Occupant Behaviour in Buildings: Advances and Challenges

Editors:
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PREFACE

Occupant behaviour in buildings has been a matter of concern all over the world. Buildings are responsible for a significant portion of energy consumption; therefore, improving the thermal and energy performance of such buildings requires knowledge about the variables that influence them. However, to increase the potential for improving thermal and energy performance of buildings, studies must also consider the occupant's interactions with the built environment. The occupant behaviour influences the conditions of the internal environment through the occupation of the spaces and through the interaction with building elements, such as air-conditioning, lighting, blinds and windows. Thus, the objective of this e-book is to put together some of these aspects, presenting advances and challenges, by means of eight chapters written by renowned researchers.

Due to recent technological innovations related to Information and Communication Technologies (ICTs), buildings are undergoing some evolutions and incorporating technologies that endow them with intelligence. However, the requirement of building intelligence to be related to the response of the occupants' needs leads to the consideration of the buildings as Cyber-Physical-Social Systems (CPSS). Combining technical and social dimensions in this new generation of buildings, occupants' satisfaction and energy use can be improved. Mateus V. Bavaresco, Ricardo F. Rupp and Enedir Ghisi concluded that by enriching data collection and presentation, more professionals can access previous outcomes and adapt their practices towards achieving comfortable and energy-efficient buildings.

People's behaviour can significantly impact both the energy consumption and the indoor thermal environment of the buildings, and of particular interest is their window opening behaviour. A better understanding of why, when and how occupants open windows is, therefore, essential in the quest to achieve low-carbon buildings. Shen Wei provided systematic criteria for selecting a suitable monitoring method for their specific research objectives. Additionally, the author demonstrates the need for a standard method for monitoring relevant influential factors, as these varied considerably between existing studies with respect to the accuracy, interval and location. Such variation clearly has the potential to influence the ability to perform cross-study comparison.

Changing and improving the heating systems have been systematically associated with a wide range of effects, such as thermal comfort and improved air quality, which are often termed as co-benefits or ancillary benefits. Literature shows that co-benefits can be decisive when users choose a heating solution. Ricardo Barbosa and Manuela Almeida used international qualitative surveys to identify, quantify and evaluate the co-benefits associated with heating solutions, to clarify the relevance of the co-benefits in the decision-making process of building users. The results suggest that both the degree of relevance and the willingness to pay for co-benefits vary significantly amongst different national contexts.

Occupancy is a paramount factor to achieve energy efficiency. The authors António Ruano, Karol Bot and Maria Ruano, proposed a new methodology to estimate the occupancy and analysed the impacts of occupants on thermal comfort and energy efficiency in buildings from two distinct sectors: residential and educational.

The knowledge of occupant actions and needs is determinant for the proper function of an intelligent building. Therefore, the building management systems (BMS) must be supplied with data from the occupants. However the data by itself does not ensure the knowledge of occupants' needs and the ability to predict their behaviours. To do that, BMSs must be gifted with artificial intelligence (AI) and machine learning (ML) techniques to data mine the information provided by the monitoring systems. Pedro F. Pereira and Nuno M. M. Ramos compared methodologies used to detect occupant actions and occupants' needs in the same case study. The compared methodologies have the ability of self-learning and, therefore, can the used in multiple circumstances.

The variability of human behaviour is not taken into account in many thermal and energy performance studies, causing inconsistencies between simulation results and reality. One of the reasons for these inconsistencies also relies on adopting an opening availability schedule which is strictly limited to the occupancy schedule of a room, especially in residential buildings. Aline Schaefer, João Vitor Eccel and Enedir Ghisi studied the dependency relationship between the room's occupancy schedule and the operation of openings in low-income houses in Florianópolis, southern Brazil. The main result has shown that the opening operation schedule often does not depend on whether the room is occupied or not and seems to rely more accordingly to a daily routine, such as the time one wakes up or goes to sleep, or leaving and coming back home.

The gap between the estimate and actual thermal and energy performance is directly and indirectly attributed to occupants. To address such issue, Arthur Santos Silva investigated the uncertainties of occupant behaviour in building performance simulation through a probabilistic approach. The author showed that the number of occupants, the schedules of occupancy of the bedrooms, the setpoint temperatures for operating the openings, the cooling setpoint of the Heating, Ventilation and Air-Conditioning system (HVAC) and the limits for operative temperatures of the rooms were the most influent variables for the thermal and energy performance, especially in the heating period. The uncertainty was up to 65.6% for estimating the degree-hours for heating (in the natural ventilation mode) and up to 59.3% for estimating the total electricity consumption with HVAC (in the hybrid ventilation mode), indicating that these operational uncertainties had a great impact on the simulation results.

Cultural heritage plays an important role in society, not only in cultural terms but also due to its touristic interest. However, it is necessary to ensure that conservation and comfort conditions are not affected, since the human body releases heat, moisture, CO_2 and odours. Hugo Entradas Silva and Fernando M. A. Henriques analysed the impact of the binomial ventilation *vs.* occupancy, simulating various combinations of ventilation and air recirculation on the indoor air quality, conservation and energy consumption in museums. Since the visits to major national museums take usually long periods, the concept of adaptation was analysed to reduce the airflow of fresh air per visitor.

Chapter 1, written by Mateus V. Bavaresco (of the Federal University of Santa Catarina, Brazil), Ricardo F. Rupp (of Technical University of Denmark) and Enedir Ghisi (of the Federal University of Santa Catarina), explores the potentials of combining objective information gathered from technological innovations with subjective inputs obtained through qualitative methods in occupant behaviour research.

Chapter 2, written by Shen Wei, of the University College London, UK, introduces existing methods that have been used to monitor occupant window opening behaviour in buildings based on a comprehensive literature review. The author also points out relevant influential factors and discusses the advantages and disadvantages of each method.

Chapter 3 was written by Ricardo Barbosa and Manuela Almeida of the Department of Civil Engineering of the University of Minho, Portugal. The authors support the decision-making process of building users in the selection of energy-efficient heating solutions by identifying and evaluating co-benefits.

Chapter 4, written by António Ruano, Karol Bot, Maria da Graça Ruano of University of Algarve, Portugal, studied the impact of occupants in thermal comfort and energy efficiency.

Chapter 5, written by Pedro F. Pereira and Nuno M. M. Ramos of the Faculty Engineering of the University of Porto, Portugal, compared different machine learning techniques used for the detection of occupant actions in buildings and the drivers of their behaviour.

Chapter 6 was written by Aline Schaefer, João V. Eccel and Enedir Ghisi, of the Federal University of Santa Catarina, Brazil. The authors investigate the dependency relationship between the room's occupancy schedule and the operation of openings in low-income residential buildings.

Chapter 7, written by Arthur S. Silva, of the Federal University of Mato Grosso do Sul, Brazil, investigates the uncertainties of occupant behaviour in building performance simulation through a probabilistic approach.

Hugo Entradas Silva and Fernando M. A. Henriques, of the Department of Civil Engineering, Faculty of Science and Technology, Portugal, wrote Chapter 8. The authors analyse the impact of ventilation on conservation, human health and comfort in museums.

We would like to thank all the authors who have contributed to this e-book, and the editorial team for their valuable work and completion of this e-book.

The views and opinions expressed in each chapter of this e-book are those of the authors.

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CHAPTER 1

Exploring The Potential of Combining Technological Innovations with Qualitative Methods in Occupant Behaviour Research

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Abstract: The literature emphasises the important role that occupants play regarding the energy performance of buildings. Scholars have applied several methods to assess occupants' preferences and practices in their field studies. Technological innovations such as Internet-of-Things (IoT) may capture valuable objective information that can be translated into mathematical models. Such models are vital in Building Performance Simulation (BPS) practices as they are expected to reduce performance gaps between expected and real energy use in buildings during operational phase. However, data-driven models strictly related to physical parameters exclude essential subjective information like occupant preferences and needs. There is enough evidence showing that individual differences impact on thermal preferences and levels of comfort indoors, which must also be considered in occupant behaviour studies. Aside from individual preferences, there is also social influence when occupants share spaces and the control of building systems. Several methods commonly used in social science studies are expected to incorporate the needed subjective information in this field if properly used. Therefore, this chapter explores the potentials of combining objective information gathered from technological innovations with subjective inputs obtained through qualitative methods.

Keywords: Behavioural sensing, Building control, Building operation, Comfort, Energy, Energy efficiency in buildings, Indoor environment, Internet of things, Occupant behaviour, Social science, Technology.

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Enedir Ghisi, Ricardo Forgiarini Rupp and Pedro Fernandes Pereira (Eds.)

INTRODUCTION

Buildings are commonly related to a high share of energy use worldwide. According to the last report by the International Energy Agency (IEA), the buildings and construction sector were responsible for 36% of the final energy use and 39% of energy and process-related CO_2 emissions [1]. Therefore, huge opportunities for energy savings and reduction of CO_2 emissions may be achieved by improving buildings. The energy use in buildings was the object of study of a group of 100 researchers from 15 countries, who gathered together and conducted strong research under the IEA and Energy in Buildings and Communities (EBC) Programme, in the IEA-EBC Annex 53 "Total energy use in buildings - Analysis and evaluation methods" [2]. Researchers concluded that there are six main factors that impact the energy use of buildings, *i.e.* climate, building envelope, building equipment, operation and maintenance, occupant behaviour, and indoor environmental conditions. As they argued, the three first are technical and physical factors, while the three last ones are human-influenced factors. Technical and physical characteristics cannot be considered as the only aspects when optimisation of energy use in buildings is intended. Indeed, technological and envelope-based interventions may reduce energy use in buildings; however, it is important to consider that they cannot guarantee this outcome alone [3]. When it comes to building operation, the literature also highlights that people in modern societies tend to spend about 85% of their time indoors [4]. It is then clear that the way occupants interact with buildings largely impact their total energy use.

Along these lines, recent research has evolved regarding the evaluation of human-related factors that impact building energy use. Considering the success of Annex 53, a different group of collaborative research was made to work on many unanswered questions. This new group, IEA-EBC Annex 66 "Definition and simulation of occupant behaviour in buildings", was then established based on the main takeaways from Annex 53. IEA-EBC Annex 66 main objectives relied on enhancing occupant behaviour research in terms of data collection, model representation and evaluation, and integrating such models in building performance simulation practices [5]. This field presented huge improvements with the completion of Annex 66, and a large amount of work was conducted throughout the world. Then, a follow-up research group was established following the conclusion of Annex 66 since there is a need for implementing advanced occupant modelling in practical activities. IEA-EBC Annex 79 "Occupant-Centric Building Design and Operation" is developing new knowledge about occupant behaviour, focusing on applying and transferring knowledge to practitioners [6]. This new research group involves a multidisciplinary team with expertise in engineering, architecture, computer science, psychology, and sociology. Its scope encompasses the conception of guidelines, recommendations for codes and standards, the establishment of data-driven methods, as well as the creation of new occupant models and simulation tools.

A common practice in occupant behaviour research is relying on sensor-based information to objectively assess indoor conditions as well as occupant presence and actions. For instance, environmental parameters may be used to infer as well as explain occupant behaviour or presence through statistical analyses or machine learning algorithms. By inferring, we mean using such environmental parameters to deduce certain actions, *e.g.*, by evaluating carbon dioxide concentration indoors, one may assume that a space is occupied or not [7]. When the actual occupant behaviour is also monitored, environmental parameters may be used to explain and determine boundaries for building adjustments. For instance, one may evaluate typical temperature thresholds that drive air-conditioning use [8]. In this way, the literature shows that several environmental parameters may be linked to the adjustment of building systems. Aside from occupancy, CO_2 concentration was also related to window control [9 - 11]. Indoor [12 - 14] and outdoor air temperatures [12,15,16] have been related to window, blind/shade, and HVAC (Heating, Ventilation, and Air Conditioning) control, as well as adaptive actions like drinking a cold drink. Indoor humidity has been associated with thermostat adjustments [17]. Specific choices like the degrees of opening in residential windows were also related to indoor and outdoor air temperatures [18]. Solar radiation and indoor/outdoor air temperature [12,19,20] were also related to the adjustments of blinds or shades. Although several environmental parameters were already linked with occupant behaviour in buildings, there is evidence that subjective aspects also play an important role in this field.

It is evident that occupant-behaviour related studies are increasing fast in the last few years; however, more work is still necessary to properly evaluate how occupants use different building systems, as several aspects influence this role [21]. More specifically, the literature supports that multi-domain physical variables, contextual and personal factors affect both occupants' perceptions and behaviours in buildings [22]. A huge body of research has focused on the influence of physical variables on occupant behaviour. However, there are still uncertainties related to the impact of contextual and personal factors in this field. Therefore, behavioural theories also significantly contribute to understanding personal factors and their relation with occupant behaviour, and a literature review synthesising the most commonly used theories was presented [23]. Authors acknowledged 27 approaches used in the literature, and they come mainly from the fields of psychology, sociology, and economics. Specifically, psychological theories were the most common, and the Theory of Planned Behaviour was the most frequent. Relying on the potential of applying qualitative knowledge on occupant-related research, another literature review presented methods commonly

CHAPTER 2

Monitoring Occupant Window Opening Behaviour in Buildings: A Critical Review

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Abstract: People's behaviour can significantly impact both the energy consumption and the indoor thermal environment of the buildings, and of particular interest is their window opening behaviour. A better understanding of why, when and how occupants open windows is, therefore, essential in the quest to achieve low-carbon buildings. Many studies have sought to answer these questions based on behavioural data measured in actual buildings. This paper introduces existing methods that have been used to monitor occupant window opening behaviour in buildings based on a comprehensive review of literature, as well as for relevant influential factors, and critically discusses the advantages and disadvantages of each method. The review has identified five methods monitoring window usage (*i.e.* self-recording, electronic recording, observing by surveyors and self-estimating), and each method has its advantages and disadvantages in terms of feasible sample size, monitoring interval and duration, recognition of window states/opening angle, and the relative dynamic nature of behaviour. The aim has been to provide researchers with systematic criteria for selecting a suitable monitoring method for their specific research objectives. Additionally, the paper demonstrates the need for a standard method for monitoring relevant influential factors, as these varied considerably between existing studies with respect to the accuracy, interval and location. Such variation clearly has the potential to influence the ability to perform cross-study comparisons.

Keywords: Behavioural modelling, Buildings, Driver, Energy, Electronic measurement, Indoor air quality, Indoor environment, Monitoring, Outdoor environment, Window opening behaviour.

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Enedir Ghisi, Ricardo Forgiarini Rupp and Pedro Fernandes Pereira (Eds.)

INTRODUCTION

The high importance of occupants' role in the performance of buildings has been demonstrated by both real measured data [1 - 7] and building performance simulation [8 - 14]. As Gram-Hanssen [15], Ben and Steemers [16] and Pisello and Asdrubali [17] have argued, how occupants use the building has a direct and significant impact on the building's indoor environment and energy consumption, no less than the building construction and building systems. Furthermore, occupants' behaviour within the buildings can also affect their comfort perceptions: when provided with a higher level of adaptive opportunities [18] (*e.g.* opening/closing windows, adjusting blind/shading positions and turning up/down thermostatic settings) to rebalance comfort, occupants displayed greater comfort acceptance [19 - 21].

In order to achieve energy efficient buildings the aspect of occupant behaviour is crucial and should not be neglected [22 - 27]. It has been demonstrated by Masoso and Grobler [28] and Guerra-Santin [29] that improper building use may cause a significant waste of energy, and user-centred building control strategy can greatly help to reduce the building's energy demand [30, 31]. Furthermore, according to Ben and Steemers [16] and Wei *et al.* [32] insufficient consideration of occupant behaviour when retrofitting/refurbishing buildings may also lead to improperly selected energy efficient measures. Aiming at a golden role proposed by Masoso and Grobler [28], *i.e.* '*If you don't need it, don't use it*', for building energy saving, a number of studies have been carried out to make occupants use buildings more energy efficiently [33 - 40], achieving low-carbon life styles [41 - 44]. Mullaly [45] has pointed out the importance of this task should be of serious concern not only by building users, but also by local and national government.

Occupant behaviour is a complex process: it is influenced by a number of factors [46 - 49] and can manifest itself in what Peng *et al.* [50], call various modes, *i.e.* time-related, environment-related and random. When introduced into building simulation models, occupant behaviour appears to be one of the biggest contributors to the gap between the predicted and actual building performance, commonly considered as performance gap [51 - 56]. This being the case, it has been argued that improved representation of occupant behaviour in building simulation is of paramount importance for the optimisation of building design for real applications [57 - 59].

Windows, as an important component of building façade, have a major impact on buildings' indoor visual environment and energy consumption [60 - 62]. In non-air-conditioned buildings, opening windows provides a useful way for occupants to adjust their indoor thermal environment [63, 64] and air quality [65, 66], *via* promoted air exchange between indoors and outdoors [67 - 70]. However when the building is heated or cooled mechanically, opening windows will cause extra energy loss [62, 71 - 74]. Wei [75] has revealed that in the past 30 years, a number of studies have been performed using engineering methods to gain a better understanding of why, when and how occupants open windows. Generally, these studies started from a field monitoring of occupant window use in buildings, concurrently with a recording of relevant environmental and non-environmental parameters, as shown in Fig. (**1**). Then the studies can be grouped into two methodological fluxes. Studies following Flux 1 were designed mainly to evaluate the impact of occupant behaviour on the building performance, such as indoor environmental quality and energy consumption, based on the real measured data from the building [68, 76, 77]. Studies based on Flux 2 were aiming for deeper research on occupant window opening behaviour, namely developing reliable behavioural models, to reduce the gap between the building simulation results and actual building performance [78 - 83]. These studies generally included a 'driver determination' stage, in which all monitored environmental and non-environmental parameters were assessed for their influence on the state of the windows. The parameters with significant influences were categorised as 'drivers'/'factors' of window opening behaviour [46, 47] and were used to build statistical models for window state predictions [84]. After a validation process, these models would be used in building performance simulation to provide more reliable simulation results to support building design and operation.

In both fluxes shown in Fig. (**1**), apparently, the monitoring stage is fundamental as it provides the raw data that is used for later analysis. Therefore, a critical understanding and controlling of the accuracies of available data collection methods are extremely important both existing data usage and future data collection. This paper, therefore, presents a critical review of existing methods that have been used to monitor occupant window opening behaviour in buildings, and discussed their advantages and disadvantages. Additionally, existing methods that have been used to monitor relevant influential factors have been critically reviewed and compared as well.

MONITORING OCCUPANT WINDOW OPENING BEHAVIOUR

In existing studies regarding occupant window opening behaviour in buildings, there are five methods that have been used to monitor the window usage (either on/off or opening angles) by building occupants:

1. Self-recording by building occupants;
2. Recording by electronic measuring devices;

CHAPTER 3

Supporting the Decision-making Process of Building Users in the Selection of Energy-Efficient Heating Solutions by Identifying and Evaluating Co-benefits

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Abstract: Space heating is responsible for a significant share of the energy consumed in European households, and the replacement of appliances with more efficient alternatives can be decisive for meeting the targets set by the European Union for 2030 and 2050. Although an estimated 60% of the heating stock consists of inefficient equipment, users are often not aware of this inefficiency and associated costs. Also, changing and improving the heating systems have been systematically associated with a wide range of effects, such as thermal comfort and improved air quality, which are often termed as co-benefits or ancillary benefits. Previous research has shown that co-benefits can be decisive when users choose a heating solution. This chapter reports on the results obtained in a study conducted in the scope of the EU H2020 HARP research project, in which an international qualitative survey was used to identify, quantify and evaluate the co-benefits associated with heating solutions, to clarify the relevance of the co-benefits in the decision-making process of building users. The results suggest that both the degree of relevance and the willingness to pay for co-benefits vary significantly amongst different national contexts.

Keywords: Building Systems, Co-Benefits, Contingent Valuation, Degree of Relevance, Economic Valuation, Heating, Qualitative survey, Willingness to Pay.

INTRODUCTION

Climate change is being recognised as one of the biggest challenges of the century, and there are considerable problems to be tackled in the next decade. One of the most well-defined issues is related to residential energy consumption, which is very significant, and it is causing determinant impacts in terms of carbon

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emissions. Energy demand in the building sector is responsible for 40% of the European Union energy consumption, and 85% of it is used for heating and domestic hot water [1].

Furthermore, heating and cooling in the European territory are still heavily dependent on the use of fossil fuels. In fact, only around 18% of the primary energy consumption for these uses are originating from renewable sources. The most used energy source for heating and cooling is natural gas (46%). Coal (15%), biomass (11%), fuel oil (10%) and nuclear energy (7%) are also used in abundance for the heating and cooling of buildings and industry in Europe [2]. There is, therefore, the need to increase the energy efficiency in this sector as heating demand has been a central problem in the majority of the European territory. In this context, it is objectively recognised that the replacement and retrofit of old heating equipment should be promoted to fulfill EU climate and energy goals, namely regarding full carbon neutrality until 2050 [3]. In particular, in the built environment, the implementation of sustainable and energy-efficient heating and cooling systems, mainly based on renewable sources, can play a determinant role in bringing these buildings closer to net-zero energy and emissions [4].

Following that direction, the European Union has been demonstrating the political will to support that transition. In 2016, as part of the Sustainable Energy Security Package, the European Commission proposed an EU Heating and Cooling strategy [5] which includes measures that should be addressed in future regulations and policies to improve energy efficiency, promote energy renewable energy sources and tackle climate change. The strategy identifies the following areas as priorities for legislative and policy actions: i) Facilitating building renovations; ii) Increasing the share of renewables; iii) Reusing the energy waste from industry and iv) Getting consumers and industry involved. In addition, the Energy Efficiency Directive (revised in 2019) [6] intends to motivate and drive the Member States to periodically assess the energy-efficiency of heating and cooling infrastructure with the objective of promoting continuous improvement.

Given the European stock of installed appliances (126 million space heaters), of which about half has an efficiency of 60% or less [5], there is considerable room for improvement. However, the current European building stock is the property of millions of different owners, which are known to have different perspectives on the investments that should be made in buildings. Private homeowners, for example, that in most cases do not have the technical expertise and capital availability to make investments, have very heterogeneous investment criteria and investment contexts, presenting a future behaviour that is not ruled by pure rationality being, therefore, very hard to envision [7].

The literature also shows that the adoption of sustainable and energy-efficient heating systems is a complex issue. Research studies indicate that public and political supports are very much needed to support a consistent adoption of this equipment, which has to be addressed from several scales and using different perspectives [8]. Factors that can incentivise the adoption of energy-efficient systems include favourable economic conditions, previous knowledge and literacy in engineering or energy-related subjects and awareness of the associated advantages [9]. On the other hand, barriers to the adoption of this type of technologies include not only habits and perceived behavioural control [10], but also issues related to investment and hidden costs, poor payback time perceived and the unperceived benefits of such an intervention [7, 11].

To deal with these barriers, there is evidence that incentives, such as subsidies, are known to be effective [12], in particular in the so-called problem-triggered interventions [13]. For homeowners driven by opportunities (as in the scope of a planned building renovation), additional factors, such as operational convenience (*e.g.* ease of use) [13] or even relative independence from fossil fuels, seem to be significant [14]. The most common argument for promoting investments in energy efficiency, such as the replacement of heating systems, is related to the energy and economic savings potentially achieved. This engineered-based perspective overlooks the results of several studies that point out that energy savings are often not the main motivation in the decision-making process. For example, improving the "indoor climate" is a known decision-making trigger for interventions that promote energy-efficiency, such as replacing a heating appliance or improving the insulation of the house (*e.g.,* [15]). In fact, besides energy and economic savings, there is a wide range of other known effects, at various scales, that are related to this type of investments. These effects are often termed as "co-benefits", "ancillary benefits" or "non-economic benefits" [16] and can be determinant in promoting the change needed to successfully address climate change and its effects [17].

However, co-benefits, because of their subjective nature, are more difficult to quantify than objective indicators, such as savings, and are consequently often ignored and rarely measured, quantified, or monetised. Despite this difficulty, identifying and quantifying the relevance of co-benefits regarding energy-efficiency investments, can bring additional knowledge and support the decision-making of building users and energy consumers, as seen in other studies addressing different contexts [18, 19]. Following the traditional engineering-based approach, energy-efficiency improvements at the private or household scale are usually evaluated by a trade-off between the savings resulting from the use of operational energy and the investment cost of such improvements. Or, in a more evolved approach, by considering the balance between the energy use and the

CHAPTER 4

The Impact of Occupants in Thermal Comfort and Energy Efficiency in Buildings

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Abstract: The chapter reviews the impact of occupancy in buildings, in particular in thermal comfort and energy efficiency. Concerning the first issue, this chapter will first propose a means to estimate occupancy, the impact of occupation in thermal comfort measured by the Predicted Mean Vote index, and its use for real-time control of HVAC equipment. All data used are measured data of a real university building under normal occupation. The effect of occupancy in energy efficiency will focus on the residential segment, using data of a recent installation of a data acquisition and control system in a household located in the south of Portugal. This work shows that the impact of occupancy in electricity consumption becomes more evident as the electric energy is being desegregated and that the availability of this information by the occupants can be used to improve energy efficiency. Moreover, the use of occupation in the design of electric consumption forecasting methods will also be discussed.

Keywords: Artificial neural networks, Computational learning, Data acquisition, Energy efficiency, Electricity consumption, Forecasting models, HVAC, Multi-objective genetic algorithms, Occupation, Thermal comfort.

INTRODUCTION

Industrialisation and globalisation powered a rapid economic development that was accompanied by progressively increasing energy consumption [1]. Three sectors of the economy stand out for the significant amount of energy they consume. They are the sectors of industry, transport, and buildings - with buildings representing the largest portion. For example, in the United States, the built environment consumes 35% of total primary energy, and about 45% of electricity, mainly through the use of Heating, Ventilating and Air Conditioning

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(HVAC) systems [2]. It is, therefore, of fundamental importance to decrease energy usage in residential and service building and, simultaneously, maintain the thermal comfort of its occupants. This can be obtained by integrating efficient passive solutions in the architecture and construction of buildings, the employment of renewable energy, and the use of efficient Home Energy Management Systems (HEMS), with a special emphasis on the control of existing HVAC systems.

Despite all advances obtained in these areas in the last decade, the maximum capacity for the use of intelligence in building systems, however, remains fallow, due to the complexity and variety of the systems, in addition to the frequent question of suboptimal control strategies [3]. Various reviews reported intelligent optimisation and control strategies in buildings [4], advanced control schemes [5], energy intelligent buildings [6] and passive and energy-efficient designs [7, 8]. Occupancy and occupant behaviour have a considerable impact on the operation and performance of the building. In [9], the motivations of occupant behaviour in a residential context are categorised. Detection of occupant actions through the usage of indoor environment monitoring systems is presented in [10].

This chapter deals with building thermal comfort, HVAC control and home energy efficiency, focusing on the impact of occupation are these three areas. The two former topics are discussed in the next section, while energy efficiency will be dealt with the subsequent section. Conclusions and future research directions are discussed in the final section of this chapter.

THERMAL COMFORT AND HVAC CONTROL

This section introduces the most used metrics for thermal comfort evaluation and proceeds to the estimation of occupancy in buildings. Subsequently, the impact that occupancy has in thermal comfort is highlighted, and a method to use the thermal comfort index for HVAC control is proposed, incorporating occupation estimation.

Thermal Comfort Metrics

The thermal sensation of occupants in buildings varies not only with the climate conditions in the rooms but also with the activity the occupants are performing, their clothing, and also between individuals. Because of that, the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) proposed a thermal sensation scale (Table **1**) to quantify the thermal sensation of people [11].

Table 1. The ASHRAE Thermal Sensation Scale.

Cold	Cool	Slightly Cold	Neutral	Slightly Warm	Warm	Hot
-3	-2	-1	0	1	2	3

The Predicted Mean Vote (PMV) index was presented by Fanger [12], aiming to allow the prediction of the average vote of a large group of persons, on the thermal sensation scale. The PMV relies upon six components: mean radiant temperature (), clothing insulation (I_{cl}), metabolic rate (M), air temperature (), air velocity () and air humidity (H_{ai}). Please note that there are other thermal comfort indexes (see, for instance [13]) but it is the one most used. It is computed utilising a heat-balance equation given by [14], as eq. (1):

$$PMV = \left(0.303e^{-0.036M} + 0.028\right)L \tag{1}$$

where L represents the thermal load in the human body, characterised as the variation between the internal heat production and the heat loss occurring when the human is in a thermal balance, as described in eq. (2):

$$\begin{aligned} L = &\left(M - W\right) - 0.0014M\left(34 - T_{ai}\right) - 3.05*10^{-3}\left(5733 - 6.99\left(M - W\right) - P_{ai}\right) - \\ &-0.42\left(M - W - 58.15\right) - 1.72*10^{-5}M\left(5867 - P_{ai}\right) - 0.0014M\left(34 - T_{ai}\right) - \\ &-3.96*10^{-8} f_{cl}\left[\left(T_{cl} + 273\right)^4 - \left(\overline{T}_r + 273\right)^4\right] - f_{cl}h_c\left(T_{cl} - T_{ai}\right) \end{aligned} \tag{2}$$

where W and M are the external work and metabolic rate, respectively, both in W/m^2, P_{ai} is the fractional water vapour pressure in Pascal. Both temperatures T_{ai} and are given in degrees Celsius. The h_{cl}, the convective heat transfer coefficient, and, clothing surface temperature (both in ºC), are given by eq. (3) and eq. (4):

$$\begin{aligned} h_{cl} &= \begin{cases} h_c^* & if\ h_c^* > 12.1\sqrt{V_{ai}} \\ 12.1\sqrt{V_{ai}} & if\ h_c^* < 12.1\sqrt{V_{ai}} \end{cases} \\ h_c^* &= 2.38\left(T_{cl} - T_{ai}\right)^{1/4} \end{aligned} \tag{3}$$

$$\begin{aligned} T_{cl} = &35.7 - 0.028\left(M - W\right) - \\ &-0.1555 I_{cl}\left[39.6*10^{-9}\left[\left(f_{cl} + 273\right)^4 - \left(\overline{T}_r + 273\right)^4\right] + f_{cl}h_c\left(T_{cl} - T_{ai}\right)\right] \end{aligned} \tag{4}$$

CHAPTER 5

Detecting Occupant Actions in Buildings and the Drivers of Their Behaviour

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Abstract: The new directive 2018/844/EU on Energy Performance of Buildings and Energy Efficiency, supports the change of building into smarter, more energy-efficient and include the perspective of the occupants' needs. The knowledge of occupant behaviour is the centre of the balance between the buildings energy efficiency and its indoor environmental quality. This chapter presents a state-of-the-art of the buildings occupant behaviour, presenting the new developments and future trends. It summarises research in which a series of methodologies were developed to supply relevant data to the building management systems (BMS). These methodologies use a monitoring system based on environmental sensors, namely relative humidity, temperature, and carbon dioxide. New methods to detect the occupant actions in the operation of building systems were summarised and compared. The methodologies were based on statistical tools and machine learning techniques. They can be applied to different case studies since they can adapt to the local environment under a self-learning strategy. The drivers of behaviour for the operation of those building systems were also analysed. Two methodologies that allowed to predict the occupant actions taking into account the parameters that influenced the occupant behaviour were described. It was also possible establishing the seasonality of drivers of behaviour. The overall results highlight that the actions, motivations, and impacts of a specific set of occupants performed in building systems can significantly vary depending on the room and on environmental parameters.

Keywords: Action detection, Drivers of behavior, Intelligent buildings, *In situ* data acquisition, Occupant behaviour.

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INTRODUCTION

Scope

Nowadays, energy efficiency in buildings is a recurring subject and one way to reduce CO_2 emissions. The 2018/844/EU [1] directive, recently approved to update the Directive 2010/31/EU [2] and the Directive 2012/27/EU [3], introduced a new concept in the balance between energy efficiency and the indoor environmental quality: the occupants. This new concept turns the focus of the energy efficiency studies to occupant centric.

Occupant Behaviour

Solar passive methods were the first studies in the energy efficiency of buildings [4]. These initial studies focused on systems and building components, drawing attention away from the study of the building occupants [5]. However, in recent years, it can be observed an increase in studies related to occupant behaviour in buildings [6].

One of the main factors contributing to the increase of the studies in occupant behaviours relies on the fact that occupancy is considered a predominant factor in the building performance and one of the main variables for the exiting gap between the simulated and the post-occupancy monitoring data [7 - 10]. The literature studied this effect from different perspectives. The occupant behaviour studies could be divided into two distinct research fields: the energy consumption impacts of occupants; and the indoor environmental quality impacts [11, 12].

This research field contains several frameworks, ontologies and reviews. One of the most cited ontology was written by Hong *et al*. [13]. According to the authors, there was a need to create an ontology to organise the research of energy-related occupant behaviour in buildings. Therefore, the authors divided the studies into four categories: drivers, needs, actions and systems (DNAS) (Fig. **1**). The first category groups the works that studied the environmental factors that motivate the occupants to perform an action that fulfills a need; the second category groups the studies where the occupants' requirements of the indoor environment of their dwelling; the third category compiles the studies on the actions performed by the occupants with the systems and the fourth category groups the buildings active and passive components that the occupants operate to fulfil the occupants' needs.

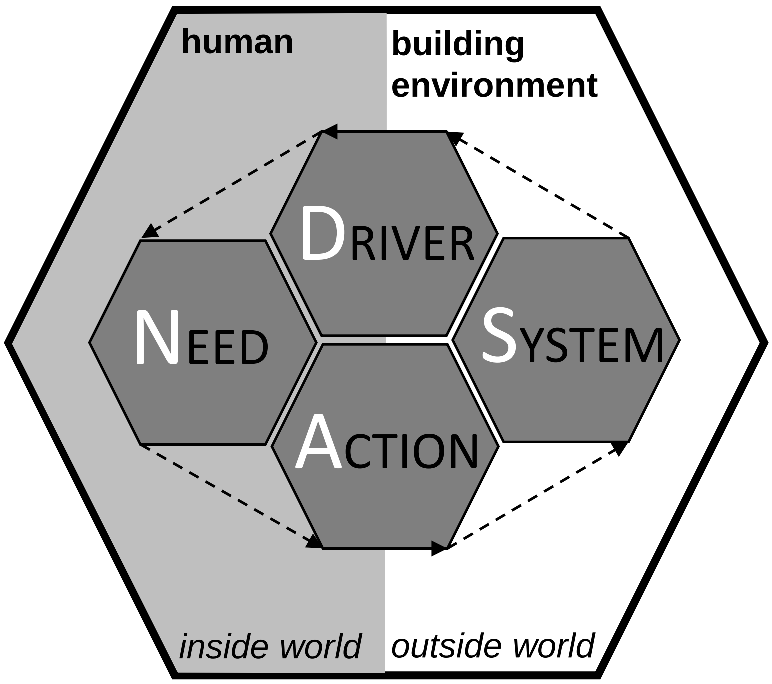

Fig. (1). DNAS ontology, extracted from [13].

In order to reduce the gap between the building simulations and the post-occupancy monitoring data, researchers have adopted two different approaches: the macro studies and the room-level. The former has the utility for city-level management and creates databases of the occupant behaviour divided into clusters to provide designers with reliable information for simulation [10]. However, the latter is more indicated to be used in the BMS that have to consider the occupants' specificities to fulfil their needs. If the former databases were employed in the dwelling BMS without the necessary adaptations to the specificities of the occupants, the occupants' needs would not be fulfilled, and the balance between occupants satisfaction, energy efficiency and indoor environmental quality will not be met. Otherwise, if the drivers of occupants' behaviours were studied, the BMS could anticipate the occupants' needs and better deal with the occupants' impacts on energy consumptions and indoor environmental quality [14 - 16]. Literature also pointed to a great diversity of drivers for the same occupants' action [17, 18], which highlights the need to focus on occupants' specificities from each dwelling [10] or room [19, 20].

CHAPTER 6

The (Not So) Close Relationship Between Occupancy and Windows Operation

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Abstract: Occupancy is one of the main factors to understand the operation and energy consumption of a building due to the variability of human behaviour. However, the variability of human behaviour is not taken into account in many thermal and energy performance studies, causing inconsistencies between simulation results and reality. One of the reasons for these inconsistencies also relies on adopting an opening availability schedule which is strictly limited to the occupancy schedule of a room, especially in residential buildings, which may not represent the reality. Thus, the aim of this study is to investigate the dependency relationship between the room's occupancy schedule and the operation of openings in residential buildings. Data on occupancy of rooms and openings operation were obtained through a database obtained by means of application of questionnaires in low-income houses in Florianópolis, southern Brazil. Descriptive analysis by means of association measures was performed in order to evaluate the level of relationship between occupancy and openings operation. In addition, cluster analysis was performed to identify different patterns of occupant behaviour in the sample. The main result has shown that the opening operation schedule often does not depend on whether the room is occupied or not and seems to rely more accordingly to a daily routine, such as the time one wakes up or goes to sleep, or leaving and coming back home.

Keywords: Association measures, Cluster analysis, Exploratory data analysis, Low-income houses, Occupancy, Occupant pattern behaviour, Occupant profile, Openings operation, Residential building, Representative profile.

INTRODUCTION

Buildings are great contributors to environmental impacts, being energy consumption one of the most significant factors [1]. Globally, 40% of energy consumption is attributed to buildings, and the residential sector accounts for approximately 30% of that [2]. In Europe, energy consumption inresidential

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buildings represents approximately 26% of the total energy consumption [3], while in the USA it represents 22.5% [4]. In Brazil, according to data from the National Energy Balance (BEN), in 2018, buildings were responsible for approximately 50% of the national energy consumption [5]. Also according to BEN, the energy consumption of residential buildings has relevant participation in this demand, being responsible for approximately 20% of the energy consumption in buildings [5]. Thus, due to the great impact that national buildings have on the demand for energy, alternatives aimed at making them energy efficient can have a very positive impact in reducing the national demand for such a resource.

Alternatives such as the use of more efficient appliances, the adoption of envelopes with high thermal performance and the use of natural lighting may reflect a significant reduction in energy consumption, without jeopardizing the comfort of building users. For example, Palacios-Garcia *et al.* [6] found an effective reduction in energy consumption by the artificial lighting system when exchanging ordinary lamps for LED lamps. Their study concluded that replacing 50% of standard bulbs with LED bulbs would reduce the annual energy consumption of the lighting system by 40%, and that an 80% replacement would reduce consumption by 65%. However, in order to be sure that the buildings will be more efficient after adopting such alternatives, there is a need to perform computer simulations, which make it possible to verify the impact of the strategies even before adopting them.

The performance of simulations can result in important data regarding the use and performance of buildings. However, in order to obtain results that are consistent with reality, it is necessary that the input data also be. The main factors influencing energy consumption in buildings can be classified as: (1) climate, (2) building envelope, (3) building energy services and systems, (4) building operation and maintenance, (5) user activities and behaviour and (6) quality of the internal environment [7]. Such influencing factors should be used in the simulations, and the more consistent with the reality of the building they are, the greater the likelihood that sound conclusions will be obtained from the simulations.

According to IEA [7], the first three factors mentioned above are linked to variables that influence building performance. They are usually calculated from standard values of the other three factors, which are linked to the functioning of the building. When using standardised data, it is assumed that all buildings analysed work within the same standard. This calculation methodology allows a coherent comparison between the energy performance of buildings, but does not allow to conclude about the real energy consumption of buildings. D'Oca and Hong [8] argue that differences between the energy consumption obtained through simulations and the actual energy consumption are the result of assumptions that are not based on practice. Thus, when the objective of the study is to understand the real energy consumption of the building, all the main influencing factors must be analysed, in order to be consistent with the reality of the buildings under study, such as, for example, the occupant behaviour [8].

The identification of occupant behaviour patterns can be based on several aspects that integrate the relationship between occupant and building, such as, for example, the pattern of turning on lamps, using appliances, using curtains, changing clothes, occupancy, windows operation, among others. Occupancy is one of the main points to understand how a building works. Page *et al.* [9] defend the idea that being in the building is the primary condition to be interaction between occupant and building and that, therefore, occupancy is, in a way, the basis for all other models. For example, when the occupants of a building stay in a room more frequently, there is a tendency for the energy consumption in such a room to be higher, since the appliances installed there will be used for a longer time, and the lamps will stay on for longer. In addition, there is a tendency that users will act in favour of maintaining a comfortable temperature, either by activating air-conditioning devices or operating windows. Thus, when using real occupancy data in thermal and energy simulations of buildings, a better understanding about the functioning of the building can be obtained, as well as conclusions consistent with reality.

There are several studies that show the importance of creating building occupancy patterns. Aerts *et al.* [10] identified seven occupancy models for households in Belgium, based on data from a national time use survey, in which 6400 people in 3455 households reported their activities and movements in a diary, starting at 4a.m. and ending at 3:50 in the morning of the next day. For the authors, occupancy patterns are of great value, since they incorporate the great variability of users' behaviours without the need to make complicated simulations. Erickson *et al.* [11] created an occupancy model from data extracted from sensors, in order to use it to program the operation of an air-conditioning system. After integrating the occupancy data with the air-conditioning system, the air-conditioning devices stopped working at maximum power unnecessarily and it was possible to reduce the annual energy consumption in the building by up to 42%.

As for the effects of the operation of the openings, in terms of the energy consumption of Brazilian residential buildings, Sorgato *et al.* [12] concluded that the operation of windows is an important alternative for maintaining thermal comfort in buildings. As Brazil is a country of abundant winds, the operation of windows can improve the thermal comfort of users without the need to use air-conditioning systems. Sorgato *et al.* [12] concluded that the occupant's behaviour

CHAPTER 7

Investigating the Uncertainties of Occupant Behaviour in Building Performance Simulation: A Case Study in Dwellings in Brazil

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Abstract: The literature states that the occupancy and related operational characteristics in buildings are key variables that cause the gap between the estimate and actual thermal and energy performance. To address such issue, the objective of this study is to investigate the uncertainties of occupant behaviour in building performance simulation through a probabilistic approach. This case study considers a model of a low-income dwelling in southern Brazil using five different construction for the envelope and with natural or hybrid ventilation. Field survey provided a dataset of uncertainties of the occupant behaviour, which was related to the occupancy of the rooms, operation of openings and use of electric appliances. The EnergyPlus programme was used to conduct the simulations and the R Studio was used for data processing, analysis, and treatment. A global sensitivity analysis was performed, along with an uncertainty analysis. The results showed that the number of occupants, the schedules of occupancy of the bedrooms, the setpoint temperatures for operating the openings, the cooling setpoint of the HVAC and the limits for operative temperatures of the rooms were the most influent variables for the thermal and energy performance, especially in the heating period. The uncertainty was up to 65.6% for estimating the degree-hours for heating (in the natural ventilation mode) and up to 59.3% for estimating the total electricity consumption with HVAC (in the hybrid ventilation mode), indicating that these operational uncertainties had a great impact in the simulation results.

Keywords: Building simulation, EnergyPlus, Energy consumption, Global sensitivity, Operational uncertainty, Performance evaluation, Sensitivity analysis, Sobol' indices, Thermal performance, User behaviour, Uncertainty analysis.

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INTRODUCTION

The global energy demand, one of the main contemporary challenges, tends to grow with the population increase and economy expansion as it can be seen in the 12.5% increase from 2010-2018, according to IEA [1]. The buildings' sector represented, in 2018, up to 29.3% of the total energy consumption and 49.3% of the total electricity consumption worldwide (by grouping residences, commercial and public services together). The energy efficiency investments at a global scale were, according to the Energy Efficiency Report from IEA [2] at 2018 base, 58% orientated to the buildings' sector (30% of it was related to the envelope, followed by the HVAC systems).

In this context, energy efficiency is considered the "first fuel" and could address some challenges such as the climate change, energy security and economic growth, without damaging the environment or negatively affecting social aspects. Energy efficiency in buildings can be defined as the reduction in energy consumption by maintaining the comfort and productivity of the occupants at adequate levels, to enable, in a macro scenario, a reduction in the growth rate of energy demand. However, as the building context becomes more complex with the emergence of new materials and technologies, the performance of buildings also becomes hard to predict or estimate. Indeed, innovations and strategies for energy efficiency are becoming difficult to model and evaluate, in the mathematical point of view, which make the strategies (*i.e.* performance measures) not trivial to implement.

The simulation programmes are key tools to analyse the performance of the building in different phases, since the conceptual, design, operational or maintenance. They also brought many advantages in analysing the energy performance and the behaviour of buildings. There are some general applications for the use of building simulation in early design [3,4], or operation and maintenance [5]. Nevertheless, despite using advanced algorithms, physical models, empirical databases and being powered with research results all over the world, this type of tool continues to be a mathematical model. Thereby, every mathematical model depends on their algorithms and logical structures in an attempt to emulate or simulate a real physical phenomenon. Another issue is that every statistical inference made on mathematical models is susceptible to Type I and Type II errors for tests of hypotheses, in which Type I can be defined as the incorrect rejection of a true null hypothesis, while Type II error is failing to reject a false null hypothesis [6].

It is common to understand the building performance analysis as a mathematical model that depends on at least three major groups of information: the building model, the external factors and the internal factors. Usually, the building model is set by defining the envelope and the building systems; the external factor represents the climate within all related variables; the internal factors are related to the occupant, operation of the systems and indoor comfort conditions and requirements. The latter is particularly interesting for this study as, since 1999, Degelman [7] stated that, despite the huge development in the thermal (and energy) processes of the mathematical models in the simulation programmes, from the 1970s until nowadays, studies on operational patterns do not achieve the same development of knowledge. The author also stated that this is, somehow, ironic as the operational characteristics of a building could exert a greater impact in the building performance than the physical properties of the envelope. However, in the last decades, one may find many publications regarding building performance and the effects of operational characteristics, especially the occupant behaviour, in all sorts of building performance aspects, as stated by Balvedi *et al.* [8].

The literature shows that similar buildings, with similar architectural aspects (shape, floor area and materials) and with reasonable similar occupancy and electric appliances possessions, can have very distinct energy consumption due to the operational characteristics of the users and the buildings' systems. This aspect is called the "performance gap" in many papers [9 - 11], and have become, itself, a whole field of research. Jia *et al.* [12] described two main purposes for studying the occupant behaviour of a building: (1) for understanding the performance gap between the simulated and actual energy use of buildings; or (2) for performing a more robust optimization of the buildings, especially by setting control and operation parameters more accurately.

A major research project has been developed, in this area, by the International Energy Agency in respect to the EBC/IEA Annex 66 [13]. The main purpose was to develop a framework for dealing with the occupant behaviour in building simulation by considering data collection, modelling and evaluation, as well as integrating these processes into the programmes for supporting designers, stakeholders, policies and other areas. This annexe also developed an approach to reduce the performance gap related to occupant behaviour.

Jia *et al.* [12] categorized five different areas for occupant modelling in a building. The (1) agent-based modelling is related to the occupant's perception and their interaction with each other and the outdoor environment, which depends on modelling their actions by algorithms powered with measured data. The statistical analyses (2) try to establish a numerical relation between the occupant behaviour and other related variables; occupant profiles can be created by grouping some influent variable in the sample. The data mining approach (3) is

CHAPTER 8

Indoor Climate Management of Museums: the Impact of Ventilation on Conservation, Human Health and Comfort

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Abstract: Cultural heritage plays an important role in society, not only in cultural terms but also due to its touristic interest. From a purely economic point-of-view, the increasing number of visitors can be a way to achieve financial sustainability. However, it is necessary to ensure that conservation and comfort conditions are not affected, since the human body releases heat, moisture, CO_2 and odours.

A suitable relation between ventilation and occupancy may be used to minimize some of these effects, but it is not easy to reach because there is no unanimity in the literature on comfort and health issues. Besides, the information about ventilation and occupancy that is used in cultural heritage buildings is scarce, even after the recent publication of the EN 15759-2.

In this chapter, a sensitivity simulation study using a hygrothermal simulation model of a generic museum is developed. This chapter aims to analyse the impact of the binomial ventilation *vs*. occupancy, simulating various combinations of ventilation and air recirculation on the indoor air quality, conservation and energy consumption in museums. Since the visits to major national museums take usually long periods, the concept of adaptation was analysed to reduce the airflow of fresh air per visitor. The study was carried out using the software *WUFI® Plus* for the hygrothermal and energy simulation.

Keywords: Air recirculation, Cultural heritage, Conservation, Computational simulation, Indoor air quality, Museums, Occupancy, Preventive conservation, Ventilation.

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INTRODUCTION

Museums play an important role in storing collections, allowing different forms of art to be presented to the world. Museums must ensure the conservation of collections and at the same time a pleasant experience for visitors, providing adequate conditions of comfort and health [1].

Despite the unquestionable importance of visitors, it is important to note that they release heat, moisture, carbon dioxide (CO_2), odours and act as an open door for exterior pollutants, which can affect the equilibrium of the indoor microclimate.

Although historic buildings are characterized by high thermal inertia, they usually present a poor hygrothermal response, which can contribute to an unstable microclimate and render it difficult to obtain a serious compromise between conservation, comfort and sustainability [2]. Sometimes the use of powerful climate control systems is unavoidable and the impossibility of changing the building façades to avoid identity losses [3] means that one of the adopted strategies for energy reduction is linked to ventilation [4]. However, it cannot be dissociated from the human occupancy since it influences the air renewal and consequently the moisture, pollutants and odours.

An excessive occupancy can constitute a serious risk to the microclimate stability and a challenge to heritage management due to degradation of the indoor air quality (IAQ) and the increase of moisture. Some articles attest the visitors' effect on the indoor climate [5, 6] and the risks of undue occupancies for conservation [7 - 9]. There are some cases of common sense in which it was necessary to limit the number of visitors or their impact to mitigate conservation risks, such as the Scrovegni Chapel in Padova [10, 11]. With the growing interest in cultural tourism, limitations to the visits may become a necessity all over Europe.

The choice of a suitable relationship between occupancy and ventilation is crucial for heritage sustainability. However, this management should be based on sound fundamentals, since ventilation has a major impact on climate stability and energy consumption, and an unnecessary limitation of the number of visitors induces revenue cuts on buildings.

There are some standards and guidelines focusing on IAQ based on comfort with wide international acceptance, but they vary in assumptions and proposed values [12 - 16]. Concerning ventilation requirements and occupancy for cultural heritage, the issue is even more ambiguous. It is assumed that excessive ventilation disrupts the microclimate stability [4], while reduced ventilation associated with a high occupancy contribute to high humidity levels, mould risk and surface condensation [10, 11, 17]. Despite this evidence, it was not possible to find methods that specifically help in ventilation and occupancy management in museums. The European standard EN 15759-2 [18] was recently published on ventilation in cultural heritage to ensure optimum preservation of buildings and collections while ensuring comfort. This document is a useful tool for the ventilation management, namely by presenting a step-by-step approach to identify factors and areas of risk, but it is more descriptive than prescriptive and does not clarify what ventilation to use.

It is necessary to develop more research in this area so that museum managers and climate designers have tools to support decision making on a subject that can have a catastrophic impact on conservation, comfort and health. In this work, the authors sought to gather information on the topic, seeking to satisfy the needs of conservation, comfort and health. A climate simulation study was developed for three European cities with different climates to test the impact of various ventilation strategies.

STATE-OF-THE-ART

General Considerations

Ventilation concerns date back to the late 18th century when humans were considered to be the main cause of pollution inside non-industrial buildings. Until the mid-1800s, the air expelled by humans was believed to be toxic mainly due to carbon dioxide, until it was demonstrated that this gas was harmless for the concentrations usually found inside buildings.

At the beginning of the 20th century, there was a paradigm shift when it was proven that the air expelled in the breathing process was non-toxic, however during the first third of the century the main concerns were related to the health and the reduction of risk contagion of endemic diseases. This approach would once again be changed when around 1930 it was possible to conclude that the spread of diseases through the air was not one of the main forms of contagion. From here, ventilation began to be seen as a comfort factor that aims to ensure that the occupants of a given space perceive the air quality as acceptable. Although humans continue to be seen as the main sources of pollution, from this period onwards the main concerns were linked to released odours [19]. Despite some adaptations, this approach remains valid until now.

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Enedir Ghisi

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