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Review Article

A review of current research on occupant-centric control for improving comfort and energy efficiency

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Abstract

Occupant-centric control (OCC) is intelligent control of building systems based on the real comfort needs of occupants. This paper provides a comprehensive review of how real-world data on energy-related occupant behavior (OB) can be integrated and applied in OCC systems. The aim is to accurately portray the real occupant needs and improve energy efficiency without sacrificing occupant comfort. This paper first introduces two types of OB: detailed occupancy states and energy-interaction behaviors, including methods to monitor, establish, and predict these OB. Then, OCC is divided into real-time control and model-based predictive control, and each of these four scenarios is discussed. It extensively reviews OCC methods for different equipment in four cases, covering control strategies, control scales, comfort enhancement scenarios, and energy-saving potential for each category. It is summarized that despite extensive research on OB, there are still significant challenges in integrating this research into OCC. A major issue is the lack of a bridge connecting monitoring acquired information and controls. In addition, the article reviews the current state of OCC platform development. The future direction should be combined with advanced Internet of Things (IoT) technologies, WiFi, and other communication technologies to obtain information about people's behavior and real needs in order to create truly energy efficient and comfortable smart environments. The article also discusses how enhancing the real-time feedback capability of the OCC system can help improve the overall control system capability and the importance of testing through experimentation.

Keywords

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Architecture and Human Behavior

1 Introduction

Building energy consumption plays a significant role in global energy usage (Deng et al. 2022a; Song et al. 2024) and carbon emission (Yang et al. 2024a), with occupant behavior (OB) has a profound impact on building energy use (Hong et al. 2017). OB has been identified as one of the six key influencing factors by the International Energy Agency's Energy in Buildings and Communities Program Annex 53 (Hong 2012), emphasizing its critical role in building energy efficiency (Yoshino et al. 2017). Occupants' daily activities, their habits of using appliances, and their spatial preferences are directly related to the use of energy-using equipment (Ding et al. 2022a), which significantly affects building energy consumption, indoor thermal comfort, and indoor air quality (IAQ) (Liu et al. 2021). However, traditional building automation systems (BAS) usually perform poorly due to the fact that they do not consider the individual needs and preferences of building occupants. Therefore, with the increasing demand for indoor comfort (Malik et al. 2022), considerations of economic benefits (Ren et al. 2023), and the requirements of energy-saving (Yuan et al. 2023a) and emission-reduction policies (Yang et al. 2024a), researchers and engineers are increasingly focusing on the impact of OB on building energy consumption (Xu et al. 2023).

Over the past decade, research into OB has been vigorous (He et al. 2019; Park et al. 2019b), with considerable studies on OB modeling and model development (Yan et al. 2017; Chen et al. 2023; Deng et al. 2023). The study of OB can

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broadly be divided into two parts: one concerning the presence and distribution of occupants within a space and the other related to behavior patterns directly connected to energy use. For instance, Cuerda et al. (2019) have shown that using actual presence profiles instead of standard profiles could lead to differences in energy consumption by as much as 15%. Moreover, studies by He et al. (2021) have highlighted the significant potential for energy savings through improvements in OB. These findings further affirm the importance of in-depth research and utilization of OB models for designing efficient and energy-saving building control systems (Sun and Hong 2017; De Bakker et al. 2018; Navarro et al. 2022). Despite significant research (Hong et al. 2018) progress in both aspects and numerous reviews on these topics, the application of occupant behavior models in practical building energy control systems remains limited (Kanthila et al. 2021).

To better integrate and apply these research findings, the IEA-EBC Annex 79 introduced the concept of occupant-centric control (OCC) (O'Brien et al. 2020), where the indoor energy-related equipment (such as heating, ventilation, and air-conditioning (HVAC) systems, lighting systems, and other electrical equipment) were controlled based on the occupants' presence information (whether in the room, the number of occupants, or the occupants' location) and their preference for indoor comfort (Unzeta et al. 2021) to satisfy the occupant demands (thermal comfort, light, air quality) (Day et al. 2020; Dabirian et al. 2022). The introduction of the OCC in BAS represents a shift from a single focus on energy efficiency to a broader emphasis on occupant comfort balanced with energy efficiency (Yano and Sako 2024). This approach is driven by the understanding that buildings are ultimately for the occupants indoor. Thus, occupant satisfaction and interaction behavior within these spaces should guide the way the building operates (Das et al. 2020). This approach not only considered the presence of occupants within the space but also dived into their energy usage behavior patterns as well as preferences (Xie et al. 2020).

In this paper, we define and illustrate the workflow of OCC as depicted in Figure 1. The process begins with data collection through sensors and surveys, which are then meticulously cleaned and prepared for analysis. Utilizing this dataset, we develop OB models that accurately reflect real-world scenarios. Previous research has proved that OCC technology can save energy by up to 60%, simultaneously improving occupant comfort. Based on the review result, Zhang et al. (2018) estimated the energy saving potential of OB to be 10%–25% for residential buildings and 5% to 30% for commercial buildings. However, due to the extremely high randomness and uncertainty within the OB, it is still challenging to construct OB models that could be widely used in OCC (Gunay et al. 2013).

A concise summary and timeline of the development of OCC research are shown in Figure 2. Annex 53 (Yoshino et al. 2017), Annex 66 (Yan et al. 2017), and Annex 79

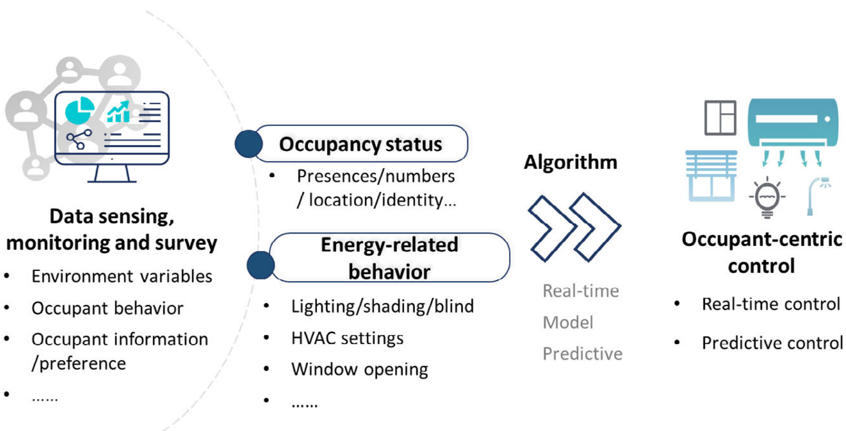

Fig. 1 Main workflows in OCC modeling

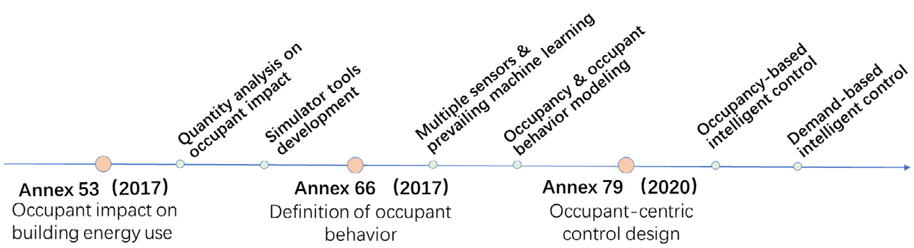

Fig. 2 Major research topics of OB and OCC

(O'Brien et al. 2020) were taken as milestones in this timeline. The major research topics about OB in the last two decades are summarized in Figure 2. Since Annex 53, many researchers have performed analyses to quantify the impacts of OB on the energy consumption of buildings and developed multiple simulation tools (Hong et al. 2018) to simulate the effects of OB (Mahecha Zambrano et al. 2021). Annex 66 further defined OB and many researchers began to depict the occupant profile indoors and conduct intelligent control on the advanced occupancy or OB profile (Hobson et al. 2021; Ouf et al. 2021).

One of the primary benefits of using real measurement data in OCC is the enhanced precision it brings to environmental control systems. Traditional BAS often operate on pre-set fixed schedules and unchanging environmental targets, which may not reflect the current needs or activities of occupants (He et al. 2022). In contrast, OCC systems equipped with advanced sensors and data analytics can detect slight changes in occupancy and environmental conditions, allowing for finer adjustments to temperature, lighting, and air quality. This not only improves comfort but also reduces energy waste by avoiding overheating, over-cooling, or over-lighting spaces that are not in use.

The implementation of OCC based on real measurement data offers several significant advantages that align with the evolving demands of modern building management (Tekler et al. 2022). This approach leverages accurate and timely data to create a responsive and adaptable building environment that prioritizes the comfort and needs of its occupants (Xie et al. 2020). Several review articles assessed crucial aspects of OB and OCC modeling research (Li et al. 2024; Soleimanijavid et al. 2024). Nagy et al. (2023) reviewed the challenges and opportunities of implementing occupant-centric building controls in real-world settings, highlighting the gap between theoretical potential and practical application and suggesting directions for making these systems more adaptable and universally applicable. Ding et al. (2022a) reviewed the occupancy data collection methods and modeling techniques. Yang et al. (2016) confirmed the diversity of OB in institutional buildings, and sensing and modeling such diversity is challenging. Dong et al. (2021) reviewed the challenges of urban-scale OB modeling, such as data sources, modeling approaches, and evaluation. Zhang et al. (2022) proposed a protocol for OCC sensing technologies in HVAC system controls with three sections, including occupancy sensor system background, test scenarios for sensor evaluation, and HVAC energy impact and assessment. Hong et al. (2017) defined ten questions in building OB research, giving researchers a specific guideline on OB's state-of-art advantages and challenges. Yang et al. (2022) reviewed the OCC development in recent years with the participation of Information & Communication Technology and Computer Science. Yang et al. (2016) listed the advantages and disadvantages of institutional buildings' occupancy number counting and modeling approaches. Park et al. (2019b) provided a critical analysis of the field implementations of OCC systems. It highlights the challenges and limitations faced when applying theoretical OCC models to real-world settings. Lorenz et al. (2023) discussed the development of a repository for OCC case studies, aimed at standardizing the methodology and terms for easier comparison among different studies. The focus is on addressing the performance gap in buildings—discrepancies between predicted and actual energy performance, often due to inadequate modeling of occupant behavior. Besides, the methodologies for modeling OB and prediction were reviewed and collected in Kanthila et al. (2021). Liu et al. (2023) comprehensively reviewed advanced control systems for smart and energy-efficient buildings, focusing on optimizing energy management, enhancing occupant comfort, and improving building safety and resilience through the integration of machine learning algorithms and smart technologies. This study aims to understand how information on occupant status and their energy interaction behaviors is utilized in control systems and what outcomes are achieved.

This research aims to provide a comprehensive review of the current state of OCC systems based on real measurement data, with a focus on two key aspects: firstly, the sensing and monitoring of occupant status and energy interaction behaviors, and secondly, evaluating how these monitoring data are applied in different model constructions to optimize building energy efficiency and occupant comfort. Additionally, this study also aims to explore how to more effectively collect and utilize data about human behavior, transforming these data into actionable information to improve control systems, thereby making OCC systems more intelligent and responsive to occupants' needs.

By reviewing existing research and case studies, this paper discusses how existing technologies handle and interpret occupant behavior data in practical applications, as well as the limitations and potential improvements of these methods in real-world scenarios. The study showcases through case studies how various data-driven models are implemented in real settings and their effectiveness in enhancing energy efficiency and occupant comfort. The paper also evaluates the applicability and scalability of these techniques and methods across different building types and environmental settings. By reviewing existing research and case studies, this article aims to highlight the effectiveness of these data and their models in practical applications and the challenges they face. In particular, the research focuses on how models can precisely predict and respond to occupants' needs, as well as the challenges of data accuracy and processing speed encountered in achieving this goal. We discuss the current shortcomings of OCC technologies in achieving truly occupant-centric smart building controls and how technological innovations can address these gaps. Ultimately, the paper proposes a series of recommendations aimed at advancing OCC systems to not only improve energy efficiency but also enhance the quality of life for occupants, promoting a more sustainable and intelligent building environment.

2 Occupant-centric control based on occupancy status

For OCC, constructing an OB model that closely mirrors real-life scenarios is crucial for developing optimized control logic that effectively enhances system performance. We initially conducted a preliminary survey on the modeling of two types of models, followed by a focused review of various controls based on these models.

2.1 Occupancy status sensing and monitoring

The occupancy models can be divided into different resolutions depending on different spatial and temporal resolutions (Wu et al. 2023a). For occupancy resolution, space occupancy (presence/absence) is important information to automatically turn on/off the lights or HVAC system (Osman and Ouf 2021; Melgaard et al. 2024). The information on occupant count in a space or a building can be used to determine the demand for ventilation for outdoor air flow rates. More detailed occupancy information, such as occupant location (Navarro et al. 2022), occupant tracking, and occupant identification, can be used for specific applications, which are very limited now (Naylor et al. 2018).

Intelligent control systems that adjust based on the occupancy of a room can effectively reduce energy waste (Wang et al. 2017a). Occupant models can be categorized based on different spatial and temporal resolutions, providing various levels of information accuracy (Fialho Pereira 2017; Wu et al. 2023b). At the most basic level of occupant resolution, the system can automatically turn lights and HVAC systems on or off depending on whether the space is occupied (present/absent) (Ding et al. 2016; Xie et al. 2020). Additionally, the system can use occupant count information within a room or building to adjust demand-controlled ventilation, determining the appropriate outdoor airflow rates (Park et al. 2019b). Beyond this, more detailed occupant information, such as the specific location of occupants, tracking movements, and identifying individuals, can also be used for specialized applications. However, such uses are currently quite limited (Jia et al. 2017; Rafsanjani et al. 2018).

We provide a review of the control of different devices based on occupancy status and analyze the control strategies, energy-saving potential, and feasibility of different devices in various scenarios.

2.2 OCC based on occupancy model

2.2.1 Real-time control based on occupancy status

In this study, we begin by discussing the application of direct occupancy-based OCC in different equipment, such as lighting, HVAC, shading and blinds, including control logic, energy efficiency, and more.

OCC lighting control model that utilizes occupancy sensing to regulate lighting systems (Li et al. 2020). It is designed to optimize energy efficiency by adjusting lighting levels based on the presence or absence of occupants in a space. Yuan et al. (2023b) observed that in public offices, lights are turned off only 70% of the time after occupants leave the room. If sensors could be employed to detect the absence of people and turn off the lights accordingly, the potential for energy savings would be significant. The OCC model offers several advantages in lighting control (Haq et al. 2014; Wagiman et al. 2020). Firstly, it reduces energy consumption by ensuring that lights are only activated when needed. This not only lowers electricity costs but also contributes to environmental sustainability (Unzeta et al. 2021). Secondly, it enhances occupant comfort and convenience by automatically adjusting lighting levels based on occupancy patterns (Xu et al. 2017). Lastly, it can be integrated with other building automation systems, such as HVAC, to achieve overall energy efficiency within a building.

In the literature we surveyed, it is quite common to control lighting based on the presence of occupants in the room (Jin et al. 2021). This method combines the location of individuals and adjusts indoor lighting brightness automatically according to the intensity of natural light in order to maintain a constant level of indoor illumination. Real-time control uses this information to immediately adjust building operations such as lighting, shading, and HVAC to reduce energy consumption. Implementing OCC on curtains is aimed at optimizing energy efficiency, lighting conditions, and occupant comfort within buildings (Day et al. 2019). On the one hand, automatic or semi-automatic adjustments of curtains can modulate light intensity based on indoor and outdoor lighting conditions, preventing harsh direct sunlight from causing glare and enhancing the indoor light environment's comfort (Nicoletti et al. 2020). On the other hand, curtains serve as a tool for regulating the indoor thermal environment (Bavaresco and Ghisi 2020). Timely adjustment of curtain coverage can help control indoor temperatures, reduce the workload of air conditioning or heating systems, and achieve energy savings while maintaining indoor thermal comfort.

Table 1 presents a detailed overview of selected studies that investigate the application of OCC for different systems based on occupancy without involving model construction. The table is structured to provide a comprehensive snapshot of each study, facilitating a clear understanding of the various approaches and outcomes associated with OCC implementations. The columns are organized as follows: "Controlled object" describes the specific building system or element being controlled, such as lighting or HVAC; "Control implemented" specifies whether the study applied

Table 1 Overview of studies focused on OCC based on the occupancy status

Reference	Controlled object	Control implemented	Basis of control	Control strategy	Control scale	Benefit
Vanage et al. 2023	Office building shading and lighting	Experiment	Multiple environmental variables (solar radiation, occupancy)	Integrated control strategies combining multiple sensors	Building-level	Reduction in total load by up to 12%, improved visual comfort without glare
Aussat et al. 2022	Office lighting	Experiment	Daylight and occupancy	Self-calibrating, adaptive control algorithm	Room-level	40% reduction in energy consumption compared to conventional lighting systems
Chong et al. 2024	Classroom lighting and utilities	Experiment	Human movement (entry/exit)	Automatic switch on/off based on dual PIR sensor counts	Room-level	Automation of electrical devices based on occupancy
Mahmud et al. 2022	Cooling and lighting loads	Experiment	Occupancy (count and location)	Zone-wise real-time control with neural networks	Building-level	Energy savings of 12.7%–36.15% for cooling, 35%–87.5% for lighting loads
Sithravel et al. 2024	Home lighting	Experiment	Occupancy and daylight availability	Automated control systems with sensors for occupancy and daylight	Home-specific	It has significantly reduced energy consumption by optimizing lighting based on real-time presence and daylight.
Tan et al. 2018	Office lighting	Simulation	User input via smartphone	Human-in-the-loop control system	Room-level	Personalized lighting control based on real-time user feedback
De Bakker et al. 2018	Office lighting	Simulation	Occupancy patterns	Occupancy-based lighting control strategies	Office-level	Energy savings in lighting
Zou et al. 2018	Lighting systems	Experiment	Occupant presence detected via WiFi	WiFi-based occupancy detection for lighting control	Building-wide	Reduced energy consumption and improved lighting system efficiency through real-time occupancy detection
Montaser Koohsari and Heidari 2022	Venetian blinds	Simulation	Daylight metrics, energy analysis	Different slat angle adjustments for visual comfort and energy	Room-specific	Improved visual satisfaction, energy efficiency
Motamed et al. 2020	Venetian blinds, electric lighting	Experiment	Glare and artificial lighting control	Integrated control system for blinds and lighting	Building-wide	Reduced glare, enhanced lighting efficiency
Kunwar et al. 2020	Venetian blinds, lighting	Experiment	Daylighting and energy savings	Dynamic control of blinds and artificial lighting	Room-specific	Demonstrated significant energy savings and improved daylighting
Ye et al. 2021	HVAC systems	Experiment	Occupant comfort and presence	Occupant-centric adaptive control	Building-wide	Reduced energy use and enhanced comfort without compromising educational activities
Pang et al. 2021	HVAC systems in residential buildings	Simulation	Energy consumption patterns	Smart thermostat control based on user presence	Nationwide homes	Significant energy savings across various climate zones in the U.S.
Zhang et al. 2022	Occupancy sensing technologies	Experiment	Occupancy detection efficiency	Development and testing of a new protocol for evaluating occupancy sensors	Building level	Improved accuracy and reliability of occupancy sensors

an actual control strategy through practical experiments or it was purely a theoretical analysis without experimental validation; “Basis of control” details the primary input or data source driving the control system, such as sensor data or manual inputs; “Control strategy” outlines the techniques and algorithms used for controlling the environment, including adaptive algorithms or rule-based systems; “Control scale” describes the scope of the control implementation, whether it is a single room, a series of spaces, or an entire building; and “Benefit” summarizes the main advantages reported in the study, such as energy savings, enhanced comfort, or reduced operational costs.

The research spans various settings, including offices (Vanage et al. 2023), classrooms (Chong et al. 2024), and residuals, with control strategies ranging from adaptive algorithms and neural networks (Cheng et al. 2020) to WiFi-based detection systems (Zou et al. 2018). According to our review, these studies demonstrate significant benefits such as energy savings of up to 40%, enhanced user comfort, and reduced operational loads by adjusting lighting based on real-time occupancy data and environmental variables like daylight and solar radiation. Aussat et al. (2022) demonstrated a significant 40% reduction in energy consumption compared to conventional lighting systems using self-calibrating, adaptive control algorithms. Vanage et al. (2023) achieved a reduction in total energy load by up to 12%, improving visual comfort without glare through integrated control strategies combining multiple sensors.

2.2.2 OCC based on the occupancy status model or prediction

We have summarized the OCC based on modeling or predicting occupancy situations. Generally, due to the high randomness of personnel presence in rooms, cases of prediction based on occupancy are relatively rare. However, constructing data-driven or statistical models based on occupancy and then establishing OCC based on these models has demonstrated significant potential for energy saving (Nikdel et al. 2018).

Table 2 provides an overview of studies focused on OCC based on occupancy status, involving the use of advanced

Table 2 Overview of studies focused on OCC based on the occupancy status

Reference	Controlled object	Control implemented	Basis of control	Model input	Model output	Control strategy	Control scale	Benefit
Cheng and Lee 2019	HVAC systems	Experiment	Similarity index and global similarity calculations	Operating environment parameters, predictive parameters, fault diagnosis parameters of the HVAC system	Control strategies of the HVAC system, energy savings and load prediction results	Optimized setting and predictive controls using AI tools (ANN + fuzzy logic, SVM, ARX)	Building scale	Improved control performance by predicting future errors and setting optimal points
Nikdel et al. 2018	HVAC systems in small office buildings	Simulation	Building owner and societal perspectives (energy cost, emissions)	Building parameters, electricity supply, utility costs, climate zone information, and the type of HVAC system	HVAC energy consumption, fossil fuel usage and greenhouse gas emissions	Occupancy-based control strategies compared to constant setpoint and programmable thermostats	National scale (U.S.)	22%–50% reduction in electricity use, significant national energy and cost savings
Liu et al. 2024	Multi-zone office buildings HVAC	Simulation	Occupant presence, clothing, activity conditions	Environmental parameters in different zones of the building, dynamic models of occupant behavior and competition and cooperation relationships between different zones	Scheduling of cooling and heating set points	Multi-agent deep reinforcement learning (MADRL) for dynamic control of heating and cooling setpoints	Multi-zone scale	4.34% and 51.09% electricity cost saving compared to single-agent and rule-based controls
Jin et al. 2021	Office lighting	Experiment	Historical occupancy	Historical occupancy status data	Prediction of occupancy patterns and the control of the lighting ON/OFF	Model predictive control using neural networks	Room-level	Highly accurate lighting control with reduced false-offs

Table 2 Overview of studies focused on OCC based on the occupancy status (Continued)

Reference	Controlled object	Control implemented	Basis of control	Model input	Model output	Control strategy	Control scale	Benefit
Park et al. 2019a	Lighting	Experiment	Occupant presence, daylight detection, light switches	Occupant presence sensors, daylight sensors, switch usage	Adjusted lighting levels	Reinforcement learning based adaptive control	Multiple offices	Optimized visual comfort, reduced energy consumption
Sharmin et al. 2017	Multi-family residential space heating	Occupant pattern prediction model	Predictive modeling based on occupant behavior patterns	Sensor data on occupancy and environmental conditions	Heating adjustments based on model predictions	Model predictive control	Building-level implementation in multi-family residential facilities	Enhanced energy efficiency and occupant comfort, reduced operational costs, and sustainable energy management practices

control strategies and AI tools such as ANN, fuzzy logic, SVM, and ARX to optimize the performance of lighting systems (Cheng and Lee 2019). The "Model input" column details the type of data or variables considered in the modeling process, such as occupancy patterns or environmental conditions. Meanwhile, "Model output" describes the outputs generated by the models, such as energy consumption predictions or comfort optimization strategies. These strategies enhance energy efficiency and user comfort across various scales—from room to building-wide applications—by dynamically adjusting settings to accommodate occupancy. The key benefits include improved energy efficiency, reduced costs, and enhanced occupant comfort.

3 Occupant-centric control based on occupant behavior

3.1 Energy interaction occupant-behavior sensing and monitoring

This paper primarily focuses on how interaction behaviors with building systems significantly influence energy consumption. These interactions include window opening behavior (Andersen et al. 2013), lighting behavior (Zhu et al. 2017), plug load behavior, and HVAC behavior (Kong et al. 2022; Lu et al. 2023). Specifically, for window behavior, most studies track the frequency of window openings (Ren et al. 2021). Regarding HVAC behavior, the literature often monitors aspects such as energy consumption (Lee et al. 2019), duration of operation (Du et al. 2018), and temperature setting preferences (Yang et al. 2024b). Studies of lighting behavior typically observe the duration of light usage, energy consumption (Xiong et al. 2019), and preferences. Preferences for shading and blinds are also frequently monitored (Eltaweel and Su 2017).

With the advancement of IoT technology, interconnectivity and data sharing among devices have become more convenient (Raza et al. 2020), offering greater possibilities and ease for device control based on the OB within a space (Rafsanjani et al. 2020; Dai et al. 2023). Nweye and Nagy (2022) proposed a smart meter-driven framework to adjust HVAC schedules, which showed a considerable energy saving potential within 1%–2% of the BEPS predictions. The occupants can interact with building systems, such as opening windows, opening doors, turning on the HVAC system, and so on (Abdeen et al. 2020). The interaction behavior with the buildings remarkably influences energy consumption. Window behavior (Andersen et al. 2013), lighting behavior (Zhu et al. 2017), plug load behavior, and HVAC behavior (Kong et al. 2022). This study summarizes controls based on different human behaviors and explores the benefits generated by each type of control.

3.2 Real-time control based on occupant behavior

Based on the reviews, types of lighting control based on the OB model generally include allowing users to adjust lighting settings according to their needs and preferences (Nagy et al. 2016; Ryu and Moon 2016; Lo Verso et al. 2021), typically achieved through smartphone apps, touchscreens, or voice controls. Additionally, lighting devices throughout a building or campus are managed via a centralized control system, which adjusts the on/off status and brightness of the lights and is often integrated with building automation systems. OCC of the HVAC system is undoubtedly the most discussed. Many studies have focused on building OCC strategies with HVAC and achieved great energy-saving effects (Wang et al. 2023a). Stopps et al. (2021) reviewed the HVAC controls in simulation and experimental research of residential buildings and gave insight into where research needs to be focused and Day et al. (2020) studied the interaction with windows, lighting, shadings, and thermostats.

Raza et al. (2020) developed a determination model to control HVAC systems with low-cost, non-intrusive technologies. Similarly, Rafsanjani et al. (2020) exhibited an IoT-based smartphone energy assistant framework to track occupants' energy use behavior.

Recently, HVAC systems have gradually considered occupant information, demand, and preference (Jia et al. 2017). According to different control parameters, OCC for HVAC systems can be divided into four different strategies (Hobson et al. 2021): (1) adapt start/stop schedule (Gunay et al. 2017b), (2) adapt building ventilation schedule, (3) adapt zone temperature setback schedules, (4) adapt zone heating/cooling setpoint (Auffenberg et al. 2018). Table 3 is organized similarly to Table 1, offering an overview of additional studies that focus on OB systems based on energy-related OB. Like Table 1, it categorizes key aspects of each study to provide a clear and structured comparison across different research.

Table 3 presents a collection of studies focused on OCC systems based on energy-interaction OB sensing. Key strategies include the use of real-time and predictive controls based on detailed occupant feedback, environmental variables, and advanced modeling techniques. Benefits highlighted across these studies include enhanced visual comfort, energy savings, improved indoor environmental quality, and optimized system performance tailored to occupant preferences and behaviors.

3.3 OCC based on occupant behavior model or prediction

Generally, the OCC aims to build an energy-efficient and comfortable proposal environment. OB models could be adopted in OCC to predict occupants' preferences and requirements (Stopps et al. 2021). The OCC model mainly

Table 3 Overview of studies focused on OCC based on the OB sensing

Reference	Controlled object	Control implemented	Basis of control	Control strategy	Control scale	Benefit
Xiong et al. 2019	Daylighting, venetian blinds	Experiment	Occupant visual satisfaction	Personalized control of blinds based on user feedback	Individual room	Optimized visual comfort and reduced energy use
Nagy et al. 2016	Lighting systems in office environments	Experiment	Balancing occupant comfort, acceptance, and energy efficiency	Occupant-centered lighting control involving user feedback to tailor lighting conditions	Office-level	Enhanced user satisfaction and energy efficiency through personalized lighting controls
Lo Verso et al. 2021	Daylighting in classrooms	Experiment	Daylight availability and occupant comfort	Daylight modeling and user feedback to optimize lighting	Room-specific (classrooms)	Improved daylight utilization and energy savings, enhanced indoor environmental quality
Shum and Zhong 2023	Automated shading systems	Experiment	Energy performance in cold climates	Optimization strategies for automated shading to enhance energy performance	Specific to cold climate zones	Enhanced energy efficiency and occupant comfort through strategically optimized shading systems
Bavaresco and Ghisi 2020	Shades	Experiment	OB and shade adjustment diversity	Aggregated vs. disaggregated behavior models	Building-wide	Identified differences in energy performance predictions between models, highlighting the impact of OB diversity on energy uncertainty
Yun et al. 2020	Internal blinds	Experiment	User interactions and comfort preferences	Development of control patterns through user-centric simulations	Room-specific	Enabled more accurate simulations of blind usage, improving design processes for user comfort and energy efficiency
Vanage et al. 2023	Shading and lighting systems	Simulation	Visual comfort and energy use	Comparison of different control strategies for shading and lighting	Small office building	Improved visual comfort and reduced energy usage through optimized control strategies
Espejel-Blanco et al. 2022	HVAC settings in buildings	Simulation	Predicted mean vote (PMV) Index	Rule-based control using PMV for energy-efficient settings	Building-wide	Improvement in energy efficiency and occupant comfort
Wang et al. 2023b	Indoor thermal comfort, air quality, and energy management	Simulation	Real-time OB	Occupant-centric heating and natural ventilation control	Room-specific (case study room)	Enhanced thermal comfort and energy savings, improved indoor air quality management

Table 3 Overview of studies focused on OCC based on the OB sensing (Continued)

Reference	Controlled object	Control implemented	Basis of control	Control strategy	Control scale	Benefit
Atam 2017	HVAC systems	Simulation	Software limitations in control design	Analysis of current software tools	Not applicable	Identification of gaps in current software tools for energy-efficient control
Hou et al. 2022	HVAC systems	Experiment	Sensor data and model accuracy	Real-time optimal control algorithms	Building-wide	Improved control accuracy and efficiency by optimizing sensor placement and model fidelity
Wang et al. 2021	Building load scheduling	Experiment	Occupant thermal preferences	Stochastic preference-aware load scheduling	Community level	Enhanced resilience and efficiency in energy management with occupant-centered decision-making
Amasyali and El-Gohary 2021	HVAC and lighting systems	Experiment	Real-time OB	Data-driven behavior optimization	Building sections	Optimization led to substantial energy savings and comfort improvements based on actual behavior.
Lei et al. 2022	HVAC systems	Experiment	Occupant feedback on comfort	Deep reinforcement learning for HVAC control	Building-wide	Improved energy efficiency and occupant comfort through adaptive, personalized HVAC control systems
Tien et al. 2022	HVAC and window operations	Experiment	Occupant activities	Integrated deep learning-based real-time monitoring	Individual rooms	Reduced energy demand by aligning HVAC operation with real-time occupancy and window status
Zhu et al. 2021	HVAC and lighting systems	Experiment	OB and preferences	Simulation of occupant-centric controls to optimize energy and comfort	Single office	Demonstrated potential benefits of OCCs for energy and comfort
Wang et al. 2022	Building HVAC systems	Simulation	Thermal comfort vs. energy consumption trade-offs	Extremum seeking control for real-time HVAC optimization	Office environment	Achieved optimal temperature settings, saved up to 22% of energy

focuses on lighting and HVAC systems. Insight into specific interaction behavior, HVAC systems and lighting got attention because they are the most energy-intensive equipment.

The potential for lighting energy-saving is often underestimated (Svetozarevic et al. 2019). Nowadays, OCC has many approaches, ranging from simple presences-based switching of lighting systems to full model predictive control (Naylor et al. 2018). Experiments (Xu et al. 2017) and simulations (Zhu et al. 2017) show great energy saving potential. This summary, shown in Table 4, provides an overview of various studies that utilize advanced control strategies for lighting and shading systems to enhance both energy efficiency and occupant comfort across different settings, from individual rooms to entire buildings. Key findings indicate that such personalized control systems can significantly reduce energy consumption—often by 20%–30%—while improving daylight utilization and reducing reliance on artificial lighting by up to 40%. The control strategies employed range from adaptive algorithms that learn from user behavior to advanced simulations and experiments that incorporate real-time occupant data and environmental variables. The benefits highlighted include improved energy efficiency, enhanced occupant comfort, and the optimization of system operations without compromising user comfort. These studies demonstrate significant gains in building performance and user satisfaction across various environments and control scales. Visual comfort is a significant aspect of occupant indoor comfort; blind/shade control is an effective solution for energy-saving and preserving visual comfort (Yao 2020).

Nevertheless, most are still controlled according to historical behavior, ignoring the room's dynamic thermal comfort characteristics. The steady-state air conditioning environment not only ignores the thermal adaptability of the occupancy but also strictly controls the ambient temperature, resulting in excessive cooling and heating load indoors and a lot of energy waste.

Key findings across the articles suggest that adaptive

Table 4 Overview of studies focused on OCC based on the OB model

Reference	Controlled object	Control implemented	Basis of control	Model input	Model output	Control strategy	Control scale	Benefit
Gunay et al. 2017a	Lighting and blinds in private offices	Simulation	OB related to light switch-on and blind closing	Occupancy data, solar irradiance, ceiling illuminance, blind position, user behavior data	Lighting control commands, blind control commands, adaptive setpoints, user interface feedback	Adaptive control algorithm that learns from occupants' light and blinds used to set optimal levels	Building-level	Reduced lighting loads without compromising occupant comfort, adaptive to visual discomfort
Ouf et al. 2021	Office lighting and HVAC settings	Simulation	Simulated occupant preferences	Occupant presence data, indoor illuminance levels, indoor temperature, occupant feedback from control interfaces	Adjusted lighting levels, adjusted heating setpoints, adjusted cooling setpoints	Simulation-based testing of various OCC strategies	Single office	Improved strategy testing, the potential for energy savings
Nicoletti et al. 2020	Venetian blinds	Simulation	User-centric design	Indoor temperature, solar irradiance, presence detection, global irradiance	Slat angle adjustments, solar radiation transmission control, visual comfort adjustment, energy consumption reduction	Simulation-based design for optimal blind control	Individual window settings	Enabled simulation-based user-centric design
Ryu and Moon 2016	Daylighting in university classrooms	Experiment	Occupant comfort and energy efficiency needs	Indoor CO_2 concentration, electricity consumption of lighting system, electricity consumption of appliances, sum of lighting and appliances power, time of the day	Lighting control signals, current state occupancy detection, future state occupancy prediction	Use of questionnaires and simulations to optimize daylight use and enhance IEQ	Room-specific	Improved daylight utilization, enhanced occupant comfort, and energy savings
Yano and Sako 2024	Air-conditioners in multi-occupancy office rooms	Experiment	Occupant preferred settings	Occupant preferences, indoor temperature, HVAC operation data, setpoint changes, weather data, operating time	Setpoint adjustments, energy consumption data, comfort metrics, applied setpoint, feedback on energy-saving performance	Feedback control adjusting setpoints based on data from previous settings, applied multiple times per day.	Room-scale	Reduced excessive use of air-conditioners energy consumption mitigation, although the full potential is not clear due to uncontrollable factors
Ding et al. 2022b	Multi-zone residential HVAC	Simulation	Occupant comfort preferences	Occupancy data, indoor temperature, indoor humidity, outdoor temperature, outdoor humidity	HVAC control commands, setpoint adjustments, energy consumption data, thermal comfort metrics	Reinforcement learning for thermal comfort control	Multi-zone residential	Reduced energy usage while maintaining comfort
Ono et al. 2022	Thermal comfort and HVAC controls	Simulation	Occupancy resolutions of comfort models	Indoor temperature, outdoor temperature, occupancy data, personal thermal preferences, historical energy consumption data	HVAC control adjustments, energy consumption metrics, thermal comfort levels, personalized setpoints	Mismatch analysis between comfort and control resolutions	Building-wide	Potential loss of 6%–12% in energy savings and comfort due to resolution mismatches
Wang et al. 2017b	HVAC systems	Simulation	Energy demand and user comfort	Occupancy data, indoor temperature, indoor humidity, outdoor temperature, CO_2 levels, HVAC system status	HVAC control adjustments, energy consumption data, indoor air quality metrics, thermal comfort levels	Flexible management strategies using advanced algorithms	Building-wide	Enhanced energy efficiency and user comfort

Table 4 Overview of studies focused on OCC based on the OB model (Continued)

Reference	Controlled object	Control implemented	Basis of control	Model input	Model output	Control strategy	Control scale	Benefit
Wei et al. 2022	HVAC system	Experiment	Internal heat gains	Occupancy data, electrical equipment usage, indoor temperature, indoor humidity, CO_2 levels	HVAC control adjustments, energy consumption data, thermal comfort levels, indoor air quality metrics, equipment usage profiles	Deep learning-based predictive control	Building-wide	Improved HVAC performance and energy reduction
Auffenberg et al. 2018	HVAC settings	Experiment	Thermal comfort preferences	User comfort feedback, indoor temperature, indoor humidity, outdoor temperature, energy price data	HVAC control adjustments, optimal setpoint temperature, user comfort levels, energy consumption data	Personalized thermal comfort adjustment	Individual rooms	Improved occupant comfort with energy efficiency through better HVAC management
Wei et al. 2020	HVAC systems	Experiment	Equipment heat gains	Equipment usage data, occupancy data, indoor temperature, indoor humidity, outdoor temperature	HVAC control adjustments, energy consumption data, thermal comfort levels, real-time equipment usage profile	Vision-based predictive analysis	Building-wide	Improved HVAC energy management through accurate heat gain prediction
Peng et al. 2019	HVAC settings	Simulation	Occupant thermal preferences	Historical building management system data, thermal comfort datasets, occupancy profiles	Thermal preference probabilities, comfort metrics, indoor temperature control	Neural network-based temperature preference learning and control system	Building level	Optimized thermal comfort and energy savings
Quintana et al. 2022	Building control systems	Experiment	Occupant thermal preferences and behavior	Occupant thermal comfort vote, temperature sensors	Adjusted thermostat setpoint	Agent-based modeling in an OpenAI gym environment for HVAC control	Building-wide	Standardized occupant modeling, potential for real-world application
Elehwany et al. 2024	Indoor climate control via smart thermostats	Simulation	Reinforcement learning utilizing unsolicited thermostat overrides	Synthetic occupant behavior models from EnergyPlus	Preferences for thermostat setpoints	Off-policy reinforcement learning RL algorithm that adapts temperature setpoints based on learned occupant behavior	Single-zone simulation in EnergyPlus environment	Optimized energy use and enhanced occupant comfort by adapting climate controls to learned occupant preferences
Park and Nagy 2020	Thermostat for HVAC	Experiment	Occupant's thermal vote, indoor air temperature	Occupant thermal comfort vote, temperature sensors	Adjusted thermostat setpoint	Reinforcement learning-based personalized setpoints	Single office	Reduced energy use improved comfort through fewer interactions

control strategies based on real-time occupancy data can significantly reduce energy consumption while maintaining or even enhancing occupant comfort. The studies demonstrate the potential for energy savings of up to 27% in scenarios where controls are optimized at an individual level, gradually tapering off as the control scale broadens to encompass larger zones or whole buildings. Moreover, the integration of technological solutions such as machine learning for temperature preference learning and occupancy sensors enhances the granularity and effectiveness of these controls. This not only reduces wasteful energy use but also caters to the diverse and dynamic nature of human occupancy and behavior in buildings.

Overall, the papers collectively advocate for a more nuanced and technologically integrated approach to building management systems, one that aligns energy conservation goals with the real-world needs and comforts of building occupants. This shift not only promises substantial operational efficiencies but also supports broader sustainability goals within the built environment sector.

4 Current tools for occupant-centric control applications

Many studies have implemented the OCC system model (Xie et al. 2020). While good results have been obtained, there is relatively little practical model-free work that demonstrates its use in guiding the operation and control of real systems. Applying these types of models directly to the real world is also a serious challenge because models are actually learning tools that synthesize the complexity and uncertainty that characterize realistic systems (Salimi and Hammad 2020). While some studies have employed simulation approaches, their actual application in the physical world remains scarce (Wang et al. 2019; Mohottige et al. 2021). Real systems are influenced by various external factors, including environmental conditions, sensor noise, system failures, and so on (Mikkilineni et al. 2019; Dabirian et al. 2022). Deng et al. (2022b) proposed a framework designed to optimize smart building management through personalized environmental adjustments, integrating real-time data and predictive analytics to precisely regulate indoor temperature and lighting via personalized digital IDs. These factors can lead to disparities between the model's predictions and the actual situation.

Additionally, applying models to real systems also entails addressing technical and engineering challenges (Azimi and O'Brien 2022). For instance, the computational requirements of the models can be high, necessitating powerful computing resources for real-time decision-making and control. Moreover, the accuracy and stability of the models are crucial issues that require thorough validation and testing (Day et al. 2020).

Nevertheless, with the continuous advancement of technology and deeper research, we can expect to see more cases of applying these models to the operation and control of real systems in the future (Yang et al. 2016; Abdeen et al. 2020; Xu et al. 2023). This will require interdisciplinary collaboration, combining knowledge from fields such as machine learning, control theory, sensor technology, etc., to address the challenges of the real world and achieve reliable applications.

5 Discussion

OCC has gained popularity as a research topic, with scholars paying more attention to the indoor environment. When building their models, about 63% of the OCC studies took into account occupant preferences, environmental factors, and historical energy use habits. The energy-saving potential for OCC based on the occupancy movement model ranges between 7% and 44% for the HVAC system and 16%–57% for the lighting system. Correspondingly, the energy-saving potential ranges between 1% and 57% for the HVAC system, 13%–83% for the lighting system, and 15% to 87% for the lighting and shading coupling system. We find that papers on Occupant-Interaction Behavior mainly focus on window-opening behavior and lighting behavior. Similarly, the HVAC behavior and blinding/shading behavior, which account for 39%, 24%, 16%, and 3%, respectively. However, more than 55% of the OCC-related articles collected in this work were focused on HVAC control, leaving about 32% on lighting control. Although the window-opening model has gained wide attention in recent years, it is rarely applied in OCC. The number of publications in this field has increased exponentially in recent years. The main discussions are as follows:

5.1 WiFi and other technologies in occupancy detection

OCC uses sensors and data-gathering technologies to comprehend how people are distributed and what they are doing within buildings. Ensuring the privacy of occupants is crucial throughout this procedure. By creating occupancy models while adhering closely to privacy standards, it is feasible to forecast the locations, numbers, and comfort requirements of inhabitants and modify building systems accordingly. These models use encryption techniques to protect the data and are based on machine learning algorithms, statistical data, or establishing usage patterns.

By incorporating IoT technology, we can obtain more detailed data to monitor and analyze real-time behaviors and environmental interactions of occupants. For example, IoT can track movements within a room, window-opening habits, and preferences for lighting and temperature. Although automation of actions like window opening and shading is still limited, the development of platforms capable of collecting and processing such behavioral data can not only optimize energy use but also enhance the overall comfort and efficiency of living and working environments. The advancement of such systems will greatly promote the practicality and energy-saving potential of OCC models.

Developing comprehensive strategies for managing the indoor thermal environment smartly involves integrating IoT and AI technologies to create a fully responsive system. These strategies are designed to balance energy consumption with occupant comfort, adapting in real-time to changes in external weather conditions and internal occupancy levels. The goal is to maintain optimal thermal conditions while minimizing energy use and reducing operational costs. In this section, we first discuss the application of IoT technology in accurately detecting the presence of occupants. By deploying a variety of sensors, such as motion sensors, environmental sensors, and thermal imaging cameras, we can obtain more detailed data on occupant behavior.

The use of these technologies is crucial for achieving highly personalized adjustments to living environments and optimizing energy use. Particularly, using WiFi signals, electronic fencing, and UWB technology allows for non-intrusive detection of occupant presence. These data require precise experimental calibration before they can be converted into effective control signals.

5.2 Integration of demand response strategies

To consider economic factors and new energy integration, demand response (DR) strategies should be incorporated into future OCC system integrations. The direct impact of DR on energy usage underscores how intelligent scheduling and automated responses can minimize energy waste and optimize supply. Furthermore, the study explores how technologies like energy storage, pre-cooling, and pre-heating might work with the grid to react to peak-valley pricing and grid signals, enabling automated control depending on occupant presence. To elaborate, the combination of DR and OCC systems allows for a more flexible and adaptable way to control building energy use.

5.3 Experimental validation of OCC strategies

Previous sections discussed the necessity of experimental validation before implementing OCC strategies. Given practical and resource limitations, scaled model platforms for initial testing are recommended. This method not only validates the tactics' efficacy but also permits modifications and enhancements prior to extensive deployment. We also go over how to achieve indoor temperature management by creating simulated loads with test rigs and optimizing them with AI approaches. Moreover, the utilization of test rigs and scaled models offers a controlled setting for simulating and analyzing various scenarios. Without the expenses and complications of extensive testing, this controlled environment aids in locating possible problems and fine-tuning the system settings. Additionally, the integration of AI techniques enhances the precision and adaptability of the system, enabling it to learn from the simulated data and improve its responses to real-world conditions. This predictive capability is crucial for ensuring that OCC systems are not only effective but also efficient and responsive to environmental change.

5.4 Development of an integrated platform

Against the backdrop of relatively mature IoT and OB research, it becomes particularly important to build an intelligent platform that can integrate control, data collection, and real-time feedback. Currently, there is a lack of solutions that effectively integrate IoT technology with control systems using complex artificial intelligence algorithms. Therefore, there is an urgent need to develop a new smart platform that not only integrates sensor technology and data processing capabilities but also optimizes control decisions through artificial intelligence and machine learning models, rapidly adjusting environmental settings based on real-time occupant demands.

5.5 The importance of occupant feedback

Lastly, we stress how important user input is to the ongoing optimization of OCC systems. We can enhance the system's overall efficacy and efficiency while better meeting occupant needs by designing it to accommodate real-time data feedback and dynamic modifications. Furthermore, it is imperative to guarantee that the incorporation of real-time feedback systems upholds and safeguards the privacy of residents. To manage and secure data, strict privacy protocols must be put in place. This will preserve confidence and guarantee that personal information is not misused.

In this paper, we mainly focused on the OCC technologies and how those technologies could be used to improve energy efficiency as well as occupant comfort. However, there is another aspect of the OCC, which is the occupants themselves. More studies should be conducted to evaluate the occupant acceptance of OCC and the conflicting needs of occupants in shared spaces.

6 Conclusions

The OCC model, derived from a realistic OB model, is designed to promote the creation of an energy-efficient, comfortable, and intelligent indoor environment by leveraging specific energy-saving technologies and methods. The research on developing the OB model concentrates on quantifying indoor occupancy movements and energy-related behaviors using advanced sensors and sophisticated data analytics techniques. Conversely, OCC research primarily focuses on incorporating occupant preferences, gathered through surveys and predictive analytics, to tailor environmental controls. Based on the research findings, we propose the following potential directions or recommendations:

(1) When monitoring the presence of people in the room, it is recommended to use multiple technologies such as WiFi, PIR and UWB for detection at different granularities and apply these technologies rationally according to different control scenarios.

(2) During the control process, both energy efficiency and economic goals, such as demand response policies and PV flexibility, should be considered.

(3) When direct experimentation is not possible, load simulation through methods such as scaled modeling platforms can be an effective alternative, allowing the implementation of appropriate policies.
(4) For energy interaction behavior, it is crucial and necessary to accurately portray the real-time demands of occupants. However, since occupant needs change over time, models that can be continuously adjusted are more relevant than static models.
(5) A platform that converts occupant data into information and then information into control signals is needed.

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Declaration of competing interest

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and ChatGPT to improve readability and detect spelling/grammar mistakes. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Author contribution statement

Yue Yuan: conceptualization, writing—original draft; Chengcheng Song: writing—review & editing; Liying Gao: literature curation; Kejun Zeng: writing—review & editing; Yixing Chen: conceptualization, review & editing, supervision.

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