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Research Paper

Influence of occupancy-oriented interior cooling load on building cooling load design

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HIGHLIGHTS

- Over-estimated occupancy results in inefficient operating chillers.
- A Markov transition matrix is built based on the survey in an office building.
- Building cooling load design is modified by a correction coefficient.
- The assurance rate of the proposed method in the case study was more than 90%.

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ABSTRACT

In the traditional mechanical design of new buildings, the occupancy number is usually over-estimated and results in over-predicted cooling loads and oversized chillers. When building occupancy is low relative to the design phase assumptions, those oversized chillers run inefficiently. To further explore the influence of occupancy on building cooling load design, the occupancy rate of office building is proposed in this paper and investigated with questionnaires.

In a case study for an office building in Tianjin, the interior heat gain from occupants, lighting and equipment accounts for 66.6% of the total cooling load, while the part load ratio (PLR) of the chiller is only 30%. A Markov transition matrix is established based on the survey results. This paper describes the occupancy pattern of the building by using a stationary distribution of a one-step transition probability. A correction coefficient is proposed for the design phase cooling load calculation, which results in a 35.9% cooling load reduction for the building case study. The simulated cooling load is validated by consistency check according to the real cooling load. Assurance analysis is also conducted to calculate the design error and predicted operation error between simulated and actual cooling loads. With above analysis, interior disturbances resulting from occupant behavior are proved to be the most important uncertainty for building cooling load design.

1. Introduction

Occupants are the dominant roles in buildings. Nearly all the building energy consumption relates with the behavior of occupants or the equipment to improve human comfort in indoor environment. Stochastic occupant behavior has received much more concerns in researches of building energy saving than ever before. A series of stochastic phenomena, including the use of demand-controlled ventilation [1], operation of lighting system [2], operation of air-conditioners [3], control methods of lighting and blinds [4], and occupancy [5] has been discovered, explored and represented by mathematical models. In office buildings in particular, the occupants' states directly determine the source and characteristics of energy consumption [6–9].

Recently, empirical models have been developed based on measurements, in particular building environments [10]. The Markov process has been widely applied in human behavior research to describe the time-varying occupancy interval [11,12]. The state transition probability and the inhabitants' presence or absence states are both important in developing cooling schedules for energy calculation [13].

Most studies focus on regularities of human behavior and energy consumption during building operation. However, the influence of human demand on a building's design phase is largely overlooked. Once the capacity of building equipment is fixed during the building design phase, their rated-efficiency and energy-saving potential is inherently limited. Between the actual demand and the nominal capacity of equipment once the building is in operation,

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the equipment efficiency will be relatively low most of the time [14]. Similarly, the capacity of air-conditioning systems is determined during the design phase when heating loads or cooling loads are calculated. If the impact of human behavior on building loads is not accurately characterized during building design, the heating, ventilating and air-conditioning (HVAC) system is often oversized. Substituting a smaller chiller in place of an oversized one improves the chiller's coefficient of performance (COP) and also reduces energy consumption [15]. Thus, there is significant potential to reduce building energy consumption by tailoring the system size during the building design phase. Theoretical energy simulations have proved that the input of real-time occupancy information during building design can reduce HVAC energy consumption by 10–20% [16–19].

This paper aims at proving the importance of occupancy on design phase by investigation and simulation of an existing office building. This research begins with analyzing the characteristics of building cooling loads. Next, occupant behavior is investigated in an office building case study, with emphasis on the significance of the occupancy rate in predicting cooling load. A correction coefficient is proposed to modify the over-predicted cooling load in design phase. Simulation is also conducted to show the reduction of cooling load and building energy consumption during the testing period. Finally, designed and predicted operation cooling loads are both compared with measured cooling load to validate our presumed importance of occupancy on building cooling load design.

2. Occupant related cooling loads

The following subsections give an overview of cooling loads and discuss the effect of a building's occupancy rate on cooling load.

2.1. Overview of cooling loads in buildings

Building cooling load consists of excessive heat that must be removed from the indoor environment. Interior heat usually originates from three sources: heat gain through exterior surfaces, heat gain from intake of fresh outdoor air, and heat gain generated indoors by equipment and occupants [20,21].

$$q_T = q_E + q_F + q_I \tag{1}$$

The cooling load from heat gain through exterior surfaces results from outdoor temperature and solar radiation and is generally determined by meteorological conditions. It can be subdivided into two parts: cooling loads formed by heat conducted from nontransparent surfaces and solar radiation through transparent surfaces. Together, these parts make up the exterior cooling load, which is affected by variations in the exterior building environment [22]:

$$q_T = q_{TR} + q_{TS} \tag{2}$$

$$q_{TR} = \frac{\sum_{i=1}^{nSURF} (t_\tau - t_n)(A_i U_i)}{A} \tag{3}$$

$$q_{TS} = \sum_{i=1}^{nEXP} (X_g X_d X_z) J_{\tau i} \tag{4}$$

The cooling load resulting from fresh air entering the building can be subdivided into sensible cooling load and latent cooling load. The fresh-air flow rate depends on occupant demand. The temperature and humidity of fresh air depend on meteorological conditions. Therefore, the cooling load of fresh air reveals the combined effect of both interior and exterior influences [21]:

$$q_F = q_{FS} + q_{FL} \tag{5}$$

$$q_{FS} = \frac{C_p n V \rho (t_O - t_n)}{A} \tag{6}$$

$$q_{FL} = \frac{r_t n V \rho (d_O - d_n)}{A} \tag{7}$$

The cooling load from indoor equipment results from heat generated by the occupants, lighting system, and equipment and is closely related to occupants' activities [21]:

$$q_I = q_{IP} + q_{IL} + q_{IE} \tag{8}$$

$$q_{IP} = q_{IPS} + q_{IPL} = \frac{\varphi (q_{MS} C_{\tau-PS} + q_{ML})}{n_P} \tag{9}$$

$$q_{IL} = \psi L C_{\tau-LS} \tag{10}$$

$$q_{IE} = \psi E C_{\tau-ES} \tag{11}$$

Broadly defined, interior building loads are demands of building occupants that fall into the general categories of demand related to comfort and demand related to work activities. For instance, the demand for comfort affects indoor air quality and illumination quality, and the demand related to work activities affects the use of computers and printers. Air-conditioning units are used for both types of demands. Because fresh air improves the indoor thermal comfort, the demand for fresh air in the category of broad defined interior loads is included. Meanwhile, a narrow definition of interior load focuses only on heat gains related to occupants, lighting and equipment.

In residential buildings, interior disturbances are limited. Because most rooms are controlled by split air-conditioning systems, a constant value can be used to roughly estimate the interior excessive heat [23]. In contrast, interior cooling loads in public buildings are considerably larger and more strongly influenced by building function and occupant schedules. Therefore, for this study, interior influences on cooling loads in public office buildings, specifically the occupancy rate, is focused on.

2.2. Investigation of the occupancy rate

The subjects of our research were the occupants in an office building, including employees and visitors in both rooms and corridors. To characterize occupants' possible movements inside and outside of the building, our investigation aimed to understand occupants' regular work patterns.

It is not possible to place cameras in all areas of an office building. Installing cameras in offices, conference rooms, eating areas and restrooms would be considered an invasion of privacy. The web-based survey is an effective measure to collect data for prediction model establishment. It has been demonstrated that a survey presenting choice among scenarios by asking respondents to choose the scenario that most closely resembled their situations at the moment could effectively capture the probabilities of occupant behavior in buildings [24]. Therefore, for this study, simple real-time surveys are applied to collect relevant information on occupants' locations during the day, both inside and outside the building, without intruding on occupants' privacy. Both paper version and electronic questionnaires are applied to building occupants in order to describe their behavior, their current location and planned movements in the next 1–1.5 hours.

In the case study, the office building occupants normally work eight hours per weekday in China, from 8:30 to 16:30. The questionnaire was distributed with 1-hour interval (9 am–4 pm) on July 31th and August 2th in 2013. This enabled us to acquire real-time data with minimal disturbance to occupants. The questionnaires were