

Article

The Interaction Effect of Occupant Behavior-Related Factors in Office Buildings Based on the DNAS Theory

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Abstract: Occupant behavior is acknowledged as a main contribution to building energy consumption. Many efforts have been devoted to identifying the impact of occupant behaviors on building energy consumption. However, the lack of understanding of the interaction effects among occupant behavior-related factors, to some extent, can lead to inaccurate results. To decode these complex interactions, this study was conducted to investigate the interaction effects of occupant behavior-related factors. A survey based on the Drive-Need-Action-System (DNAS) theory was used to describe the occupant behaviors. Then, based on the survey, a simulation model of an office building was applied for estimating the energy consumption led by different occupant behaviors. Finally, an orthogonal design of experiments (DOE) method combined with Pareto analysis was used to quantify the interactions of occupant behavior-related factors on energy consumption. Results show that factor combinations with strong interaction effects include: (1) lighting control and lighting fixture type and (2) computer control and tolerance of temperature range. The results provide important reference for building designers and facility managers toward a better understanding of the influences of occupant behaviors on building energy consumption.



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Keywords: occupant behavior; factor interaction; building energy consumption; building performance simulation; the Drive-Need-Action-System theory

1. Introduction

A building consumes a large amount of energy throughout its life cycle. Because of the fast development of urbanization, energy issues in buildings have become more prominent since the building sector is a major energy consumer [1,2]. The quantity of building energy consumption has constantly increased in recent years. In some countries, building energy consumption has even exceeded industrial energy consumption [3]. It is estimated that building energy consumption accounts for about 40% of global energy consumption [4]. According to data from the International Energy Agency: In 2018, global carbon dioxide emissions reached a record high of 33.1 billion tons. Among them, China reached 9.5 billion tons, accounting for 28.6% of the total global emissions, ranking first [5–9]. The CO₂ emissions in global construction industry accounted for 39% of the total global CO₂ [9–11]. Compared to the energy consumption of other building types, the energy consumption of office buildings is one of the highest [12,13]. Meanwhile, office buildings, with the rapid growth of construction speed [14], may also prove to have great energy-saving potential [13]. Therefore, achieving the reasonable reduction of office building energy consumption is a major concern for building energy reduction overall.

According to the research, the factors influencing building energy consumption mainly include the climate, building envelope structure, building equipment, building operation and maintenance, occupant behavior and the indoor environment [15–35]. In the operation stage, the energy consumption of buildings is different due to various occupant behaviors, because although the building itself does not consume energy in the operation stage,

equipment inside the building causes energy consumption. People control the equipment in different ways, even in the same situation, so the amount of energy consumed differs as well. Occupant behavior, as one of the six major factors affecting building energy consumption, is the focus in the work on building energy conservation during the operation stage [36–38]. There are interaction effects among different factors relating to occupant behaviors. For example, the use of air conditioning is often accompanied by the action of closing a window. Therefore, it is necessary to explore the interaction effects among occupant behavior-related factors.

In this study, the Drivers-Needs-Actions-Systems (DNAS) theory was applied to explore the key occupant behaviors-related factors in office buildings; it quantifies the interaction effects of occupant behavior-related factors in office buildings using the design of experiments (DOE) method. The results provided a better understanding of occupant behaviors in buildings, which can provide a reference and basis for both energy-saving design and energy-saving policymaking.

2. Literature Review

In the past decades, research has been conducted to study the energy-related occupant behaviors in buildings, covering different focuses that range from definition of occupant behaviors in buildings to the effects of occupant behaviors on building energy consumption.

2.1. Definition of the Occupant Behaviors in Buildings

To study occupant behaviors, most of the related research defined them on the basis of occupant movements [39–43] and the control actions of occupants on windows, lights, air conditioning terminals and other equipment [26,44–51]. Wang et al. [40] indicated that building occupant behaviors can be broken down into two aspects: occupancy, which refers to the in-building rate; and occupants' control behaviors on building devices, including windows, doors, blinds, air conditioning terminals, lights and equipment (TVs, computers, printers, etc.). There are also some studies that classified occupants' behaviors with direct energy consumption outcomes and energy time use data, in a way that the classification rules were undetermined in advance. Diao et al. [43] identified 10 distinctive behavior patterns through unsupervised clustering analysis in light of direct energy consumption outcomes and energy time use data. Yu [20] also classified four building groups by cluster algorithm. Each group contained one type of highly similar occupant behaviors.

In addition to the above described occupant behaviors by classification, Turner and Hong [52] presented a DNAS theory to describe occupant behaviors. The DNAS theory framework provides a standardized way to represent the occupant behaviors from four perspectives, namely drivers, needs, actions and systems, which can be applied to guide behavioral program design, implementation and evaluation, and facilitate the occupant behavior models' integration with building simulation tools. This DNAS theory framework can effectively solve the problem of the inconsistency of standards in the process of occupant behavior description and can make the research on occupant behavior in buildings more standardized and systematic.

2.2. The Impacts of Occupant Behaviors on Building Energy Consumption

"Buildings do not use energy, but people do" [53]. The impacts of occupant behaviors on building energy consumption cannot be ignored. Studies on building energy performance that do not consider the occupant behaviors confronted the problem that the actual situations were not in line with their expectations, e.g., the ignorance of occupant behaviors led to significant differences between the building energy predictions and the actual energy consumption. Therefore, more and more studies relating to building energy consumption have paid attention to the occupants and their behaviors. Fan et al. [54] and Rinaldi et al. [55] considered the basic information of occupants (including age, gender, occupation, etc.) when investigating the factors affecting building energy consumption. Roussac et al. [56] quantified the occupant factors in office buildings on the basis of the

data of occupants' specific technology investments and actions. The research showed that there is an interaction between occupant behaviors and other factors relating to building technologies.

Some scholars [17,43,57–62] have studied the interaction effects between occupant behaviors and the non-occupant behavior factors on building energy. Yu et al. [20] discussed the impact of climate conditions on occupant behaviors, and thereby, on building energy consumption. Tim et al. [57] concluded that there is an interaction between occupant behaviors and architectural ventilation performance. Carmenate et al. [58] developed a simulation approach to capture the diverse attributes and dynamic behaviors of building occupants at the interface of human-building application interactions [59]. The results of these investigations showed that there are complex relationships among occupant behaviors, buildings, climate conditions and equipment.

Some previous research also aimed to reveal the associations and correlations among different occupant behaviors [63–68], and the results showed that interactions exist between different behaviors, and these interactions can provide detailed recommendations for building energy conservation. Therefore, a systematic and comprehensive exploration of occupant behavior-related factors can better explain the components of energy consumption and achieve better energy-saving effects. This study will extract the office building occupant behavior-related factors on the basis of the DNAS theory, and then explore the interaction effects of these factors on building energy consumption, so as to provide a better understanding of occupant behaviors for building designers, facility managers and occupants, and present effective strategies for energy reduction in office buildings.

3. Methodology

An overview of the methodology and the process of the interaction effects analysis of occupant behavior-related factors is illustrated in Figure 1. There are three stages in this study. In the first stage of data collection, a questionnaire survey, which was composed on the basis of the DNAS theory, was conducted to collect the basic information of occupant behaviors in office buildings. After the analysis by the statistical methods of cross-analysis, sensitivity analysis, and building energy simulation, the key occupant behavior-related factors were extracted, and the factor levels were categorized. In the experiment design stage, the key factors and their corresponding levels, which were the outputs of the first stage, were used to set up an orthogonal array to provide guidance for the implementation of the experiments. The "experiment" in this study was a building energy simulation using DeST-c (a software used for commercial building thermal environment design simulation). After the response values of energy consumption were obtained by simulation, the results of the experiments were analyzed as input parameters for the subsequent interaction analysis of occupant behavior-related factors. In the third stage, the Pareto analysis was adopted to test whether the interactions of occupant behavior-related factors exist, and to calculate the influence on the response value caused by the interaction between every pairing of two factors. The details of the entire analysis are introduced as follows.

3.1. The DNAS Theory

The DNAS theory is a logical language framework to describe the behaviors of building occupants proposed by Turner and Hong [52]. According to this theory, occupant behaviors are divided into four parts: drivers, needs, actions and systems. Factors in the "systems" part inhabit the "outside world" (i.e., the building environment), while factors in the "needs" part inhabit the "inside world" (i.e., the cognitive processes of human beings). The "drivers" and "actions" parts inhabit both the "outside" and "inside world". The parts of "drivers, needs and actions" are directly related to occupants, but the "systems" factors influence occupants indirectly. These four parts are explained in detail as follows:

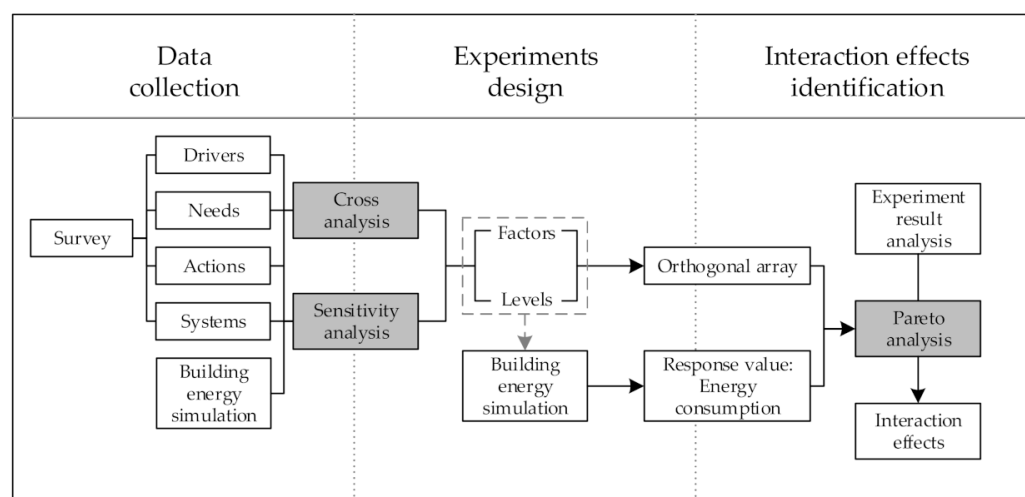


Figure 1. Overview of the research methodology.

Drivers: Under the stimulation of the external environment of buildings, occupants usually adopt a series of behaviors to meet their physiological and psychological needs. The “drivers” include environmental factors. For example, in office buildings, the location of the building belongs to the “drivers” factor, because in different geographic locations, the corresponding climate and other external building environments vary, which drives occupants to make different choices regarding energy use behaviors.

Needs: Considering physical and non-physical demands, occupants in buildings are inclined to take a series of actions to make the indoor environment meet their satisfactions. For example, in office buildings, it is required that lighting should be no less than 500 lx [69], that is, only indoor illumination reaching 500 lx is considered to meet occupants’ normal work and life needs.

Actions: This part connects the occupants and the external environments of buildings. It refers to the occupant’s direct actions toward the external environment, including behaviors to satisfy comfort and related adjustments of the building system. For example, this includes the occupant’s intuitive behaviors, such as window control, light switching, air conditioning control, etc.

Systems: This part directly affects the overall internal environment of a building, including the equipment and mechanisms inside the building. Occupants can maintain the overall comfort of the building environment by adjusting the systems. Typical systems, including the air conditioning system, lighting system and other systems, are also important factors affecting building energy consumption.

The objective of the DNAS theory is to present a framework for describing occupant behaviors in buildings, and then to address issues such as: (1) the large deviation between the predicted and actual energy consumption, caused by the neglect of the impact of occupant behaviors; (2) excessive simplification of occupant behaviors in architectural design and operation periods; and (3) the neglect of the relations between occupant behaviors and building systems (e.g., attributes of structure, building materials and construction equipment).

The DNAS theory provides a framework for describing occupant behaviors. Some researchers [70] have used it to decompose the energy consumption behaviors of residential buildings and extract the influencing factors from the aspects of drivers, needs, actions and systems. Most of the research on the DNAS theory is still in the program code of building simulation software [71,72]. Take DeST software as an example, the DNAS theory simulates occupant behaviors more accurately. Hong et al. [72] compiled the programming language in “.xml” format on the basis of the DNAS theory, realizing the application of occupant behaviors in the form of “.obxml” in building simulation software, which realized the interoperable relationship between occupant behaviors and building

simulation software. Functions that can be directly realized by the DNAS theory include: predicting the energy consumption value of buildings, simulating occupant behaviors in buildings, micro-analysis of the determinacy and randomness of occupant behaviors, monitoring the impacts of occupant behaviors on building energy consumption, etc.

The DNAS theory can be used in the three stages of the building life cycle, which are the design, operation and renovation stages. In the design stage, the DNAS theory can be used to promote the prediction of building energy consumption to be more accurate. A written program based on the DNAS theory has been applied in the occupant behavior module in DeST and EnergyPlus to support decision-making at the early stage of building design. In the operation and maintenance stage, the DNAS theory is mainly applied to establish the building energy prediction model and the algorithm framework of software development considering occupant behaviors. According to the DNAS theory, users can provide customized energy-saving advice via intelligent man-machine integrated communication. In the reconstruction stage, the DNAS theory can assist building owners to evaluate the solutions to different building technologies affected by occupant behaviors.

3.2. The Orthogonal Design of Experiments

3.2.1. The Orthogonal Design of Experiments (DOE) Method

The orthogonal DOE method, belonging to mathematical statistics, integrates experimental design and analysis, and can be applied for multifactor and multilevel experimental designs [73]. When examining the influences of multiple factors on response variables, especially with multiple levels, complete experiments are often difficult to carry out because of their large scales. Under the limited experiment conditions, the orthogonal DOE method is used to determine the best combination of factors, which can simplify experiments by reducing the required number of experiments. In this study, the main advantage of using the orthogonal DOE method was to reduce the number of building energy simulations needed to get as much information as possible. Another advantage of the orthogonal DOE method is that it can dig out the interactions among different factors. Therefore, the interactions among different factors relating to occupant behaviors in this study were explored.

3.2.2. Operation of the Orthogonal DOE Method

The orthogonal DOE method is divided into two parts: design and analysis of the experiments. In the design stage, the first step is to determine the input variables of the experiments. The input variables include the parameters, which have the potential of influencing the response variables, and the appropriate settings of each parameter. In the orthogonal DOE method, the parameters are called factors and the parameter settings of each factor are called levels. Then, the combination matrix of the input variables can be created by applying the orthogonal array. In this study, the factors were the energy-related occupant behaviors. Since the experiments were already designed, the response variables could be obtained by operating the corresponding experiments.

In the analysis stage, the results of the experiments by the orthogonal DOE method were used for data analysis. Regarding the orthogonal DOE method, with consideration of the research objectives, there are two potential analysis methods: (1) main effect analysis corresponding to the effects of individual factors on the response variables, and (2) interaction analysis corresponding to the effects of a combination of factors. In this study, the interaction analysis method was employed. Interaction refers to the phenomenon that the effect of one variable on the response variables will vary to some extent depending on the factor level of the other variables. The existence of interaction indicates that the effects of several factors studied at the same time on the response variables are not independent. The interaction analysis can show whether the interactions of factors exist and measure the degrees of the interaction effects. The Pareto analysis is an effective method to illustrate the interaction effects. In this study, the Pareto chart, the output of the Pareto analysis, was used to rank the factors and factor combinations according to their importance, which can clearly screen the factor combinations with interaction effects.

4. Case Study

This section presents the case study that involved three parts: (1) data collection from questionnaires, (2) determination of the occupant behavior-related factors and corresponding factor levels and (3) identification of the interactions among occupant behavior-related factors by the orthogonal DOE method.

4.1. Survey Design and Data Collection

The survey was designed on the basis of the DNAS theory. The questionnaire of this study included 48 basic questions from four perspectives of the DNAS theory, covering the basic attributes of office buildings and the general behaviors of occupants. The contents of the questionnaire are detailed in Table 1, and the original questionnaire is in Appendix A. This survey distributed a total of 350 questionnaires and retrieved 254 of them. Among the retrieved questionnaires, 58 were from the South and 196 were from the North. Since the heating measures of the South and the North are different, in order to make the research more accurate, the 196 qualified questionnaires from the North were analyzed in this case study.

Table 1. Design of the questionnaire under the Drive-Need-Action-System (DNAS) theory.

Classification		Formulation
	Item	Content
Drivers	Occupant information	Age Gender Weekday working time Weekend working time Whether near window
	Building properties	Location Orientation Building type Construction time Structure type Area Number of occupants
Needs		Temperature preferences Shading Building daylight The occupant distance to window
Actions		Window control Curtain control Lighting control Air conditioner control Printer control Water dispenser control Other electrical equipment
Systems		Lighting fixtures type Air conditioning type Office equipment type

4.2. Survey Design and Data Collection

Factors belonging to “drivers” and “needs” were determined by the results of the cross-analysis based on the results of preceding questionnaires. These obtained factors are the significant factors that affect occupant behaviors. Factors belonging to “actions” and “systems” were extracted according to the sensitivity of building energy consumption by sensitivity analysis. These behaviors are the key factors affecting building energy consumption. Through the above process, the key factors that affecting occupant behaviors

were obtained and the sensitivity of different behaviors was analyzed. After that the factors and factor levels were determined, the interaction effects among occupant behavior-related factors could be studied by the orthogonal DOE method.

4.2.1. Factors from “Drivers” and “Needs”

The cross-analysis was conducted for the factors extracted from “drivers” and “needs” (containing 15 different factors) with the factors extracted from “actions” (containing 7 different factors) in the questionnaires. The cross-analysis of all possible combinations of factors was done in order to find the most significant ones. Then, based on the results of the cross-analysis, we found out whether the factors extracted from “drivers” and “needs” were significant, and the reasons behind the differences were analyzed. The three significant factors of “orientation, building natural daylight and the occupant distance to window” were obtained. The detailed analysis results of these three significant factors toward occupant behaviors are shown in Tables 2–4.

Table 2. The significant results of the cross-analysis of factors from “actions” with orientation.

Factors from “Actions”	Category	Orientation				Total	p Value
		South	North	East	West		
Turn on the light	Turn on at a fixed time	5 ^a (4.81 ^b)	5 (10.00)	6 (28.57)	1 (4.76)	17 (8.67)	0.009
	Turn on when dark	96 (92.31)	40 (80.00)	14 (66.67)	18 (85.71)	168 (85.71)	
	Others	3 (2.88)	5 (10.00)	1 (4.76)	2 (9.52)	11 (5.61)	
Total		104	50	21	21	196	
Turn off the light	Turn off at a fixed time	5 (4.81)	7 (14.00)	7 (33.33)	2 (9.52)	21 (10.71)	0.005
	Turn off when natural light is enough	92 (88.46)	36 (72.00)	13 (61.90)	17 (80.95)	158 (80.61)	
	Others	7 (6.73)	7 (14.00)	1 (4.76)	2 (9.52)	17 (8.67)	
Total		104	50	21	21	196	
Ventilation by opening window	Never	35 (33.65)	17 (34.00)	11 (52.38)	13 (61.90)	76 (38.78)	0.046
	Always	69 (66.35)	33 (66.00)	10 (47.62)	8 (38.10)	120 (61.22)	
Total		104	50	21	21	196	

^a It represents the number of questionnaires containing this response under the corresponding condition (the same as in the following table). ^b It represents the percentage of the number of questionnaires containing this response in all the responses under the condition of corresponding column (the same as in the following table).

Table 3. The significant results of the cross-analysis of factors from “actions” with building natural daylighting.

Factors from “Actions”	Category	Facing Sun	Facing Shade	Total	p Value
Open window after entering office	Never	35 (54.69)	49 (37.12)	84 (422.86)	0.020
	Always	29 (45.31)	83 (62.88)	112 (57.14)	
Never turn off the light	Never	60 (93.75)	131 (99.24)	191 (97.45)	0.022

Table 3. Cont.

Factors from “Actions”	Category	Facing Sun	Facing Shade	Total	<i>p</i> Value
Control temperature by AC	Always	4 (6.25)	1 (0.76)	5 (2.55)	0.020
	Never	30 (46.88)	85 (64.39)	115 (58.67)	
	Always	34 (54.13)	47 (35.61)	81 (41.33)	
	Never	62 (96.88)	111 (84.09)	173 (88.27)	
Use curtain	Always	2 (3.13)	21 (15.91)	23 (11.73)	0.009

Table 4. The significant results of the cross-analysis of factors from “actions” depending on the occupant’s location (near a window or not).

Factors from “Actions”	Category	Near Window	Not Near Window	Total	<i>p</i> Value
Close window after work	Never	57 (43.51)	41 (63.08)	98 (50.00)	0.010
	Always	74 (56.49)	24 (36.92)	98 (50.00)	
Lower the temperature by AC	Never	84 (64.12)	31 (47.69)	115 (58.67)	0.028
	Always	47 (35.88)	34 (52.31)	81 (41.33)	
Ventilation by opening the window when occupant feels hot	Never	44 (33.59)	32 (49.23)	76 (38.78)	0.034
	Always	87 (66.41)	33 (50.77)	120 (61.22)	

Orientation: The factor of orientation, belonging to the architectural attributes, refers to the orientation of the specific side of a building with the most windows in this study. It can be divided into four directions: south, north, east and west. Studies have shown that there are differences in window opening behavior among different orientations. In transition seasons (in general, spring and autumn are the transitional seasons), south is the best orientation, and the window opening rate is the highest [59]. The factor of orientation was analyzed with the factors from “actions” by cross-analysis and the results demonstrate that there is a significant difference in the action of window control under different orientations. Occupants in buildings facing south and north are more inclined to open windows for ventilation. For the action of lighting control, there are also differences under different orientations. There are differences in triggering conditions of switching lights due to different orientations.

Building daylight: In view of building daylight, the results of the cross-analysis showed that obvious differences exist in occupant’s control of the windows, lights and air conditioning under different building daylight conditions. The conclusions are: (1) occupants in sunny positions are more inclined to open windows when entering the room, (2) occupants in shady positions are more likely to turn off the lights than occupants facing to the sun and (3) occupants in shady positions are more willing to adjust the indoor temperature by using air conditioning.

The occupant distance to the window: This factor, which is denoted by whether the occupant is near the window or not, reflects the location characteristics of the occupants in their offices. The results of the cross-analysis suggest that the occupant action of controlling

lighting and air conditioning has significant difference depending on the occupant's distance to the window. It was shown that occupants near windows tend to close the windows after work and open the windows when they feel hot; while the occupants who are located away from the windows prefer to use the air conditioner to keep comfortable.

After the above cross-analysis, the significant factor belonging to "drivers" includes orientation, and the significant factors of "needs" include building daylight and the occupant's distance to windows. For the subsequent implementation of the orthogonal DOE method, after determining the factors from "drivers" and "needs", it was necessary to select the appropriate levels for these factors.

In this study, the number of factor levels was set as two with the consideration of the experiments' implementation costs. For the factor of orientation, this study chose the south direction and the north direction as the two levels. The "Standard for Lighting Design of Buildings" [74] stipulates that office buildings with an illumination environment between 300–500 lx can be considered comfortable. So, 300 lx and 500 lx were set as the two levels in this study.

4.2.2. Factors from "Actions" and "Systems"

The factors from "actions" and "systems" were consistent with the corresponding part in the questionnaires, including air conditioning use behaviors, lighting use behaviors and computer use behaviors. An office building information model was established in this study to measure the impacts of different factors from "actions" and "systems" on the total energy consumption of the office building with the same equipment. The sensitivity was regarded as the benchmark to select the levels of these factors.

Simulation model development: An office building in Dalian, China was used as a case in this study. The total building area is 8422 m², and the layout is inverted L-shaped, as shown in Figure 2. The final model of the office building is shown in Figure 3. The model was built by the software of DeST-c, which was developed by the Department of Architectural Technology Science of Tsinghua University. The descriptions of the occupant behaviors in the building systems were set up according to the options in the questionnaires.

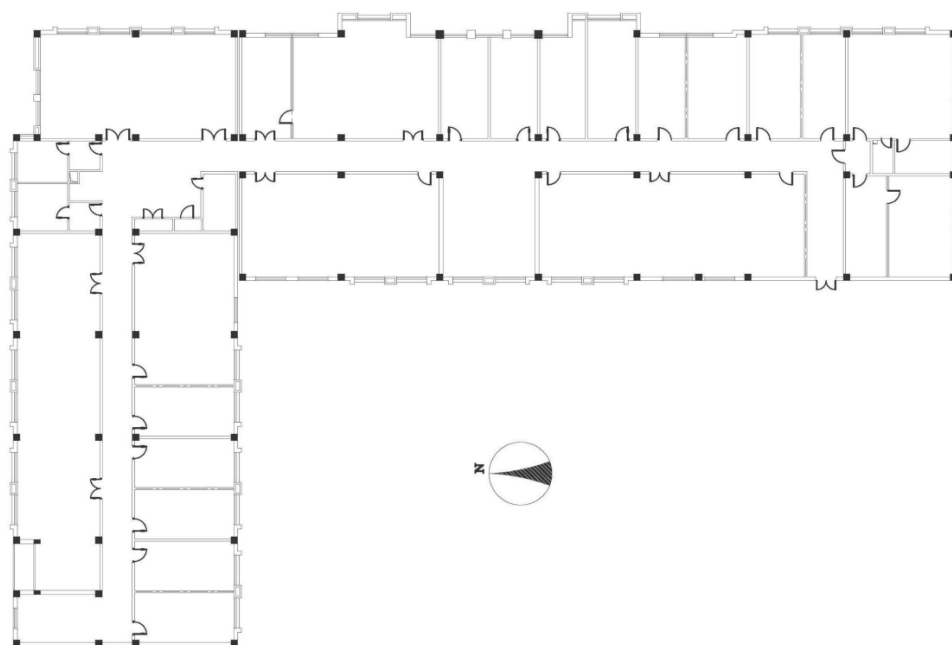


Figure 2. The L-shaped layout of the building.

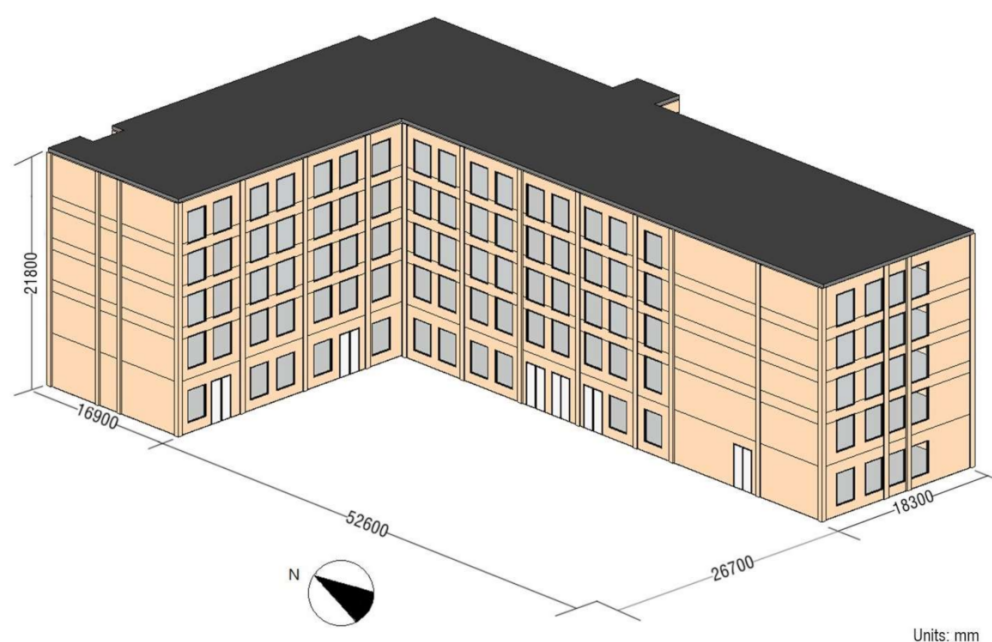


Figure 3. Building information model of the case.

Sensitivity analysis: In this study, sensitivity analysis was used to determine the factors levels from “actions” and “systems”. By setting different behavior modes with the same equipment, the changes of energy consumption can be obtained, and then, the sensitivities of the behaviors can be procured. In this study, the sensitivity was used as follows:

$$w_n = \frac{W - W_n}{W_n} \quad (1)$$

where w_n is sensitivity of the n th behavior, W is the energy consumption value of the reference behavior and W_n is the energy consumption value of the n th behavior.

The sensitivity values were used to classify the three sensitivity levels of the occupant behaviors of less sensitive, sensitive and more sensitive (see Table 5).

According to the sensitivities of different behavior modes on energy consumption, the mode of “on when reach, off when leave” of air conditioner use behavior, lighting use behavior and computer use behavior was regarded as low-factor level and the mode of “always on” was the high-factor level.

The factors of the tolerance temperature setting and lighting fixture type in the “systems” part are also reflected indirectly in the results of sensitivity analysis. For the tolerance temperature setting of the air conditioning, most people intend to set the air conditioning temperature to be about 26 °C according to the results of the questionnaire survey, so the central value of the fluctuation range of the air conditioning tolerance temperature setting was 26 °C under both two factor levels. In this study, 23–28 °C was chosen as one factor level, while 25–26 °C was chosen as another factor level. According to the survey, the common lighting fixtures are fluorescent lamps with a power of 18 W and the energy-saving lamps with a power of 12 W. Therefore, the factor levels of lighting fixture types were the 12 W energy-saving lamp (LED) and the 18 W fluorescent lamp.

According to the questionnaire and cross-analysis, the three factors of “orientation”, “building natural daylight” and “occupant distance to window” showed significant influences toward occupant behaviors. Occupant behaviors further affected the building energy consumption. As for the input of the simulation, “building natural daylight” and “occupant distance to window” can be summarized as the “illumination” factor of the building. Therefore, the “orientation” and “illumination” factors were set as the influencing factors in the factors set. According to the analysis above, seven factors were extracted, and

each factor was assigned two factor levels, which were the high level (+1) and the low level (−1), respectively. These seven factors and their corresponding levels are shown in Table 6.

Table 5. The sensitivity of occupant behaviors.

Category	Description	Sensitivity Degree (%)	Sensitivity Level
AC use behavior	Always on	13.06	A ^a
	On when reach, off when leave	1.85	B ^b
	The range length of tolerance temperature (°C) ^d		
	5	−0.41	C ^c
	On when reach and hot, off when leave	4	/
		3	C
		2	C
		1	C
Lighting use behavior	Always on	16.79	A
	On when reach, off when leave	3.94	B
	The range length of tolerance illumination (lx) ^e		
	On when reach and dark, off when leave and the natural light is enough	200	/
		190	C
		180	C
		170	C
		160	C
Computer use behavior	On when reach, off when leave	0	/
	Always on besides weekend	14.21	A
	Always on	24.13	A

^a Sensitivity level A (sensitivity > 10) indicates that the behavior is significantly sensitive to energy consumption. ^b Sensitivity level B (sensitivity ranges from 1 to 10) indicates that the behavior is sensitive to energy consumption. ^c Sensitivity level C (sensitivity ranges from 0 to 1) indicates that the behavior is nearly insensitive to energy consumption. ^d The range of tolerance temperature refers to the indoor temperature. If it is over the boundary, the occupants will change the air conditioning from the status “off” to “on”. ^e The range of tolerance illumination refers to the amplitude value that occupants can tolerate outside the range of comfortable illumination. For example, when the indoor illumination is 500 lx, it is regarded as a comfortable condition, and the range of tolerance illumination is set to be 200 lx, meaning that occupants will not make lighting control behaviors within the illumination range between 300 and 700 lx.

Table 6. Seven factors and their corresponding levels based on the DNAS theory.

Category	Factor	Name	Low Level (−1)	High Level (+1)
Drivers	A	Orientation	Facing south	Facing north
	B	Illumination	300 lx	500 lx
	C	Lighting control	On when reach, off when leave	Always on
Actions	D	AC control	On when reach, off when leave	Always on
	E	Computer control	On when reach, off when leave	Always on
Systems	F	Lighting fixtures type	12 W	18 W
	G	Tolerance temperature range	23–28 °C	25–26 °C

4.3. Implementation of the Orthogonal DOE Method

In this study, the software of Minitab 17 was used to construct the orthogonal matrix of factors relating to the occupant behaviors. The DeST-c software was used to calculate the energy intensity 64 times for different combinations of the factor levels, and the energy use intensity was taken as the final response variable. The orthogonal matrix of the occupant

behavior-related factors and the calculation results of energy consumption are shown in Table 7.

Table 7. The orthogonal matrix and calculation results of energy consumption.

Run Order	A	B	C	D	E	F	G	Energy Use Intensity (kWh/a.m ²)
1	−1	−1	1	1	−1	1	−1	187.19
2	1	1	1	−1	−1	1	1	165.43
3	1	1	1	−1	1	−1	1	115.25
4	1	1	1	1	1	1	1	93.99
5	−1	1	−1	−1	−1	1	1	212.95
6	−1	−1	−1	−1	1	−1	−1	243.13
7	−1	−1	1	1	1	−1	−1	112.03
8	1	−1	1	−1	−1	1	−1	180.01
9	1	−1	1	1	−1	−1	−1	171.59
10	1	−1	1	1	−1	1	1	160.43
11	−1	1	−1	−1	1	−1	1	182.97
12	−1	1	−1	1	−1	1	−1	210.23
13	−1	−1	−1	−1	−1	−1	1	257.01
14	−1	1	−1	−1	−1	−1	−1	242.48
15	1	1	−1	−1	1	1	1	115.25
16	−1	1	1	−1	−1	1	−1	165.68
17	−1	1	−1	−1	1	1	−1	153.45
18	−1	−1	−1	1	1	1	−1	183.99
19	1	−1	1	1	1	−1	1	135.66
20	1	−1	1	−1	1	−1	−1	132.09
21	1	1	−1	1	1	1	−1	162.03
22	1	1	−1	−1	−1	−1	1	285.59
23	−1	1	1	−1	1	−1	−1	112.06
24	1	1	−1	1	−1	1	1	190.03
25	−1	−1	−1	1	−1	1	1	211.05
26	1	1	−1	−1	1	−1	−1	192.89
27	1	−1	−1	1	−1	1	−1	254.01
28	1	−1	1	1	1	1	−1	122.50
29	−1	1	1	−1	1	1	1	165.68
30	−1	−1	1	1	1	1	1	123.15
31	1	−1	−1	1	1	1	1	167.15
32	−1	1	−1	1	1	1	1	153.45
33	1	−1	−1	1	−1	−1	1	196.16
34	−1	−1	1	−1	1	−1	1	122.03
35	−1	1	−1	1	−1	−1	1	242.48
36	1	−1	−1	−1	1	−1	1	198.36
37	−1	1	1	1	1	1	−1	106.17

Table 7. Cont.

Run Order	A	B	C	D	E	F	G	Energy Use Intensity (kWh/a.m ²)
38	1	1	−1	1	−1	−1	−1	252.39
39	−1	−1	−1	−1	−1	1	−1	257.01
40	1	−1	−1	−1	−1	1	1	190.98
41	1	1	−1	−1	−1	1	−1	212.89
42	−1	1	1	1	−1	−1	−1	242.48
43	1	1	1	1	1	−1	−1	112.04
44	−1	−1	1	−1	−1	1	1	182.66
45	1	−1	1	−1	−1	−1	1	197.16
46	1	1	−1	1	1	−1	1	226.09
47	−1	−1	−1	−1	1	1	1	193.99
48	1	1	1	−1	−1	−1	−1	171.54
49	−1	1	1	1	1	−1	1	171.56
50	−1	−1	1	−1	−1	−1	−1	218.41
51	−1	−1	1	1	−1	−1	1	196.39
52	1	−1	−1	−1	−1	−1	−1	257.87
53	−1	1	1	−1	−1	−1	1	171.56
54	−1	1	−1	1	1	−1	−1	182.97
55	−1	−1	1	−1	1	1	−1	163.14
56	1	−1	−1	−1	1	1	−1	163.47
57	−1	−1	−1	1	−1	−1	−1	292.37
58	1	1	1	−1	1	1	−1	105.92
59	−1	−1	−1	1	1	−1	1	197.51
60	1	−1	−1	1	1	−1	−1	198.36
61	−1	1	1	1	−1	1	1	155.68
62	1	1	1	1	−1	−1	1	159.61
63	1	1	1	1	−1	1	−1	165.43
64	1	−1	1	−1	1	1	1	172.36

Based on the data obtained by simulation, the interaction effects among the above seven factors affecting building energy consumption were studied by interaction analysis using the Pareto analysis, and the Pareto chart of interaction effects is shown in Figure 4.

The Pareto chart shows the standardized effects of factors on energy use intensity, and the factors with a cumulative percentage of effects within 0–70% are the main elements, while the factors with a cumulative percentage of effects within 70–85% are the secondary elements and the factors with a cumulative percentage of effects within 85–100% are the general elements. The chart draws a line as a reference (marked in red dash line) to distinguish the main elements. The factors exceeding the reference line are the most significant. In the light of the Pareto chart, the order of the seven single factors with the effect size from high to low was: lighting control, computer control, lighting fixtures type, illumination, orientation, tolerance temperature range and air conditioning control. The main effect of computer control was higher than that of air-conditioning control, because the meteorological data of the transition seasons corresponding to the building region (the region with hot summer and warm winter) of the case was imported into the energy consumption simulation. In this study, there were two factor combinations

as the main elements: (1) lighting control and lighting fixtures type, and (2) computer control and tolerance temperature range. After screening the cumulative percentage of the effects, the secondary elements were also selected, which were: (1) illumination and air conditioning control, (2) illumination and lighting fixture type, (3) illumination and tolerance temperature range, and (4) lighting control and tolerance temperature range. The others were regarded as general elements, and it can be considered that there is almost no interaction between these factors. After the analysis of the Pareto chart, the interaction effects were divided into three levels: “grade I” represents the strong interaction between two factors, “grade II” represents the slight interaction, and “grade III” represents the basic absence of interaction between two factors. The results are shown in Table 8.

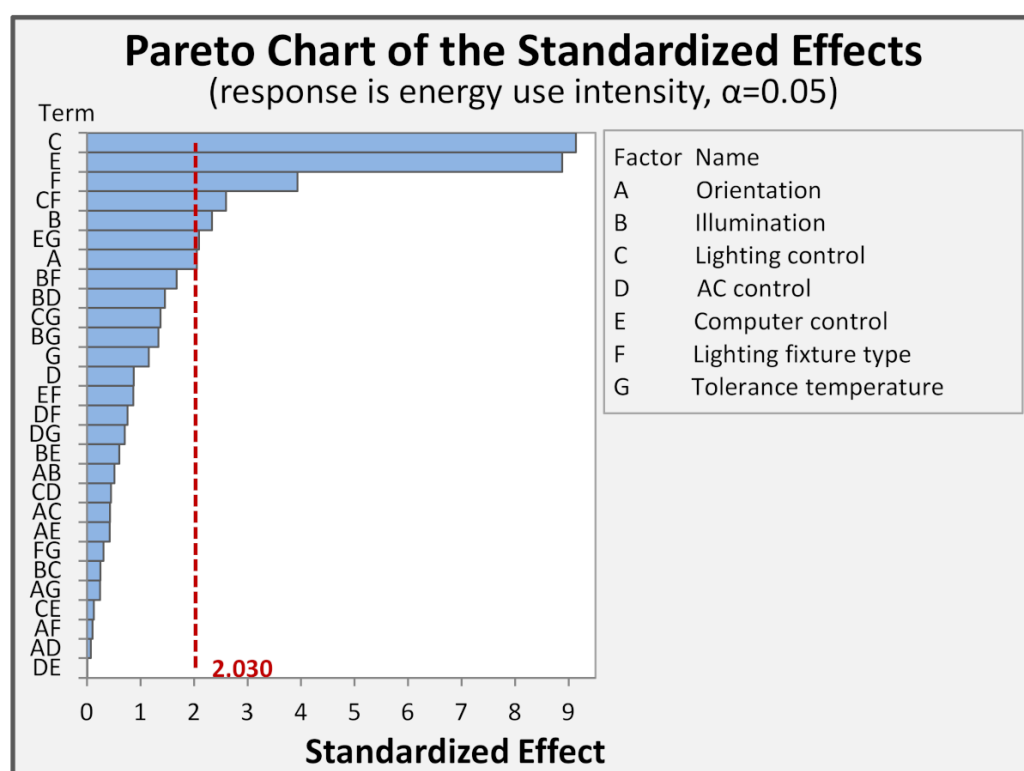


Figure 4. The Pareto chart of the standardized effects.

Table 8. Interaction effect table.

Name	Orientation	Illumination	Lighting Control	AC Control	Computer Control	Lighting Fixtures Type
Illumination	Grade III	Grade III				
Lighting control	Grade III	Grade II	Grade III			
AC control	Grade III	Grade II	Grade III	Grade III		
Computer control	Grade III	Grade II	Grade I	Grade III	Grade III	
Lighting fixtures type	Grade III	Grade II	Grade I	Grade III	Grade III	Grade III
Tolerance temperature range	Grade III	Grade II	Grade II	Grade III	Grade I	Grade III

■ Grade I ■ Grade II ■ Grade III.

5. Results and Discussion

According to the above results, there are 2 groups with strong interaction effects, 4 groups with slight interaction effects, and 15 groups without interaction effects. The results of strong interaction effects among occupant behavior-related factors are meaningful because combinations of these factors generate different effects on building energy consumption when compared with the main effects of individual factors.

In this study, the factor combinations with strong interactions were only two groups: (1) the lighting control and lighting fixtures type, and (2) the computer control and tolerance temperature range. On the basis of the Pareto chart, the interaction effect of lighting control and lighting fixture type was significant. This means that under various conditions of lighting fixture types, the influences of different occupant control actions of lighting on building energy consumption had obvious distinctions. Thus, when studying the impact of different occupant lighting control behaviors on building energy consumption, it is very important to take lighting fixture types into consideration. It can also be concluded that the main effects of both the single factors of lighting control and lighting fixtures type were larger than the interaction effects between them, which means that only studying the influence of single factor of lighting control or lighting fixtures type could exaggerate the actual effects of these factors. For the combination of computer control and tolerance temperature range, the effect considering the interaction was larger than the sole effect of tolerance temperature range, but smaller than the sole effect of computer control. In light of this situation, research on the interaction effect between computer control and tolerance temperature range is more meaningful than research on the effects of a single factor, because with respect to computer behaviors, the influence of the tolerance temperature range on building energy consumption becomes obvious.

In this study, there were four factor combinations with slight interaction: (1) illumination and air conditioning control, (2) illumination and lighting fixtures type, (3) illumination and tolerance temperature range and (4) lighting control and tolerance temperature range. The interaction effect of illumination and lighting fixture type was smaller than the single effect of the factors, respectively. The other three combinations all showed the situation that the interaction effect of two factors was larger than the main effect of one factor, but smaller than that of another one. For the combination of illumination and air conditioning control, the order of their effect sizes from high to low was: main effect of illumination, interaction effects and main effect of air conditioning control. For the combination of lighting control and tolerance temperature range, the order of their effect sizes from high to low was: main effect of lighting control, interaction effects and main effect of tolerance temperature range, which illustrated that the tolerance temperature range had a negative impact on the effect of lighting control on building energy consumption. For the combination of illumination and tolerance temperature range, the order of their effect sizes from high to low was: main effect of illumination, interaction effects and main effect of tolerance temperature range. The results show that, although the main effects of illumination and lighting control are obvious, their interaction effects with the consideration of other factors (e.g., air conditioning control and tolerance temperature range) are weakened. Thus, when studying the impact of illumination on building energy consumption, the interaction effects of illumination with others should be considered important by researchers.

Factor combinations which have almost no interaction effects can be ignored and the optimization for these factors can be achieved independently. It is noteworthy that the factor of orientation had nearly no interaction with the other six occupant behavior-related factors, though its main effect was significant. Thus, research on this factor should pay more attention to its main effect.

In this study, the interactions between seven factors were proposed, and three levels of interaction were used to quantify the interaction between the two factors. The degree of energy consumption toward different occupant behaviors can be scientifically described, which is helpful for clarifying both the relationship and the degree of relationship between occupant behaviors and electrical equipment, and can guide occupants to take green behaviors to save building energy consumption. This study can provide reference for building designers to make green office building designs and for project owners to promote sustainable building management during the operation stage.

6. Conclusions

This study extracted seven occupant behavior-related factors from four aspects of the Drivers-Needs-Actions-Systems theory. Factors from “drivers” and “needs” were determined by the results of the cross-analysis of the questionnaires, which were designed based on the DNAS theory as well, and their factor levels were determined by the relevant standards, while factors from “actions” and “systems” and their factor levels were selected by sensitivity analysis. Then, the combination matrix of these seven key factors was constructed by the orthogonal DOE method, and according to the results of the experiments, the building energy simulations were performed by DeST-c. Based on the data obtained from these experiments, the subsequent analysis was carried out, and with the application of the Pareto analysis, the interaction effects between different factors were studied. The main conclusions are as follows:

- (1) By extracting the factors from “drivers” and “needs” based on cross-analysis of the related items in the questionnaires, differences among these factors were discovered. The results showed that the orientation, building daylight and the occupant distance to windows had the significant differences. These factors were used for establishing the set of occupant behavior-related factors.
- (2) The sensitivity of common electrical appliances used in office buildings, such as air conditioning, lighting, computers and other technology was calculated. The control behaviors of air conditioning, lighting and computers were found to be the most sensitive. Therefore, the final factors from “actions” and “systems” were selected, and their corresponding factor levels were divided by sensitivity levels or survey results.
- (3) This study analyzed the interaction effects of occupant behavior-related factors. This study proposed the interaction table of the seven factors and quantified the interaction effects between every pairing of two factors. The two factor combinations with strong interaction effects included: (1) lighting control and lighting fixtures type and (2) computer control and tolerance temperature range. The four factor combinations with slight interaction effects included: (1) illumination and air conditioning control, (2) illumination and lighting fixtures type, (3) illumination and tolerance temperature range and (4) lighting control and tolerance temperature range. In order to better achieve building energy saving optimization, these factor combinations should both be paid more attention during the building design and operation periods.

This study used scientific methods to describe the impact of a single behavior and the interaction impact of multiple behaviors. The study conducted a cross-analysis of office building attributes, occupant attributes, and occupant behaviors to find out the behavior differences. Through the research, it was found that factors such as gender, orientation, whether there is shading to the sun and whether the building is against the window reflected differences in various occupant behaviors, which provided a scientific basis for the establishment of factors affecting energy use behaviors. During the operation phase of office buildings, intelligent management systems can be designed for air conditioning and lighting systems to ensure that they meet the normal life and work standard for users. Reasonable control and exact machine factors of the air conditioning and lighting equipment can be used to reduce building energy consumption. Of course, this method can also evaluate the energy-saving effects after the building is put into use. The conclusions of this study have significant meanings for building energy conservation. The results of this study can scientifically guide building occupants toward green behaviors. Also they are beneficial to realize design optimization by providing a reliable and effective reference for equipment management with energy-saving modes.

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Appendix A

Questionnaire on Energy Use Behavior of Office Occupants

Dear Mr./Ms.,

Hello!

We are carrying out a survey on energy use behavior in the office. We hope to analyze the current situation of office building energy use in China through your feedback. Thank you for taking the time to participate in our survey. The information you fill in will be very valuable to us.

We promise to be completely anonymous when using the information and to be sure not to disclose your personal information to any organization or individual. This study will not bring you any risk.

Thank you again for your support and cooperation!

1. Your age is [Blank-filling question]*

.

2. Your gender is [Single-choice question]*

- Male.
- Female.

3. Your office is located in [Single-choice question]*

- North China.
- North-east China.
- East China.
- South China.
- Central China.
- North-west China.
- South-west China.
- Other.

4. What is the orientation of your office? [Single-choice question]*

- Southward.
- Northward.
- Eastward.
- Westward.

5. Is your office shady or sunny? [Single-choice question]*

- Shady.
- Sunny.

6. What kind of office are you in? [Single-choice question]*

- Administration office building (administrative office buildings of Party and government organs, people's organizations, institutions, and industrial and mining enterprises at all levels).
- Professional office building (scientific research office building, design agency office building, commercial, investment, trust, and other industrial office buildings).
- Business office building (leasing office composed of one or more unit office planes based on business).

- Others.
7. Is your location near the window? [Single-choice question]*
- Yes.
 - No.
8. When was your office building constructed? [Single-choice question]*
- Before 1970.
 - 1970–1980.
 - 1980–1990.
 - 1990–2000.
 - 2000–2010.
 - After 2010.
9. What is the structure of your office building? [Single-choice question]*
- Masonry structure.
 - Steel structure.
 - Reinforced concrete structure.
 - Other.
10. What is the size of your office? [Single-choice question]*
- Within 10 m³.
 - 11–20 m³.
 - 21–30 m³.
 - 31–40 m³.
 - 41–50 m³.
 - More than 51 m³.
11. How many people are there in your office? [Blank-filling question]*
- .
12. What time do you work during your working days? [Blank-filling question]*
- .
- (e.g., if you go to work at 8:00, fill in 0800.)
13. What time do you have for lunch? [Blank-filling question]*
- .
- (e.g., if you leave at 11:30, fill in 1130.)
14. What time do you work in the afternoon during your working days? [Blank-filling question]*
- .
- (e.g., if you go to work at 13:30, fill in 1330.)
15. What time do you get off work during your working days? [Blank-filling question]*
- .
- (e.g., if you get off work at 18:00, fill in 1800.)
16. Will you go to the office on weekends? [Single-choice questions]*
- Yes (Please skip to question 17).
 - No (Please skip to question 19).
17. What is the difference between going to the office on weekends and the usual time? [Single-choice question]*
- Less than an hour earlier than usual.
 - As usual.
 - Less than an hour later than usual.
 - One to two hours later than usual.
 - More than two hours later than usual.
 - Other

18. What is the difference between leaving from the office on weekends and usual? [Single-choice question]*

- More than an hours earlier than usual.
- Less than an hour earlier than usual.
- As usual.
- Less than an hour later than usual.
- One to two hours later than usual.
- More than two hours later than usual.
- Other

19. What do you like about your working environment? [Single-choice question]*

- 21 °C and lower in colder environment.
- 22–23 °C in cold environment.
- 24–26 °C in moderate cold and hot environment.
- 27–28 °C in hot environment.
- 29 °C and higher in hotter environment.

20. Do you have an open window in your room? [Single-choice question]*

- Yes, I have exterior windows which can be opened.
- No, I have exterior windows which cannot be opened.
- No, I don't have exterior windows.

21. Will you open the window voluntarily when there are many people in the office? [Single-choice question]*

- Yes.
- No.
- Not sure.

22. What is your habit of opening windows in your office? [Multiple-choice question]*

- Open windows as soon as I get into the office.
- Open windows when I feel hot.
- Open windows when there is a smell in the office.
- Open windows when the air conditioner is turned off.
- Open windows regularly, and the time is (e.g., if you open the windows at 8:00 a.m. every day, fill in 0800.)
- Open windows when I get off work.
- Never open windows.
- Other

23. What is your habit of closing windows in your office? [Multiple-choice question]*

- Close windows as soon as I get into the office.
- Close windows when I feel cold.
- Close windows when the air conditioner is turned on.
- Close windows when there is noise outside.
- Close windows when the outside environment is bad (rainy, windy, dusty, etc.).
- Close windows regularly, and the time is (e.g., if you close the windows at 8:00 p.m. every day, fill in 2000.)
- Close windows when I get off work.
- Never close windows.
- Other

24. What is your demand for shading at work? [Single-choice question]*

- I like to bask in the sun and leave the curtains open.
- I like the appropriate sunshine.
- I do not like the sun.

25. Will you adjust the curtains voluntarily when there are many people in the office? [Single-choice question]*

- Yes.
- No.
- Not sure.

26. When do you pull down the curtains at work? [Multiple-choice question]*

- When feeling dazzling.
- When feeling hot.
- Other

27. When do you pull back the curtains at work? [Multiple-choice question]*

- When lighting is needed.
- When ventilation is needed.
- Other

28. What is the type of lamp is in your office? [Single-choice question]*



- Fluorescent lamp.



- Grille lamp.



- LED lamp.
- Other

29. What is the switch control for the lamps in your office? [Single-choice question]*

- One switch controls all lamps with nonadjustable illuminance.
- One switch controls all lamps with adjustable illuminance.
- One switch controls partial lamps with nonadjustable illuminance.
- One switch controls partial lamps with adjustable illuminance.
- Other

30. Will you adjust the lamps voluntarily when there are many people in the office? [Single-choice question]*

- Yes.
- No.
- Not sure.

31. Why do you turn on the lamps? [Single-choice question]*

- Turn on the lights regularly, and the time is. (e.g., if you turn on the lights at 8:00 a.m. every day, fill in 0800.)
- When feeling dark.
- Other

32. What percentage of the office lamps are turned on at work? [Single-choice question]*

- 100%

- 75%
- 50%
- 25%
- 0%

33. Why do you turn off the lights? [Single-choice question]*

- Turn off the lights regularly, and the time is. (e.g., if you turn off the lights at 8:00 p.m. every day, fill in 2000.)
- When feeling bright enough.
- Other

34. How to cool the office in the summer? [Multiple-choice question]*

- By taking off clothes.
- By opening window for ventilation.
- By turning on the air conditioner and set the temperature to °C.
- By pulling down the curtains.
- By turning on the fan or other electrical equipment.
- Other

35. How to heat the office in the winter? [Single-choice question]*

- By central heating.
- By turning on the air conditioner and set the temperature to °C.
- By electrical equipment except for the air conditioner.

36. In winter, there are electric heating equipment used in your office. [Blank-filling question]*

37. Will you adjust the air conditioner voluntarily when there are many people in the office? [Single-choice question]*

- Yes.
- No.
- Not sure.

38. What is the form of air conditioner in your office? [Single-choice question]*



- Split air conditioner.



- Central air conditioner.
- Other

39. What is the equipment used in your office? [Multiple-choice question]*

- Laptop.
- Desktop.
- Miniature printer.
- Large printer.
- Water dispenser.

- Shredder.
 - Kettle.
 - Other
40. On weekdays, your laptop is generally used for h, standby for h;
On weekends, your laptop is generally used for h, standby for h when you are in the office. [Blank-filling question]*
41. On weekdays, your desktop is generally used for h, standby for h;
On weekends, your desktop is generally used for h, standby for h when you are in the office. [Blank-filling question]*
42. There are miniature printers in your office, printing about A4 papers per day on average. [Blank-filling question]*
43. There are large printers in your office, printing about A4 papers per day on average. [Blank-filling question]*
44. Is your printer used regularly? [Single-choice question]*
- Yes (Please skip to question 45).
 - No.
45. When do you use the printer? [Multiple-choice question]*
- Before 8:00.
 - 8:00–10:00.
 - 10:00–12:00.
 - 12:00–14:00.
 - 14:00–16:00.
 - 16:00–18:00
 - After 18:00.
46. How do you use the water dispenser in your office? [Single-choice question]*
- Turn on it all day.
 - Turn on it at work.
 - Turn on it when needed.
 - Others
47. How often do you use the shredder in your office? [Single-choice question]*
- Less than once a day.
 - 1–5 times a day.
 - 6–10 times a day.
 - More than 10 times a day.
48. How often do you use the kettle in your office? [Single-choice question]*
- 1–5 times a day.
 - 6–10 times a day.
 - More than 10 times a day.

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