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Data analysis and stochastic modeling of lighting energy use in large office buildings in China

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Data analysis and stochastic modeling of lighting energy use in large office buildings in China

Abstract

Lighting consumes about 20% to 40% of the total electricity use in large office buildings in China. Commonly in building simulations, static time schedules for typical weekdays, weekends and holidays are assumed to represent the dynamics of lighting energy use in buildings. This approach does not address the stochastic nature of lighting energy use, which can be influenced by occupant behavior in buildings. This study analyzes the main characteristics of lighting energy use over various timescales, based on the statistical analysis of measured lighting energy use data from 15 large office buildings in Beijing and Hong Kong. It was found that in these large office buildings, the 24-hourly variation in lighting energy use was mainly driven by the schedules of the building occupants. Outdoor illuminance levels had little impact on lighting energy use due to the lack of automatic daylighting controls (an effective retrofit measure to reduce lighting energy use) and the relatively small perimeter area exposed to natural daylight. A stochastic lighting energy use model for large office buildings was further developed to represent diverse occupant activities, at six different time periods throughout a day, and also the annual distribution of lighting power across these periods. The model was verified using measured lighting energy use from the 15 buildings. The developed stochastic lighting model can generate more accurate lighting schedules for use in building energy simulations, improving the simulation accuracy of lighting energy use in real buildings.

Keywords: Building simulation; Energy use; Lighting modeling; Occupant behavior; Office buildings; Poisson distribution; Stochastic modeling

1. Introduction

In 2011, buildings consumed 28% of total primary energy in China. Therefore, building energy retrofit measures will play a key role in achieving China's energy goals. China aims to reduce energy use per unit of GDP by 16% as part of the '12th Five-Year Plan' from 2011 to 2015 [1]. Among all commercial buildings (often referred as 'public buildings' in China), the office building is the most common type in China. Office buildings with a total floor area of more than 20,000 m^2 are defined as large office buildings, and have a higher energy use intensity (EUI) than smaller buildings, due to higher occupancy levels and higher plug-loads [1]. Furthermore, the total floor area and energy use of large office buildings in China are on the rise posing a strong challenge but also an opportunity for energy savings.

In China, lighting electricity use in large office buildings represents about 20% to 40% of the total electricity use in buildings [1]. This fact has caught the attention of practitioners, researchers, and policy makers. Studies have shown that the two main factors affecting lighting energy use are outdoor illuminance and occupant behavior [2-10]. From field studies and computer simulations, it has been concluded that lighting energy use is correlated with outdoor illuminance. When the outdoor illuminance is above a certain level, people working around perimeter zones with access to natural light are less likely to use artificial electrical lights, and the artificial illuminance needed to meet design illuminance levels is lowered [2-6]. However, other studies have shown that occupants exert a crucial influence on lighting energy use, regardless of illuminance. Through case studies of actual buildings, Yun et al. [7] found that in open-plan offices, lighting energy use was not influenced by outdoor illuminance, but was strongly dependent on the indoor activities of the occupants. Yun et al. [8] demonstrated that outdoor illuminance was not a statistically significant factor affecting indoor lighting energy, rather the operation of lighting was more strongly correlated with the time of day. Additionally, other studies have also found that in offices without daylighting control, occupant use of electrical lighting was more dependent upon whether the room was occupied, than the outdoor illuminance [9-10].

The above studies [2-10] on lighting energy use were mostly focused on small office and residential buildings, with the research findings greatly dependent on building layout and daylighting control systems. The analysis methods and conclusions from these studies [2-10] provide some baseline understanding of the role of illuminance on lighting energy use in buildings. However, due to limitations associated with the building layout and limited measured data, the complete picture of lighting energy use and the influencing factors, remains unclear.

One common method to predict lighting energy use, includes combining lighting power density information with lighting schedules. The office building design specifications in China require the standard value of illuminance to be 300 lux for general offices and 500 lux for high-grade offices, when measured on a horizontal plane at a height of 0.75 m [11]. Design standards provide an easy guide, when actual lighting power density levels are unknown. For example, the Chinese design standard for the energy efficiency of public buildings, prescribes lighting energy use levels at 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 [12-14]. Several studies measured lighting power densities, with results ranging between 5 and 25 W/m^2 [15-17]. However, other studies used lighting schedules selected from the recommended occupant schedules, outlined by Chinese design standards [14]. This resulted in the generated lighting schedules which were too simplistic and lacked verification against measured data [18]. Also, this lead to large discrepancies between simulated and measured lighting energy use [19-20]. Furthermore, the annual variation of actual lighting energy was not captured.

More complex lighting energy use models have been reviewed. Hunt [21] 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 lights increased only when the illuminance of the working surface was below 100 lux. Newsham [22] 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 [23] improved the Lightswitch model (named Lightswitch-2002) to calculate the probability of occupants arriving and leaving offices, and the related probability of the occupants turning on and off lights. Reinhart used the Lightswitch-2002 model to evaluate the energy savings from different lighting control strategies. Joakim Wide´n et al [24] used Markov chains to estimate the probability of occupant movement. 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 [21, 23] and residential buildings [24], suggesting a strong need to conduct more research on lighting energy use in large office buildings.

Based on hourly measured data from 15 large office buildings in China, this study analyzed the characteristics of lighting energy use in large office buildings, focused on acutely capturing the daily and seasonal lighting energy use patterns. A stochastic model was developed to effectively capture the random-natured characteristics of lighting energy use. The model accounted for the time-varying nature of lighting energy use, including peak usage, at certain times of the day. Due to the limitation of source data, the analysis and lighting energy use models developed are only applicable to large office buildings without daylighting controls or any other automatic lighting controls (such as occupancy sensors). However, the experimental and modeling components of this project provide a better understanding of lighting energy use in large office buildings in China and as a whole, advance the state of knowledge of occupant behavior on building energy consumption.

The four main research objectives are as follows:

(1) Understand the main characteristics of lighting energy use in large office buildings in China.
(2) Develop models to represent the stochastic nature of lighting energy use related to occupant behavior.
(3) Improve the accuracy of simulated lighting energy use in large office buildings using the

developed stochastic lighting models.

(4) Provide some insights into retrofit strategies for lighting systems in order to reduce lighting energy use in large office buildings in China.

2. Methodology

Fig. 1 illustrates the research route employed in this study. There are five steps, marked as A to E (Fig. 1). The lighting energy use data from 15 large office buildings was measured with sub-metering systems in Beijing and Hong Kong (Box A). The data collected was then used to build the data source of this study (Box B). The characteristics and influencing factors of lighting energy use in large office buildings were determined through the analysis of the lighting energy use data (Box C). After having an understanding of the characteristics and main influencing factors of lighting energy use, a whole-building stochastic model was developed (Box D). The model applied statistical analysis and probabilistic models to represent the daily distribution, annual distribution and time-dependent properties of lighting energy use. The intent of the model was to be able to predict lighting energy use in large office buildings without daylighting controls or any other automatic lighting controls. For validation, the model was applied to all the 15 buildings to simulate the lighting energy use and compare the simulated results with the measured data (Box E).

The analyses of the characteristics (Box C) focused on four timescales:

1) Annual lighting energy use: Yearly lighting energy use was compared in order to identify the characteristics of annual variations.
2) Monthly lighting energy use: Lighting energy use was classified by month in order to identify the characteristics of monthly variations.
3) Daily lighting energy use profile: Daily average hourly lighting energy use curve was analyzed in order to identify the characteristics of daily 24-hour profiles.
4) Annual variation of hourly lighting energy use: Variation of hourly lighting energy use on different days of a week across a whole year was used to identify the characteristics of annual hourly variations.

Then, the two main factors influencing lighting energy use, outdoor illuminance and occupant behavior, were analyzed. To determine the influence of outdoor illuminance on lighting energy use in large office buildings, the lighting energy use between different seasons and different building levels (above-ground areas and basements) were compared. The effect of occupant behavior was analyzed by comparing lighting energy used on different types of days (workdays and weekends), and by comparing lighting energy use under different occupancy schedules.

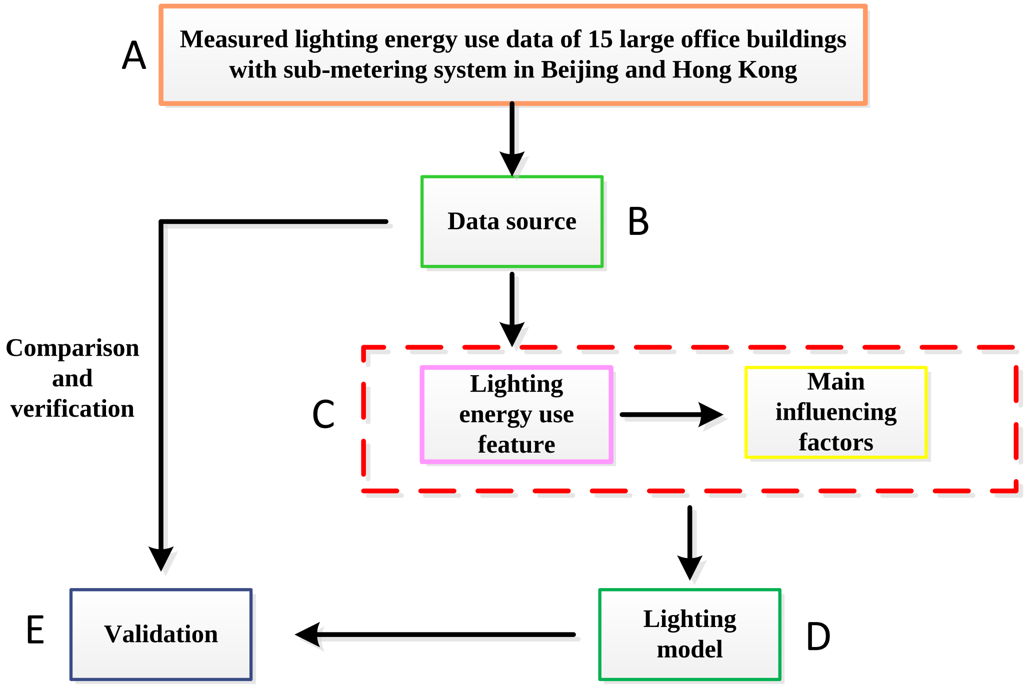


Fig.1. Research route

3. Data collection

Field data of lighting energy use was collected from 15 large office buildings in Beijing and Hong Kong, China. Automatic building energy submetering systems were installed in each building and recorded the lighting energy consumption of each lighting branch within a building using a sampling frequency of one hour. The experimental uncertainty of the lighting power was maintained within ±5%. Key characteristics of the size, location and function of the investigated buildings are further summarized in Table 1. All 15 buildings had a gross floor area of more than 20,000 m^2, the threshold which defines large office buildings in China. Each building had a relatively small perimeter area, especially when compared with small office buildings. There were no daylighting controls or any other automatic lighting controls (e.g. occupancy sensors) within the 15 buildings. Occupants manually turn on and off the lights according to their visual comfort needs or behavior. Commonly, building operators would switch off all the lights at night when a building was no longer occupied. The layout and lighting control of the buildings sampled were representative of typical large office buildings in China.

Fig. 2 and Fig. 3 show the annual lighting energy use intensity and the ratio of lighting consumption to building total electricity. The annual lighting energy use intensity varied from 15 to 70 kWh/(m^2·a). The ratio of lighting consumption in different office buildings varied from approximately 30% to 70%. With the exclusion of some consumption items (e.g. elevator, heating station), the ratio in some buildings exceeded the projected range of 20% to 40% [1]. The results from the data collection, indicate that the lighting energy consumption is an important component in the total energy consumption of large office buildings, and should be considered in greater depth.

Table 1. Key characteristics of the investigated 15 office buildings

Building	A	B	C	D	E	F	G
Building types	G	G	G	G	G	G	B
Year of construction	2004	2004	2005	1987	1985	1996	1989
Location	Beijing	Beijing	Beijing	Beijing	Beijing	Beijing	Beijing
Gross floor area (m^2)	37,000	33,000	24,000	39,000	29,000	42,000	54,000
Orientation of the front facade	North	East	East	South	East	East	South-East
Date of measurement campaign	2009	2009	2009	2009	2009	2007-2009	2007-2010
Photos							

Building	H	I	J	K	L	M	N	O
Building types	B	B	B	B	B	B	B	B
Year of construction	2004	1985	1988	2003	1993	1994	1998	1999
Location	Beijing	Beijing	Hong Kong	Hong Kong	Hong Kong	Hong Kong	Hong Kong	Hong Kong
Gross floor area (m^2)	39,000	62,000	83,000	29,000	99,000	82,000	45,000	64,000
Orientation of the main entrance	South-West	South	South-East	South-West	West	South	East	West
Date of measurement	2009	2009	2009	2009	2009	2009	2009	2009

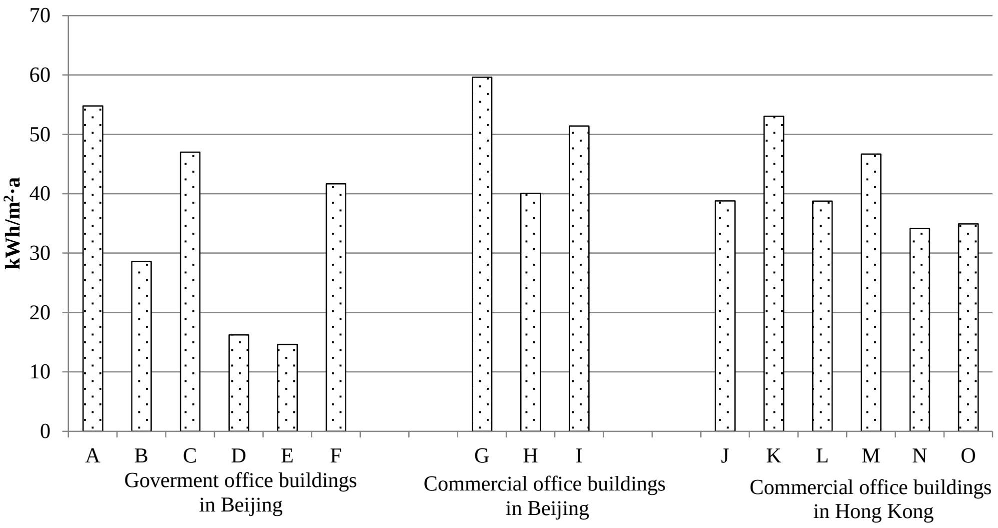


Fig. 2. Lighting energy consumption in 15 large office buildings

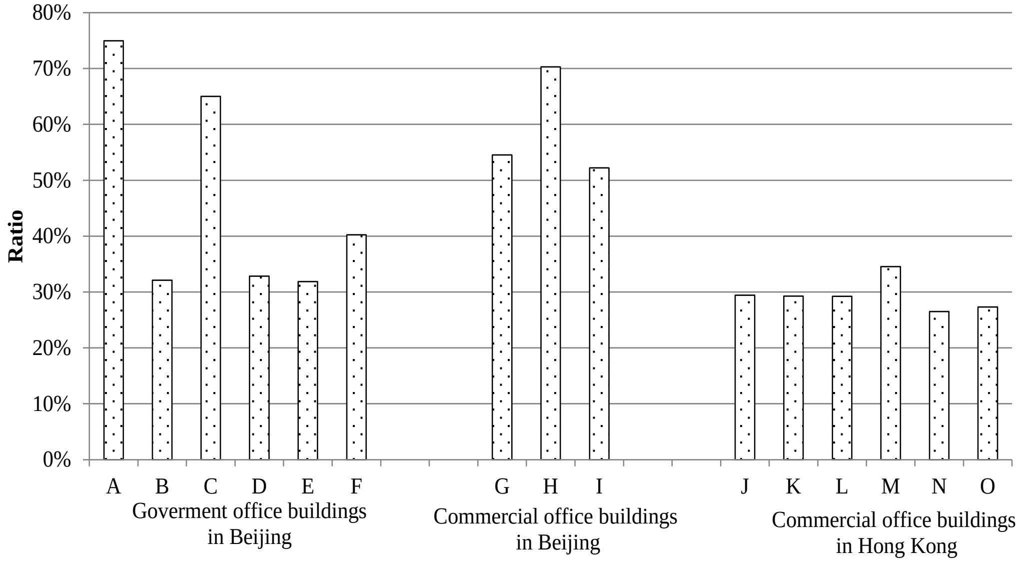


Fig.3. The ratios of lighting consumption to building total electricity use in 15 large office buildings

4. General characteristics of lighting energy use

Based on the measured data from the 15 large office buildings in Beijing and Hong Kong, general characteristics of the lighting energy use were analyzed at annual, monthly, and daily timescales.

4.1. Annual lighting energy use

Building G in Beijing, with the longest period of measured lighting energy data, was used for the annual lighting analysis. Fig. 4 shows the year-to-year variation of lighting energy use from 2008 to 2010. It can be observed that the annual lighting energy use is approximately constant, with a total change of less than 5%, from 2008 to 2010. The relatively minor variation can be attributed to the fixed installed lighting power, consistent occupancy rate and steady habits of occupants to control the lights.

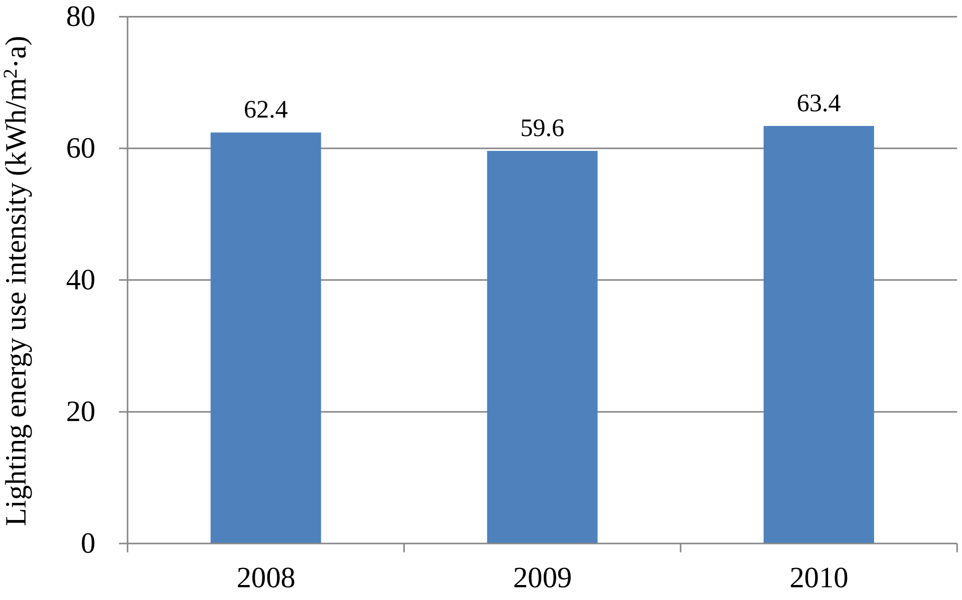


Fig. 4. Year-to-year variation of lighting energy use for Building G

4.2. *Monthly lighting energy use*

To investigate the monthly trend of lighting energy use, Fig. 5 shows the average daily lighting energy use curve for each month for the 15 office buildings. Each curve corresponds to one building, and the points on the curve represent the daily lighting energy use for each month in sequence. The average daily lighting energy use curve was used instead of the monthly total because different months had different numbers of days. Fig. 5 demonstrates no obvious monthly distribution pattern in lighting energy use in large office buildings. Additionally, it is difficult to determine a specific month where consumption would be expected to be the most (or least), with regards to lighting energy use.

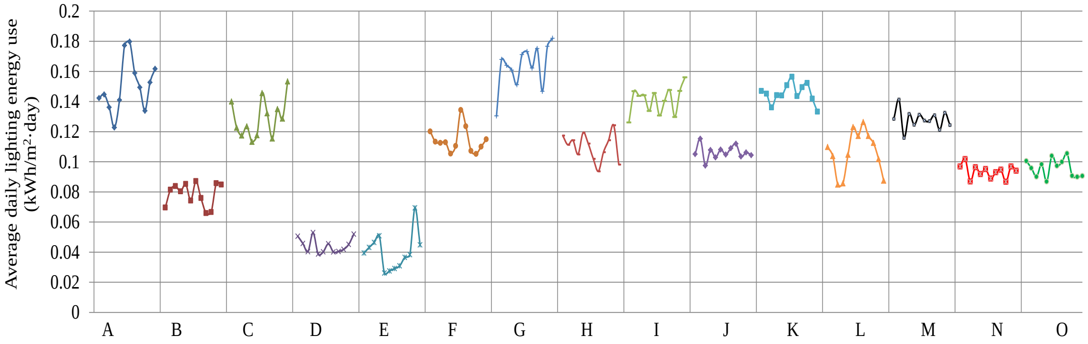


Fig. 5. Monthly average daily lighting energy use curves

The coefficient of variation was used to represent the variability in 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 of the lighting energy use intensity). Fig. 6 shows the coefficient of variation for the monthly lighting consumption in all the 15 buildings. The V_σ value for most buildings was about 0.1, while Building E had the greatest V_σ value of 0.3. The results reveal that the lighting consumption changed very little from month to month, for most buildings.

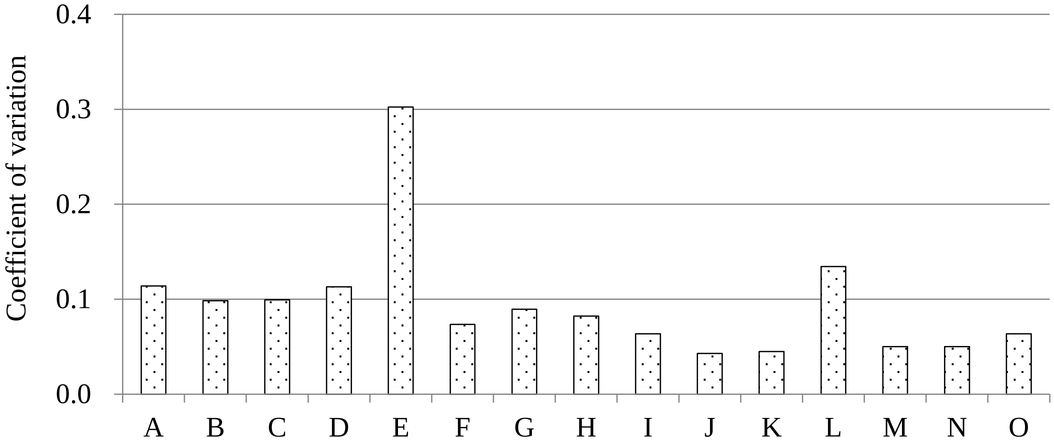


Fig. 6. The coefficient of variation for monthly lighting consumption

4.3. *Daily lighting energy use profile*

The daily 24-hour profile of lighting energy use data was further processed to identify potential patterns. Fig. 7 shows the hourly lighting energy use curve for a typical workday for Building G. The lighting power used in the following discussion represents the hourly average lighting energy use. The curve has dual peaks and can be divided into six time periods:

- The Night Period: no occupants at night and only 24-hour running lights (emergency and security lights) are on;
- The Going-to-work Period: occupants arrive successively, and the lighting power increases until reaching the output of the Morning Period;
- The Morning Period: occupants are working, and the lighting power remains at the highest level;
- The 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;
- The Afternoon Period: similar to the Morning Period, occupants are working, and the lighting power stays at the highest level;
- The Off-Work Period: occupants leave the building, 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 the rate at which it increases in the Morning Period.

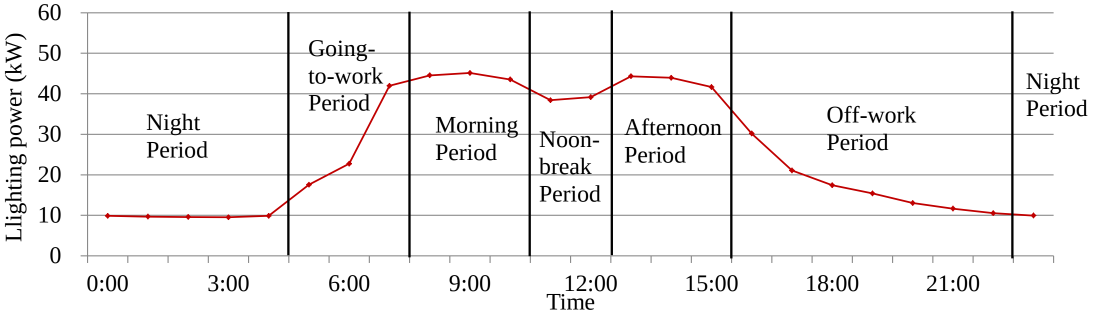


Fig. 7. Lighting power curve for a typical workday in Building G

4.4. *Annual variation of hourly lighting energy use*

Fig. 8 shows the statistical results of hourly lighting use from a single lighting branch in Building G. The red line in Fig. 8 represents the daily mean lighting power, the edges of the blue boxes are placed at the 25% and the 75% quartiles, and the maximum and minimum data points are presented. The lighting branch controls a building floor area of approximately 6000 m2. This lighting branch is common for the typical floor area in charge and lighting usage of occupants. The mean lighting power output for each day of the week was calculated and then averaged over a one-year period. It can be seen that during the one-year period the hourly lighting energy use during a typical weekday was not constant. For example, the average value of the lighting power at 11 am was almost the same across all the weekdays, but extreme and quartile values reveal that the value changed during the year timescale. Additionally, large differences in the average lighting power and the distribution between weekdays and weekends was also observed. The results reveal that the lighting energy use, on different days of the weekdays, followed similar patterns. However, the lighting energy use patterns on weekdays and weekends were quite different.

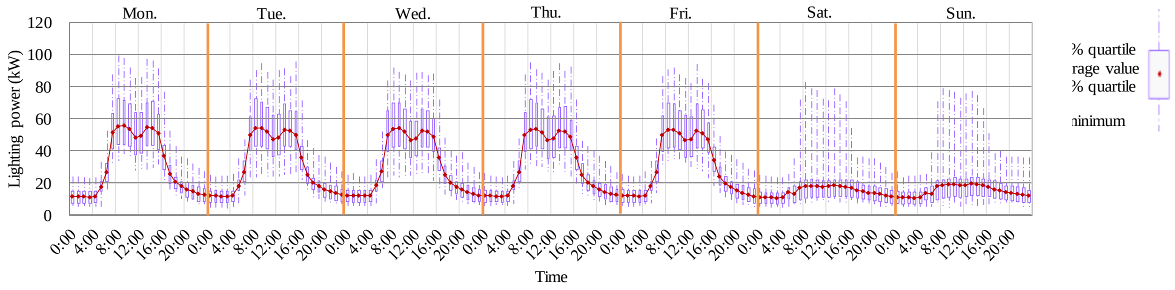


Fig. 8. Annual average hourly lighting energy use curves

5. Analysis of influencing factors

From the analysis of the average consumption and variation of lighting energy use at different timescales, the results suggest that there was no obvious yearly or monthly variation in lighting energy use. However the daily and annual distributions of lighting energy use follow certain patterns, which can be driven by two main influencing factors: the outdoor illuminance and occupant behavior.

5.1. Outdoor illuminance

5.1.1. Comparison of lighting energy use between the basement and the above-ground floors

To assess the influence of outdoor illuminance on the lighting energy use, the basement floor and the above-ground floors were compared. Building F was the only building with underground floors, so it was chosen for this analysis section. The basement floor and the above-ground floors were served by two separate lighting branches. Most of the space on each floor consisted of offices with the same occupant density of 10 m^2/person. The layouts of offices on the above-ground and basement floors were generally similar, but the offices in the basement had no access to outdoor light. There were no daylighting controls or any other automatic lighting controls (occupancy sensors) in the building. Building operators switch off all the lights at night when the building was no longer occupied.

Fig. 9 presents the lighting energy use for the basement and above-ground floors in Building F. Noticeable differences in energy use between the basement floor and the above-ground floors occurred mainly due to floor area differences. Similarities existed between the shapes of the average hourly lighting power curves, being both flat before the working time, gradually increasing during the 1 to 2 hours before working. A lunch hour can be inferred from the data due to a curve decrease around noon time. From about 3pm onward, the lighting power curves gradually decreased in parallel with people leaving work. The ending result showed the curve become flat, indicating all occupants had left the building. This phenomenon revealed that the outdoor illuminance had no obvious effect on lighting energy use in Building F. Fig. 9 also shows that the discrete range of lighting power was higher in the above-ground floors than the basement floor. However, due to the lack of detailed information about the use of the offices (such as the job category of the occupants), it was hard to justify the influence of outdoor illuminance on the fluctuations of the lighting energy use.

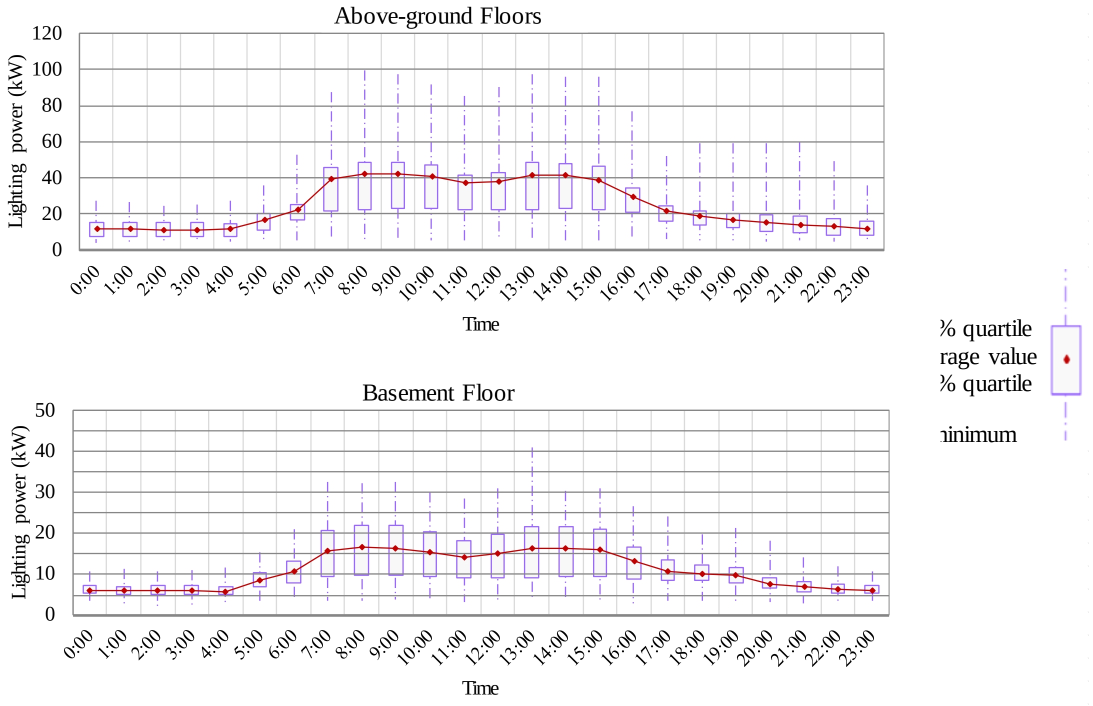


Fig. 9. Comparison of lighting energy use between the basement floor and the above-ground floors

5.1.2. Comparison of lighting energy use between seasons

To further study the influence of outdoor illuminance on the lighting energy use, different seasons were compared. The objective of this comparison was to ascertain more information on the effect of seasonal natural lighting duration and outdoor illuminance levels on building lighting energy use. Using data from the lighting branch serving the above-ground floors in Building F, the recorded lighting power for each week of the four seasons (spring, summer, winter and fall) was averaged to obtain four weekly lighting profiles as shown in Fig. 10. The seasonal variation of the natural lighting duration and outdoor illuminance had no identifiable impact on lighting energy use. Therefore, the lighting energy use in each season followed the same curve, which further confirmed that outdoor illuminance had no obvious influence on the shape of the indoor lighting energy use curve.

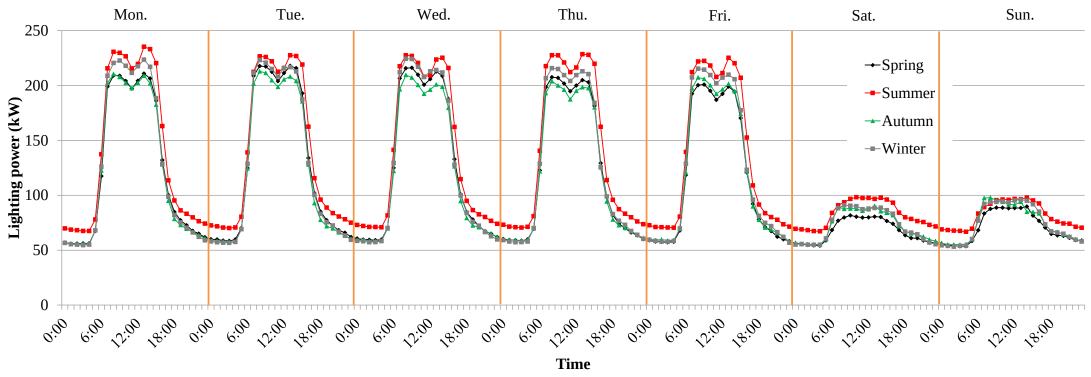


Fig. 10. Weekly profiles of average lighting energy use curves for the four seasons

It can be concluded that for large office buildings in China, the outdoor illuminance has no noticeable influence on the total lighting energy use. Apart from the absence of automatic daylighting or occupancy controls, potential explanations for this phenomenon are: (1) the large office buildings had a smaller fraction of perimeter floor area exposed to daylight, and (2) the action of occupants manually turning off artificial lights, due to abundant available daylight, was limited or ignored.

5.2. 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 was compared. Fig. 11 and Fig. 12 present the average lighting power draw on workdays and weekends, with the 95% and 5% probabilities reflecting more general trends. Distinct difference in occupant presence occurred between workday and weekends resulting in the lighting power on workdays being considerably higher than weekends. Different occupancy events such as arriving at work, going out for lunch, and leaving work were detected from the workday lighting power curve. On weekends, the discrete range of lighting energy use was much larger and a homogeneous lighting schedule cannot be easily detected, due to the uncertainties in the overtime hours worked and other undocumented weekend events.

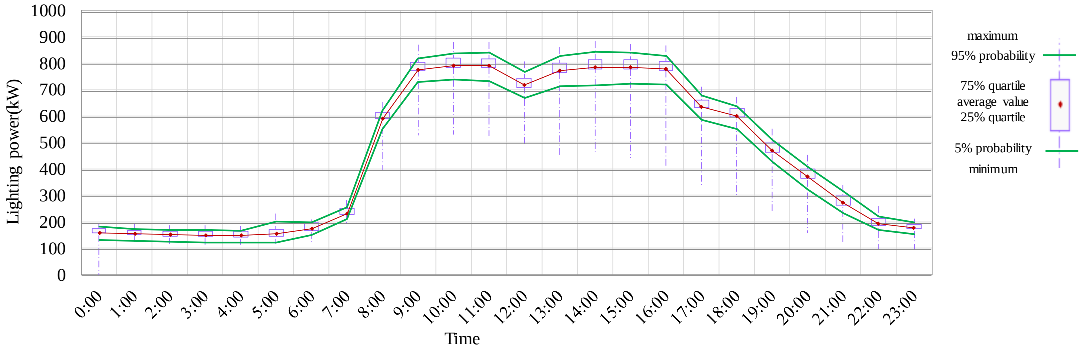


Fig. 11. Average hourly lighting power draw on workdays

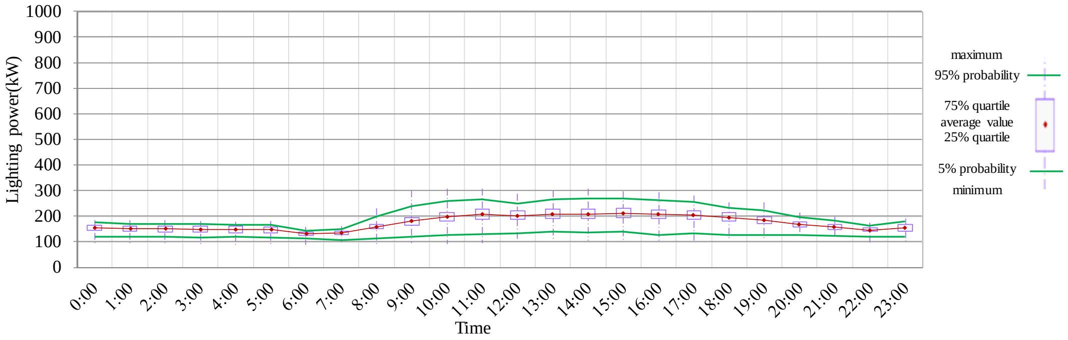


Fig. 12. Average hourly lighting power draw on weekends

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.

6. Stochastic modeling of lighting energy use

Based upon the collective information ascertained from the experimental data analysis, a clearer understanding of the main characteristics and influencing factors of lighting energy use in large office buildings, without daylighting controls or any other automatic lighting controls, could be inferred. With this knowledge, a stochastic model of lighting energy consumption was developed. The daily and annual lighting distributions were two main features of the lighting consumption in large office buildings and therefore were used to build the stochastic lighting energy use model.

6.1. Segmenting the daily lighting energy use profile

The daily 24-hour lighting consumption curve was divided into six time periods: the Night Period, the Going-to-work Period, the Morning Period, the Noon-Break Period, the Afternoon Period and the Off-Work Period. From this segmentation and according to unique properties associated with each period, the six periods were further divided into two categories, constant and variable power.

6.1.1. Constant Power

The four periods, the Morning Period, the Noon-break Period, the Afternoon Period and the Night Period, were represented by a flat curve with a constant lighting power. Table 2 lists the maximum coefficient of variation for each of the four periods.

Table 2. Maximum coefficient of variation of lighting energy use in the four periods

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

From Table 2, it could be observed that the variability of lighting power draw was relatively small during the four periods. This indicated 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 a day.

6.1.2. *Variable Power*

The daily distribution of lighting energy use, during the Going-to-Work and Off-Work periods satisfied an exponential curve, derived from probability theory and confirmed by experience that the two variables indeed had a certain relevance. However, multiple uncertain influencing factors created difficulties in building a deterministic physics model. Therefore, an empirical regression model, using a statistical approach would be one workaround to analyze of the relationship between the time of day and the lighting energy use during the Going-to-Work and the Off-Work periods, in this study. Wang et al [25] 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 as shown in Eq. 1.

$$P\{X = k\} = \frac{\lambda^k}{k!} e^{-\lambda} \qquad (1)$$

where $\lambda = \frac{1}{T}$ and T is the average time before k people arrive in the offices. Therefore, 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 lights being turning on is related to the probability of people arriving, the assumption was made that the higher the probability of people arriving resulted in a higher the probability of lights being turned on and thus could be linked to lighting energy use.

Using a least squares regression for an exponential distribution with confidence level $\alpha = 0.05$, the results were obtained and shown in Fig. 13. The scheduled value presented in the y-axis represents the hourly lighting power divided by the maximum lighting power. From the regression curve almost all of the data was within the confidence interval, confirming that the curve fitting technique was adequate. The RMSE (root-mean-square error) was 0.056.

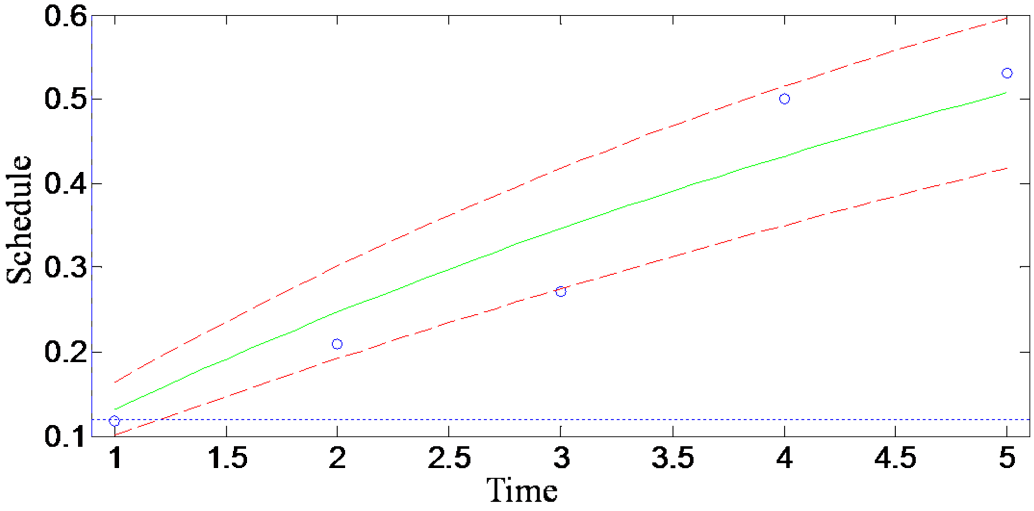


Fig. 13. The daily regression curve for the Going-to-Work Period [λ =0.89]

Note: The hollow circles are the input data; the green solid line is the regression curve; the red dashed lines mark the confidence interval

Moreover, during the Off-Work Period, the probability of people leaving the office could be represented by an exponential distribution, which meant that the probability of people in the office was calculated as $P = 1 - P\{k > 0\}$. Similarly, it was assumed that the probability of turning on lights approximated the probability of people being present in an office. Following the same probability analyses by regression, it was found that λ =0.78, with the regression curves presented in Fig. 14. The RMSE was 0.041.

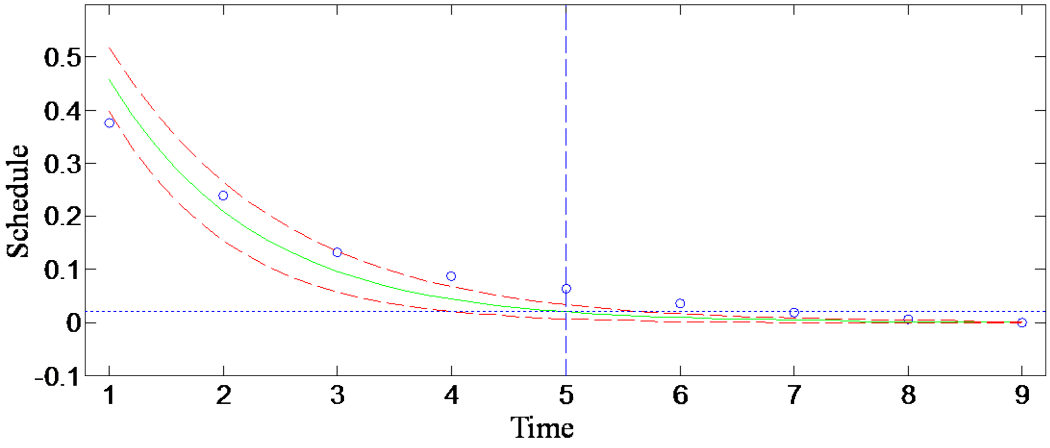


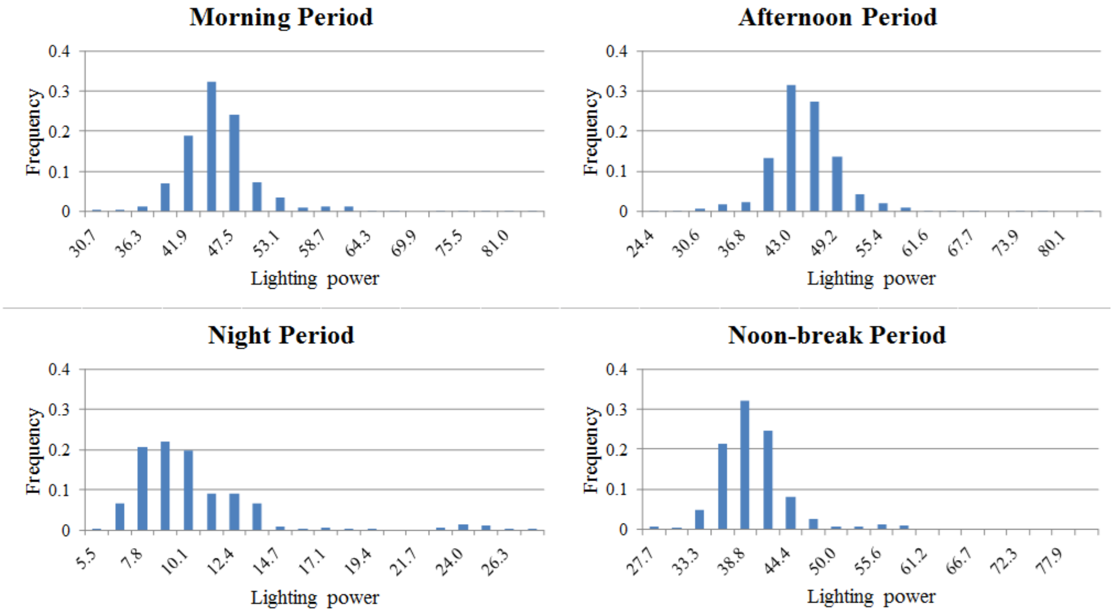
Fig. 14. The daily regression curve during the Off-Work Period [λ =0.78]

Note: The hollow circles are the input data; the green solid line is the regression curve; the red dashed lines mark the confidence interval

The assumption that the probability of people being present in the office equals the probability of people turning on lights, 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 technique is only a rough approximation of reality. The errors associated with this assumption are indicated by the data points which lie outside the interval.

6.2. Annual distribution of lighting energy use

Although the results indicate that constant values for the Morning Period, the Noon-Break Period, the Afternoon Period and the Night Period can be expressed, Fig. 8 shows that the lighting consumption across a whole year is not constant. Fig. 15 shows the bar charts of frequency distribution of lighting power during the four periods. The variation range of lighting power during each time period was divided into 20 groups, and the frequency of lighting power in each group was calculated.



Morning Period

Afternoon Period

Night Period

Noon-break Period

Fig. 15. Frequency distribution of the lighting power

From Fig. 15, it can be observed that the distributions approximated normal distributions with least square regression RMSEs of less than 0.06. A least square regression was performed using a confidence level α of 0.05. The confidence intervals are shown in Fig. 16. Most of the data lie within the confidence interval, which proves that the annual variations in lighting power used during each of the four periods can be represented with a normal distribution.

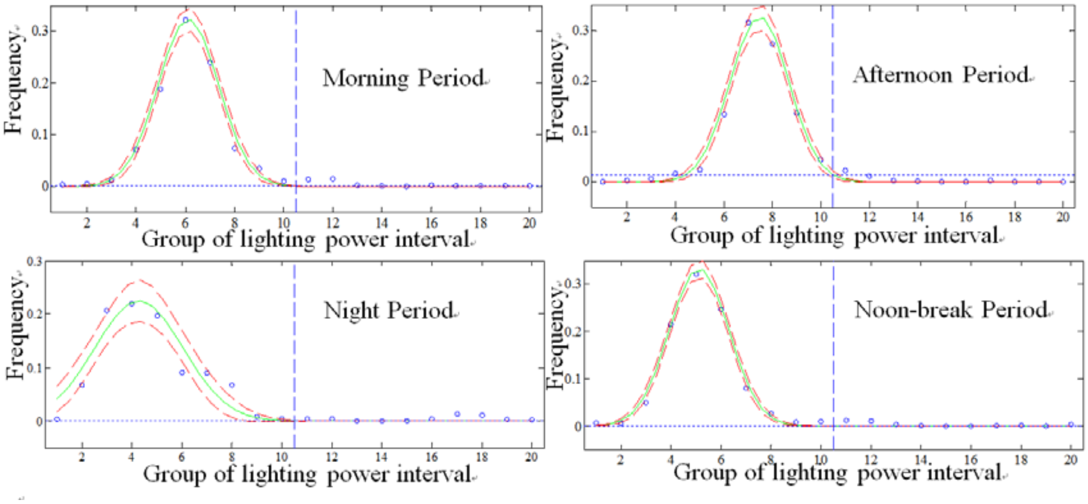


Fig. 16. The normal distribution of the lighting power

Note: The hollow circles are the input data; the green solid line is the regression curve; the red dashed lines mark the confidence interval

Further analysis and verification was conducted on the time-dependence of lighting power between each period. Taking the time-dependent property of lighting power between the Morning Period and the Afternoon Period as an example, the daily average lighting power of the Morning Period was subtracted from that of the Afternoon Period, and the distribution of the differences studied. Fig. 17 presents the regression results, and bears similarity to Fig. 15 and Fig.16. The x-label in Fig.17 corresponds with the 20 groups of variation range of lighting power. It can be seen that the distribution of the differences follows a normal distribution, and the RMSE was 0.0087. The results indicates that the lighting power is time-dependent, and the modeling of lighting power in the Morning Period and the Afternoon Period should not be independent.

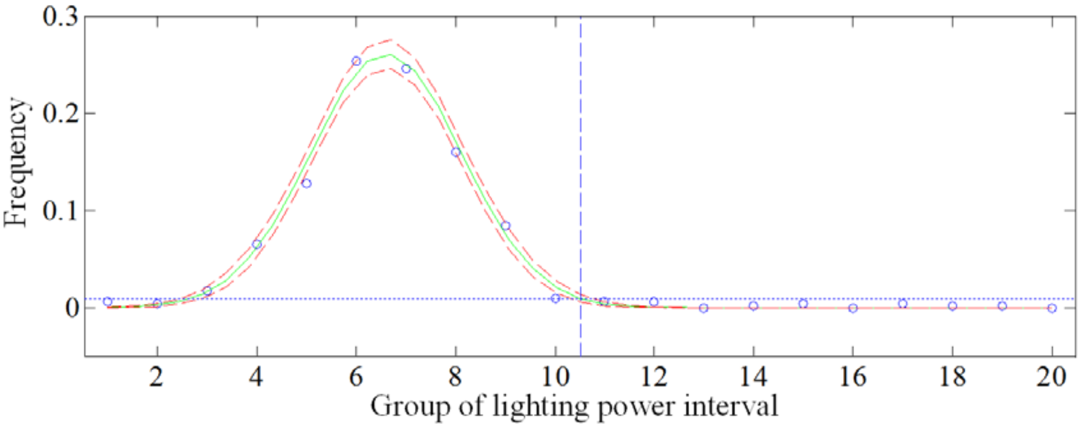


Fig. 17. Regression of the differences of the daily average lighting power between the Morning Period and the Afternoon Period

Note: The hollow circles are the input data; the green solid line is the regression curve; the red dashed lines mark the confidence interval

Fig. 18 shows the energy-time correlation between the Morning Period and the Night Period, with RMSE as 0.030. The RMSE value from the regression analysis of the time-dependency between the Morning and Afternoon Period was much smaller, only 0.0087, so the Morning Period and the Night Period would be described as two independent periods.

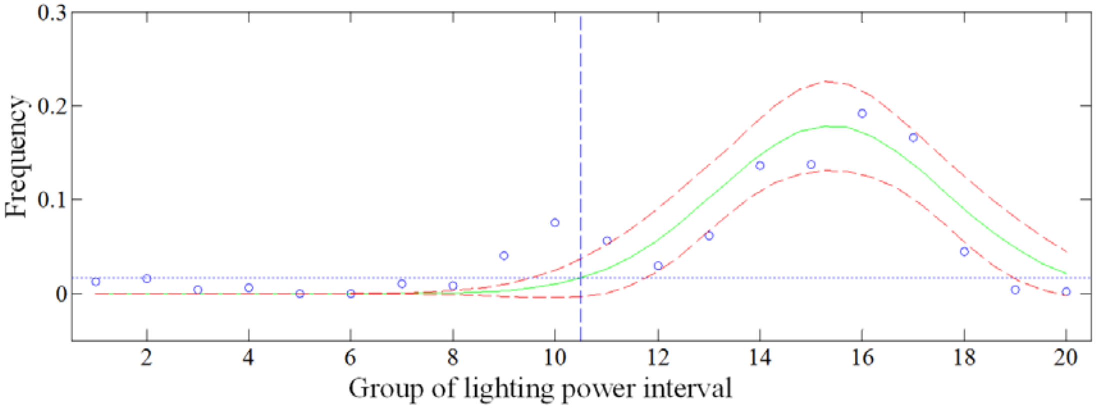


Fig. 18. Regression of the differences of the daily average lighting power between the Morning Period and the Night Period

Note: The hollow circles are the input data; the green solid line is the regression curve; the red dotted lines mark the confidence interval

6.3. *The stochastic lighting model and its use*

Based on the above analyses, a stochastic lighting model for the large office buildings was developed with three main components: (1) the start and end time of the six time periods during one day; (2) the normal distribution of annual lighting energy use during the Morning Period, the Noon-break Period and the Night Period, and the normal distribution of the differences of the daily average lighting power between the Morning Period and the Afternoon Period; and (3) the exponential distribution of lighting energy use during the Going-to-Work and the Off-Work periods. The formulas used in the stochastic lighting model are summarized in Eq.2-4:

Constant value model: $f(x) = A$ (2)

Normal distribution model:
$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp(-\frac{(x-\mu)^2}{2\sigma^2}) \quad (3)$$

Exponential distribution model:
$$f(x) = \frac{\lambda^x}{x!} e^{-\lambda} \quad (4)$$

For a large office building, the lighting consumption schedule for a typical weekday can be generated by the following steps. First, a uniformly-distributed random number between 0 and 1 was generated. The random number was used as an input to the inverse function of the cumulative normal distribution to find the corresponding value of lighting consumption schedule during the

Morning Period. The equation form of the cumulative nominal distribution was obtained from the regression analysis in Fig. 16. This process was repeated to obtain the lighting energy use in the Noon-break Period and the Night Period, and the differences in the daily average lighting power between the Morning Period and the Afternoon Period. As the lighting power during each of these time periods within a day changed very little (as described in Section 6.1), it was assumed to be a constant value for the corresponding time period on a typical day. After that, an exponential distribution was used to smoothly connect the lighting energy use for the Night Period and the Morning Period in order to compose the Going-to-Work period. The equation for the exponential distribution was obtained from the regression analysis shown in Fig. 13. The modeling of the Off-Work period followed a similar process. The same process was repeated 364 times to form an annual lighting energy use schedule for a given building. The resulting annual lighting energy use schedule can be used as an input to building simulation.

7. Model validation

Previous sections describe the development of a stochastic model of the lighting energy use based on the daily lighting curves and the annual normal distribution of variation. This model can be applicable to large office buildings without daylighting controls or any other automatic lighting controls, where the lighting energy use has almost no correlation with the outdoor illuminance, but is closely correlated with the occupancy schedule. To validate the stochastic lighting model, energy data from another typical lighting branch in Building F was used as an example, to demonstrate the simulation results. Recall, that only the lighting energy use on workdays was simulated and validated in this case study (Table 3 lists the main input parameters for the lighting model).

Table 3. Main input parameters to the stochastic lighting model

Time Period	Start and end time	Parameters and Values x: average value σ : variance
Night	00:00 - 05:00	x：4.47；σ：1.77
Going-to-work	06:00 - 08:00	λ=0.89
Morning	09:00 - 11:00	x：6.12；σ：1.23
Noon-break	12:00 - 13:00	x：5.11；σ：1.19
Afternoon	14:00 - 16:00	Moring-Afternoon difference x：6.6；σ：1.53
Off-work	17:00 - 00:00	λ=0.78

Fig. 19 presents the simulated and measured lighting energy use on weekdays during a whole year and shows a difference of less than 2.5% between the simulated and measured results.

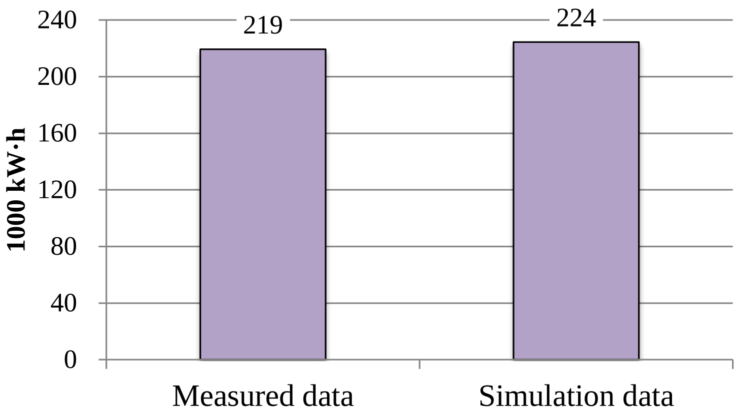


Fig. 19. Total consumption comparisons

The daily and annual distributions are two main features of the lighting consumption in large office buildings. The stochastic model also aims to predict the monthly and yearly variations in lighting energy consumption. Fig. 20 shows the measured and predicted daily lighting power time profiles. 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%. The simulated daily lighting power curve had close agreement with the measured data. The annual distributions for the six periods (Fig. 20), demonstrate that the simulation results fall within the measured range of distributions. Further investigation into the discrepancies between the simulated and measured annual distributions which occurred for the Going-to-Work and the Off-Work periods is needed, with more detailed hourly lighting energy use data to improve model accuracy.

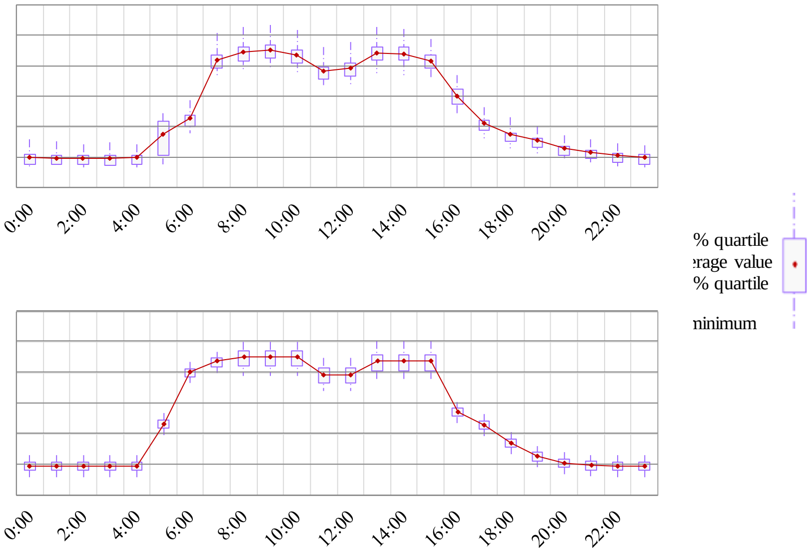


Fig. 20. Comparison between simulated and measured lighting energy use

In addition, a Kolmogorov-Smirnov (KS) Test was applied to the measured and simulated daily lighting energy use to verify consistency. The KS Test is a non-parametric test for the equality of continuous, one-dimensional probability distributions that can be used to compare two samples (two-sample KS Test). The two-sample KS Test was sensitive to differences in both location and shape of the empirical cumulative distribution functions [26]. From the KS Test, H and p-values were calculated. H-values indicate whether the two samples have the same form of distribution. The P-value indicate the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true [27]. Usually, the null hypothesis will be rejected when the p-value is less than a certain significance level. Typical significance values are either 0.05 or 0.01 [28]. In this study a significance level of 0.05 was used because it imposed a more stringent criterion for comparing the consistency of two samples. In other words, if the p-value was greater than 0.05, the lighting energy model could be regarded as calibrated and the lighting models were also verified to be accurate.

The KS Test results are shown in Table 4. It can be seen that the simulation results for lighting energy use passed the KS test, which proved that the stochastic lighting energy use model for weekdays worked well to capture the random characteristics of lighting energy use in large office buildings in China.

Table 4. Results of the KS Test of the simulated and measured lighting energy use

	Results using the KS Test	
	H (0: same distribution; 1: different distribution)	p-value
Lighting energy use on weekdays	0	0.216

The stochastic model was then applied to all the 15 buildings listed in Table 1, with the simulation results presented in Table 5. The simulation results were in agreement with the measured data, with the differences within 10%. Additionally, all of the simulation results passed the KS test, which demonstrated the validity of the stochastic lighting energy use model.

Table 5. Validation results of the lighting energy use in the 15 buildings

Building	**Total lighting energy consumption (kWh/m^2)**		**Error (%) = abs(Simulated - Measured) / Measured**	**Results using the KS Test**	
	Measured	Simulated		H (0: same distribution; 1: different distribution)	p-value
A	54.78	52.57	4%	0	0.861
B	28.61	30.58	7%	0	0.622
C	47.02	51.87	10%	0	0.109
D	16.22	15.82	2%	0	0.051
E	14.64	13.56	7%	0	0.216

F	41.68	43.64	5%	0	0.506
G	59.61	56.02	6%	0	0.109
H	40.08	40.29	1%	0	0.387
I	51.43	51.61	0%	0	0.216
J	38.79	41.64	7%	0	0.216
K	53.04	54.86	3%	0	0.051
L	38.75	39.44	2%	0	0.216
M	46.67	47.84	3%	0	0.051
N	34.13	33.64	1%	0	0.109
O	34.93	34.36	2%	0	0.387

8. Conclusions

This study analyzed the main characteristics and major influencing factors of lighting energy use in 15 large office buildings in China based on measured data. A stochastic model was developed to accurately simulate lighting energy use. The model accounted for uncertainty in occupant behavior and seasonal variations of lighting use. The analysis results and lighting energy use model are applicable to large office buildings in China without daylighting controls or any other automatic lighting controls (such as occupancy sensors). The main findings from this study include:

1. In large office buildings in China, lighting energy use was mainly driven by the occupant schedule. The influence of the outdoor illuminance was very weak as most large office buildings in China do not have automatic daylighting controls. Design and retrofit strategies to harvest daylight with automatic controls should be encouraged for large office buildings in China to reduce lighting energy use.
2. The stochastic properties of daily lighting power profiles and annual variations in lighting energy use can accurately be described using Poisson and normal distributions.
3. A stochastic whole-building lighting energy use model was developed based on daily lighting curves and annual distributions of lighting power levels. The model was verified using measured lighting energy use data from all 15 office buildings.

The developed stochastic lighting model can be used to generate lighting schedules for current building energy modeling programs to improve the accuracy of simulated lighting energy use of large office buildings, without daylighting or automatic lighting controls. Future work will aim to improve the simulation accuracy of the annual distribution of lighting power levels for the Going-to-Work and Off-Work periods. Additionally, a lighting model for weekends should also be developed and verified.

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