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10 Questions

Ten questions concerning occupant behavior in buildings: The big picture

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ABSTRACT

Occupant behavior has significant impacts on building energy performance and occupant comfort. However, occupant behavior is not well understood and is often oversimplified in the building life cycle, due to its stochastic, diverse, complex, and interdisciplinary nature. The use of simplified methods or tools to quantify the impacts of occupant behavior in building performance simulations significantly contributes to performance gaps between simulated models and actual building energy consumption. Therefore, it is crucial to understand occupant behavior in a comprehensive way, integrating qualitative approaches and data- and model-driven quantitative approaches, and employing appropriate tools to guide the design and operation of low-energy residential and commercial buildings that integrate technological and human dimensions. This paper presents ten questions, highlighting some of the most important issues regarding concepts, applications, and methodologies in occupant behavior research. The proposed questions and answers aim to provide insights into occupant behavior for current and future researchers, designers, and policy makers, and most importantly, to inspire innovative research and applications to increase energy efficiency and reduce energy use in buildings.

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1. Introduction

Worldwide, the building sector consumes more than one-third of the total primary energy [1]. To address the challenge of climate change and meet urgent energy reduction goals worldwide [1], innovation in the construction and use of buildings is essential. Unfortunately, technological solutions and innovations in building materials in the building sector are insufficient, because buildings are dynamic systems, and the occupants behave in complex ways. Recent research has shown that the development of a comprehensive understanding of energy-efficient building methods and tools, coupled with the integration of the stochastic nature and diversity of occupant behavior (OB), is an essential starting point for bridging the existing "credibility gap" of energy-efficiency in buildings [2]. Further explorations regarding energy usage for building occupants are imperative, and efforts need to begin with the development of informative resources to educate a wide spectrum of stakeholders in an interdisciplinary arena, from building designers to social scientists and policy makers.

1.1. Understanding occupant behavior in low-energy buildings

Understanding occupant behavior is crucial for achieving high-performance and low-energy use in buildings, both in the commercial and the residential field. In office buildings, the pivotal role of OB lies in determining the large variability regarding comfort settings and energy use, and involves the occupants' interactions with energy control systems (i.e. thermostatic valves and HVAC system set points), building components (i.e. windows, blinds, and shades), and appliance usage (i.e. artificial lighting system, computers, and plug loads) [3–5]. The '*dark side*' of the influence of OB on building energy use was verified by Masoso et al. [3], who determined that more energy was consumed during non-working hours than during working hours due to OB, i.e. leaving lights and equipment on at the end of the day, as well as poor building zoning and controls. Statistical analysis and simulation studies of occupancy and behavioral patterns in open-plan offices [4] confirmed that occupants with a "wasteful" work style consumed up to double the energy of the standard (non-wasteful, non-

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austere) occupants, while "austere" work-style occupants used half of the energy of the standard occupants.

Studies have shown that energy consumption at the household level varied largely based on residents' behavior, and this was an international phenomenon without geographical bounds. A study conducted in Denmark [6] demonstrated a factor of three in the variation of energy consumption for apartments in the same block and with comparable characteristics regarding orientation, building systems (i.e. heating and ventilation systems), and composition of the building envelope. A similar trend in variation up to a factor of two was confirmed by a comparison of total energy use in a German residential sector [7]. Aside from installation faults, malfunctioning of the engineering plant systems, and poor performance of the building envelope, OB was recognized as one of the major causes for the gaps in energy consumption and comfort requirements. Similarly, studies conducted in China [8,9] revealed that electricity consumption for summer air-conditioning varied up to a factor of ten for similar-sized apartments in the same building.

Notably, for low-energy buildings that rely on passive design features (e.g. natural ventilation or use of daylight) or proactive interaction between occupants and building systems, the prediction error for energy consumption was even larger [10]. Buildings compliant with standards regarding high performance, Zero-Net-Energy (ZNE), low carbon emissions, and passive house design have the potential to reduce energy use significantly and have a positive impact on the occupants' comfort, satisfaction, and productivity, but only if the buildings are operated as designed. A recent study [11] concluded that the probability of achieving the actual performance of high performing buildings depended on the occupants' knowledge required to operate passive design systems and high-efficiency technology, as well as the occupants' expectations with regard to comfort and satisfaction with their environment. Turner and Frankel [12] confirmed this outcome, highlighting that *"as technical performance standards ratchet tighter, behavioral factors gain relative importance."* This study compared the simulated energy consumption in the design phase with the measured energy use of a group of LEED-certified buildings in the U.S., and demonstrated a lack of reliability for predictions of energy building performance in the design stage. The disparity among the individual dwellings' actual energy consumption indicated that different occupants behaved differently because of heterogeneous ways of understanding and using the building control systems. Importantly, the topic of innovative technologies affecting occupants' ability and approaches to adapting to the indoor environment remains little understood [13].

1.2. Occupant behavior research over the building lifecycle

Integrating occupant behavior into the research on the building life cycle is critical to achieving the goal of low or ZNE buildings. Studies have demonstrated the consideration of behavior in building energy use during the design, operation, and retrofit of buildings (Fig. 1).

The systematic interconnection of the human-building interaction is paramount at three different scales, from individual zones, to the building level, and to the district scale. Therefore, in the study of OB, it is essential to focus on individual, group, and collective behaviors. Data are gathered, analyzed, modeled, standardized, and simulated at the three scales, producing outcomes and evaluation metrics for different time-spans (hourly, daily, weekly, monthly, and annual). However, the connection of these scales and the focus of the research are not always linear. Rather, a trans-scalar approach must be adopted to explore possible solutions to overcome existing limitations and shortcomings in state-of-the-art research (Fig. 1). Different stakeholders with diverse roles during the building life cycle are involved in the research. These include. but are not limited to energy modelers, building occupants, architects, HVAC engineers, building operators, managers, owners, building technology vendors and practitioners, building performance software developers, as well as researchers and policymakers in the energy and social science fields (Fig. 1).

1.3. Main objective of occupant behavior research

The main objective of occupant behavior research is to leverage energy-related occupant behavior as a fundamental aspect influencing the global energy performance and bridging the gap between predicted and actual energy consumption in buildings, and to leverage this *human factor* to the same extent as technology innovations.

Over the last 30 years, the research community has focused on the topic of energy-related OB in buildings. Current research has dedicated efforts to the observation of state-of-the-art advances in many international studies and the extensive evaluation of limitations of recent investigations [18]. The main limitations can be synthesized as in Fig. 2:

- Oversimplified or ignored adaptive and non-adaptive occupant behaviors throughout the whole building operation process;
- Lack of common agreement on validity and applicability of OB modeling and simulation approaches;
- Unclear interdisciplinary solutions to improve the occupant's comfort, satisfaction, and health and to leverage potential energy savings, behavioral programs, and policy effectiveness from the building level scale to the community scale.

Correspondingly, this article provides up-to-date research suggestions and insights for the international community to improve the understanding of and address such limitations in behavior research and application in the form of ten questions (Fig. 2):

- Monitoring techniques for human-building interaction for quantifying impacts on building energy performance (Questions 1, 2, 3);
- Evaluating behavior modeling approaches for implementation in BPS programs (Question 4);
- Enriching BPS programs, behavioral programs. or policy via behavior model simulation applications (Questions 5, 6);
- Promoting social science insights (e.g., social psychology) and methods to enhance effective human-building interactions for individuals and groups (Questions 7, 8) from the zone level up to the building and community scale;
- Analyzing achieved results and determining future research challenges (Questions 9, 10).

2. Ten research questions regarding OB in buildings

2.1. Question 1: What are the specific occupant behaviors that influence building energy performance?

Answer Energy-related occupant behavior can be grouped into two separate categories: (1) adaptive actions [19], and (2) non-adaptive actions [20] (Fig. 3).

As explained by Humphrey's principle [21] – "*if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*". Thus, when performing energy-related "adaptive behaviors" [19] occupants either a) engage in actions to adapt the indoor environment to their needs or preferences – e.g. opening/closing windows, lowering blinds, adjusting thermostats, turning lighting on/off, and/or b) adapt themselves to their

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