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The impact of occupants' behaviours on building energy analysis: A research review

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ABSTRACT

Over the past 15 years, the evaluation of energy demand and use in buildings has become increasingly acute due to growing scientific and political pressure around the world in response to climate change. The estimation of the use of energy in buildings is therefore a critical process during the design stage. This paper presents a review of the literature published in leading journals through Science Direct and Scopus databases within this research domain to establish research trends, and importantly, to identify research gaps for future investigation. It has been widely acknowledged in the literature that there is an alarming performance gap between the predicted and actual energy consumption of buildings (sometimes this has been up to 300% difference). Analysis of the impact of occupants' behaviour has been largely overlooked in building energy performance analysis. In short, energy simulation tools utilise climatic data and physical/ thermal properties of building elements in their calculations, and the impact of occupants is only considered through means of fixed and scheduled patterns of behaviour. This research review identified a number of areas for future research including: larger scale analysis (e.g. urban analysis); interior design, in terms of space layout, and fixtures and fittings on occupants' behaviour; psychological cognitive behavioural methods; and the integration of quantitative and qualitative research findings in energy simulation tools to name but a few.

1. Introduction

Over the years, the need to be more sustainable has significantly increased global focus towards energy related analysis. Climate change is foreseen to be the greatest environmental threat and challenge of modern times. International agreements such as the Kyoto Protocol; European agreements such as the European Emissions Trading Scheme and European Directive on the Energy Performance of Buildings (EPBD); and UK national measures such as the United Kingdom's Climate Change Programme (UKCCP) and the Climate Change Levy (CCL); all demonstrate its prominence. Thus, government, businesses and wider society all have a pivotal role to address human impact (hence, occupant behaviour) on the environment. In this regard, predicting energy demand is becoming more important in the design and construction of buildings, from early design stages to post occupancy. According to Janda [1], the growth in knowledge and public concern with regards to climate change has ensured increased attention towards energy consumption in relation to buildings. Statistics have affirmed that buildings are colossal consumers of energy. As published in the "International Energy Outlook" by the U.S. Energy Information Administration [2], 20% of the total energy consumed worldwide is within the building sector (including residential and commercial). Another study [3] demonstrated that from 1970 to 2014, the domestic sector alone used between 24% and 27% of the total energy consumption in Europe. Likewise, a separate study undertaken by the European Environment Agency (EEA) [4] presented similar results in their analysis. In 2015, EU statistics [5] reported that buildings (including services and households) consumed around 40% of the total energy use in 2015. In China and India, the building sector accounts for 37% [6] and 35% [7] of the total energy consumption, respectively.

Such that is the acute need to drive down energy consumption, in 2002, the Energy Performance Building Directive (EPBD) announced new regulatory conditions for all EU countries to decrease the energy needed for heating, cooling, ventilation and lighting in buildings. Therefore, estimated energy efficiency level of buildings has to be considered in the design of buildings, and subsequently in construction documentations [8] as part of the planning process.

Energy consumption of buildings is related to various factors including: the thermo-physical properties of the building elements,

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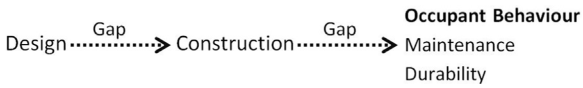

Fig. 1. The gap between the predicted and actual use of buildings.

its construction technical details (energy-efficient building elements may not perform efficiently if poorly-constructed), climatic location characteristics, the quality (and maintenance) of the installed HVAC system, and occupants' behaviour and activities towards energy utilization [9,10]. During the design stage of buildings, energy simulation is used to predict energy consumption of buildings based on design information, however, several studies [8,11–16] showed that there was a considerable discrepancy between the predicted and actual energy consumption of buildings. The studies demonstrated that the actual energy consumption of buildings is sometimes up to 3 times greater than the estimated calculation. Thus, this performance gap is due to the difference between the building design and the as-built building in terms of the technical workmanship and installations, choice of equipment and material during the construction stage, and the energy behaviour of occupants, which has been disregarded in the energy simulation process [8,16] (Fig. 1).

Nevertheless, post occupancy energy-use evaluation has been analysed in numerous research projects. For example, the ROWNER project [14] considered three stages: design and construction, post-occupancy evaluation and overheating. The project analysis [14] demonstrated a significant difference between the total energy consumption between two flats within the same building block due to differing occupant behaviours, including: different presence at home, different occupancy levels, and variations in the occupants' thermal preferences. Similarly, major differences in energy consumption of similar building blocks were reported in another study [17]: Martinaitis, Zavadskas [13] conducted five different studies to highlight that buildings did not perform as predicted, even when the energy simulation was very accurate. They concluded that human behaviour and occupant preferences as an important contributor of the gap between the predicted and actual building energy performance. Furthermore, Schakib-Ekbatan, Çakici [12] identified occupants' behaviour as the most overlooked parameter that "might not be considered as part of the energy design" within the chain of design, construction, operation and maintenance. As such, a range of studies have ensued focusing on the influence of occupants' behaviour on building energy consumption with the focus to interpolate behavioural aspects into building energy simulation tools to improve their accuracy [18]. However, despite active research being undertaken in this area, the findings are fragmented and, therefore, there is a real need for international collaboration in the sharing of collected data and discovered findings [19]. This paper aims to undertake a comprehensive review of existing studies in this area to identify research trends and gaps for future studies.

2. Method and material

2.1. Research method

This review paper aims to provide a summary of the extant literature. The selection criteria of the literature used for this critical review paper was primarily based on the direct relevance to the subject, and also a number of studies which focused on related subjects due to their substantial importance.

Review papers usually follow a process of 'search' for relevant publications, utilising citation indexes against pre-determined criteria for eligibility and relevance to form an inclusion set relating to the research area. To reduce bias in this process, an objective and transparent approach for research synthesis was adopted, including both quantitative analysis and qualitative reviews. Therefore, Science Direct and Scopus databases, two of the leading citation index organisations, were used. For this study, the terms "building energy" and "occupant" were used to select any papers where it was found in the title, abstract and/ or keywords. In order to limit this wide scope (more than a thousand papers were identified by Science Direct and Scopus) and to focus closely on the influence of occupant behaviour on building energy consumption, a further search was made through the existing database using more relevant keywords. As a result, both "occupant behaviour" and "energy consumption" have been repeatedly used in the title, abstract and as keywords of various research papers that were considered as the closest key words for the topic of this research review paper. Following such, a search up to and including August 2016 identified more than 100 research papers for this review, with the majority directly related to the impact of occupant behaviour on building energy consumption were published between 2013 and 2016, to reflect this fast developing research area.

According to the reviewed papers, the most frequent key words used by scholars in this subject area are 'occupant behaviour', 'energy consumption or energy use', 'energy simulation or modelling' and 'energy efficiency or performance', followed by 'comfort' and 'behaviour' (Fig. 2). Thus, this identifies the notable relevance of comfort-related studies in occupant behaviour.

The papers identified were subsequently categorised in terms of the methodology used, building type (i.e. residential, offices, etc), occupants' interactions with buildings and the influential parameter(s) identified in the papers on occupants' energy behaviours (see Table 1).

Analysis of Table 1 is concluded as follows:

- Residential buildings and offices respectively account for 44% and 31% of the reviewed studies in this topic area. Less than 20% of these studies used commercial and educational buildings as their case studies, and cultural and recreational buildings and health centres have not been sufficiently researched and reported, and thus, require further investigation. The number and percentage of each building types used as case studies in the reviewed papers is illustrated in a pie chart (Fig. 3).

- The majority of studies focused on one or more particular types of occupant's interaction, such as the use of electricity and plug loads (31%), window opening behaviour (18%) and use of fans/ air conditioning (15%) (Fig. 4). Although the use of hot water (4%) is limited in the literature, it starts to appear in the more recent publications.

- Many studies focused on one or more influential parameters of the occupant's choice of behaviour and satisfaction. Among those parameters, climatic (environmental, physical) and personal (psychological and physiological) parameters have attracted more attention than other parameters, and accounted 33% and 28% respectively of the totally review papers. Other parameters, such as

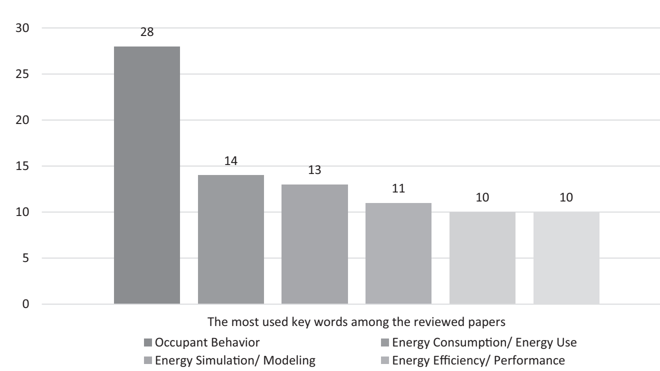

Fig. 2. Frequency of the key words among the 43 occupancy related papers.

Table 1
Categorisation of the reviewed papers by year of publication, methodology, building types, occupants' interactions with buildings and influential parameters.

Author (s), year	Methodology	Building type	Occupants interactions	Influential parameter
Gandhi and Brager (2016) [20]	2 Years Field Study, Data Analysis Using Rstudio	Commercial, Offices	Plug Load (desktops, laptops, monitors, and task lights)	Personal (Influence of Game)
Jang and Kang (2016) [21]	Case Study, Survey, Gaussian Process Classification	Residential (High-Rise)	Heating and Electricity consumption	–
Rafsanjani and Ahn (2016) [22]	Non-Intrusive Occupant Load Monitoring (NIOLM)	Commercial	Occupants' energy behaviours	Arrival- Departure
Karatas et al. (2016) [23]	Pre and Post-occupancy Measurements, Clustering	Residential, Commercial	Occupants' energy behaviours	Personal (Behavioural Studies)
Karjalainen (2016) [24]	Case Study, Survey	Offices	Occupants' energy behaviours	Design Features
Ahn and Park (2016) [25]	Experiment, Real-time Monitoring	Laboratory	Occupants' Presence and energy behaviours	–
von Grabe (2016) [26]	Decision Theory, Qualitative Data	–	Occupants' energy behaviours	Personal (psychological)
Salcido et al. (2016) [27]	Review	Offices	Use of mixed-mode ventilation	Climatic
Ryu and Moon (2016) [28]	Experiment, Decision Tree and Hidden Markov Model	Building Integrated Control Test-bed	Electricity Consumption	Climatic
Pisello et al. [29]	Case Study, Monitoring using sensors	Educational	Electricity Consumption and windows/ doors opening	Personal/ Climatic
Pellegrino et al. (2016) [30]	Case Study, Field Measurement	Residential	Use of air conditioning	Climatic
Ouf et al. (2016) [31]	Case Study	Educational (School)	Electricity Consumption	Old/ New Building - Type of Activity
Khosrowpour et al. (2016) [32]	Sensor-based Monitoring, Classification and Predictions	Commercial	Use of appliances	Personal
Kazmi et al. (2016) [33]	Case Study, Monitoring, Sensitivity Analysis	Residential	Use of hot water	–
Calì et al. (2016) [16]	Field Study, Monitoring	Residential	Occupants' energy behaviours	–
Langevin et al. (2016) [34]	Agent-based Behaviour Model, Case Study Simulation	Offices, Building Controls Virtual Test Bed	Occupants' energy behaviours	–
Yu et al. (2015) [35]	Existing 2-year Survey Data, Data mining-based Methodology	Residential	Use of appliances	–
Hong et al. (2015) [18]	Ontology	–	–	Personal (Behavioural Studies)
Wang et al. (2015) [36]	Field Measurement, Questionnaire Survey, Sensitivity Analysis	Residential	Heating	Climatic
Tetlow et al. (2015) [37]	Questionnaire	Offices	Electricity Consumption	Socio-Personal (psychological: TPB)
HUB (2015) [14]	Case Study, Occupant Questionnaire, Post Occupancy Measurements	Residential	Gas, Electricity and Water consumption	Socio-Personal
Indraganti et al. (2015) [38]	Thermal Comfort Survey, Logistic Regression	Offices	Occupants' satisfaction	Personal(Age, Gender)
Feng et al. (2015) [39]	Agent-based Model, One-year Field Study	Offices	Occupants' energy behaviours	Climatic, Behaviour Theories
Schakib-Ekbatan et al. (2015) [12]	Case study, Monitoring Data, Logistic Regression Analyses	Offices	Windows opening	Climatic (Indoor/outdoor temperature)
Langevin et al. (2015) [40]	Longitudinal Case Study, Survey, Measurements, Human Tracking	Offices	Occupants' energy behaviours	Personal
Rijal et al. (2015) [41]	Survey, Measurements	Residential	–	Climatic (Humidity)
Mohamed et al. (2015) [42]	Survey, Questionnaire	Residential	Occupants' energy behaviours	Socio-Personal
Gulbinas et al. (2015) [43]	Experimental data analysis	Commercial	Occupants' energy behaviours	Personal
Wang and Ding (2015) [44]	Multiple-Case Study, Polynomial and Markov Chain–Monte Carlo Methods	Offices (Business, Administration, Scientific Research)	Use of appliances (Computers)	Type of activity
Heydarian et al. (2015) [45]	Experiment	Virtual Environments	Lighting choice	Design Features
Chen et al. (2015) [9]	Multiple-Case Study, Statistical Survey	Residential	Occupants' energy behaviours	Classification of Influential Parameters
Feng et al. (2015) [39]	Review, Simulation	–	Occupancy	–
Zhao et al. (2014) [46]	Experiment, Data Mining	Offices	Use of appliances	Climatic
Masoudifar et al. (2014–2015) [47]	Monitoring, Real Time Location Systems, Wireless Energy Meters	Offices	Occupancy	–
Johnson et al. (2014) [48]	Time Use Survey, Markov Chain Statistical Model	Residential	Occupants' interactions	–
D'Oca et al. (2014) [49]	Dynamic Simulation Tool IDA Ice	Residential	Thermostat, Window opening	–
Gunay et al. (2014) [50]	Kalman Filter Algorithm	Offices	Lighting/ Window blinds	–
Jiayu et al. (2014) [51]	Experiment, wireless Network for Monitoring	Educational, Commercial	Occupants' energy behaviours	–
Li et al. (2014) [52]	Field Observation, Data Analysis Using SPSS Statistical Software	Offices	Window opening	Climatic
Simona D'Oca and Hong (2014) [53]	Combined Statistical Analysis (with two data-mining techniques: cluster analysis and association rules mining)	Offices	Window opening	–
Yun et al. (2014) [54]	Case Study, Field Monitoring	Offices	HVAC system (Air handling unit)	–
Rijal (2014) [55]	Thermal Comfort Survey, Occupant Behaviour Survey	Residential	Window opening / use of fans	Climatic
Burgas et al. (2014) [56]	Case Study, Monitoring, Data mining	Educational	Electricity Consumption	Climatic
Romero et al. (2013) [57]	Field Study, Survey	Residential (Low-income)	Electricity Consumption (Air conditioning)	Climatic/ Economic/ Building quality
Langevin et al. (2013) [58]	Interview	Residential (Low-income)	Occupants' energy behaviours	Personal/ Economic
Blight and Coley (2013) [59]	Sesitivity Analysis, Multiple Regression Techniques	Passive Residentials	Heating	–

(continued on next page)

Table 1 *(continued)*

Author (s), year	Methodology	Building type	Occupants interactions	Influential parameter
Kavousian et al. (2013) [60]	Smart Meter Data Analysis	Residential	Electricity	Climatic
Chen et al. (2013) [61]	Survery Study	Residential	Occupants' energy behaviours	Socio-Economic (age and income)
Agha-Hossein et al. (2013) [62]	Pre and Post-occupancy Surveys	Offices	Occupants' satisfaction	Old/ New Building (Refurbishment)
Fabi et al. (2013) [8]	Case study, Medium/Long-term Monitoring	Residential	Window opening	–
Andersen et al. (2014) [63]	Case Study, Markov Chain	Offices	Presence	–
Martinez-Gil, et al. (2013) [64]	Experiment	Residential, Offices	Electricity consumption	–
Aldossary et al. (2014) [65]	Multiple-Case Study, Interviews	Residential	Occupants' energy behaviours	Climatic
Jain et al. (2013) [66]	Empirical Study	Residential	Occupants' energy behaviours	Personal (Information)
De Meester et al. (2013) [67]	Case Study	Residential	Heating	Personal (lifestyle), House/ Family size
Andrews et al. (2013) [68]	Year-round Survey	Commercial	Occupants' energy behaviours	–
Fabi et al. (2012) [8]	Review	–	Window opening	Influential Parameters
Park and Kim (2012) [69]	Field Study, Airflow Measurements, Energy Data Collection, Questionnaire	Residential	Use of fans	Climatic/ Economic
Peng et al. (2012) [70]	On-site Observations, Quantitative Data Measurements	Residential	Occupants' energy behaviours	Socio-Personal (lifestyle)
Dall'O' et al. (2011) [71]	Monitoring, On-site Survey, Regression Analysis	Residential	–	–
Yu Zhun Jerry et al. (2011) [72]	Case Study, Data mining	Residential	Occupants' energy behaviours	–
Rijal et al. (2011) [73]	Field survey, Observation	–	Use of windows and fans	–
Schweiker and Shukuya (2011) [74]	Field Measurement, Internet-based Survey	–	Heating and Cooling	Personal (Information)
Goldstein et al. (2011) [75]	Case Study	Offices	Occupancy	Space Layout Design/ Type of Activity
Guerra Santin (2010) [76]	Governmental Database, Regression Analysis	Residential	Occupants' energy behaviours	Regulations
Larsen et al. (2010) [77]	Review, Mixed Method	Residential	Occupants' energy behaviours	–
Indraganti and Rao (2010) [78]	Field study	Residential	Occupants' satisfaction	Climatic/ Socio-personal
Steemers and Yun (2009) [79]	Existing "Residential Energy Consumption" Survey (RECS)	Residential	Occupants' energy behaviours	Socio-Economic/ Climatic
Juodis et al. (2009) [80]	Variability Analysis of Existing Data	Residential	Heating	–
Page et al. (2008) [81]	Stochastic Model, Markov Chain	Offices	Presence	–
Yun and Steemers (2008) [82]	Case Study, Monitoring Data	Offices	Window opening	Arrival- Time Dependant
Rijal et al. (2008) [83]	Adaptive Algorithm, One-year Field Survey	Offices	Windows, doors and fans	Climatic
Page et al. (2007) [10]	Stochastic Model/ Markov Chain	Offices, Educational	Occupant presence and energy behaviours	–
Reinhart (2004) [84]	Case Study, Field Data, Use of Sensors	Offices	Electricity lighting/ Blinds	–
Al-Mumin et al. (2003) [85]	Case Study, Survey	Residential	Use of appliances (Electricity)	Personal (lifestyle)

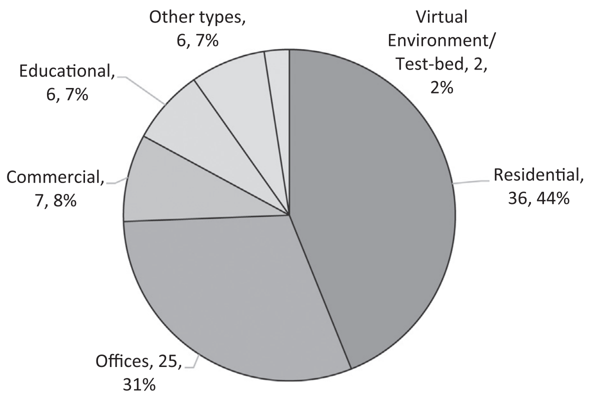

Fig. 3. Different building types used as case studies.

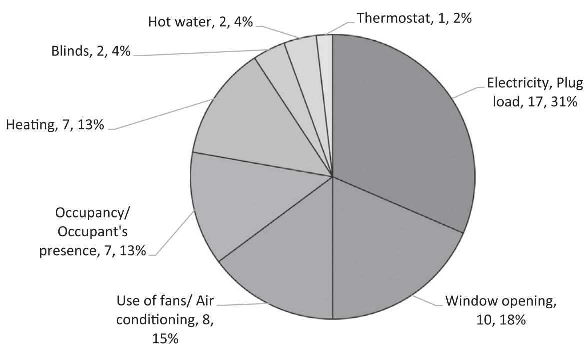

Fig. 4. Different types of occupants interactions.

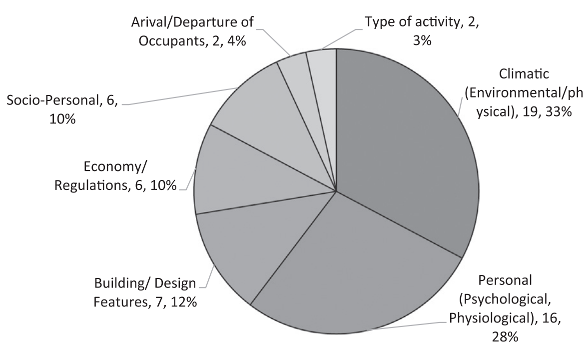

Fig. 5. Influential parameters on occupants' energy behaviours.

building features (old/ new conditions and design quality), economy and regulations, socio-personal, occupant's arrival and departure, and type of activity, were investigated in different studies (Fig. 5).

Thus, in undertaking this review, a number of key topics from the existing studies on the influence of occupants on building energy consumption were also identified as pertinent. A review of each of the topics is discussed in the following sections.

2.2. Occupant behaviour

Occupant behaviour refers to the interaction with building systems in order to control the indoor environment for health, and to obtain thermal, visual and acoustic comfort inside buildings. Mankind's "desire for control" [86] over environmental factors is not limited to the outside environment, but also, within their living spaces. According to Bluyssen [87], improvement in air quality (by bringing fresh air and eliminating air pollution and odour), acoustical conditions (by avoiding unwanted noise and vibrations), visual or lighting quality (by controlling luminance ratios, reflections and glare) and aesthetic status, in addition to, improving thermal comfort inside the living environment, are the building inhabitants' prerequisites for being able to adjust building systems and components. Therefore, occupants can influence the indoor environment through their presence and activities in the building.

Cabanac [88] coined the term "alliesthesia," composed of two words "allios" meaning "changed" and "aisthesis" meaning "sensation". Using this term, the author described that "a given external stimulus can be perceived as either as pleasant or unpleasant depending upon signals coming from inside the body". People naturally try to avoid unpleasant conditions and look for pleasant ones. "If a change occurs, such as to produce discomfort, people react in ways to restore their comfort" [89]. However, due to physical, physiological and psychological differences between people, and many other external drivers such as economic and regulatory issues, people do not "receive, perceive, and respond" the same way [87].

The term "thermal comfort" was introduced during the late 19th century. The principal definition of thermal comfort was described by the American Society of Heating and Air-Conditioning Engineers [90] as: "that condition of [the] mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation". Despite the subjective nature of thermal comfort, two quantitative formulas, first developed by Fanger [91], are used for its measurement: predicted mean vote (PMV) and predicted percentage dissatisfied (PPD). PMV models integrate the impacts of temperature (air temperature and mean radiant temperature), humidity, air velocity, the metabolic heat rate and clothing thermal properties to predict the thermal comfort level [92]. Since their emergence, thermal comfort and specifically PMV and PDD models have been studied widely and modified by several researchers for use in different types of buildings worldwide.

Thermal comfort factors discussed in PMV models (such as: indoor temperature, humidity, clothing type, etc.) are considered in building energy assessment tools, however, there is the individual aspect in thermal comfort related to personal experiences and expectations which is not reflected in the estimation of energy consumption in buildings.

The total energy consumption of buildings are not only influenced by the metabolic heat produced by occupants passively, which is considered within the occupancy section of energy simulation software, but also by their active energy use. Occupants interact with control systems and building elements to reach their own personal desired level of comfort in different ways: use of building openings (e.g. opening and closing windows), use of lighting and controlling solar shading (e.g. adjusting blinds), use of HVAC systems (e.g. turning air-conditioning on or off and adjusting thermostat temperature), use of hot water and electrical appliances (Fig. 6).

The occupant's choice of the type of controls to reach his/ her

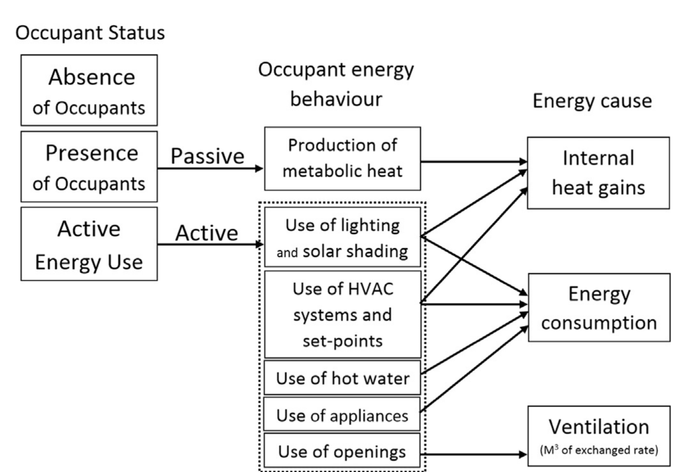

Fig. 6. Occupants' types of activities affecting building energy consumption. Adapted from [81].

comfort is based on its efficiency, ease and its potential unwanted consequences [73]. Hong, D'Oca [18] identified actions (such as adjusting the level of clothing, opening a window and turning down the thermostat temperature) and inactions (such as moving to a different location and tolerating some discomfort) as differing strategies of occupants 'behave' (behaviour) towards the same thermal discomfort. These approaches, however, impact on the amount of energy use, and thus, it is important to understand the relationship between the building and its users' living style and their energy use behaviour [9,12,18]. HVAC systems, electrical devices and lighting that enable users [occupants] to manage their own thermal and visual comfort, are the key sources of energy consumption in buildings [93] and variations in using these systems can cause significant variations in the total energy consumption in buildings, and hence, accounts for the gap between actual use and predicted energy consumption.

Several scholars have categorized occupants and their energy attitudes to different groups. D'Oca, Fabi [49] divided occupants into active, medium and passive users of energy. The active user changes the heating set point to get warmer/ cooler; conversely, the passive user choses to do nothing and tolerates some level of discomfort. In another categorisation, Hong, D'Oca [18] ranged people's actions more descriptively from "energy frugal" to "energy profligate" via "energy indifferent". Operating another method, Chen, Yang [9] classified behavioural factors within residential buildings into three levels according to their complexity: simple, intermediate and complex. Further, he suggested three research methods to study each category: statistical analysis, case studies and detailed diagnostics/ simulation, respectively. Thus, occupants profiling based on their energy behaviours could lead to more accurate assumptions in the energy analysis of buildings. However, a large-scale comprehensive study with significant quantitative data is needed to produce reliable energy profiles, which is presently not available.

Additionally, some scholars have focused on a single activity of occupants affecting building energy consumption. For example, the window opening behaviour of occupants has been widely studied within various building types in differing climates [8,12,29,49,52,53,73,82,94,95]. Most of the studies on window opening behaviour have focused on the effect on ventilation [96] and studied the time, frequency and duration of opening windows. However, the calculation of the influence of an open window on building energy consumption requires complex air movement considerations that are not effectively accomplished in any of the existing studies.

Moreover, a number of studies have focused on other types of occupants' energy behaviours such as: the use of appliances and electrical consumption [10,20,28,29,32,35,44,46,56,60,64,68,85], use of lighting [31,45,50,84], use of fans [69,73] and air conditioning [30,54], adjusting blinds [50,84] and changing thermostat set-points [49]. The use of hot water also has been considered, albeit in fewer studies [9,14,33,97]. A recent study [93] showed that water heating accounts for 7% and 18% of the total energy consumption in residential and commercial buildings in the USA, respectively, which is considered as the 4th and 2nd most sources of energy consumption in these building types. Therefore, depending on the building type, it would appear that the use of hot water might have critical influence on the total energy consumption of a building; however, this requires further investigation to be conclusive.

Of critical consideration, the majority of existing studies focus on a single energy behaviour, however, in reality, energy behaviours are often inter-linked. The inter-relationship between different energy behaviours of occupants has been highlighted by some scholars in the literature. Bourgeois, Reinhart [98] criticised that although the findings of some studies showed that using automated control in lighting decreased the lighting consumption, in some cases it did not reduce the total energy consumption. In this regard, they [98] suggested the link between the use of natural lighting and energy consumption through cooling or heating and thus developed the "lighting: cooling:heating ratio". In another study, Yan, O'Brien [99] discussed how occupants' use of window blinds affects the use of daylight. Studies on the inter-relationship between various energy behaviours of occupants are useful but currently limited and further analysis is much needed.

In addition to active energy use, the metabolic heat produced by occupants themselves impact on the building's energy passively by directly increasing the internal heat gain. Occupant's presence and movement within building spaces have been investigated and modelled by a number of scholars [10,13,47,63,81] using various indoor localisation techniques, such as crowd modelling tools and other statistical analysis methods [10,13,47,63,81]. Page, Robinson [81] reported occupant's presence "as an inhomogeneous Markov chain" which was disrupted with absence periods. Later, a model of the presence profile in office buildings with single or more occupants using observation together with inhomogeneous Markov chains was proposed by Andersen, Iversen [63]. The findings of these studies can improve the accuracy of occupancy profiles in building energy predictions, and are beneficial to be extended and used in studies on occupants' active energy behaviours. As an example, Masoudifar, Hammad [47] applied two wireless sensors, one for occupancy location monitoring and the other for monitoring their energy behaviours; in conclusion, they demonstrated a link between occupant's presence and active energy behaviours. Moreover, several studies have demonstrated that the consequences of occupants' behaviours significantly increase the total energy consumption of buildings during non-working and unoccupied hours [15]. A study on the energy consumption of six commercial buildings in South Africa (with hot and dry climates) reported that 56% of the total energy consumption was consumed during non-working hours which was believed to occur simply because of occupants failed to turn off the HVAC system and lights before vacating buildings [100].

Human behaviour is a complex phenomenon; therefore, most human behaviour studies adopted probabilistic methods. Fabi, Andersen [8] underlined that the gap between simulated and actual energy consumption of buildings was the result of deterministic methods and unrealistic schedules used in simulation tools. In a fixed environmental condition, a person may behave completely differently on different occasions, which confirms the importance of using comprehensive data. This emphasizes the importance to use more realistic and comprehensive methods in this subject area.

2.3. Parameters influencing occupants' energy behaviour

As discussed earlier, comfort (specifically thermal comfort) is a state of mind that varies from person to person due to personal (physiological, psychological) and social parameters, which directly affect occupant's energy use. In addition, climatic parameters, economical parameters, regulations and policies, architecture and interior design of the space and building types directly influence energy behaviour of occupants (Fig. 7). Fabi, Andersen [95] reported the influential parameters on window opening behaviour of occupants, and classified these parameters into five groups: physical environmental factors, contextual factors, psychological factors, physiological factors and social factors.

Climatic (environmental, physical) parameters such as outdoor temperature, relative humidity, solar radiation, wind and rain are important parameters influencing occupants' interactions with building systems to acquire thermal comfort. A research study [73] used a clear description of the climatic parameters by providing an example of an office block consisting of different cellular offices: it considered each cellular office had a window and was occupied by one person; the outside weather was cold and all the windows were closed. The research concluded that if the room temperature increased gradually, more and more occupants would feel too warm and would open their windows. The outcome of this research can be presented as a curve to

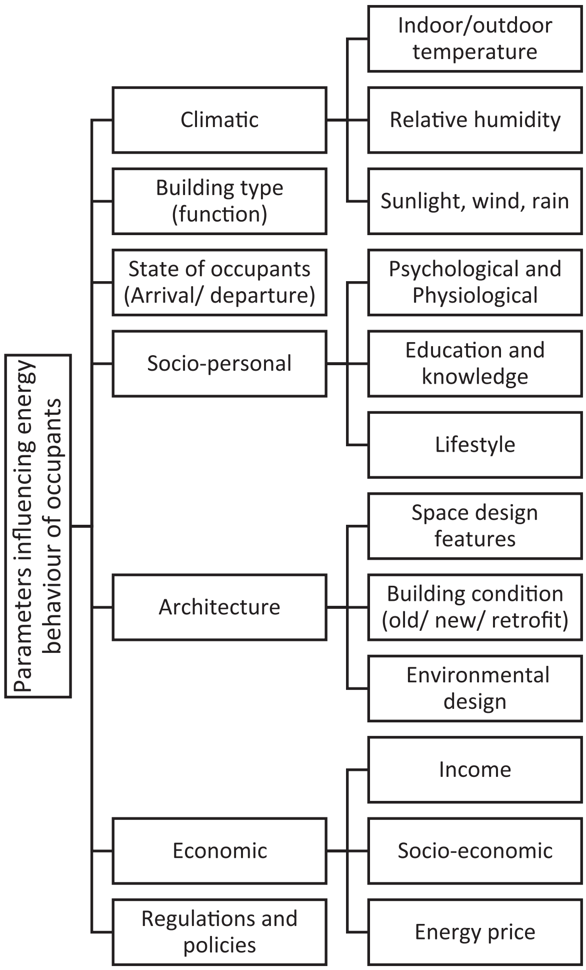

Fig. 7. Factors and sub-factors influencing energy behaviour of occupants.

show the probability of having open windows, which can be extended to other activities using different scenarios. The influence of climatic parameters on occupants' energy behaviour has been widely studied for different types of climatic conditions [12,36,41,46,52,55,60,61,65,83,94,101]. These parameters are time/ date dependant, therefore, in many studies stochastic models are used to estimate the probability of potential outcomes. Monitoring occupants' real interactions or (and) occupant behaviour surveys, in addition to, year-round thermal measurements are introduced and used in these climate related studies [94].

The building type determines the type of activity, clothing type, production of metabolic heat, together with the occupants' specific needs and expectations and their possible degree of interactions with building systems. Various research studies have focused on particular **building types (or type of activities)**, focussing heavily on residential buildings [8,9,13,16,21,23,30,33,35,36,41,42,55,57–61,65–67,69–72,76–80,85,89,94,102] and offices [12,20,24,25,27,34,37,38,40,44,46,47,52–54,62,75,81,101]. The level of attention paid to residential buildings and offices is due to their critical impact on the total energy consumption in the building sector. Some studies have investigated commercial [20,22,23,32,43,51] and educational buildings [29,31,51,56] with limited findings. There have been sparse studies undertaken on other public building types such as exhibitions and health centres.

Social and personal (psychological and physiological) parameters play a substantial role in occupants' comfort and energy attitude and has been broadly studied. Martinaitis, Zavadskas [13] identified social and personal factors affecting energy behaviour of households such as: users' awareness of energy issues, gender, age, employment, family size and socio-cultural belonging. Also, Janda [1] highlighted the effect of education and awareness-raising on people's energy attitude. Some studies have discussed one social or individual parameter; for example, the differences between male and female thermal preferences have been stated by some scholars [38,78,103,104]. However, the most dependable and comprehensive studies with regards to social and personal factors in this subject area, combined two parameters using human behavioural theories by Tetlow, van Dronkelaar [37] and Ajzen [105] to study occupants' electricity consumption in office buildings. Also, Hong, D'Oca [18] applied an ontology called DNA's framework, using a behavioural-cognitive theory, to suggest four key components governing occupants' energy behaviour: drivers, needs, actions and systems. Various behavioural theories, for example, the theory of planned behaviour [105], cognitive complex theory [106] and cognition as a network of task [107], considered the changeable human cognition process by connecting human and environment. Unfortunately, there is little evidence to suggest that the findings have been incorporated into building energy assessment tools. The authors believe that a multi-disciplinary approach is needed to bring together social scientists, energy modellers and construction engineers to tackle this complex problem. In addition, more detailed quantitative studies governing the sociology aspects of occupants' behaviours are suggested as necessary by some scholars [19], which is essential to improve the accuracy of energy consumption predictions in buildings.

Energy regulations and **economical parameters** such as energy price and employment have been discussed in various studies. In addition, the influence of these parameters on occupants' energy consumption behaviour in buildings has been raised by some scholars [13,14,16,36,57,58,69,73,76]. Studies show that when occupants are directly responsible for pay energy bills they act more energy frugal [36]. Rijal, Tuohy [73] investigated the relationship between energy price and occupants' thermal tolerance, which affects the total energy consumption of buildings. According to the findings of the study by Park and Kim [69], more than half of the respondents to their questionnaire indicated that energy costs as the main reason for avoiding the use of mechanical fans and accepting some level of discomfort. However, Romero, Bojórquez [57] showed that in harsh climatic conditions (e.g. very hot weather), low-income occupants consumed more electricity for cooling in comparison to other households due to the inadequate thermal insulation of the buildings. Similarly, Chen, Wang [61] stated that occupants' economic situation could determine the quality and size of their housing, which would consequently affect energy consumption. In another study, Langevin, Gurian [58] conducted semi-structured interviews of occupants in low-income public housing, which revealed notable differences of energy behaviours between rental paying occupants and government subsidised occupants.

A number of studies have revealed that occupants tended to adjust building systems and appliances more at arrival than at departure of a building. Therefore, **state of occupants** (arrival, presence in the space and departure) have been considered and modelled in a number of research projects [10,22,81,82] and the connection between occupants' movements and their behaviours have been investigated. In order to simulate the occupant's presence, Page, Robinson [81] proposed an algorithm by supposing present/absent status of occupants in each zone as a miscellaneous Markov Chain. Some studies used different indoor tracking methods to capture occupants' movements and presences such as: sensor-based systems (e.g. passive infrared (PIR) motion sensors) [108], vision-based methods [109,110], ultrasound [111] and WLAN location fingerprinting [112,113]. Furthermore, integration of these methods in studies related to occupant's energy behaviour can provide new insight towards the subject area.

The impact of **architecture and interior design features** on occupant's behaviour has been broadly studied [114,115]. With regards to energy consumption, the term “sustainable interior design” describes the integration of sustainability principles in the interior design of space as part of building construction [116]. The practice is mainly focused on use of green material and energy efficient systems [117]. The interior design of space can influence occupant behaviour in differing ways, including: visual quality of building openings (windows and doors), the architecture circulation and colours, material and compositions of interior spaces which may change occupants' thermal perception. However, the effects of interior design of space on occupants' energy attitudes have not been studied extensively. The differences between occupants' behaviours in old and new (or refurbished) buildings have been reported in several studies [31,62]. Moreover, Goldstein, Tessier [75] stated that space layout could influence occupant's presence, as it could link to the type of activity that occurs at the location within a space. Therefore, the probability of occupant's presence in certain locations based on different functions of the space could be simulated. Also, there is a proven link between lighting design and the occupant's lighting consumption. Gandhi and Brager [20] investigated the influence of occupants on plug load (electricity and lighting) energy consumption in office buildings and proposed an energy efficient strategy by decreasing the general ambient lighting and using task lights instead. Based on a rational statement, Karjalainen [24] suggested that using fixed and robust design strategies can decrease the effects of occupant behaviour on energy consumption in buildings, however, some studies highlighted that built environments with fixed thermal properties consume more energy and do not provide more thermal comfort for the occupants [118].

The term “design for sustainable behaviour,” which is mainly used in product design, refers to the role of designer in directing sustainable user behaviour during the design stage [119,120]. It is posited that if appropriate strategies are applied to the design of a product, the designer can positively influence the sustainable use of the product [119]. Also, a number of studies have confirmed the successful role of games, such as Cool Choices [121], as a motivation for occupants to practice more sustainable behaviours [20]. In order to change occupant's energy behaviour, two main approaches have been suggested: disincentive and motivation approaches (e.g. laws and regulations) and by increasing individual's knowledge and awareness [122]. Day and Gunderson [123] pointed out that it is essential to educate occupants and improve their knowledge and understanding of building systems, especially in high-performance buildings. Karatas, Stoiko [23] embraced a framework to measure the results of occupant's behavioural change in energy consumption using a “motivation-opportunity-ability” method. As a result, the study demonstrated effective behavioural change approaches to attain falls in energy consumption in buildings.

Furthermore, the vast majority of research on occupants' energy behaviour focuses on single buildings and there are only a few studies that investigate the urban scale impacts [69,71]. It is suggested that future research could extend to the urban design scale [68] as the understanding of the impact of occupants' energy behaviours on energy consumption on a larger scale improves the credibility of energy consumption policies made using more realistic data. The existing methodologies used to study the subject area in single buildings can be adjusted and used as the basis of further similar studies on the urban scale.

2.4. Occupancy factor in energy simulation

Energy simulation of a building is a mathematical analysis of the physical properties of the building elements, considering thermal and lighting aspects [8]. Jang and Kang [21] explained “building form, thermal properties and energy controls” as different inputs of building energy modelling. Current energy simulation engines such as TRNSYS, ESP-r, IES Virtual Environment or EnergyPlus, follow an almost similar procedure to calculate energy consumption in buildings. The final outputs are heating/ cooling/ ventilation design data, lighting data, CO_2 emission, the total energy consumption and cost. The reliability of the final output is strongly related to the accuracy of the initial energy model (which is sometimes a simplified version of a complex volume), together with, the ability to set correct data to all the available parameters of the software.

For example, in DesignBuilder, a leading energy simulation tool, energy behaviour is considered in the “activity” section of the software. This section includes: occupancy (to modify the density of people within each zone), activity factor, gender adjustments, clothing and use of computer and other equipment. Another widely used tool, EcoDesigner, has less occupancy inputs including: occupant's presence schedule and type of activity that determines the human heat gain. Autodesk Revit Architecture's energy section is also limited to occupancy schedules. Thus, the majority of specialists entrust default occupancy schedules of energy simulation software for energy analysis. Martinaitis, Zavadskas [13] confirmed the reliability of default occupancy for the energy efficiency assessment of households consisting of 4 occupants with high accuracy, concluding that there is a direct relationship between the importance of occupancy information in energy simulation and the “complexity” factor of the energy performance assessment.

However, neither within both energy efficiency certification methods nor in energy simulation software are occupants' energy behaviours fully evaluated or considered [13]. Yang, Santamouris [15] highlighted the critical importance of occupancy information in indoor environmental quality, energy consumption and building energy simulation. Occupant's impact on building energy consumption is only considered in the occupancy section of energy simulation software. Input data regarding occupancy in energy simulation software is limited to occupants' presence in fixed and scheduled patterns, and these do not reflect reality [8,13]. As an example, in residential buildings, the default occupancy is measured based on the floor area [14]. The ROWNER research project [14] showed that use of electricity in residential buildings was directly related to occupant behaviour and lifestyle. This research project and other similar studies, demonstrated that by neglecting occupants' interactions with building systems in building energy calculations leads to inaccuracies. Wetter, Bonvini [124] criticised the use of imperative programming paradigm in current energy simulation software and suggested using computer algebra instead, which is faster and more accurate. They also highlighted problems such as difficulty for programmers to further develop the current programs, or to add new parameters. The consensus from researchers is that behavioural parameters should be fully incorporated into energy simulation tools in order to provide more accurate energy predictions,

3. Conclusion: current research limitations and recommendations for future studies

The impact of occupants' behaviour on buildings is a growing research topic given the need to address climate change challenges. Numerous studies have investigated the impact of occupants on the energy consumption in buildings with the need to reduce the performance gap between the predicted and actual energy consumption of buildings. Occupants' active and passive energy behaviours (including: window opening, use of solar shading and blinds, adjusting HVAC setpoints, use of hot water, etc.) are not fully considered in current energy analysis tools. Thus, there is an inherent demand for energy modellers, researchers and designers to improve the calculation of energy consumption of buildings by considering energy behaviour of occupants. The main challenge is the complexity and dynamic nature of occupant's energy behaviour, which are influenced by various internal and external, individual and contextual factors. Therefore, occupants' motivations and reasons, and the various factors influencing their decisions to interact with building systems together, with the impacts of their actions on the total energy consumption of buildings, have to be studied in a multi-disciplinary approach to incorporate the factors from a sociology, psychology, economics, engineering and design perspectives.

This paper reviewed more than 100 publications related to occupant energy behaviour in buildings with the aim to identify the research gaps for future studies. A summary of the key findings are:

- Approximately 75% of the reviewed research, which directly studied the impact of occupant behaviour on building energy consumption, have focused on residential and offices buildings (44% and 31% respectively); fewer number of studies have analysed commercial and educational buildings, while, some building types such as exhibitions, recreational and healthcare facilities have been given sparse attention and require further analysis.
- The review of the literature also revealed that the majority of the research concentrates on single buildings, and urban scale impact has not been investigated adequately, forming a highly recommended area for future research. Likewise, at the micro level, the impact of interior design in terms of space layout, fixtures and fittings on occupants' action scenarios, thermal perceptions, and consequently on their energy behaviour has been overlooked and requires further investigation.
- In terms of the parameters influencing occupants' energy behaviours, personal (physiological and psychological) parameters have been taken into account in many studies (approximately 30% of the reviewed papers). The most recent behavioural methodologies suggest the consideration of not only the individual and personal characteristics of occupants, but also the particular features of their social context. However, only 10% of the reviewed papers have focused on both social and personal (socio-personal) factors. Therefore, the authors believe multi-disciplinary approaches are needed to combine socio-personal parameters through psychological cognitive behavioural methods (e.g. theory of planned behaviour [105], cognitive complex theory [106] and cognition as a network of task [107], which could provide new insights to the domain.
- According to the reviewed publications, the different types of occupants' interactions with building systems, such as use of electricity, use of fans (or air conditioning) and use of building openings (windows and doors), have been investigated. However, some areas, such as the use of hot water has a significant impact on energy consumption in some building types (e.g. residential), have received scant attention in comparison but are considered to have a likely impact on energy use. Furthermore, future investigations about the inter-relationship between different energy behaviours of occupants are needed, which will generate more realistic assumptions in building energy predictions.
- A considerable number of studies contain detailed methodologies including case studies and experiments, using different types of qualitative and quantitative data gathered by pre and post-occupancy surveys, occupant monitoring (using sensors or observation), field measurements and questionnaires, followed by data analysis (Markov Chain, Monte Carlo and logistic regression) and simulations. The findings of these studies have provided a clearer insight towards understanding the impacts of occupants' behaviours on the energy consumption in buildings. However, the findings, at present, have yet to offer significant improvements in predicting occupants' energy behaviour in buildings. Particularly, the translation and integration of the findings of these studies into building energy simulation tools to reduce the gap between predicted and actual energy consumption in buildings still remain a significant research challenge in this area.

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