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Influence of occupancy-oriented interior cooling load on building cooling load design

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Abstract:

In the traditional mechanical design of new buildings, the occupancy number is usually over-estimated and results in over-predicted cooling loads and oversized chillers. When building occupancy is low relative to the design phase assumptions, those oversized chillers run inefficiently. To further explore the influence of occupancy on building cooling load design, the occupancy rate of office building is

proposed in this paper and investigated with questionnaires.

In a case study for an office building in Tianjin, the interior heat gain from occupants, lighting and equipment accounts for 66.6% of the total cooling load, while the part load ratio (PLR) of the chiller is only 30%. A Markov transition matrix is established based on the survey results. This paper describes the occupancy pattern of the building by using a stationary distribution of a one-step transition probability. A correction coefficient is proposed for the design phase cooling load calculation, which results in a 35.9% cooling load reduction for the building case study. The simulated cooling load is validated by consistency check according to the real cooling load. Assurance analysis is also conducted to calculate the design error and predicted operation error between simulated and actual cooling loads. With above analysis, interior disturbances resulting from occupant behavior are proved to be the most important uncertainty for building cooling load design.

Keywords: cooling load, part load ratio, occupancy rate, correction coefficient, assurance rate

Nomenclature

A -building floor area, m^2 ;

$C_{\tau-ES}$ -cooling load coefficient for sensible heat gain from equipment;

$C_{\tau-LS}$ -cooling load coefficient for sensible heat gain from lighting;

$C_{\tau-PS}$ -cooling load coefficient for sensible heat gain from occupants;

C_w -specific heat of chilled water, 4.18 kJ/(kg·°C);

C_p -specific heat of air, 1.01 kJ/(kg·°C);

d -mean value of the difference between two groups of data;

d_o -outdoor air humidity ratio, kg (water)/kg (dry air);

d_n -indoor air humidity ratio, kg (water)/kg (dry air);

E -power density of the office equipment, W/m²;

Er_{des} -design error between simulated and actual cooling loads, %;

Er_{ope} - predicted operation error between simulated and actual cooling loads, %;

G -flow rate of chilled water, m³/h;

$nEXP$ -number of different exposures;

$nSURF$ -number of heat conduction surfaces;

$J_{\tau i}$ -solar heat gain from windows, W/m²;

k -group number of compared cooling load data;

L - lighting power density, W/m²;

ρ - fresh air density, kg/m³;

φ -heat gain percentage; adjusted heat gain is based on normal percentage of men, women, and children for the application listed, with the postulate that the gain from an adult female is 85% of that for an adult male and that the gain from a child is 75% of that for an adult male;

ψ -simultaneous usage coefficient;

m -number of rooms;

n -number of occupants;

n_d -design occupancy;

n_r -actual number of occupants;

n_p -office area per capita, m^2 /person;

OR -occupancy rate, %;

OR_{max} -maximum occupancy rate, %;

P - probability of a stochastic process, %;

PLR - chiller part load ratio, %;

Q_m -measured cooling loads, kW;

Q_n - chiller cooling capacity, kW;

q_E -hourly cooling load from building envelopes, including hourly heat transferred from roof, exterior walls and windows, and hourly solar heat radiated from windows, W/m^2 ;

q_F -fresh air cooling load, W/m^2 ;

q_{FS} - fresh air sensible heat, W/m^2 ;

q_{FL} - fresh air latent heat, W/m^2 ;

q_I -hourly interior building cooling load from occupants, equipment and lighting, W/m^2 ;

q_{IE} - indoor equipment hourly cooling load, W/m^2 ;

q_{IL} - lighting system hourly cooling load, W/m^2 ;

q_{IP} - occupants' hourly cooling load, W/m^2 ;

q_{IPL} - occupants' latent heat, W/m^2 ;

q_{IPS} - occupants' sensible heat, W/m^2 ;
 q_{ML} - male adult hourly latent heat, W ;
 q_{MS} - male adult hourly sensible heat, W ;
 q_T - hourly total cooling load, W/m^2 ;
 $q_{T, sim}$ - hourly simulated cooling load, W/m^2 ;
 $q_{T, act}$ - hourly actual cooling load, W/m^2 ;
 q_{TR} - cooling loads including heat transmission through walls, roof and windows,
 W/m^2 ;
 q_{TS} - solar radiation cooling load, W/m^2 ;
 r_i - latent heat of vaporization of $t^\circ C$ moisture air, kJ/kg ;
 S_d - standard deviation of the difference between two groups of data;
 t_i - time series of stochastic process;
 t_{in} - supply chilled water temperature, $^\circ C$;
 t_{out} - return chilled water temperature, $^\circ C$;
 t_r - hourly outdoor design air temperature, $^\circ C$;
 t_n - indoor design air temperature, $^\circ C$;
 t_o - outdoor air temperature, $^\circ C$;
 U - heat transfer coefficient, $W/(m^2 \cdot K)$;
 V - fresh air volume, m^3/h ;
 X_g - glass structure correction coefficient;
 X_d - building location correction coefficient;
 X_T - stochastic state on certain time;

X_z -glass shading coefficient;

1. Introduction

Occupants are the dominant roles in buildings. Nearly all the building energy consumption relates with the behavior of occupants or the equipment to improve human comfort in indoor environment. Stochastic occupant behavior has received much more concerns in researches of building energy saving than ever before. A series of stochastic phenomena, including the use of demand-controlled ventilation [1], operation of lighting system [2], operation of air-conditioners [3], control methods of lighting and blinds [4] and occupancy [5] has been discovered, explored and represented by mathematical models. In office buildings in particular, the occupants' states directly determine the source and characteristics of energy consumption. [6-9]

Recently, empirical models have been developed based on measurements in particular building environments [10]. The Markov process has been widely applied in human behavior research to describe the time-varying occupancy interval [11-12]. The state transition probability and the inhabitants' presence or absence states are both important in developing cooling schedules for energy calculation [13].

Most studies focus on regularities of human behavior and energy consumption during building operation. However, the influence of human demand on a building's design phase is largely overlooked. Once the capacity of building equipment is fixed during the building design phase, their rated-efficiency and energy-saving potential is inherently limited. Between the actual demand and the nominal capacity of equipment

once the building is in operation, the equipment efficiency will be relatively low most of the time [14]. Similarly, the capacity of air-conditioning systems is determined during the design phase when heating loads or cooling loads are calculated. If the impact of human behavior on building loads is not accurately characterized during building design, the heating, ventilating and air-conditioning (HVAC) system is often oversized. Substituting a smaller chiller in place of an oversized one improves the chiller's coefficient of performance (COP) and also reduces energy consumption [15]. Thus, there is significant potential to reduce building energy consumption by tailoring the system size during the building design phase. Theoretical energy simulations have proved that the input of real-time occupancy information during building design can reduce HVAC energy consumption by 10 to 20% [16-19].

This paper aims at proving the importance of occupancy on design phase by investigation and simulation of an existing office building. This research begins with analyzing the characteristics of building cooling loads. Next, occupant behavior is investigated in an office building case study, with emphasis on the significance of the occupancy rate in predicting cooling load. A correction coefficient is proposed to modify the over-predicted cooling load in design phase. Simulation is also conducted to show the reduction of cooling load and building energy consumption during the testing period. Finally, designed and predicted operation cooling loads are both compared with measured cooling load to validate our presumed importance of occupancy on building cooling load design.

2. Occupant related cooling loads

The following subsections give an overview of cooling loads and discuss the effect of a building's occupancy rate on cooling load.

2.1 Overview of cooling loads in buildings

Building cooling load consists of excessive heat that must be removed from the indoor environment. Interior heat usually originates from three sources: heat gain through exterior surfaces, heat gain from intake of fresh outdoor air, and heat gain generated indoors by equipment and occupants [20] [21].

$$q_T = q_E + q_F + q_I \quad (1)$$

The cooling load from heat gain through exterior surfaces results from outdoor temperature and solar radiation and is generally determined by meteorological conditions. It can be subdivided into two parts: cooling loads formed by heat conducted from nontransparent surfaces and solar radiation through transparent surfaces. Together, these parts make up the exterior cooling load, which is affected by variations in the exterior building environment [22].

$$q_T = q_{TR} + q_{TS} \quad (2)$$

$$q_{TR} = \frac{\sum_{i=1}^{nSURF} (t_\tau - t_n)(A_i U_i)}{A} \quad (3)$$

$$q_{TS} = \sum_{i=1}^{nEXP} (X_g X_d X_z) J_{\tau i} \quad (4)$$

The cooling load resulting from fresh air entering the building can be subdivided into sensible cooling load and latent cooling load. The fresh-air flow rate depends on occupant demand. The temperature and humidity of fresh air depend on

meteorological conditions. Therefore, the cooling load of fresh air reveals the combined effect of both interior and exterior influences [21].

$$q_F = q_{FS} + q_{FL} \quad (5)$$

$$q_{FS} = \frac{C_p n V \rho (t_o - t_n)}{A} \quad (6)$$

$$q_{FL} = \frac{r_i n V \rho (d_o - d_n)}{A} \quad (7)$$

The cooling load from indoor equipment results from heat generated by the occupants, lighting system, and equipment and is closely related to occupants' activities [21].

$$q_I = q_{IP} + q_{IL} + q_{IE} \quad (8)$$

$$q_{IP} = q_{IPS} + q_{IPL} = \frac{\phi(q_{MS} C_{\tau-PS} + q_{ML})}{n_p} \quad (9)$$

$$q_{IL} = \psi L C_{\tau-LS} \quad (10)$$

$$q_{IE} = \psi E C_{\tau-ES} \quad (11)$$

Broadly defined, interior building loads are demands of building occupants that fall into the general categories of demand related to comfort and demand related to work activities. For instance, the demand for comfort affects indoor air quality and illumination quality, and the demand related to work activities affects the use of computers and printers. Air-conditioning units are used for both types of demands. Because fresh air improves the indoor thermal comfort, the demand for fresh air in the category of broad defined interior loads is included. Meanwhile, a narrow definition of interior load focuses only on heat gains related to occupants, lighting and equipment.

In residential buildings, interior disturbances are limited. Because most rooms are controlled by split air-conditioning systems, a constant value can be used to roughly estimate the interior excessive heat [23]. In contrast, interior cooling loads in public buildings are considerably larger and more strongly influenced by building function and occupant schedules. Therefore, for this study, interior influences on cooling loads in public office buildings, specifically the occupancy rate, is focused on.

2.2 Investigation of the occupancy rate

The subjects of our research were the occupants in an office building, including employees and visitors in both rooms and corridors. To characterize occupants' possible movements inside and outside of the building, our investigation aimed to understand occupants' regular work patterns.

It is not possible to place cameras in all areas of an office building. Installing cameras in offices, conference rooms, eating areas and restrooms would be considered an invasion of privacy. The web-based survey is an effective measure to collect data for prediction model establishment. It has been demonstrated that a survey presenting choice among scenarios by asking respondents to choose the scenario that most closely resembled their situations at the moment could effectively capture the probabilities of occupant behavior in buildings [24]. Therefore, for this study, simple real-time surveys are applied to collect relevant information on occupants' locations during the day, both inside and outside the building, without intruding on occupants' privacy. Both paper version and electronic questionnaires are applied to building

occupants in order to describe their behavior, their current location and planned movements in the next 1 to 1.5 hours.

In case study, the office building occupants normally work eight hours per weekday in China, from 8:30 to 16:30. The questionnaire was distributed with 1-hour interval (9am-4pm) on July 31th and August 2th in 2013. This enabled us to acquire real-time data with minimal disturbance to occupants. The questionnaires were sent or given to staff that were at work in offices in the building, remotely telecommuting and, in some cases, walking in corridors of the building. The questionnaire, shown in Table 1, consisted of four single-choice questions. Whether distributed online or in hard copy, it could be completed in one minute.

Table 1: Occupancy rate survey questions

Sample questionnaire			
1) If you are working in your office room now, in the next 0.5-1 hour, are you more likely to ()			
A. keep working in your office	B. attend a meeting	C. go somewhere else in this building	D. go outside this building
2) If you are attending a meeting now, in the next 0.5-1 hour, are you more likely to ()			
A. go back to work in your office	B. keep attending meetings	C. go somewhere else in this building	D. go outside this building
3) If you are handling business in a location other than your own office in this building, in the next 0.5-1 hour, are you more likely to ()			

A. go back to work in your office	B. attend a meeting	C. remain where you currently are in this building	D. go outside this building
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4) If you are handling business in a location other than this building, in the next 0.5-1 hour, are you more likely to ()

A. go back to work in your office	B. attend a meeting in this building	C. go somewhere other than your own office in this building	D. remain outside this building
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Because there is no aftereffect of the Markov process, which means the “future” and “past” state are mutually independent, a Markov matrix can be formed to describe the movement of the occupants in an office building.

A stochastic process was established as follows:

$$X_T = \{X_t, t \in T = (0, 1, 2, \dots)\} \quad (12)$$

The state space is $I = \{0, 1, 2, \dots\}$, and k represents any positive integer. With $t_i \in T, t_i < t_{i+1}, i = 0, 1, 2, \dots, k+1$ and nonnegative integer i_0, i_1, \dots, i_{k+1} , a Markov chain was formed:

$$P\{X_{t_{k+1}} = i_{k+1} | X_{t_0} = i_0, X_{t_1} = i_1, \dots, X_{t_k} = i_k\} = P\{X_{t_{k+1}} = i_{k+1} | X_{t_k} = i_k\} \quad (13)$$

Specifically, if $k = 1$, the one-step transition matrix from state i to state j is listed as follows:

$$p = (p_{ij}) = \begin{bmatrix} p_{00} & p_{01} & \cdots & p_{0j} \\ p_{10} & p_{11} & \cdots & p_{1j} \\ \vdots & \vdots & \cdots & \vdots \\ p_{i0} & p_{i1} & \cdots & p_{ij} \end{bmatrix} \quad (14)$$

Based on the valid results retrieved, the values in the Markov matrix and the probability distribution of occupants' states were determined. The occupancy rate was defined as follows.

$$OR = \frac{n_r}{n_d} \quad (15)$$

2.3 Measurement and simulation of building cooling load

The actual cooling load can be calculated with measured flow rate and water temperature from the chiller side. By installing surface temperature data loggers (HOBO U12-014) on the chilled water pipes, it is able to acquire the chilled water temperature. The data loggers contain thermal couples of K type, which has a temperature range of 0-1250 °C and a precision of ± 0.4 °C. The chilled water flow rate can be monitored by water flow meters (TDS-100P). Such flow meter has an accuracy of $\pm 1\%$ and can work for 24 hours continually. During the measurement period, the temperature data loggers were recorded with 10-minute interval. The flow meter was read and recorded with 1-hour interval, synchronous as the questionnaire distribution, from 9am to 4pm every day.

Based on the probability distribution of occupants' states, occupancy rate can be evaluated. After inputting the new occupancy profile, cooling loads can be calculated by building simulation tools. A building model is established with TRNSYS and the

Bland-Altman plot method is used to compare the simulation cooling loads with the measured actual loads.

3. Case study

The subsections below describe a case study of cooling loads in an office building in Tianjin, China.

3.1 Design and actual cooling loads

The office building for the case study was built in 2010. It has 10 stories and a floor area of 31,204 m². The total area of the first through the fourth floors is 19,324 m². The area of the fifth through the tenth floors is 11,880 m². The window-wall ratios are 0.46 on the south face, 0.48 on the east, 0.30 on the west and 0.29 on the north.

This building has two predominant characteristics: occupant-driven interior cooling loads are the main component of building cooling loads (and therefore of special concern), and the chillers operate at a very low part-load ratio. Each of these characteristics is described in more detail below.

(1) Occupant-driven interior cooling loads are the main component of building cooling loads.

According to the building's blueprints, the building envelope's thermal performance is good, and the design meets current national energy efficiency standards [25]. Table 2 lists the design indices.

Table 2: Tianjin building case study design indices

Building Envelope	U-value (W/m ² ·K)	Indoor factors	Design Indices
External Wall	0.52	n_p	5 m ² /person
Door (external/internal)	1.5	φ	0.97
External Window	2.3	L	11 W/m ²
Internal Wall	0.61	E	20 W/m ²
Ground Floor	1	V	30 m ³ /(h·person)
Roof	0.46	t_n	26 °C

Using the values in Table 2, the building's cooling loads can be calculated based on formulas (1) through (11) given above. The building's total cooling load is 75.0 W/m². The interior human, lighting and equipment cooling loads account for 66.6% of the total. Exterior cooling loads account for only 11.9% of the total. The results are shown in Table 3.

Table 3: Cooling loads in building case study

	External	Fresh Air	Human	Lighting	Equipment	Total
Cooling load (W/m ²)	8.9	16.2	18.9	11.0	20.0	75.0
Percentage (%)	11.9	21.6	25.2	14.7	26.7	100.0

(2) The chillers' part load ratio (PLR) is extremely low.

Fan coil units and fresh air units are applied in this building. All terminal units

functioned well during the testing period. The building has two water-cooled chillers to meet cooling loads. The #1 chiller serves the fifth through the tenth floors and has a nominal cooling capacity of 1407 kW, and the #2 chiller serves the first through the fourth floors and has a nominal cooling capacity of 1579 kW. There are no mechanical malfunctions or blockages in pipes. However, the chillers operate sub-optimally during the cooling season. The PLR of the #1 chiller is always less than 50%. The situation of the #2 chiller is even worse because this chiller often shuts-off automatically because of low loads.

The performance of the #1 chiller is measured during cooling conditions. The chilled-water temperature was recorded by data loggers, and the flow rate was recorded by ultrasonic flow meters installed on the pipe. The actual cooling load and PLR of the chiller can be calculated by using equations (16) and (17):

$$Q = \frac{C_w G(t_{out} - t_{in})}{3.6} \quad (16)$$

$$PLR = \frac{Q_m}{Q_n} \times 100\% \quad (17)$$

Table 4 shows the performance of the #1 chiller. The hourly PLR is averaged during the testing period. The PLR here represents the ratio of total cooling load to the rated cooling capacity of the #1 chiller. It can be seen that the PLR is lower than 0.4 most of the time.

Table 4: Average hourly PLR of #1 chiller

Time	Min	Mean	Max	Standard Deviation
------	-----	------	-----	-----------------------

9:00	0.198	0.306	0.340	0.042
10:00	0.222	0.311	0.364	0.040
11:00	0.222	0.302	0.358	0.039
12:00	0.252	0.295	0.346	0.028
13:00	0.245	0.291	0.340	0.030
14:00	0.239	0.293	0.358	0.036
15:00	0.251	0.309	0.340	0.030
16:00	0.245	0.307	0.340	0.035

The PLR of the #1 chiller shows that the hourly cooling load is relatively stable, with only slight fluctuations. The variation in daytime cooling load is limited to $\pm 20\%$. However, the average PLR is low, only 30%. Generally, a chiller's COP decreases sharply as the PLR decreases. The actual COP will be considerably lower than the rated COP when the PLR is below 0.4 [15].

(3) Because of the heat absorption of indoor surfaces, changes in heat gain will not cause immediate variation of cooling load. Although such inertia effect blurs the connection between the cooling load and occupants' activities, similarities can still be seen in the patterns of the chiller PLR and the building's occupancy rate.

Based on the #1 chiller's hourly PLR, the maximum cooling loads are at 10:00 and 15:00. This pattern is similar to the occupancy rate. More occupants are present in the office before lunchtime in the morning and before closing time in the afternoon.

To understand this trend in depth, the building's occupancy rate is investigated in more detail as described in the next subsection.

3.2 Investigation of the case study for the building's occupancy rate

Because the #1 chiller responds to the cooling load for the fifth through the tenth floors, the occupancy rates of the offices on those floors are focused on. Although the number of volunteers was limited, 93 workers were invited in the surveys, and the recovery rate for the questionnaires was approximately 80%. Based on the statistical results of 74 valid questionnaire responses, a Markov transition matrix can be roughly established.

$$P = \begin{matrix} & \begin{matrix} 0 & 1 & 2 & 3 \end{matrix} \\ \begin{matrix} 0 \\ 1 \\ 2 \\ 3 \end{matrix} & \begin{bmatrix} 0.68 & 0.10 & 0.13 & 0.09 \\ 0.56 & 0.37 & 0.06 & 0.01 \\ 0.53 & 0.03 & 0.19 & 0.25 \\ 0.27 & 0.02 & 0.14 & 0.57 \end{bmatrix} \end{matrix} \quad (18)$$

where state 0 represents an occupant remaining in his or her office, state 1 represents an occupant attending a meeting, state 2 represents an occupant in a place in the building other than his or her own office, and state 3 represents an occupant outside the building. State 3 is mainly set for non-administrative employees, because they often travel for business reasons during normal work hours.

As a pre-condition, formula (19) is applied,

$$X_0 + X_1 + X_2 + X_3 = 1 \quad (19)$$

By solving the equations of the Markov matrix with a stationary distribution, the possibility that occupants will be in each of the states outlined above can be

determined.

$$P\{X_0=56.7\%, X_1=10.3\%, X_2=13.3\%, X_3=19.8\%\} \quad (20)$$

3.3 Statistical analysis of occupancy rate

Our investigation showed that the probability of state 0 is 56.7%, which is the highest of all of the states. This indicates that an occupant is most likely to stay in his or her own office during work hours.

Offices on the fifth to tenth floors of the building were categorized into five types, and typical offices representing the five types were selected for monitoring the number of occupants per office. Table 5 lists the five types of offices.

Table 5: Different types of offices in the building case study

Office Type	Occupant Capacity	Average Room Area (m ²)	Room Function	#Room number	Volunteer number
A	>40	287.0	Design Studio	#506, #510, #706, #710	25
B	30-40	243.0	Design Studio	#504, #604, #606, #704	19
C	20-30	104.0	Business	#610, #808	15
D	10-20	60.0	Administration, Consultation	#612, #812	6

E	<10	33.6	Administration,	#605, #705,	9
			Printing	#711, #821,	
				#909, #920,	
				#1001	

The occupancy rate is related to the time schedule, so the five typical offices were monitored hourly at a fixed time. Occupancy rate monitoring lasted nearly two weeks (from July 29– August 9, with a one-day break on August 3). Figure 1 shows the average occupancy rates.

Figure (1-a): Occupancy rate in A type Office

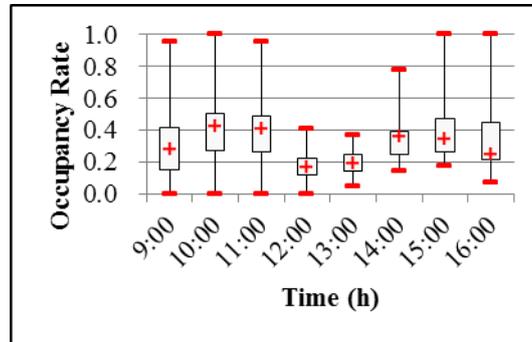


Figure (1-b): Occupancy rate in B type Office

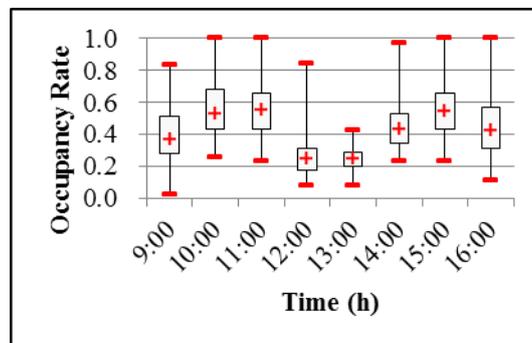


Figure (1-c): Occupancy rate in C type Office

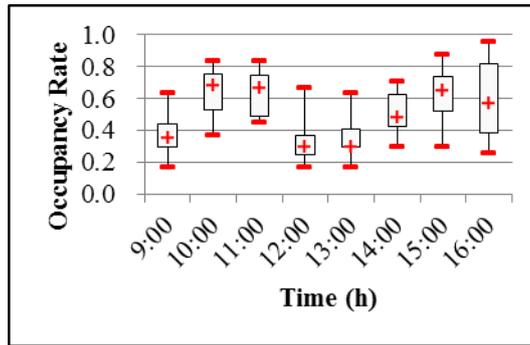


Figure (1-d): Occupancy rate in D type Office

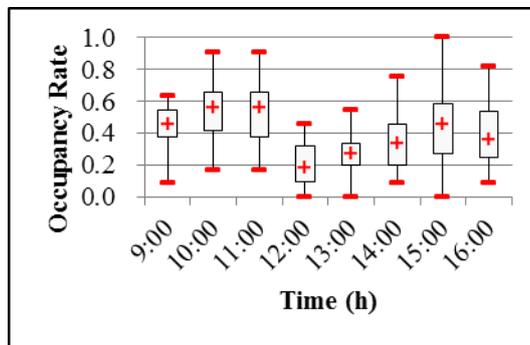


Figure (1-e): Occupancy rate in E type Office

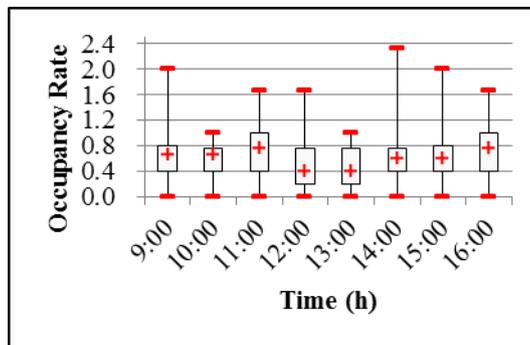
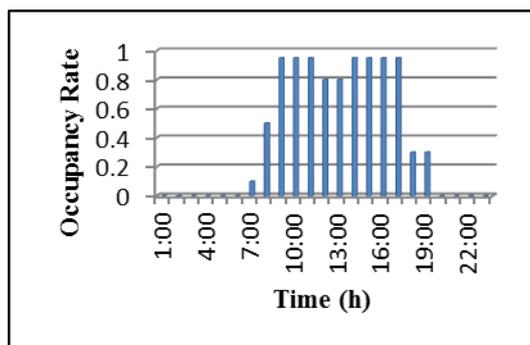


Figure (1-f): Occupancy rate in current design code

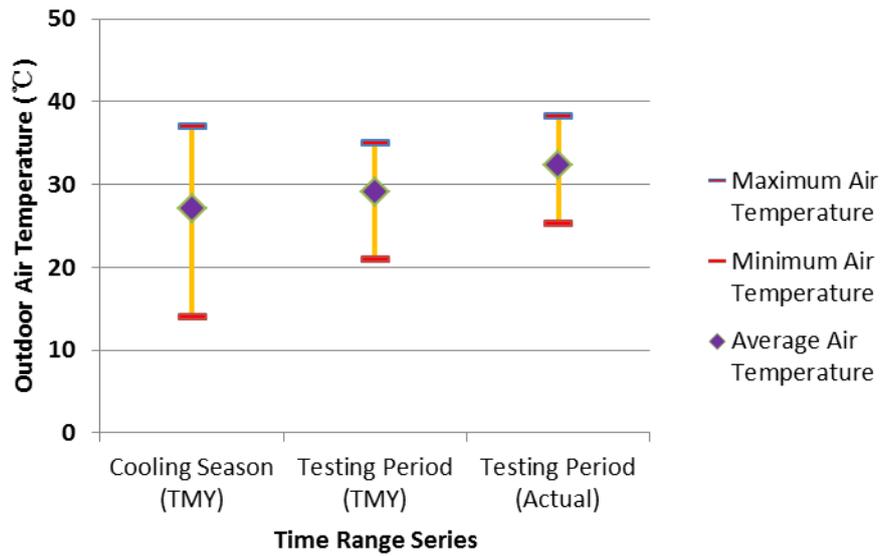


Expected patterns can be seen in the time-based occupancy rate. The maximum occupancy rate always occurs during the periods from 9:00 to 11:00 and 14:00 to 16:00. Occupancy is normally relatively low during the lunch period from 12:00 to 13:00. The average occupancy rate in the rooms on the fifth to tenth floors is less than 50%. Even during the periods from 9:00 to 11:00 and 14:00 to 16:00, the occupancy rates in most of the offices on those floors are lower than 80%. Compared with the occupancy rate (shown in Fig (1-f)) that was calculated with an area-based design index [22], the actual occupancy rate is considerably lower.

3.4 Actual cooling loads

Because the cooling load consists of both interior and exterior factors, the chiller's cooling capacity is influenced by both interior and exterior disturbances. The fluctuation of actual cooling loads is always evaluated by PLR. The PLR of the chiller correlates with the designed capacity and the capacity determined based on the calculated cooling loads [15]. Interior cooling loads, which represent the occupancy rate, account for the largest proportion of the total design cooling loads. Therefore, occupancy rate was chosen as a critical index to compare to the PLR of the chiller. The average indoor air temperature can be used to represent the interior disturbance. Figure 2 shows the fluctuation of PLR and air temperatures during the measurement period.

Figure 3: Comparison of measured outdoor air temperature and TMY data



In Figure 3, measured outdoor air temperature was close to the temperature ranges in TMY year. It means that extreme weather did not appear during testing period. Actually, exterior disturbances were not the reason for low PLR. The average occupancy rate was only 0.4, and the average PLR was only 0.3. Both occupancy rate and part load ratio have design values as the denominators: design indoor occupancy and design chiller’s capacity. This means that the design cooling load in the subject building is oversized, and both the occupancy rate and the design cooling load are oversized to nearly the same degree. In other words, there is a relatively large discrepancy between the design values and actual performances.

4. Modification of occupant related cooling loads

The subsections below describe the steps to modify the design phase cooling load calculation to make it more accurately reflect actual occupancy.

4.1 Modified cooling loads

4.1.1 Occupancy rate correction coefficient

To prove the influence effect of the occupancy rate on the design cooling load, an average maximum occupancy rate (OR_{\max}) is defined as a correction coefficient for modifying the occupant related cooling load calculation method.

$$OR_{\max} = \max \sum_{i=1}^m (OR_i) \quad (21)$$

$$n = \frac{A}{n_p} \cdot OR_{\max} \quad (22)$$

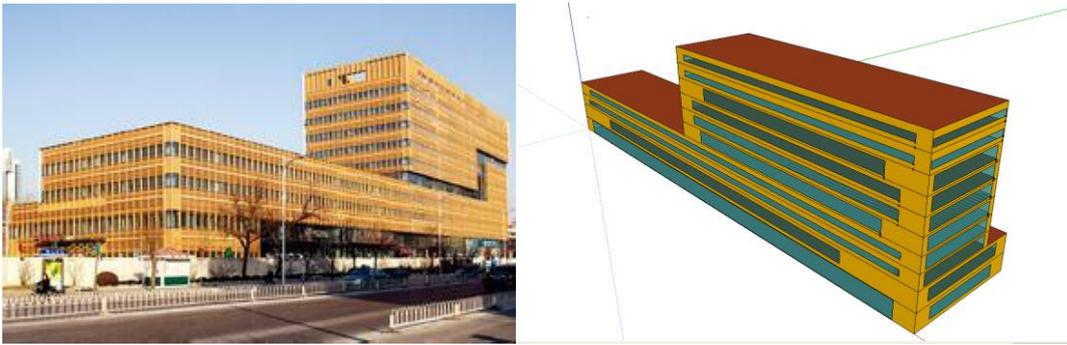
Our case study investigation showed that OR_{\max} tends to occur between 9:00 and 11:00 and 14:00 and 16:00. Because the work and occupancy schedules seem quite different for small offices (less than 10 occupants) compared to large offices (more than 10 occupants), separate correction coefficients for these two types of offices are explored. The OR_{\max} for small offices is 0.65, and the OR_{\max} for large offices is 0.47. Surprisingly, the average value of OR_{\max} is 0.56 for both types of offices, which is similar to the information acquired from the occupant questionnaires.

4.1.2 Building cooling load simulation

To calculate the building cooling load based on the modified occupancy rate, the TRANSYS tool was used to simulate the building cooling loads for the case study. The building model was established by the Sketchup tool. The window area was determined by using the window-wall ratio, so the specific locations of windows are

not represented. Figure 4 shows a photo of the building case study and an image of the simulated model.

Figure 4: Photograph and simulation model of the building case study



Changes in office occupancy cause variations in fresh air, equipment, and lighting loads. The fresh air load varies with the fresh-air flow rate. Assuming that a computer, a screen, and a printer make up the basic office equipment for a building occupant, the building's design index is only 240 W/person.

Because our investigation focused on the fifth through the tenth floors, simulation results were exported separately for the first through the fourth floors and the fifth through the tenth floors. TMY weather data was applied in the simulation under the design cooling loads condition. Figure 5 shows a comparison of the simulated and actual cooling loads.

Figure 5: Comparison of simulated and actual cooling loads

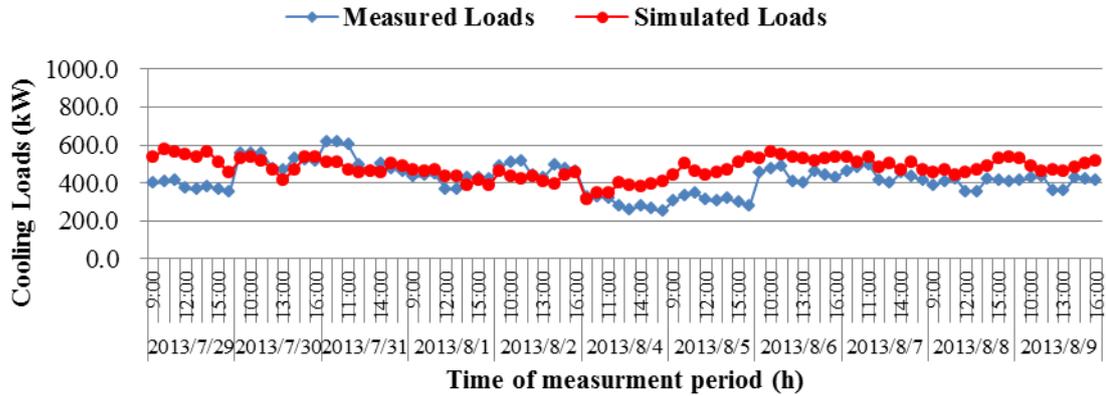


Figure 5 shows that the modified occupancy rate brought the simulation results close to the actual cooling loads. The maximum simulation cooling load 571.4 kW was appearing in 10:00am, 29th, July, which was considered to be the modified design cooling load. Table 6 shows the results of the modified cooling loads, not including the change in lighting demand from the modified occupancy calculation.

Table 6: Modified design cooling loads for building case study

	External	Fresh Air	Human	Lighting	Equipment	Total
Modified Cooling	8.9					
Loads (W/m ²)		5.0	5.9	13.5	14.8	48.1
Percentage (%)	18.5	10.4	12.3	28.1	30.8	100.0

After modifying the occupancy rate, the building's total cooling load was reduced to 48.1 W/m², which is only 64.1% of the design cooling load in Table 3.

The interior cooling loads driven by occupants, lighting system and equipment

account for 71.2% of the total cooling loads, while the exterior cooling load accounts for 18.5%. Less fresh air flow is required with the decrease in occupants, so fresh air load will also be reduced. Table 6 shows that the occupant related cooling loads remain the main component of modified total cooling loads in the case study building.

4.2 Validation and assurance analysis

To test the validity of the occupancy rate modification, the consistency of the simulated and actual cooling loads, as well as the consistency of the calculated and actual cooling loads, is checked. Bland-Altman consistency check was conducted for the cooling loads [27].

$$S_d = \sqrt{\frac{1}{k-1} \sum_{i=1}^k (d_i - d)^2} \quad (23)$$

In general, if the number of points within the bounds of the range of consistency ($d \pm 1.96S_d$) account for more than 95% of the total points, it can be concluded that the two groups of values have good consistency. Figure 6 shows the results of the consistency check.

Figure 6: Consistency between measured and simulated cooling loads

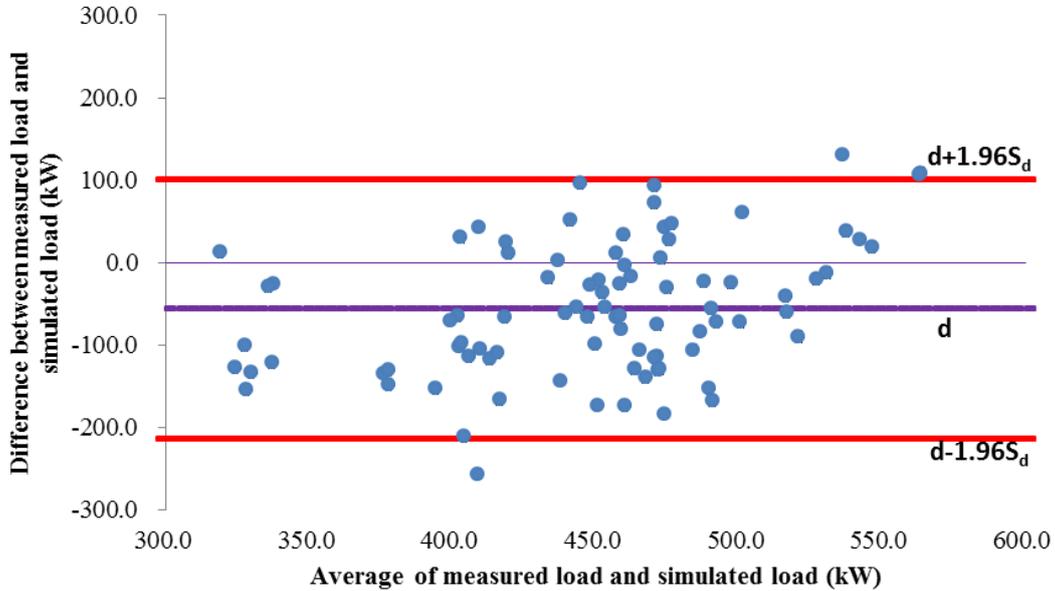


Figure 6 shows that only three out of the 88 sets of data are out of range for both data series, which means that 96.6% of the points are within the consistency bounds. This indicates that the simulated cooling load are very close to the actual cooling load after taking the occupancy rate into account.

Error between simulated and actual cooling loads is shown in Fig. 5. It is caused by the difference between the TMY and actual weather data. As shown in Fig. 3, the maximum and average actual outdoor temperatures are slightly higher than that of TMY data respectively during the testing period. Thus the simulated cooling loads might be generally lower than the actual ones and fluctuations are inevitable. In order to quantify the assurance rate of the modified cooling loads, the design cooling loads and predicted operation cooling loads error are identified respectively:

$$Er_{des} = \frac{|Max(q_{T,sim}) - Max(q_{T,act})|}{Max(q_{T,sim})} \times 100\% \quad (24)$$

$$Er_{ope} = \frac{|Ave(q_{T,sim}) - Ave(q_{T,act})|}{Ave(q_{T,sim})} \times 100\% \quad (25)$$

Under design conditions, the cooling load should be the maximum hourly cooling load in order to ensure cooling capacity of chillers. Under operation conditions, the hourly cooling loads are various with outdoor temperature. So the average cooling loads are adopted in operation error calculation.

The design and predicted operation error were 8% and 10% respectively based on the cooling loads data shown in Fig. 5. It means that the modified design cooling load can satisfy 92% assurance rate. Additionally, the predicted cooling load based on TMY data can satisfy 90% assurance rate under operation conditions. So chillers can be selected based on the modified design cooling load by multiplying an additional coefficient of 10%.

In conclusion, after taking the occupancy rate into consideration, the modified cooling load are effective and reliable for application in building cooling load calculation.

5. Discussion

There are two main areas of research on the energy-saving potential of the behavior of building occupants: one area focuses on the control of building operation and the other area focuses on optimizing building design. Research on controlling building operations relies on monitoring systems such as cameras and the personal

profiles of building occupants. In this area, building energy consumption can be reduced by quick responses to short-term predictions regarding the demand on energy systems. In contrast, optimizing building design depends largely on the accurate prediction of building loads and enables a reduction in energy consumption before the energy system is installed.

The design calculation of occupant related cooling load has a major impact on a building's energy use and is vulnerable to error. If the number of building occupants is estimated based on office floor area, chillers will likely always be oversized and will operate at low efficiencies. Apart from occupancy rate, calculation assumptions were made according to the design codes [20] [25]. With the updates of national codes, design cooling loads may be further reduced. For example, heat gain percentage was assumed 0.97 in the case study building. If all the staffs' personal information, such as age and sex can be acquired, a precise heat gain percentage will then be provided in the calculation of cooling load. At present, as our case study shows, the number of occupants plays a decisive role in the cooling load design.

For a building's HVAC system, variations in the number of occupants and their behavior have stochastic characteristics. These characteristics originate from the differences in individual habits and work patterns. For example, the variation in occupancy rates in small offices (E type) is quite different from the rates in large offices that have more than 10 occupants. First, the occupancy rate in large offices has a strong relationship with the time schedule, but there is no obvious relationship between the occupancy rate and time schedule in small offices. Second, the number of

people in small offices often exceeds the maximum design value for occupants, while the maximum occupancy rate in large offices seldom exceeds one. Design values are limited for small offices, so it is easy to exceed the occupancy rate; at the same time, small offices normally belong to managers and leaders, so visitors are more likely to be present in those offices. Above all, a building's usage patterns can be revealed and incorporated into design decisions by considering staff work patterns during the design phase.

The occupancy rate correction approach will be different for buildings with different modes and patterns of work. The more flexible the work schedule is, the more uncertain the occupancy rates will be. The activities, such as telecommuting and frequent business travel, will largely influence the occupants' work schedules. Thus, the correction coefficient proposed in this paper can only be applied to office buildings with relatively stable work schedules.

The occupancy rate should be taken into consideration in the design stage in order to improve COP of HVAC system. Because the equipment in existing buildings has already been installed, the occupancy rate proposed in this paper is focused on cooling load design for new buildings. In addition, improper chillers should be replaced in energy efficiency retrofit of existing buildings. The occupancy rate calculation method in this paper can be applied in the energy efficiency retrofit scheme design.

Although the delay and attenuating effects of building cooling loads means that real-time cooling loads are not immediately affected by interior or exterior

disturbances, it can be found that by comparing the occupancy rate and the chiller's PLR in the building case study, the chiller cooling capacity was oversized to the same extent as the occupancy rate. Because a chiller's efficiency during operation depends on accurate prediction of the cooling capacity needed in a building, an oversized chiller will run inefficiently at a low PLR and may shut down frequently for self-protection.

6 Conclusions

This paper focused on the occupant related cooling load in office buildings. By investigation of the occupancy rate in an office building in Tianjin, China, measurement and simulation were also conducted to validate the modified building cooling load. Based on the above analyses, the following conclusions can be drawn:

- (1) The occupant related cooling load can be largely influenced by occupancy rate during a building's design phase. After our modification of the occupancy rate, the total cooling loads of the office building case study was reduced by 35.9% with the assurance rate of more than 90%. The reduction level was influenced by weather data.
- (2) Over-estimated occupancy results in inefficient operating chillers. Accurate prediction of a building's occupancy rate will not only reduce the interior cooling loads but also size a chiller's capacity properly. Had this modified occupancy rate been used when the building was designed, the chillers would operate more efficiently.
- (3) A correction coefficient for modifying the occupant related cooling load calculation method was proposed based on questionnaires. Our validation of the modified cooling

load using simulated and measured building data showed good agreement. The assurance rate of the proposed method on cooling load was 90% during operation stage.

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Figure Captions

Figure (1–a) Occupancy rate in A type Office

Figure (1–b) Occupancy rate in B type Office

Figure (1–c) Occupancy rate in C type Office

Figure (1–d) Occupancy rate in D type Office

Figure (1–e) Occupancy rate in E type Office

Figure (1–f) Occupancy rate in current design code

Figure 2 Fluctuation of occupancy rate, chiller PLR and air temperatures

Figure 3 Comparison of measured outdoor air temperature and TMY data

Figure 4 Photograph and simulation model of the building case study

Figure 5 Comparison of simulated and actual cooling loads

Figure 6 Consistency between measured and simulated cooling loads