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A review on the approaches in analysing energy-related occupant behaviour research

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ABSTRACT

The effect of occupant behaviour on the energy performance of a building is one of the most important and critical parameters in building energy studies. Occupant behaviour, driven by dissatisfaction can lead to significant disconnect between the predicted and actual building energy performance. To monitor occupant behaviour as a variable in energy performance studies, it is imperative to select the appropriate method of data collection and interpretation. This paper investigates the research conducted on energy related occupant behaviour, which can be utilised for energy performance studies and simulations. Specifically, this review focuses on the findings of the works conducted post-2015 in separate sections within this paper and attempts to shed light on the various occupant behaviour analysis methods employed by the researchers, with the aim of transferring the data obtained into building energy performance simulations. An overview of selected studies is given in the form of a comprehensive review matrix, linking those with six different types of simulation methods, the different variables and the experimental investigations considered for the study.

1. Introduction

The energy related occupant behaviour depends on the occupant expectations towards the indoor environment, building design considerations, indoor air quality, properties of HVAC systems, lighting control, as well as their perception of comfort under specific conditions [1]. Studies have linked these factors with occupant productivity, health and comfort [2–4]. Indoor environment and energy consumption related occupant behaviour research combine multiple disciplines, besides built environment and HVAC automation, and controls it also involves physiology and social psychology. The latter plays an important role in driving the occupants to interact and adapt to the indoor environment. It is collectively driven by the attitudes and perception towards comfort and building controls [5]. Exploring the different aspects of occupant behaviour is necessary to understand it better and to develop accurate tools for building energy performance predictions. In the paper [6], Hong et al. (2015) has focussed on the advancements in data collection techniques, analytical and modelling methods, and the simulation techniques for occupant behaviour. Also, they have considered only commercial and residential buildings, for the review. There have been many publications since 2015 that have built on the improvements mentioned in their review. The review matrix explained in the later chapters of this paper, clearly shows how the publication trend is progressing. The current review paper also discusses the approaches not mentioned in Ref. [6].

In a subjective sense, the occupant perception of indoor comfort and satisfaction depends on their environment as the thermal comfort influences the psychophysiological response of the occupants [7,8]. Objectively, occupants may develop coping mechanisms which are directly linked to their attitude and social norms, as studies have revealed that the occupants tend to adapt or interact with their surroundings until the environment around them reaches their perceived level of personal comfort [9,10]. This reaction of occupants could be in the form of changes to the clothing levels, window operation, altering temperature controls etc. [11]. However, while interacting with building controls, occupants are usually facing trade-off between thermal comfort air quality or acoustic comfort. These interactions can also be different in single and open-plan offices, and in turn, can be a major disruptor in building energy performance studies [12]. This review paper investigates two aspects of energy consumption related occupant behaviour research. The first one being the outlook of the ways occupant behaviour studies are usually carried out – climate chambers vs in-situ,

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indoor climate parameters triggering the behaviour etc. The comprehensive review matrix of the recent studies has been developed to tackle this task. The other aspect was to analyse how these behavioural aspects can be transferred into building energy performance simulations, and how the diversity of occupants can be modelled. In the discussions section the most common and least analysed approaches employed within the original research of energy related occupant behaviour are outlined, as well as possible ways forward for this research area are discussed.

2. Parameters affecting energy related occupant behaviour simulations

Considering the factors affecting occupant behaviour, various methods of data collection/analysis are available. These methods elaborate the common techniques that have been employed for mapping energy consumption data while involving the occupant behaviour as a parameter. But ultimately the end goal of any of these studies is to conserve energy through sustainable solutions. As the world population is galloping towards the 10 billion mark by 2050, the quality of life would eventually worsen, if left unaddressed, especially in the cities which are expected to house over 6.5 billion people. Statistics from the United Nations show that in the year of 2016 alone, the buildings sector consumed about 30% of the total energy use and produced 28% of global CO_2 emissions [13]. This strengthens the case for a better understanding of the behaviour of building occupants, as they have the potential to conserve about 10–25% of energy [14]. By forecasting the energy use, the occupants and service providers can anticipate the energy consumption rates beforehand. This could prove to be beneficial in capping the usage to limit the energy wastage [15]. Being a subjective attribute, the occupant behaviour depends heavily on the psychological and physiological aspects of the occupants. In addition to that, it also depends on various other behavioural constructs such as the social norms, attitudes, and perceived behaviour [16]. To understand and map the behaviour accurately, there is a need for more research and review into the various methods that simulate occupant behaviour, as the reliability of the methods depends on their accuracy. If more emphasis is laid on the energy conservation without compromising on the occupant's comfort, then the occupants are more likely to be actively involved in the process. It can be effectively mapped using accurate predictive behaviour models. Previous review studies based on occupant behaviour have focussed on the human building interactions [17], behaviour theories [16,18], tools and methods for building performance simulations [19], etc., but there has been limited research comparing and analysing the data collection methods, reviewing their findings in a way that shows pathways to increasing the accuracy of building energy performance simulations by including more precise occupant behaviour predictions.

2.1. Occupant adaptation as a driver for energy related behaviour

A systematic approach to explore the factors affecting energy related occupant behaviour in buildings, the ways to track this behaviour and its implications, is provided in Fig. 1 Workflow of adaptation processes for building occupants. As it can be seen, occupant interaction with HVAC controls, windows opening, clothing adjustment etc., are considered part of the behavioural adaptation, which has direct impact on energy consumption. It is quite challenging to obtain the energy consumption data from simulation methods with high accuracy. To carry out any kind of simulation and to model the occupant behaviour for research, it is

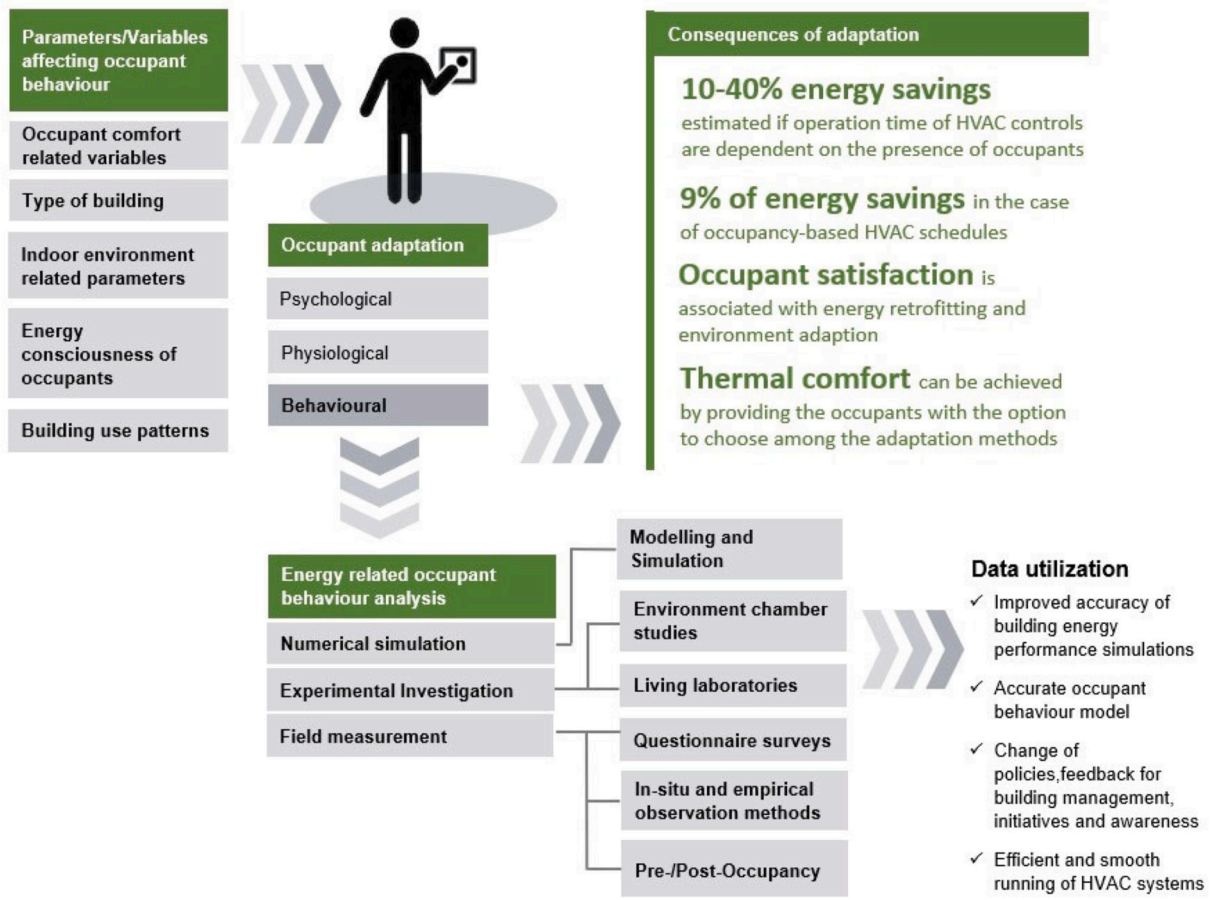


Fig. 1. Workflow of adaptation processes for building occupants.

necessary to take as many parameters into account as possible, as each of them influence the overall prediction accuracy. The quality of data collected, primarily, depends on the vital parameters such as the indoor environmental conditions and the location of the building [20]. A study defines this scenario as the 'perception of comfortable surroundings for human beings', that can only be achieved when the occupant alters physical parameters of the indoor environment such as, lighting, temperature, etc. This depends on the occupants' past experiences of a comfortable environment [21]. There are various other factors which influence occupant perception, e.g., equipment control, clothing adjustment, air quality, thermal comfort, adaptive practices of users, lighting and acoustics [22] are a few of the most common occupant related metrics. For a better understanding of these factors, a broad classification has been made which is designed in the form of a matrix (as shown in Table 1 Review Matrix of the selected original research papers, published within 2015–2020 in the field of energy related occupant behaviour). The matrix also shows the combination of parameters which have been more frequently monitored in the occupant behaviour studies and the methods of testing/approach used for a corresponding set of parameters considered for each study. These are given in vertical columns with the parameters named at the top of each column. Depending on the nature of the approach/method, the published studies have been grouped into four categories:

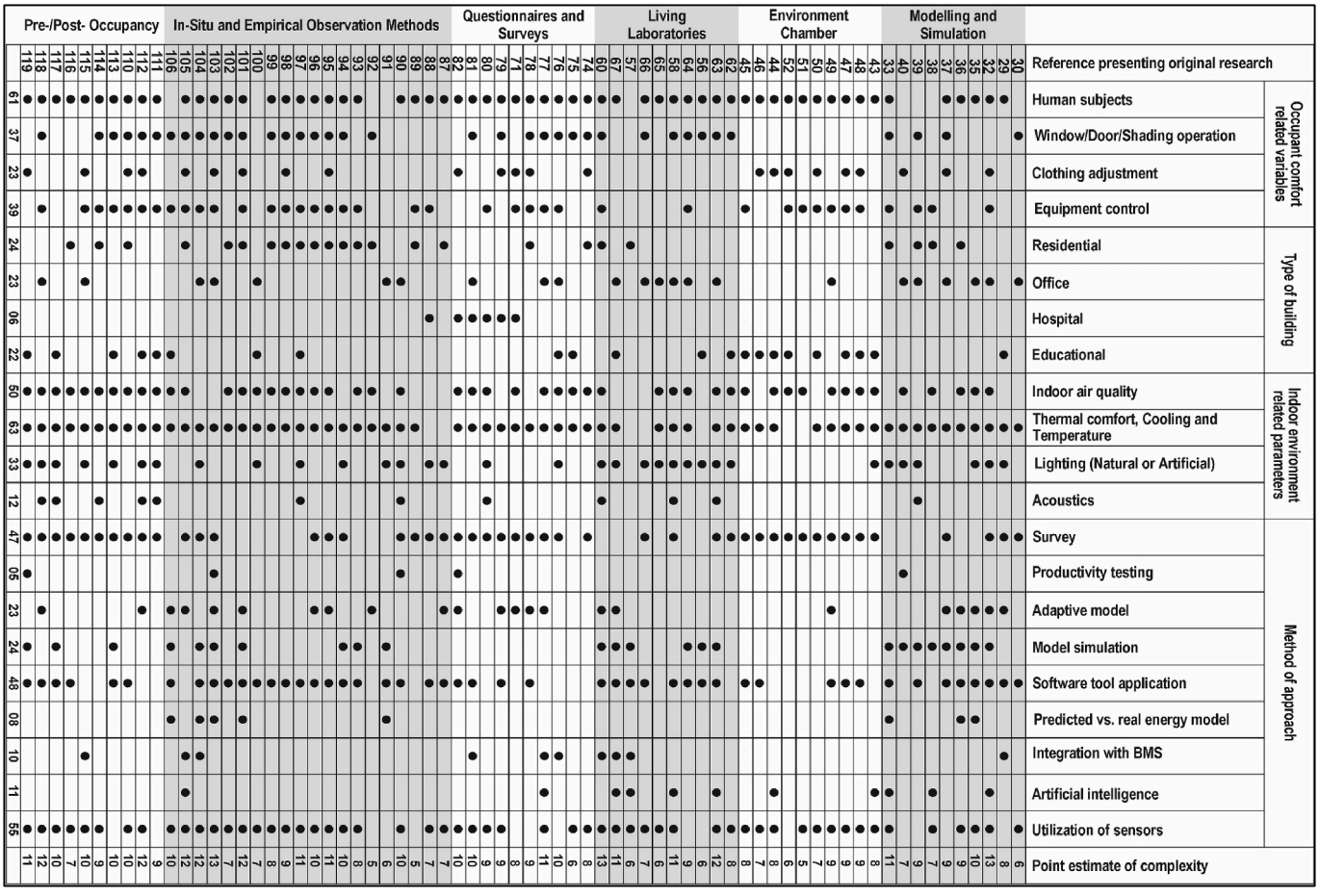
1. Occupant comfort related variables: The basic variables that have been commonly used in the studies for the experiments, such as, considering a building's window/door/shading operation in the experiment, allowing clothing adjustment for the occupants, or giving the equipment control (like, temperature control, lighting control, etc.) to the occupants, have all been grouped under this category. For a particular study to receive a point for each these variables in the review matrix, they should have that variable included in their study.

2. Type of building: While trying to understand the trend of popular methods, approaches and variables as shown in the review matrix, it will also be interesting to understand what type of approaches are being used for certain types of buildings. For instance, sophisticated technology and methods are needed for commercial or offices while simplified methods are sufficient for residential buildings. The 'Hospitals' category covers a wide range of medical facilities including, nursing homes, clinics, etc. and 'Educational buildings' include, research facilities, university dormitories, etc.

3. Indoor environment related parameters: Among several parameters affecting the occupant comfort, some of them have been repeatedly focussed on by many authors. Indoor comfort parameters such as the CO_2 level, humidity, air volume, etc. have been grouped under 'Indoor air quality'. Similarly, the cooling levels, temperature measurement, etc. have been grouped under the 'Thermal comfort' category, while artificial lighting, natural lighting, etc. have all been grouped under the category of 'Visual comfort'. While awarding points if a paper includes the measurement of parameters such as CO_2 levels, for instance, a point would be awarded to the category of 'Indoor air quality' for the corresponding paper.

4. Method of approach: For a paper to have selected a particular combination of the above-mentioned parameters and variables, there would also be a suitable approach to conduct experimentation for

Table 1
Review Matrix of the selected original research papers, published within 2015–2020 in the field of energy related occupant behaviour.



analysis. The authors have selected one or more forms of approaches for the experiments. A large portion of the papers have conducted surveys either in the form of online surveys, paper-based surveys, interviews, or diary entries.

Some of the authors have made use of the modelling software packages, for simulation and analysis of the building models, while there are also other software applications which have been used for the purpose of statistical and numerical analysis. Many authors have also made use of the sophisticated technology and tools for data gathering such as the building and energy management systems, environment and body sensors, and artificial intelligence tools (neural networks, Fitbit, smart technology, etc.). There are also few important yet over-looked approaches such as testing the productivity of occupants, creating an adaptive building model, and studying the energy performance gap between real and predicted energy model of buildings.

3. Methodology

As discussed in the previous sections, different ways of approaching the energy related occupant behaviour tracking exist. This review paper provides condensed insight into selected original research papers in a form of a review matrix (Table 1 Review Matrix of the selected original research papers, published within 2015–2020 in the field of energy related occupant behaviour). The review matrix was developed by arranging the major parameters and variables affecting occupant behaviour and its observation and prediction methods into rows and columns. It allows the reader to see the dominant trends of original research carried out over the past 5 years – what indoor environmental parameters are tested the most, what types of buildings are usually analysed, what are the dominating research approaches etc. The structure of the review matrix indicates the gaps in original research, as well as allows scoring the original review papers by the level of complexity.

The papers considered for this analysis have been selected from across the databases of Scopus, Springer, ScienceDirect and Web of Science. Upon entering the key terms, “occupant behaviour”, “energy performance of buildings”, “indoor environment”, “occupant comfort”, “occupant behaviour simulation”, the search had returned thousands of results that also included papers from other fields of engineering. Advanced search tools within the online databases were used, by using the AND-NOT functions, to refine the results. This excluded the papers not relating to buildings or building occupants. There were still hundreds of results, reaching as far as the year 1997. To keep the review limited to the present and latest research, the papers published post-2015 were taken into consideration. For each of the different types of simulation methods, the key terms were changed depending on the type of simulation, “building modelling and simulation”, “building occupant surveys”, “living laboratories”, “occupant behaviour monitoring environment chamber”, “building performance pre/post-occupancy”, “occupant behaviour in-situ observation methods”, etc. At this point, for further streamlining the review process, the review matrix was brought into the picture. The most popular and recurring parameters were selected, and the review matrix scored each study in the form of bullet-points based on those parameters (*listed as column heads in Table 1 Review Matrix of the selected original research papers, published within 2015-2020 in the field of energy related occupant behaviour*). The process of filtering and selection was done through review matrix from the large pool of papers. One bullet-point is assigned to the study if it includes the corresponding parameter in its research or experiments. The total number of points achieved by each study is provided in the last column to the right. The higher the total number of bullet-points per study, more complex is the approach utilised in that specific publication. From the final obtained list, for a study to be considered for the review, it should have gained at least five points from the review matrix. After this rigorous process of short-listing, 70 papers have been selected for a detailed analysis in separate sections in Section 4 as reported in this review. Each section is dedicated to a particular data gathering method/approach. Also, the total number of papers which include a particular parameter in their study is provided in the bottom row. The points in the bottom row indicate the frequency of occurrence of a parameter in the set of 70 selected research papers. This allows for identifying the dominating research approaches and research gaps in the field.

4. The outline of the original research trends in the field of energy consumption related occupant behaviour

4.1. Advances in building energy modelling and simulations

There are various methods available for collecting and analysing building energy performance data, which in turn can be linked to occupant behaviour. Surveys, and energy monitoring devices, sensors, smart controllers, living laboratories, to name a few, can provide valuable insights into occupant behavioural effects on energy use in buildings. In turn, this data can be further utilised to enhance simulations and predictions. To realistically predict occupant behaviour patterns in relation to energy consumption, there are numerous variables to consider. Collecting the appropriate data, developing simulation methods, and verifying the simulation results is where the challenge lies. In most cases, the energy performance gap between the simulation results and the real case data can be attributed to the insufficient data collected, or failing to involve qualitative data (for instance, the user’s habits) in the energy calculations. The performance gap can be reduced by maintaining the accuracy of the data being fed to the modelling and simulation tools, by including qualitative data. One of the ways to increase the accuracy of data collection and the simulation results is by monitoring electricity meters and sub-meters along with the occupancy patterns [23]. Also, the Indoor Environmental Quality (IEQ) parameters have the potential to effect the energy performance through occupant behaviour which if considered for energy calculations, can aid in closing the performance gap [24]. Numerous studies with different approaches have stated that the occupant satisfaction, psychological or physiological, with the indoor climate has an influence on the energy consumption rates. It implies that energy consumption can be linked to occupant satisfaction or adaptive behaviour [25,26]. Yet, by simply imparting a sense of responsibility towards energy savings or creating awareness about the building’s consumption rates has shown to be effective in reducing the overall energy consumption [27]. Since the occupant behaviour is a pivotal variable in the building energy studies, selecting an appropriate method for data collection and simulation is essential. There are several variables which could be involved in these methods, but only a few recurring variables have been considered for the review. The methods analysed in this paper, give an insight over the common variables used by different researchers for each approach.

Over the years, the numerical simulation tools for the simulation building energy performance have witnessed innovative solutions which are far more advanced than the conventional methodologies. The conventional ways of simulation had deterministic data sets filled with uncertainties and input variabilities [28]. Recent studies have shown the Agent-based Modelling (ABM) method to be gaining popularity. Being simulation-based, the method is mostly employed in research for its dynamic nature by considering multiple attributes for each of the agent involved in the study and the interaction among other agents assumed for the study. In the studies [29–31], the ABM method has been used along with other software platforms (as shown in Table 2 Methods used in selected papers with regards to Advances in building energy modelling and simulation). Another advancement is with the use of Artificial Neural Network (ANN) models in the building energy performance simulations [32,33]. The historical/realistic data is to be fed to the ANN model to compare the results with the raw data obtained, often through calculating the mean, median, standard deviation, and the confidence range. The comparison helps in reducing the gap between energy performance results. The reliability of the results achieved through the ANN

Table 2
Methods used in selected papers with regards to Advances in building energy modelling and simulation.

Reference number	Summary	Software tools/ Modelling methods	Country
[30]	The focus is on the physiological and psychological aspects of occupant behaviour, in addition to external factors, which are evaluated in the form of a new Agent-based Modelling (ABM) method.	• PMFserv • ABM	United States
[29]	Aimed to establish realistic guidelines for building energy management, by comparing different energy consumption scenarios through ABM method.	• AnyLogic • ABM	China
[32]	The method uses EnergyPlus and Artificial Neural Network (ANN) models to simulate and analyse the energy performance gap.	• EnergyPlus • ANN model	United States
[35]	An energy model was developed to collect the duration of operation of various indoor units and the thermostat settings upon the influence of occupant behaviour.	• Designer's Simulation Toolkit (DeST)	China
[36]	The method combines various datasets from measured, statistical, and logistic regression data, to model the occupant behaviour using EnergyPlus.	• EnergyPlus	China
[37]	Analysis of occupant behaviour and satisfaction with environment based on a field study.	• EnergyPlus	Qatar
[38]	Infrared thermography and sensors were used to study the building performance after retrofitting.	• Deep Level ANN model • Infrared thermography	United Kingdom
[39]	Aims to propose a modelling approach by integrating certain environmental factors for maximizing natural ventilation and indoor comfort.	• TRNSYS	France
[40]	Proposes a method to optimize energy consumption cost and occupant productivity by focussing on the occupant preferences within a building.	• MATLAB • Multi-Objective Optimization (MOOP) method	Canada
[33]	Proposes an ANN model integrated with BIM for increasing accuracy of energy performance prediction by accounting for occupant behaviour influence on energy consumption in buildings.	• Integration of BIM and ANN models	Australia

models depends on the training and validation of the data being fed into the model [34].

It is evident from the above-mentioned studies that for observing multiple occupant behavior patterns to be modelled and simulated, Complex Adaptive Systems (CAS) and Agent-Based Modelling (ABM) are advisable. The studies which comprise multiple case study buildings and focus variables, complex datasets are expected to be obtained. For such cases, the Artificial Neural Networks (ANN) modelling is suggested, as the ANN is a powerful method to handle nonlinear datasets. It also allows for multiple complex variables to be involved in the study. Some studies have also used linear and logistic regression methods but with their own limitations. The linear regression is limited to predicting the probability values outside acceptable range, i.e., 0–1, while the logistic regression is often preferred as it predicts the probabilities in between 0 and 1. But when compared, ANN models deliver significantly higher accuracies.

4.2. Environment chamber studies

The climate chamber studies allow for experiments to be done with desired indoor environmental conditions. Within these conditions, thermal environment, indoor air quality, lighting, etc. can be set to required levels [41], and the chamber maintains these levels to monitor and observe the changes in the occupant behaviour [42]. The possibility to closely monitor the occupants and the data, increases the chances of obtaining accurate results. Also, various other behaviour patterns could be monitored through climate chamber studies, which would otherwise be difficult to monitor in the natural setting of occupants, for instance sleeping behaviour or virtual reality influence. Some studies require specific equipment installations for carrying out the experiments, for instance, a thermoelectric air duct cooling system (TE-AD) [43,44]. The methodologies used in these studies are briefly explained in Table 3 Methods used in selected papers with regards to Environment chamber. In some of these studies, researchers have focussed on the sleeping behaviour of occupants and monitored them in a climate chamber, with the use of various sensors for monitoring thermal variables. Their findings reveal that the sleep satisfaction was higher with the presence of TE-AD system. Also, when compared to the female subjects, the male subjects preferred cooler sleeping environments. Apart from gender as a parameter, studies have also revealed that the thermal background, perception of control and thermal expectations of the occupants would have an impact on their energy consumption levels [44,45]. Similar climate chamber studies have compared the difference in the thermal responses of subjects when subjected to virtual reality environments and real indoor environments [47,48]. While focussing on heart rate and skin temperature of the subjects, the studies have given that their physiological response to the thermal conditions have significant differences between both the virtual reality and real indoor settings. The major limitation with climate chamber studies is the sample size. Since the chambers can have limited test subjects at a time, increasing the sample size would mean increasing the period of study that would only make the experiment tedious and unsuitable for such meticulous experiments.

The above-mentioned studies have pointed out that the thermal sensation of occupants inside the environment chamber is very sensitive, as per the PPD results. For the subjects being considered for the environment chamber study, their thermal history, expectation, adaptation, and control are crucial factors. The latest technological approach involving the Immersive Virtual Environment (IVE), helps in understanding the occupant perception more accurately. Using the environment chamber concept, the studies have clearly distinguished between the natural environment, immersive environment and the IVE. The results show that the IVE affects the occupants' physiological responses and the thermal perception, which was evident depending on the differences in skin temperatures.

4.3. Living laboratories

The inter-dependent relationship between the built environment and the behaviour of building occupants is very complex to be simulated through resolute models and algorithms [53]. For developing accurate building models for energy simulations, large amounts of data need to be collected from the occupants. There are various simulation methods available, which can be employed for obtaining behavioural, physiological, and psychological information from building occupants [54].

Table 3
Methods used in selected papers with regards to Environment chamber.

Reference number	Summary	Dimensions of chamber (m)/ Area (m^2)	No. of subjects	Country
[43]	Comparing the sleeping behaviour of subjects in rooms with and without thermoelectric air duct cooling system through subjective and objective assessments.	2.7 x 2.8 x 2.8	15	Malaysia
[48]	Investigating the affects to thermal sensation and physiological response of subjects when introduced to an immersive virtual environment compared to real indoor environment by focussing on heart rate difference.	4.5 x 2.9 x 1.6	16	United States
[47]	To investigate and determine if there are differences in subjects' physiological responses and environmental sensations when subjected to immersive virtual environment and real indoor environment focussing on skin temperatures.	4.5 x 2.9 x 1.6	16	United States
[49]	Investigating the effect and impact of daylight on the indoor lighting preferences of occupants.	48	37	Germany
[50]	To explore difference of thermal comfort, sensation, and acceptance between older and younger subjects.	5.4 × 5.4 × 2.65	70	United States
[51]	The method aims to test the effects of metabolic rate of subjects on their perception of thermal comfort.	2 x 2 x 2	31	China
[52]	To measure the VOC emissions from a human body through various sampling methods.	2 x 2 x 2	14	China
[44]	To examine the sleeping behaviour of the subjects based on their gender, by subjecting them to three different indoor environment conditions.	2.7 x 2.8 x 2.8	30	Malaysia
[46]	To explore the impact of thermal backgrounds of occupants on the comfort perception by investigating the physiological and psychological responses under two different types of air-conditioning systems.	3.25 × 3.45 × 3.35	60	China
[45]	Study analysed the perception of comfort in warmer environmental conditions of subjects from diverse thermal backgrounds.	2.50 x 3.65 x 2.55	40	Hungary

The data can be collected through sensors, interviews, observations, etc. But the amount of information and accuracy of the collected data, varies among different simulation methods. Designing experiments in a detailed format and including as many variables as needed in the study, is where the concept of living labs proves to be efficient when compared to the other methods. In addition to that, the method allows for altering the indoor environmental parameters for close monitoring of occupant behaviours [55]. Parameters such as lighting [56], acoustics, thermal comfort [57], indoor air quality [58], etc., can be compared basing on their, intended or unintended, influence on the behaviour of occupants. Unlike the in-situ monitoring method or the environment chamber method, the duration of experiments within a living laboratory can stretch up to months or even over a year [59,60] (as shown in Table 4). To test an experiment with human subjects for longer durations in realistic environments, provides dependable and sustainable results [61].

The reviewed studies on living labs, find no correlation between the energy use and the factors that are not directly related to daily-use activities, for instance, thermal comfort, natural light availability, etc. Strong correlation has been found between the occupant presence in the kitchens, choice of appliances and the energy use. The occupant presence also effects the airflow patterns which further effects the concentration of the air pollutants.

4.4. Questionnaires and surveys

The problem of performance gap between predicted and actual building energy performance results can be addressed with the insights obtained from occupant surveys. These surveys provide information that could help in mapping the human-building interaction, which can be used in both theory and practice. Studies have utilised various forms of surveys to collect the subjective data from buildings. (see Table 5 Methods used in selected papers with regards to Questionnaires and Surveys). For instance, the thermal comfort perception of occupants can be understood through their responses to the questionnaires, surveys, or thermal sensation votes (TSV). These responses can also be used to understand their adaptive behaviours to make up for the thermal discomfort [68]. It is complicated to understand or even quantify the discomfort levels, as a study has established that the occupants would feel discomfort due to outside temperatures higher than the operative temperature in natural ventilation [69]. This situation could be better addressed through the creation of thermal comfort zones, which would have fixed temperature set-point depending on the perception of occupants allotted to those particular zones [70,71]. Comfort perception being a subjective parameter, questionnaires/surveys are the best way to collect the data for analysis. As the method depends entirely on the responses given by occupants, there is a scope of error while collecting the data, as many of the occupants to whom the questionnaire is sent out to, may not end up taking part in the survey. This results in the number of effective and complete responses to the survey to be really low, like in the case of [72]. In this study, the response rate was just 36%, i.e., the number of responses received was 360 out of 1000. Hence, researchers have used different forms of surveys to counter this problem, by taking the survey responses in person, face-to-face interviews, online voting format, etc. Yet, the limitation of this method is the sample size taken for each study. Conclusive understanding of the surveys could be readily achieved with large sample sizes for the surveys, or with integration

Table 4
Methods used in selected papers with regards to Living laboratories.

Reference number	Summary	Time Period (weeks)	No. of subjects	Area (m^2)	Country
[62]	To observe the diverse group of participants and conduct interviews in sequential order of their stay, in the form of a comparative analysis of their actions which were expected and those which were not.	21	12	Dwellings vary from 52 to 185	Norway
[63]	Subjecting occupants to different combinations of indoor environment settings to note the occupant experience and test if the conditions effected the satisfaction, feelings, and health behaviours outside the building, throughout the day.	18	8	124	United States
[56]	To establish a relation between natural lighting and use of artificial lighting by comparing data from experiments and simulations.	24	14	100	Norway
[64]	To develop a modelling framework through simulation of occupant behaviour and building energy to understand the effect of outdoor air pollution on the indoor air quality during wildfires.	1	2	20	United States
[58]	Re-analysing the living lab experiment to focus on occupancy profiles and usage patterns from the data obtained from the monitoring systems and sensors.	21	12	Dwellings vary from 52 to 185	Norway
[65]	The method aims to develop a public dataset to create a benchmark for occupant sensing and building analytics, through relevant data collection (counting occupants and environment quality).	14	1000	8500	Denmark
[66]	The method involves testing of modern window shading systems and comparing it with manual control of the windows.	20	14	124	United States
[57]	Ten residential buildings were turned into living labs with various energy monitoring equipment. Mixed methods were used for data collection pertaining to heating and cooling usage by occupants to note the factors influencing consumption.	52	35	–	Australia
[67]	To develop a framework model through a multidisciplinary approach, for reducing the building energy consumption.	39	650	Multiple buildings of various square areas	Italy
[60]	Subjective data was collected with the help of wireless sensor networks and correlated with physical parameter data. The method investigates the thermal comfort and the energy of a building in real time through an advanced monitoring system by focussing on the occupant behaviour.	49	1–3	144	Italy

[73] of the survey method with other forms such as interviews, physical measurements, etc (see Table 6).

The reliability of the occupant behavior survey responses depends on the indoor variables considered for the survey. Other modes of survey such as in-person or telephone interviews, diary entries, etc. are precise yet labor-intensive and may become a limitation for sample size. The telephone interviews were found to be comfortable and faster for each of the respondents, also it avoids any confusion with the survey questions.

Table 5
Methods used in selected papers with regards to Questionnaires and surveys.

Reference number	Summary	Type of survey	Sample size	Country
[74]	To analyse the field data for the influence of environmental parameters on the manual window operation.	Questionnaires and sensation vote	23	South Korea
[75]	The method analyses the collected data from classrooms for checking if the correlations conform between environmental parameters and the occupant actions, and window operation behaviour models are developed.	Interviews	2	Hungary
[76]	Questionnaires were given to the occupants, and a portion of the questions were based on Likert scale while the remaining were open-ended. The responses were used for correlation between comfort perception of occupants and satisfaction.	Questionnaires and interviews	170	Canada
[77]	The method included three parts: observation of thermal comfort at usual indoor temperature levels, altering the temperature levels to notice difference in the occupant responses and, finally, temperature levels demand-driven by the occupants. The occupants were asked to vote on the online form every 15 min per day.	Online voting form	16	Denmark
[78]	The data from HVAC systems and responses from the online questionnaire are used to understand and quantify the relationship between occupant behaviour and indoor climate.	Online questionnaire	450	Italy
[71]	Thermal conditions and comfort preferences were obtained through the field survey and thermal environment measurements were performed through sensors. The thermal comfort variables were analysed through correlation and regression methods to find a relation among the variables and determine the thermal comfort zone.	Field survey	389	Malaysia
[79]	The participants were asked to fill the questionnaire survey during the in-person interview, for thermal sensation identification. Also, a wireless sensors network system was put in place for real time thermal data collection.	In-person interviews and questionnaires	60	China
[80]	Simultaneously conducting the subjective survey and objective physical measurement of the Indoor Environmental Quality (IEQ)	Post-Occupancy Evaluation (POE) method survey	1810	China
[81]	The method analyses the thermal transition zones within the indoor work areas (a hospital and an office) to understand the occupants' thermal perception, which was done through questionnaires and physical measurements.	Questionnaires	96 (from hospital wards) 142 (from office)	The Netherlands
[82]	The thermal comfort perception was determined for the nursing staff. Subjective and objective measurements were carried out for summer and autumn seasons. The method divides the hospital ward into thermal zones for different temperature levels depending on the comfort perception of the patients and staff.	Thermal comfort perception survey	89 (during summer) 43 (during autumn)	The Netherlands

Table 6
Methods used in selected papers with regards to In-Situ and empirical observation methods.

Reference number	Summary	Equipment, sensors, or techniques used for data collection	Country
[87]	A field study was carried out twice in 2012, to observe the behavioural responses of occupants to thermal discomfort through the qualitative and quantitative data collected.	Interviews, questionnaires, visual diaries, and indoor environment monitoring sensors (temperature, relative humidity, light intensity, and air velocity)	United Kingdom
[88]	Empirical studies were carried out to observe the factors affecting the occupant perception of optimal lighting.	Questionnaires and data loggers to monitor lighting use	Sweden
[89]	An empirical study was carried out to collect the occupant responses and electricity data to correlate and identify the factors affecting energy consumption the most.	Questionnaires and energy consumption data of the households from local providers	China
[90]	The study focused on assigning and relocating occupants to new workspaces based on their activity. Data is collected from the pre- and post-relocation studies to compare the occupant performances in both scenarios.	POE surveys, measuring IEQ parameters on spot and step-count monitoring	Australia
[91]	The method involves modelling the indoor space into a software simulation for analysing and running heat and light transport simulations. The iterative processes with simulations and indoor fixtures can increase the accuracy of predictions and establish the best scenario for indoor comfort.	Radiance (IES-VE software) for lighting simulations and ANSYS Fluent for air flow and thermal simulations	Singapore
[92]	Measurements were carried out in apartments to study the influence of location and occupants on the horizontal and vertical alignment of the buildings.	Physical measurements of thermal comfort and indoor air temperature	Portugal
[93]	The method analyses three thermostat setback scenarios through the in-situ measurements for different test houses. One house is kept at constant indoor temperatures while the setback scenarios were tested in the other house, the process is repeated for different combinations.	Air temperature, relative humidity, air velocity data collected from sensors, energy consumption data and external weather conditions from the weather station	Canada
[94]	The study monitoring period lasted for 12 months in villas, to observe occupant behaviours, buildings characteristics and energy usage patterns through survey data and building energy modelling.	Weekly energy and temperature readings, physical survey of building characteristics, occupant surveys and interviews	Kuwait
[95]	The method involves analysing overheating risks from the data obtained by monitoring a Passivhaus dwelling for a 21-month period.	In-situ monitoring of dry-bulb temperature and relative humidity through sensors, and external environment conditions from weather station	United Kingdom
[96]	Empirical results obtained from the data collected, to design a thermal comfort control method that satisfies both economic and comfort requirements.	Thermal comfort survey, IEQ sensors, window status monitoring	South Korea
[97]	The method analyses the energy signature of the building along with the IEQ parameters for which the measurements for the study were taken during the summer months.	In-situ measurements of CO_2, temperature, energy consumption, relative humidity, Volatile Organic Compounds (VOCs)	Greece
[98]	In-situ monitoring and collecting data of occupant actions using the depth registration camera with high accuracy.	Depth registration camera and Microsoft Kinect	–
[99]	The method proposes an algorithm for detecting daily actions of occupants through sensors and verifying through the journal entries by occupants.	Temperature, relative humidity, and CO_2 data collected from sensors	Portugal
[100]	The method obtains the main characteristics of a building by proposing changes to the method defined in ISO 9869.	Measurements of air quality, brightness levels, heating and lighting systems, and outdoor environmental conditions	Spain
[101]	The method aims to improve the comfort models through collecting data in real time from the indoor environment.	Clothing, heating, and thermal comfort data collected from sensors, monitoring occupants' indoor activities	The Netherlands
[102]	The field study collects in-situ measurement data to assess the actions of the building occupants and to evaluate the accuracy of the data obtained from both sensors and surveys.	Sensors to detect window status, CO_2 sensor, centralized heating and ventilation system and surveys	Portugal
[103]	The method develops and validates an agent-based occupant behaviour model from the data collected.	Background survey, daily surveys, IEQ and behaviour measurements	United States
[104]	Four different variations of controls were set up to observe the occupants' interaction with the shading and lighting.	Online questionnaires, manual and automated controls of switches, wireless occupancy sensors, photometric	United States

(continued on next page)

Table 6 (*continued*)

Reference number	Summary	Equipment, sensors, or techniques used for data collection	Country
		sensors, DSLR camera, thermocouples	
[105]	The method involved conducting surveys to observe the adaptive behaviour of occupants, like the window operating behaviour and clothing adjustment.	Occupant behaviour survey, indoor air temperature measurement,	Japan
[106]	The building is modelled using the data collected, and the relevant tests are performed for obtaining the in-situ data. The model is then calibrated with the data obtained. Comparing the two, provides insights into quantifying the building energy performance prediction gap.	Air pressure test, electric co-heating test, building survey, dynamic energy simulations	United Kingdom

The online/paper-based methods may receive shorter and vague answers that could be difficult to infer. Higher response rate could be obtained if the survey is designed in a multiple-choice response format for each question.

4.5. In-situ and empirical observation methods

A way of observing the human-building interaction, could be done at the site of the considered buildings itself. This way the data gathered could be used as a representative occupant behaviour model. Some of the problems faced by the occupants in the existing buildings, may not be possible to recreate in an experimental setup [83]. Also, the genuine response of occupants to these problems can be studied in a much-detailed manner. The in-situ method consistently gathers the data without disturbing the natural setting of the building occupants using the various sensors and data collection equipment [84]. Though the in-situ observation methods look promising, the primary issue with these methods are the willingness of the occupants to take part in the experiment, citing privacy concerns. In this regard, the environment chambers and living laboratories score over the in-situ observation method. For instance, monumental or historic buildings for which it is difficult to perform lab experiments for energy analysis, the in-situ measurements can prove to be quick and cost effective methods [85]. In such cases, experience and skill of the researchers is required to tackle the situations. While the in-situ method offers first hand evidence of occupant behaviour, the empirical observation studies analyse and quantify the evidence for logical results, especially when the sample size is low [86]. The advantage of the empirical study is also a limitation, as a large sample cannot be considered for the study. Yet, the available sample size gives significant results. Such studies may even be quicker to conduct when compared to the others. The objective of these empirical studies is not always to establish a relation between the various variables, but to derive explanations from what has been initially observed.

Unlike the environment chamber or living laboratory studies, the in-situ measurements are easier to conduct. As the in-situ measurements can be conducted in the occupants' natural environment, for a detailed analysis, longer observation time for the experiment is desirable.

4.6. Pre-/post-occupancy

Evaluating the energy performance of a building, before and after the occupancy can give us the realistic data of the difference in the amount of energy consumed, mostly using post occupancy surveys, interviews, group meetings, or any other data gathering and techniques (as discussed in Table 7). Usually, this method is employed when there is a retrofitting or refurbishment to take place in a building. The comparison of occupants' behaviour and comfort perception before and after the refurbishment gives a complete understanding of the occupants and their comfort criteria which could possibly increase their productivity [107]. Apart from refurbishment cases, the energy conservation awareness among occupants was also tested in a study where the authors have observed behavioural changes in occupants from before and after occupying a new building [108]. The energy performance gap as mentioned earlier, may also be reduced by the post occupancy evaluation studies, by optimizing the design processes [109]. In addition to the psychological changes, the Indoor Air Quality (IAQ) parameters can also be monitored for changes before and after the refurbishment. By subjecting the occupants to improved indoor conditions, the changes in the indoor environment may be observed and also improvements, if any, may be made [110].

The POE studies are often combined with building use survey which help the stakeholders in understanding the comfort level of occupants. For buildings that are retrofitted, pre- and post-occupancy evaluation studies help in educating the occupants about various energy efficient strategies. The studies also helped in understanding the impact of the year of construction on the energy efficiency of the building.

Different combinations of the methods discussed in this section, as suitable, can be used depending on the type of study to be carried out.

- ANN is suggested for modelling occupant behaviour data.
- IVE bridges the latest virtual reality technology, and the occupant behaviour studies.
- The living laboratories concept offers a deeper understanding of the indoor environment in the presence of occupants, like the air flow patterns and their effect on the concentration of air pollutants.
- Small sample size is only one of the issues with occupant surveys. Selecting the most appropriate mode of the survey and the inclusion of incentives for the respondents, would help in achieving better and dependable survey results.
- In-situ observation method is an improvement from environment chambers and living labs. The results from in-situ studies are more dependable as the observations are taken from the natural environment setting of the occupants.
- The combination of any of the above studies with POE method, increases the accuracy and the dependability of the results.

5. Discussion and conclusions

The comprehensive review of energy related occupant behaviour research in buildings, reported in this paper, have provided insights on dominating approaches in terms of research methodology and parameters observed.

The review matrix has enabled deriving insights on the major trends reported in the original occupant behaviour research:

- About 90% of the studies were focused on thermal comfort, heating, and cooling, and 78% of studies have utilised sensors. There is a significant overlap between the thermal comfort approach, linking it to window operation and solar shading operation. 62% of the total number of studies reviewed have thermal comfort and window/shading operation included in their occupant behaviour analysis.
- The types of buildings that are usually analysed for occupant behaviour studies are residential, offices and educational buildings, with almost equal presence in the original research. These trends match the types of buildings where people spend the most of their time – homes, offices, educational buildings. However, there were not enough studies, that applied a similar research methodology in

Table 7
Methods used in selected papers with regards to Pre-/post-occupancy.

Reference number	Summary	Post-occupancy data gathering and techniques	Country
[111]	Comparing the post-occupancy analyses of the interviews and questionnaire survey for energy consumption habits with an in-situ test for IEQ measurement.	Interviews and questionnaire surveys	China
[112]	Occupant surveys were conducted in two buildings under specific conditions and recorded the thermal sensation and preference votes for calculating the Predicted Mean Vote (PMV). The objective energy data gathered from monitoring systems was compared with CIBSE Part F and TM46 benchmarks.	Occupant surveys, power, and energy monitoring systems	United Kingdom
[110]	Thermal parameters (temperature and relative humidity) and indoor air pollutants (IAPs) (CO, CO_2, etc.) were measured pre- and post-energy retrofit of 15 semi-detached dwellings.	Pre and post retrofit surveys, physical measurement of IAPs and thermal parameters	Ireland
[113]	Occupancy profiles were gathered from classroom schedules, energy consumption data for three consecutive years was obtained from energy bills while the detailed consumption was obtained from smart meters. All the data obtained was compared for extracting key indicators.	Annual and monthly energy bills, smart meters	France
[114]	The method involved conducting post occupancy questionnaire surveys for 16 respondents and in-situ measurements were conducted for identifying relative humidity, air temperature and CO_2 rates, in three apartments.	Questionnaire surveys and in-situ physical measurements	Luxembourg
[115]	Indoor temperature data was gathered from sensors and Building Management System (BMS) for a one-year period. External environmental data was obtained from the weather station. All the quantitative data was analysed and compared with the POE survey data (qualitative).	Physical monitoring through sensors, BMS and POE survey	United Kingdom
[116]	The method collaborates POE studies and Building Information Modelling (BIM), for information exchange in three stages, for data to be available for all stakeholders. Data was collected through surveys and analysed to test against building standards. In-situ measurements were also carried out for calculations.	Surveys, modelling and simulation, and physical in-situ measurement	Chile
[117]	Using multiple data gathering techniques, various building performance requirements were identified, measured and evaluation studies were carried out. Focus group meetings were held to filter out qualitative information from surveys.	Walkthroughs, physical IEQ measurements, surveys, focus group meetings	Russia
[118]	The method focuses on checking the occupant comfort criteria in Minergie energy certified buildings. Data was obtained from surveys and sensors. IEQ parameters were measured through monitoring campaigns for two times in the one-year experiment period.	Online questionnaire survey, Physical IEQ measurement	Switzerland
[119]	POE technique is employed for the evaluation of thermal comfort indoors. PMV/PPD data is analysed and compared with questionnaire and simulation results of thermal parameters.	Physical monitoring and measurement of energy performance statistical data, questionnaires, and interviews	Egypt

several types of buildings, e.g., homes and offices. Such approach might provide insights if occupants in offices behave differently compared to homes, and what is the role of social environment, group dynamics and sense of ownership in occupant behaviour patterns.

- In terms of research methodology, 67% of the selected studies have used occupant surveys, 68% have included simulation tools. The occupant surveys and the simulation tools can help reduce the energy consumption of HVAC systems by focussing more on the occupant behaviour, mainly the interaction between the occupants and their adaptation with the indoor environment (e.g., window operation). On an average, Machine Learning can reduce up to 23% of the energy consumption through optimizing the HVAC systems, increasing efficiency of building controls and enhancing the occupant behaviour prediction models [120,121].
- However, only 11% of the studies have performed the predicted vs. real energy consumption comparison. There is a lack of studies that provide the “loop approach”, where the results of the survey would be used for increasing the accuracy of energy performance predictions.

- The novel approaches to track occupant behaviour and energy consumption by utilizing building management systems (BMS), applying machine learning are not yet widely applied yet, and only 15% of the studies have integrated these approaches in their research methodology. There were no studies that provided open datasets from building management systems linked to occupant behaviour patterns. Such data sets would be very valuable for the research community.
- Linking occupant behaviour and productivity is not common. It can be concluded that occupant productivity is a separate research area, however, 7% of the selected studies have investigated both occupant behaviour and productivity. This relation could be examined further, linking the adaptive environments, satisfaction levels with productivity and analysing the trade-off between energy and productivity by using the cost-benefit approach.

From the review matrix, it is evident that the highest number of points that a paper could receive in the selected 70 papers, is 13. points Upon calculating the number of papers that crossed at least 10 points, the method 'Pre-/Post-Occupancy', stands first. The review suggests that this method enables the inclusion of more variables. This has been proven by the high number of publications utilizing this method that could easily be found, due to the feasibility and practical reliability of the method.

It is clear, that there is a need of more efficient methodology and algorithms to include occupant behaviour models in energy performance predictions. The ability to predict the behaviour would also lead to design decisions which are more user-friendly, or which give the optimal level of freedom for occupants to control their environment. Majority of the original research publications provide insights on specific occupant behaviour aspects, and there is still lack of approaches that analyse the energy related occupant behaviour as an extremely complex systems, that would enable research based on operational analytics and predictive analytics.

IEA EBC Annex 66 "Definition and Simulation of Occupant Behavior in Buildings" (2013–2017) and IEA EBC Annex 79 "Occupant-Centric Building Design and Operation" (launched in 2018) are focused on tackling the challenge of formalizing occupant behaviour monitoring and protocols, as well as application and knowledge in buildings with the life-cycle approach in mind. One of the most important tasks of Annex 79 is the development of Occupant Presence and Action (OPA) modelling method, by shifting the approach from occupants as passive participants to dynamic and complex two-way relationship [122]. O'Brien et al. (2020) have identified the need for unified theoretical framework for perceptual and behavioural theory of building occupants and envisions data-driven occupant modelling as a way forward.

The review of original research provided in this paper supports the vision of IEA EBC Annex 79, and due to the complexity of occupant behaviour patterns, confirms that there is currently a major shortcoming of the following:

- Standardized occupant behaviour and energy consumption monitoring protocols, enabling the establishment of common language between the researchers, asset managers and technology developers,
- Open datasets that are fully compliant with international data protection regulations, that provide the live data streams based on the Digital Twins principles; data collection from wearable devices should also be considered,
- Data analytics tools and methodologies that helps navigating the asset management from the live data streams, ensuring the two-way relationship between the building systems and occupants, providing sense-making and the logic for operational analytics. Open data driven hypothesis for deeper research which could be carried out by the methods outlined in this paper, such as climate chamber studies, in-situ etc., as well as deeper look into relationships between the environmental parameters.

The major insights on energy related occupant behaviour can be achieved by applying data analytics on complex demonstrator buildings datasets through the Digital Twins approach. In turn, this data can form the basis of the international standardisation. While thermal comfort model, developed by P. Ole Fanger is well established within both international standards and various numerical simulation tools and building management systems, the recent review of 23 regions' building energy codes showed that there is no unified approach to energy related occupant behaviour [123]. This is currently a significant barrier in achieving the integrating occupant behaviour into building energy performance simulations.

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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