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An occupant-based energy consumption prediction model for office equipment☆

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ABSTRACT

Occupant energy demand plays an important role in whole building energy consumption. To improve building energy efficiency, the stochastic characteristics of occupant behavior should be explored. In this paper, an occupant-based energy consumption prediction model was proposed based on the analysis of the relationship between occupant behavior and equipment energy consumption, drawing from an indoor occupancy rate model and computer input power model. Polynomial and Markov chain–Monte Carlo methods were applied to describe the time-varying indoor occupancy rate and the computer input power in multi-occupant office rooms. The computer energy consumption and occupant activity were related through the time-varying indoor occupancy rate. The energy consumption of office equipment was calculated by time accumulation and necessary correction. Three office buildings with different functions were selected as case studies, which are mainly used for business, administration and scientific research. The error rate between the predicted energy consumption from the model and actual energy consumption record was below 5%.

1. Introduction

With the continuous updating of building energy efficiency standards [1,2], the thermal insulation of the building envelope has greatly improved. Compared to the energy consumption of heating, ventilating and air-conditioning (HVAC) systems, the energy consumption of indoor equipment and lighting accounts for the largest percentage of the total building energy consumption [3,4]. The energy consumption of office buildings can be divided into two categories. One is the building energy consumption caused directly by work demands, mostly the energy consumption of office equipment. The other one is the energy consumed to provide indoor thermal comfort for occupants, such as building energy consumption of the HVAC and lighting systems. Office equipment and lighting systems produce heat in the indoor environment, which becomes part of the air-conditioning load. Therefore, office equipment has an intimate connection to occupants in office buildings, and the energy consumption of office equipment is directly influenced by occupant behavior.

Recent studies have shown how the influence of occupant behavior in office buildings can be an important factor for energy efficiency [5]. Azar and Menassa [6] recorded the utilization of equipment and lighting systems, temperature and HVAC schedules to demonstrate the significance of occupant behavior. Cheng Li et al. concluded that occupant behavior, operation and maintenance significantly influenced building energy consumption by studying 51 high performance buildings across the world [7]. The energy consumption systems in those studies were mainly HVAC and lighting. Few studies concern the relationship between occupant behavior and energy consumption of office equipment. Some studies even applied the same energy consumption prediction model to represent the performance of both office equipment and lighting systems [8]. In fact, office equipment serves as a unique part of the energy system in office buildings, and occupant behavior influences the energy consumption of office equipment.

The common method of studies concentrated on energy consumption related to occupant behavior and demands is to modify simulation tools by embedding specific schedules. The impact of occupant behavior on energy consumption could be found by comparing the differences of energy consumption simulation results before and after modifying the occupant behavior model [9–12]. Those studies calculate the energy consumption of office equipment roughly by accumulating working time and rated powers. The variation of real input power caused by stochastic occupant

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behavior was not considered. Therefore, the real energy consumption under stochastic occupant behavior cannot be predicted by simply modifying the embedded settings of building simulation software.

The aim of this paper was to propose an occupancy-based energy consumption prediction model, adopting the stochastic method. Three offices from different building categories were taken as case studies. The model was established based on three parts of exploration: rules of occupant behavior, rules of office equipment energy consumption and the relationship between the above two parts.

2. Methodology

2.1. Stochastic method

The common mathematical methods for the stochastic process are the Markov chain and the Monte Carlo method. In a Markov chain, the next state of a stochastic process is independent of the past and is only dependent on the present state [13]. Such an assumption is suitable for predicting electricity demand [14]. The accuracy of the predicted results with Markov chain is extremely influenced by the amount of data, which restricts its application. We adopted the Monte Carlo method to offset this disadvantage [15]. A combined model with both the Markov chain and the Monte Carlo method was applied in this paper to improve the accuracy of the prediction results and to retain the time consecutiveness of the presumed state. The procedures of the Markov chain–Monte Carlo (MCMC) method suitable for energy consumption prediction are shown as follows:

(1) The Markov chain of the prediction object is

$$X(t_n) = X(t_0) \cdot P_{ij}^{k}(n) \tag{1}$$

The model transition matrix $P_{ij}^{(k)}(n)$ is a constant time-invariant matrix independent from the step number n

$$P_{ij}^{(k)}(n) = \frac{count(ij)}{\sum_1^m count(ij)} = \begin{bmatrix} P_{00}^{(n)} & P_{01}^{(n)} & \cdots & P_{0m}^{(n)} \\ P_{10}^{(n)} & P_{11}^{(n)} & \cdots & P_{1m}^{(n)} \\ \vdots & \vdots & \ddots & \vdots \\ P_{m0}^{(n)} & P_{m1}^{(n)} & \cdots & P_{mm}^{(n)} \end{bmatrix} \tag{2}$$

where m is the number of states. In this paper, m represents the states of computers, which were defined by the instantaneous power.

The model transition matrix can be obtained based on the field monitoring data.

(2) A stochastic series x_i can be generated in the extent of the prediction objects. Steady data can be calculated using Eq. (1). The effective sample is obtained by random sampling.

(3) Calculate the integration based on the Monte Carlo method:

$$G = \int x_i \cdot P_i \tag{3}$$

where G is the predicted result.

2.2. Data collection method

To improve the accuracy of the prediction results, the data collected for analysis should be reliable. The rules of occupant behavior and occupant preferences for equipment utilization can be thoroughly explored by a period of investigation. The data collection methods are shown in Table 1.

Table 1
Data collection methods.

	Occupant behavior	Equipment utilization	Energy consumption
Method	Field monitoring with cameras	Questionnaires, cameras and power meters	Electricity consumption bill
Duration	One week, working time	One week, working time	2012–2014, two years
Record frequency	Real-time	10 min	Not a constant value
Analysis frequency	10 min	10 min	Annual

Table 2
Information for the business, administration and scientific research multi-occupant offices.

	Business office	Administration office	Scientific research office
Schedule	Flexible, focused on 9:00–18:00, overtime possible	Fixed in 8:30–17:30, little overtime working	Flexible, focused on 8:00–18:00, overtime possible
Indoor activity	Low probability	Minimal probability	Low probability
Outdoor activity	Relatively high probability	Minimal probability	Low probability
Visit frequency	Relatively high probability	Minimal probability	Low probability

Occupant behavior was observed by cameras with sufficient memory space. Occupant preferences for equipment utilization were monitored by two approaches. One was survey questionnaires, which occupants in the case study buildings were asked to fill out. The questions concentrated on occupant general utilization habits of the office equipment. The other approach was measurement with cameras and power meters. There are different categories of office equipment, and their rated power and instantaneous power also vary. Therefore, we used power meters to measure the input power of common office equipment, such as computers. The power meter type was UT230C with a measuring scope of 0.1–2200 W and a measuring accuracy of 0.01 W. The input power was recorded manually with 10 min intervals. The same time interval was applied for recording both occupant behavior and equipment input power. No obvious difference could be found in the energy consumption of office equipment; therefore, one week of data was representative [16]. Prepayment kilowatt-hour meters were installed in the case study buildings. The kilowatt-hour meters were DDSY738 with a measuring accuracy of 0.01 kWh. The lighting and plug energy consumption were recorded and could be obtained from the electricity consumption bills. The charging period was decided by the office managers. Therefore, we used the electricity bill from March 2012 to March 2014 to validate the accuracy of the proposed prediction model.

3. Investigation results and discussion

3.1. Case study objects

Office buildings can be categorized by building functions. Three types of office buildings, business, administration and scientific research office buildings, were investigated. The regularities of occupant behaviors and equipment utilization were found and are listed as follows:

(1) Office rooms are the majority of the space in office buildings, occupying 50–80% of the building floor area. Other areas are accessory rooms, including meeting rooms, dressing rooms, and play rooms. The accessory rooms consume less energy because