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Probability of occupant operation of windows during transition seasons in office buildings

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ABSTRACT

Abstract: Window operation is not only an important method for improving the indoor thermal environment and air quality, but also a significant way to reduce energy consumption of air-conditioned rooms during off-running periods in transition seasons. The occupants' window-operation behavior is influenced by both objective factors, such as thermal comfort and indoor air quality; and objective sensation, such as psychology and physiology, introducing considerable randomness and uncertainty. A two-month field observation of occupant window-opening behaviors for natural ventilation in an office building during the transition seasons was carried out in Chongqing, China. Multi-factor analysis of variance was conducted in data analysis using SPSS statistical software. The results showed that outdoor air temperature significantly affected window opening among other factors such as outdoor relative humidity, indoor air temperature, indoor relative humidity, and indoor CO_2 concentration, which have much less effect. The main trigger point for opening windows in the transition seasons is from occupants' desire to improve the indoor thermal and air quality environment. A probability model of occupants' window operation was proposed based on logistic regression analysis. Meanwhile, the Monte Carlo simulation results indicate that during transition seasons (when outdoor temperature varied from 15 to 30 °C), the probability of window opening in office buildings follows a normal distribution and increases linearly along with the outdoor temperature growth.

1. Introduction

A comfortable indoor environment at the workplace is important for workers' quality of life, health, and productivity. The behaviors of people seeking to control the indoor environment include adjusting elements of the building structure (e.g. windows, curtains, and sunshades), lighting, and indoor equipment. Among these, window operation is an efficient and common measure to improve the indoor thermal conditions. Understanding the rules and characteristics of window operation by occupants and establishing a model that describes this behavior will be of great value for the improvement of building energy-efficiency research and design, indoor air quality, natural ventilation, thermal comfort, and other relevant factors.

Building energy simulation has become increasingly important in energy efficient design. The popularly-used building energy simulation software packages include Energy Plus, TRNSYS etc. [1] It should be noted that existing building energy simulation programs are based on basic building physical parameters such as the heat transfer coefficient of envelopes, occupant density, efficiency of equipment and systems, and operation schedules. Usually, heating/cooling system operation schedules are determined by two modes: working days and off-working days. To date, the majority of these programs have little consideration of the impact of occupants' behaviors on energy consumption within the building. As a result, relatively large deviations of energy consumption in buildings occur between the predicted and the actual monitored, for both office and residential buildings [2–4]. Therefore there is a need to incorporate occupant behavioral models into the building energy simulation programs in order to improve the accuracy of the simulation results for new building design and existing building retrofit. This should provide reliable results for energy-efficiency strategies to policy-makers.

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2. Background information

Research emphasizing the importance of occupant behaviors emerged in the 1990s and mainly focused on the adaptive thermal comfort [5]. Operations of windows are one of the popular behaviors of occupants to regulate and adapt thermal environments. It has a close relationship with the outdoor weather conditions, including outdoor temperature, solar radiation, and wind speed [6]. Among these weather conditions, outdoor temperature was shown to be the most important factor, whereas solar radiation and wind speed had relatively weaker influences on the behavior of window opening. When the outdoor temperature is less than 15 °C, only a very few people will choose to open a window to improve indoor environments; but when the outdoor temperature is higher than 25 °C, most people will choose to open a window for ventilation [7]. The probability of thermal discomfort is determined, to a great extent, by whether or not a window is open. This indicates that the operation of windows has a significant relationship with the thermal comfort of the occupants.

Some studies have modeled window-opening behavior. Herkel et al. [8] proposed a method that uses the random model to primarily forecast and simulate the open status of windows in office buildings. Yun et al. [9] proposed a calculation rule describing the probability of people's behaviors, with the aim of integrating the probability of window opening into the process of the dynamic simulation of energy consumption. Nicol [10] and Humphries [11] used Probit Analysis to build a random model of the relationship between window opening and outdoor temperature, with the goal of applying this model within simulation software to reduce differences between simulation results and actual conditions as a result of the neglect of occupant behaviors during the simulation process. Macdonald and Strachan [12] introduced Monte Carlo Analysis and Differential Sensitivity Analysis to the simulation of outdoor meteorological parameters and building envelope thermal performance and applied these methods to addressing random variable factors in the simulation software ESP-r. Yun and Steemers [13] developed a random model for the relationship between the probability of window opening of residents and indoor/outdoor temperatures. Haldi and Robinson [14] used three analysis methods including multivariable logistic regression, the Markov process, and survival analysis to analyze the building environment and residents' indoor conditions and built a model of window-opening behavior. Shen et al. [15] presented a longitudinal study observing people's use of windows in cellular offices with a mixed mode of ventilation systems.

Jiang [16] proposed a random weather model – the multivariate time series model – for the randomness of weather conditions during the calculation of air conditioning load in order to decrease the inaccuracy resulting from unstable outdoor weather parameters during energy-consumption simulation. Jiang and Hong [17] studied building thermal heat transfer behavior and its probability distribution using stochastic analysis methods, including a multivariate time series model and state space method and demonstrated that the stochastic model was a promising method. In order to quantitatively study the effect of occupant behavior on building energy consumption, Zhou [18] et al. incorporated the developed random model of occupant behavior into a building energy simulation tool and compared the building simulation results with those of actual monitored data. The commonly used method of incorporating occupancy behavior/occupancy patterns in building simulation tools is to default the patterns and by assumptions [19].

It can be seen that the impact of occupant behavior, especially the behavior of opening doors and windows, on building energy consumption has drawn research attention internationally. However, at present, most probability models of window opening are set up mainly for free-running buildings, with a relatively wider range of outdoor temperatures. A hybrid system is a promising measure to improve the indoor environment. When the air-conditioning system is inoperative, opening/closing the windows during the transition seasons provides suitable natural ventilation for cool rooms. This research aimed to study occupant behavior when operating window systems for the improvement of the indoor environment and the impact of energy efficiency.

3. Experiment settings

A five-storey office building in Chongqing (Fig. 1 and 2) was selected for the experimental study. The building information is listed in Table 1. The monitoring period was between 09:00 and 18:00 on weekdays from September 11 to October 31 in 2012, whilst the weather conditions were those of a typical transition season, with climatic characteristics of daily average outdoor temperature between 15 and 30 °C. The air conditioning system was not allowed to operate during the period, and there was no mechanical ventilation in operation either. Occupants' thermal comfort needs could only be met by natural ventilation via window operations.

During the transition season, the major purposes of opening windows/doors for ventilation are to improve the indoor air quality and thermal comfort. Based on these two requirements, we identified six possible factors that may affect the window opening behavior of occupants: indoor air temperature, indoor air relative humidity, indoor CO_2 concentration, outdoor air temperature, outdoor air relative humidity, and wind speed.

There is no smoking-free policy in office buildings in China. Smoking can produce pungent smoke composed of inhalable particles, CO, nicotine, polycyclic aromatic hydrocarbons, nitrosamine, and other carcinogenic substances [20–22]. Whether or not someone smoking inside the room is an important factor affecting occupants' behavior of opening windows. However, in this study, only non-smoking rooms were selected as experimental sites. In addition, the influence of outdoor noise on window opening was

Fig. 1. Exterior view of the experimental office building.