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Advances in research and applications of energy-related occupant behavior in buildings☆

Tianzhen Hong[a,*], Sarah C. Taylor-Lange[a], Simona D'Oca[b], Da Yan[c], Stefano P. Corgnati[b]

[a] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
[b] Polytechnic of Turin, Corso Duca degli Abruzzi, 24, Turin 10129, Italy
[c] Tsinghua University, 30 Shuangqing Rd, Haidian, Beijing, China

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ABSTRACT

Occupant behavior is one of the major factors influencing building energy consumption and contributing to uncertainty in building energy use prediction and simulation. Currently the understanding of occupant behavior is insufficient both in building design, operation and retrofit, leading to incorrect simplifications in modeling and analysis. This paper introduced the most recent advances and current obstacles in modeling occupant behavior and quantifying its impact on building energy use. The major themes include advancements in data collection techniques, analytical and modeling methods, and simulation applications which provide insights into behavior energy savings potential and impact. There has been growing research and applications in this field, but significant challenges and opportunities still lie ahead.

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* Corresponding author. Tel.: +1 510 486 7082; fax: +1 510 486 4089.
E-mail address: thong@lbl.gov (T. Hong).

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1. Introduction

An occupant's interaction with building systems attributes to the sizeable variation in building energy use. Therefore it becomes paramount that solutions in both energy efficient behavior and technology robustness collectively contribute toward achieving low energy buildings [1–3]. Social scientists have been scrutinizing occupant behavior for decades, particularly in the areas of user behavior, attitudes, individual or household consumption patterns etc. [4]. Recently, the need to integrate social science aspects into energy research has brought more awareness to the role of occupants in buildings [4,5]. Energy related occupant behavior, in its simplest form, includes adjusting thermostat settings, opening/closing windows, dimming/switching lights, pulling up/down blinds, turning on/off HVAC systems, and movement between spaces. In addition, behavioral adaptations, such as clothing adjustments, the consumption of drinks and changes in the human metabolic rate, all directly affect individual comfort which in turn influences building energy consumption. In fact, direct and indirect drivers, at the individual, local, whole-space or zonal level each impact the building energy consumption differently. Langevin et al. [6] demonstrated that the use of personal heating/cooling devices could allow for an increase in the thermostat set point enhancing thermal comfort, while reducing the total energy use. An occupant's interaction with building systems and the available systems, play a significant role in influencing the total energy use of buildings. A study by Danny Parker of Florida Solar Energy Center [7] (Fig. 1) showed that the total energy use of 10 identical homes varied by a factor of three, even though they had the same floor area (102 m^2), were on the same street, built in same year and with similar efficiencies. This variation is even larger at the energy end use level (e.g. up to 10.6 times in space heating energy use).

Due to the uncertainty associated with occupant behavior model inputs, simulation results often vary widely from actual building energy consumption [8]. Eguaras-Martínez et al. [9] suggested that the inclusion or exclusion of occupant behavior in simulations, resulted in differences of up to 30%. A comparison between the simulated energy consumption in the design phase and the measured energy use for LEED (Leadership in Energy and Environmental Design) certified buildings in the U.S., shows a significant error (root mean square error of 18%) in a group of 62 buildings [10]. The prediction error is even larger for low energy buildings which use passive designs, such as natural ventilation, relying more on occupant interactions. Therefore, occupant behavior is a leading source of uncertainty in predicting energy use [11].

ASHRAE 90.1 Standard [12] Appendix G states that there are large discrepancies between measured and building design energy consumption. This limits the application and potential impact of building performance simulation (BPS) in industry. Thus, having a better understanding of occupant-building interactions will help bridge-the-gap between actual and predicted energy consumption [13]. However, quantifying the impact of these behaviors proves challenging. The International Energy Agency Energy in the Buildings and Communities Program (IEA EBC) Annex 53: Total Energy Use in Buildings, indicated that there are six driving factors of energy use in buildings: (1) climate, (2) building envelope, (3) building energy and services systems, (4) indoor design criteria, (5) building operation and maintenance, and (6) occupant behavior. While significant progress has been made in quantifying these primary drivers, there lacks scientific and robust methods to define and model energy related occupant behavior in buildings.

Recent advances, presented in journal articles from 2013 to 2015 (up to February), have shown significant improvements in the three thematic areas shown in the occupant-building interaction energy behavior loop (Fig. 2). On the *data collection* front, data driven techniques such as real-time remote sensing to investigate occupants' interaction with building technologies is at an all-time high, with more data on occupant actions collected than ever before. On the *analytical and modeling* front, advanced statistical, data mining, and stochastic modeling methods are being developed and applied to extract behavioral models from the experimental data. An ontology to standardize the representation of energy related occupant behavior in buildings has been proposed. The combination of observation and modeling aspects will subsequently help to improve *simulation* techniques to quantify the impacts of the energy-related occupant behavior and to provide insights toward energy saving behaviors and robust architectural design. The article is organized according to the three themes shown in Fig. 2. Additionally, this review covers both residential and commercial buildings at a higher level, with the understanding that specific differences exist between these unique building types. Some influential differences include: (i) behaviors in each building are usually different considering the different activities performed and who is responsible for paying the energy bill, (ii) negotiations and group behavior may be different between a commercial setting and home environment and, (iii) the system controls are often different [14]. These considerations, among others, are particularly important to keep in mind during the data collection and model input phases of occupant behavior research.

2. Advances in data collection techniques

Gathering data to change building operation and occupant behavior is the next frontier in sustainable design. Improvements to data collection techniques, the accuracy of individual sensors, and the information obtained, has led to progress in the areas of (i) occupant movement and presence, (ii) thermal comfort, (iii) windows, shades and blinds and, (iv) lighting and electrical equipment.

2.1. *Occupant movement and presence*

The use of sensors in wireless networks and wearable devices provides the unprecedented ability to easily capture occupant movement and presence, a preeminent factor that affects lighting, thermostat, plug loads, HVAC equipment, fresh air requirements and internal heat gains or losses within a building. Energy simulation programs often rely on homogenous and standardized occupant schedules, often unrepresentative of actual occupancy diversity. Data and analytics has enabled the active reforming of occupancy schedules to better capture the stochastic nature of occupants, with improved schedules demonstrating as much as 46% difference from the prescribed ASHRAE 90.1 Standard [12,15,16]. Individualized occupancy patterns facilitate more accurate modeling of occupant movement and presence and their implementation into BPS provides one method to assess the impact of occupant behavior on building energy consumption [17–19]. For example, Motuziene and Vilutiene [20] used four different occupancy profiles from homes in Lithuania in conjunction with BPS, to demonstrate up to 31% savings depending upon heating strategies. Moreover, excessive energy use during vacancy has proven to hold substantial energy savings potential [21,22]. For example, dormitories in South Korea use up to 31.5% of all energy while unoccupied [23].

2.2. *Thermal comfort*

Thermal comfort is defined as an occupant's gratification with their thermal environment [24]. Energy consumption can fluctuate subject to the HVAC control strategy, with the primary physical-behavioral forces including ventilation, thermostat set-point and indoor thermal environment [25,26]. Thermostat control is used by different users with varied privileges dependent upon the organizational policy of the building [17]. About 30% of programmable

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