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Impact of occupants' behaviour on energy consumption and corresponding strategies in office buildings

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Abstract. Among commercial buildings, office buildings have the largest number and have the highest total energy consumption (about 14% of the energy consumed by all commercial buildings). Energy used by the HVAC and lighting systems to create comfort indoor thermal and visual environments account for more than half of the total energy usage. The utilization rate of space affects the actual requirement of space heating, cooling and lighting, as well as the performance of equipment and systems. A slow but steady increase in office vacancy is observed as more people work asymmetrically across increasingly remote locations or with a more flexible schedule. Unlike in traditional offices, work style in many new offices involves towards a shared workplace with diverse work activities. This paper focuses on the impact of occupants' behaviour on energy utilization in different types of office buildings and corresponding workplace spatial strategies. The features of the energy use for space cooling, heating and lighting with different occupant rates in different spatial settings, such as private office, open office and coworking office, are depicted. Furthermore, the potential for energy savings with optimization technique, i.e., integrating the real time occupancy data into building air-conditioning and lighting systems for usage-based demand control strategies, are estimated with the method of simulation. According to the calculation results, strategies for improving energy consumption for different office settings are proposed respectively for design and operation.

1. Introduction

Energy saving in office building is becoming increasingly crucial as the total energy consumption of office building is growing so rapidly that accounts for 14% of the energy consumption of all commercial buildings in recent years. However, the office vacancy is increasing slowly but steadily due to the development of communication technology and changes in people's habits. According to the statistics, the average vacancy rate of office building in Shanghai reached 14.8% during 2017^[1], which causes not only the waste of land resources, but also the waste of energy due to the normally opening of air-conditioning system and lighting system which accounts for more than half of the total energy consumption. Meanwhile, high building area per capita in a conventional office building, such as private office, is also a key factor which increases the energy consumption per capita^[2].

To resolve the aforementioned problems in conventional office building, coworking office has been proposed, and the prevalence of that is becoming increasingly significant nowadays. By online booking, occupants can choose the appropriate time to use the shared workplace, and that means the coworking



office can be utilized all of the days to satisfy different occupants' requirements. Because of the high utilization rate of the office building, the energy consumption of air-conditioning system and lighting system during night can be reduced effectively. Compared with private office and team office, the relatively higher building area per capita can also improve the energy utilization rate. Furthermore, the flexibility of shared workplace offers the possibility to cooperate between departments and specialties, which is helpful for solving problems and building new community relations.

In this paper, the characters and differences between coworking office and conventional office (including private office and open office) are depicted in detail. The changes of occupants, air-conditioning system and lighting system during a typical day are described with the help of on-site investigation of typical office buildings in Hangzhou, Zhejiang Province, China. Furthermore, according to the aforementioned findings, the energy consumption in the three types of the office buildings is evaluated with the method of simulation to illustrate different energy usage in three kinds of the office buildings and propose strategies for improving energy consumption in design and operation, respectively.

2. Comparison of three types of office

2.1. Plane layout

The traditional private office space is mostly a small enclosed space. Due to the limitation of the fixed size of the space, it is difficult to change its plane layout to meet different demands. In order to increase the number of workstations, the furniture layout of open office is compact. In coworking office, the furniture is freely arranged and the office staff can walk around, encouraging people to interact^[3] (see Figure 1).

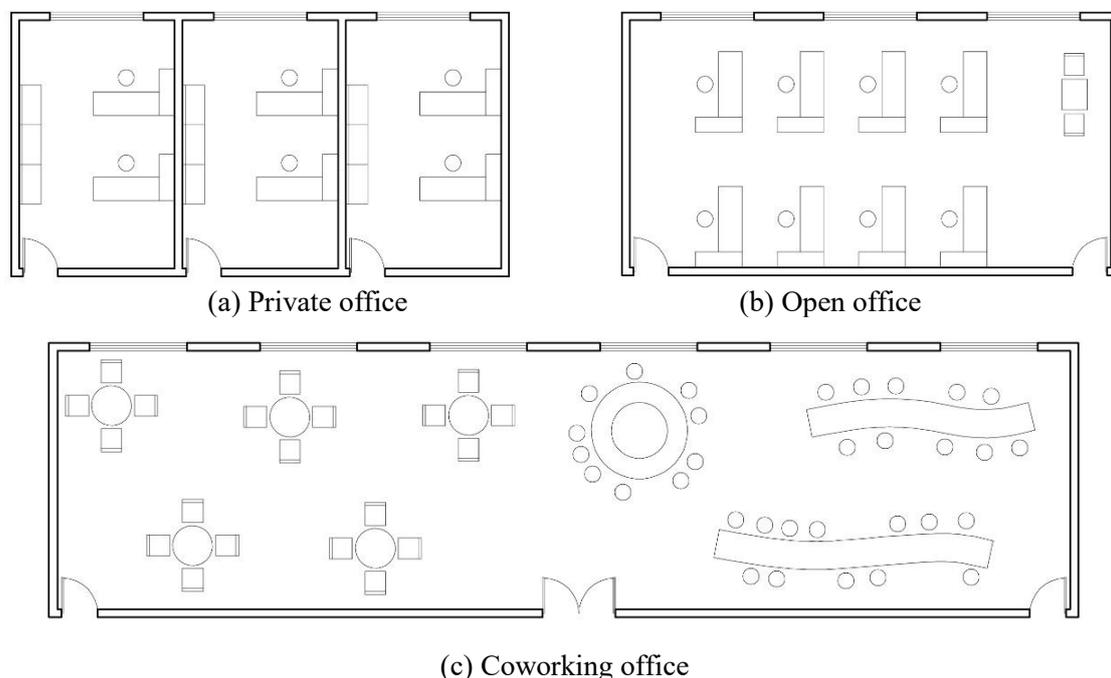


Figure 1. Plane layout

2.2. Work schedule

The main users of private office and open office are the leaders and employees. Staff of those two offices go to work and get off work according to the prescribed time. However, as for coworking office, the main users are freelancers and the members of the entrepreneurial team^[4]. Coworking office meets their

temporary office needs, so they are free to allocate their working hours. Therefore, the business hours of coworking office buildings are longer than those of private office and open office.

2.3. Usage of devices

The main energy-using equipment that related to the occupants' schedule in office buildings include lighting, air conditioning and office devices. In private office, the devices are turned on when people are in the office while the equipment is turned off when people are not in the office. As for open office, the lighting and air-conditioning systems need to be continuously operated regardless of the personnel density. Therefore, lighting and air-conditioning systems are turned on when the personnel density in open office space is low, resulting in waste of energy. However, lighting and air-conditioning are always on when personnel density is relatively high in coworking office. Thus, the utilization rate of devices is high in coworking office.

3. Model

3.1. Building model

The building is located in Hangzhou, Zhejiang Province, China, and the building faces in the south. This building has three floors, the height of which is 3.3 m respectively. The total construction area of the building is 1,249.1 m²(Figure 2). The model of the building is developed using DesignBuilder which is a comprehensive user graphical interface simulation software developed for the building energy dynamics simulation program EnergyPlus. Office staff work model and equipment system usage model is input into the building model for energy simulation. The specific param of building simulation are shown in Table 1.

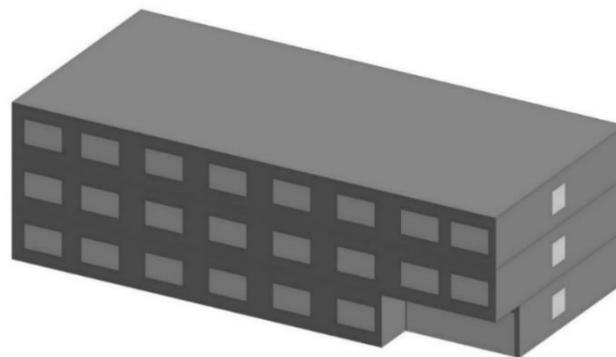


Figure 2. Building model

Table 1. Building simulation param

Item	Parameter value	
Fresh air	3 ACH	
Public lighting	9 W/m ²	
Office devices (computer)	200 W/set	
air-conditioning system	VRV	
Heating period	Dec. 15 th – Feb. 15 th	
Cooling period	Jun. 15 th – Sep. 1 st	
Indoor temp.	Heating	18°C
	Cooling	26°C

The extruded polystyrene board is adopted as the roof insulation material and the heat transfer coefficient of the roof is $0.36 \text{ W}/(\text{m}^2 \cdot \text{K})$. The insulation material of exterior wall of the building is rock wool board while the window frame is made of heat-insulating metal profile. The detailed structure of the building envelope structure is shown in Table 2.

Table 2. Thermal param of the enclosure structure.

Name	Material (from outside to inside)	Heat transfer coefficient $\text{W}/(\text{m}^2 \cdot \text{K})$
Roof	Cement mortar (20.0 mm), Extruded polystyrene board (80.0 mm), Waterproof materials (3.5 mm), Cement mortar (20.0 mm), Light aggregate concrete (80.0 mm), Reinforced concrete (120.0 mm), Lime cement mortar (10.0 mm)	0.36
Exterior wall	Lime mortar (5.0 mm), Mineral wool felt (55.0 mm), Cement mortar (12.0 mm), Aerated Concrete (240.0 mm), Lime mortar (20.0 mm)	0.51
Floor	Tamping clay (1,000.0 mm), Pebble concrete (150.0 mm), Waterproof materials (1.2 mm), Reinforced concrete (300.0mm), Fine stone concrete (50.0 mm)	0.84
Window	low light transmission Low-E glass (6.0 mm) +air (12.0 mm) +transparent glass (6.0 mm)	2.4
	Insulating metal profiles	5

The area of office in a private office is 25.2 m^2 (Figure 1 (a)). And the building consists of 32 offices. There are 10 private offices on the first floor of the building, of which 6 offices in the north are double rooms and 4 offices in the south are single rooms. The layout of the second floor of the building is basically the same as the first floor of the building. The building can accommodate 56 people working at the same time. The building area per capita is 22.3 m^2 , including two stairwells and one toilet on each floor.

There are 10 open office offices (Figure 1 (b)), which include three types of office space. The building contains 100 stations and the building area per capita is 12.5 m^2 .

There are two large offices on each floor of the coworking office, with a building area of 166.3 m^2 (Figure 1(c)) and 100.8 m^2 . The coworking office building contains 100 stations, and the building area per capita is the same as the open office which is 12.5 m^2 .

With a same model of buildings conditions and climate, the influence of models of private office, open office and coworking office on energy consumption are analyzed in the following section.

3.2. Behavior model

By investigating the occupancy rates of private office mode, open office mode and private office mode in an office building in Hangzhou, China, the following behavioural model simulation curves were obtained.

3.2.1 Work schedule. The working time of people in private office is from Monday to Friday. The staff goes to work around 8:00 in the morning; have lunch at around 12:30 and get off work at 18:00. Private office is mainly used by management personnel, and there are meetings and dining activities. Figure 3 shows the occupancy rates of private office staff. 1 means the office is full while 0 means that the office is empty^[5]. The average occupancy rate of office is 0.7.

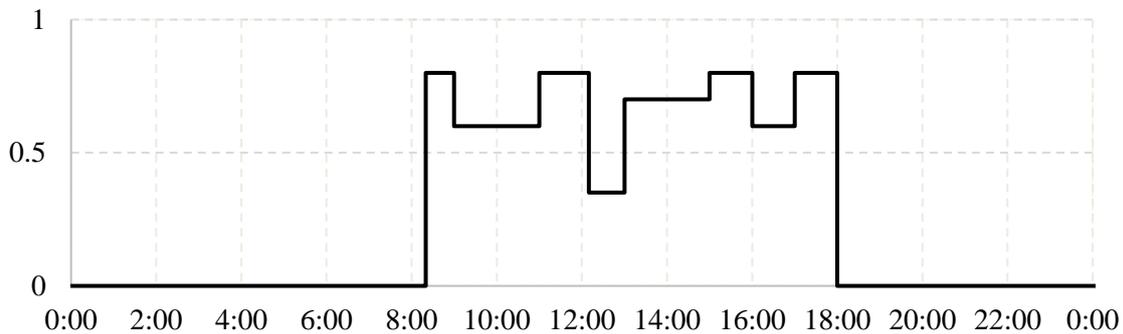


Figure 3. Private office occupancy rate

The main users of the open office are employees. And about half of them are in the office at noon. Figure 4 shows the occupancy rate of open office. The average occupancy rate of office staff is 0.7.

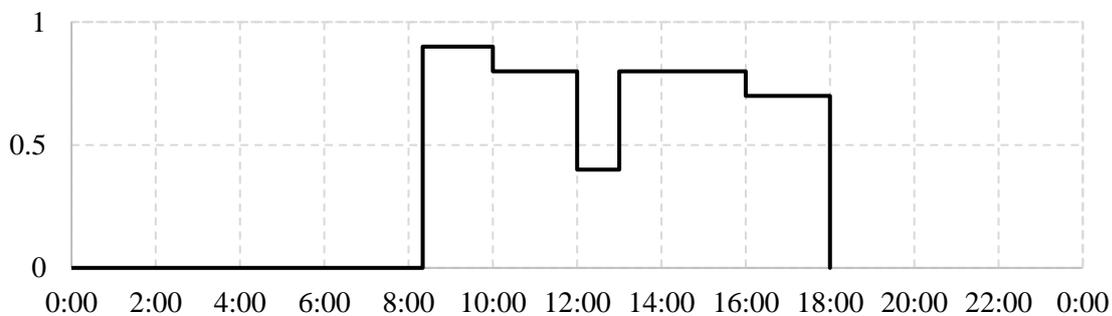


Figure 4. Open office occupancy rate

There is a big difference between the behaviour of office staff in the coworking office and that in the other types of office space. The office hours of office staff are relatively free. The coworking office space is open for work, study and communication from Monday to Sunday. Figure 5 shows the occupancy rate of coworking office. The average occupancy rate of the office staff is 0.9.

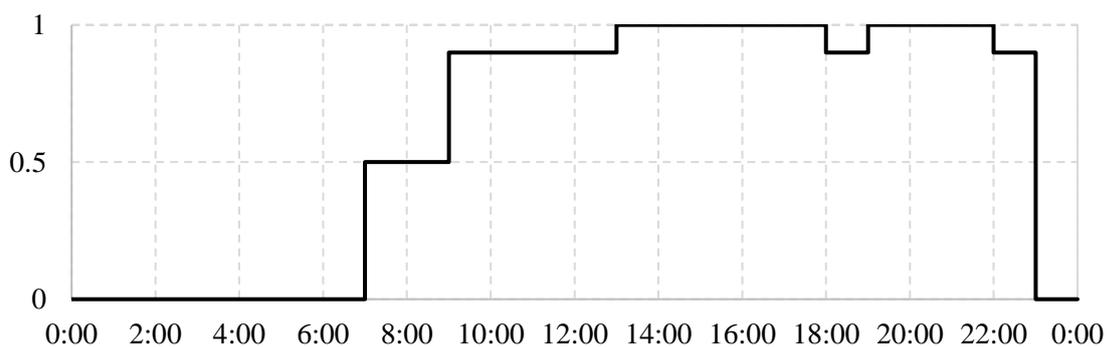


Figure 5. Coworking office occupancy rate

3.2.2 Schedule of equipment usage. The lighting behaviour of the office staff of the three types of office space is basically the same. Public lighting is turned on when the first office staff goes to work while the lighting is turned off when the last person gets off work. Public lighting has been turned on since there are always people in the coworking office. The office devices are mainly computers. And the office staff in the three office spaces have the same behaviour model for the computer. When a staff starts working, the computer is turned on. After work, the computer is turned down. Air-conditioning system

is turned on when the first office staff starts working. After the last person got off work, the air-conditioning system is turned off.

4. Simulation results and analysis

4.1. Annual energy consumption

The simulation results of energy consumption per month of three types office buildings are shown in Figure 6. As shown in the figure, the lighting behaviour and the usage of office devices have nothing to do with the month. The lighting energy consumption per month and the energy consumption of office devices per month are basically the same. Therefore, in non-heating and non-cooling periods, private office, open office and coworking office consume the same amount of energy each month.

The annual total building energy consumption of private office is 74,521 kWh, of which air conditioning energy consumption is 34,020 kWh, accounting for 46% of total energy consumption; lighting energy consumption is 23,608 kWh, accounting for 32% of total energy consumption; office devices energy consumption is 16,893 kWh, accounting for 23% of total energy consumption.

Since the personnel density of open office is about double of that in private office, the total energy consumption of open office buildings is higher than that of private office buildings. The annual total building energy consumption of the building reaches 94,338kWh, of which the air conditioning energy consumption was 31,597 kWh, accounting for 33% of the total energy consumption; the lighting energy consumption was 26,231 kWh, accounting for 28% of the total energy consumption; the office devices energy consumption was 36,510 kWh, accounting for the total. 39% of energy consumption.

The personnel density of coworking office is higher than the two types of office that mentioned above, so the energy consumption of coworking office is higher than that of private office and open office. The annual total building energy consumption reaches 212,842 kWh, of which the air conditioning energy consumption was 62,586 kWh, accounting for 29% of the total energy consumption. the lighting energy consumption was 45,136 kWh, accounting for 21% of the total energy consumption; the office devices energy consumption was 105,120 kWh, accounting for 49% of energy consumption.

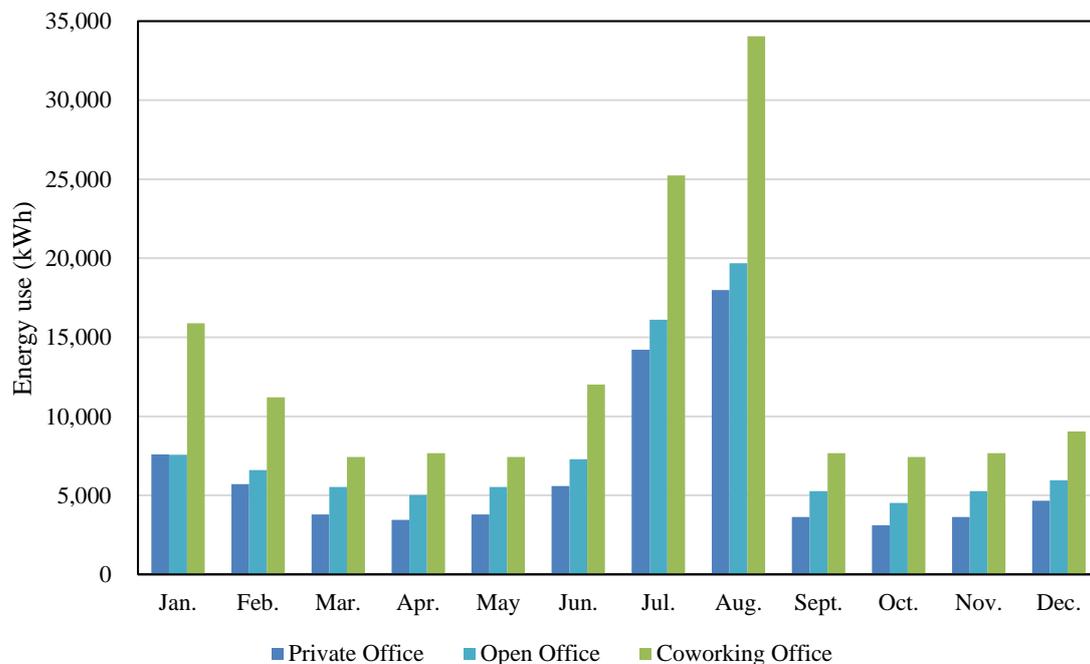


Figure 6. Energy consumption per month of three types office buildings

The energy consumption per unit area of private office, open office and coworking office is shown in figure 7. As shown in the figure, the annual energy consumption per unit area of private office, open office and coworking office is 60 kWh/m², 76 kWh/m² and 170 kWh/m² respectively.

In terms of energy consumption per unit area, the private office is lower than that of the open office and coworking office. The result is mainly due to that the use of building energy consumption per unit area to evaluate building energy consumption ignores the impact of factors such as personnel density and working hours. High personnel density and long office hours often mean high devices energy consumption.

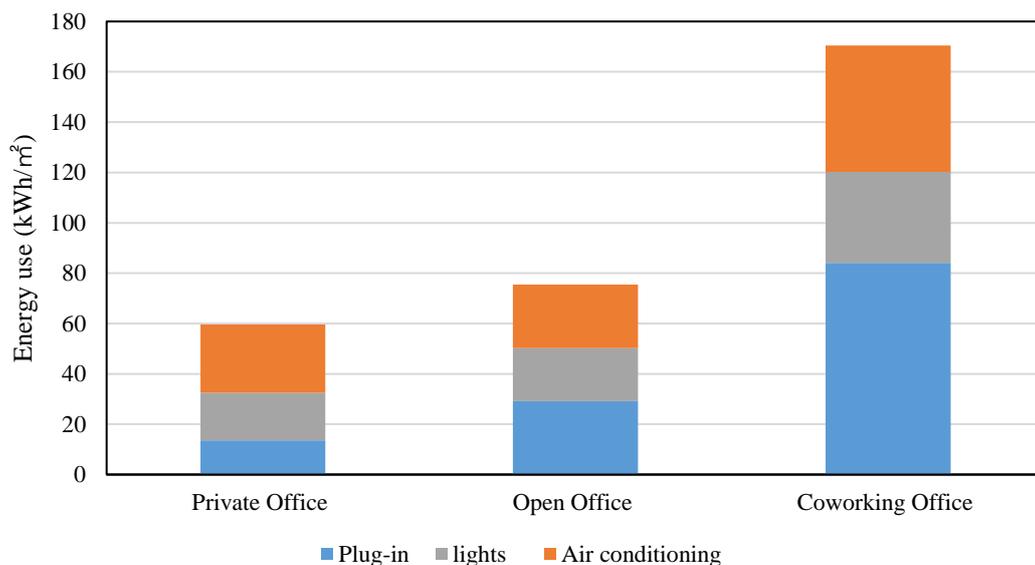


Figure 7. Annual building energy consumption of three types office buildings

4.2. Building energy consumption in terms of personnel density

4.2.1 Building consumption energy per capita per hour. Building energy consumption per capita of private office in typical heating day (January 8th) and cooling day (July 3rd) is shown in figure 8 and figure 9. Because of the wall heat storage and low temperature in the morning, the building energy consumption per capita of air-conditioning peaks at the first hour when air-conditioning system operates in a typical heating day. Due to the decrease in personnel density in noon and afternoon, there are two peak periods of per capita energy consumption per hour. On a typical cooling day, the lighting energy consumption per capita and air-conditioning energy consumption per capita are consistent with the typical heating day. At around 13 p.m., the highest outdoor temperature caused high energy consumption of air-conditioning. At the same time, due to the low personnel density, the air-conditioning energy consumption per hour reaches the maximum value of the day. Building energy consumption per capita per hour of open office on typical heating and cooling days is shown in figure 10 and figure 11 while building energy consumption per capita per hour of coworking office on typical heating and cooling days is shown in figure 12 and figure 13. The maximum daily energy consumption per capita of private office, open office and coworking office on the typical day of heating appear when the office staff just start going to work. On a typical cooling day, private office and open office have a maximum building energy consumption per capita per hour around 13 p.m. Because of high personnel density in coworking office, there is no maximum value at 13 p.m. On typical heating day and cooling days, the lighting energy consumption per capita per hour and office devices energy consumption of private office, open office and coworking office are consistent.

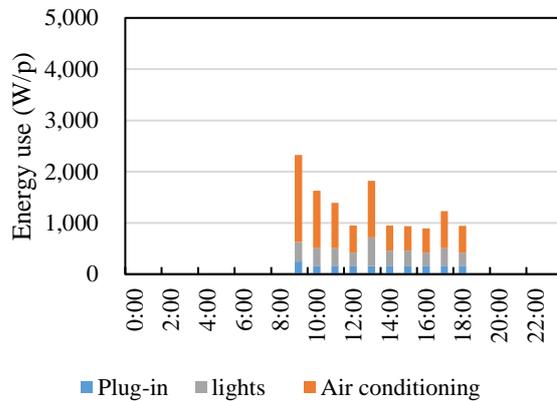


Figure 8. Building consumption energy per capita per hour for private office on typical heating day

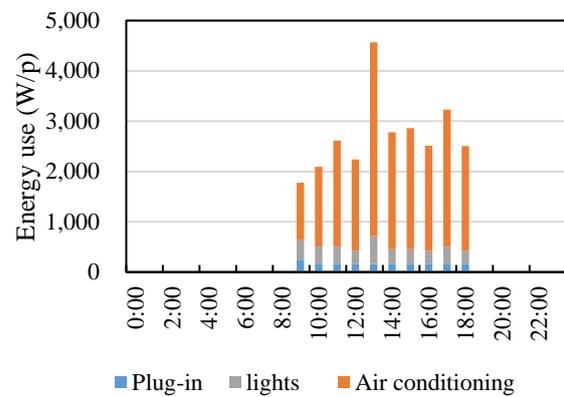


Figure 9. Building consumption energy per capita per hour for private office on typical cooling day

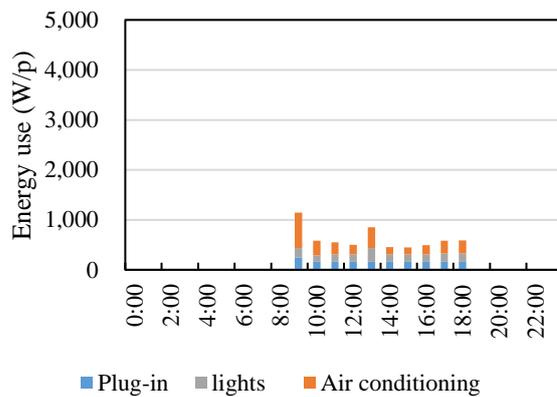


Figure 10. Building consumption energy per capita per hour for open office on typical heating day

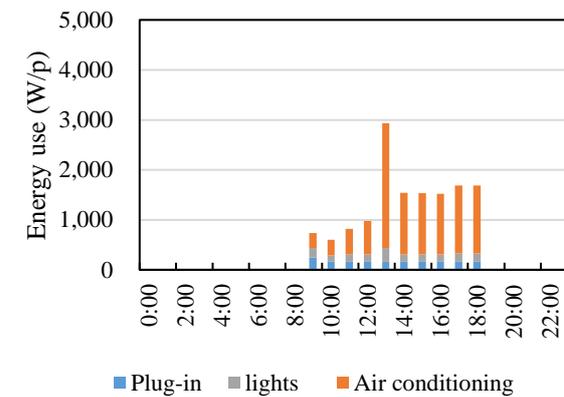


Figure 11. Building consumption energy per capita per hour for open office on typical cooling day

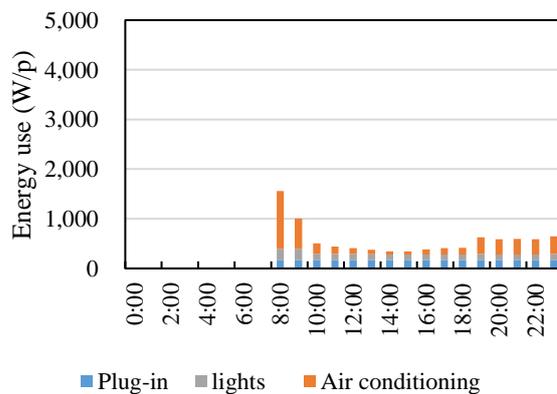


Figure 12. Building consumption energy per capita per hour for coworking office on typical heating day

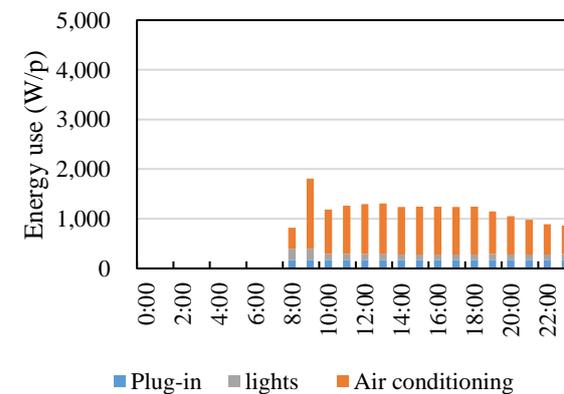


Figure 13. Building consumption energy per capita per hour for coworking office on typical cooling day

4.2.2 Annual building energy consumption per capita. The annual per capita building energy consumption of private office, open office and coworking office is 1,331 kWh/p, 943 kWh/p and 2,128

kWh/p (see Figure 14). The annual building energy consumption per capita of open office is lower than that of private office. The main reason is that under the same building area, open office can accommodate more office people than private office. In this building, the number of staff in open office is nearly double of that in private office. It can be seen from Figure 14 that the building energy consumption per capita of the coworking office is more than double of that of the open office. The main reason is that the coworking office has long business hours and high personnel density, leaving the air conditioning and public area lighting turning on for a long time.

4.2.3 Annual building energy consumption per unit of time per capita the year. Two indicators of building energy consumption per capita and building energy consumption per unit area are used to analyze the energy consumption evaluation of office buildings. When the building energy consumption per capita is used as the evaluation indicators, the energy consumption of the private office is higher than that of the open office. When the building energy consumption per unit area is used as the evaluation indicators, the energy consumption of the open office is higher than that of the private office. Thus, both the building energy consumption per unit area and building energy consumption per capita can't objectively reflect the building energy consumption level. Therefore, in this case, the concept of building energy consumption per unit of time per capita is introduced. Assuming that the working efficiency, and social and economic benefits are the same, the lower building energy consumption per unit of time per capita, the lower the energy consumption required to produce the social and economic benefits. The building energy consumption per unit of time per capita of private office, open office and coworking office is 0.89 kWh/(p·h), 0.51 kWh/(p·h) and 0.40 kWh/(p·h) respectively, which is shown in Figure 15. Therefore, the building energy consumption per capita for coworking office hours is the lowest and the energy consumption for generating social and economic benefits is the lowest.

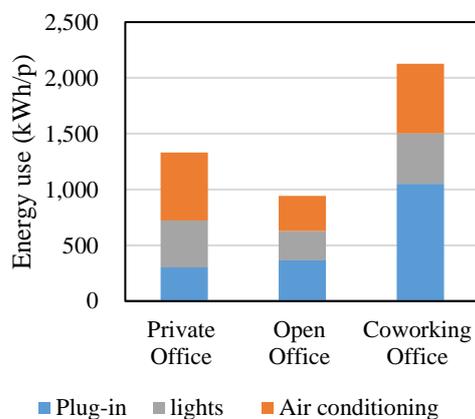


Figure 14. Building energy consumption per capita of three types of office buildings

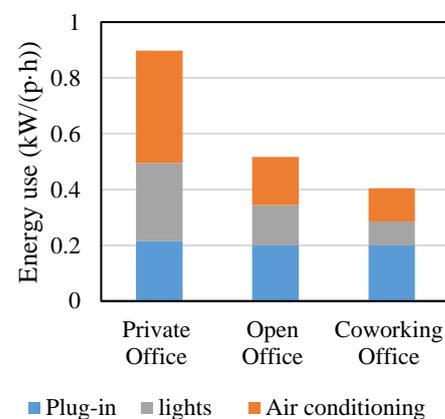


Figure 15. Building energy consumption per unit of time per capita of three types of office buildings

4.3 Energy saving strategies

4.3.1 The design and operation of air-conditioning system. In the design of air-conditioning system, private office should adopt non-central air-conditioning system such as split air-conditioning system and multi-line air conditioning system while open office and coworking office should use centralized air-conditioning system. However, due to the fluctuation of the personnel density in open office, the fresh air system will run at full load when the personnel density in open office is low. The operation of fresh air system will greatly increase the energy consumption of air-conditioning. Therefore, an intelligent real-time feedback mechanism needs to be established. At low personnel density, fresh air system provide fresh air based on the number of staff, ensuring good indoor air quality while reducing air-

conditioning energy consumption. The coworking office has a high personnel density and a stable load demand, so high efficiency of system operation is conducive to building energy saving.

4.3.2 Design and operation of office devices and lighting system. The lighting system should be controlled by zone during design. For private offices, each office is separated by space and the lighting system is relatively independent while for open office and coworking office, space lighting system should be controlled according to the location of the station. The energy-saving effect of office devices and lighting system largely depends on the energy-saving awareness of office staff that they should turn off office devices and lighting when they leave, which is the key to energy savings by turning off office devices and lighting when staff leave.

5. Conclusion

This paper analyses the characteristics and differences between private office, open office and coworking office. Investigating the behaviour of the three types of office, as well as the use of air-conditioning system, lighting system and office devices. Through statistical analysis of data, the personnel behaviour model, office devices use model, lighting use model and air-conditioning use model are obtained. Three kinds of different human behaviour modes are input to DesignBuilder to simulate building energy consumption. The following conclusions are drawn:

On heating day, the energy consumption per capita per hour of private office, open office and coworking office reach the maximum value when the devices start operating. On the cooling day, the energy consumption per capita per hour of private office and open office reaches the maximum value at around 13 p.m.

The building energy consumption per unit of time per capita of the coworking office is the lowest. When the working efficiency is the same, the energy consumption required to generate the social and economic benefits is the lowest. Therefore, in terms of building energy efficiency, office buildings should adopt a coworking office model whenever possible.

Private office adopts non-centralized air-conditioning system while open office and coworking office adopt centralized air-conditioning system. The supply of fresh air for open office should be adjusted in real time according to the number of staff and the lighting system of the office building should be controlled by district. It is important to cultivate the energy-saving awareness of office staff.

Acknowledgements

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