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Ten questions concerning occupant-centric control and operations

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A B S T R A C T

Occupant-Centric Control and Operation (OCC) represents a transformative approach to building management, integrating sensing of indoor environmental quality, occupant presence, and occupant-building interactions. These data are then utilized to optimize both operational efficiency and occupant comfort. This paper summarizes the findings from the IEA-EBC Annex 79 research program's subtask on real world implementations of OCC during the past 5 years. First, in Q1 and Q2, we provide a definition and categorization of OCC. Q3 addresses the role of building operators for OCC, while Q4 describes the implications for designers. Then, Q5 and Q6 discuss the role and possibilities of OCC for load flexibility, and for pandemic induced paradigm shifts in the built environment, respectively. In Q7, we

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provide a taxonomy and selection process of OCC, while Q8 details real world implementation case studies. Finally, Q9 explains the limits of OCC, and Q10 provides a vision for future research opportunities. Our findings offer valuable insights for researchers, practitioners, and policy makers, contributing to the ongoing discourse on the future of building operations management.

1. Introduction

Building operations management is a multidisciplinary field that encompasses a range of activities aimed at ensuring the optimal functioning of building systems [1]. This includes the maintenance and control of heating, ventilation, and air conditioning (HVAC) systems, energy management, safety and security systems, and other aspects of building performance. The ultimate goal is to provide a safe, comfortable, and productive environment for occupants while minimizing energy use and environmental impact. In recent years, the field has been undergoing a significant transformation, driven by the increasing integration of technology and the growing focus on sustainability and occupant comfort. Occupant-centric controls (OCC) have emerged as a key concept in this transformation, shifting the focus from traditional building- (or better system-) centric operations to a more occupant-focused approach.

The OCC approach is underpinned by a rich array of data, encompassing occupant behavior, building performance, and environmental conditions. This data-driven approach enables more precise and responsive control strategies, which can significantly enhance energy efficiency, occupant comfort, and overall building performance. OCC has been extensively studied in the IEA EBC Annex 79 research project *Occupant-Centric Design and Operations of Buildings* [2]. This paper reports on some of the key findings from its subtask 4. While many topics in building design and control could be considered *occupant-centric*, e.g., equity and inclusion, privacy, trust, etc, [3], in this paper we will mainly focus on Indoor Environmental Quality (IEQ) for our discussion.

2. Questions

This manuscript delves into the core aspects of OCC, addressing ten critical questions that span the breadth of this field. We begin by defining OCC (Q1) and its foundational data categories (Q2), followed by an exploration of the evolving role of building operators in the OCC context (Q3). We then discuss the simulation of OCC for building controls (Q4) and its potential role in residential demand response programs (Q5). The manuscript also examines the impact of OCC on the recent paradigm shift in building occupancy and operations (Q6) and presents a classification of occupant-centric operations case studies (Q7). We further delve into the OCC strategies implemented and evaluated in these case studies (Q8), and discuss the limits of occupant behavior sensing and strategies to ensure occupant satisfaction (Q9). Finally, we conclude with a forward-looking discussion on the future directions and trends in OCC research and development (Q10).

2.1. Question 1: What is occupant-centric controls and operation?

Traditionally, control and operation of buildings' heating, ventilation, and air conditioning (HVAC) and lighting systems has been based on constant or steady-periodic setpoints and schedules [4], which are often selected conservatively by designers to cater to unrealistically high occupancy and occupied durations. For example, it is commonplace for HVAC equipment to operate at full or near-full capacity during operating hours which start and end many hours before and after occupants first arrive or last depart, respectively -as determined by a static daily or weekly schedule [5], regardless of when, where, or how many occupants are present, or what their preferred indoor environmental conditions are. Despite this traditional one-size-fits-all approach to operations, occupancy and the preferences of individual occupants in buildings are diverse; workplaces have been rapidly moving away from rigid 'nine-to-five' work schedules for almost a quarter of a century [6], while occupants have been shown to have individually preferred indoor air temperatures and illuminance levels [7,8], for example. Occupant preferences further extend to other aspects of how occupants experience and interact with the built environment (e.g., location and type of seating, olfactory sensitivities or preferences, access to views, flexible working hours, etc.) which ultimately impact their productivity and well-being. Any attempt to address this diversity with conservative setpoints and schedules is to provide services to buildings blindly, which ultimately wastes energy, affects indoor environmental quality (IEQ), and causes occupant discomfort. This problem is not limited to a single building type (i.e., commercial, or residential) nor to a single country, culture, or climate zone.

One potential antidote to the problems created by traditional control and operation strategies that has developed since the early 2000s [9] is the concept of occupant-centric control. The position paper published by IEA EBC Annex 79 defines OCC as an approach which involves "sensing indoor environmental quality, occupants' presence, and occupants' interactions with buildings" [2]. These data can then be used in control algorithms to adapt the sequences of operation in a manner that provides building services when and where they are needed, and in the amount that they are needed [10] based on occupancy and occupant preferences, thus improving energy efficiency, IEQ, and occupant comfort without impacting usability and perceived control for the occupants. In parallel, this data could be used to reinforce human-building interaction by giving feedback to occupants about the IEQ and energy consequences of their behavior and engaging them to energy efficient building systems control for a healthy environment. Park et al. [11] provide a review of over 35 published field studies which document the viability of various OCCs which attempt to derive setpoints and schedules for HVAC equipment and lighting controls based on occupancy and occupant preferences. They grouped these OCCs as either occupant behavior- or occupancy-centric. The former adjusts the indoor environment based on occupants' preferences that are learned either actively or passively; active preference learning is achieved by soliciting occupants' feedback explicitly through an interface (e.g., smartphones or wearables), while passive preference learning is achieved by monitoring occupants' interactions with the buildings' environmental control systems (e.g., thermostats or lighting switches) and determining their preferred environmental conditions implicitly. Occupancy-centric controls, on the other hand, adjust the indoor environment based on either the presence/absence or number of occupants (e.g., turning off equipment or using a setback when spaces are unoccupied). In both cases, the data needed to inform the controls and the sequences of operation can be gathered from proprietary sensing technologies, leveraged from existing sensors already present in the building for other purposes, or determined using a collection of sensors and data-types via sensor fusion. Additionally, data regarding occupant satisfaction and overall system performance can be gleaned from qualitative sources such as surveys and, increasingly, from emerging datasets like computerized maintenance management systems (CMMS).

Fig. 1 proposes a framework for OCC by illustrating its contextual processes within the built environment. This model includes four types of energy, mass, and information transfers that take place between the indoor and outdoor environments, occupants, and various building systems, primarily HVAC, windows, and lighting systems, as indicated by the colored arrows. These systems can actively transport mass, such as fresh air, and energy in the form of heat or light, or they can passively regulate the energy exchange between the indoor and outdoor environments, as with windows and blinds. In the former scenario, energy generation is required, while in the latter, the energy expenditure from the occupants is utilized. These processes could lead to energy/fuel consumption and impact the quality of the indoor environment. Along with the outdoor conditions, these factors act as stimuli that prompt the occupants' actions and perceptions [12]. Additional stimuli for occupants include interactions with other occupants and information regarding the building's operation, conveyed via visual displays (either fixed or app-based). The information necessary for OCC may be derived from four types of data, represented by the following sensing points: occupants' presence, movement, performance (physiological and psychological data), well-being, IEQ variables, human-interface interactions, and energy consumption. Moreover, OCC could benefit from actively involving the occupants in judicious control, achieved by sharing relevant information with them through, for instance, visual displays or well-designed interfaces [13]. This could inspire the occupants to take action themselves by adapting their behaviors, such as changing their clothing or consuming cold/warm beverages, thereby expanding the range of thermal comfort conditions and reducing energy consumption [14].

By this definition, OCC covers a wide swath of interventions with a range of complexities that can be performed to improve the built environment for occupants. For example, it could be argued that an occupant simply opening a window to mitigate thermal discomfort is an occupant-centric operation. A 'smart' thermostat with integrated motion-detection capabilities can infer if a home is unoccupied and apply a temperature setback of several degrees to reduce energy use as a form of OCC. A single-occupant office may record illuminance readings and an occupant's interactions with the light switch to determine what lighting level results in the lowest rate of interaction with the light switch and, implicitly, what lighting level the occupant prefers. Alternatively, an application on a smartwatch could periodically poll the occupant about their satisfaction with the lighting levels instantaneously to gather the same data explicitly. This would allow for artificial lighting to be reduced when natural light can meet or exceed the occupant's preferred illuminance, increasing both occupant comfort and energy savings via this occupant behavior-centric control [15].

While some OCCs have become relatively commonplace (e.g., demand-controlled ventilation (DCV)), widespread adoption of OCC at scale has yet to be realized [16]. However, emerging software and hardware for sensing, data-archiving, and control, continued advancements in data mining tools and techniques, and demonstrable savings from a growing number of case studies have all contributed to an increased interest in OCC and operation by practitioners. For example, the ASHRAE Handbook of HVAC Applications now includes a chapter devoted to OCC [108]. At the same time, enterprise-grade commercial solutions for OCC applications have begun to emerge. It is likely that the rate of adoption of technologies and strategies that enable OCC will increase dramatically as the benefits to occupant comfort, productivity, and well-being become increasingly clear.

2.2. Question 2: What are the basic categories of OCC data?

As OCC is enabled largely by sensors and data, the categories of OCC can be related back to quantitative occupant-related data available in a building. Based on the framework introduced by Melfi et al. [17], data relating to building occupants can be grouped into the occupant, spatial, and temporal resolutions. The occupant resolution can be further subdivided into four grades: presence, count, activity, and identity. Presence data enables learning binary patterns of space use, which can be used for scheduling the availability of building services (e.g., automatically turning lighting or HVAC equipment off when a space is empty and unlikely to be occupied in the immediate future). Occupant count data can enable modulation of available building services proportional to the space use intensity (e.g., occupancy-based demand-controlled ventilation, whereby ventilation is reduced or increased depending on how heavily occupied a space is) [18,19]. Occupant activity data (e.g., thermostat use behavior, comfort feedback solicited through Web, mobile, or wearable applications) enables customization of the delivery of building services for each space type (e.g., learned preferred indoor temperatures for a specific room) [8,11,20–23,104]. Occupant identity data can be of practical use if an occupants' location inside a building frequently changes to ensure that the services delivered at their given location match their activity and preferences (e.g., learned preferred indoor temperatures for a specific occupant). The identity grade of occupant data is not as useful in spaces with transient occupancy characteristics as individual occupants do not occupy these spaces frequently or long enough to establish individualized occupant behavior-centric

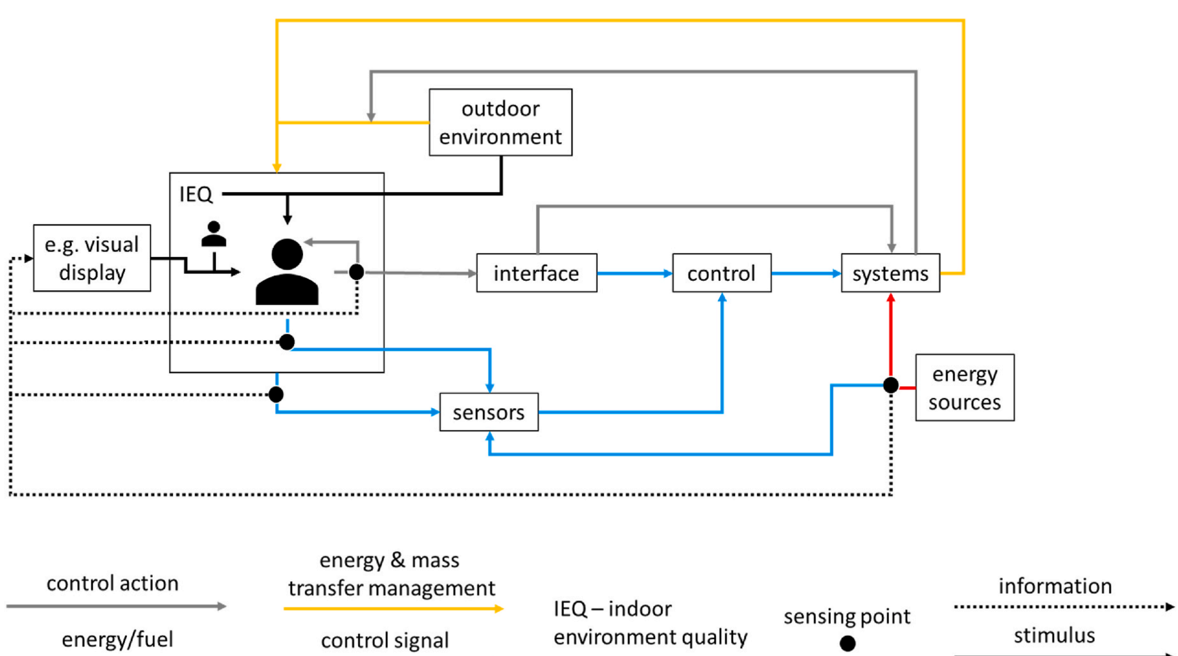

Fig. 1. Framework for OCC implementation in built environment. OCC is based on systems control using data from sensing points and could also engage occupants by presenting them collected data in relevant way.

controls (e.g., airports, hotels, restaurants). It should be noted that there are privacy and security related implications associated with explicitly identifying individual occupants either directly or indirectly. In buildings or spaces that are occupied by the same occupant(s) (e.g., a residence, single- or multi-occupant office spaces with assigned seating, etc.), OCC can be tailored to individual occupants' preferences without the need for explicit identity data. Simply put, monitoring occupants' activities in such spaces yields individualized controls without the need for explicitly identifying the occupant or tracking their movements. These types of data are inherently pseudonymized per GDPR [24]: while the data in each individual building or space can be attributed to the same occupant(s), the explicit identity of the occupant(s) is not collected. For this reason, the identity grade of occupancy data has not been necessary for OCC in most applications to date [11,21]. These types of data can, however, still be linked back to the individual occupant(s) explicitly using additional information (e.g., seating plans, office directories, etc). Therefore, any OCC which uses the identify grade of occupant data either directly or indirectly should consider the sensitivity of the data being collected, best practices (e.g., anonymization, pseudonymization, or de-identification), and the prevailing legislation for the jurisdiction in which the OCC will be conducted. Further work on this topic as it relates to OCC should parallel the continually evolving landscape around data and privacy as a whole.

Occupant data grades can be acquired at different spatial resolutions and can broadly be categorized at the system/building-level and room/zone-level resolution. Depending on the building considered, system-level data may not apply to a whole building, but to a subset of zones that are controlled by a single unifying system (e.g., the zones controlled by a single air handling unit (AHU) in a building with multiple AHUs, where the AHU is the 'system' in this context). Similarly, it is not uncommon for multiple rooms to be grouped together as a zone (e.g., multiple rooms controlled by a single variable air volume (VAV) terminal unit, where the multiple rooms are collectively the 'zone' in this context). Therefore, when considering the spatial resolution of an OCC, consideration must be given to the granularity of the building's HVAC systems and lighting equipment. This is why higher spatial resolution (e.g., down to the workstation or sub-room level), while a promising research topic, is not considered in this paper; most buildings do not have infrastructure to support OCC at resolutions below the room/zone-level. Generally, because occupants and their preferences are so diverse, energy savings and occupant comfort increase as the spatial resolution of OCC becomes more granular [25]. However, occupant data at higher spatial resolutions requires denser sensing and data-collection/storage infrastructure, which increases installation and maintenance costs. The higher burden on controls-integrators that the increasing complexity of high-resolution OCCs brings cannot be discounted. This burden will likely decline as OCC and operation become standardized, such as recent efforts by O'Neill et al. [26], to incorporate OCCs such as DCV directly into sequences of operation via codes and standards like ASHRAE Guideline 36 [27].

The temporal resolution at which occupant-related data are collected can vary. For example, monthly energy use data have been used to develop virtual meters for system-level equipment which enables the number of occupants within the system to be estimated [28]. While this may be used to inform the occupancy-centric operation of these equipment, controls-oriented applications (i.e., those which modulate equipment in real- or near real-time based on occupancy and occupant behavior) typically require data at a sub-hourly resolution for OCC. Similar to the spatial resolution, higher temporal resolution data will increase the burden on building automation systems (BAS) and building energy management systems (BEMS) as the sheer volume of data will increase network traffic and associated infrastructure requirements (e.g., data-collection and storage). Therefore, the selection of timesteps for the collection of occupant-related data should be done carefully. When developing OCCs, especially those that rely on data from multiple sensors or sources, consideration should be given to whether the data are collected concurrently, or if they are offset, how this can be accounted for during controls development.

Considering the above, the following categories can broadly be used to group OCC:

- Category 1 relates to presence/absence at the system/building level.
- Category 2 relates the same to the zone/room level.
- Categories 3 and 4 represent occupant counts at the system/building and zone/room levels, respectively.
- Categories 5 and 6 indicate occupant activities at the system/building and zone/room levels, respectively.

Even categories (2, 4, and 6) correspond to the higher spatial resolution of the zone/room level, while odd categories (1, 3, and 5) correspond to the system/building level. Occupant identity grades and lower spatial resolutions are omitted for the reasons previously discussed. These categories, summarized in Fig. 2 , are adapted from [2,29].

2.3. *Question 3: How does the role of building operators change when adopting OCC?*

Building operators fulfill various roles and responsibilities covering crucial areas such as maintenance, efficiency, safety, sustainability, and satisfaction. For example, operators are responsible for assessing, scheduling, supervising, and sometimes conducting maintenance activities, including inspections, repairs, and replacements of systems and equipment such as HVAC, electrical, plumbing, and fire safety. In addition, operators strive to optimize energy and water consumption by monitoring usage, identifying areas of excess waste, and implementing reduction measures through upgrading equipment or automation. Furthermore, operators ensure compliance with safety regulations, conduct regular inspections and coordinate with security personnel to develop and implement effective security protocols. Increasingly, operators play a vital role in promoting sustainable practices. For example, they implement recycling programs, reduce waste, monitor water usage, and explore renewable energy options. More importantly, operators are responsible for fostering a pleasant environment for occupants by serving as a point of contact and addressing their needs as necessary.

The climate-adaptive operations movement has already significantly transformed the role of operators by increasing the focus on efficiency and sustainability. Implementing OCC will continue to transform the role by prioritizing customization and personalization of the built environment to meet occupants' specific needs and preferences.

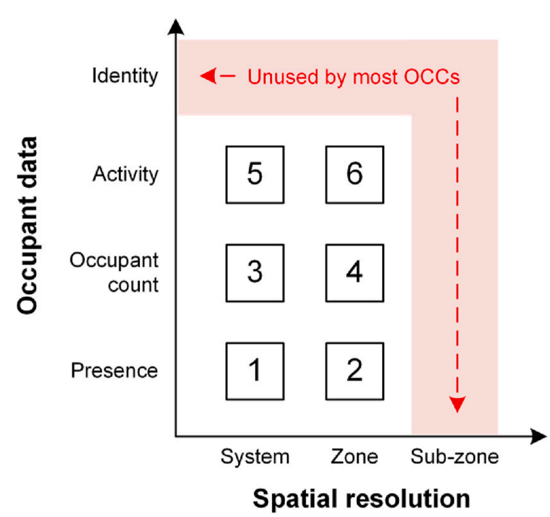

Fig. 2. Categories of occupant-centric controls (OCCs) based on occupant-related data used and spatial resolution of controls. [2,29]

Successfully incorporating OCC requires operators to enhance their expertise in advanced technology integration, effective communication, and educational strategies. However, like all paradigm shifts, fundamentally changing the role of operators will be met with several challenges [30]. The first major challenge for operators will be balancing historical quantitative measurements such as standards, cost, and efficiency with modern qualitative measurements, including comfort, productivity, and happiness. To prepare for their future as OCC operators, both tenured and new operators will need adequate training on integrating technology, state-of-the-art communication methods, and educating occupants. Overcoming these existing knowledge gaps will foster healthy operator and occupant relationships critical to transitioning from traditionally managed buildings to OCC buildings[107].

Technologies such as building information modeling (BIM), CMMS and facility management systems (FMSs) provide operators with a wealth of fundamental support-related information that can then be collected, analyzed, and integrated into the larger building systems [31]. However, training and knowledge is necessary to properly apply these technologies. It is also necessary that organizations value their use and understand the benefits they present in supporting operators' work. Studies show that the opportunity for occupant engagement is either neglected or hindered by the presence of organizational or structural factors despite the operational benefits these systems and the information provides [32]. Often these factors include operational goals limited to quantitative metrics such as cost and emissions. When these technologies are affordable, durable, maintainable, and easily integrated, they help operators achieve these quantitative goals. Once these goals are met, operators can overcome structural barriers to dedicate more time and resources to the human-facing aspects of their job, such as fostering a healthy relationship with occupants while also meeting qualitative goals. However, for those technologiesa key component of a healthy relationship is communication. Unfortunately, existing communication methods between operators and occupants are poorly implemented, resulting in broken information feedback loops leading to both poor building performance and occupant dissatisfaction [33]. For occupants and operators, advanced communication systems and methods that promote regular, direct, and electronically tracked feedback mechanisms help foster a healthy relationship [34]. These systems include but are not limited to post-occupancy evaluations [35], occupant voting [36], and occupant wearables [37]. As occupants provide feedback, operators can make decisions that benefit both occupants and operation without major detriment to one or the other.

However, communication is not limited to feedback. Operators must also provide occupants with adequate education by hosting training sessions and providing resources on technology and their built environment to encourage occupant autonomy without negative impacts on operation. For example, window signaling methods indicate when occupants can and cannot open windows in mixed-mode ventilation systems. Occupants who are educated about the window signaling system, as well as the personal and environmental benefits of following it, are more likely to participate in using it and using it properly [38]. By proactively educating occupants on how to interact with the system positively, operators mitigate instances where occupants negatively interact with the system where they may cause discomfort to their peers, excess energy use, or harm to the system. Occupants and operators must work together for OCC to be successful.

Another challenge in changing the role of operators when adopting OCC is that there are an insufficient number of operators entering the field to account for the high rate of retirement that will occur in the next ten to fifteen years [39]. This can be attributed to the limited number of formal academic programs and training specifically aimed at training operators. Expanding access to certifications, training, and education is a critical component of adopting OCC and preparing operators for the changes OCC brings to the operator's role. However, the lack of training and education opportunities is also associated with a lack of guidelines and standards developed and tested to effectively help operators to implement OCC worldwide. Studies that demonstrate ways of implementing and overcoming barriers need to be expanded to create a consolidated knowledge base for these reference materials [40].

2.4. *Question 4: Why and how to simulate OCC for building controls?*

OCC performance is subject to several sources of uncertainty which include typical culprits, such as weather fluctuations and envelope performance. However, occupant preferences and OCC configurational settings, especially the selection of hyperparameter values if machine learning models are used, can have a more significant effect on OCC performance [41]. OCC hyperparameter tuning is typically done through trial-and-error at the expense of occupant comfort and energy savings potential, leading to loss of stakeholder confidence in OCC solutions [11,21,42]. This is also constrained by other logistical and cost-related challenges, such as the limited number of rooms with near identical conditions in which OCC can be tested, as well as concerns and hesitation from facility operators towards adopting new control strategies [43,44]. These are the main barriers to implement OCC for actual building systems [11,21].

To this end, building performance simulation offers a flexible environment to investigate alternative OCC formulations and assess their impact on energy performance and indoor environmental quality [45]. However, the integration of OCC in building simulations is not a straightforward process. While typical building simulation inputs with regards to building design parameters are relatively straightforward, the way in which occupancy, occupant behavior and OCC is represented in building simulation is not trivial. Several approaches have been presented in the literature to achieve this integration, which are summarized in Fig. 3. In general, OCC simulations can be categorized based on the way in which occupants and their interactions with building systems are integrated in the simulation. The first category relies on identifying occupant-related metrics offline by analyzing historical data which are then used as inputs for OCC simulations. The second category focuses on integrating models to represent occupancy and occupancy-building interactions, which influence OCC operations at each simulation time-step.

The main advantage of the first simulation approach with offline occupant-related inputs, is its practicality and relatively less complicated workflows. For example Hobson et al. [16], introduced a library of OCC functions in R, which leverage building sensor data to identify five different occupancy- and occupant behavior-centric control-oriented metrics (e.g., presence/absence times at the building and zone levels), which were integrated into building simulations. This was demonstrated using BAS data collected from 29 private offices, then several OCC strategies were simulated, showing that the energy use and thermal discomfort could be reduced by up to 37% and 65%, respectively, when OCCs are implemented. An alternative approach for OCC simulation was also presented by Pang et al. [46], who quantified potential nationwide energy savings due to implementing occupant presence and occupant count sensing OCCs for ventilation in large hotels. The authors modified occupancy schedules in building simulations based on previous data on hotel occupancy patterns to provide a more realistic representation of hotel occupancy. Based on simulations in 19 different climate zones, they showed that HVAC energy savings varied between 24 and 58%, with occupant presence sensing, which increased by an additional 5–15% when using occupant counting sensors [46].

Since OCCs require human-building interactions, the second OCC simulation approach relies on coupling detailed occupant behavior models with building simulations. These models may represent both adaptive and non-adaptive behaviors; the latter are mainly related to schedule factors, (e.g., occupancy (absence/presence), and equipment usage). On the other hand, adaptive behaviors are defined as actual responses of internal or external stimuli [47,48]. For example, occupants who are adaptive to their indoor environments can control thermostats, light switches, and windows to adjust their environment [49]. To the

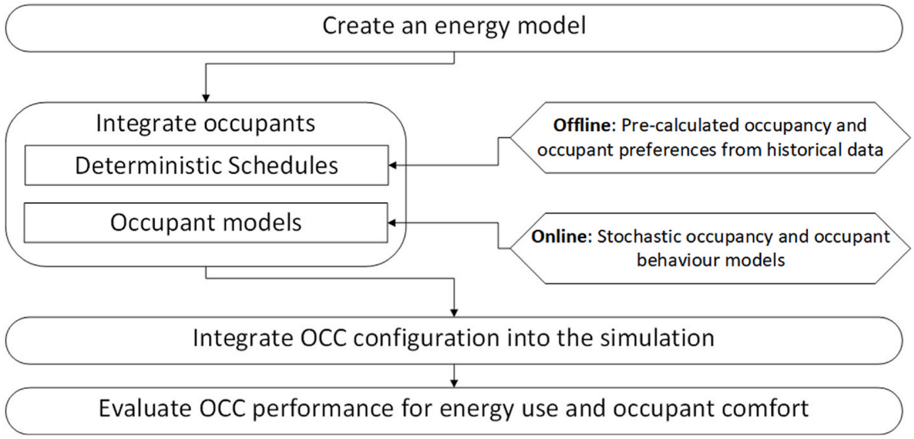

Fig. 3. Overview of simulation-based approaches for OCC.

best of our knowledge, few studies entailed coupling such adaptive occupant behavior models in OCC simulation. Ouf, Park and Gunay [50] introduced a workflow for such integration, which was tested in a case-study to simulate OCCs for lighting and heating/cooling setpoint adjustments in a single office under various occupant types, as well as OCC settings and design configurations. Zadeh and Ouf [44] leveraged this workflow to optimize OCC hyperparameters then identify configurational settings and design parameters that minimize energy consumption and maximize occupant comfort under various occupant scenarios [51]. used a different approach by mapping predicted occupant comfort to sensor measurements, which were represented in a simulation environment for lighting and blinds control to minimize glare discomfort as well as energy use. In a different study, Elehwany et al. [52] used the Python API within EnergyPlus to represent thermostat interactions and implement a reinforcement learning algorithm that identifies preferred setpoints and adjusts them accordingly, thus reducing occupant interactions as well as energy use. Overall, these studies demonstrated the advantages of fully representing OCC operations in a simulation environment, which allows for exploring their full potential in ways that may not be feasible in field implementations.

2.5. Question 5: What role can OCC play in current and future residential demand response programs to improve the reliability and magnitude of available load flexibility?

Traditional residential demand response (DR) programs aim to shed peak electric demand on the grid through direct-load control of home HVAC systems [53]. Despite some residential DR programs resulting in 30% occupant overrides and a 30% reduction in the program's energy savings capacity, DR programs currently do not include occupant behavior or comfort models in their control strategy [54]. This lack of OCC-integrated DR control results in these programs failing to meet their peak shaving goals, threatens reliability of the grid, and places large financial penalties on the DR provider [55,56]. When integrated with DR, and grid-interactive efficient buildings (GEBs) generally, the value of OCC is amplified from the scale of a single building to the scale of an entire regional power grid. This magnified value in turn magnifies the stakes for getting OCC right.

Recent research has attempted to understand underlying dynamics of occupant behavior in pursuit of informing future OCC-integrated DR programs. Current occupant models have looked to understand DR occupant override behavior based on the accumulation of thermal frustration, noting the significance of lagged occupant response to automated DR thermostat setbacks [57]. These data-driven models show that the time to occupant override is inversely and exponentially related to the magnitude of the setpoint override. These findings have the potential to improve the reliability of DR programs by aiding in the prediction of when and by how much occupants will override DR controls. Additionally, these findings can help inform the design of future DR programs to balance the occupants' need for a thermally satisfactory environment and the grid's need for increased magnitude and duration of load flexibility. In addition to developing DR behavior models, the standard ASHRAE Standard 55 thermal comfort models have been analyzed to explore their potential application in the context of DR. This research has revealed that the wide spatial temperature variation common in residential buildings is a major barrier to using these existing models for DR. It was found that there was an average spatial temperature variation of approximately 2 °C with a standard deviation of 1.2 °C across the homes studied. Given that indoor temperature is an input parameter of both the Predicted Mean Vote model and the Adaptive Thermal Comfort model, this wide temperature range increases the uncertainty of the models' predictions as the actual temperature an occupant is experiencing remains unknown. This research further found that while the adaptive thermal comfort model is sufficiently good at predicting thermal satisfaction of occupants, it is not able to accurately predict thermal dissatisfaction. It was found that 84.8% of the dissatisfied votes occurred within the 80% acceptability range. This suggests that thermal dissatisfaction models, rather than satisfaction models may better suit the needs of DR controls. Another barrier to using the standard ASHRAE 55 thermal comfort models is related to the temporal variation of the temperature during DR. These models do not account for the psychophysiological phenomena of thermal overshoot and thermal alliesthesia affecting thermal comfort during the induced dynamic thermal conditions [58]. As such, they do not provide any indication on how to better control DR for increasing occupant comfort and pleasure.

Thermal discomfort is not the only reason for unreliable DR programs. One study found that occupant routines related to thermostat interactions were the most important drivers of overrides, as occupants often manually changed their setpoint at the same time of day regardless of whether it coincided with a DR event or not [59]. However, the study also showed that the likelihood to override a DR event decreased after participants had been exposed to several events. Another related study conducted with the same dataset highlighted the need to study occupant behavior and OCC not only during the DR event but also before and after it. In the studied dataset, the occupants received a notification at least a day ahead informing them that the DR event was occurring. Approximately one in four users manually adjusted the setpoint temperature before the DR event, while only 13% of the DR events were interrupted by a user's adjustment. Among those DR events, different types of rebound effects in terms of intensity and durations were observed. These rebound effects could only be partially explained in terms of physical thermal aspects [60]. Finally, studies have suggested that participants' lack of familiarity with DR programs and smart thermostats can result in program disengagement [59]. At times, this lack of familiarity can also lead to diminished energy and financial savings as occupants may over-correct when manually overriding thermostat controls. These findings suggest that an important feature of OCC is not just intelligent control systems, but also the strategic sharing of information about these systems with building occupants.

While DR programs are inherently motivated by the periodic need for load reduction, understanding occupant behavior is the key to deploying reliable DR programs. It has been shown that manual setpoint change behavior of thermostats can differ significantly between homes in terms of setpoint change frequency, mean setpoint value and the spread of setpoint values. These findings suggest that the development of unique control strategies could be advantageous to the reliability of DR. Recent studies have suggested that personalized models could be tailored to a particular occupant behavior pattern by clustering similar behavior together. This clustering would allow for future DR control strategies to address the inherent diversity of occupant behavior which is especially relevant when scaling the implementation of OCC DR at larger district or regional scales.

2.6. Question 6: What is the role of OCC in the recent paradigm shift in building occupancy and operations?

At the beginning of 2020, the world was thrust into an unprecedented crisis in the form of the global COVID-19 pandemic that has forever changed how we live, work, and play. Health and well-being were brought to the forefront of every aspect of life. Building operations were no exception as buildings - by their very nature - are spaces in which people congregate, which introduces potential for the spread of viruses via infectious aerosols. Consequently, indoor air quality (IAQ) has become pervasive in the minds of the general public in a way that has not been seen since the rise of sick building syndrome nearly five decades ago. This paradigm-shift has fundamentally changed the way buildings are used, with the line between home and work blurring as flexible work schedules and remote work options become increasingly prevalent. Although this transition away from rigid work schedules had been underway for the past two decades[106], the full momentum had not been realized until the COVID-19 pandemic. For example, over an eleven-year period between 2006 and 2017, the number of Canadian office workers who spent less than three days a week in their physical workplace rose to 47%; during the COVID-19 pandemic, the number of office workers working fully from home spiked to over 80% in a matter of weeks [61]. While the return to work has varied across countries and industries, it is widely regarded that occupancy, especially in office buildings, will likely never return to pre-pandemic levels.

As a result of these changes in when and where people were working, the energy use patterns in buildings were expected to change. Intuitively, if an office building is unoccupied, energy use should decrease correspondingly, while residential energy use should increase. While the latter increase in residential energy use was observed, recent research has shown that energy use in many commercial buildings remained relatively unchanged in the early months and even over the course of the pandemic despite a drastic drop in occupancy in many jurisdictions. For example, the consumption of electricity and natural gas by the commercial building sector during the initial months of the pandemic in the United States fell by just 4.7% and 2.0%, respectively, compared to pre-pandemic levels [105]. This eye-opening experience has highlighted flaws in the way we traditionally operate our buildings, and many have adopted a new normal (i.e., hybrid, remote, and in-person work) for which current operational practices are still unprepared for.

As discussed in Question 1, OCC has revealed itself as a promising approach for controlling and operating buildings based on occupancy and occupant preferences. The benefits of such an operational approach in this new paradigm (i.e., with sparser and less-predictable occupancy) are self-evident. For example Hobson et al. [62] also found that an office building with a system-level occupancy-based ventilation OCC scheme was able to save 43% and 17% on heating and cooling energy, respectively, after the building was largely emptied in the initial months of the pandemic, compared to pre-pandemic energy use. In brief, buildings with OCC are inherently more adaptable to the variable occupancy that will be seen in many buildings moving forward as they can increase or decrease the amount of services delivered to a space based on occupant-related data.

While few buildings currently have OCC implemented, OCC utilizes sensors and data that have been available in buildings pre-pandemic and continue to be available. The data streams that can be leveraged range from the most basic data available in all buildings (e.g., bulk-metered energy data for an entire building) to data from the most detailed and granular sensor networks (e.g., occupant-counting cameras in each zone), and from implicit sources (e.g., occupants' impact on data streams such as CO_2 concentrations, energy use data, thermostat interactions, etc.) to explicit sources (e.g., dedicated occupant counting/sensing technologies, prompting occupant feedback via wearables, etc.). OCC can be developed based on a single available data stream, as well as by combining data streams via various machine learning methods and sensor fusion [63]. The use of sensor fusion in particular can allow for occupancy and occupant-preference to be inferred by leveraging the implicit sources commonly available in existing buildings, allowing for low- or no-cost 'opportunistic' [17] approaches to acquiring these data for OCC purposes [64]. During the pandemic, these data became invaluable for estimating building occupancy levels to comply with public health requirements (e.g., social distancing, minimum ventilation rates, etc.). This represented perhaps the largest leap in practitioner interest in the field of sensor fusion and occupant-related data to date. With the increased knowledge of the potential power that these data hold, the importance of implementing OCC in buildings moving forward may begin to be realized. It should be noted that a lack of OCC adoption during the pandemic (and in general) may not be due to a lack of willingness on the part of building operations personnel, but rather due to limitations in the systems and/or controls of their buildings which prohibit such interventions.

Much of the benefit of OCC explored so far relates to saving energy when buildings are partially or fully unoccupied, however, OCC also benefits occupant comfort by providing services when, where, and in the amount that they are needed as tailored to occupants [10]. Such OCCs may even result in increased energy use where demands for service are high, such as in instances during the pandemic when increased outdoor airflow rates were mandated by ASHRAE [65]; this increase in energy use is undeniably justifiable for the purpose of safeguarding human health. While occupants have been shown to be satisfied in buildings with improved IEQ and IAQ [66] as provided by OCC, directly quantifying metrics such as well-being and productivity into the development and deployment of OCC is an area of research that is actively underway. The emphasis on this holistic understanding of OCC and operations that considers well-being explicitly likely represents the future of this topic within the research community.

2.7. Question 7: How can occupant-centric operations case studies be classified?

Findings from the literature review conducted as part of the Annex 79 research program and briefly presented in the previous questions revealed various case studies on OCC in buildings [11,21]. In an effort to classify the different types of OCC implementations found in the extant literature, we propose the classification categories illustrated in Fig. 4. On the first level, a distinction is made between *observation* and *intervention-based* studies. An observation-based study is one that collects data in a case study and seeks to explore those data for general insights. No comparisons are made "within" the case study, but comparisons might be made with standards or other studies. An intervention-based study includes a comparison between a control/test group *or* a before/after condition. In both cases, the study can be centered around humans (occupants and/or operators) or systems (HVAC, sensors,

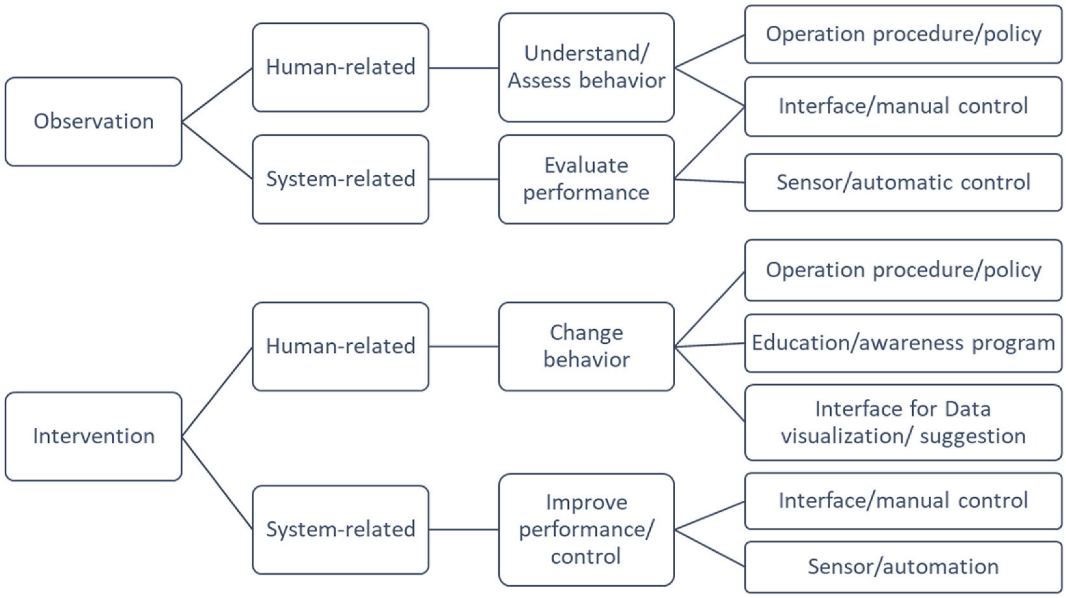

Fig. 4. Classifications for OCC studies.

lighting, interfaces, etc.).

On the second level, case studies can be *human-related* or *system-related*. In general, *human-related observation* studies try to understand human behavior and assess its impact on building performance as well as the occupants' own responses, such as their satisfaction. *System-related observation studies* evaluate the effectiveness of available systems, controls, and interfaces. Two approaches are identified for *human-related observation* studies. Case studies may analyze either an existing operation procedure or policy, or an interface or manual control. In many cases, human interaction with the building happens through occupant-control interaction. Thus, depending on whether the study is more focused on the human side or the control side, evaluation and analysis of an interface or manual control may also be part of a *system-related observation* study. Next to this, *system-related observation studies* may evaluate the performance of an existing sensor-based automation control, another type of automation system, or even a manual control interface.

Intervention studies usually aim to characterize how a specific technology can improve performance. *Human-related intervention* studies commonly try to influence occupant behavior to improve building operations. *System-related intervention* studies on the other hand, typically aim to achieve improvements by changing or optimizing the system (HVAC, lighting, etc.) or system control. Three approaches are identified for *human-related intervention* studies. Firstly, to achieve a behavior change in operators or occupants, the policy or operation procedure may be changed. For example, control limitations may be imposed, and a schedule change or a new communication approach may be implemented. A second approach to achieving behavior change is through an awareness campaign or other educational-based intervention to stimulate occupants to change their behavior based on the information provided, and increase awareness of their impact on building performance [67]. The third approach is through interface design, be it to provide information for occupants to make an informed decision, or to suggest behavioral changes through notifications. Examples are the use of notification to prompt/nudge occupants the best moment to open the windows [68] or real-time space distribution of occupants' thermal perception within a space to help operators to control the environment [69].

For *system-related interventions*, two approaches were identified. Firstly, performance may be improved by changing the system or type of manual control implemented. Examples include case studies on improving a control or interface to make it easier to use, adding controls for occupants, like a personal conditioning system [70,71], or imposing constraints on manual control such as resetting setpoint temperatures. Secondly, *system-related intervention* studies may opt for an automation strategy, which may be schedule-based or include sensor feedback. For example, a lighting system may be installed that regulates the luminance flux of light bulbs based on available daylight measured through a daylight sensor [72]. Automation strategies may either be reactive or predictive. Reactive control implements a change in system control following an event or sensor measurement. Alternatively, control may be predictive, and this means that a system control algorithm adapts to a predicted event or outcome based on sensor information collected in real-time. Examples include model predictive control algorithms [73].

A variety of approaches to OCC have been evaluated in simulation- or field-based studies. The impact of such approaches varies depending on building and occupant characteristics, and the baseline to which they are compared [11,21]. Knowledge of available systems, interfaces, procedures and space characteristics is therefore crucial to understanding the study conditions. In research, this knowledge is usually built by analyzing collected data. Observational studies are important in that sense, as they can help with understanding occupant patterns or identifying issues related to the implemented system. Therefore, observation studies can underline improvement opportunities that can later be tested in an intervention study, showing a behavior or system diagnostic. The other important application of observation studies is the development of better models to represent occupant behavior in a space with OCC, which sometimes differs from ideal simulation conditions or expected relations. The last branch of Fig. 4 provides an overview of possible strategies depending on the study focus. Compared to observation studies, intervention studies are typically more challenging to set up, as a new system or control may need to be implemented, and occupants and operators need to agree to the testing conditions, which may affect building use and the evaluation of the environment. These types of studies are, however, necessary for the validation of OCC strategies, as they allow for pre-post performance comparison. Because of the differences in building and occupant characteristics, baselines used in the comparisons, and differences in study objectives and results, determining the best case study approaches is difficult, and case-dependent. It is not possible to rank the strategies, as each of them will be applicable to a given situation. Furthermore, the above-noted approaches may also be combined and emerge as complementary.

Therefore, the aim of the study should be clearly defined so the applicable approach that will bring the expected outcomes can be identified. In this sense, with the objective of further providing useful references on implemented OCC approaches, an online survey was disseminated to collect case studies and compose a reference library. An overview is presented in the next question.

2.8. Question 8: Which OCC are implemented and evaluated in case studies?

An online survey has been designed and distributed among the research community with the aim of creating a comprehensive library of case studies that can serve as a reference for future research. A case study in this context is defined as "a deployment of a single set of occupant-centric technologies, techniques, and/or policies across a real-world spatial context (single zone all the way up to a campus of buildings) for a certain period of time". The survey questions were developed to be able to cover both observation and intervention studies. The information was grouped by i) building type, occupant demographic, operators and policies, ii) the building system that is being controlled, iii) the type of data that is being collected, iv) the type of strategy, which may be focused on occupant-, operator-, or building automation-based solutions, v) machine learning deployments, and vi) the degree of occupant centeredness. Fig. 5 shows the results of four main questions: Q1) location, Q2) the focus of study and data gathered, Q3) occupant types and Q4) building type. As of January 2023, the library includes 54 case studies from around the world.

The Q1 listed in Fig. 5 shows the database includes data from worldwide, which indicates OCC is being researched in field studies all over the world. The studies that are featured in this survey are mostly distributed among Europe (31%), Asia (31%) and North America (24%), with additional studies from Oceania and South America (4% each). The high amount of Singaporean studies stems from one of the survey planners being located at the National University of Singapore (NUS).

Q2 listed in Fig. 5 deals with the type of data that is being collected and the methods that are being implemented in the case studies. The recorded studies in this survey are evenly split between intervention and observation studies. Among collected observational studies, 66% can be classified as human-focused as opposed to only 19% of interventional studies (a study was classified as human-focused when it did not include data on either HVAC or lighting systems). Building HVAC systems are much more commonly researched in interventional studies (81%) compared to observational studies (26%), revealing that interventional studies tend to be more system-focused.

User interaction interfaces are featured in 37% of all recorded studies, while HVAC systems are investigated in 54% of all studies. This indicates that although most studies collect data on their users (69%), the user's actions to influence the IEQ are often not tracked and are under-represented compared to HVAC systems.

Out of the recorded studies that include residential buildings, only 45% stated that they feature data about the occupant compared to 74% in non-residential studies. This indicates that occupant data is harder to obtain in residential contexts than in public/office settings. The most likely reason for this difference is privacy concerns, which are stricter in private homes.

Q4 listed in Fig. 5 indicates most of the non-residential studies are university buildings, therefore, university facilities (including different space usage) are the most common typology at which OCC case studies are applied. This probably stems from the ease of access for researchers and also for allowing the test of not ready to use solutions. Although having these benefits, the concentration of case studies in an academic context creates some bias. First, university staff which mostly consists of Ph.D. candidates, postdocs and students are usually concentrated in a limited age range, which is relevant for IEQ perception and behavior [74,75]. Second, university staff and students might be more familiar with the research topics of these field studies compared to the general public. This may affect their attitudes, willingness to participate, and prior knowledge. These characteristics of the occupants need to be accounted for when applying research results to different settings.

These initial results highlight some trends in current OCC field study characteristics worldwide. By the inclusion of additional case studies, we expect this database to contribute to future studies, allowing comparisons and giving examples of possible approaches as it becomes public.

2.9. Question 9: What are the limits of occupant behavior sensing and how to make sure OCC strategies do not cause occupant dissatisfaction?

As we continue to advance and advocate for OCC, it is important to reflect on the intrinsic limits of OCCs in accurately capturing and addressing occupants' needs, as well as to consider the way occupants will understand, perceive, and interact with these new control systems.

2.9.1. The challenges of predicting IEQ perception

IEQ perception does not only depend on environmental variables which can be easily measured. A number of personal (psychological and physiological) and contextual factors also have a determining influence on human perception and needs and are reflected in occupant-building interaction [12,76]. Examples include availability and accessibility of control options, occupants' cultural background, their mental stress level and their opinion of the building management [12,77]. The behavioral uncertainty associated with these factors contributes to an already existing performance gap of modern control systems resulting from the difficulty of creating reliable models of occupant preferences and behavior. In a recent study, a framework was developed for analyzing anecdotes of occupants' behaviors and experiences from international research projects. It was found that occupants' priorities related to their comfort and personal control in real buildings were not always understood by the researchers, building designers or operators, potentially leading to discomfort and poor energy performance [78].

To advance researchers' understanding of occupants' needs, qualitative methodologies such as occupant surveys, open-ended questions, interviews and story collection should be more widely applied in building and energy research, as they constitute a very useful addition to quantitative data collection. They enable a deeper understanding of building occupants and description of the drivers of their behavior, increasing the chance of success of future occupant-centric building operation strategies [79,80]. Besides, qualitative data can also be collected directly for the purposes of building operation. For instance, such qualitative methodologies have been included in occupant feedback systems in real building operation [81,82]. Research has also shown that incorporating qualitative elements in post-occupancy evaluations is essential to improve the building operators' understanding of occupants' preferences and address the discrepancy between intended purpose of building controls and actual usage [83]. Researchers planning to implement OCCs in real buildings are encouraged to assess their performance via a combination of objective measurements and subjective investigations among occupants and operators.

2.9.2. Automation vs personal control

An important question to be raised when addressing OCCs is whether occupants actually expect specific personalized environments, which can be delivered by a self-learning proactive control system, or rather require more options to reactively control their surroundings in an easy and effective way [84]. Control systems can be fully automated, based on a 'human-in-the-loop' approach [85], or provide occupants with control for the purposes of an algorithm tuning process, after which human-in-the-loop control will be bypassed. In the late 1990s, the scholars behind the PROBE post-occupancy evaluation studies already warned researchers and building managers against the temptation of highly complex automated building control strategies for IEQ optimization. They argued that "users are satisficers not optimisers" [86] and

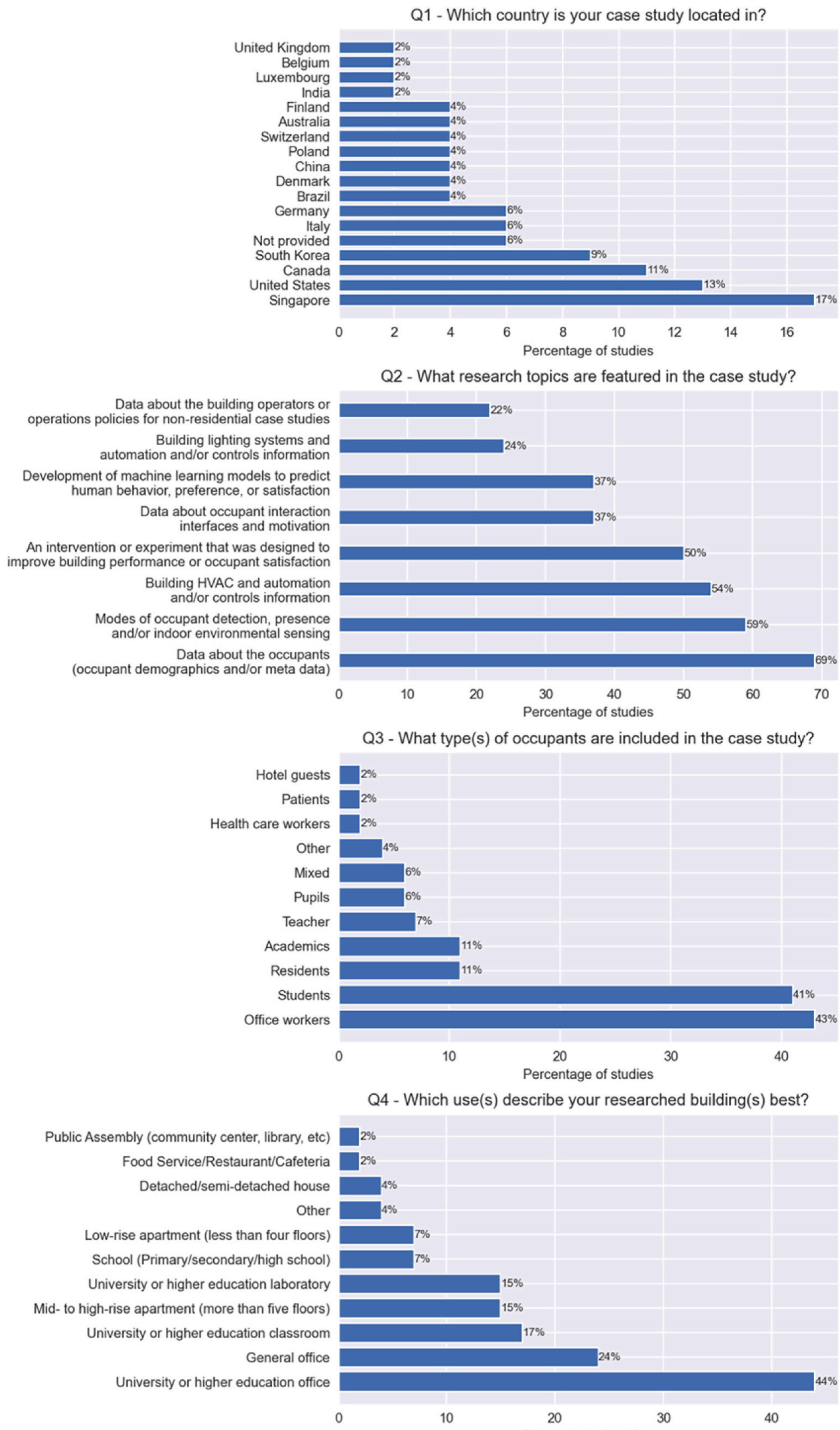

Fig. 5. Library case studies characteristics.

that it was more important for them to retain a degree of control on the environment than to achieve optimal conditions thanks to advanced building controls, which according to the study rarely achieved this goal anyways.

In systems that lean more towards automation, or where occupant information is used for algorithm tuning rather than direct control, occupants can also be granted “secondary” control, when they, for example, provide feedback via an interface or address complaints to the facility manager [77]. As already mentioned in this article, this requires good communication and a trust relationship between occupants and operators. However, such secondary control has the potential to be more stressful than primary control [87], e.g., an occupant using a thermostat directly. The reason is the time lag between requested change and successful adjustment which is due to the need to rely on others (e.g., facility manager) or algorithms (e.g., OCC). Therefore, the experience of success in the control action might be diminished, leading to a lower level of perceived control and therefore of satisfaction [77].

In addition, it is important to address the challenges in serving a diversity of occupants in the same space using an OCC approach. As shown by Schweiker and Wagner [88], higher numbers of people in rooms decrease perceived control over the indoor environment. On the other hand, among others, higher perceived control reinforces occupants’ intention to conform to the norms of sharing environmental control features [31]. Some solutions for this situation seem to be Personal Comfort Systems (PCS) [89], which provide control diversification however require additional investment. There is still a need for research to develop guidance for user control in the built environment, e.g. [90], and the development of technology for integrating local manual control to the environment system when they are complementary [70,71]. IEQ standards include little information about user control requirements, as for example on operable windows [91]. However, it has been demanded to include personal control as a design goal into standards [77,92–94].

Personal control over the indoor conditions remains an important driver of occupant satisfaction [95–97]. It is therefore important that future OCCs do not fully take this possibility away from occupants. As stressed in Q1 of this article, OCCs should not aim at removing occupants from the decision loop, but rather at modulating operation around their inputs to reduce energy waste and dissatisfaction.

2.9.3. Occupant education, control transparency, and the importance of interfaces

The current literature points to several more areas that are crucial to the success of advanced control strategies [78], including information, education and the human-building interface. For instance, providing training to occupants on building systems and controls was shown to increase their satisfaction with IEQ, both in offices [98], and in homes [99]. The transparency of the control algorithm is also an important factor of occupants’ acceptance: research showed that occupants are more tolerant of automated controls if they know what to expect from them [84].

The building interfaces are particularly crucial, as they are the primary link between users and the building[100]. A framework to critically analyze building interfaces and controls in a consistent way to evaluate their design, selection, and operation was developed [101]. These ideas were considered in the context of resiliency, unexpected events, and equity in which it is argued that designers must think carefully about interface selection to ensure the health and safety of occupants under extreme conditions such as rolling blackouts, wildfires, and more [101].

Well-designed interfaces have the potential to increase transparency of the control systems in buildings, and can provide users with the information they need to effectively use their systems [102,103]. Furthermore, Hellwig et al. proposed a design process for adaptive opportunities for occupants that approaches building design and operation planning through the lens of occupants and takes into account how occupants would want to adapt themselves in case they feel discomfort [93,94]. Solutions with redundancy in adaptive opportunities, e.g., sensing and communication interfaces and operable windows, serving diversity among occupants due to their different backgrounds, experiences and capabilities are preferable.

Such human-centric measures could therefore complement sensor-based OCC strategies in order to take into consideration the agency required by occupants to feel in control of their environment, thereby avoiding discomfort and unintended interventions by occupants. This paper therefore argues in favor of a stronger focus on detailing the modalities of building operation in the planning phase. Planning for building operation should not only encompass the design of building controls but also the definition of operational strategies that ensure the success of these controls, including training of operators, interface design and information of occupants [76] as also stressed in Q3 and Q6 in this paper.

2.10. Question 10: What are future directions and trends in OCC research and development?

The significant growth of Information and Communication Technologies has been the catalyst for OCC development and pilot deployment in existing buildings. Therefore, future research trends will focus on using these advancements to develop more advanced OCC algorithms, especially in applications that enhance buildings’ energy flexibility such as demand response (DR), as well as storage capabilities that could rely on widespread electric vehicles’ adoption for example. While OCC developments generally aim to reduce energy consumption while improving occupant comfort, future research directions will take a more comprehensive approach to comfort that includes occupants’ health and well-being, (including mental wellbeing), as well as productivity to improve occupants’ overall experience within buildings. Other research trends also investigate different ways of collecting direct occupant feedback, such as using smart phone or watch applications for continuous and real-time data collection instead of making inferences from historical building automation systems’ data, which has been the typical approach.

Nevertheless, previous studies show OCC development is not just a technical matter, the comprehension of the relationship between humans and buildings is crucial. The new knowledge from future research should be based on a multidisciplinary approach, joining at least engineering, medicine and social science, as OCC is a kind of socio-technical transition. For successful implementation of promising OCC technologies appropriate standards and design procedures have to be developed to make this approach used worldwide efficiently. Finally, standardized quantitative and qualitative performance metrics should be developed for evaluating any new OCC developments with respect to energy efficiency as well as improving occupant comfort, health, well-being and acceptance of these technologies represents one of the main research directions on this topic.

3. Conclusion

This paper has provided a comprehensive exploration of Occupant-Centric Control and Operation (OCC), a transformative approach to building operations management that aims at balancing occupant comfort and operational efficiency. Through the lens of ten critical questions, we have delved into the core aspects of OCC, from its definition and foundational data categories to its real-world implementations and future research directions.

Our exploration has underscored the potential of OCC to enhance both energy efficiency and occupant comfort, highlighting the rich array of data that underpins OCC strategies. We have also discussed the evolving role of building operators in the OCC context, emphasizing the need for operators to manage complex OCC systems and make decisions based on diverse data inputs. The potential of OCC in residential demand response programs and its role in addressing pandemic-induced shifts in the built environment have been examined. We have presented a taxonomy for OCC and detailed case studies of real-world implementations, providing valuable insights into the practical application of OCC strategies.

Despite the promise of OCC, we have also acknowledged its limitations, particularly in relation to occupant behavior sensing and the need to ensure occupant satisfaction. Looking ahead, we have identified several promising directions for future research in the OCC domain.

In conclusion, this paper contributes to the ongoing discourse on the future of building operations management, offering valuable insights for researchers, practitioners, and policy makers. As the field continues to evolve, OCC is poised to play an increasingly central role, driving advances in energy efficiency, occupant comfort, and overall building performance.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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