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

In 2011, buildings consumed 28% and 41% of total primary energy in China and the U.S. respectively. The building sector plays a key role in achieving energy goals of the two largest economies in the world. The U.S. aims to save 20% of energy by 2020 for existing commercial buildings, and to reach net-zero energy for new commercial buildings by 2030. China aims to reduce energy use per unit of GDP by 16% as part of the '12th Five-Year Plan' from 2011 to 2015. Among all commercial buildings (often referred to public buildings in China), office buildings are the most common type in the U.S. and China. Large-size office buildings with a total floor area of more than 10,000 m^2, have a higher energy use intensity (EUI) than smaller buildings, due to higher occupancy levels and higher plug-loads. Furthermore, the total floor area and energy use of large office buildings in China are rising, which poses a strong challenge but also an opportunity for energy savings.

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. Figure 1 and Figure 2 show energy use profiles of typical large office buildings in both countries. Figure 1 was compiled from sub-metering the electricity end-use of dozens of large office buildings in Beijing, China. Figure 2 was based on 130 large office buildings in the California Commercial End-Use Survey (CEUS 2006).

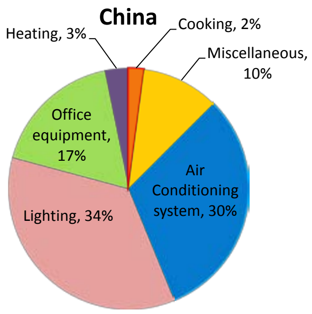

Figure 1 Electricity end-use profile of typical large office buildings in Beijing, China

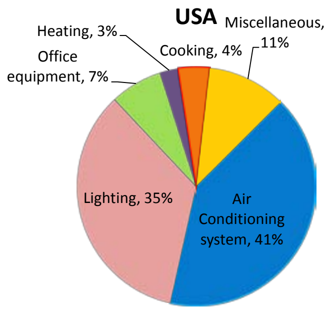

Figure 2 Electricity end-use profile of typical large office buildings in California, U.S.

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 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. Due to the limited amount and source of measured data, the complete characteristics of lighting energy use and influencing factors are unclear. In China, a common method to predict lighting energy use involves combining lighting power density information with lighting schedules. Most studies on office buildings use lighting power density levels from design standards. For example, the Chinese design standard for energy efficiency of public buildings prescribes lighting energy use levels in large office buildings of: 11 W/m^2 for general offices and meeting rooms (18 W/m^2 for high-grade offices), and 5 W/m^2 for corridors (Yu et al 2010, Wen 2009, Zhu et al 2009, Liu 2010, Wang 2010). In several studies, the lighting power densities were measured between 5 and 25 W/m^2 (Yan and Xu 2009, Zhang 2009, Yang and Zhang 2009, Chen 2007, Xu and Zhang 2006).

In other studies, lighting schedules are selected from the recommended occupant schedules in the same Chinese design standard (Wen 2009, Wang 2010). 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.

Methodology

The research method in this paper is shown in Figure 3. 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: through the comparison among different buildings, understand the current situation of lighting energy use in total quantity, per square meter and percentage of total energy use in large office; 2) monthly distribution: classify the lighting energy use by month and discuss the characteristics of monthly changes; 3) daily feature: average the lighting energy use according to different time of the day to obtain the daily average lighting energy use curve, and analyze the distribution of lighting energy use and discuss variations of daily profile; and 4) annual distribution: classify the lighting energy use according to different days of a week, then use the quartile figure to understand the hourly variations within a day. 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.

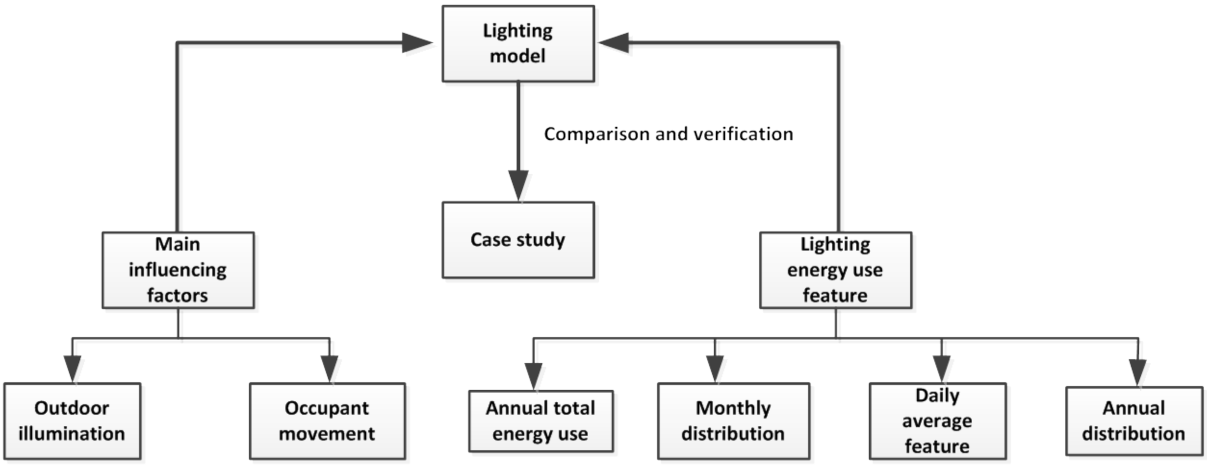

Figure 3 Research route

Analysis of influencing factors

The influence of outdoor illumination

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

To assess the influence of outdoor illumination, the lighting energy use of the basement floors and the above-grade floors is compared. The basement and the above-grade floors are within the same building, but the basement floors are not exposed to outdoor light. The basement floors and the above-grade floors are served by two separate lighting branches, and most areas of these floors are offices with the same occupant density of 10 m^2/person. There are no daylighting controls or any other automatic lighting controls (occupancy sensors) for the building. Building operators switch off all the lights at night when the building is no longer occupied.

The lighting energy use is shown in Figure 4. 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 can be seen that the shapes of the average lighting power curves are almost the same, which reveals that the outdoor illumination has no obvious effect on the shape of the average lighting power curves in large office buildings. The discrete range of lighting power is higher in the above-grade areas, but due to a lack of detailed information about the offices (such as the job category of the occupants) it is hard to define the influence of outdoor illumination on the fluctuations in magnitude of the lighting energy use.

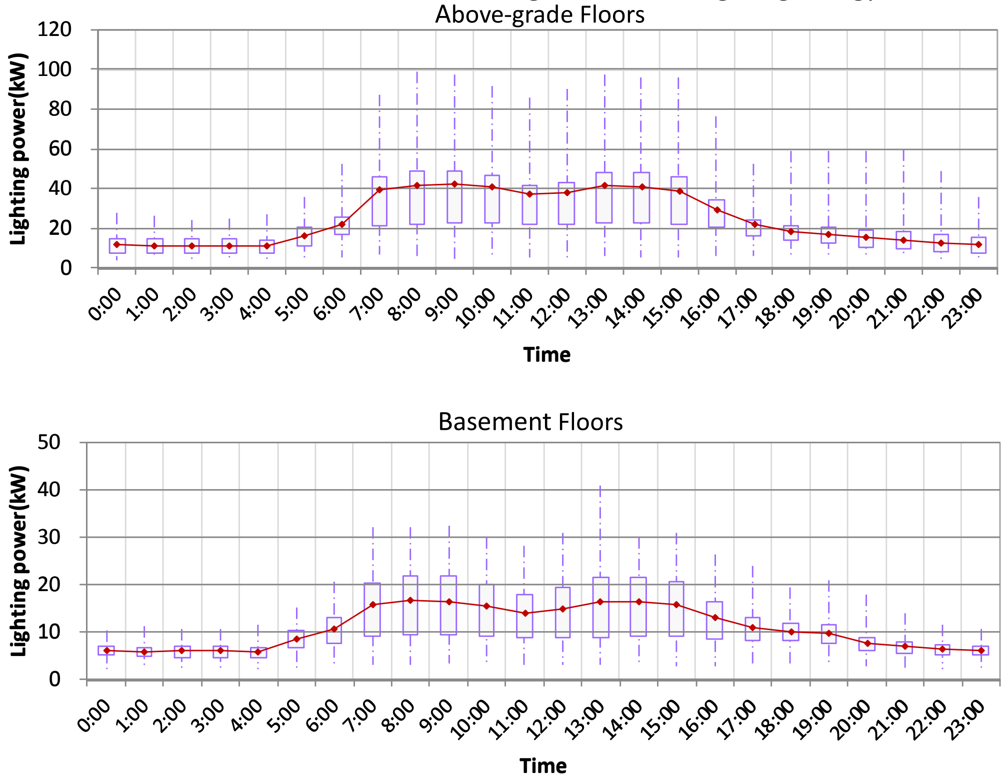

Figure 4 Comparison of lighting energy use between the basements and the above-grade areas

Comparison of lighting energy use between seasons

To further study the influence of outdoor illumination, the lighting energy use between different seasons is compared. This was to ascertain the effect of natural lighting duration and outdoor illumination levels on building lighting energy use. Using data from the lighting branch serving the above-grade floors, the recorded lighting power for each week of the four seasons was averaged to obtain the four weekly lighting profiles as shown in Figure 5. The natural lighting duration and outdoor illumination vary with season. However, their impact on lighting energy use cannot be identified. The lighting energy use in the different seasons follows the same curve, which adds further proof that outdoor illumination has no obvious influence on the shape of the indoor lighting energy use curve.

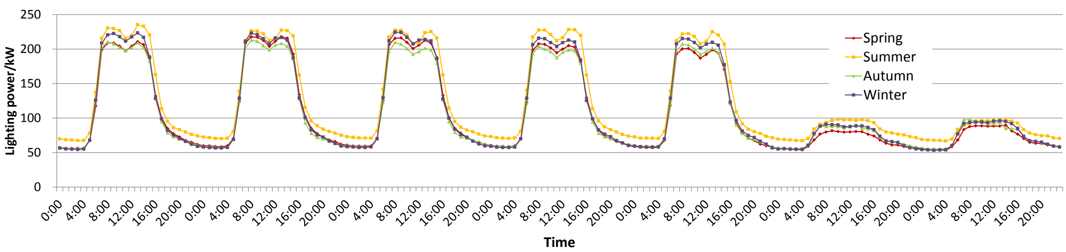

Figure 5 Weekly profiles of average lighting energy use for the four seasons

It can be concluded that outdoor illumination has no noticeable influence on the total lighting energy use. Besides the absence of automatic daylighting or occupancy controls, probable explanations for this phenomenon are: 1) the lighting operation schedules are almost the same among large office buildings, 2) large office buildings have a smaller fraction of perimeter floor area exposed to daylight, and 3) the effect of occupants manually turning off or turning down artificial lights due to available daylight is very limited.

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. The average lighting power draw on workdays and weekends are calculated and shown in Figure 6 and Figure 7. 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.

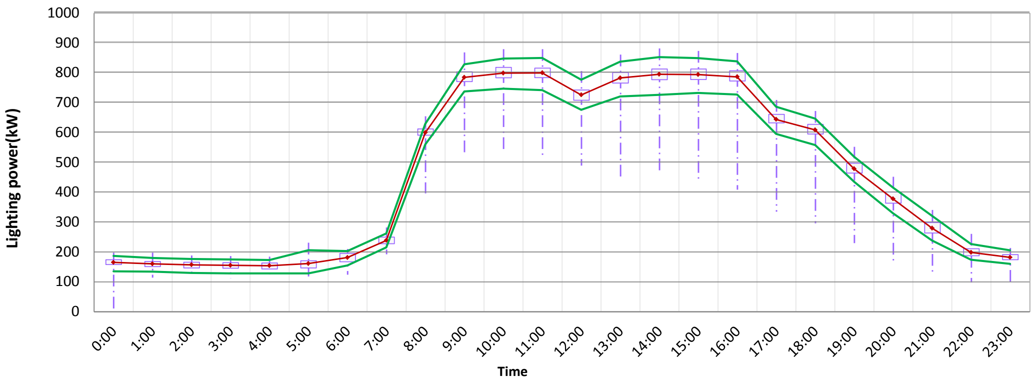

Figure 6 Average lighting power draw on workdays

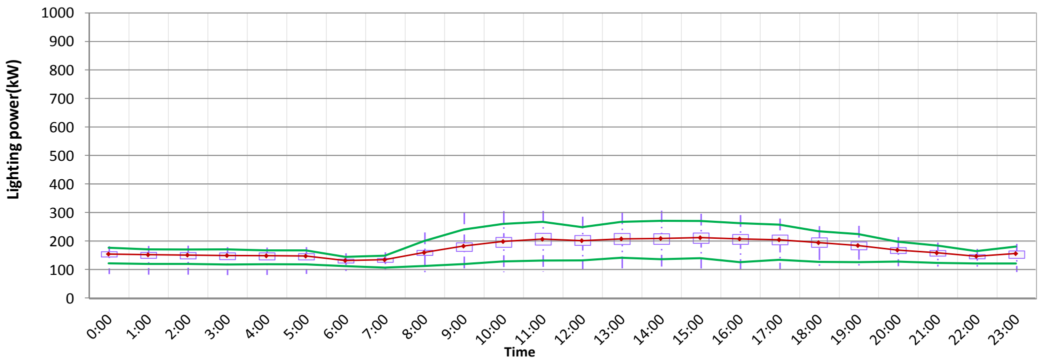

Figure 7 Average lighting power draw on weekends

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.

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. Three time scales are used: annual, monthly, and a typical day. A lighting energy use model is then developed based on the results.

Annual lighting energy use

The electricity end-use intensities are calculated and shown in Figure 8. It can be seen that the offices in Hong Kong have greater electricity use intensity. The lighting energy use intensities are around 40 kWh/m^2 per year among all the office buildings, except for a few government buildings and teaching office buildings. For the office buildings in Beijing, lighting consumes about 40% of the total building electricity energy; while the percentages are lower for office buildings in Hong Kong due to the much higher electricity use for air conditioning. However, lighting is still a significant portion of the total electricity consumption. Since lighting is a major electricity end-use for large office buildings, it is crucial to identify and understand the characteristics of lighting energy use and develop robust models to calculate the lighting energy use.

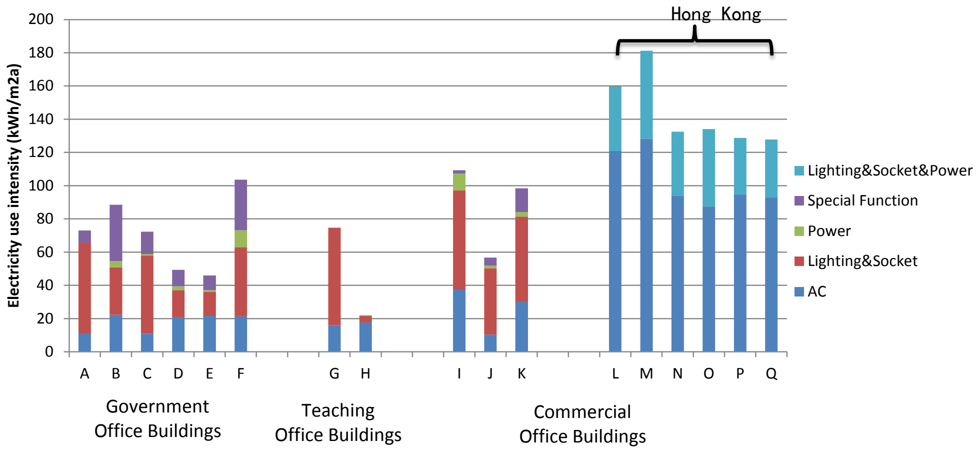

Figure 8 Electricity use intensity of large office buildings in Beijing and Hong Kong

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

Taking Building I in Beijing as an example, the variation of annual lighting energy use from 2008 to 2010 is shown in Figure 9. It can be observed that the annual lighting energy use is approximately constant, with a change of less than 5%, from the year 2008 to 2010. The small changes are mainly caused by the fixed installed lighting power, consistent occupancy rate and operation mode.

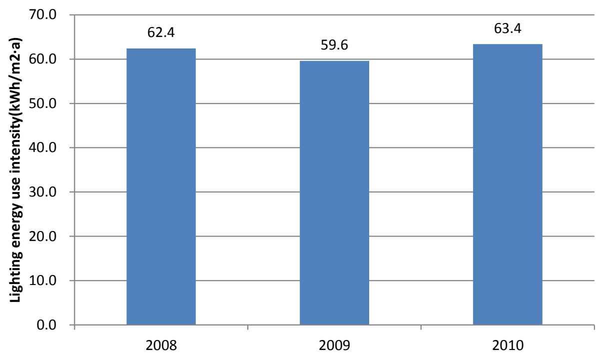

Figure 9 Variation of annual lighting energy use for Building I

Monthly distribution of lighting energy use

To look at the monthly trend of lighting energy use, the average daily lighting energy use for each month for the 17 office buildings is shown in Figure 10. The average daily lighting energy use is used instead of the monthly total because lighting energy use for each workday and weekend changes very little, and different months have different numbers of days.

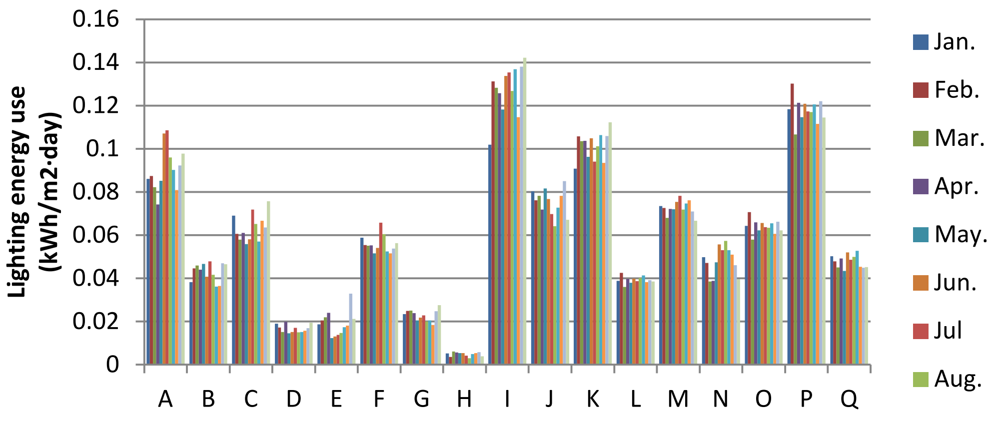

Figure 10 Monthly average daily lighting energy use

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. This confirms that lighting energy use in large offices has no obvious relation to the month of year.

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
A	7	4
B	7	9
C	12	5
D	4	5
E	11	5
F	7	10
G	12	10
H	3	8
I	12	1
J	11	8
K	12	1
M	2	3
N	7	12
O	8	2
P	2	2
Q	2	2
R	9	5

Daily distribution of lighting energy use

It is essential to look into the daily 24-hour distribution of lighting energy use to identify any pattern. The hourly lighting energy use for a typical workday for Building F is shown in Figure 11. The curve has dual peaks and can be divided into six time periods:

- Night Period: no occupants at night and only 24-hour running lights (emergency and security lights) are on;
- Going-to-work Period: occupants arrive successively, and the lighting power increases until it reaches the level of the Morning Period;
- Morning Period: occupants are working, and the lighting power remains at the highest level;
- Noon-Break Period: occupants go to lunch successively, and a portion of the lights are turned off, which leads to a decrease in total lighting power;
- Afternoon Period: similar to the Morning Period, occupants are working, and the lighting power stays at the highest level;
- Off-Work Period: occupants leave the building successively, and the lighting power decreases gradually to the level during the Night Period. Due to some occupants working overtime and possibly building cleaning services, the lighting power decreases at a slower rate than it increases in the Morning Period.

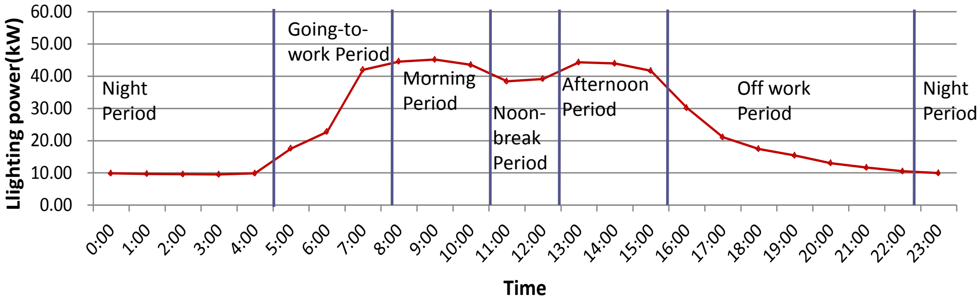

Figure 11 Curve of lighting power for a typical workday

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. A coefficient of variation is used to represent the variability of the data: $V_\sigma = \sigma/x$, where V_σ is the coefficient of variation, σ is the mean square deviation, and x is the average value. Table 2 lists the maximum coefficient of variation for each of the four periods.

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	0.22	0.13	0.25	0.31

From Table 2, it can be observed that the variability of lighting power draw is relatively small during the Morning, Noon-Break, Afternoon and Night Periods for one day. This indicates that the variation can be ignored, and a flat curve can be used to describe the lighting energy use for each of the four periods during one day.

2. Variable power

The daily distribution of lighting energy use during the Going-to-Work and Off-Work periods satisfies an exponential curve. In probability theory, if there is no deterministic physics model between dependent variable y and independent variable x, but based on knowledge, experience or observation, two variables indeed have certain relevance; this implies that multiple uncertain factors affect their relationship. The method to study such problem is to collect a series of x,y data, and build an empirical regression model, using statistical approaches (Jiang et al. 2005). This method is used for the analysis of the relationship between the time of day and the lighting energy use during the Going-to-Work and Off-Work periods in this paper.

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. As the probability of lighting turning on is related to the probability of people arriving, the higher the probability of people arriving, the higher the probability of turning on lights and the more lighting energy use.

Using the least square regression model, confidence level α = 0.05 is assumed, and the functional form is set to the exponential distribution. The results are shown in Figure 12. The y –axis represents the fraction value of the lighting power schedule. From the regression curve, almost all the data is within the confidence interval, which proves that the curve fitting is good.

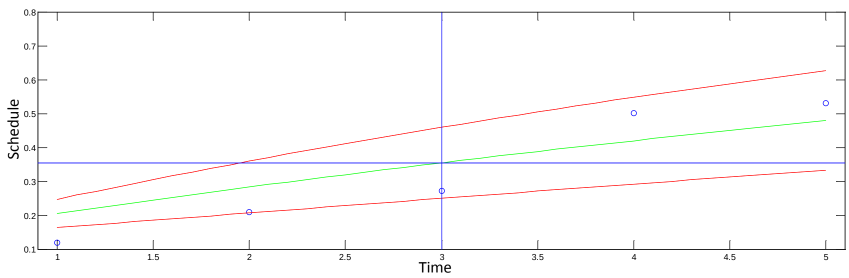

Figure 12 The daily regression curve during the Going-to-Work Period [λ =0.89]

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 $P = 1 - P\{k > 0\}$. Similarly, it is assumed that the probability of turning on lights approximates the probability of people being present in an office, so by regression analysis, λ =0.78. The regression curves are shown in Figure 13.

Although most data points are within the confidence interval, some data points are outside the range. The main reason is due to the assumption that the probability of people in the office equals the probability of people turning on lights. This assumption is reasonable if every person controls a single light, and the person turns on the light when entering the room and turns off the light when leaving the room. Therefore this is an approximation of reality.

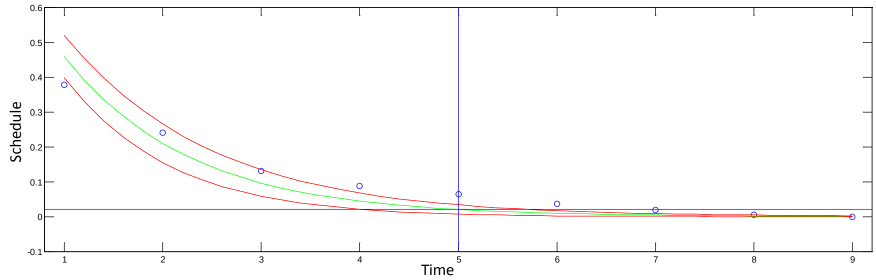

Figure 13 The daily regression curve during the Off-Work Period [λ =0.78]

Annual distribution of lighting energy use

As discussed above, during one day, the lighting energy use during the Morning Period, the Noon-Break Period, the Afternoon Period and the Night Period can be taken as constant values. However, from the spread of hourly lighting use from a single lighting branch shown in Figure 14, it can be seen that during one year the lighting energy use during these periods is not constant.

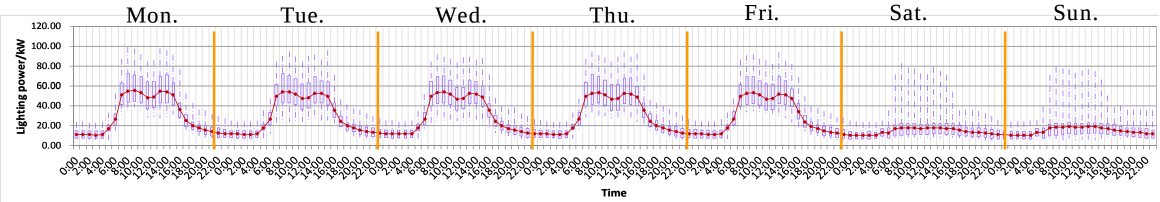

Figure 14 Annual hourly lighting energy use

Figure 15 shows the histogram of lighting power during the four periods.

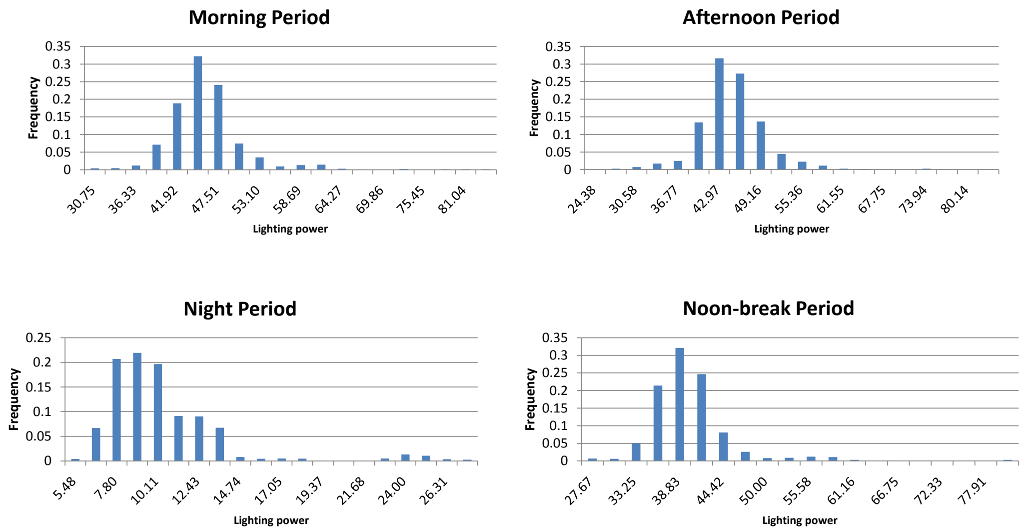

Figure 15 Frequency distribution of the lighting power

From Figure 15, it can be observed that the distributions approximate the normal distribution. So regression analysis is used to verify the distribution characteristic. α is set to 0.05, and the confidence intervals are shown in Figure 16. 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.

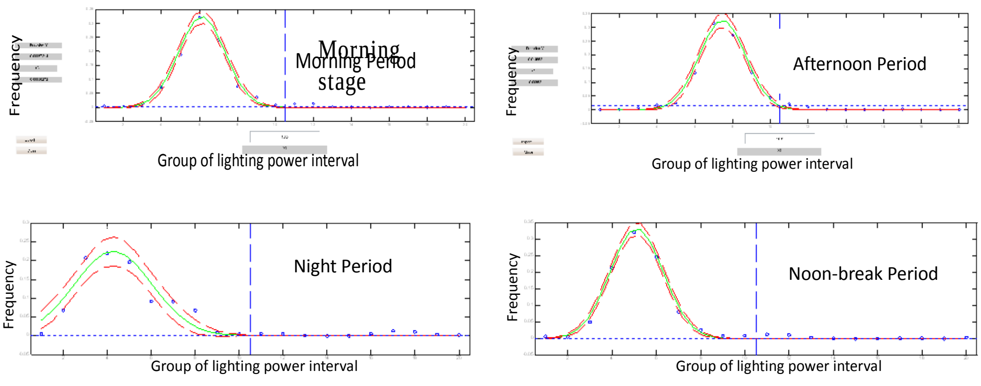

Figure 16 The normal distribution of the lighting power

Further analysis and verification is conducted on the time correlations between each period. Taking the time-relevant property between the Morning Period and the Afternoon Period as an example, the daily average lighting power of the Morning Period is subtracted from that of the Afternoon Period, and the distribution of the differences is studied. From the regression shown in Figure 17, it can be seen that the distribution of the differences is a normal distribution. This indicates that there exists a time-dependency, and the description of the Morning Period and the Afternoon Period should not be independent.

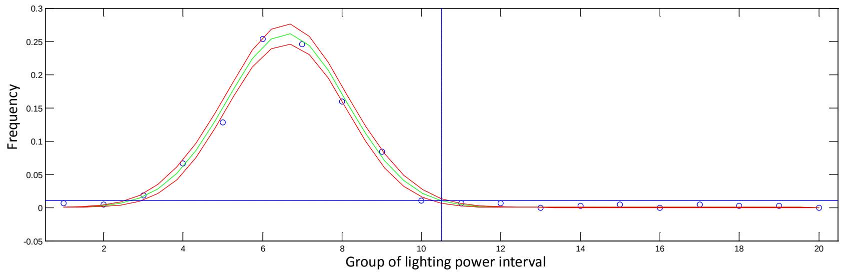

Figure 17 Regression of the differences of the daily average lighting power between the Morning Period and the Afternoon Period

However, there is no time correlation between the Morning Period and the Night Period as shown in Figure 18, so they can be described as two independent periods.

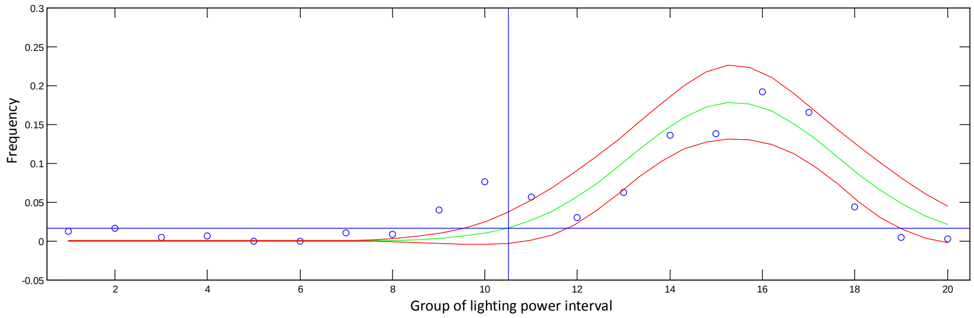

Figure 18 Regression of the differences of the daily average lighting power between the Morning Period and the Night Period

Case study

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 19. 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. However there are some discrepancies between the simulated and measured annual distributions of the data for the Going-to-Work and the Off-Work periods. This needs further work in order to improve the accuracy of the lighting energy use model.

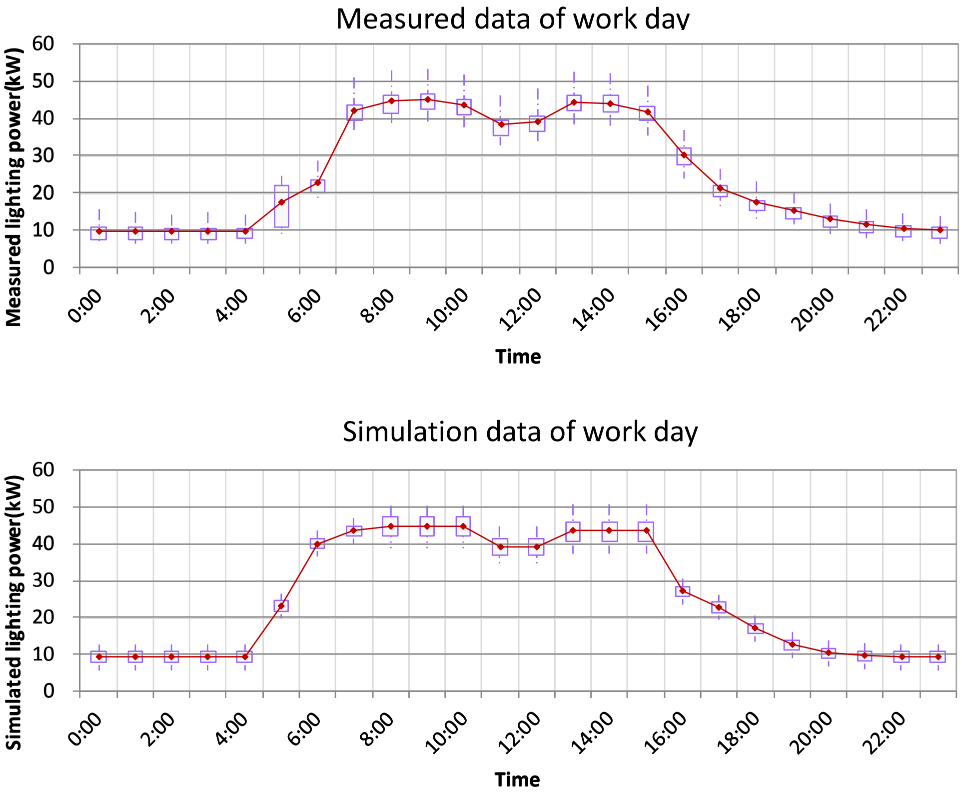

Figure 19 Comparison between the simulated and measured lighting energy use

Conclusions

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.

Acknowledgements

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