Towards a Post-Occupancy Evaluation linking occupant behaviour and energy consumption to mitigate the energy performance gap in residential retrofitted buildings: a literature review

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Abstract: Building retrofit has become a leading sustainable action in the built environment and is expected to deliver the most energy savings by 2050. However, an Energy Performance Gap (EPG) has been identified in literature and practice related to occupant behaviour. Although links between EPG and occupant behaviour are being increasingly investigated, a lack of mixed-method studies in the field and technocentric approaches have not delivered the expected energy savings. Post-Occupancy Evaluations (POE) have proven to evaluate performance effectively, thus providing critical information to face the EPG. However, unravelling the impact of physical parameters and occupant behaviour on energy consumption requires new perspectives integrating contextual, societal and physical elements. Although current POE practice and recertification schemes consider occupant behaviour, it is evaluated simplistically and subjectively, resulting in a lack of assessment of Occupant-Building Interactions (OBI). This paper reviewed previous studies on EPG in retrofitted buildings, occupant behaviour and energy consumption, POE and rating systems, OBI, and socio-technical approaches to identify gaps in knowledge and opportunities for an innovative POE framework assessing behaviours leading to EPGs in retrofitted residential buildings. It was found that despite an increasing interest in the impact of occupant behaviours on energy consumption in buildings, there is a critical need for research assessing energy-related behaviours, magnitudes, and resulting energy savings from behavioural interventions.

Keywords: Energy performance gap; occupant behaviour; post-occupancy evaluation; retrofit.

1. Introduction

The Paris Agreement (UNFCCC, 2015) urged the need to reduce greenhouse gas emissions, limit the rise in temperatures, and increase the ability to adapt to the impacts of climate change. In this regard, improving energy efficiency in buildings has become a critical strategy (Yoshino *et al.*, 2017), as the building sector is responsible for over 30% of the final energy consumption and close to 40% of total CO_2 emissions in its entire life cycle (IEA, 2020).

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It is estimated that the existing building stock will compose 70% of buildings in 2050 (Visscher *et al.*, 2016), and currently, about 61% of the construction projects are renovations (Regnier *et al.*, 2018). Thus, building retrofit must be the leading strategy to achieve projected energy savings and emissions reductions. In this regard, the residential sector has emerged as a crucial niche for building retrofit and climate change mitigation (Ahern and Norton, 2020). The impact of occupants' behaviours on energy consumption in this sector is critical as occupants have more interactions with energy-consuming systems (e.g. HVAC and appliances), and behaviours are highly variable and uncertain compared to other sectors (Mo and Zhao, 2021).

Studies have demonstrated a discrepancy between estimated and actual energy savings (Zou *et al.*, 2018b), known as the Energy Performance Gap (EPG), representing risk in tackling climate change challenges. Although several factors contribute to the EPG, occupant behaviour is increasingly recognised as crucial for achieving efficient buildings (Hong *et al.*, 2017; Salvia *et al.*, 2020). Therefore, interdisciplinary studies and holistic methodologies are needed to understand better the links between occupants and buildings (D'Oca *et al.*, 2017; Day *et al.*, 2020).

This paper aims to gather, review and discuss extant literature about EPG in retrofitted buildings, occupant behaviour and energy consumption, POE and rating systems, OBI, and socio-technical approaches to identify gaps in knowledge and opportunities for an innovative POE framework assessing behaviours leading to EPGs in retrofitted residential buildings.

2. Building retrofit and Energy Performance Gap

Building retrofit has become one of the principal actions toward sustainability in the built environment (Xing *et al.*, 2011). However, it must meet the predictions as many governments have set energy conservation goals and strategies based on performance to face the growth in energy demand and consumption (Zou *et al.*, 2018b). A margin of error is perhaps inevitable between predicted and measured energy consumption due to uncertainties in the design and operation of buildings, limitations of measurement systems (van Dronkelaar *et al.*, 2016), simulation errors, and variations in observations (Wilde, 2014). However, such a margin goes beyond the acceptable boundaries (i.e. ±10% according to Van den Brom *et al*. (2019)) and can be as much as 2.5 times higher than predicted (Wilde, 2014).

The EPG in the residential sector has still not been well understood due to some peculiarities, such as the impact of occupant behaviour, privacy issues blocking data collection, and the variety of building characteristics (Swan and Ugursal, 2009). Studying the EPG in this sector is vital because identical dwellings with similar installations have shown significant energy use variations (Rinaldi *et al.*, 2018). Such variations are characteristic of residential buildings due to the diversity of occupant behaviours (Rouleau *et al.*, 2018) and, more specifically, the interaction between these behaviours and the building technology (Bauer *et al.*, 2021). Although it is evident that occupants' behaviours play a critical role in residential energy consumption, assessing such energy-related behaviours (e.g. profiles and patterns) and their magnitude remain a crucial challenge (Osman and Ouf, 2021) and a significant research and knowledge gap.

2.1 Rebound and prebound effects

The EPG phenomenon leading to significantly fewer energy savings cannot be understood entirely without two critical concepts: the rebound and prebound effects. The rebound effect may be defined as the increased demand for a building energy service as a direct consequence of improving its efficiency (Calì, Osterhage, *et al.*, 2016). Therefore, it is an induced demand in energy consumption primarily affected by occupant behaviour. In turn, the prebound effect is the underconsumption of energy services before a retrofit is done or in the total absence of it (Cozza *et al.*, 2020). Sunikka-Blank and Galvin (2012) introduced the concept after finding that the energy performance rating considered greater energy consumption pre-retrofit, hence driving fewer energy savings post-retrofit "as retrofits cannot save energy that is not actually being consumed" (Sunikka-Blank and Galvin, 2012, pp. 270). Occupant behaviour is also critical for the prebound effect, as demonstrated by Teli *et al*. (2016). They conducted a pre-retrofit study in a UK social housing building where they gathered thermal information and created occupant behaviour profiles to be used in the simulations. The simulation results showed that the actual energy savings would be around 40% less than predicted when using standard guidelines rather than actual occupants' behaviour. The researchers concluded that more studies assessing OBI in social housing are needed to inform carbon reduction programmes and reduce the EPG.

3. Occupant behaviour and energy consumption

The strong influence of occupant behaviour on energy consumption in buildings is now well recognised (Yan *et al.*, 2015), and several researchers determined that one of the main reasons for the EPG is occupant behaviour. Occupant behaviour is critical for energy consumption in residential buildings as this sector presents a high variability of actions like occupancy patterns, control of windows and doors, lifestyle, thermal comfort preferences, or interaction with building systems (Stazi *et al.*, 2017; Rouleau *et al.*, 2019). While improvements in the building's characteristics and materials, like those made in retrofits, substantially affect the energy performance in dwellings, such a techno-centric approach does not necessarily affect occupants' behaviour (Miller *et al.*, 2021). Despite all of this, only a few studies have focused on proposing and testing a solution based on energy-related occupant behaviour even though it seems crucial for closing the EPG, and that focusing on occupant behaviour is more cost-effective than merely technological approaches (Sunikka-Blank and Galvin, 2012).

Chen *et al*. (2021) classify energy-related occupant behaviour into three groups: occupancy, interactions, and behavioural efficiency. Occupancy refers mainly to the physical presence of occupants in buildings with parameters such as number, location, and duration of stay. In turn, the interactions group is more complex, referring to how occupants interact with systems and building technologies such as HVAC, lighting, and windows. Finally, behavioural efficiency refers to a qualitative group with parameters related to education and training. This group can jeopardise the building's energy efficiency but, at the same time, hosts the most cost-effective actions for new and retrofitted buildings, focusing on detecting and resolving inefficient energy behaviours through occupant awareness. In this regard, the authors acknowledge that more studies assessing energy savings achieved by behavioural interventions are needed.

Zou *et al*. (2018a) conducted a literature review of energy-related occupant behaviour from peer-reviewed papers published between 2007 and 2017. The papers were classified according to the research methodology adopted: quantitative (83.48%), qualitative (0.87%), mixed (5.22%), and review or conceptual (10.43%). The results show that although the nature of the topic is multidisciplinary, there is a lack of mixed-method studies explaining why and how energy-related occupant behaviours are generated. The following section discusses how commonly-used evaluation schemes address the impact of occupants' behaviour on energy consumption in new and retrofitted buildings.

4. Post-occupancy evaluation and green building rating systems

POE is an alternative to facing the EPG by providing designers with factual information about buildings' performance during the operational stage (Menezes *et al.*, 2012). Its importance has grown in the last few years as the data collected can be compared against estimates (Miller *et al.*, 2021). However, it has been acknowledged that, aside from energy performance and occupant satisfaction, other aspects, such as occupant behaviour and systems operation, can and should be assessed in POEs (van Dronkelaar *et al.*, 2016). The link between POE and building retrofit was introduced by Chiu *et al*. (2014). According to them, the building retrofit practice is currently limited by a black-boxing effect (i.e., the more technological development, the more blurred and obscured it gets) that will only succeed from the associations between physical elements of buildings, technology, and occupants, while effective POEs allow that option. In other words, unravelling the impact of physical parameters of the buildings and occupant behaviour on energy consumption requires POEs adopting a new perspective with close integration of contextual, societal and physical elements. However, most POE projects published mainly focus on indoor environmental parameters and energy use without exploring the links with occupant-related parameters such as driving factors and comfort (Colclough *et al.*, 2022).

Green Building Rating Systems (GBRSs) are other assessment tools used in the built environment with increasing interest in occupant-related parameters and retrofitted buildings. The official manuals from some of the most commonly used GBRSs (e.g. LEED, BREEAM, Green Star, WELL, Living Building Challenge) show that versions have been created to evaluate the performance in existing and retrofitted buildings (e.g. LEED O+M, BREEAM In-Use, Green Star Performance, WELL Performance Verification) and that parameters such as occupants' satisfaction, occupant's comfort, and occupants' feedback have been incorporated. However, there is still more to do to move from satisfaction evaluation and training to objective correlations highlighting wasteful behaviours.

5. Occupant-building interaction

The Occupant-Buildings Interaction (OBI) was not recognised and investigated until the last decade, going from 156 papers published in 2009 to 475 in 2019 (Harputlugil and de Wilde, 2021). Such interaction with buildings is necessary to preserve and enhance occupants' productivity, health, and well-being, but at the same time, it significantly impacts the performance of buildings (Harputlugil and de Wilde, 2021), which can be pretty significant even if parameters such as weather conditions, building materials, and system characteristics are accurate (Yan *et al.*, 2015). For instance, buildings with higher temperature setpoints or higher levels of window operation consume more energy than others (Calì, Andersen, *et al.*, 2016). In other words, it is not the occupant behaviour alone that causes the EPG but the conscious and unconscious occupant practices developed from the interaction with the building's elements (Bauer *et al.*, 2021).

There is still a lack of understanding of the complexity of the OBI (Harputlugil and de Wilde, 2021), and the way occupants behave while controlling the building's systems is very different from the modelled one (Stazi *et al.*, 2017). Moreover, only a few building elements are intuitive; therefore, learning how to use them is crucial to ensuring the correct building energy performance (Glad, 2012). The elements and systems that have been identified as part of the OBI are luminaires, windows, blinds, domestic hot water, thermostats, fans, electrical appliances, and doors (Yan *et al.*, 2015; Rouleau *et al.*, 2019; Chen *et al.*, 2021; Mahdavi *et al.*, 2021).

5.1 Classification and driving factors for the occupant-building interaction

Mahdavi *et al*. (2021) classified OBI into four categories: envelope (i.e., operation of elements directly in contact with the exterior), mechanical systems (i.e., interaction with HVAC controls), plug loads and lighting (i.e., interaction with appliances and lighting controls), and internal heat gains (i.e., occupant density and schedules that lead to internal heat gains). Many driving factors can influence the OBI, and researchers have no universal agreement on the specific factors (Stazi *et al.*, 2017). For instance, Van Den Brom *et al*. (2019) identified demographics such as income, employment, and occupancy to impact energy consumption in the residential sector. Alternatively, Rinaldi *et al*. (2018) and Day *et al*. (2020) divide them into internal (e.g., biological and psychological aspects) and external factors (e.g., contextual and environmental conditions).

In turn, Stazi *et al*. (2017) gathered from a literature review a more robust classification of driving factors, including environmental factors (e.g., air temperature), time-related factors (i.e., actions repeated in specific periods), contextual factors (e.g., ease of control), physiological factors (e.g., sensitivity to brightness), psychological factors (e.g., need for privacy), social factors (e.g., organisation policy), and random factors (i.e., actions depending on uncertain factors). However, it is acknowledged that among these factors, the physical ones are objectives and strongly affect occupants, whereas the contextual, psychological and physiological factors are subjective and are rather influential.

5.2 Personality traits, profiles and patterns

Personality traits can be a compelling parameter for predicting energy consumption (Milfont and Sibley, 2012), particularly considering that the classifications of driving factors include psychological and social factors. The most accepted classification for personality traits is based on the 'Big five personality traits' theory, divided into neuroticism, agreeableness, conscientiousness, openness to experience and extraversion (Shen *et al.*, 2020). According to Milfont and Sibley (2012), the agreeableness trait refers to cooperative, pleasant and compliant occupants seeking their well-being. Conscientiousness refers to organised, responsible and meticulous occupants tending to long-term planning. The openness trait refers to imaginative and intelligent occupants engaged with novel endeavours. The extraversion trait refers to active, outgoing, and confident occupants tending to maximise social interactions, and the neuroticism trait refers to insecure and anxious occupants.

Occupancy profiles and patterns are other important concepts for OBI. Occupant profiles group people according to demographics based on parameters previously identified as driving factors. According to Yoshino et al. (2017), simulations tend to use standard occupancy profiles to simplify reality with fixed values concerning energy-related behaviours such as setpoints or control of windows and blinds (Yoshino, Hong and Nord, 2017). Although more complex and dynamic simulation tools are increasingly used to accurately predict thermal comfort and energy use, more information on OBI is needed to benefit further from simulations. For instance, methodologies incorporating sensitivity and uncertainty analysis have highlighted the importance of model calibration in existing buildings (Yoshino, Hong and Nord, 2017). Such calibration requires more and more detailed assessment tools gathering information on occupant behaviours and their interaction with building elements. Moreover, the simulation output is the result of assumed behaviours (aside from technical and environmental parameters); thus understanding behaviours in different contexts is also critical as it cannot be assumed that individual personality traits can apply to broad generalisations in profiles between cultures (Milfont and Sibley, 2012).

Occupancy patterns are long-term behavioural effects that characterise actions and reactions on a specific time scale (Harputlugil and de Wilde, 2021). Such patterns are directly linked to the behavioural efficiency classification and can be redefined over time due to improved awareness or training, and their definition requires comprehensive monitoring. Both characteristics indicate that incorporating the assessment of occupant behaviours into POE frameworks would allow the definition of occupancy patterns and how they change over time. Previous attempts to classify patterns include Galvin (2013), who used a simple pattern classification based on the energy-use intensity dividing consumers into light, medium or heavy consumers. In contrast, Vogiatzi *et al*. (2018) proposed six patterns based on data gathered through surveys applied to residents of Athens, grouping them into environmentally friendly, adopting energy-saving practices, having economic motivation behind energy-saving practices, environmentally uninvolved, and environmentally unaware.

6. Socio-technical and cognition-centred approaches

Given the contextual and environmental nature of the topic, socio-technical and interdisciplinary studies are now conducted, integrating multiple theories around energy efficiency in buildings and OBI (D'Oca *et al.*, 2017). However, a paradigm shift is crucial to stop seeing the occupant as a source of heat gain content in a standardised indoor space (O'Brien *et al.*, 2020) and to start defining the OBI as mutually constitutive, shaping and changing each other (Salvia *et al.*, 2020). In this regard, Gupta et al. (2015) presented the intent and outcomes of a deep retrofitting social housing programme in the UK. They found an EPG and concluded that future retrofitting programmes must adopt a socio-technical approach considering building and occupants addressing social and physical factors influencing energy performance. It is estimated that a socio-technical approach coupling technical infrastructure and behavioural change could result in over half a reduction of the final energy demand from the entire building sector by the end of this century (Levesque *et al.*, 2019) and around a 20% reduction in the US residential sector (Hong *et al.*, 2017).

Behavioural change has proven to result in more benefits than installing new technologies. Therefore, guiding occupants to identify energy-related harmful behaviours and applying other strategies, such as financial incentives, can promote informed occupant-building interactions in residential and non-residential buildings (Chen *et al.*, 2021). According to Sangalli *et al.* (2020), future directions and current efforts for this approach require identifying occupancy patterns, needs, perceptions, and cultural values, which can provide valuable information about the variation in energy use in residential buildings. Thus, the need to have POE methodologies gathering data on energy-related occupant behaviours is evident.

According to Khani et al. (2021), although behavioural change in buildings is challenging and unsteady, it can be achieved with systematic monitoring of behaviours and savings. Moreover, researchers from engineering and psychology have also agreed that understanding and influencing behavioural change is firmly dependent on culture and context, as different applications may be practical on different occupants even within countries (Milfont and Sibley, 2012). These perspectives support the implementation of POEs from a socio-technical approach accounting for the interaction between social practices and physical elements, something critical to understanding the EPG and practical issues in residential retrofit (Chiu *et al.*, 2014). Opportunities for socio-technical approaches come from the expertise of social sciences, architecture, and technological development, capturing objective and subjective aspects of OBI (D'Oca *et al.*, 2017). Thus, interdisciplinarity represents an alternative to merging knowledge in novel ways to have holistic research connecting occupants and energy systems (D'Oca *et al.*, 2017). However, it is required to benefit from historically-informed theories and problem-oriented thinking for sustainable transitions (Smith *et al.*, 2010).

An alternative route for behavioural change is to focus on cognition. A multidisciplinary project supporting this was introduced by Schoot Uiterkamp and Vlek (2007). The project called "HOusehold Metabolism Effectively Sustainable" (HOMES) was active between 1994 and 2000, analysing occupants' energy consumption in the residential sector while connecting the data to environmental impacts. Findings revealed that occupants generally decide about energy-related behaviours based on their cognitive system; thus, interventions using feelings and cognition are a promising direction to obtaining pro-environmental behaviours (Habib *et al.*, 2021). Authors like Mitchell (2021) have indicated that one of the challenges for behavioural change comes from traditional epistemology separating mind and body to resolve sustainability challenges such as the EPG. Instead, technical infrastructure must promote behavioural change through user-friendly, stimulating, easy-to-adopt, culture and context-focused building elements (Barthelmes *et al.*, 2019) while perceived as self-decided.

7. Conclusions

This paper reviewed previous studies on EPG in retrofitted buildings, occupant behaviour and energy consumption, POE and rating systems, OBI, and socio-technical approaches to identify gaps in knowledge and opportunities for an innovative POE framework assessing behaviours leading to EPGs in retrofitted residential buildings. This study highlights that, despite an increasing interest in the impact of occupant behaviours on energy consumption in buildings, there is a critical need for research assessing energy-related behaviours, magnitudes, and resulting energy savings from behavioural interventions. In this context, an innovative approach for POEs assessing behaviours leading to EPGs in buildings emerges as a viable solution for closing several gaps in knowledge, such as the lack of mixed-method studies explaining why and how energy-related occupant behaviours are generated or the need for assessment tools gathering information on occupant behaviours and their interaction with building elements. Despite this, it was found that most of the published POE projects mainly focus on indoor environmental parameters and energy use without exploring the links with occupant-related parameters such as driving factors and comfort, and GBRSs only consider parameters such as occupants' satisfaction and feedback.

Focusing on residential retrofitted buildings is also of great importance as building retrofit has become a leading sustainable action towards tackling climate change, and occupant behaviours have a critical impact in residential buildings due to the increased interaction with building elements and high variability of actions, even within contexts and cultures. In this regard, researchers have highlighted the need for POEs to adopt socio-technical approaches to identify occupancy patterns, needs, perceptions and cultural values. Such an approach can provide valuable information about the variation in energy use in residential retrofitted buildings to be used in other innovative approaches linking occupant behaviour and energy consumption, such as dynamic simulation tools based on adaptive behaviours, behavioural interventions or future directions like cognition-centred approaches and usability of building systems.

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