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Occupant behavior modeling for building performance simulation: Current state and future challenges

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ABSTRACT

Occupant behavior is now widely recognized as a major contributing factor to uncertainty of building performance. While a surge of research on the topic has occurred over the past four decades, and particularly the past few years, there are many gaps in knowledge and limitations to current methodologies. This paper outlines the state-of-the-art research, current obstacles and future needs and directions for the following four-step iterative process: (1) occupant monitoring and data collection, (2) model development, (3) model evaluation, and (4) model implementation into building simulation tools. Major themes include the need for greater rigor in experimental methodologies; detailed, honest, and candid reporting of methods and results; and development of an efficient means to implement occupant behavior models and integrate them into building energy modeling programs.

1. Introduction

Building energy consumption accounts for 30% of the global energy consumption revealing a great potential for energy conservation (IEA [1]). To address this issue, building simulation is gaining widespread application as a cost-effective method to support energy efficient design and operation of buildings. Building simulation includes the evaluation of the performance of architectural concepts, HVAC systems, or energy-saving approaches and technologies. The International Energy Agency (IEA), Energy in the Buildings and Communities Program (EBC), Annex 53: Total Energy Use in Buildings, identified (1) climate, (2) building envelope, (3) building energy and services systems, (4) indoor design criteria, (5) building operation and maintenance, and (6) occupant behavior, as the driving factors of energy use in buildings. While there has been significant progress in the first five focus areas, there lacks scientific and robust methods to define and model energy related occupant behavior in buildings. These behaviors include occupants' interactions with operable windows, lights, blinds, thermostats, and plug-in appliances. The importance of the "human factor" in building performance simulation is evident [2–4]. In short, occupant behavior affects building energy consumption significantly and is a leading source of uncertainty in predicting building energy use [5].

Due to the significant uncertainty of building model inputs, simulation results sometimes deviate widely from the actual energy consumption of a building. Fig. 1 shows a comparison between the simulated (predicted) energy consumption modeled during the design phase and the measured energy consumption for 62 Leadership in Energy and Environmental Design (LEED) certified buildings in the United States. For some buildings, models are relatively good predictors of the actual building performance. Nevertheless, there is a normalized root-mean-squared error of 18%.

To illustrate the impact of the uncertainty occupant behavior has on energy use, consider a study where Li et al. [7] investigated the cooling electricity use in 25 households in a large residential building in Beijing during a summer. The results are shown in Fig. 2.

With an identical building envelope, the measured electricity consumption for air-conditioning in different apartments varied widely. The discrepancy was caused by the operating mode of the

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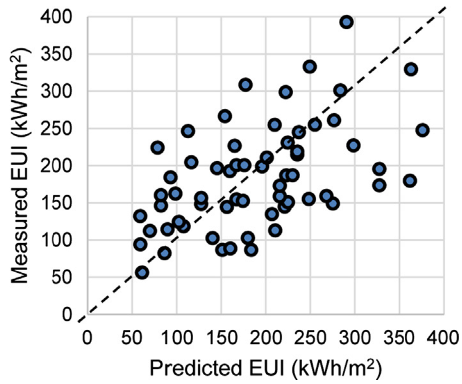

Fig. 1. Comparison of measured and predicted energy use for 62 LEED New Construction buildings.
Modified from Turner et al. [6].

split-type air conditioning (AC) system. An apartment where the occupant kept the air conditioning on for longer durations or in larger spaces consumed more energy than an apartment using the AC for a shorter period of time and/or in smaller spaces. Thus, the occupant is the driver of the energy use, rather than the design of the apartments.

Clevenger and Haymaker [8] studied uncertainty in occupant behavior in building energy models, using various occupancy schedules and environmental preferences and found that the energy consumption differed 150% (or more) if the occupant-related inputs were maximized and minimized (even for typical occupant behavior patterns). Guerra Santin et al. [9] studied the influence of occupant behavior on heating, and found that the way occupants used the heating system made a significant difference on heating energy consumption. It can be concluded that occupants' presence and interaction with various building components significantly affect the energy consumption predictions made by energy simulation, even if the weather conditions, the building envelope, and the equipment are well-defined.

Occupant behavior is a key factor in the evaluation of technologies used in building design and retrofit. Case studies have demonstrated that occupant behavior influences the adaptability and implementation of building technologies. For example, Fabi et al. [10] studied the robustness of building design with different operations of windows and movable shadings, and found that a description of occupant behavior will result in robust building designs. Belessiotis and Mathioulakis [11] reported that the energy savings potential, by increasing building insulation, depends heavily on occupants' use of terminal heating systems.

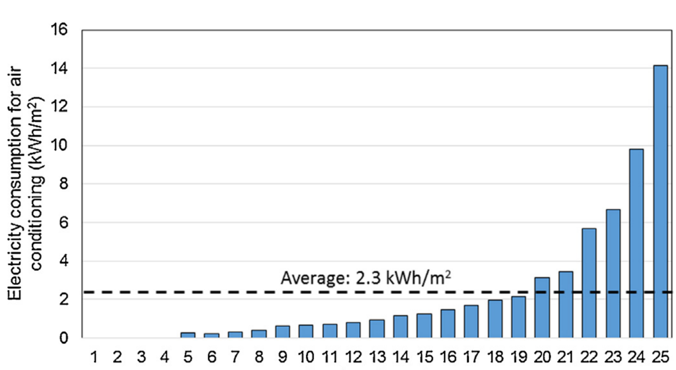

Fig. 2. Measured air conditioning electricity consumption per unit floor area in the summer in a residential building in Beijing.
Modified from Li et al. [7].

Understanding the interactions between occupant behavior and building technologies are critical to improving building design and operation. Different occupant behavior patterns require corresponding technical solutions, which may induce or alter behavior patterns. More important than the technology efficiency is the effective interaction between occupants and building systems to achieve their comfort and health needs.

Occupants undertake behaviors that can be modeled stochastically [12,13]; meaning that occupants' presence and behavior patterns not only vary between each other, but also tend to evolve in time. For example, occupants' behavior may differ due to the individual variance of environmental perception. Reinhart and Voss [14], by monitoring lighting control in ten offices, found that the workplane illuminance levels triggering a light switch action varied significantly from one individual to another. Similarly, Galasiu and Veitch [15] found that an individual's preferred work plane illuminance ranged from 230 to 1000 lux. Al-Mumin et al. [16] investigated summer air-conditioning use in residential buildings, and concluded that the thermostat setpoint could vary from below 19 °C to above 25 °C. Brager et al. [17] observed that identical thermal conditions can lead to both window opening and closing in different offices.

Occupant behavior is a complicated mechanism and influenced by multiple contextual factors. Research carried out by Warren and Parkins [18] indicated that the primary factor motivating occupants to open windows in the winter is the indoor air quality. While in the summer noise from outside was reported to be the primary factor leading a window closing action. Other factors leading to window operation include indoor humidity [19] and weather conditions (e.g., windy or rainy [20]). Mahdavi [2] observed a relationship between closing shades and the magnitude of vertical irradiance, but opening shades did not reveal a clear relationship to the amount of incident solar radiation. Sociological or psychological factors also contribute to influencing occupant behavior. Zhang and Barrett [21] studied the factors influencing blind operation in a naturally ventilated building, and reported that the desire to maintain view and connection to outdoors drove occupants to open the blinds. Whereas, Foster and Oreszczyn [22] suggest that occupants in offices which face other buildings tend to keep the blinds down for privacy reasons.

Occupants in building simulation tools are conventionally represented in terms of static schedules [5]. This simplification does not properly model the complex influence of occupant behavior on building energy consumption and the indoor environment [23,24]. In reality, there should be a dynamic interaction between a building and its occupants so that more sustainable designs can be identified. For example, without modeling occupant use of window blinds, simulation results may indicate that maximizing the window area will lead to maximized daylight utilization. However, in reality, very large windows may merely prompt occupants to close blinds and exclusively rely on electric lighting due to glare issue. Evidently, the use of static schedules to represent occupant behavior in building simulation tools fails to reflect this dynamic interaction between the users and a building's design. To mimic the dynamic interactions between a building and its occupants, several dozen occupant behavior models have been developed based on long-term observational studies [25]. Several stochastic models have been developed to describe window operations [26–31], blinds [21,32–35] and lighting [33,36–38]. Other behaviors such as operation of air-conditioning [39,40] and clothing adjustment [41] have been studied less. These models typically require large amounts of data to establish a statistical relationships between the environmental factors and the targeted operation(s). However, these models barely scratch the surface considering the requirement for the numerous building typologies, cultures, climates, etc.