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EDITED BY
Prem Prakash Jayaraman,
Swinburne University of Technology,
Australia

REVIEWED BY
Abhik Banerjee,
Swinburne University of Technology,
Australia

*CORRESPONDENCE
Stephen Lee,
✉ stephen.lee@pitt.edu

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IoT-enabled user agency for building sustainability

Stephen Lee*, Ousmane Dieng, Longfei Shangguan, Jacob Biehl, Adam Lee, Daniel Mossé and Panos K. Chrysanthis

Department of Computer Science, University of Pittsburgh, Pittsburgh, PA, United States

Buildings are a significant source of greenhouse gas emissions, and many organizations recognize that reducing commercial building-related emissions is crucial to achieving a carbon-neutral future. However, leveraging state-of-the-art building energy-efficiency techniques can be expensive and require installing new equipment, resulting in only a small percentage of energy-efficient commercial buildings. To address this challenge, our paper focuses on empowering building occupants to become informed change-makers that drive building efficiency through an IoT-based solution. By leveraging the data collected from low-cost sensors, we envision creating personalized dashboards and interventions for individuals, fostering energy transparency and empowering people to optimize their space usage while reducing emissions. Moreover, we can leverage human flexibility and flexible environments to further improve space usage and realize energy and emissions reduction opportunities. Thus, by enabling human-building interaction, our approach will be more effective in achieving the full potential of reducing energy and emissions in existing buildings.

KEYWORDS

smart buildings, building automation system (BAS), internet of things (IoT), energy-efficiency, raising awareness, behavior change, human factors

1 Introduction

Decarbonizing buildings is essential to tackling climate change, as buildings are responsible for almost 30% of global greenhouse gas emissions. The majority of buildings are decades old, with outdated equipment and *building automation systems* (BASs), if any. Despite technological advancements that have enabled energy savings of up to 90% or more with modern state-of-the-art systems Rolnick et al. (2022); Urge-Vorsatz et al. (2013), most buildings have yet to benefit from such efficiency improvements despite renovations.

Decarbonizing buildings is a complex challenge that involves various mitigation actions, including improving energy efficiency, reducing energy demand, and utilizing advanced building technologies. A primary barrier is the high upfront costs associated with retrofitting existing buildings with advanced building technologies. Building owners and operators may be hesitant to invest in these upgrades due to the perceived lack of immediate return on investment. Thus, it is essential to develop cost-effective solutions that provide value over the long term. Another challenge in sustaining and proliferating low-emission buildings is encouraging occupants to adopt sustainable habits that reduce energy demand. Research has shown that occupants who exhibit wasteful behavior can consume twice the amount of energy compared to the average Hong et al. (2017). Addressing this requires changing behaviors and attitudes toward energy use. This can be achieved by making buildings smarter and letting buildings educate occupants about their consumption habits and advise them on how higher savings can be achieved. This, in turn, will enable smart buildings to enact sustainable controls.

There have been decades of research focusing on improving energy efficiency in buildings Gershenfeld et al. (2010); Gul and Patidar (2015); Olsthoorn et al. (2019). However, a key limitation of these studies is that systems are not adaptive and do not leverage humans in the energy saving process. Recent studies show that combining energy-efficient building methods that couple interactions with building occupants are an effective way to achieve low-energy use buildings Paone and Bacher (2018); Garbi et al. (2019); Ramallo-González et al. (2022); Rusek et al. (2022). Since occupants are the primary consumers of energy within buildings, their behavior can significantly impact energy use. Even in buildings designed with net-zero energy features (e.g., maximizing the use of daylight and natural ventilation), achieving optimal performance is often contingent upon occupants' knowledge of these systems and their behavior Paone and Bacher (2018). For example, even if we employ advanced building automation systems, occupants who leave lights or equipment on when not in use can lead to wasted energy and increased costs.

Our key insight is that IoT systems for buildings need to learn from and influence occupants' behaviors and preferences to significantly impact energy efficiency. In this paper, we outline how to reduce building emissions by embracing hybrid workspace practices and encouraging human-building interaction. So far, most work environments require employees to work from a fixed location, such as an office, and follow a set schedule of working hours. Similarly, building operators often operate HVAC systems setpoint on set schedules assuming fixed work practices. This leads to energy wastage, as the entire building may need to be heated or cooled even if some spaces remain almost empty. However, the COVID-19 pandemic has significantly altered how physical spaces are utilized, with flexible work practices becoming pervasive across various regions and sectors Rusek et al. (2022). This increased workforce flexibility presents *an opportunity for optimizing building operations* by adjusting energy usage based on occupancy patterns and by influencing occupancy behaviors to reduce emissions. In essence, a symbiotic relationship between occupants and smart buildings.

We envision flexible environments in which occupants easily move from one area to another, as suggested by the buildings, thereby enabling optimiziation of space utilization and energy savings by turning off HVAC and lights in the now-empty spaces. This technique requires coordination between occupants and buildings that inform occupants of their emission footprint within building spaces and educate them on energy-efficient practices to reduce energy and emissions. Towards this, we posit that a scalable solution must support the following four functionalities:

- Low-cost IoT-based Automation
- Human Behavior and Occupancy Modeling
- Space & Emission Optimizations
- Dashboard for Information and Intervention

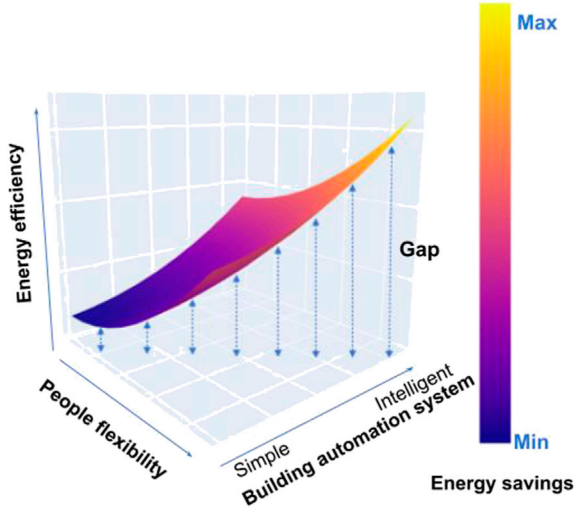

FIGURE 1
Leveraging human flexibility in building automation systems can reduce energy waste and close the energy efficiency gap.

2 Human-building interaction platform

Understanding the available energy controls in existing buildings is crucial to integrating occupant behavior into the energy performance of buildings. Our design centers around BASs with varying degrees of monitoring and automation to improve energy efficiency, reduce costs, and increase occupant comfort. As illustrated in Figure 1, basic BASs with simple HVAC and lighting controls do not provide detailed information on building performance and cannot adjust to changing conditions, leading to wasted energy and lower energy efficiency. Although simple BASs are less efficient in optimizing building performance, they have low upfront costs. On the other end of the spectrum, intelligent BASs that can monitor and control a wide range of building systems at varying granularity, optimize building performance and comfort in real time, reducing energy waste, but still require human involvement to achieve optimal performance. While advanced BAS systems can respond to changes in human behavior, it fails to fully leverage human flexibility, resulting in suboptimal energy savings. As shown in Figure 1, this gap can be significant as BAS systems are not typically designed to encourage occupants to adjust their behavior.

2.1 Design

To realize the vision of making simple BASs smart, we argue that humans and building systems need to work together. However, additional hardware and software abstractions are needed to enable humans to interface with buildings. Figure 2 depicts the overall architecture and consists of the following:

- *IoT sensing devices and data service*: BAS systems can often be opaque to building occupants and may lack the capability to fully integrate with all available sensors and real-time data,

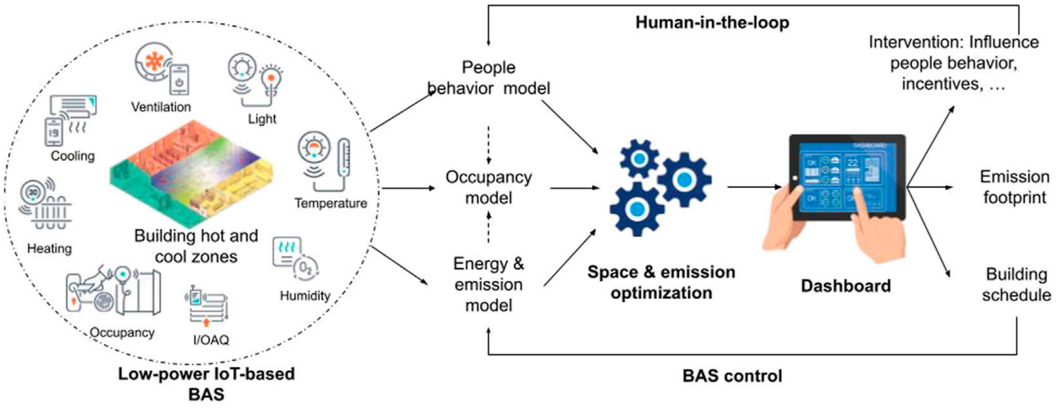

FIGURE 2
Overall architecture of the human-building interaction platform.

resulting in missed opportunities for energy savings. To address this, our approach involves implementing an IoT sensing system that utilizes various low-cost sensors (e.g., temperature, air quality, occupancy) to gather data on different aspects of the building environment. This sensing system serves as the substrate that enables the BAS and building operators to dynamically respond to changes in the environment. However, since IoT systems do not typically provide long-term storage capabilities, we require an additional data service system to store historical sensor data and provide necessary analytics. This data service

Ensures that the models have access to the required historical data for accurate analysis.

- *Occupancy Model*: The architecture includes a fine-grained occupancy model that uses historical occupancy data from the data service to make data-driven decisions about the building's energy and space use. Previous studies have employed a range of IoT-based techniques (e.g., Bluetooth, Passive Infrared (PIR) sensors, and WiFi) to develop occupancy models that can be effectively utilized within our system. Agarwal et al. (2011); Balaji et al. (2013). In flexible environments with hybrid workspaces, a key challenge is the highly stochastic and diverse nature of occupancy patterns, which requires modeling human behavior. However, we can incorporate human inputs, such as remote work schedules, to minimize the unpredictability of these models. For instance, if we know that a particular occupant will be working from home, we can use this information as a constraint to refine the occupancy prediction. This enables the building management system to make more informed decisions, leading to greater energy efficiency.
- *Behavior Model*: Behavior models can provide valuable insights into people's energy-saving habits, including their openness to changes and responsiveness to incentives. For example, one way to influence behavior is by utilizing temperature setpoint data and appliance usage information to inform how lowering the setpoint or replacing appliances with more energy-efficient ones can reduce energy. Lyu et al. (2023). In addition, incorporating social network dynamics into behavior models can lead to significant energy savings, as studies have shown that social interactions between building occupants play a significant role in energy consumption Peschiera and Taylor (2012). By considering group dynamics, for instance, groups of people working together can be scheduled to maximize energy efficiency. As a result, behavior models can play a crucial role in space and energy optimization, enabling buildings to achieve greater energy savings and reduce their carbon footprint.
- *Energy and Emission Model*: In addition to behavior and occupancy model, a fine-grained energy and emission model is necessary to understand how the use of space impacts the building's overall energy consumption and emissions. Simply reducing energy consumption does not necessarily lead to a corresponding reduction in emissions. The emissions generated by a building depend on how the energy is produced, and thus a more comprehensive model is required. For example, if the building's heating or cooling is generated from renewable energy sources, the overall emissions will be zero. Thus, our system includes energy and emissions model that considers the energy source and provides insight into how to optimize energy usage while minimizing emissions. This model is crucial for both providing occupants insights into their emissions and for optimizing building performance.
- *Space and Emission Optimization*: By analyzing occupancy data, the model identifies areas with low occupancy and recommend ways to consolidate occupants, thereby minimizing energy usage and emissions. Additionally, the optimization model provides feedback to individual occupants on how they can use space more efficiently to reduce the overall energy footprint of the building. For example, it can offer insights into how an individual's use of space affects other occupants sharing the same area and suggest strategies to reduce energy usage and emissions.
- *Space and Emission Dashboard:* The BAS dashboard provides real-time information on space usage, energy consumption,

and emissions for each occupant. It can be accessed through various devices, including displays in managed spaces and individual users' mobile devices. The dashboard calculates the consumption per space and informs occupants about their individual contributions to emissions in that space. Additionally, occupants receive personalized recommendations on reducing their environmental impact. For example, the optimization module may suggest that a specific user work from home if others are also working remotely or propose that a single occupant of a space moves to a different area.

The dashboard system can also include incentive mechanisms to encourage users to adopt sustainable practices. Moreover, building operators can access fine-grained schedules through the dashboard to reduce emissions while ensuring the comfort of the occupants.

2.2 Application

We describe how we can use the above system to control and provide personalized recommendations to optimize use and save energy.

2.2.1 Building energy optimization and control

Different building management systems offer varying levels of control, allowing for the optimization of building performance at different time scales. Advanced building energy management systems provide real-time control, enabling immediate adjustments to HVAC and lighting systems to optimize energy usage. Our approach enhances such systems by optimizing space utilization and energy use through the relocation of occupants. On the other hand, basic building systems only allow for pre-determined or direct control, often hourly, daily, or weekly. While these schedules may be inflexible, our platform offers more dynamic operational schedules that adapt to unexpected changes in occupancy behavior in real time. This ensures that energy is not wasted due to occupant behavior changes that are not accounted for in pre-determined schedules.

2.2.2 Flexibility and incentives

The flexible working environment and hybrid working model present another opportunity.

- *Flexible working environments* empower stakeholders to improve both space and energy efficiency. In flexible workspaces, hot desking and office hoteling are common practices that allow building spaces to be available on a first-come-first-serve basis or reserved in advance. These practices provide greater flexibility and movement of occupants, resulting in more efficient use of space. However, some spaces, such as printer and conference rooms, may not be flexible and are reserved for fixed use. Hence, optimizing space use to reduce energy consumption requires careful consideration of the type of flexibility the space provides and how to efficiently assign these spaces without compromising user comfort and productivity. Such preferences can be provided as input to the optimization to determine intervention strategies for relocating occupants within spaces.

Implementing hot and cool zones at fine-grained granularity can further optimize energy usage in buildings by allowing for more personalized temperature control based on occupant preferences. Heating or cooling different rooms of the building differently can create comfortable workspaces while reducing the overall energy consumption. This strategy can be particularly effective in flexible workspaces where occupants have different temperature preferences or move frequently throughout the day. However, it is essential to carefully plan and design these zones to ensure that they do not create discomfort or conflicts among users.

- *Hybrid workspaces* present another opportunity to optimize space use and energy efficiency. For example, we can encourage employees to work from home or remotely when the office is expected to have minimal occupancy, which can reduce the overall energy consumption of the building by allowing unused spaces to be closed or unoccupied areas to have reduced heating or cooling. Additionally, hybrid work practices can be used to implement a staggered work schedule where employees work from the office on alternate days or schedules that minimize peak demand on energy systems, thereby enabling more effective use of space.

To facilitate sustainable practices, *incentive mechanisms* can be designed to encourage individuals to be aware of their energy use. Studies have shown that feedback and intervention strategies can effectively reduce building energy consumption Kempe et al. (2003); Evins (2013); Hoes et al. (2009); Gulbinas and Taylor (2014). Based on occupancy and energy models, the dashboard can report individuals' current and historical energy use in using building spaces. Additionally, incentives such as rewards (e.g., monetary incentives) and recognition (e.g., leader board) can motivate individuals to adopt energy-efficient behaviors. For example, we can provide users with information about their energy usage and how it compares to others, which can encourage users to adopt more sustainable behaviors.

Additionally, it is essential to communicate the benefits of energy efficiency to users and how their actions can contribute to a more sustainable future.

3 Discussion

To improve energy efficiency, it is often necessary to replace existing automation systems with advanced building automation systems, which can be expensive. However, in many buildings, this may not be feasible or practical. Our approach offers an alternative solution by augmenting existing building systems with low-cost sensors, which can provide advanced sensing capabilities and achieve high building performance. This approach is scalable and cost-effective since these sensors are cheap and widely available. Furthermore, optimizing space usage patterns can lead to indirect efficiency gains in various aspects of building operations. For example, efficient space utilization can influence water usage patterns and water heating schedules. Moreover, it can facilitate more efficient maintenance practices, reducing the need for unnecessary cleaning in underutilized areas. However, it is important to take into account the following design considerations.

3.1 IoT and BAS

While prior studies have indeed highlighted the challenges of integrating IoT-enabled BAS with interoperability and integration, leveraging human flexibility through IoT introduces additional technical complexities Jung and Jazizadeh (2019). One such challenge is ensuring seamless connectivity and synchronization between personal devices (e.g., smartphones) and the BAS. Thus, designing smart feedback IoT systems that effectively facilitate user interaction and engagement and cater to individual preferences and comfort becomes crucial for ensuring user adoption and engagement. In addition, achieving effective data synchronization between different systems is necessary to ensure smooth communication and data flow between personal devices and the BAS. This involves establishing synchronization mechanisms that enable real-time data exchange, ensuring that user commands, preferences, and feedback are accurately transmitted and reflected in the BAS system.

3.2 Privacy

IoT devices such as occupancy sensors can pose a privacy risk as they collect data on users' physical presence and movements. To address these concerns, it is essential to safeguard the privacy of users by anonymizing the data before storage and analysis. Additionally, access mechanisms and interfaces should be provided to ensure that users understand what data is being collected, who, and how it is processed to answer queries. This way, users can make informed decisions about what kinds of data they are comfortable sharing and what kinds of questions they are comfortable with that data being used to answer. It is also important to note that flexible environments, such as hot desking, may reduce some privacy concerns as desks are not assigned to specific users. However, it is important to ensure that the data collected cannot be used to identify specific individuals or their activities. Adhering to privacy regulations and guidelines can not only safeguard the users' privacy but also build trust and confidence in the system.

To preserve privacy, we envision the system to operate on aggregated data from non-intrusive privacy-preserving techniques Zou et al. (2018, 2019), analyzing shared spaces utilized by groups of users. This approach anonymizes individual identities, enhancing privacy protections. While the system primarily relies on aggregated data, the inclusion of individual data, such as work schedules and preferred locations, can further refine the system's ability to meet user needs. Participatory-based approaches, where individuals can opt-in, can provide a balance between privacy needs and efficiency, allowing users to receive personalized recommendations and interventions. The effectiveness of our approach is contingent upon the flexibility offered by the spaces themselves. Spaces that prioritize common areas over private offices provide more opportunities for optimizing efficiency and promoting energy-saving practices.

3.3 Human-in-the-loop

One of the main challenges in optimizing building performance is dealing with the human factor. Changing human behavior can be difficult, especially when accommodating occupants with diverse backgrounds and characteristics. Understanding their personal comfort preferences and how they affect user satisfaction and productivity is essential. This remains an open problem as different individuals may have varying levels of reluctance to change their behavior. Thus, it is crucial to design interventions that address the specific needs and preferences of each individual user. There is also a need to develop incentive strategies that appeal to people and encourage them to adopt sustainable practices. While these strategies are mostly targeted toward individuals, they will need to work within social and organizational constraints to be effective.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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