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A review of occupancy-based building energy and IEQ controls and its future post-COVID

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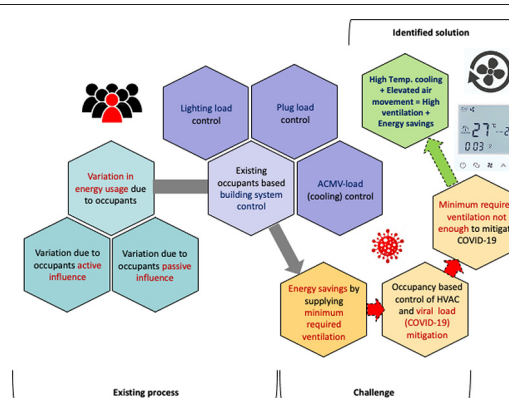
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HIGHLIGHTS

- Maintaining ASHRAE 62.1 specified minimum required ventilation based on occupancy schedules may lead to air-conditioning energy savings.
- ASHRAE 62.1 specified minimum required ventilation may not be sufficient to mitigate the SARS-CoV-2 virus spread in confined spaces.
- Occupants' IEQ requirements vary in contrast to the assumption of nearly homogeneous IEQ conditions.
- Personalised ventilation can be used to minimize the indoor spread of SARS-CoV-2.
- High-temperature cooling augmented with elevated air movement can maintain higher ventilation without an energy penalty.

GRAPHICAL ABSTRACT



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ABSTRACT

Occupancy schedules and density can have a substantial influence on building plug, lighting, and air conditioning energy usage. In recent years, the study related to occupancy and its impact on building energy consumption has gained momentum and is also promoted by ASHRAE as it has created a multi-disciplinary group to encourage a comprehensive study of occupant behaviour in buildings. Past studies suggest that building systems do not consume the same energy and provide similar Indoor Environmental Quality (IEQ) to their designed specifications due to inaccurate assumptions of occupants and their behaviour. Supplying ASHRAE 62.1 specified minimum required ventilation based on accurate occupancy may lead to significant air-conditioning energy savings. However, the same strategy is not suitable in the current time since minimum required ventilation may not be sufficient to mitigate the SARS-CoV-2 virus spread in confined spaces. High-temperature cooling augmented with elevated air movement across an acceptable range of velocity can maintain the health and comfort of occupants by providing higher ventilation and without an energy penalty. The analysis of the literature highlights strengths, weaknesses, and key observations about the existing occupancy monitoring and occupancy-based building system control methods to help in the direction of future occupancy-based research.

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1. Introduction

International Energy Agency (IEA) has identified energy efficiency of buildings as one of the main criteria towards limiting CO₂ emissions in the long term (IEA, 2018a). Governments around the world are working actively with IEA on various initiatives and regulations to promote energy efficiency in the building sector. The prime objective of this energy-efficient built environment goal is to save energy as well as to create a healthy and comfortable environment for occupants. Therefore, the aim is to be able to relate the operation of various energy use systems in a building to its occupants' usage patterns, so that a demand-based operational strategy could be conceived. However, this cannot be successfully achieved if accurate information on the interaction between occupants and energy use systems is incomplete or absent during the operation of buildings. Further, the Indoor Environmental Quality (IEQ) of modern buildings is of utmost importance today, as humans spend 87% of their time within an indoor built environment in general (Klepeis et al., 2001) and the same has reached as high as 100% as a result of COVID-19. The concern of the virus spread in confined spaces due to inadequate ventilation has successively raised the need to improve Indoor Air Quality (IAQ). Building IEQ is significantly dependent on the performance of building plug, lighting and Heating Ventilation and Air-conditioning (HVAC) systems (Klepeis et al., 2001; Amoatey et al., 2020; V et al., 2020; Megahed and Ghoneim, 2021; Jin et al., 2021; Agarwal et al., 2021).

2. Methodology

In view of aforementioned, current and past research related to energy-efficient building system control has been reviewed to develop the theory and hypothesis. The literature review begins with a description of the factors that affect energy usage inside a building, with the identification of occupancy being a primary factor influencing building

energy usage, both actively and passively. Then the subsequent section discusses the reported variations in building energy usage due to occupancy. In further sections of the literature review, the current developments in occupancy-based building control to enhance the energy efficiency of plug-load, light-load and HVAC-load usage are discussed. Additionally, various occupancy monitoring methods are also reviewed. Further, the potential role of occupancy-based HVAC control in viral load mitigation has been reviewed with respect to current COVID-19 pandemic and any such events in future. Finally, the summary and key observations are discussed. A description of multiple sections is presented in Fig. 1.

3. Factors affecting energy usage in buildings

Buildings comprise of up to 40% of the global energy demand and are responsible for a large amount of CO₂ emissions. In a typical office building, there are three primary forms of energy usage i.e. HVAC, lighting, and equipment (Plug Loads), which collectively account for about 85% of the total energy consumed (Anand et al., 2019a). However, this distribution may vary significantly for other types of buildings.

The International Energy Agency (IEA) has identified six factors (see Fig. 2) that cause variation in energy usage in different building types (IEA, 2018b). Earlier studies have shown significant progress in understanding the influence of five factors identified by IEA, i.e., Climate, Building Envelope, M&E Systems, Indoor Design Criteria, and Operation & Maintenance on building energy usage (Yoshino et al., 2017). Though many research studies have been conducted for investigating the effect of occupant behaviour, they are not as broad as the research done for the other five factors. This could be attributed to the limitation of access and availability of precise occupancy data, as well as difficulties in deciphering the various forms of data because of the stochastic nature of occupants (Duarte et al., 2013). In recent years, occupancy behaviour related research has gained momentum due to the advancement of

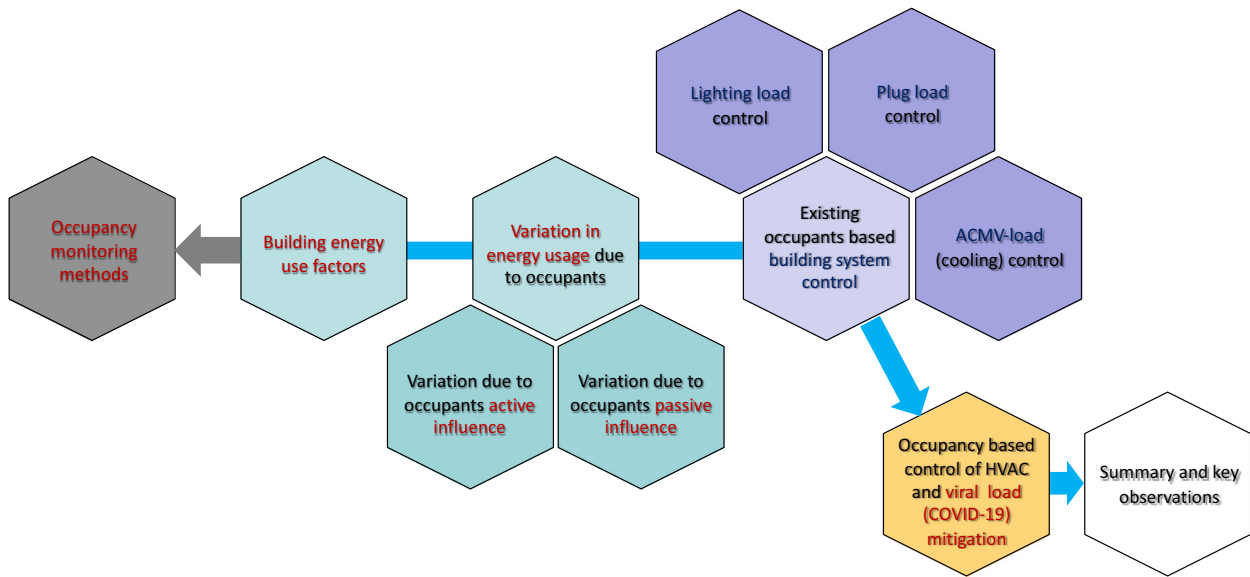


Fig. 1. Description of the various literature review sections.

occupancy counting methodology (Anand et al., 2017, 2018, 2019a, 2019b, 2019c; Yang et al., 2018; Rueda et al., 2021; Martínez-Mariño et al., 2021; Panchabikesan et al., 2021; Zhan and Chong, 2021; Wei et al., 2019; Anand, 2019; Chong et al., 2021; Wang et al., 2021).

4. Variation in building energy usage due to occupants

The variation in building energy usage due to occupants can be divided into two main categories: ‘variations due to occupant active interaction with building systems’ and ‘variations due to occupant passive interaction with building systems’ (see Fig. 3) (Zhao and Poh, 2015). While active interaction is defined by the actions taken by occupants to control the building systems, passive interaction is defined by the factors associated with occupant’s presence without any physical action taken by them to control building system.

The active interactions by occupants are the control of lighting systems (Light loads) to enhance their visual comfort and use of plug

loads for electrical equipment. In institutional buildings, occupants may use numerous lighting and electrical equipment, increasing the heat gains of the space and thus subsequently causing an increase in cooling load. Thus, it can be concluded that the active interaction of occupants has a significant impact on building energy usage directly from the use of systems (plug-loads and lighting) and indirectly from the heat load generated by in-use systems. Similarly, the occupant’s passive interaction with building systems (e.g. HVAC) influences energy consumption in buildings to a great extent, affecting the building thermal comfort and indoor air quality (IAQ). In this case, although the interaction between occupant and HVAC system is passive, occupants actively influence the energy usage by acting as a movable heat and CO₂ source (Zhao, 2014). In the following subsection, the outcome of several studies conducted in the past to quantify the occupants active and passive influence over building energy usage, is summarized.

4.1. Variation due to occupant’s active influence

Active interaction of occupants with building energy systems is a complex mechanism, affected by numerous parameters such as number of occupants, behaviour of occupants, type of space, type of work, day and time etc. (Melfi et al., 2011). Overall, these parameters can be grouped into three resolutions: a) Temporal, b) Spatial and c) Occupancy (see Fig. 4). Temporal resolution states the scale of time, spatial resolution states the information of space and occupancy resolution states the behaviour of occupants. In general, the sociological or psychological aspects significantly influence occupant behaviour (Mahdavi, 2011; Zhang and Barrett, 2012; Foster and Oreszczyn, 2001).

To measure the active influence of occupants over building energy usage, accurate information of each resolution is essential. However, due to the high uncertainty of occupant behaviour, it is difficult to capture each energy-usage action and associated contributing factor. This uncertain occupant behaviour affects the indoor environment and thus is a major reason for large variations in energy consumption. Conversely, indoor conditions (temperature, humidity, lux level, etc.) also affect occupant behaviour which in turn changes the total building energy consumption.

The simpler forms of energy-related occupant behaviour include thermostat regulation, dimming/switching lights and usage of appliances. Langevin et al. (2014) verified that having individual level control of thermostats could allow for an increase in the set-point temperature to enhance thermal comfort leading to a reduction in the total energy usage

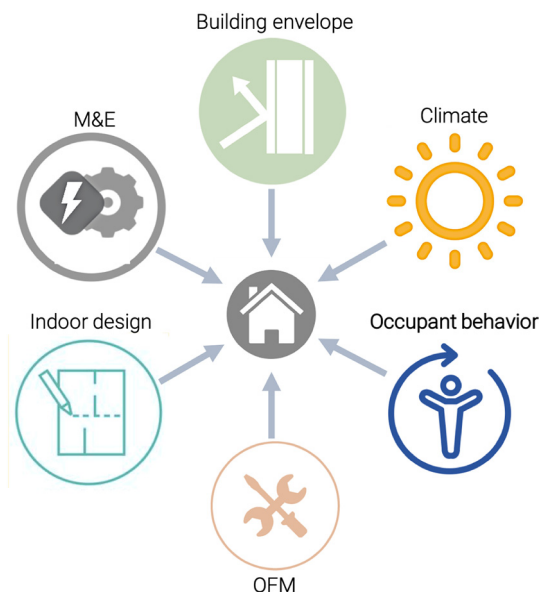


Fig. 2. IEA identified factors for building energy usage.

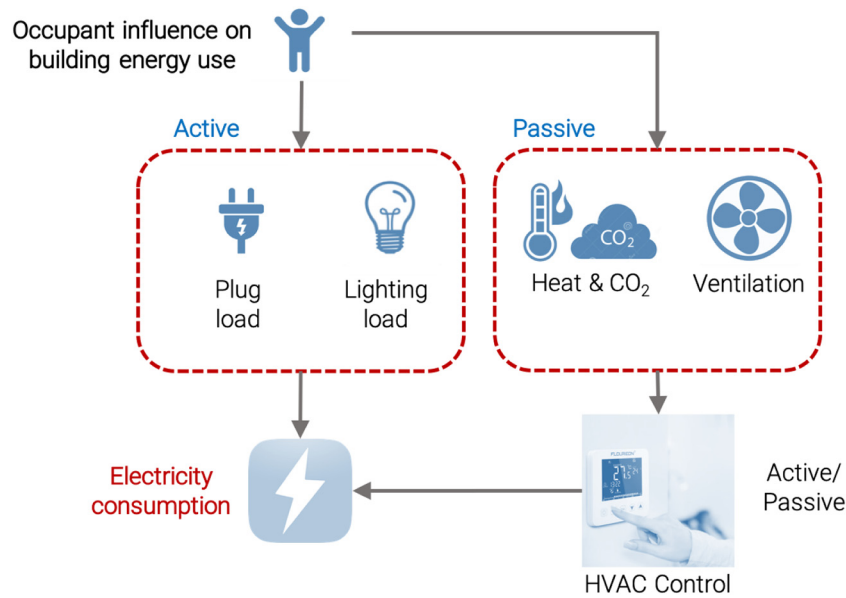


Fig. 3. Influence of occupants active and passive interactions on building energy usage.

(Langevin et al., 2014). Further, Li and Zhaojian (2007), examined the electricity used by 25 houses for cooling with an identical envelope (large residential building) in Beijing (Li and Zhaojian, 2007). This study was conducted during summer and the results show a wide variation among measured electricity consumption for air-conditioned houses. The variation was between 1 kWh/m² and 14 kWh/m² and was mostly triggered by the operation hours of split-type air-conditioning system. Houses where the occupants operated air conditioning for longer hours, ended up having a higher consumption of energy, and thus concluded that the occupants were the main drivers of energy usage. However, it can be argued that a part of the aforementioned variation could be due to the model/type of split-type AC systems installed. Similarly, Guerra Santin et al. (2009) found that the way occupants use heating systems strongly affects heating energy consumption (Guerra Santin et al., 2009).

Studies discussed above acknowledged a significant variation in energy usage by similar building spaces due to varying occupant's behaviour. However, the amount of variation also depends on buildings types (Azar and Menassa, 2012; Menezes et al., 2012; Hoes et al., 2009; Rijal et al., 2007; Clevenger and Haymaker, 2006). Therefore, an accurate knowledge of occupant behaviour and its variation among different building types is crucial to determine operational strategies for building energy use systems. These strategies should accommodate both

occupant behaviour patterns as well as changes in behaviour. To accomplish occupant comfort and well-being requirements, active interaction between occupants and building systems is more significant than the efficiency of systems alone (Yan et al., 2015). It has been verified through case studies that occupant action affects the flexibility and operation of building M&E systems. For example, a research by Fabi et al. (2013) inspected the robustness of building design with diverse usage of windows, doors and portable shadings, and found that efficiency of building energy usage can only be achieved through the integration of occupant behaviour in design (Fabi et al., 2013). Similarly, energy saving potential through increase in building insulation, as investigated by Belessiotis and Mathioulakis (2002a), found that the saving potential highly depends on usage pattern of terminal heating systems by occupants (Belessiotis and Mathioulakis, 2002a).

4.2. Variation due to occupant's passive influence

Passive interaction of occupants with building energy system depends only on presence and absence of occupants. The presence of occupants is denoted as the occupied hours and absence of occupants denotes the unoccupied hours of building operation.

Inefficient operation of Mechanical and Electrical (M&E) systems can lead to high wastage of energy during unoccupied hours. Keeping this fact in context, certain researchers have investigated building energy usage during different operational phases and have discovered that 26–65% of energy is used during unoccupied hours, as opposed to the work hours of 07:30 am–04:30 pm (Kim, 2014). Out of the total energy use in the buildings, 19–28% (mostly electricity and HVAC) was expended during non-functional weekends. Percentage energy usage and corresponding energy saving potential of these above-mentioned studies are summarized in Table 1 (Kim, 2014).

These studies were conducted through experimental setups and simulations, with findings stating that up to 45% of energy wastage can be recovered by the use of intelligent occupancy sensors (Masoso and Grobler, 2010; Agarwal et al., 2010; Von Neida et al., 2001; Martani et al., 2012b).

Historically, most studies were focused on basic energy consumption with little importance given towards occupant studies as a driver of energy usage in a building. The current state of research pays special attention to this aspect, having gained momentum towards understanding its random behaviour, like the research by Martani et al. (2012b) examining the impact of real-time occupant count on energy

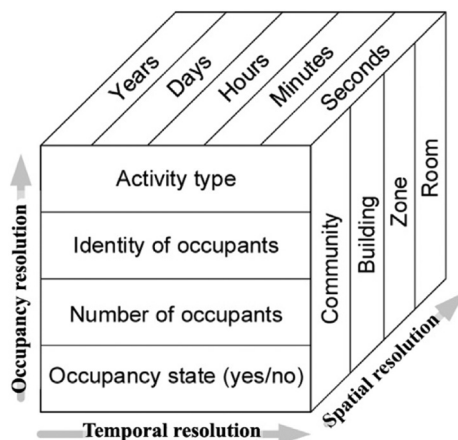


Fig. 4. Resolutions occupancy interaction with energy systems (Melfi et al., 2011).

Table 1
Energy usage during non-working hours and weekends.

Research team, year & location	Building type/space type	% Energy usage during weekend	% Energy usage (unoccupied hours)	% Energy saving potential	Energy usage type
(Masoso and Grobler, 2010) Botswana, S.A & Johannesburg, S.A	University Campus	25	65		Total power consumption (Electrical, Mech. and Plug Loads)
	Physics block	23	63		
	Office 1 (Private)	23	59	10–40%	
	Office 2 (Private)	28	54	HVAC	
	Office 3 (Govt.)	19	49	5–45% HVAC	
(Agarwal et al., 2010) U.S.A	Office 4 (Govt.)	20	55		Plug loads, lighting, and mechanical equipment
	Office Building	28	60	25–45% Office Lighting 35% Plug Load	
(Von Neida et al., 2001) Data from 24 states of U.S.A	Manufacturing companies, Healthcare organizations, Primary and secondary education, and Gov. office.	14–24%	26–44%	10–20% Lighting	Lighting Systems
(Martani et al., 2012a) MIT campus U.S.A	Large non-domestic buildings	26	64		Electricity, steam and chilled water

usage (Martani et al., 2012b). Taking the number of wi-fi users as a typical value for the number of occupants, the results showed a variation between 63 and 69% of the total electricity consumption due to variation in occupant density over a period of time for institutional buildings (Martani et al., 2012b). Mahdavi (2009) investigated the effect of the occupancy ratio using statistical methods for the lighting consumption of office buildings. Based on occupancy ratio, the variation in correlation ranged from 70 to 90%. The energy usage for lighting proves a good correlation benchmark with the occupant counts for most of the building types (Mahdavi, 2009). Hotel buildings tend to show a good correlation with the consumption of steam for heating during the winter season (Gao and Zhang, 2011). However, the correlation between HVAC energy usage and occupancy show a varying result with buildings types. In the case of campus buildings, a weak correlation has been found between occupancy rate and energy usage (Martani et al., 2012b). This fragile correlation is possibly due to the 'fixed' HVAC operation scheduled by facility managers for campus buildings. Thus, there exists a research opportunity to develop a framework using occupancy load as an input to better optimize HVAC operations. This will lead to energy savings as well as enable a better zone level thermal comfort for the occupants of campus buildings.

Some studies on prediction of cooling load based on occupancy and floor area information are currently available. For example, a study by Kwok (2011) demonstrates an increase in the precision of the cooling load prediction model when real-time occupancy and real-time weather data were used as simulation inputs compared to a fixed occupancy schedule alongside weather input (Kwok, 2011). However, this study used CO₂ concentration for measuring real-time occupancy, which is less accurate for estimating occupancy in large spaces because such spaces end up removing air via return ducts before it is measured by the CO₂ sensors.

5. Occupancy detection methods

To study the dynamic schedule and behaviour of occupants, this section showcases current studies which comprise data collection methods such as occupant observation, occupant surveys and experiments. The monitoring methods of occupancy can be broadly divided into two key categories: (a) Observational studies; and (b) Experimental studies.

5.1. Observational studies

In this type of study, occupants' activities, attendance, and indoor environmental parameters are inactively supervised using sensors. Based on seasonal variation (e.g., summer and winter) and building component usage type (e.g., windows and blinds), the monitoring

period and the selection and placement of occupancy sensors can be determined (Rijal et al., 2008) and (O'Brien et al., 2013). These observational studies could be further divided into two types: (1) Occupants presence and their equipment use and (2) Monitoring occupant's adaptive behaviour. The monitoring of occupancy and plug loads are combined, as these are less dependent on building design compared to adaptive behaviour, e.g., switching light on/off and windows open/close (Belessiotis and Mathioulakis, 2002b).

5.1.1. Occupants presence and their equipment usage

Occupant recognition methods in previous studies comprise wearable detectors (e.g., fit-bit), motion sensors (e.g., passive infrared and ultrasonic), CO₂ sensors, video cameras, Information Technology Networks (e.g., Cellular data, Wi-Fi etc.) and security-based systems (e.g., GPS) (Yang et al., 2018; Zhao and Poh, 2015; Zhao, 2014; Richardson et al., 2008; Lam et al., 2009). Among these, the use of motion sensors is the leading technology used for occupancy detection (Lam et al., 2009), but is not relevant for the detection of motionless or near motionless occupants, e.g. at an office workstation). However, it can reliably measure the state of occupancy transition such as arrival, departure and long transitional vacancy periods (Yan et al., 2015).

Some researchers found that the integration of motion detectors and CO₂ sensors can improve the accuracy of occupancy detection (Hailemariam et al., 2011; Federspiel, 1997; Wang and Jin, 1998). However, a significant delay is found between occupant presence and increase in CO₂. So, this process is problematic in zones with several sources of supply and several sinks for CO₂ e.g., an open-plan office. (Lam et al., 2009).

In the past, researchers have used cameras to count occupants and to identify every individual. Using computer vision techniques, this counting and identification can be done with high accuracy (Trivedi et al., 2000). However, the same has been identified as a computationally rigorous method which involves substantial cost and confidentiality implications (Lam et al., 2009).

There are numerous researchers who measured the potential of using current technology advancements for occupancy counting and detection, i.e. global positioning system (GPS), cellular data, wireless local area network (WLAN) and Bluetooth (Gu et al., 2009; Atallah et al., 2007; Wang et al., 2003; Liu et al., 2007; Hallberg et al., 2003; Hallberg et al., 2009). These advancements have the potential of becoming a part of the future of building operation and management systems. Among these, comparatively novel choices are the GPS location and Wi-Fi based occupancy counting (Zhao et al., 2015), which are appropriate for buildings with several entrance points, where installation of cameras or other technologies are very costly. Wi-Fi based occupancy counting

methods are the most economical, as they do not need additional infrastructure and existing building management with sophisticated algorithms would be enough for monitoring occupants via wi-fi. However, the uniform distribution of sensors is critical for garnering accurate information, especially for buildings having a large scale (like Institutional buildings).

5.1.2. Monitoring occupants' adaptive behaviour

In the past, researchers have observed occupants to undergo various energy usage behaviours which include switching on/off lights, door/window/blinds operation, thermostat-adjustment, and other adaptive measures like use of fan or clothing adjustments. However, a detailed monitoring process was recognized to be costly, time-consuming and likely to have low accuracy (Rea, 1984). Labour-intensive monitoring approaches (e.g., manual photographing and recording) caused a restriction with regards to sample size and duration. Nevertheless, they were valued for recognizing key behavioral patterns and more importantly motivations behind those behaviours. Numerous researchers have tried to automate this chaotic manual data collection method (O'Brien et al., 2013; Meerbeek et al., 2014). For example, a researcher collected occupant interaction from motorized blinds electronically and found that these blinds are used more often than manual blinds (Sutter et al., 2006). Perhaps, the least laborious procedure for observing blind/window usage is by proximity sensing devices. Similarly, window/blinds operating behaviour can also be supervised via photographic methods and by questionnaire surveys (Rijal et al., 2007; Haldi and Robinson, 2008; Haldi and Robinson, 2009). However, a limitation with this sensor is that it is unable to differentiate a situation between full and partial opening of windows (Herkel et al., 2008). In a similar kind of study, researchers have found that the opening of doors are less associated with indoor or outdoor environmental conditions (like change in temperature) (Haldi and Robinson, 2008; Ooka and Komamura, 2009).

To monitor thermostat adjustments, integrated sensors or set-point logs have been used in the past (Woods, 2006; Burak Gunay et al., 2014; Weihl and Gladhart, 1990). Contemporary digital thermostats have logging abilities and the collected data can be frequently transferred to a database via the internet. Most of these past studies on thermostat control were based on questionnaire surveys (Peffer et al., 2011). The use of a fan is the foremost technique for cooling in several buildings, predominantly for spaces where air conditioning is not available or treated as a luxury. It has been examined by numerous researchers using opinion polls or mature plug-level energy data (Haldi and Robinson, 2008; Nicol, 2001; Goncalves, 2011). Clothing levels have no direct influence on energy usage, but it disturbs occupant thermal comfort leading to adaptive actions by occupants. It cannot be sensed electronically, so observations and surveys are to be used (Haldi and Robinson, 2008; Schiavon and Lee, 2013; Morgan and de Dear, 2003).

5.2. Experimental studies

Experimental studies play a vital role in measuring occupant comfort conditions (Thermal and IAQ related) which influence its behaviour. There are several examples on the success and reliability of this method, such as Fanger's thermal comfort model and Daylight Glare Probability model (Fanger, 1970; Wienold and Christoffersen, 2006; Wymelenberg, 2013). In experimental studies, subjective responses and environmental parameters are collected simultaneously within a controlled environment such as a living laboratory. This kind of study is very useful in understanding the physiological and psychological influence over occupant behaviour based on different groups of age, culture, gender, etc. (Andersen et al., 2009; Karjalainen, 2007; Parsons, 2002; Boyce, 2014). However, it is uncertain whether generalized models of occupant behaviour can be achieved as the behavioral data of occupants could be specific to the data collection period. For example, numerous behaviour patterns can be infrequent and can occur on daily

or monthly basis (C.F and Reinhart, 2003). So, an adequate number of subjects, measurement duration and frequency are highly important for this kind of study (Rea, 1984; Haldi, 2010). Most developed occupant behaviour models used a 5-min frequency for data collection (Wu et al., 2013).

Utmost behaviour is comparatively occasional; for example, switching on the light can be a single time action every day and operation of windows/blinds can be seen on a daily basis, though rarely, and dependent on arrival and departure. Therefore, sampling durations of 15 min to 1 h are usually appropriate and any outliers can be ruled out over a yearly simulation (Wang et al., 2011). Regarding sample sizes, current study related to occupant monitoring generally range from two-digit to some thousand digits of occupancy (O'Brien et al., 2013). As there is significant diversity among individual behaviour, an acceptable sample from the common population is essential (C.F and Reinhart, 2003; Haldi, August 26–29, 2013).

There are some well-known procedures for defining acceptable sample size, such as power analysis (Stangor, 2014). Other than that, replicating a realistic environment with proper regard to social restraints and dynamics is not very likely. Many other limitations to study occupant behaviour in a living laboratory have been discussed in the past (L and Berkowitz, 1982; List, 2005). One researcher has summarized the pros and cons of various occupancy counting systems and concluded computer vision based systems incorporating cameras to be the most accurate (Yang et al., 2018).

In summary, occupancy monitoring can be categorised as occupant density, equipment density, and adaptive behaviours. The first and second group can be studied through several occupancy detections and counting methods listed in Table 2 and electrical power meters. However, price, confidentiality and precision continue to be a challenge. Similarly, monitoring of adaptive behaviour needs monitoring of occupant actions and measurement of environmental variables simultaneously. To get unbiased data, preferably, occupants should not be aware that they are being under observation as this may influence their behaviour (Zhou et al., 2015). There are organizational and legal restrictions (e.g. personal data protection act) within which this kind of study is to be conducted. Comprehensive procedures on all deliberated features of occupant monitoring is a part of IEA EBC Appendix 66 (Yan et al., 2015).

6. Existing occupancy-based building system controls

In recent years, occupancy-based building system control related research has gained momentum in both academia and industry. Such research has been conducted considering actual and predicted occupancy as an input to the building system control logic to control the operation of plug, lighting and HVAC loads. The efficiency of this kind of control logic is normally based on the level of occupancy information such as their a) presence/absence, b) individual level preference and c) action/behaviour as a group or individual (Nguyen and Aiello, 2013).

6.1. Plug-load control

6.1.1. Presence/absence-based control

Real-time response to occupancy for plug-load control is still a complex process. There are some products available for spaces with few occupants such as residential spaces or individual offices to switch on/off their equipment based on occupancy information (Naylor et al., 2018). However, the same is not common for spaces which have varying occupancy level due to the complexity of identifying the presence of equipment users out of the total occupancy. To control plug-load, some researchers have tested methods such as local motion sensors and wearable Bluetooth devices, to detect the presence/absence of computer users, to allow computer to reboot/sleep (Zhao and Poh, 2015; Harris and Cahill, 2005; Kashif et al., 2013; Park et al., 2013). It has been concluded that thorough information related to the needs of

Table 2
Summary of various occupancy monitoring methods.

Techniques	Benefits	Drawbacks	Reported accuracy	Reference
Visual inspection	Low cost	Labour- and time-consuming	Equal to ground truth	NA
Radio frequency	Commercially available	Affected by indoor electric-magnetic conditions	>73%	(Radio frequency occupancy sensing load control https://patents.google.com/patent/US9696701B2/en2014 (accessed May 16, 2014; Domenico et al., 2016)
Infrared	Low cost, commercially available; low power consuming	Binary output and coarse-grained nature of the data, not suitable for demand control ventilation	>76%	(Leech et al., 2017; Mikkilineni et al., 2019)
Ultrasound	Low cost	More susceptible to false-positive error	>85%	(Jaramillo and Linnartz, 2015; Hammoud et al., 2017)
Camera	More accurate and fine-grained data	Privacy concern	>95%	(Yang et al., 2018; Akkaya et al., 2015; Gutta, 2001; Chen et al., 2018)
CO ₂	Can be applied for demand control ventilation	Slow response; problematic in areas or spaces with several sources and sinks	>92%	(Yang et al., 2018; Dong and Andrews, 2009; Dong and Lam, 2011; Zuraimi et al., 2017)
Global positioning system (GPS), cellular data, wireless local area network (WLAN), Bluetooth, FitBit	Suitable for buildings with multiple overlapping access points for connection	Privacy issue; inconsistent connection	>80%	(Yang et al., 2018; Zhao and Poh, 2015; Zou et al., 2017; Performance et al., 2018; Liu et al., 2018; Shen and Newsham, 2016)

occupants is essential for trustworthy plug-load control. There may be a case when occupants have left their computer switched on intentionally to finish their computational work in their absence, so forcefully shutting down their system or keeping the systems in sleep mode in the absence of users may be a loss to their work and is undesirable. Overall, the real-time response to occupancy for plug-load control has a significant potential for further improvement as the same is in its nascent stage.

6.1.2. Preference-based control

The control of plug-load by thorough learning of individual preferences over time has also been explored by research. Most of the research related to learning individual preferences are specific to residential buildings, with focus on a single occupant (Kolokotsa et al., 2006; Chen et al., 2009; Zhao et al., 2016). However, one research had developed a generic method to learn the needs of individual occupants over a period of time in any type of space, irrespective of occupancy size, though this requires further validation studies (Moreno-Cano et al., 2013).

6.1.3. Action/behaviour-based control

During the early stages of occupant-centric building control research, it has been realized that predicting appliance usage patterns based on past common patterns is very useful in enabling a predictive control of power supply, especially for household appliances which usually have less variation on a daily basis (Mozer, 2005; Cook et al., 2003). However, the study related to the control of plug-load based on their specific behaviours is not widely explored in academia, because of difficulties in accurately detecting activity, due to the limited control present in building systems. There are a few research studies which demonstrate activity based control of plug-loads, based on the monitoring of occupant presence and computer usage (Zhao and Poh, 2015; Milenkovic and Amft, 2013).

6.2. Lighting-load control

6.2.1. Presence/absence-based control

Realtime lighting control based on occupancy is well-established in commercial buildings, especially in comparison to plug-load control. Illuminance of a space is generally controlled by sensing the motion of occupants using the Passive Infrared (PIR) based motion sensors. This system turns on lighting when motion is detected and switches it off after a fixed time delay from last movement detection. Improvements to this system by optimizing the time delay have been discussed in previous research (Garg and Bansal, 2000). Additionally, researchers have

also discussed the possibility to further optimize the control of lighting in large open-plan spaces by confining lighting only to areas where occupants are nearby to offer greater energy efficiency (Labeodan et al., 2016; Xu et al., 2011). However, the optimization of lighting by confining to occupied zones only and the energy savings associated with this method have not been reported so far for institutional building spaces.

6.2.2. Individual level preference

Some control applications such as automated control of lighting or HVAC system have the flexibility to take individual's comfort preferences as input. Such options with control application can provide personalized lighting and air-conditioning. Personalisation in lighting levels have been applied in a previous scenario by recording lighting adjustments made by each occupant (Singhvi et al., 2005).

6.2.3. Action/behaviour-based control

This system of occupant-based control is based on the assumption that a user's activity and specific behaviour dictates their environmental requirements. One research has lighting control implemented through visual detection of occupant location and activity (Lee et al., 2011). Similarly, another research study investigated a method to control the electrical equipment and HVAC system/equipment based on the occupant presence and occupant activity (computer use) (Milenkovic and Amft, 2013). A domestic study demonstrates the use of Infrared cameras and presence sensors to define activity categories. (Pallotta et al., 2008). Faster response controls for lighting and control of appliances has prediction horizon transients in the order of minutes (Harle and Hopper, 2008) or incorporate methods to predict the next action in sequence. This system is useful for controlling household appliances, lighting etc., demonstrated in the Adaptive House (Mozer, 2005) and MavHome (Cook et al., 2003) projects, where action sequences and environment conditions around the user are detected and recorded, followed by the system attempting to automate repetitive actions.

6.3. HVAC load control

6.3.1. Presence/absence-based control

In the past, many researchers have discussed the possibilities of HVAC system related energy savings by controlling the cooling requirement of spaces with an accurate presence/absence information of occupants (Agarwal et al., 2010; A.D. Institute of Electrical and Electronics Engineers., M.J. Association for Computing Machinery, and Arvind, 2011;

Gruber et al., 2014a; Batra et al., 2013; Goyal et al., 2013; Goyal et al., 2015). Most of the reported energy savings are obtained by not providing supply air during unoccupied hours. However, these studies are mainly conducted for a small space that have single or low occupancy, to achieve a controlled test environment. There are a few studies for larger or multi zone spaces which also show significant improvement in energy use using real-time occupancy levels in HVAC system control (Radhakrishnan et al., 2016; Peng et al., 2017). However, none of the past studies have been conducted for institutional spaces such as classrooms, which have significant variation in occupancy during operational hours and may require a more complex control strategy. Additionally, to overcome the complexity of data collection, most of the earlier studies are conducted through energy simulations.

6.3.2. Individual level preference

The control of HVAC system based on occupancy is subject to individual thermal comfort preferences. These control preferences can be obtained using thorough thermal comfort survey (Yong et al., 2007; Jazizadeh et al., 2014), or by monitoring the thermostat adjustments over a period of time (Hagras et al., 2004). In contrast, preference-based control systems are highly specific to space typologies and occupant density.

However, these studies are mainly conducted for small spaces that have single or low occupancy, to achieve a controlled test environment. There are a few studies for larger or multi-zone spaces which also show significant improvement in energy use using real-time occupancy levels in HVAC system control.

Application of preference-based control systems is highly reliant on occupant density and space/building typology. Earlier studies are mainly applicable for single occupant residential scenarios (Hagras et al., 2004), with a few based on generic platforms that can incorporate any type of space and occupancy (Moreno-Cano et al., 2013; Moreno et al., 2014). Preference-based control systems have been demonstrated to create conflict in comfort between individuals in multi-occupancy spaces. Further research is required to find common ground among conflicting comfort standards for multi-occupancy spaces. One potential future approach could be based on the distinction between tracked occupant groups and occupancy detected by ambient sensors (Yeh et al., 2009).

6.4. Effectiveness of control system

A difference between actual energy saving and estimated energy saving from the above mentioned control methods is very common. (Richman et al., 1996) studied effectiveness of occupancy-based lighting control from the data of 141 spaces of 13 space types. They used loggers to record the duration when lights were switched on along with occupancy. Finally, they estimated the energy saving based on hypothetical cases of occupancy-based lighting control, using sensors with time delay settings of 5, 10, 15 and 20 min. This assumption is made based on typical operation occupancy, which works based on a time delay setting, where time-delay is the time for which lights remained switched on after the last occupant departed. They reported up to 50% and 86% energy savings for private offices and restrooms respectively. As expected, with a decrease in delay time, energy saving increases. It has been concluded that the energy saving of any space depends on the availability of daylight, space usage, and occupant's density over time.

Floyd et al. (1996) has investigated the energy savings from 56 offices and 72 classrooms by installing PIR and ultrasonic based occupancy sensors compared to manual control (Floyd et al., 1996). They monitored energy consumption of the spaces studied for a year (6 months with manual control and another 6 months with occupancy-based control). Up to 19% of energy saving possibilities were found for office building and 11% for schools. Additionally, there were several incidences of sensor malfunction which caused an increase in energy consumption in certain spaces. It has been speculated that the increased

energy consumption of spaces might have been caused from the false activation of lights during night time.

Maniccia et al. (1999), studied monitored energy use in perimeter and interior offices over a period of 4 months, finding that 43% energy savings can be achieved by using PIR occupancy sensors that had a 30-min time delay as their setting instead of the conventional office hour (08:00–18:00) scheduling of lights (Maniccia et al., 1999).

A study comparing energy savings among various lighting control options like occupancy sensing, manual dimming, brightness adjustment and daylighting found that 20–26% savings could be achieved by occupancy sensing strategies (Jennings et al., 2000).

Chung and Burnett (2001) compared simulated and measured lighting energy consumption in a building, and developed a model based on occupancy probabilities at different times of the day. Their predicted energy savings from the model, in comparison to continuous occupancy, were 26.1% with a 20-min time delay and 33.3% for 5-min time delay (Chung and Burnett, 2001).

For a typical VAV based HVAC system, the required supply air rate normally derives from zone set-point temperature. Pressure-independent Terminal-Box (TB) can control both minimum and maximum required supply air rates regardless of duct pressure. However, in conventional control, a fixed minimum supply air rate is provided to zones to ensure that sufficient ventilation air is delivered to the zone served irrespective of the thermal load (Montgomery, 2008). The minimum airflow rate through a terminal box is normally chosen to prevent poor air mixing, along with ventilation, but is also dependent on the type of diffuser and its sizing (Taylor and Stein, 2004). This rough calculation of minimum airflow leads to overcooling of zones and wastage of energy in HVAC systems. This common occurrence has led to research on better control strategies for VAV terminal controllers.

In addition to the various other control strategies based on either supply air set point reset or occupancy based controls discussed in Section 1.3.2, Liu et al. (2002) and Zhu et al. (2000) proposed a control strategy of resetting set points in terminal boxes during unoccupied and lightly occupied hours (Liu et al., 2002; Zhu et al., 2000).

However, there are also reported cases that show small or insufficient improvement in HVAC energy savings by following a proactive control strategy based on occupancy sensing and prediction. Oldewurtel et al. (2013) found that predictive control for a single-occupant office space did not provide significant improvement over a reactive control system (Oldewurtel et al., 2013; Sekhar et al., 2018). Similarly, another study explored various VAV terminal box control strategies which compares fixed schedules to reactive occupancy based control and simulation based predictive control (Goyal et al., 2013) and experimentation (Goyal et al., 2015) for a small office space and found no significant improvement in energy savings between the reactive and predictive control. Small spaces with low occupancy are not ideal candidates for predictive control systems as found in (Gao and Keshav, 2013; Gruber et al., 2014b).

7. Potential role of occupancy-based HVAC control for viral load mitigation

Ventilation plays an important role in mitigation of viral loads in a confined space (Amoatey et al., 2020; V et al., 2020; Megahed and Ghoneim, 2021; Jin et al., 2021; Hu et al., 2021; Leng et al., 2020; Ge et al., 2020; Ahlawat et al., 2020; Guo et al., 2021; Morawska et al., 2020). However, enhanced ventilation through HVAC systems to mitigate viral load and maintain the health and comfort of occupants can lead to significantly higher energy requirements (Anand et al., 2019b). Occupancy-based supply of required ventilation and elevated air movement at an increased zone set-point temperature thermal comfort and perceived air quality can be achieved (Anand et al., 2019c; Sundell et al., 2011; Gong et al., 2006; Dahlan and Gital, 2016; Lipczynska et al., 2018; Schiavon and Melikov, 2008; Zhai et al., 2015). Other investigations found that an operative temperature range of 24–27 °C, with

an air velocity of 0.4 m/s, was considered to be thermally acceptable to building occupants in hot-humid climate countries (Cândido et al., 2011; Toe and Kubota, 2013). Some earlier studies also found that better thermal comfort and perceived air quality was observed at both 26 °C and 29 °C if the zone is supplied with enhanced ventilation and elevated air movement employing ceiling fan (Lipczyńska et al., 2018; Schiavon et al., 2017). Elevated temperature set point brings significant energy savings reported in several studies (Anand et al., 2019c; Hoyt et al., 2015; Zhang et al., 2017; Moon and Han, 2011; Aghniaey and Lawrence, 2018; Ghahramani et al., 2014; Tham et al., 2021). Energy savings in the range of 32–73% among HVAC systems at widened temperatures band could be achieved with fans or personal ventilation (Hoyt et al., 2015). There have been reports suggesting that indoor air can be an important vehicle for a variety of human pathogens including respiratory viruses (influenza and coronaviruses), enteric viruses (norovirus and rotaviruses), bacteria (staphylococci and legionellae), bacterial spore formers (*Clostridium difficile* and *Bacillus anthracis*), mycobacteria (tuberculous and nontuberculous), fungi (*Aspergillus*, *Penicillium*, and *Cladosporium* spp. and *Stachybotrys chartarum*) (Ijaz et al., 2016). A personalized ventilation (PV) approach can enhance both thermal comfort and IAQ satisfaction. Supplying clean and treated outdoor air directly to the occupant's breathing zone in simulated air-conditioned environments have been shown to enhance thermal comfort and IAQ, and also have the potential to minimize the risk of spread of bio aerosols via recirculation of contaminated air (Gong et al., 2006; Faulkner, 1999; Sekhar et al., 2005; Cermak et al., 2006; Kaczmarczyk et al., 2006; Melikov et al., 2002). Furthermore, whether the simple alleviation of thermal discomfort without considering ventilation affects measured and perceived air quality need to be ascertained (Zhai et al., 2015; Cândido et al., 2011; Toe and Kubota, 2013; Schiavon et al., 2017).

8. Key observations

Different aspects of occupancy-based building system control have been studied through objective specific literature review and from these past research outcomes, it can be hypothesised that occupancy is one of the main drivers behind the performance of building systems. Inaccurate information of occupants may lead to poor IEQ along with energy wastage. Occupancy information can be measured by understanding occupant's energy usage pattern along with their presence/absence. The measure for poor IEQ could be temperature, humidity, air movement and ventilation; and finally, the energy wastage could be determined by measuring the plug, light and cooling loads of the building studied.

8.1. Research gap

A thorough literature review has highlighted various aspects of occupancy-based building system control. Although many studies exist that analyse the potential of occupancy information in controlling building systems to enhance energy efficiency and IEQ, there are specific gaps in these approaches which are highlighted below.

- Although many studies have been done for office and residential spaces, there is a limited study that combines and compares energy use variations among different kind of spaces.
- In recent year the use of artificial intelligence-based algorithms to model high variability data has gained momentum. However, as per our knowledge, there is no study so far that has developed a single model for different spaces which can explain energy and occupancy relationship.
- Energy savings by optimizing the occupant's energy use behaviour of plug and light loads during occupied hours has not been studied significantly for institutional building spaces with varying occupancy levels. Additionally, there could be a vast potential for energy saving just by confining the lighting to occupied zones for a larger space as the same level of illuminance is not required for entire spaces.

- In the research of cooling load control by optimizing VAV operation, most of the earlier studies are conducted for small space with few occupants to avoid the complexity of data collection from a larger space. Although few researchers have discussed larger/multizone spaces, these studies were mostly based on simulation data which lack actual building operational data.
- The implication of occupancy based VAV operation is limited to energy saving assessment and there is insufficient reported case for its implications over IEQ especially AHU to zone level temperature and humidity control.
- To address this issue, researchers from both industry and academia are working towards occupancy-based Indoor environmental quality (IEQ) control via sensing and associated control of temperature, humidity and CO₂. However, a single integrated system for multiple sensors sharing a common transceiver platform and networked with key actuators/actuating systems have yet to be deployed though few initial prototypes have been developed.
- It is important to recognize the varying IEQ requirement of occupants rather than expecting them to adapt to nearly homogeneous IEQ conditions. For example, a sensor-actuated network can be used to collect individual level CO₂ data that can be used to minimise the spread of SARS-CoV-2 virus through personalised ventilation. Further, the proposed network could be used to improve occupants' health by knowing that people need exposure to a 24-hour cycle of light and dark to maintain circadian rhythm.

9. Conclusions

The literature review highlights that the primary reasons for the discrepancy between the planned and actual performance of a building are due to the assumption that the interaction between occupants and building systems (such as plug, light, and air-conditioning) is inactive or constant. However, in reality, the interaction between building systems and their occupants is dynamic, and the oversimplified understanding of occupancy does not correctly replicate the complex impact of occupancy over building systems. However, most of the occupancy-based VAV operation is limited to energy-saving assessment and there is an insufficient reported case for its implications over IEQ especially AHU to zone level temperature and humidity control. The reported energy saving is due to the supply of minimum required ventilation. However, in current COVID times, ventilation plays an important role in the mitigation of viral loads in a confined space and enhanced ventilation through HVAC systems to mitigate viral load can lead to significantly higher energy requirements. So, the post COVID-19 occupancy-based HVAC system control requires the consideration of novel sustainable strategies such as personalized ventilation and the supply of adequate ventilation at an elevated air movement and increased zone set-point temperature to create a synergy between occupant's health, IEQ perception, and building energy efficiency.

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.

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