Comparative Study of Air-Conditioning Energy Use of Four Office Buildings in China and USA

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Abstract:

Energy use in buildings has great variability. Understanding and quantifying key factors influencing building energy performance is crucial to design and operate low energy buildings as well as to establish building energy codes and standards and effective energy policy. This study investigates air-conditioning (AC) energy use of four office buildings in four locations: Beijing, Taiwan, Hong Kong, and California, and employs building simulation to quantify the influences of key factors, including climate, building envelope and occupant behavior. Through simulation of various combinations of the three influencing elements, it is found that climate can lead to AC energy consumption differences by almost two times, while occupant behavior resulted in the greatest differences (of up to three times) in AC energy consumption. The influence of occupant behavior on AC energy consumption is not homogeneous. Under similar climates, when the occupant behavior in the building differed, the optimized building envelope design also differed. Overall, the optimal building envelope should be determined according to the climate as well as the occupants who use the building.

Keywords:

Climate, building envelope, occupant behavior, office buildings, energy consumption,

technological choice

1 Introduction

Building energy consumption is a major concern worldwide. In 2009, the global public building energy consumption was more than 2 billion TCE, representing 11.4% of the total energy consumption (US Energy Information Administration, 2011). As an important component of the energy consumption, office buildings account for almost one-fifth of the total building energy use (Perez-Lombard et al., 2008). In the United States of America, the energy consumption ratio of office buildings to total public buildings is 18%, while it is about 25% in China (Building Energy Research Center in Tsinghua University, 2013). Therefore, office building energy consumption is an important component of public building energy consumption.

Air conditioning (AC) can account for 30–40% of the total building energy consumption of office buildings (California Energy Commission, 2006). AC energy consumption is influenced by many factors, including climate, building envelope, mechanical equipment performance, and occupant behavior. A large body of research (e.g., Li et al. 2014) has examined the influencing factors of AC energy consumption in buildings. According to a study by the International Energy Agency, Annex 53 (Yoshino et al. 2017), factors influencing building energy performance can be classified into four components, namely, climate, building envelope, building equipment, and occupant behavior. Here, occupant behavior includes building operation and maintenance, occupancy, and indoor environmental conditions.

Climate directly and significantly contributes to building energy consumption. The potential impacts of various types of weather forecast models, weather data, and building prototypes have been studied from various perspectives (Long, 2006;

Crawley, 2008; Wilcox and Marion, 2008; Xu et al., 2008; Hong et al. 2013; Cui et al. 2017). Meanwhile, many researchers have revealed that the building envelope has a major role in controlling energy consumption in buildings and maintaining indoor comfort (Al-Obaidi et al., 2015; Wang et al., 2016), because it acts as a thermal barrier to prevent heat loss and provides shading to control solar gains (Barbosa and IP, 2014; Liu et al., 2017). At the same time, several researchers have studied the performance of building equipment, especially AC equipment, including cooling plants, pumps, and fans (Chow et al., 2004; Nagota et al., 2008).

Researchers are increasingly realizing that occupant behavior is one of the most important factors influencing the building thermal loads, energy consumption, and technical suitability (Hoes et al., 2009; Yan et al., 2015; Hong et al. 2017; Yan et al. 2017; D'Oca et al. 2017; Sun et al. 2017). Many models have been developed with consideration for occupant behavior have been developed, such as the occupant movement model (Page et al., 2008; Richardson et al., 2008; Wang et al., 2011; Zhao et al., 2014; D'Oca et al., 2015; Feng et al., 2015; Chen et al. 2017), the window opening model, and the appliance usage model (Nicol, 2001; Reinhart, 2004; Rijal et al., 2007; O'Doherty et al., 2008; Wei et al., 2014).

To understand the actual situation and quantify the impact of influencing factors on building AC energy consumption, four buildings, one each in Beijing, Taiwan, Hong Kong, and California, were chosen as the study cases. The four buildings are located in different climate zones. The occupants come from different cultural backgrounds, leading to differences in AC, lighting, and other equipment usage. Meanwhile, the thermal characteristics of the building envelope vary among the four buildings. These differences result in discrepancies in the energy consumption among the four buildings. Based on the field measurement data, this study examines the differences in climate, envelope, and occupant behavior, and uses building simulation to conduct a sensitivity analysis of each element. Then, their influences on AC energy consumption in office buildings are determined through an analysis of the various combinations of the three influencing elements.

2 Methodology

This research was conducted from three perspectives. First, the influence of climate on AC energy consumption was analyzed through a comparison of the AC energy consumption of each building under the four climates. Secondly, an optimization analysis of the envelope was performed through a comparison of the AC energy consumption of the four buildings, each with a different envelope type. Thirdly, the influence of occupant behavior on AC energy consumption was analyzed through a comparison of AC energy consumption of each building under four types of occupant behavior.

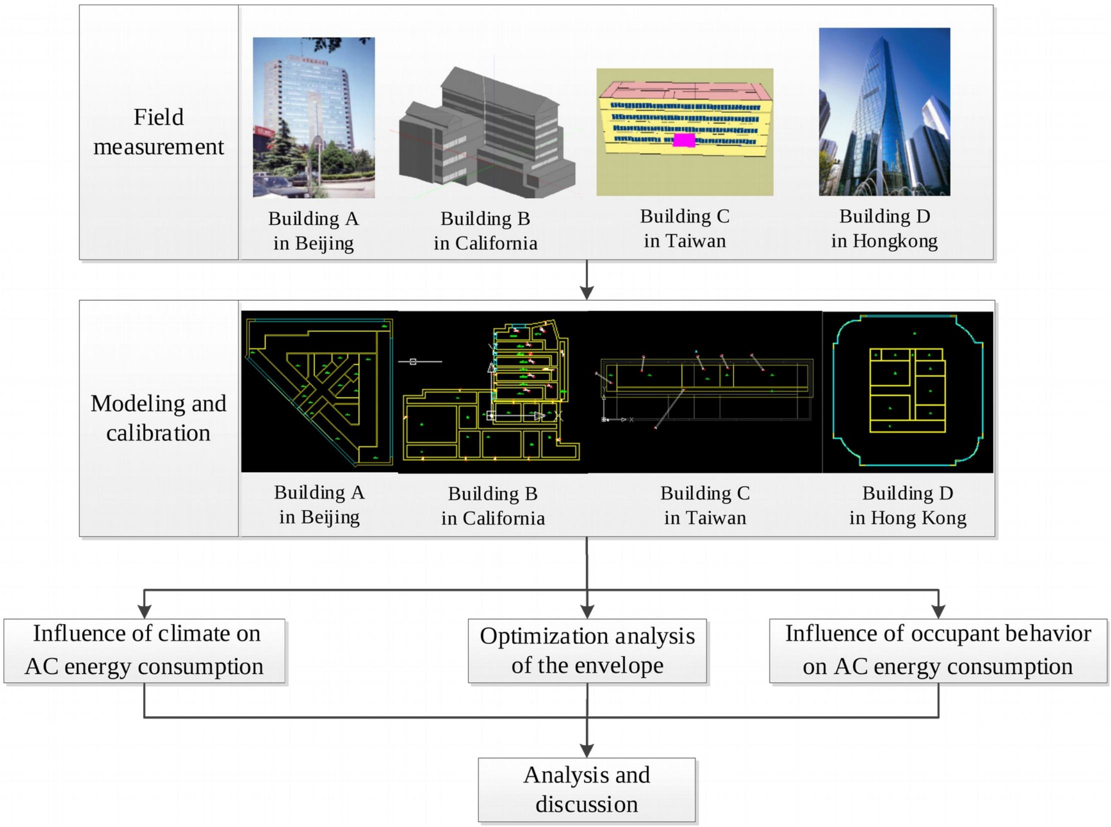

Figure 1 Overview of the technical approach

Figure 1 presents the technical approach used in this study. The DeST (Designer's Simulation Toolkits) software was used to conduct the simulation analysis. DeST is a building energy modeling program developed at Tsinghua University in the late 1980s aimed at aiding teaching, research, and the practical use of building energy analyses and simulations in China (Yan et al., 2008; Zhang et al., 2008). DeST has been used widely in China, with some applications in Europe and Japan. It has been applied to around 25 million m^2 of building design and commissioning applications, and more than 4,000 users currently use DeST as a building simulation tool (Yan et al., 2008). The results from comparative tests on building loads and heating, ventilation, and air conditioning system calculations show small differences in those from DeST, EnergyPlus, and DOE-2 (Zhu et al., 2013; Zhou et al., 2014).

Based on the calibrated building models, simulations were conducted to analyze the influence of climate, envelope, and occupant behavior on AC energy consumption separately. It should be noted that this study focused mainly on the influence of these elements on the AC heating and cooling loads, and the performance of AC equipment was not considered. During the simulation, the AC equipment performance was simplified so as to be the same in the four buildings. The annual cooling coefficient (cooling consumption/cooling electricity consumption) was set to 3.8, and the annual heating coefficient (heating consumption/ heating electricity consumption) was 2.3.

3 Basic information of the four buildings

Table 1 presents the main information of the four buildings, including the location, number of floors, AC area, AC type, AC operation duration, AC temperature settings, and building envelope. Besides the differences in location, the sizes of the buildings also differed. Meanwhile, four buildings employed different types of AC including the constant air volume (CAV) AC systems, the variable air volume (VAV) AC systems, and the fan coil unit (FCU) AC systems. Terminal reheat was also used in the building in California.

Table 1 Basic information of the studied buildings

Building	**A**	**B**	**C**	**D**
Location	Beijing	California	Taiwan	Hong Kong
Number of floors	21 floors with 1 floor underground	8 floors with 1 floor underground	5 floors with 1 floor underground	67 floors with 0 floors underground
AC area (m^2)	30186	14493	5729	118690
AC type	VAV	VAV+Reheat	FCU+CAV+VAV	VAV

AC operation duration		8:00-23:00 except for computer engine rooms with 24-h AC	24-h AC	Workdays: 7:00-18:00 Weekend: closed	8:00-22:00 except for computer engine rooms with 24-h AC
Temperature Settings		20–24°C	21.1–22.2°C	16–29°C	20–24°C
Thermal performance of the envelope	External wall (m^2·K/W)	7.56	2.70	0.20	0.81
	Roof (m^2·K/W)	0.47	2.61	2.58	1.07
	Floor (m^2·K/W)	0.03	2.65	0.09	0.03
	Window (W/m^2·K)	3	5.56	2.61	1.60

The climate differed in the four regions. As shown in Figure 2, based on the outdoor dry bulb temperature, the outdoor temperature in Beijing exhibited the largest range, with distinct winter and summer seasons. The outdoor temperature in California was mainly within 0–30°C, and the temperature was within 10–15°C for half the year. The outdoor temperatures in Taiwan and Hong Kong were similar, with ranges of 10–35°C, but between 20 and 30°C for more than half the year.

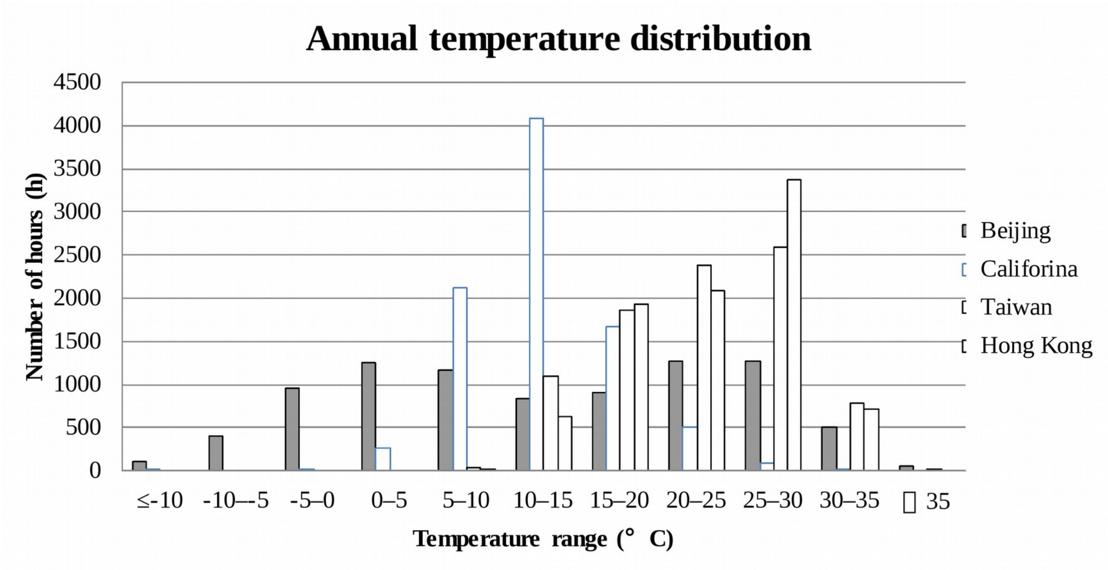

Figure 2 Outdoor dry bulb temperature in the four locations

4 Modeling and Calibration

The field data of the four buildings showed different levels of detail. Building A

(Beijing) only had cooling consumption data for the cooling season. Building B (California) had hourly AC electricity consumption and cooling consumption data. Building C (Taiwan) only had monthly AC electricity consumption data. Finally, Building D (Hong Kong) had annual cooling consumption data. We built the model and completed the calibration according to the situation of each building (Figure 2). The monthly differences between the simulation results and the measured data were less than 20%.

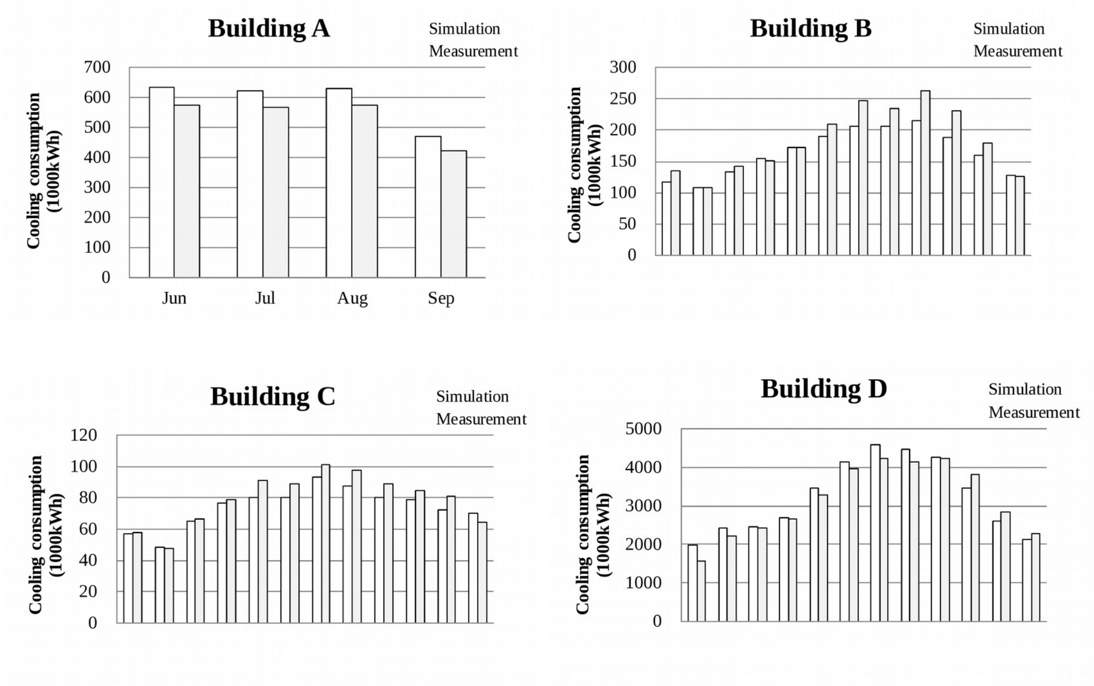

Figure 3 Calibration results

The simulated cooling consumption results based on the calibrated models are shown in Figure 4. Cooling consumption varied among the four buildings, with different monthly change trends. The cooling consumption curve of a typical summer day is shown in Figure 5. The change point of the cooling curve differed among the buildings due to the influences of the operation mode.

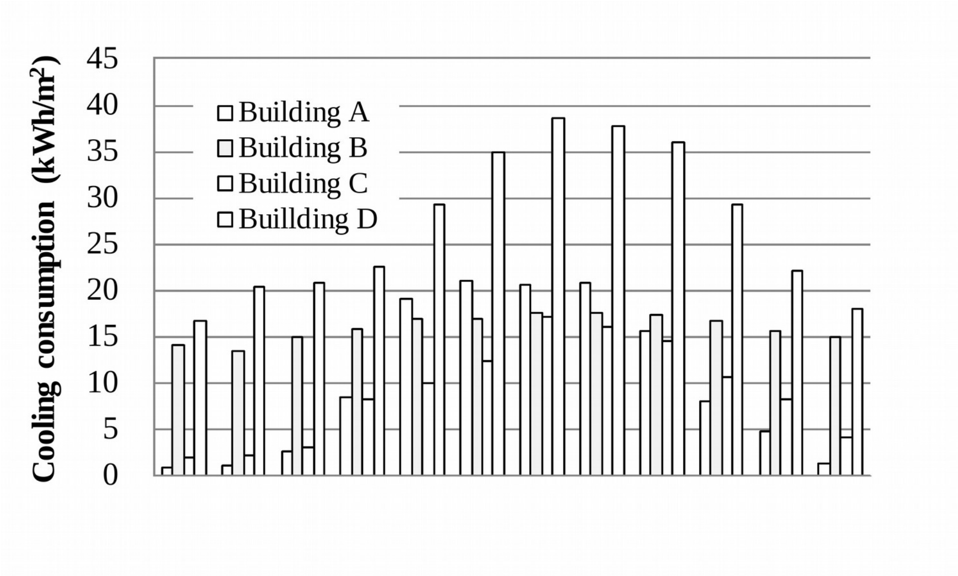

Figure 4 Comparison of cooling consumption of the four buildings

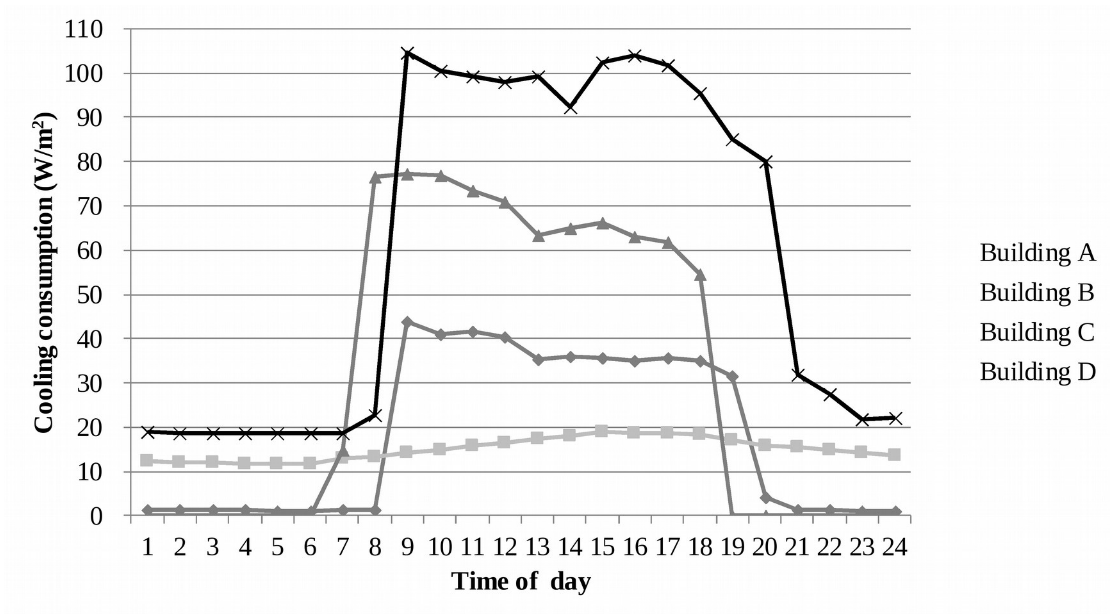

Figure 5 Cooling consumption curve on a typical summer day for the four buildings

5 Analysis of the influencing elements

5.1 Influence of climate

This simulation case operated under the following conditions: the four buildings maintained their original envelope thermal performance and occupant behaviors, and only climate data changed. The climate data of Beijing, California, Taiwan, and Hong Kong were applied to each building separately to simulate AC consumption. Using the AC consumption under the original location as the base line, Table 2 shows the degree of change in AC consumption under different climates with respect to the original state.

Table 2 AC consumption under different climate data

Climate / Building	Beijing	California	Taiwan	Hong Kong
A (Beijing)	0	1.4%	72.5%	52.4%
B (California)	18.7%	0	84.8%	91.6%
C (Taiwan)	-16.1%	25.1%	0	-0.7%
D (Hong Kong)	-32.2%	-34.9%	0.9%	0

The climate data had a large influence on AC energy consumption, in agreement with other research. For example, when Building A experienced a Taiwan-like climate, its AC consumption doubles. Therefore, in the following analysis of other influencing elements, the effect of climate data was accounted for.

5.2 Influence of the building envelope

Table 3 shows the thermal performance of the envelope in the four buildings. Building A had the lowest U value for external walls. Meanwhile, Building D had the best thermal performance of windows, with the lowest U and SC values for windows. Buildings A and D had larger window-to-wall ratios than Buildings B and C.

Table 3 Thermal performance of the building envelope

	Envelope A	**Envelope B**	**Envelope C**	**Envelope D**
U value of the window $W/(m^2 \cdot K)$	3	5.559	2.612	1.6
SC value of the window	0.82	0.85	0.72	0.19
U value of the external	0.13	0.35	2.836	1.03

wall W/(m²·K)					
U value of the roof W/(m²·K)		1.605	0.361	0.365	0.812
U value of the interior wall W/(m²·K)		2.486	1.725	2.187	1.515
R value of the floor (m²·K)/W		0.026	2.646	6.836	0.026
Window -to-wall ratio	East	0.71	0.04	0	0.74
	South	0.05	0.09	0.28	0.71
	West	0.80	0.17	0	0.74
	North	0.75	0.17	0.28	0.75

Figures 6–8 present the simulation results for each building with each of the four types of envelope thermal characteristics. Under the thermal performance of envelope B, the heating and cooling consumption of Building A decreased, especially the cooling consumption. Meanwhile, under the thermal performance of envelopes C and D, the change in heating and cooling consumption showed similar trends. The thermal performance of windows had an important role in the results. When the parameters of the other envelopes were similar, Building A in Beijing had a larger window-to-wall ratio, and the U and SC values of windows for envelope A were larger. Therefore, in winter, the thermal conductivity was an important factor of heating consumption. In summer, solar radiation was the main component of the cooling load, which was also related to the thermal performance of windows.

For Building B in California, under the thermal performance of envelope D, the cooling consumption was relatively small. This was because solar radiation was the main component of the cooling load in California, and envelope D had the lowest SC value of windows. However there were no obvious differences in AC energy consumption caused by the envelope, and Building B in California generally had a low sensitivity to the thermal performance of the four envelopes.

Winter is warm in Taiwan; therefore there was no heating load throughout the entire year for Building C in Taiwan. From the perspective of AC energy consumption, Building C followed the envelope performance order of B < D < C < A. This was the same trend observed for Building A, but the differences in AC energy consumption under the four envelopes were smaller for Building C.

Building D in Hong Kong had a low sensitivity to the thermal performance of envelopes B, C, and D. Under envelope A, building D in Hong Kong had the greatest cooling consumption. This was because solar radiation is strong under the climate of Hong Kong, which is not suited for the larger window-to-wall ratio and SC value of windows of envelope A.

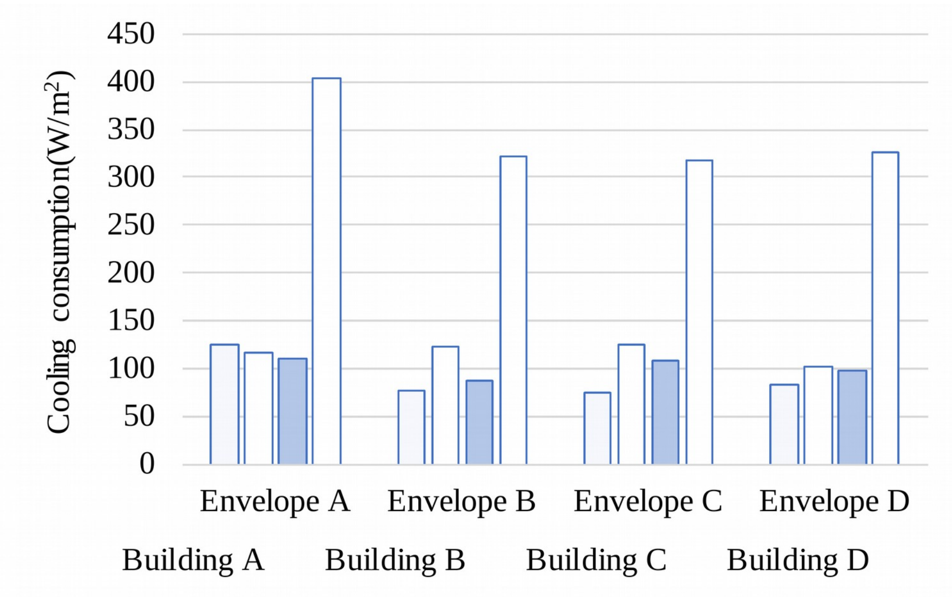

Figure 6 Cooling consumption results under different envelope thermal performances

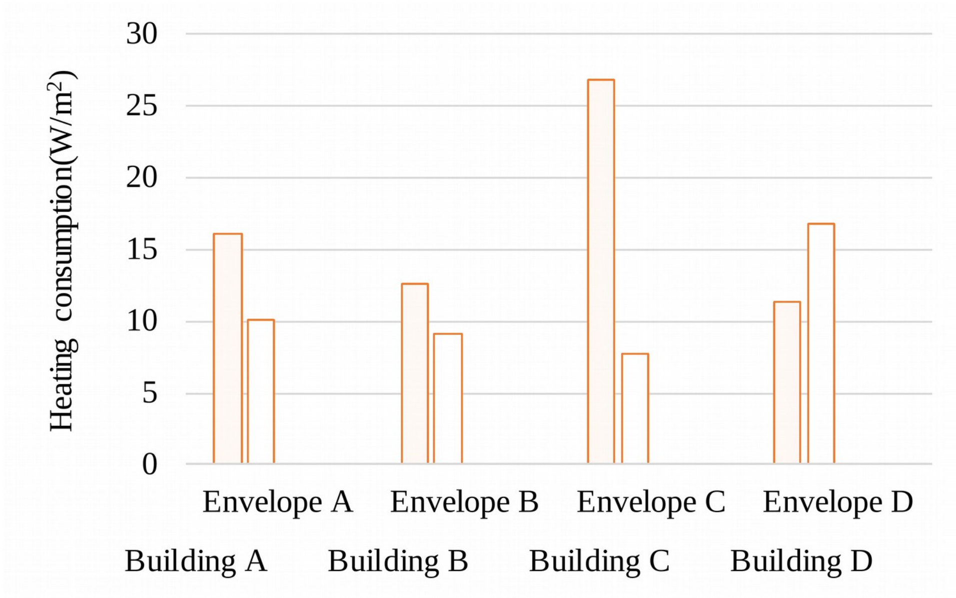

Figure 7 Heating consumption results under different envelope thermal performances

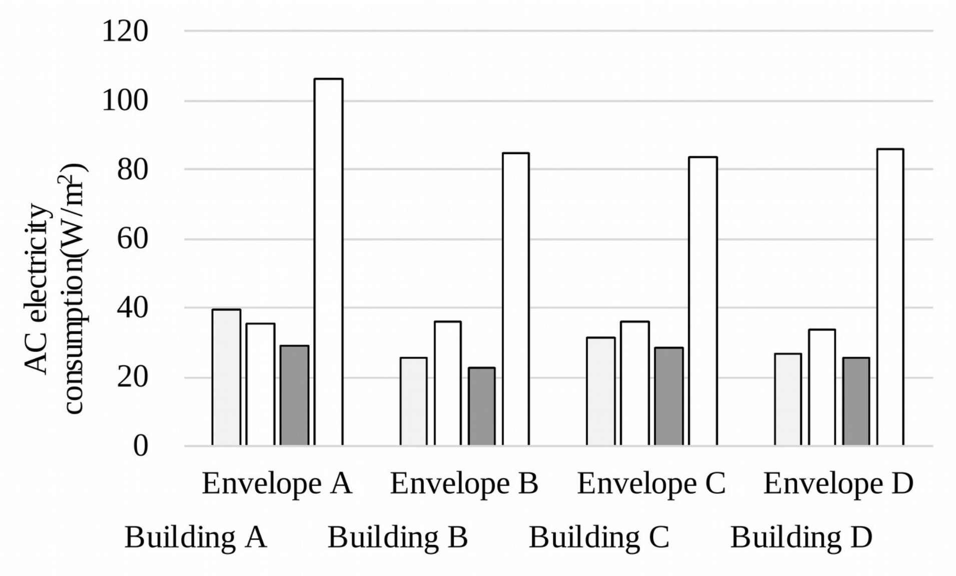

Figure 8 AC electricity consumption results under different envelope thermal performances

Using the AC consumption under the thermal performance of the original envelope as the base line, Table 4 shows the degree of change in AC consumption with respect the original state under different envelope thermal performances. In the different regions, the choice of the thermal characteristics of the envelope had different emphases. In regions with larger cooling loads, such as Hong Kong and Taiwan, the main focus of design should be to effectively prevent solar radiation intrusion. Based on the comparison of the envelope optimization results in the different regions, the applicability of the envelope thermal performances could be determined, and no envelope thermal performance can be optimal or worst in all situations. For example, when applying the thermal parameters of envelope A to Buildings A, C, and D, the AC electricity was relatively higher; however, energy savings were observed when they were applied to Building B.

Table 4 AC consumption under different envelope thermal performances

Envelope / Building	A	B	C	D
A (Beijing)	0	-34.8%	-21.2%	-32.7%
B (California)	-2.7%	0	-0.3%	-6.1%
C (Taiwan)	1.5%	-20.0%	0	-9.6%
D (Hong Kong)	24.0%	-1.3%	-2.6%	0

5.3 Influence of the occupant behavior

Many studies have found that occupant behavior can greatly influence building energy consumption. However, whether the impact is considerable or consistent in all cases remains unknown. Therefore, the influence of occupant behavior in the four buildings was simulated and analyzed.

Occupant behavior relates to the occupancy, AC setting temperature, AC operation time, usage density, duration of lighting and equipment, etc. Table 5 shows the occupant behavior in the four buildings. Building B had a higher occupancy density and longer working time. In addition, the occupant behaviors of Buildings B and D showed no differences between workdays and the weekend. Building B also had a higher intensity of lighting usage, whereas Building C had a relatively shorter lighting usage duration. Regarding AC usage, Building B had a higher indoor temperature requirement, and the AC was turned on all day. Meanwhile, in Building C, the indoor temperature had a larger fluctuation range, and the AC operation duration was the shortest among the buildings.

Table 5 Information on occupant behavior (OB)

Item	**Room type**	**OB in building A**	**OB in building B**	**OB in building C**	**OB in building D**
Occupancy density m^2/person	General office	0.066	0.11	0.05	0.089
	High-grade office	0.066	0.11	0.08	0.089
	Overtime office	0.066	0.11	0.01	0.089
Occupancy	General office	Workdays: 9:00-20:00, weekend off	24 h	Workdays: 7:00-24:00, Weekend: off	9:00-22:00,
	High-grade office	Workdays: 9:00-21:00, Weekend: 10:00-19:00	24 h	Workdays: 7:00-24:00, Weekend: off	Workdays: 9:00-21:00, Saturday: 9:00-23:00 Sunday: off
	Overtime office	Workdays: 9:00-21:00, Weekend: 9:00-20:00	24 h	Workday: 7:00-24:00, Weekend: off	Workdays: 9:00-24:00 Weekend: 9:00-22:00
Lighting density W/m^2	General office	11.74	11.95	18	10.66
	High-grade office	11.74	9.65	18	10.66
	Overtime office	11.74	11.1	6	10.66
Lighting use duration	General office	Workdays: 9:00-20:00, weekend off	24 h	Workdays: 7:00-24:00, Weekend: off	8:00-24:00
	High-grade office	Workdays: 9:00-21:00, Weekend: 10:00-19:00	24 h	Workdays: 7:00-24:00, Weekend: off	8:00-24:00
	Overtime office	Workdays: 9:00-21:00, Weekend: 9:00-20:00	24 h	Workdays: 7:00-24:00, Weekend: off	8:00-24:00
Equipment density W/m^2	General office	6	10.85	8	16.85
	High-grade office	6	13.26	8	16.85
	Overtime office	6	14.66	4	16.85
Equipment	General office	Workdays: 9:00-	24 h	Workdays: 7:00-	8:00-24:00

use duration		20:00；weekend off		24:00；Weekend: off	
	High-grade office	Workdays: 9:00-21:00；Weekend: 10:00-19:00	24 h	Workdays: 7:00-24:00；Weekend: off	8:00-24:00
	Overtime office	Workdays: 9:00-21:00；Weekend: 9:00-20:00	24 h	Workdays: 7:00-24:00；Weekend: off	8:00-24:00
AC use duration	All offices	8:00-23:00	24 h	Workdays: 7:00-18:00；Weekend: off	8:00-22:00
Temperature setting	All offices	20–24°C	21.1–22.2°C	16–29°C	20–24°C

The simulation results for each building based on each of the four types of occupant behavior are shown in Figures 9–11. Building A in Beijing had the highest AC energy consumption under behavior mode B. AC consumption could differ by up to 2 times under the influence of occupant behavior.

For Building B in California, under the different occupant behaviors, the change trend in AC energy consumption was similar to that of Building A, and occupant behavior mode B also led to the highest consumption. Occupant behavior modes A, C, and D had almost no heating consumption, while occupant behavior mode B included a heating requirement of 9 kW/m^2.

The AC energy consumption of Building C in Taiwan increased by about 3 times under occupant behavior mode B. Under occupant behavior mode B with a high indoor thermal environment requirement, a small heating requirement still existed even in Taiwan.

Similarly, the highest AC energy consumption for Building D in Hong Kong was achieved under occupant behavior mode B. However, differing from Building C, the AC energy consumption for Building D was the smallest under occupant behavior mode A.

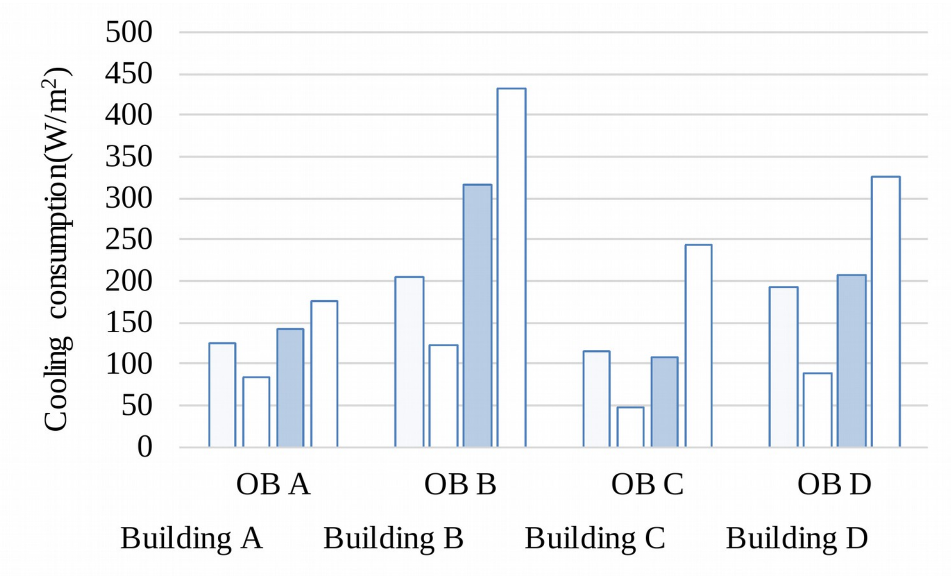

Figure 9 Cooling consumption results under different occupant behaviors (OBs)

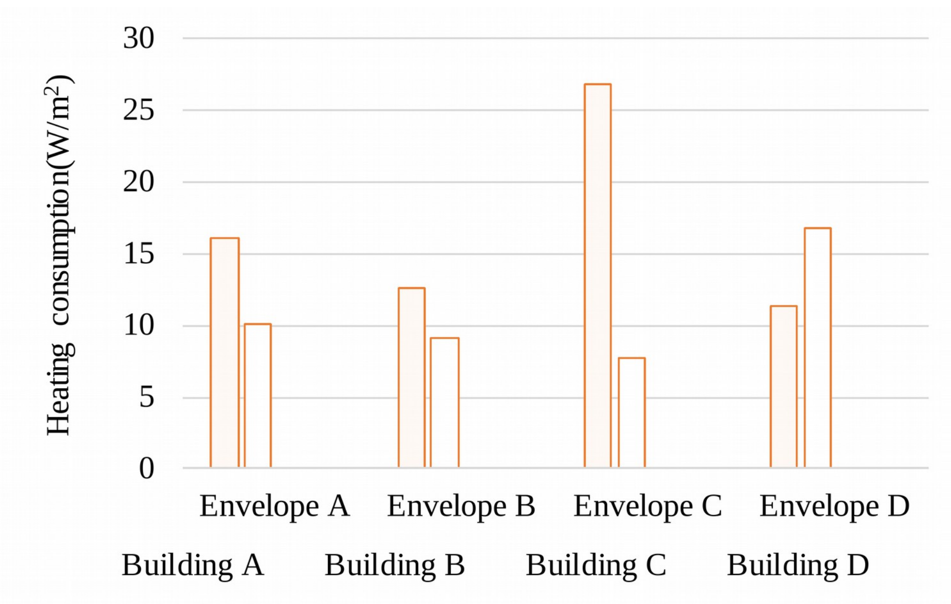

Figure 10 Heating consumption results under different occupant behaviors

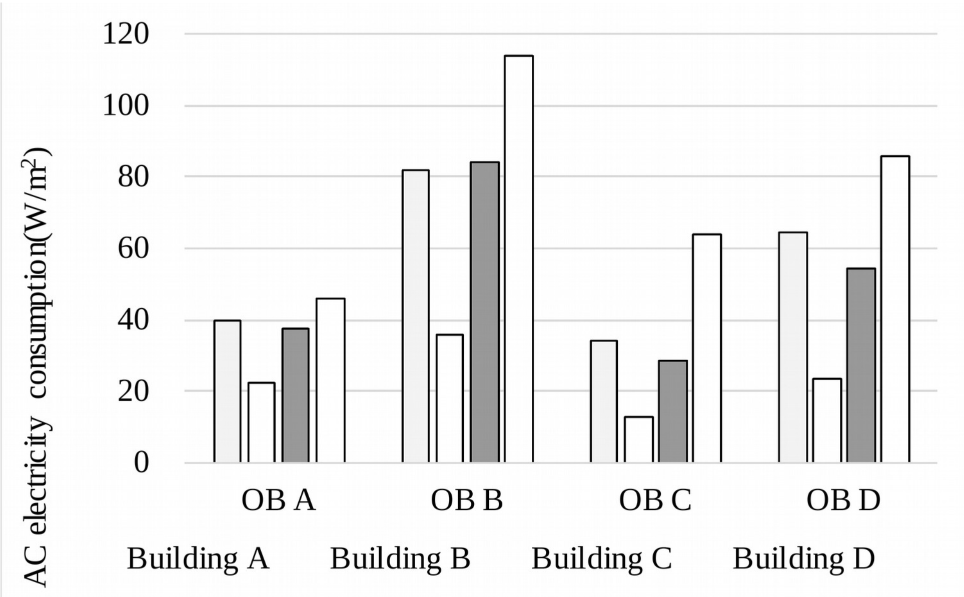

Figure 11 AC energy consumption results under different occupant behaviors (OBs)

From these simulation results, it can be concluded that occupant behavior has a significant influence on AC energy consumption. Using the AC consumption under the original occupant behavior as the base line, Table 6 shows the degree of change in AC consumption with respect the original state under different occupant behaviors. For Building C in Taiwan, under occupant behavior mode B, the AC energy consumption increased almost 3 times. Certain occupant behaviors resulted in greater energy consumption, but the influence of occupant behaviors on building energy consumption was not monotonous. For example, Buildings A, B, and C had the lowest AC energy consumption under occupant behavior mode C, while Building D had a lower AC energy consumption under occupant behavior mode A.

Table 6 AC consumption under different occupant behaviors

OB / Building	A	B	C	D

A in Beijing	0	106.5%	-14.2%	62.6%
B in California	-37.9%	0	-63.8%	-34.2%
C in Taiwan	31.5%	194.9%	0	90.9%
D in Hong Kong	-46.3%	32.4%	-25.2%	0

6 Analysis and discussion

6.1 Comparison of influencing elements

Using the AC consumption under the original condition as the base line, Figure 12 shows the increasing ratios of AC consumption caused by climate, envelope, and occupant behavior.

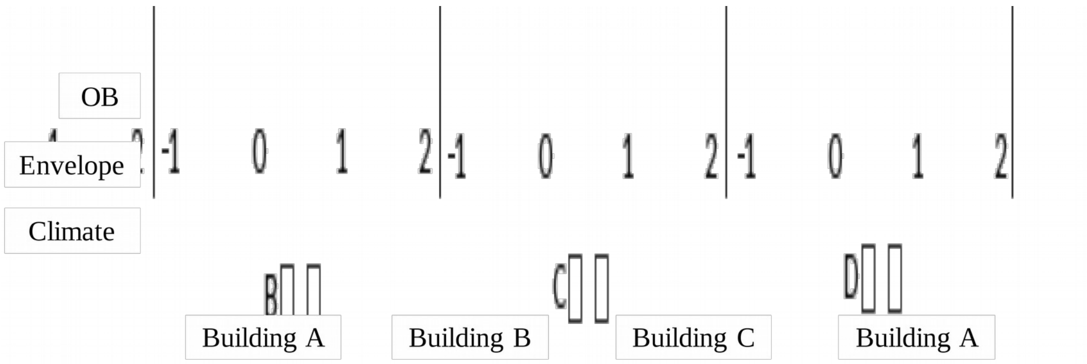

Figure 12 Comparison of the three studied influencing elements

Compared with the climate and occupant behavior, the influence of envelope thermal performance on AC energy consumption was relatively small. In particular, in buildings with high internal heat gains, the sensitivity of the envelope thermal performance decreased (e.g., Building B). Based on the different climate data, the AC energy consumption varied greatly, resulting in differences of up to 2 times. Regarding the four cases in this study, occupant behavior had the greatest influence on AC energy consumption, resulting in differences of up to 3 times.

6.2 Influence of occupant behavior on the most suitable building envelope

Figure 13 shows the AC energy consumption results under the different thermal performances of the envelope of Building B in California operated under occupant behavior modes B and C. Under occupant behavior mode B, the sensitivity of AC energy consumption to the change in envelope thermal performance was small, and the four types of envelopes had little influence on the AC energy consumption of Building B under occupant behavior mode B. However, when occupant behavior mode C was applied to Building B, the influence of envelope thermal performance on AC energy consumption increased. Under occupant behavior mode B, envelope D led to a decrease in AC consumption, while under occupant behavior mode C, envelope C was the optimal envelope. These results underline the influence of occupant behavior on the selection of the most suitable technologies.

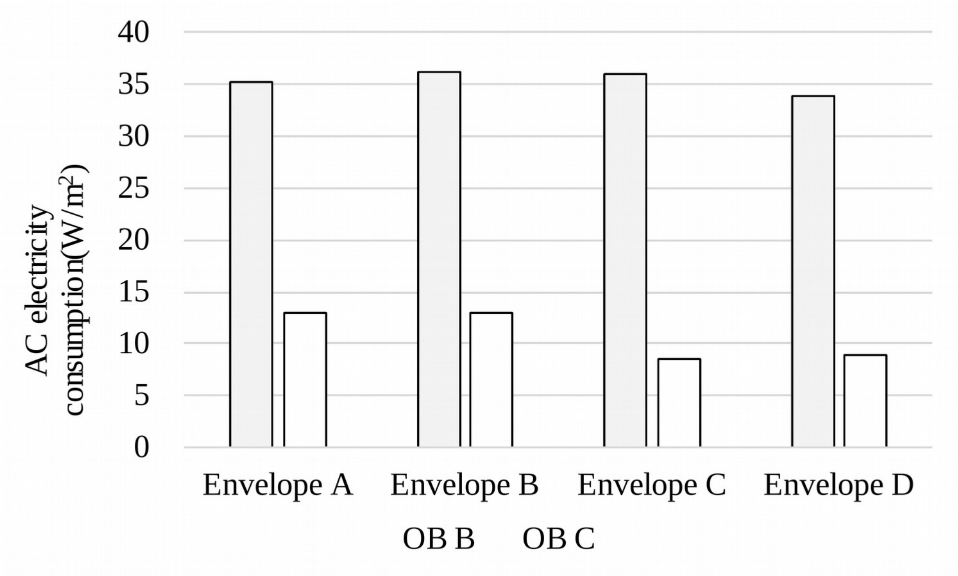

Figure 13 AC energy consumption results of Building B under different envelope and

occupant behaviors (OBs)

Based on these simulation results, both the influence of climate and the effect of occupant behavior should be considered when choosing the most suitable envelope for thermal performance. Building design or energy retrofit in similar climate zones should not be simply based on previous cases without considering the behavior of the people who use the building.

7 Conclusions

Based on the analysis of field data, this paper presents the differences in climate, envelope, and occupant behavior among four buildings and a sensitivity analysis of each element based on a simulation. Through the various combinations of the three influencing elements, main findings from this study are as follows: 1) Climate is an important influencing element of AC energy consumption, and can lead to energy consumption differences of almost 2 times; 2) Based on the study case of the four buildings, the influence of the envelope thermal performance is relatively small, especially in buildings with high internal heat gains; 3) The influence of occupant behavior is the largest, which can lead to differences in consumption of up to 3 times; 4) The influence of occupant behavior on building energy consumption is not monotonous; and 5) Occupant behavior has an important role in the choice of the most suitable envelope thermal performance. For several types of occupant behavior, the sensitivity of AC energy consumption to the change in the thermal performance of the envelope is small, while under other types of occupant behavior, different envelope thermal performances have major effects on AC energy consumption.

Acknowledgments

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