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Authors

Hong, Tianzhen

Yan, Da

D'Oca, Simona

et al.

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Ten Questions Concerning Occupant Behavior in Buildings: The Big Picture

Tianzhen Hong¹, Da Yan², Simona D'Oca¹, Chien-fei Chen³

¹ Building Technology and Urban Systems Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA

² School of Architecture, Tsinghua University, Beijing 100084, China

³ Department of Sociology, University of Tennessee, Knoxville, TN 37996, USA

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.

Keywords.

Occupant Behavior; behavior modeling; building performance; building simulation; energy use; interdisciplinary

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-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 (Figure 1).

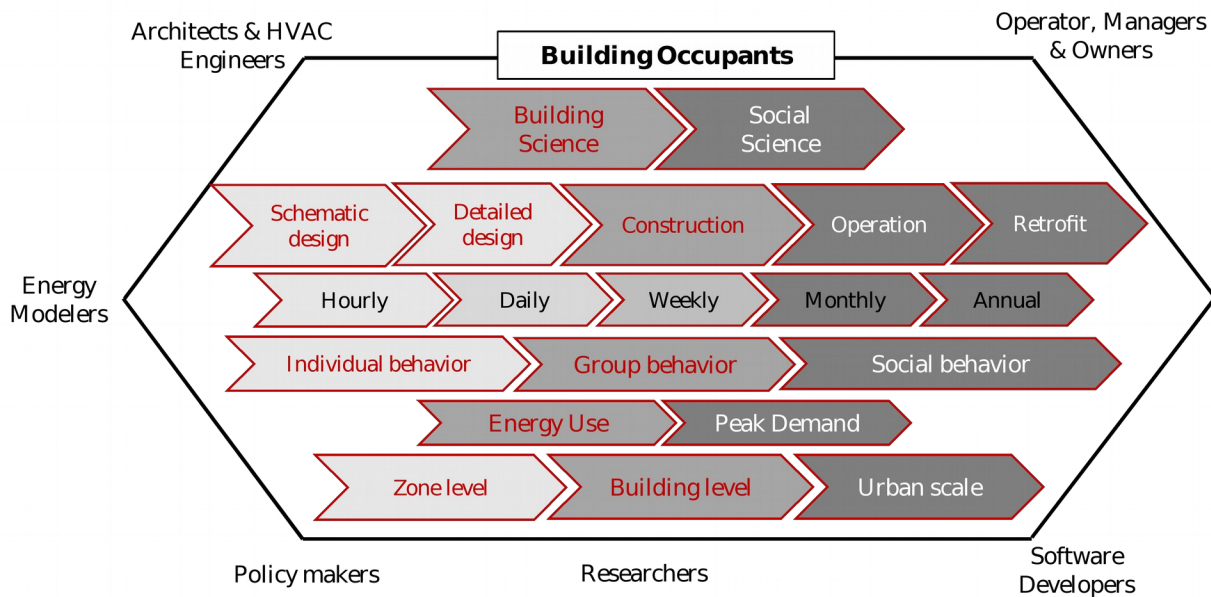


Figure 1. Spatial, temporal, and contextual fields of application of the behavior research and stakeholders

- Building performance simulation (BPS) programs, integrating advanced behavioral models, have been demonstrated to enhance the quality and robustness of building **design** (from schematic to detailed design phases), reducing the gap between predicted and measured energy consumption and comfort level during the operational phase [14,15].
- Buildings with humans-in-the-loop (HIL) sensing and controls can improve **construction, operation, and management** of the buildings, achieving savings in the range of 4-5% of annual energy operating costs in commercial buildings [16].

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- A better understanding of human factors in building energy use can support the definition of efficient and targeted *retrofit* strategies. In this context, including evaluations of technology adoption and penetration based on socio-economic variables in current energy retrofit scenarios can support the acceptance and uptake of robust energy efficiency measures [17].

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 (Figure 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 (Figure 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 Figure 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.

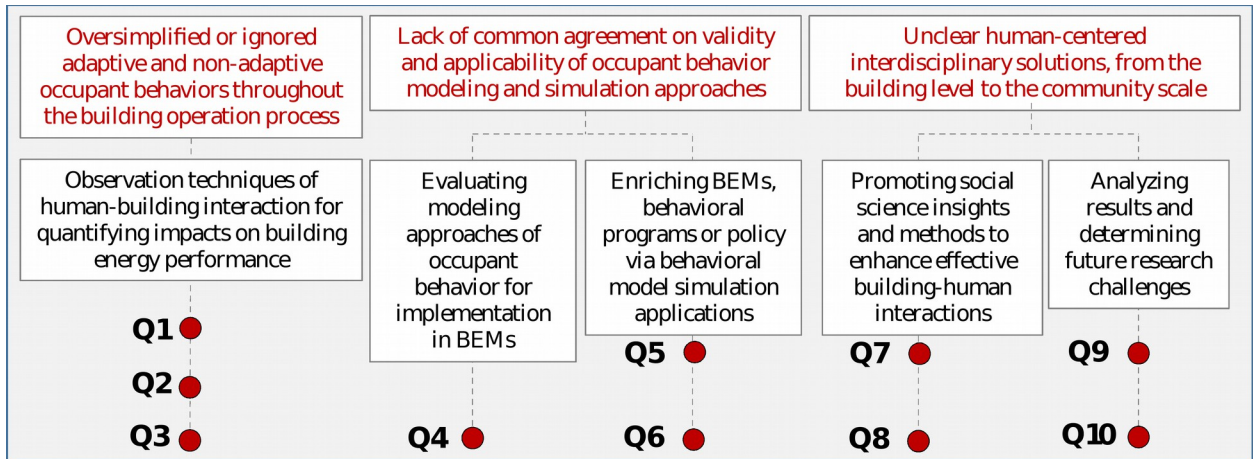


Figure 2. Schematic overview of current limitations of state-of-the-art investigations into occupant behavior and corresponding highlighted research questions

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 (Figure 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] (Figure 3).

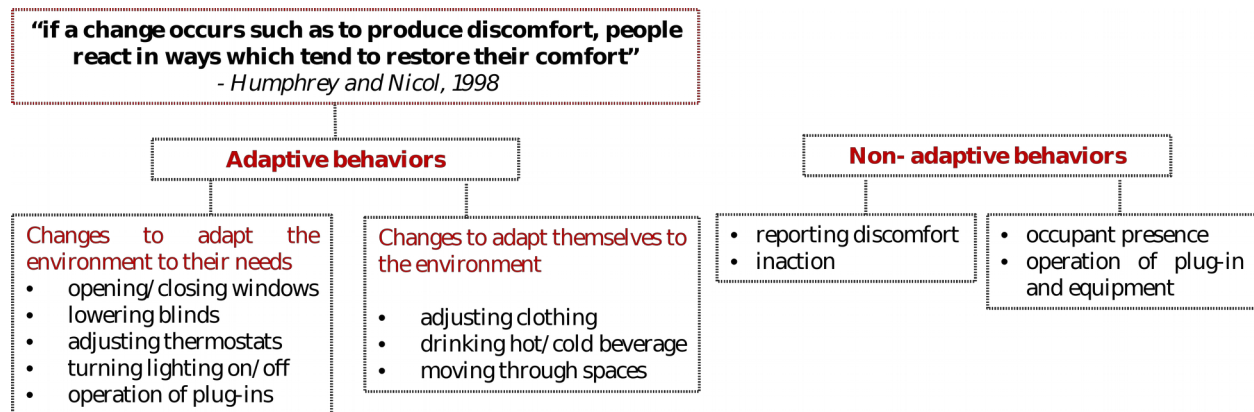


Figure 3. Energy-related OB influencing building energy consumption and comfort.

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 environment – e.g. adjusting clothing and moving through the building. Non-adaptive actions such as occupant presence and operation of plug-ins and electrical equipment (e.g., office and home appliances), as well as reporting complaints regarding discomfort to building managers have an influence on final building performance (energy consumption and comfort). Usage of plug-ins also refers to “adaptive” operations of personal heaters, fans, and electrical systems for space heating/cooling to meet the occupants’ comfort needs, which have an influence on building energy consumption (i.e. electricity loads). This type of plug-in usage directly depends on the occupants’ comfort requirements (and/or preferences) and entails inclusive implications for the overall building performance. Furthermore, occupants can choose inaction – in the case of no access to suitable systems, or as an awareness choice, i.e. accepting more “forgiving” indoor environmental conditions [22,23]. In this paper, energy-related occupant behavior refers to the general population in both residential and commercial buildings without specifying a particular type of occupant (e.g., children, students, or the elderly). The authors recognize the importance of different types of buildings and populations, such as the energy-related behavior of children in schools or the elderly in elder care buildings. Although there is a fundamental association between energy-related behaviors on the one hand and learning behavior and education on the other hand, this particular focus is not included in the scope of this investigation. We also recognize that other types of energy-related behavior (i.e. investments for vehicles used for commuting and personal transportation, purchasing of goods and food, waste management) have influential impacts on an individual’s energy footprint. However, these behaviors are not strictly related to building energy usage, and were therefore excluded from our scope of discussion.

2.2. Question 2: How does occupant behavior influence building energy performance?

Answer Occupants, not buildings, are the primary consumers of energy [24] because they behave proactively within their indoor environments to seek comfortable personal conditions and to perform

energy-related tasks. Accordingly, they consume energy in buildings for the purpose of HVAC (heating, ventilation, and air-conditioning/cooling), lighting, plug loads/appliances, and domestic/service water heating.

The occupants’ adaptation mechanisms [25] to their indoor environments have consequences for the building performance, namely energy use and environmental quality in the buildings over time – and this relationship is twofold. On the one hand, environmental conditions trigger occupants to interact with the building’s control systems, causing changes to the energy loads. On the other hand, any adaptive action undertaken by the occupants generates a perturbation of the indoor environmental conditions. Considering the case of an occupant opening a window to provide fresh air during wintertime, the occupant might be driven to open the window to achieve or restore a comfort condition (i.e. because it is too hot or the air is stuffy), or because of a contextual motivation (i.e. first arrival in the space). In both cases, the action of opening the window will lead to changes in the building’s environmental conditions and energy flows, e.g., an increase in the consumption of heating energy due to an increase in the ventilation airflow rate. The impact of OB on building performance can be quantified using two approaches: (1) by comparing the actual energy performance of similar buildings with different OBs, and (2) by simulating building performance using BPS programs with different OB inputs and models. In both cases, the procedures to develop (1) the direct assessment of behavioral influences or (2) simulated behavioral models are grounded in advanced data-driven quantification methodologies.

2.3. Question 3: How can we measure occupant behavior to quantify its impacts on building energy performance?

Answer: Rigorous, objective, and subjective measuring techniques must be used to study impacts of occupant behavior on building energy performance based on real-data.

Gathering data on human-building interaction is a new horizon for achieving energy efficiency in the building sector. The use of measurements regarding occupancy (i.e. presence and movement), interaction with the building envelope (i.e. windows, shades, blinds), and use of control systems (i.e. HVAC, lighting systems, and plug-loads) is increasing in the evaluation of energy use in residential and commercial buildings. For example, researchers have monitored building systems to identify the correlation between observed system states (i.e. windows being opened/closed, shades being drawn,), conditions or variables of the indoor and outdoor environment (i.e. indoor and outdoor air temperature, relative humidity), subjective OBs, and energy performance. Measurements of energy-related behavior are collected using (a) physical sensing, and (b) non-physical sensing methods (Figure 4).

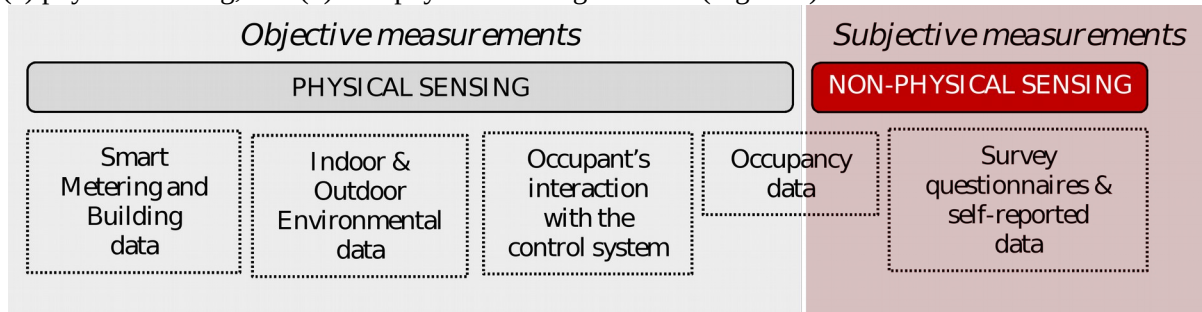


Figure 4. Schematic of the sensing methodological approach of energy-related occupant behavior in buildings

a. Objective measurements

Objective measurements consist of smart metering (e.g., plug loads, electricity) and building data (e.g., indoor environmental quality, energy loads) as well as indoor and outdoor environmental data (e.g., air temperature, relative humidity, air velocity, CO₂ concentration). Objective physical sensing of the occupants includes monitoring adaptive interactions with the control systems as well as gathering occupancy data using occupancy sensors. A summary of typically used tools and techniques involving occupancy sensors was recently published [18]. More recently, innovations based on virtual-reality, such as the Kinect technology [26], MIMO (multiple-input, multiple output) techniques [27], Wi-Fi through-wall imaging (TWI) techniques [28,29], RF body reflection [30], and eye tracking technology (ETT) [31], are setting the stage for improvements in the field of occupancy detection, sensing, and recognition in building spaces. The reader can refer to [32,33] for a comprehensive review of innovative methods and measures for physical occupancy sensing.

b. Subjective measurements

Innovations in the sensing of human-building interaction go beyond monitoring individual behaviors and gathering building-related data. Research has focused on developing interdisciplinary observation methods regarding individual, collective, and social motivations, as they are crucial in influencing behavioral patterns, and have various consequences for building energy consumption and indoor environmental comfort. Subjective measurements have been employed extensively to identify individuals' responses to indoor environments, to identify the dominant factors influencing occupant interaction with building control systems, and to record information about human-building interaction [34–45]. Subjective occupant data are typically gathered using self-reporting methods, such as mail- or web-based surveys or interview techniques.

One of the key limitations of the survey methodology is the inconsistency between actual and self-reported behaviors [46]. Moreover, lengthy surveys have often been criticized, because people are experiencing fatigue in tracking and reporting behaviors and actions over time [35]. Responses might be biased due to the so-called Hawthorne effect, also referred to as the “observer effect”, a type of reaction in which subjects modify or improve features of their behavior in response to their awareness of being observed [47]. However, occupant survey solutions overcome key barriers to the adoption of state-of-the-art sensing technology, which includes high costs for initial installation, operation, and maintenance of sensors, and the difficulty of integrating the sensors with existing building management and control systems. In addition, surveys are a valid alternative to behavior sensing when direct monitoring techniques are not allowed or are insufficient with regard to the scope of the investigation. Importantly, to fully understand the motivations and mechanisms of behavior, survey methodology has emerged as an appropriate tool for discovering multiple levels of social, contextual, or group interactions that drive behavior and motivate individuals. Additionally, different types of occupant behaviors can be identified through surveys conducted in various countries, cultures, and climates [48].

2.4. Question 4: How do we develop occupant behavior models for use in building performance simulation?

Answer: Behavior models do not represent deterministic events, but move into a field where actions are described by stochastic laws.

Occupant behavior is complex, stochastic, and diverse and has interdisciplinary characteristics. However, at a certain level, it can be represented quantitatively. Behavior is induced by the effect of certain stimuli,

also called *drivers of behavior* [49–52]. By understanding the correlation between drivers and behavior, we can presumably obtain a predictive curve of operating behaviors, integrating the observed behaviors and influencing triggers over time. Based on such suppositions, we establish a *stochastic behavior model* [52,53]. Stochastic behavior models can implicitly interpret the state of the building component as a proxy for behavior or, more accurately, explicitly account for the state-transition of a building component or a variable of the indoor environment in continuous time steps (e.g., every 10 minutes) or for discrete events. Different approaches for implementing such data-driven behavioral models have emerged in published research [54,55]. The adoption of diverse methodologies is not necessarily a matter of complexity.

In some cases, behavior models need to encompass singular instances of individual behaviors to identify patterns of behavior [56–63]. The discovery of data patterns using statistical analysis procedures, data mining, and machine learning techniques has been widely adopted in recent research to automatically extract valid, novel, potentially useful, and understandable behavior patterns from big data streams [64–70]. Analytical techniques for big data (such as Knowledge Discovery and Data Mining [71]) have the capability to provide qualitative and quantitative information on diverse user profiles in a block of buildings, enabling the use of more realistic 24-hour schedules in BPS programs, and to cover diversity in environments (i.e. air-conditioned/naturally-ventilated, residential/commercial buildings). Data mining techniques are not intended as a substitute to or contrast with direct stochastic modeling approaches. More likely, the knowledge discovered through such procedures aims to overcome the shortcomings of more traditional techniques, specifically when dealing with big data streams, by providing reliable models of energy-related behavior with the potential for rapid analysis and high replication.

Notably, the consistency of behavior models must be evaluated by rigorous validation procedures [72,73]. Behavioral models should also strive for consistency in character. Reporting plausible general behaviors among a group of people might be more significant than exactly describing individual and isolated behaviors [74]. A tradeoff in model accuracy and scalability is hence needed to achieve high impact results and bridge the credibility gap for energy efficiency in buildings. Using the right axioms and sharing methodologies will likely assure that internal inconsistencies will be avoided when adopting behavior models in BPS programs.

2.5. Question 5: How are behavior models and related inputs typically implemented in BPS programs?

Answer Typically, simplified static and deterministic occupant schedules and profiles are used as direct inputs to the most widespread BPS programs, such as EnergyPlus, IDA ICE, ESP-r, DeST, TRNSYS, and DOE-2.

Over the last 30 years, human-building interactions have been virtualized in BPS programs using inputs reflecting the variability of behavior to improve the outcome of simulations of building energy consumption. In BPS tools, deterministic input values provide a simple representation of behavior over the entire building life cycle. For example, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 90.1-2004 [23] provides homogenous occupancy schedules for different building types, which can be used to design the building-user interaction when actual occupancy and operational schedules are undefined (Figure 5). These schedules take the form of a daily profile, applied differently to weekends and weekdays, and composed of hourly values, each of which

corresponds to a fraction of the occupancy or the energy use (e.g., lighting, plug loads). The main advantage of using such deterministic behavior inputs is their ease of use and interpretation. Even non-expert modelers can incorporate them quickly into building models to represent lighting, plug load usage, interaction with natural ventilation and HVAC systems, and occupancy levels [75]. Another advantage is that the replication of the behavioral phenomena is supported by empirical and experimental studies on responses of human physiology [76,77], and that environmental comfort has been recommended as an index for EU and US international specifications for occupant comfort conditions and criteria [78]. However, major drawbacks of this modeling approach are steady-periodicity and weakness in capturing the diversity in behavior. Despite simulation assumptions, there is no certitude that occupants will be present in a space at fixed time steps, or that they will behave in a certain manner when triggered by the same environmental factors. This randomness creates substantial inconsistencies between simulated and actual building energy performance, which has led to the application of stochastic rather than deterministic behavioral inputs in BPS programs. In an ever increasing trend, behavioral interactions with buildings and systems have been virtualized in BPS programs using stochastic models reflecting the variability in human behavior (e.g., in Annex 53, EBCP 2013) to improve the outcome of the simulations for building energy consumption.

2.6. Question 6: What are the main applications of occupant behavior models in BPS research?

Answer Dedicated occupant behavior modeling tools and case studies have been recently developed and integrated into BPS programs to capture the complexity and diversity of occupant behavior, to calculate their impact on building performance [79], and to support behavioral programs or policy research that target programs for behavioral change [48].

Dedicated OB modeling and simulation tools aim to provide better data to improve assumptions for occupant modeling in building performance simulations to evaluate technology performance and compare scenarios in building design. This can help reduce the gaps between predicted and actual energy use in buildings, improve the development of building codes and standards, as well as enable energy policy making by considering the uncertainty and adaptive opportunity of occupant behavior in buildings. Newly developed modeling tools include: (1) an ontology to represent occupant behavior in buildings [80] and an XML schema (obXML) implementing the ontology [81] to provide a standardized representation of behavior models for use in different BPS programs and different user-developed energy models; (2) the occupant behavior functional mockup unit (obFMU) that can co-simulate with BPS programs such as EnergyPlus [82]; and (3) the Occupancy Simulator web application [83] using a Markov chain OB model [84], to simulate occupant presence and movement in buildings, and to generate stochastic occupancy schedules that can be used with BPS programs (Figure 5).

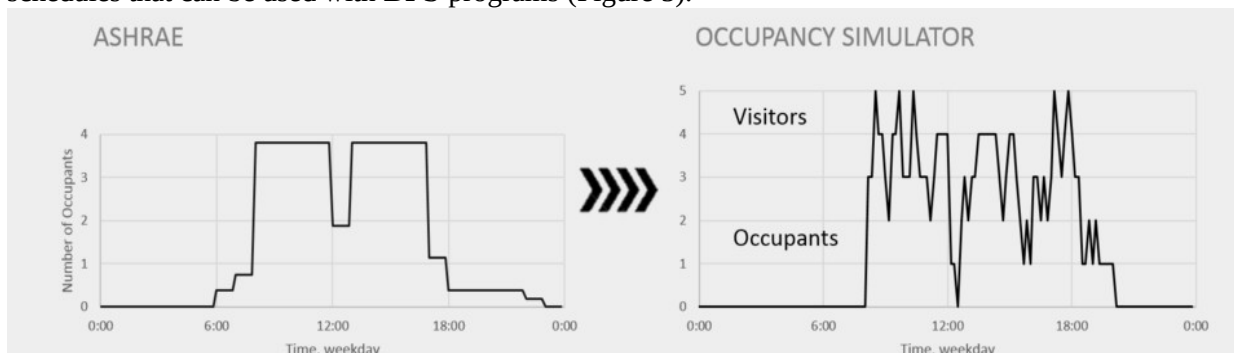


Figure 5. Typical Monday-Friday Schedule representing diversity profiles in ASHRAE Standard 90.1-2004 compared to stochastic occupancy schedules generated by LBNL's Occupancy Simulator

Simulation-based *case studies* generally include quantification of OB impacts, such as hidden energy and comfort drawbacks. The objective is to support building energy designers, modelers, operators, and managers to develop specific energy efficiency measures, and to evaluate technology adoption levels by taking into account the OB impacts. In addition, the knowledge gained from the case studies aims to support energy and urban planners to develop informed energy policies, programs, codes, and standards (e.g., technology driven incentives and retrofit measures). Case studies also aim to support the development of robust energy design tools targeting energy efficiency goals in the building sector. The concept of building “robustness” was firstly provided by Hoes et al. [85] as “the sensitivity of identified performance indicators of a building design for errors in the design assumptions.” Accordingly, a robust building is a building that shows little variation in performance despite changes in occupant behavior (e.g., as a function of diverse occupancy profiles or patterns of interaction with building systems and components). In addition, building robustness can be addressed with respect to dissimilar design options for the building envelope (e.g., the thermal and solar transmittance of glass, visible transparency, thermal mass and resistance). Behavior research aims to drive retrofit measures at the building level and to assess the potential for renovation penetration in a city district, based on the characteristics of the building’s occupants. The inclusion of archetypal occupant profiles in the estimation of the feasibility and dissemination of energy policy and measures, in particular at the urban scale, aims to support decision making in policy formulation by determining spatial differences in the social conditions of occupant behavior [17].

2.7. *Question 7: How can quantitative research methods in social science, such as survey methodologies, provide insights into occupant behavior?*

Answer In social science, researchers may use qualitative or/and quantitative methods to conduct their research. Qualitative research, such as interviews and focus groups, is used for exploring how individuals or groups relate to a social problem whereas quantitative research, such as survey and experiments, are used for testing specific theories by examining the relationships among variables [86]. Experimental studies generally include laboratory and field experiments, which can demonstrate cause and effect relationships in a compelling manner [87]. Specifically, laboratory experiments offer the possibility to study occupant behavior in a controlled environment whereas field experiments are conducted in the real-life environment of the participants using manipulated treatments. There is a growing trend to apply survey methodologies to investigate occupant behavior; therefore, we focus on the discussion of conducting an appropriate survey.

Unlike experimental or field observation methods, an appropriate survey design can generalize research results from samples to a population by providing a quantitative description of trends, attitudes, or opinions of that sample [88,89]. Survey methodology is valuable in discovering new knowledge of relationships among a group of variables beyond simply collecting information regarding occupants’ backgrounds (e.g., demographics). There is a general doubt about the validity of surveys in terms of whether self-reported answers are valid or trustworthy, since there is a discrepancy between reported answers and observed behaviors. However, researchers should recognize that surveys have limitations just like other methodologies, such as simulations and modeling. For example, simulation research may only

apply to a small number of occupants [90] or suffer from a lack of diversity in simulated behaviors [91]. The use of sensors could be limited by only collecting selected data or limited amounts of data due to time and technological disadvantages in some buildings or the lack of a validation standard [91]. Additional limitations might include the issue of consistency in OBs, overly predictable energy-use behaviors that do not apply to more intensive energy-use settings, and the plethora of social, cultural, and behavioral factors that are not considered in the simulation [92]. Importantly, many buildings do not install sensors; and even if they are installed, they might not be present throughout the building. Therefore, data collected by sensors could be limited by the lack of representing diversity in the OB. In order to achieve successful policy implementation and community advocacy efforts, it is necessary to gain a more comprehensive understanding of social-psychological factors influencing OB and habits (more details are discussed later). To offset the limitations of experimental design and sensor technology, survey methodology provides a suitable tool to estimate a set of drivers and mechanisms of occupants' decision-making processes, social-psychological factors, behavioral patterns, barriers to behavioral acceptance, and other perceptions and motivations, at the individual, group, and building or community level.

With reliable measurements and appropriate social science theories, surveys are particularly useful for measuring latent variables (the underlying phenomenon or construct reflected at a particular scale [93]), or variables that cannot be observed directly, such as energy concerns, behavioral intentions, norms, attitudes, perceived risks, trust, emotions, and so on [94,95]. It is important to note that many OBs are measured by the absolute response concerning a particular choice in dealing with latent variables (e.g., are you satisfied with temperature settings in the building? Are you concerned about energy consumption?). However, people are invariably more accurate or consistent when making comparative responses related to two or more choices depending on the situation and personal experiences [96].

Often, researchers might want to reduce respondents' burden by using only single items or a brief scale. The costs of using only one item or a short scale may be greater than the intended benefits [93]. Some social science researchers have suggested that a reliable questionnaire with only 50% completion is better than an unreliable questionnaire completed by all respondents [93,96]. Using a measurement or scale that does not reflect the applicable theories can lead to inaccurate findings. Therefore, it is necessary to use multi-items and combine several items based on theories or appropriate published scales when measuring a social-psychological attribute. When using survey methodologies, it is important to first obtain a representative sample from a population by using simple random sampling, stratified random sampling, or cluster sampling, while also ensuring a proper sample size [89]. Using a convenience sample or a small sample size is one of the main limitations in many OB studies. If conducting a survey through a convenience sample, researchers should address this limitation, the strategies of overcoming this limitation, or compare their samples with census data of the affected population.

Second, researchers should recognize various sources of survey error (e.g., sampling, cover, nonresponse, measurement, and processing) [88,89]. Third, researchers should understand the definition of the variables and associated levels of measurement including nominal, ordinal, interval, and ratio [93,96]. In addition, the means for achieving high levels of reliability and various types of validity (e.g., face validity, content validity, convergent validity, and discriminant validity) should be considered. Finally, researchers should recognize the importance of the aesthetics and layout of the questionnaire, as these can affect respondents' answers. Importantly, writing a good questionnaire requires formal training and knowledge. Dillman [89] has suggested certain principles, including (1) choose simple over specialized words, (2) avoid vague quantifiers when more precise estimates can be obtained, (3) avoid specificity that exceeds the respondent's potential for giving an accurate, ready-made answer, (4) use equal numbers of positive

and negative categories for scalar questions, (5) eliminate check-all-that-apply question formats to reduce primary effects (or randomize the answer choices), (6) develop response categories that are mutually exclusive, (7) avoid double-barreled questions, (8) soften the impact of potentially objectionable questions, and (9) avoid asking respondents to make unnecessary calculations or estimations from long-term memory. In summary, a good survey design should be based on research questions, theories, hypotheses, and well-defined explanations of variables. Unlike physical scientists, social scientists tend to rely on several theoretical models to measure rather narrowly defined social phenomena or contexts [93]; therefore a full understanding of social science theories about the level of measurement is crucial to behavior researchers.

2.8. Question 8: How can social-psychological factors help behavior researchers and policymakers understand the effectiveness of promoting energy efficiency strategies and contribute to interdisciplinary behavior research?

Answer A full understanding of occupant behavior and the potential for energy efficiency at the community level is only possible with an interdisciplinary investigation by integrating both the physical and social sciences [88,89].

Although there is a growing emphasis on the interaction between occupants and their building environment, researchers often promote technological solutions, while ignoring the social-psychological or environmental factors that determine occupants' attitudes and behaviors [88,90]. Regarding building design and behavioral modeling, human influence and interaction need to be considered by thoroughly conceptualizing the decision-making processes [91,92]. These decision processes tend to be complex due to the diverse characteristics of occupants (e.g., habits or culture) and other structural factors (e.g., leadership, or organizational policy) beyond building design and technology. For example, predicting occupants' thermal comfort is complicated because certain environmental factors and biological needs can affect thermal comfort [93–95]. Social and psychological factors may also influence thermal comfort and energy behaviors, including beliefs, values, trust, social status, and habits [96]. Importantly, the reliability of occupant or energy modeling could be low if the researchers were sensitive to cost assumption or technology availability without considering other drivers of behaviors, such as social equality, group identity, norms, and policy [88]. Therefore, integrating social-psychological factors allows researchers to comprehend the dynamics of energy problems and thus develop practical solutions [97,98]. Many social-psychological factors include latent or unobservable variables, such as peer influence, norms, energy saving attitudes, perceived behavioral control, environmental concerns, trust, and motivations [13,89,99]. How can these factors or approaches help researchers and policy makers increased their understanding of occupants' behavior and the effectiveness of energy efficient strategies? Understanding these social-psychological factors could help researchers improve the modeling of occupant behavior, and design behavioral change strategies in a more holistic approach.

Regarding effective strategies for changing energy saving behaviors, researchers reviewed 38 intervention studies from 1977 to 2004 in the fields of social and environmental psychology, and classified various strategies aimed at household energy conservation into two broad categories: antecedent and consequence strategies [100]. Antecedent strategies involved goal-setting, provision of information and resources, and providing examples of recommended behaviors. Consequence strategies included the approaches of feedback (continuous, daily, weekly, and monthly) and monetary rewards. The researchers [100] concluded that information alone was not very effective, and media campaigns could increase knowledge and self-reported behavior, but little was known about actual behavior. In addition, providing frequent feedback was a rather successful strategy for reducing energy consumption. However, viewing feedback

from high-energy users regarding their energy consumption through the approach of normative comparison had the potential to increase the energy consumption of low-energy users.

Regarding the analysis of the effectiveness of information- and feedback-based interventions in residential buildings, Delmas et al. [101] offered the most comprehensive meta-analysis of experiments conducted from 1975-2012, including evidence from 156 published field trials and 525,479 subjects [102]. Their analysis suggested that non-monetary and information-based strategies were effective for reducing the electricity consumption of individuals by 7.4% [102].

Therefore, information and education programs targeting behavioral changes to reduce energy consumption should be considered. However, it is less clear which information strategies work best, in part, because many experiments often use more than one method, leading to confounding issues. Delmas et al. [101] also concluded that strategies providing individualized audits and consulting were comparatively more efficient for saving energy than strategies providing historical, peer-comparison energy feedback [94].

However, this finding may have been affected in part by small sample sizes for the majority of comparative or normative feedback. Interestingly, pecuniary feedback and incentives led to a relative increase in energy usage rather than influencing energy conservation, and the reduction effect disappeared as the rigor of the study increased. Similarly, monetary rewards were effective in changing behavior, but only until the intervention was discontinued [103]. This insight was also supported by other studies [89,97]. Results of these comparisons provide important policy implications for future design of effective strategies for changing energy-related behaviors.

The issues of energy use and OB extend to organizations as well. This is an important research topic to explore because the factors affecting OB within organizations and workplaces are different from those in homes and public contexts. For example, employees typically are not responsible for utility costs and thus have to reduce energy use.

Moreover, appliances and facilities are shared among coworkers, which may inhibit a sense of individual responsibility for conservation. Further, employees' behaviors are easily observed, and there is often a high degree of social interaction in workplaces regarding energy behaviors, thermal comfort, and job satisfaction [13,99,104].

Mounting evidence indicates that the three components in the theory of planned behavior (TPB) [105], including attitudes, subjective norms, and perceived behavioral control, significantly influence occupants' energy behavior at work [99]. For example, Greaves et al.'s (2013) study determined that the TPB explained 61% of the variance in employees' intention to turn off their computers when leaving their desk, and 53% of the variance in their intention to recycle at work [99]. Chen and Knight's study (2014) reported that injunctive norms and perceived behavioral control had direct and positive effects on intentions to conserve energy among Chinese utility company employees [90].

Regarding behavioral interventions, there is a growing trend to incorporate social influence or network factors into studies of behavioral change. A study conducted for 24 university buildings found that group-level feedback and peer education resulted in a 7% and 4% energy reduction at work, respectively [106]. Other studies also highlighted that group-level feedback might promote a sense of collectiveness and help achieve the desired outcome of pro-environmental behaviors [107]. Social messages, such as reciprocity, appeared to be the most effective at gaining occupant feedback compared with foot-in-the-door and direct message methods [108].

Evidence has shown that normative feedback and messages focusing on environmental concerns [109–111] were important in promoting energy conservation and collective behaviors; but the long-term effect is unknown. One recent study discovered that normative messaging positively influenced the long-term durability of behavioral change [112].

The long-term effect of energy behavior change was twice as prevalent in occupants with high concern for social norms. Aside from individual-level factors, organizational or structural factors were important

in influencing OBs in commercial buildings. For example, top management support and organizational culture were key determinants in explaining workplace pro-environmental behavior [46,113].

2.9. Question 9: What are the credible outcomes of occupant research achieved to date?

Answer Energy-aware occupant behavior has proven to be a low-cost and effective measure to save up to 20% of energy consumption in buildings, depending on the type of behavioral intervention (Table 1).

Table 1. Potential energy savings of behavioral measures targeting occupant behavior in residential and commercial buildings

Intervention Strategy	Intervention Type	Investment Cost	Range of energy saving
Technical	Buying and substituting old and inefficient equipment with more efficient ones	High	-
Social	Indirect feedback (i.e. enhanced billing)	Low	Average of 2%
Technical-social	Direct feedback (including smart meters and target setting)	Medium-Low	5–15%
Technical-social	Humans in the loop sensing and control systems	Medium	15-20%

A recent study [114] evaluated the energy-efficiency potential of residential behavioral-based intervention and the corresponding merits and disadvantages of diverse estimation methods. Based on an extended review of twelve potential studies published in international journals and conference proceedings (e.g., ACEEE, ECEEE, BECC) between 2008-2016, the report estimated a potential reduction in California’s statewide emissions (carbon, electricity, energy) of 0.26% to 15%. Potential energy-saving methods in these studies included various types of behavior including investments in energy efficient equipment, actions regarding personal transportation (such as investment in electric vehicles and technologies), as well as the choice of low-carbon goods and services.

Researchers in the interdisciplinary research fields have advanced three general strategies to achieve behavioral energy savings in buildings: (1) deploying *technical* solutions capable of achieving widespread usage for high-efficiency equipment and building systems; (2) pursuing *sociological* approaches leveraging on behavioral programs and energy engagement techniques; and (3) promoting *socio-technical* behavioral programs supported by smart monitoring systems and demand-side control and management technologies.

2.9.1. Technical strategies

The *first technical* route requires a high capital investment for buying and substituting old and inefficient equipment with more efficient ones. This approach can achieve results in a relatively short term, e.g., an immediate reduction in electricity consumption (up to 60%) due to the installation of more efficient LED lighting systems [115]. The introduction of energy labeling, implemented by EU Directives and US Energy Star in the past ten years, has produced a positive trend in customer’s adoption of more energy efficient appliances. Although improvements in energy efficiency have been attained in home appliances and lighting, the average electricity consumption in EU-25 households has increased by about 2% per year over the last decade [16]. Similarly, for the U.S., the International Energy Agency (IEA) estimated [1] that, even with a continuation of all existing appliance policies, electricity consumption will grow up

to 3600 TWh/year by 2030. Some of the reasons for such increases in electricity consumption are associated with a higher degree of comfort requirements and level of amenities, and the penetration of new technologies and widespread utilization of new types of loads. Phenomena such as the rebound effect [103,116] in which the increasing use of energy-efficient equipment may directly result in increased energy consumption, have been reported. Indeed, some researchers [117,118] have suggested that the increase in the availability of new energy-efficient technologies might eventually result in increases in energy consumption.

2.9.2. *Non-technical (sociological) strategies*

A *second non-technical route* to induce energy savings can involve sociological approaches. Successful behavioral campaigns in the residential sector (e.g., OPower [119]), leveraging on peer comparison strategies to foster energy consumption reduction at the household level, demonstrated achievable energy savings of 2% on average. However, these numbers strongly depended on the social intervention type and length of the studies. Typically, the endowment of green energy tariffs from energy companies, utilities, or non-profit social enterprises related to household energy consumption (e.g. Energy Saving Trust) have established efforts to sensitize the population to energy savings, promoting the awareness of energy-efficient products and services. Based on results from 218 large-scale behavioral feedback programs conducted across more than 8 million households and 88 U.S. utilities, studies have estimated that the deployment of behavioral programs was cost-effective and could generate 19,000 GWh in annual electricity savings and \$2.2 billion in end-consumer savings per year [120].

2.9.3. *Socio-technical strategies*

A *socio-technical route* encompasses the promotion of “energy-conscious” behavior by requiring medium-low capital-intensive investments, such as the installation of smart monitoring in-home systems [121,122] or demand-side building automation control in commercial buildings [123,124]. The financial expenses typically refer to the costs of intervention strategies or small technical infrastructure, as well as additional investments to support behavioral change programs (e.g., monetary incentives and benefits). In office buildings, the state-of-the-art of the humans-in-the-loop sensing and controls technologies (e.g. Comfy) include occupant-driven demand-controlled operation and set-point optimization of HVAC systems. Evidence has shown that such advanced building automation systems can provide tangible energy savings of an average of 15-20% in typical office buildings [125].

Confirming this assessment, a study conducted by McKinsey quantified the savings potential of behavioral interventions at 16%-20% of total US residential energy use [126]. Achieved behavioral changes appear to be stable over time and similar in various geographical regions worldwide [127]. As explained in [42,128], consumers tended to respond positively to changing their energy use when motivated by financial rewards. For this reason, energy providers and utility programs commonly apply financial incentive strategies to influence individual energy use. Studies [117,129] demonstrated that in recent decades, energy intervention strategies in homes had been mostly promoted by energy utilities rather than government initiatives, to follow market-based trends and measures. Such outcomes highlight the importance of social influence with regard to positive energy-saving behaviors, as well as the high dependency of behavioral change processes on the sphere of social norms [42].

2.10. *Question 10: What are the main challenges of occupant behavior research going forward?*

Answer Although significant advancements have been achieved in occupant behavior research in the past ten years, substantial challenges remain, and additional studies of an interdisciplinary nature are needed.

Given the stochastic nature of human behavior, one of the key research challenges is the issue of generalization of behavioral findings across multidisciplinary research arenas. Without common languages, unified methods, metrics, benchmark, and platforms to compare results and test the scalability of findings and case studies, research outcomes are destined to remain of limited use or lacking actionable power.

Occupant behavior research can solve part of the substantial remaining challenges by exploiting the potential of interdisciplinary collaborations among engineers, building designers, and social scientists. Interdisciplinary open topics that should be addressed in future occupant behavior research are synthesized as follows:

- I. First, researchers should pay increased attention to occupants and their social contexts, and identify the specific social-psychological variables influencing the human-building interaction. These variables may vary due to target behaviors (curtailment vs. efficient behaviors), demographics (e.g., income level), and building type (commercial vs. residential). In addition, motivations for specific occupant behavior should be considered. For example, evidence shows that a pro-environmental or energy-saving behavior is guided by a combination of self-interest and pro-social rationale, meaning people might care about environmental issues because they care about themselves or their children [32]. Therefore, a more comprehensive set of social-psychological factors relating to occupant behavior should be considered.
- II. Second, occupants are not homogeneous and have diverse backgrounds and characteristics. Thus, it is crucial for researchers to consider a more representative sample in order to generalize the results at the population level. In this context, the research arena needs big data from integrated sources (utility energy consumption, community income maps, demographics of the resident population for ZIP codes, etc.) to cover the diversity of occupants (population, culture, location, time, gender, age, etc.) and the diversity of environments (e.g., air-conditioned/naturally-ventilated, residential/commercial) driving the choice of energy-related behaviors in buildings. However, the complexity of gathering human subject data is a challenging task due to privacy and data protection issues.
- III. Third, understanding and modeling group or collective behaviors in commercial buildings has received limited attention so far but remains of paramount importance, because most occupants live in shared spaces. Social science theories and practices can support the engineering community in gaining insights into the relationships between personal and group norms with regard to motivations, satisfaction, or productivity in a complex indoor environment. Additionally, understanding and modeling sequences of multiple adaptive behaviors and their implications on comfort and energy requirements remain difficult problems to be resolved. Significant improvements in the design and operational phases of commercial buildings can proffer by considering human-in-the-loop technologies, and model predictive control algorithms by integrating data-driven knowledge regarding human perception, habits, and behaviors. In this

context, advanced methodologies for integrating self-reporting and simulated behavioral data require further investigation and validation.

- IV. Fourth, intervention strategies such as financial incentives and information have added complexity and are multi-dimensional compared to the classical rational choice theory [10]. For example, single antecedent interventions are not very effective in certain cases [100,130]. Importantly, researchers should clarify and preclude confounding effects when using multiple interventions [15]. Therefore, identifying the underlying mechanism, barriers, or determinants of behaviors is important. In particular, there is a great need to investigate the intervening and mediating variables to explain why certain interventions or behavioral analyses have not been successful. Importantly, while considering latent variables, such as attitudes, perceptions, or motivations, the view of multi-dimensional concepts based on social science theories should be considered.

3. Summary

This paper has presented ten questions and answers highlighting the most important issues regarding energy-related occupant behavior research and applications in buildings. The proposed topics of the questions aim to provide useful insights into the state-of-the-art advances in research as well as into the evaluation of limitations of recent investigations related to monitoring, analyzing, modeling, simulating, and engaging occupant behavior. Answers were provided based on scientific works, critical findings gathered from the international scientific community, and credible results of market deployment. Questions and answers have been conceived in various approaches to satisfy the requirements of being mutually exclusive and collectively exhaustive.

Key takeaways are summarized as follows:

- Occupants interact proactively with their indoor environments in seeking a personal comfortable condition, driving the prediction gaps between the building's design and operation phases with regard to energy consumption and comfort settings. This prediction gap was greater for low-energy buildings with more passive design features.
- Integrating occupant behavior research during the design, operation, and retrofit stages is critical to achieve the goal of low or zero-net-energy buildings. Different stakeholders with diverse roles over the building life cycle are involved in the research arena, including but not limited to energy modelers, building occupants, architects and 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.
- Occupant behavior impacts on building energy performance have been largely oversimplified or ignored throughout the entire process of building operation. To study OB's impact on building energy performance based on actual data, rigorous objective and subjective measuring techniques must be applied.
- At the current stage, a lack of common agreement on validity and applicability of OB modeling and simulation approaches has emerged among the research community. Models of OB must encompass the representation of deterministic events, and move into a field where actions are associated with statistically relevant patterns or are described by stochastic laws. Nonetheless, simplified static and deterministic occupant schedules and profiles are typically considered as

direct inputs to the most widespread BPS programs. More recently, dedicated simulation modeling techniques, simulation tools, and case studies have been developed and integrated into BPS programs to capture the complexity and diversity of OBs, to calculate their impact on building performance, and to support behavioral programs or policy research that target interdisciplinary behavioral programs.

- Nevertheless, limited effective interdisciplinary solutions have emerged to leverage the energy saving potential of OB to reduce energy consumption. Quantitative research methods in social science, such as survey methodologies, represent a growing trend to provide insights into OB in buildings. In addition, a full understanding of both physical and social-psychological factors of OB can help researchers and policymakers understand the effectiveness of promoting energy efficiency strategies and contribute to interdisciplinary OB research. Credible outcomes of programs integrating interdisciplinary approaches for studying OB demonstrate potential behavioral energy savings ranging from 5 to 20%, depending on the type of behavioral intervention.
- Although significant advancements have been achieved in OB research in the past ten years, there are substantial challenges remaining, and further studies of an interdisciplinary nature need to be nurtured.

Although this paper cites many articles to support the framing of and answers to the ten questions, emerging behavior research contains additional, valuable information. Two international projects, Annex 66 [131] and Annex 53 [52], under the International Energy Agency's Energy in Buildings and Communities Program, provide rich resources for occupant behavior research, including a searchable literature database, journal articles, technical reports, modeling tools, and case studies. Another IEA project is Task 24 (Part I and II), focusing on the understanding of the complexities of human energy-using behavior, at the individual, societal, and whole-system perspective. Many global experts participate in IEA Task 24 (researchers, funders, policymakers, DSM implementers, and energy end users) in order to achieve potentially considerable end-user behavior change for DSM programs, estimated to be in the range of more than 30% [132]. The International Building Performance Simulation Association (IBPSA) holds regular global and local conferences on building performance simulation, which includes presentations of recent and on-going behavior modeling and simulation research. BECC, the Behavior, Energy and Climate Change Conference, has been a key annual conference focused on understanding individual and organizational behavior and decision-making models relating to energy usage, greenhouse gas emissions, climate change, and sustainability. During its biennial summer study, ACEEE dedicates a behavior panel to studying energy efficiency in buildings. There are a growing number of behavior seminars at ASHRAE conferences, and ASHRAE recently formed a multi-disciplinary task group to focus on behavior research. There are also many articles on behavior published in journals including *Building and Environment*, *Energy and Buildings*, *Building Performance Simulation*, *Building Simulation*, *Energy*, *Energy Policy*, *Energy Research and Social Science*, *Building Research and Information*, as well as *Nature Human Behavior* and *Nature Energy*.

As a famous scientist once said, "We have not succeeded in answering all our problems. The answers we have found only serve to raise a whole set of new questions. In some ways we feel we are as confused as ever, but we believe we are confused on a higher level and about more important things".

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Expertise of the authors

- Dr. Tianzhen Hong is a Staff Scientist and Principal Investigator of the Building Technology and Urban Systems Division of LBNL. He is an Operating Agent of the IEA EBC Annex 66, and the chair of ASHRAE Multidisciplinary Task Group on OB in buildings. He leads a research team at LBNL developing occupant behavior modeling tools and applying them to the building life cycle to improve energy efficiency. He co-authored more than 15 peer-reviewed journal articles on the subject.
- Dr. Da Yan is an Associate Professor in Tsinghua University, China. He is an Operating Agent of the IEA EBC Annex 66. His research focuses on the energy efficiency of buildings including human energy-related behavior modeling and simulation in buildings, DeST research and development, building energy code and standards, and national building energy and policy study.
- Dr. Simona D'Oca, Architect, Ph.D. in innovation technology for the built environment, focuses her interdisciplinary research on the effect of energy-related OB on building energy consumption and comfort, both through quantitative and qualitative methodological approaches.
- Dr. Chien-fei Chen, Ph.D. in Sociology, is a research professor and director of education & diversity at NSF-DOE Center for Ultra-wide-area Resilient Electrical Energy Transmission Networks (CURENT), the University of Tennessee. Her research focuses on social psychological analysis and interdisciplinary research OB (both at the individual, and group levels), occupant energy saving behaviors, demand response, and public acceptance of renewable energy technology.

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