity end-use intensities are calculated and shown in Figure 6. It can be seen that the offices in Hong Kong have greater electricity use intensity.

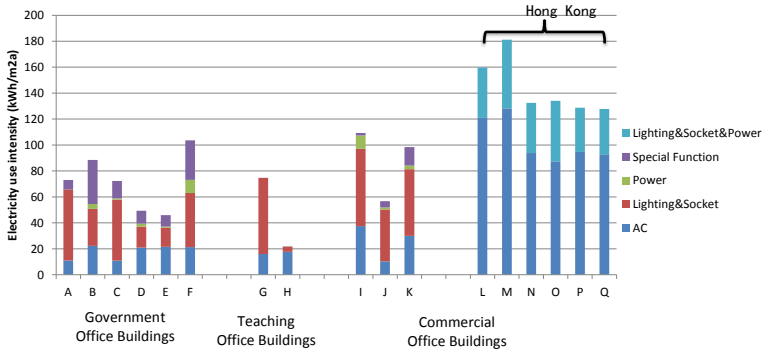


Figure 6 Electricity use intensity of large office buildings in Beijing and Hong Kong

Note：Power refers to utilities equipment like elevators; AC refers to HVAC equipment.

2.2 Monthly distribution of lighting energy use

Table 1 shows the months with the maximum and minimum daily lighting energy use for the 17 buildings. It cannot be judged statistically from the results which months have the greatest or least daily lighting energy use.

Table 1 Months with maximum and minimum daily average lighting energy use

Buildings	The month with the maximum daily lighting energy use	The month with the minimum daily lighting energy use	Buildings	The month with the maximum daily lighting energy use	The month with the minimum daily lighting energy use
A	7	4	H	3	8
B	7	9	I	12	1
C	12	5	J	11	8
D	4	5	K	12	1
E	11	5	M	2	3
F	7	10	N	7	12
G	12	10	O	8	2
R	9	5			

2.3 Daily distribution of lighting energy use

The hourly lighting energy use for a typical workday for Building F is shown in Figure 7. The curve has dual peaks and can be divided into six time periods: 1)Night Period; 2)Going-to-work Period:; 3)Morning Period; 4)Noon-Break Period; 5)Afternoon Periodl; 6)Off-Work Period.

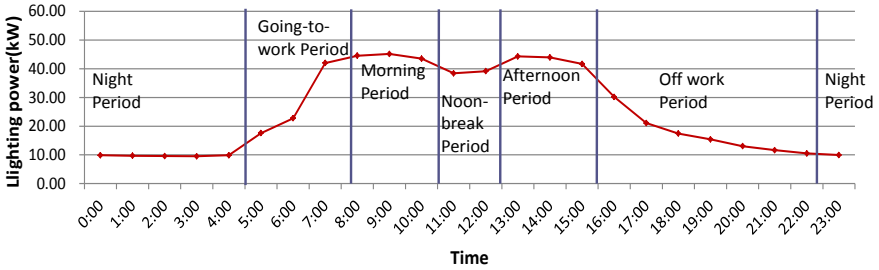


Figure 7 Curve of lighting power for a typical workday

The six periods can be divided into two categories:

1. Constant Power

Morning Period, Noon-break Period, Afternoon Period and Night Period are periods that can be represented by a flat curve with a constant lighting power. Table 2 lists the maximum coefficient of variation for each of the four periods. It indicates that the variation can be ignored.

Table 2 Maximum coefficient of variation for the four constant power time periods

	Morning Period	Noon-break Period	Afternoon Period	Night Period
Coefficient of variation V_σ	0.22	0.13	0.25	0.31

Note: $V_\sigma = \sigma/x$, where V_σ is the coefficient of variation, σ is the mean square deviation, and x is the average value

2. Variable power

The daily distribution of lighting energy use during the Going-to-Work and Off-Work periods satisfies an exponential curve. Wang et al (2005) proved, with measured data, that the probability of

a certain number of people (represented by k) arriving during a certain time period fits a Poisson distribution:

$$P\{X = k\} = \frac{\lambda^k}{k!} e^{-\lambda}$$

$\lambda = \frac{1}{T}$, where T is the average time before k people arrive the office. So the probability of some people arriving during a certain time period fits $P = P\{k > 0\}$, which is an exponential distribution. And the probability of lighting turning on is related to the probability of people arriving. During the Off-Work Period, the probability of people leaving the office can be represented by an exponential distribution, which means that the probability of people in the office is calculated as $P = 1 - P\{k > 0\}$.

Taking Going-to-Work period as an example, using the least square regression model, confidence levelα= 0.05 is assumed, and the functional form is set to the exponential distribution. The results are shown in Figure 8. From the regression curve, almost all the data is within the confidence interval, which proves that the curve fitting is good.

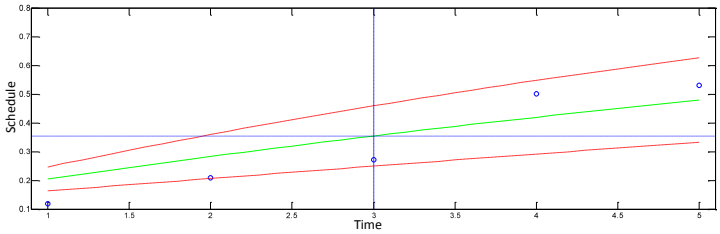


Figure 8 The daily regression curve during the Going-to-Work Period [λ=0.89]

3 Annual distribution of lighting energy use

From the spread of hourly lighting use from a single lighting branch shown in Figure 9, it can be seen that during one year the lighting energy use during these periods is not constant.

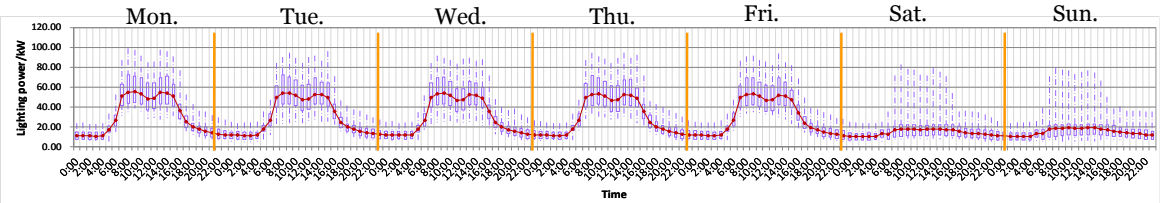
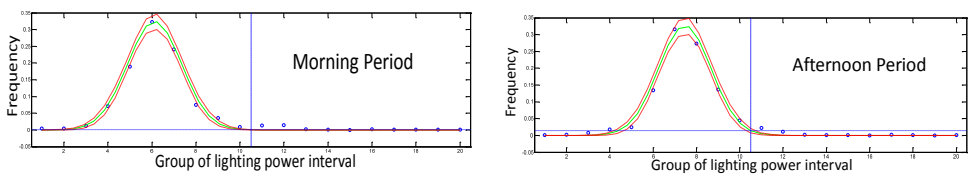


Figure 9 Annual hourly lighting energy use

Regression analysis is used to verify the distribution characteristic, as shown in Figure 10. Most data are within the confidence interval, which proves that the annual variations of the lighting power during each of four periods can be represented with a normal distribution.



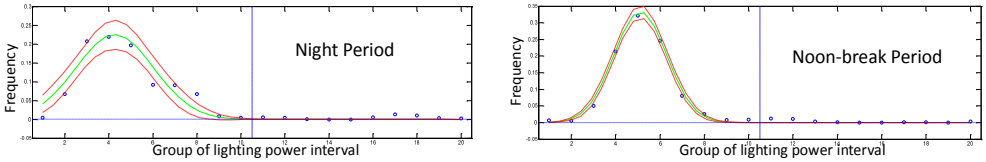


Figure 10 The normal distribution of the lighting power

DISCUSSION

A model of the whole-building lighting energy use was developed based on the daily lighting curves and the annual distribution properties. This model is applicable to large office buildings, where the lighting energy use has almost no relationship with outdoor illumination, but has a close relationship with the occupancy schedule. Only the lighting energy use on a typical workday is simulated here. The simulated results of a lighting branch in Building A are shown in Figure 11. With the consideration that simulation aims to represent the most typical scenarios in reality, the data edges of this quartile graph are the data points at the probabilities of 95% and 5%. It can be seen that the simulated daily lighting curve agrees quite well with the curve from the measured data. The annual distributions of each period are also described.

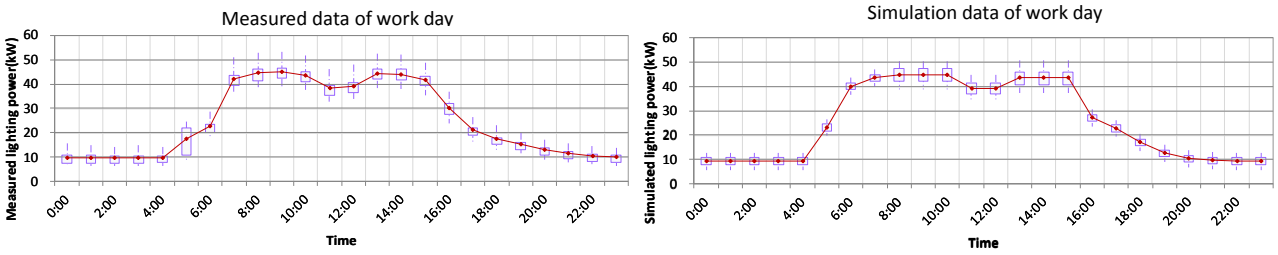


Figure 11 Comparison between the simulated and measured lighting energy use

CONCLUSION AND IMPLICATIONS

This paper analyzed the main characteristics and major influencing factors of lighting energy use in large office buildings, based on measured lighting energy use of 17 large office buildings in Beijing and Hong Kong. It is important to describe the daily lighting profiles accurately in order to represent the various characteristics of lighting energy use in large office buildings. A stochastic lighting model was developed to quantify the uncertainty of occupant behavior. This paper focused on the description of lighting energy use curves.

Main findings in this study include:

1、In large office buildings, the lighting energy use is mainly affected by the occupant schedule, and the influence of outdoor illumination is very limited.

2、In large offices, the time when lights are turned on is closely correlated with the time when most occupants arrive. While turning off lights is related to the time most occupants leave. Accurate prediction of the presence of occupants in offices is crucial to predict lighting energy use.

3、Lighting is a major electric end-use in large office buildings. The annual lighting energy use per square meter is similar for large offices in Beijing and Hong Kong.

4、Poisson and normal distributions can accurately describe the stochastic properties of daily lighting power curves and annual variations.

5、A whole-building lighting energy use model is developed based on daily lighting curves and annual distribution of lighting power levels. The model is verified using measured lighting energy use from an actual building.

Future work can be done to improve the simulation accuracy of the annual distribution of lighting power levels for the Going-to-Work and Off-Work periods. A lighting model for weekends can also be developed and verified.

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