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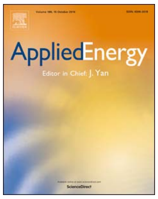

A novel stochastic modeling method to simulate cooling loads in residential districts

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HIGHLIGHTS

- A stochastic modeling method with OB models to predict district loads is proposed.
- This method was applied to a case study in China using the DeST simulation engine.
- This study summarizes the typical occupancy schedules and OB modes in HSCW of China.
- The proposed method performs better than two conventional simulation methods.
- Applications and limitations of the proposed method are also discussed.

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ABSTRACT

District cooling systems are widely used in urban residential communities in China. Most of such systems are oversized, which leads to wasted investment, low operational efficiency and, thus, waste of energy. The accurate prediction of district cooling loads that can support the rightsizing of cooling plant equipment remains a challenge. This study develops a novel stochastic modeling method that consists of (1) six prototype house models representing most apartments in a district, (2) occupant behavior models of residential buildings reflecting their spatial and temporal diversity as well as their complexity based on a large-scale residential survey in China, and (3) a stochastic sampling process to represent all apartments and occupants in the district. The stochastic method was applied to a case study using the Designer's Simulation Toolkit (DeST) to simulate the cooling loads of a residential district in Wuhan, China. The simulation results agreed well with the measured data based on five performance metrics representing the aggregated cooling consumption, the peak cooling loads, the spatial load distribution, the temporal load distribution and the load profiles. Two prevalent simulation methods were also employed to simulate the district cooling loads. The results showed that oversimplified assumptions about occupant behavior could lead to significant overestimation of the peak cooling load and the total cooling loads in the district. Future work will aim to simplify the workflow and data requirements of the stochastic method for its application, and to explore its use in predicting district heating loads and in commercial or mixed-use districts.

1. Introduction

Energy consumption in residential buildings accounts for a large percentage of total worldwide energy consumed. In 2006, the U.S. residential sector accounted for more than 20% of total primary energy consumption in the country [1]. In the northern part of the European Union, residential buildings account for 30% of total energy consumption [2]. In China, building stocks are expected to account for approximately 35% of total energy consumption by 2020, with heating, ventilation, and air-conditioning (HVAC) systems responsible for 65% of residential energy consumption [3]. Therefore, the reduction of energy consumption in residential buildings has been attracting increasing research attention in recent years, and new technologies have been developed and implemented.

District heating and cooling (DHC) systems have become increasingly popular in recent years in China and other countries [4–6]. A DHC system can simultaneously provide heating and/or cooling to many buildings, usually a campus or an urban district. Therefore, it requires equipment with larger capacity and higher efficiency than decentralized equipment (e.g., split-type air-conditioners) as well as

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community-scale sources of renewable energy (e.g., underground water) [6,7]. To make proper use of DHC systems, high efficiency and low energy consumption are desirable. To this end, the thermal load demands of building users in a district need to be accurately understood.

Two methods are typically used to estimate the thermal loads of buildings in a district. The first is the so-called full-time full-space (FTFS) method, which considers climatic conditions as the most important factor influencing loads and assigns lower importance to internal heat gains in buildings. In the simulation of thermal loads, the FTFS method assumes that internal heat gains remain constant and do not change with time or space, and that the air-conditioning is always on in every room of every building. The FTFS method is still used in design standards in China and widely used in HVAC systems [8]. With the development of dynamic simulation tools to estimate energy consumption in residential buildings and greater awareness of occupant behavior, a growing number of researchers have realized that occupant behavior significantly influences building performance, and more realistic inputs of occupant-related schedules (i.e., occupancy schedules and appliance use schedules) should be used to simulate the thermal loads of buildings. Otherwise, the predicted results can significantly deviate from actual measurements [9]. The second method conventionally used to estimate thermal loads is the Fixed Schedules method, which uses predefined schedules for occupancy and appliances based on building type and climate zone, derived from examinations of real buildings. Several researchers have attempted to determine input schedules to simulate the energy consumption of buildings. Based on a questionnaire survey, Zhang [10] summarized a group of fixed schedules for occupancy, lighting, and equipment among the factors affecting the energy consumption of office buildings, and applied these schedules to determine indicators for China's standard for energy consumption in non-residential buildings. Jian [11] and Xia [12] performed measurements in residential buildings and presented typical household schedules to estimate the thermal performance of residential buildings. They recommended that typical uniform schedules should be simple and limited to one or a few sets of schedules for practical engineering purposes. Moreover, Chow [13] and Gang [14] considered different schedules for several building types (e.g., office, school, and hotel) for the prediction of cooling load in their studies, and analyzed system performance based on the predicted loads.

In contrast to a single house or residential buildings, a district has tens or hundreds of households with varying thermal demands. Thus, their load profiles present significant spatial and temporal diversity. Weissmann et al. [5] used the load profiles of two buildings to highlight load diversity and its impact on the central supply peak load. Fonseca and Schlueter [15] emphasized the importance of understanding the characteristics of the spatial and temporal load diversity of district systems for equipment sizing and the application of a suitable control strategy. Moreover, Brounen et al. [16] investigated 305,001 dwellings in 2008–2009 and found a wide variation in household consumption. Therefore, a method is needed to represent the load diversity within districts.

Past studies have analyzed load diversity mainly based on building type, orientation, and envelope performance [5,15,17]. However, occupant behavior is another key factor influencing the load diversity of buildings. Gilani et al. [18] and Hoes et al. [19] examined the importance of occupant behavior models in simulation-aided design and code compliance in Canada and the Netherlands. Sun et al. [20] concluded that energy-saving occupant behavior could save energy by as much as 22.9% for individual behavior and 41.0% for integrated behavior. Ruan et al. [21] pointed out that the ages of occupants should be considered in residential community planning as it can significantly influence the time occupants spend in their residences and their use of air conditioners. They [21] also performed simulations for Qingdao city with uniform correction coefficients for various household types to determine optimal residential community planning. Zhou et al. [22] showed that the stochastic feature of the use modes of air-conditioning was the main factor in the difference between predicted performance based on design and the actual energy use of the building. However, Zhou et al. [22] only considered one type of occupant behavior (i.e., air-conditioning use) and assumed that it was influenced only by an occupant's thermal comfort.

In simulations of building performance, past research has described realistic occupant behavior using probabilistic models based on monitoring, sensors, and/or survey data. These observational studies have revealed the relationships between indoor and outdoor environmental factors and occupant behavior [23]. Hong et al. [24] identified the major types of occupant behaviors in buildings, including occupant presence, movement, and actions pertaining to windows, shades (blinds), lighting, thermostat, HVAC, and plug-in equipment. Data were collected at various locations and types of buildings worldwide to construct a library of stochastic models for occupant behavior [25–33]. For example, window-opening behaviors were described by probabilistic models (logit or Weibull functions) based on field data and large-scale surveys. These models were used by several building performance simulation (BPS) programs to determine when occupants open or close windows [34,35]. Note that stochastic models do not necessarily produce better results than other simpler and/or non-probabilistic models of occupancy, especially in terms of annual building energy consumption [36]. Yan et al. [23] concluded that simple occupancy-related models, such as code-based models or descriptive representations of occupant behavior, can be used to determine aggregated indicators, such as annual heating and cooling consumption. However, in other situations, more detailed occupant behavior models must be considered.

BPS programs are commonly employed to evaluate the performance of building energy systems and technologies. Occupant behavior in buildings has been widely acknowledged as a major factor contributing to the gaps between measured and simulated energy consumption in buildings [23,37–39]. Eguaras–Martinez et al. [40] showed that the inclusion or exclusion of occupant behavior in building simulations could result in up to a 30% difference in predicted energy use. The International Energy Agency's "Energy in Buildings and Communities' Programme," in Annex 53: "Total Energy Use in Buildings," [41] recognized the impact of occupant behavior as one of the six driving factors of energy use in buildings, along with climate, building envelope, building energy and services systems, indoor design criteria, and building operation and maintenance. However, in practice, simulation users tend to apply default standards or representative settings for occupants in a simplified and homogeneous way using temporal schedules and static assumptions. This can result in significant discrepancies between simulation and measurement data.

In conclusion, the above studies either only apply occupant behavior models to a single house or use simplified methods to represent the diversity of occupant behavior within a district. Few studies have applied detailed occupant behavior models to the district level, and the influence of realistic occupant behavior on district load prediction is an unsolved problem. This study aims to tackle this important topic and provide insights into the following questions:

(1) What percentage of occupant behavior must be considered in district load prediction?
(2) What are the actual occupant behaviors in residential districts?
(3) What are the pros and cons of using stochastic occupant behavior models in district load prediction compared with conventional simplified methods?
(4) What are the potential applications of stochastic occupant behavior models to residential districts?

This study proposes a novel stochastic occupant behavior method (the SOB method) to consider the behavior of multiple occupants for district load prediction. Based on questionnaire surveys, the method