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Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models

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ABSTRACT

Energy consumption in buildings is influenced by several factors related to the building properties and the building controls, some of them highly connected to the behaviour of their occupants.

In this paper, a definition of items referring to occupant behaviour related to the building control systems is proposed, based on studies presented in literature and a general process leading to the effects on energy consumptions is identified.

Existing studies on the topic of window opening behaviour are highlighted and a theoretical framework to deal with occupants' interactions with building controls, aimed at improving or maintaining the preferred indoor environmental conditions, is elaborated. This approach is used to look into the drivers for the actions taken by the occupants (windows opening and closing) and to investigate the existing models in literature of these actions for both residential and office buildings. The analysis of the literature highlights how a shared approach on identifying the driving forces for occupants' window opening and closing behaviour has not yet been reached. However, the reporting of variables found not to be drivers may reveal contradictions in the obtained results and may be a significant tool to help direct future research.

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1. Introduction

The behaviour of building occupants can have large effects on building energy use, and it results in huge gaps between real and predicted energy performance of buildings. The differences between real and predicted energy use depends on differences between the predicted and actual final realisation of the construction, technical installations, and the real use of the built systems operated by occupants [12,49,55]. Recently, it has been shown that occupant behaviour plays a fundamental role on the amount of energy used in buildings, e.g., by the time and type of window opening, the use of air-conditioning (AC) units or the choice of indoor temperature set point [4,29,34,62,66]. Consequently, the occupant has a great influence on the variation of energy consumption in different kinds of buildings: several studies [20,48,69,71] have shown that the behaviour of the household members may vary to such an extent that residential energy use differs by a factor of two, even when the equipment and appliances are identical [11,28,57]. Haas et al. [31], and Filippìn et al. [24] state that occupant behaviour affects energy use to the same extent as mechanical parameters, such as equipment and appliances: in an experimental study conducted over 3 years in multifamily buildings in Switzerland, Branco et al. [12] noted that the real energy use was 50% higher than the estimated energy use (246 MJ/m^2 as opposed to 160 MJ/m^2). The differences between the two values were due to the real conditions of utilisation, the real performance of the technical system and the real weather conditions. In the case described by Branco et al. [12], assumptions made about the behaviour of the occupants were not in agreement with the real behaviour of the occupants. In that case, a more realistic model of the occupants' behaviour patterns would have narrowed the gap between predicted and actual energy use. A vital part of developing such models is to know which variables to take into account, i.e., the variables that affect the occupants' behaviour patterns.

In literature, different energy end-uses determined by technical and architectural characteristics and by the occupants' behaviour have been studied. In this paper, a literature review regarding the relationship between occupants' interactions with building controls and the effects on the indoor environment and energy consumption is presented. Specifically, the paper is focussed on the topic of natural ventilation, and in particular on window opening behaviour, taking residential and office buildings into account. In

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the paper, the literature for evidence of factors with an influence on occupants' window opening behaviour is surveyed.

2. Occupant behaviour: a complex process

Much is still unknown about the motivation of the building control related occupant behaviour. Occupant behaviour is influenced by quite a large number of causes, both "external" to the occupant itself (e.g., air temperature, wind speed), and internal or "individual" (e.g., personal background, attitudes, preferences) and building properties (e.g., ownership, available heating devices) [5,67].

It is worth to highlight, that occupants' interactions with building control systems are only one aspect of human behaviour. Human behaviour can be expressed throughout the results of a continuous combination of many factors crossing different disciplines, from the social to natural sciences.

Concerning the building science area, occupant behaviour related to building control systems has traditionally been connected above all to indoor and outdoor thermal conditions. In early studies, the outdoor air temperature accounts for most of the variations in the interaction of the occupants with the elements of the built environment (e.g., windows or radiators) [13,17]. These parameters can be named as "external factors" as proposed by Schweiker [67] and the number of studies concerning them have increased in the last years [5,32,51,52,66].

In the field of social sciences, human behaviour is set in relation with causes which could be called "internal or individual factors" (Schweiker [67],), such as preference, attitudes, cultural background and so on. In addition to external factors, they influence the occupant behaviour with a range of cognitions and actions in a very complex way. Research on the individual factors leading to one action rather than another has been conducted in the field of behavioural psychology [1,2,27,61].

The theoretical basis of the following analysis is the so-called "adaptive approach", which states that "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" [54]. According to the adaptive approach, if an individual is in a state of discomfort, then she/he will take actions that would restore a state of wellbeing.

The adaptive approach [16] is based on the notion that the occupants' level of adaptation and expectation is strongly related to outdoor climatic conditions: in this way, at the base of adaptive model of comfort is the belief that the occupants consciously or unconsciously, play an active role in realizing indoor environmental conditions. In general, research has demonstrated that occupants are more comfortable and suffer fewer SBS symptoms when they have a high degree of control opportunities and a freedom of choice to adapt their conditions in a clear and intuitive way [72,73]. Furthermore it has been demonstrated that small adaptive changes (for instance clothing or posture) can lead to dramatic differences in physiological comfort [7,53].

It is important to note that to choose the adaptive approach for a building at the design stage implies by consequence to provide building occupants with rich opportunities of interacting with controls. However, the higher level of satisfaction and lower level of SBS symptoms also apply for buildings designed using the conventional approach [72]. By consequence, providing the occupants with rich opportunities seems to be beneficial, regardless of the design approach. But doing so implies a larger degree of influence by the occupants on the indoor environment and energy consumption.

As a consequence, the behaviour of the occupants becomes increasingly important and the consideration of occupants' behaviour in the design process becomes a necessity.

Hoes et al. [35] conducted a study on the effects of occupant behaviour on the simulated energy performance of buildings and concluded that the simple approach used nowadays for design assessments applying numerical tools are inadequate for buildings that have close interactions with the occupants. The approach of analysis through simulation has been used by Corgnati et al. [15] for the assessment of categories of indoor environmental quality and building energy demand for heating and cooling. They highlight that the comfort requirements by occupants in terms of thermal conditions and indoor air quality in buildings represent a high expense of energy. So in the challenge of reducing the environmental impact, it is important to understand the occupant interactions with the indoor environment in order to provide comfortable conditions in the most efficient ways.

2.1. Steps of behaviour

The general process leading from occupant behaviour driving forces to energy consumption can be identified as shown in Fig. 1 [22] and described in the following.

Factors influencing occupant behaviour, both external and individual, that could be named with the general term *"Drivers"*, are the reasons leading to a reaction in the building occupant and suggesting him or her to act (they namely "drive" the occupant to an action).

These drivers have been divided into five groups: physical environmental factors, contextual factors, psychological factors, physiological factors and social factors.

- Physical environmental:

Examples of physical environment aspects that drive occupant behaviour with an effect on energy consumption are temperature, humidity, air velocity, noise, illumination, and odour.

- Contextual:

Contextual drivers are factors that have an indirect influence on the human being. They are determined by the context. The insulation of buildings, orientation of façades, heating system type, thermostat type (e.g., manual or programmable), etc. are examples of contextual drivers.

- Psychological:

Occupants tend to satisfy their needs concerning thermal comfort, visual comfort, acoustical comfort, health, safety, etc. Furthermore, occupants have certain expectations of e.g., the indoor environmental quality (temperature, etc.). Other examples of psychological driving forces are awareness (e.g., financial concern, environmental concern), cognitive resources (e.g., knowledge), habit, lifestyle and perception.

- Physiological:

Examples of physiological driving forces are age, gender, health situation, clothing, activity level, and intake of food and beverages. These factors together determine the physiological condition of the occupant.

- Social:

Social driving forces refer to the interaction between occupants. For residential buildings this depends of the household composition (e.g., which household member determines the thermostat set point or the opening/closing of windows).

With reference to indoor environmental quality, the occupant reacts consciously or unconsciously to an external or internal stimulus ("Occupant Stimulus" in the flux diagram proposed in Fig. 1) in order to improve, restore or maintain the comfort conditions (thermal, lighting, acoustics, indoor air quality,...). In this way, the occupant becomes the central operator with control of the energy consumption. In such a way, occupant behaviour can be defined as proposed by Schweiker (2010) [67] "*a human beings unconscious and conscious actions to control the physical parameters of the surrounding built environment based on the comparison of the perceived environment to the sum of past experiences*". The physical parameters can be different: visual, auditory, olfactory and, in particular, thermal.

This is a quite exhaustive definition, but it only takes the perceived environment into account and in this sense is restricted to the field of physical environmental sciences. It does not describe the connection with the environmental education and social science. For example, Andersen [3] found that some people ventilated by opening the windows for 10 min at the same time every day, regardless of the environmental conditions. This behaviour was driven by concerns about health effects of poor indoor climate and was not based on perception or past experience, but rather on knowledge and education.

The third point in the Fig. 1 is represented by the action scenarios. This term indicates the occupant reactions since she/he was stimulated by a driver or a combination of them. Window opening or closing, set-point changes, clothing changes are all examples of this kind of actions. In general, behavioural actions cannot be regarded singular, because they continuously interact with each other and the borders cannot be distinguished in every case. The reactions could be determined both by some "action logics" operated by the occupants themselves and by the system and equipments controls and partly by the building behaviour itself. Consequently, the term *"action scenarios"* has been chosen.

There are several possibilities for the occupants to control the indoor environment.

The control related actions performed by the occupants can be divided into changes that alter the environment to make it more comfortable, into changes that adapt the occupant to the prevailing environment and finally into actions that have an effect on the indoor environment indirectly. The first might be to adjust the heating set-point, to open/close a window, to turn lights on or off or to adjust the solar shading, while adjusting clothing, adjusting body posture and consuming hot or cold drinks fall into the second category. The third category include actions related to the chance of internal heat gains/energy use: operations of this second kind are the use of appliances and equipment (use of TV, refrigerator, etc.), use of hot water (taking bath or shower) and cooking [58].

All the operations aimed by the occupants to improve or maintain the indoor environmental quality have a consequence on the indoor environment. A variation in air change rates or room air temperature are examples of the "parameter variation" due to the window opening. Different action scenario outcomes could have a direct influence on both indoor environmental quality and on the energy consumption.

Indoor environmental quality and energy consumption are the "process output": their variability range could be very wide, as shown before, and depending on many variables.

It is significant to observe how this whole process is not a closed system, i.e., the changes brought by the effects of the action scenarios on energy use and indoor environmental quality are themselves an element of influence on "the drivers". Pushed to the desire to emphasize this continuity that is an inherent part of the process, it is more accurate to argue for a cycle of processes that influence user behaviour. In this way the energy consumption becomes a driver that affects the behaviour along with the environmental quality. The energy output could be minimum if actions scenarios are managed in a prudent way or maximum if the users follow actions logics scenarios maximizing the energy wasting. In this way, it is possible to identify different users' behaviour typologies depending on the way the actions sequences are performed. From an energy perspective occupants could be named "energy saving users" or "energy wasting users". From an indoor environmental perspective, occupants could be divided into air quality users or thermal comfort users or both.

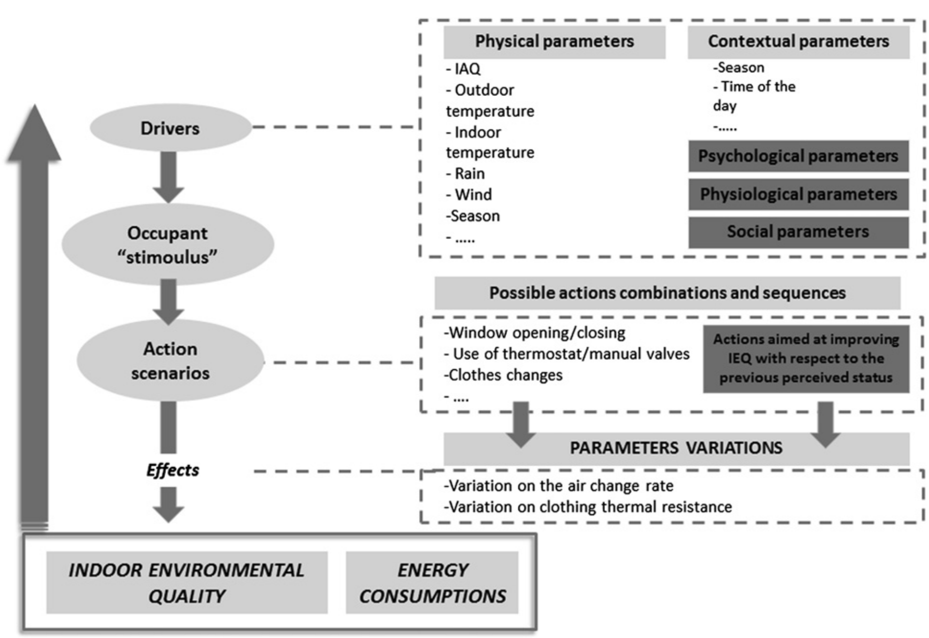

Fig. 1. Flux diagram: from drivers to energy consumption and indoor environment.

3. Effect of occupant behaviour on energy consumption in buildings

One way of highlighting and investigating the influence of occupant behaviour on the energy performance of a building is by comparing energy consumption of identical buildings.

Socolow [69] used this method, and the same approach was used by Sonderegger [70] and Seligman et al. [68]. They were amongst the first to point out that the behaviour of occupants had a significant impact on the energy performance of a building. In his paper Socolow [69], investigated energy consumption in 28 identical town houses and found the largest variation in energy consumption to be two to one. Furthermore, the energy consumption of the houses depended on the occupants. Sonderegger [70] measured gas consumption used for heating in 205 town houses located in the same group of houses as the study of Seligman et al. [68] and Socolow [69]. He found the highest consumption to be more than three times as high as the lowest consumption. 54% of the variance in gas consumption was explained by design features of the houses, such as number of rooms, area of windows etc. which left 46% of the variance unexplained by the design features. By comparing changes in gas consumption between two heating seasons of occupants who moved into the houses with that of occupants who stayed in the houses, they concluded that 71% of the unexplained variance was due to occupant related consumption patterns.

Also Gartland et al. [26] used the method of energy consumption comparisons. They monitored energy consumption in four houses of identical layout in Washington from 1987 to 1992. Two of the houses were built so they represented construction practices in the 1980s while the other two were better insulated and more air tight. They found that changes in heating set-point patterns accounted for as much as 27% of the total energy used for heating, while variations in the door and window opening behaviour accounted for up to 17%. The houses had a monthly average infiltration rate of 0.6–1.9 h^{-1} which is much higher than what was found by Offerman [56] and Price and Sherman [59] in Californian homes. A comparison of the energy consumption in the four houses revealed that the behavioural variations became more significant in the buildings that were better insulated and more air tight. As such, a lower infiltration rate would conserve energy but increase the impact of occupant behaviour on the energy consumption.

In a more recent study, Juodis et al. [41] compared energy consumption for space heating and domestic hot water in 2280 similar apartment buildings in Lithuania. They found the factor between highest and lowest consumption to be between 1.22 and 1.7, when comparing identical buildings. The comparison was made on a building level and did not include analysis of differences between apartments. The authors conclude that the observed differences originate from differences in initial design and construction uncertainties and they do not discuss differences in occupants behaviour patterns. While the diversity of the apartments' construction will have an effect on the different energy performances of the buildings, it seems evident that the occupants' different behaviours significantly affect the consumption. As a consequence, it would be worth to take the occupants' behaviour into account in the analysis.

Maier et al. [48] used the method of comparing identical buildings on 22 houses in Germany, comparing energy consumption over a two year period. Apart from the ventilation principle, the houses were identical. Amongst the 12 houses that were ventilated identically, the highest consumption was 2.84 times higher than the lowest consumption. The house with the lowest consumption of energy had the lowest average temperature implying that the occupants had a behaviour aimed at conserving energy by having a lower heating set-point in the heating season.

While some scientists use energy consumption comparisons to infer the effects of occupant behaviour on energy consumption, others have used questionnaire surveys to investigate the determinants for energy consumption. This method was employed by Sardianou [65]. She found that the age of the respondent, family size, annual income, and size and ownership status of the dwelling impacted the consumption of oil used for space heating. This indicates that the socioeconomic status has an impact on the behaviour patterns of occupants.

Also Guerra-Santin and Itard [30] conducted a questionnaire in Dutch households. With a response rate of 5% they were able to explain 11.9% of the variance in energy consumption using three behaviour variables. Furthermore they found that the type of heating system and ventilation system had an influence on the behaviour of the occupants.

A further analysis that could allow an overall view of both the performance of buildings and the subjective indications given by users could be to compare the data obtained through questionnaires with the results of analysis of real measurements in field.

These studies showed that occupant behaviour does indeed have a very large effect on the energy performance of buildings (Table 1). This underlines the need for guidelines or models of behaviour patterns for implementation in simulation programs.

3.1. Influence of window opening behaviour on air change rate

One parameter having a high influence both on the energy consumption and on indoor environmental quality is the air change rate. Since the thermal load for ventilation is related to the air change rate, a close examination of this indicator is important to consider when investigating the effects of the occupant behaviour.

The air change rate is affected by the occupants' behaviour, indoor environment and weather, but how dependent is the air change rate on the behaviour of the occupants?

As early as 1943 Bedford et al. [8] conducted 358 measurements of the air change rate in six properties in London using the decay of coal-gas (containing about 50% of hydrogen) liberated into the air. They discussed the effects of flues, air gratings, cracks and leakages

Table 1
Major findings in literature about variation of energy consumption due to the occupants.

Paper	Number and type of dwellings	Measured consumption	Max/min consumption [-]	Variance in consumption explained by occupant behaviour [%]
Seligman et al. (1977/78)	28 town houses	Gas and electricity	2	
Sonderegger (1977/78)	205 town houses	Gas used for heating	3	33
Socolow (1977/78)	28 town houses	Gas used for heating	2	
Gartland et al. ASME 1993	4 houses	Electricity used for heating		
Juodius et al. EaB 2009	2280 similar apartment buildings		Between 1.22 and 1.7	
Maier et al. (2009)	22 houses		2.84	
Gerra-Santin and Itard BRaI 2010	Questionnaire survey of 313 households	District heating and gas for heating		11.9

on the air change rate in the houses and finally noted that any reasonable amount of ventilation could be obtained if liberal window openings were provided. They obtained as many as 30 air changes per hour by means of cross-ventilation in experimental rooms. Since then, houses have been tightened and sealed, increasing the relative effect of window opening on the air change rate. In fact, when Wallace et al. [74] measured air change rates in a house in Virginia during a year, they found that the window opening behaviour had the largest effect on air change rates, causing increases ranging from a few tenths of an air change per hour to approximately two air changes per hour. In another paper describing the same measurements Howard-Reed et al. [36] stated that opening of a single window increased the air change rate by an amount roughly proportional to the width of the opening, reaching increments as high as 1.3 h^{-1}. Multiple window openings increased the air change rate by amounts ranging from 0.10 to 2.8 h^{-1}.

Bedford et al. [8], Wallace et al. [74], Howard-Reed et al. [36] and Offerman et al. [56] focussed on the exposure to contaminants at low air change rates. While Bedford et al. [8] found an average air change rate of 0.8 h^{-1} and with only 11% of the measurements under 0.4 h^{-1} in London, Offerman et al. [56] found that 75% of homes without mechanical ventilation had air change rates lower than 0.35 h^{-1}, suggesting that homes had been tightened to such an extent that occupants needed to actively adjust building controls to obtain adequate supply of fresh air. Also, Price and Sherman [59] found that, depending on season, between 50% and 90% of Californian homes had air change rates lower than 0.35 h^{-1}. The results of Offerman et al. [56] and Price and Sherman [59] suggest that many houses in California are under-ventilated according to local standard recommendations because ventilation systems are too small and because the occupants do not operate the windows adequately. This was especially evident in the winter months implying that the occupants opened windows to a smaller degree in winter than in summer (Table 2).

According to Keiding et al. [42] who conducted a questionnaire survey in Danish Dwellings, 53.1% slept with an open window during autumn while 25.2% had a window open during the night in winter time, which in most situations should ensure an air change rate of more than 0.35 h^{-1}. They found that 91.5% of the respondents vented by opening one or more windows each day throughout the year. The results showed that a large proportion of Danish occupants use windows to adjust the supply of fresh air to the dwelling. Since the lowest temperatures occur during night time in winter, the effects of this behaviour on the energy consumption might be substantial. However, when Bekö et al. [9] measured ventilation rates in 500 bedrooms, they found that 57% of the bedrooms had a lower air change rate than 0.5 h^{-1}. In a later paper Bekö et al. [10] attempted to model air change rates based on the same measurements. Their best model explained 46% of the variance in the air change rates. This model contained variables related to both building characteristics and behaviour, while models inferred only from variables that are related to building characteristics or occupant behaviour explained 9% and 30% of the variation, respectively (Table 2).

Kvistgaard et al. [43] measured air change rate and temperature in 16 Danish dwellings and found an average air change rate of 0.68 h^{-1} (Table 2). They suggested a classification of air change rates as follows:

- Basic air change: Air change of unoccupied house with all windows and door closed. Varies with wind velocity and interior/exterior temperature differences.
- Air change from ventilation system: air change from a mechanical ventilation system, if it exists in the building.
- User-influenced air change: air change caused by window and door opening.
- Total air change: the sum of the three categories above.

In a later paper Kvistgaard and Collet [44] noted that there was considerable difference in the total air change between the individual dwellings. As the basic air change was fairly similar in the dwellings, it was concluded that it was the user influence on air change (i.e., the behaviour of the occupants) that caused these large differences. This conclusion was confirmed by Weihl [76], who concluded that a substantial variation in ventilation behaviour found among seven households, reflected different occupant functions and management strategies.

Iwashita G and Akasaka [38] were able to quantify the effect of occupant behaviour on air change rate. They investigated the relationship between occupants' behaviour and the energy consumption used for air conditioning, by means of tracer gas measurements and questionnaire surveys in Japan, and concluded that 87% of the total air change rate was caused by the behaviour of the occupants.

The studies mentioned above show that air change rates vary significantly from home to home and the window opening behaviour of the occupants has a considerable effect on the air change rate. We have not been able to find studies investigating the direct connection between air change rate and energy consumption, but since the air change rate has a big impact on the energy consumption it is evident that different behaviour patterns will result in differences in energy consumption. One aspect that affects the air change rate is how often and for how long the windows are opened but also the degree of opening will have an impact.

4. Windows opening behaviour: identification of driving forces

Several studies have been carried out in recent years regarding air change rates, indoor air quality and window opening habits in

Table 2
Major findings in literature about variation of air change rate due to the occupants.

Paper	Number and type of dwellings	Measurement method	Average air change rate [h^{-1}]	Percentage of measurements lower than 0.4 h^{-1}
Bedford et al. (1943)	358 observations in 6 properties	Decay of Hydrogen	0.8	11%
Wallace et al. (2002)	1 single family house	One year (SF6 as tracer gas)	0.65	–
Offerman et al. (2008)	73 new naturally ventilated single family houses	24 Hours (PFT tracer gas)	Not stated (median: 0.25)	75% lower than 0.35 h^{-1}
Price and Sherman (2006)	1515 new single family houses	Questionnaire survey	–	Between 50% and 90% lower than 0.35 ACH
Kvistgaard et al. (1985)	16 single family houses	205 days (N_2O and SF6 as tracer gas)	0.68	20%
Bekö et al. (2010)	3–5 days of measurements in 500 bedrooms	Build-up of CO_2 emitted by occupants	0.46	–

residential buildings [18,46,47,64]. These studies revealed that in residential buildings with natural ventilation the occupants' ventilation behaviour is the most important variable in the determination of the air change rate.

In particular, the topic of occupant behaviour with regard to control of the indoor environment has mainly been studied with two aims: investigating the window opening and ventilation behaviour to find if occupants are provided with adequate fresh air, and energy related investigations of occupant behaviour. The former category of studies has usually been carried out in dwellings and has had a health or a comfort perspective, while the latter category has focussed on studied in offices with a comfort, and energy performance perspective.

Even though dwellings are responsible for consuming more than a quarter of the total primary energy in the EU member states [19], the studies that are aiming at implementing realistic behaviour patterns in simulation programs have been based mainly on occupant behaviour in offices [32,34,62].

Analysing the results of several studies conducted both in residential and in office buildings [18,29,33,34,38,62,63,71], there is a distinction to be made within the factors influencing the occupant behaviour in relation to the natural ventilation. These factors can be named as "drivers" of the behaviour as discussed before (Fig. 1). In the following Tables 3 and 4, the major parameters found in literature driving the occupant behaviour aimed at controlling the indoor environment in relation to natural ventilation are split into five categories of influencing factors for residential and office buildings.

4.1. Residential buildings

Since the effectiveness of natural ventilation is strongly dependent on characteristics of ventilation openings and their controllability (aspects closely related to the type and size of the windows and its placements within facade) the window opening and closing behaviour is strictly connected to the building characteristics. Type of dwelling (single house or apartment), orientation and type of the room (bedroom, living room or kitchen) are the main parameters found to have an influence on occupant behaviour related to window opening and closing [18].

The study of IEA – ECBCS Annex 8 [18] on occupant behaviour with respect to ventilation involving Belgium, Germany, Switzerland, the Netherlands and the United Kingdom focussed on a combination of questionnaires and observations to determine which action is taken by occupants to ventilate their homes and to evaluate their reasons for these actions. The study showed that the type of dwelling (house or apartment) influences the length of time windows are open and has an effect also on how wide windows are left open. In the same research it appeared that in houses compared to apartments' windows in living rooms and kitchens were open on average for shorter periods, whereas windows in bedrooms were open for longer. The type of the dwelling (detached one-storey residence) was found to affect the residential openness in a pilot study conducted by T. Johnson and T. Long [40] in North Carolina between October 2001 and March 2003.

Table 3
Driving forces for energy-related behaviour with respect to ventilation/window operation in residential buildings.

Physiological	Psychological	Social	Physical environmental	Contextual
Age	Perceived illumination	Smoking behaviour	Outdoor temperature	Dwelling type
Gender	Preference in terms of temperature	Presence at home	Indoor temperature	Room type
			Solar radiation	Room orientation
			Wind speed	Ventilation type
			CO_2 concentrations	Heating system
				Season
				Time of day

Table 4
Driving forces for energy-related behaviour with respect to ventilation/window operation.

Physiological	Psychological	Social	Physical environmental	Contextual
		Shared offices	Outdoor temperature	Window type
			Indoor temperature	Season
			Solar radiation	Time of day
			Wind speed	
			Rain	

According to the study of IEA – ECBCS Annex 8 [18] the main ventilation zones are bedrooms, while the greatest percentages of windows never opened are in living rooms, kitchens and bathrooms. This finding is consistent with the findings of H. Erhorn [21] in 24 identical flats in Germany. Even in the extreme winter weather, bedrooms were ventilated more frequently than all of the rooms on averageand the windows opening time in bedrooms exceeded the average for all rooms by some 50% during the entire measuring period. The orientation of rooms is important as well. The IEA – ECBCS Annex 8 project [18] found that, when the sun was shining, south facing living rooms and bedrooms were more likely to be ventilated for longer periods than similar rooms orientated in other directions. It seems most likely that it is the effect of solar radiation and temperature, rather than the orientation itself that affected the occupants' window opening behaviour.

The investigations have shown different daily patterns for the different types of the rooms. Typically, the maximum of window openings occur in the morning. During early afternoon (when cooking) the number of open windows is still relatively high but gradually decrease during the afternoon till the return home of working inhabitants (at about 5 p.m.) [18]. Time of the day is found to determine the transition probabilities (closed to open and open to closed) in the aforementioned study of Johnson and Long [40].

Looking at opening frequency and transition probability are quite different approaches. The strengths to analyse the open frequency is that it is easier to measure. Noting the window position and the present conditions every hour (or even every day) results in a dataset that could be used to infer the probability of having a window open. But since the indoor conditions are affected by the window position, it is problematic to use these as explanatory variables in the model.

This problem can be overcome by inferring the probability of opening and closing a window (transition probabilities) instead of looking at the window state probability. On the other hand the problem of this method is that it can only be used if the conditions just before an opening/closing event are known. As a consequence, data with a much smaller timely resolution is needed to acquire data on the environment before the transition.

The window opening behaviour is strongly related with the perception of comfort with respect to the microclimate in dwellings. Due to this correlation the most important environmental parameters are investigated in many studies.

Not surprisingly the outdoor temperature had a considerable impact on the window opening behaviour. An early study of J.B. Dick and D.A. Thomas [17] found that the outdoor temperature was the single most important explanatory variable when investigating the number of open windows in 15 houses. Most of the investigation in the IEA – ECBCS Annex 8 project [18] have shown that in the temperature range between −10 °C and +25 °C a direct linear correlation exists between window use and outdoor temperature. Brundrett [13] found the temperature (mean monthly temperature and average temperature swing) to be an important explanatory variable for the occupant's opening of windows. Erhorn [21] found that a change in ventilation behaviour was stated at temperature of 12 °C. Below 12 °C, daytime ventilation increased by 75% per degree temperature differences and by 1.1% per °C. above 12 °C. In terms of ventilating frequency this represents an increase of about 50%. The results of Andersen [3] are consistent with these findings. The statistical analysis related to the questionnaire survey carried out in 2006 and 2007 in Danish dwellings has shown that window opening behaviour is strongly linked to the outdoor temperature. Recently, the results of logistic regression model based on a long-term monitoring of behaviour and environmental variables into 15 dwellings confirm that outdoor temperature, indoor temperature, solar radiation and the indoor CO_2 concentration were the most influencing variables in determining the opening/closing probability [6].

Erhorn [21] tried to correlate the season with window opening behaviour and found that windows were open longest in summer and shortest in winter This finding was supported by the successive study conducted by Herkel et al. [34] in office buildings, where the percentages of open windows were highest in summer, lowest in winter and intermediate in autumn and spring. Regarding the seasonal variations, the open question is if the season itself or the changes in outdoor conditions that drive the occupant behaviour.

The IEA – ECBCS Annex 8 [18] showed that windows are opened more often and for longer periods in sunny weather. The finding of Andersen et al. [6] fit with these earlier studies. In Erhorn's investigation [21] a distinct dependence on solar radiation cannot be confirmed, as the influences of outdoor air temperature and global irradiance are superimposed.

The influence of wind speed was investigated in the aforementioned studies [18,21], and the results show a significant decrease in the prevalence of open windows at high wind speed. Dubrul [18] found that nearly all windows were closed at wind speeds above 8 m/s.

Based on an average wind velocity of 3 m/s Erhorn [21] proposed to introduce the wind influences as a correction term for temperature-related window ventilation periods. While this might be viable way forward, it would give a clearer picture of the relation, if multiple regression is used, which would allow for the inclusion of wind speed as an explanatory variable.

The interaction between occupant's gender and perceived illumination had a statistical impact on the window opening behaviour [5]. Since the influence of perceived illumination has not been investigated by others, this result has neither been confirmed nor challenged.

The investigation of Guerra-Santin and Itard [30] of households in the Netherlands in autumn 2008 showing that the behaviour of elderly people significantly differed from that of younger people, fit with the results of IEA – ECBCS Annex 8 [18], who reported that the window position was affected by the presence of children.

IEA – ECBCS Annex 8 project [18] highlighted a clear correlation between smoking behaviour and the airing and ventilation of living rooms. Moreover, the longer the dwelling is occupied the more the windows, especially the bedroom windows were kept open, and in this way the Annex 8 concluded that the presence of the occupants in the home and use of the windows were related. No other of the surveyed studies took into account the occupant lifestyle as explanatory variable of the model.

Finally, Dubrul [18] noted that indoor climate preferences in terms of temperature are one key driver of the behaviour of the occupants, but this driver is strongly connected to the occupant's perception of comfort.

In summary, the previously identified driving forces for energy-related behaviour with respect to ventilation/window operation in residential buildings are grouped and listed in Table 3.

4.2. Office buildings

Based on field surveys many studies have focussed on monitoring user behaviour in offices to identify the influential variables. These studies have focussed on energy consumption and thermal comfort, which are affected by the use of manually-controlled windows.

Field studies about window operation and its impact on energy consumption (heating, primarily) date back to the 1980s in office buildings. Since studies in homes found that weather (temperature, humidity, wind) could explain a majority (∼65–70%) of window interactions [13,17], Warren and Parkins [75] applied similar methods to five naturally-ventilated office buildings in the UK and found outdoor air temperature to explain 76% of variance in window state, and that solar gain and wind speed also played a role (8% and 4% respectively). In addition to field monitoring, the study asked occupants why they used windows, and found fresh air to be the most common reason for opening windows in both winter (51%) and summer (74%) and of equal importance to "keeping cool" during the summer. Although air quality wasn't used as an independent variable for analysing behaviour, an analysis of small/slightly open windows compared to large open windows led to the conclusion that there are two control modes for windows, one related to air quality and the other to temperature. Moreover, Warren and Parkins [75] differentiated between small and large openings. Small windows were open to satisfy indoor air quality requirements, while large windows were strongly affected by outdoor temperature and solar gain.

Until recently, subsequent attempts to characterize window operation have been based exclusively on outdoor and/or indoor temperatures [25,37,51,52,60]. The analyses are based on control actions collected predominantly from buildings without cooling systems in Europe and the UK. The focus on temperature makes intuitive sense given that windows aren't likely to be opened if it is too hot or cold outside, and given the important role of indoor temperature in maintaining occupant comfort. However, this single sided focussing on temperature as the only driver seems to exclude any other variables as drivers, even though these cannot be ruled out a priori.

Raja et al. [60], studying the use of building control in 15 naturally ventilated offices in UK, reported that the proportion of open windows increased with an increase in indoor and outdoor temperature. Only few windows were open when the outdoor temperature was below 15 °C, whereas most windows were open when temperatures exceeded 25 °C. Nicol [50] conducted a survey on the use of windows, lighting, blinds, heaters and fans in different countries and showed how the use of each control varies with outdoor temperature. Although significant variation was found between different climates, occupants opened windows when the outdoor temperature was above 10 °C in all countries where the surveys were conducted. As outdoor temperature increases there is an increase in the probability of an open window. These results fit with the results of Herkel et al. [34] who analysed 21 offices in Germany and found that the highest percentage of open windows was reached at a temperature of 20 °C. At higher temperatures the percentages of open windows seemed to decrease. Moreover, they found that the correlation of the percentages of open windows to the indoor temperature was smaller than the correlation with the outdoor temperature.

However, consensus has not been reached about whether to use indoor temperature, outdoor temperature or both as the independent variable when simulating window use, because of the inherent interactions between indoor and outdoor temperature in naturally-ventilated buildings. For instance, rising indoor temperatures might drive the opening of windows, but how long the window stays open might depend more on outdoor temperature. Haldi and Robinson [32] argued that indoor temperature would be a better predictor of window opening behaviour than the outdoor temperature because indoor temperature is a driver for opening and closing windows to a much larger extent than outdoor temperature. However, the indoor temperature is affected by the windows' state, which makes the analysis of window state based on indoor temperature difficult to interpret. The problem is that the predictive variable is influenced by the state that it is trying to predict. In a cold climate the low indoor temperatures would occur when the windows are open and not when they are closed. In such a case the result of the analysis would be that the inferred probability of a window being open increases with decreasing indoor temperature, with the illogical implication that the probability of opening a window would increase with decreasing indoor temperatures.

On the contrary, Schweiker [67] stated that neither outdoor nor indoor temperature are suitable predictors because from the viewpoint of perceptual control theory, the best predictor would be the controlled value itself (thermal comfort). From one hand, occupants cannot control the outdoor temperature, which depends on the weather conditions. On the other hand, also the indoor temperature alone cannot be the value to be controlled by the full range of occupant behaviour, because e.g., thermal comfort depends also on mean radiant temperature, air speed, relative humidity, clothing insulation and metabolic rate [23].

In office buildings, user behaviour was found to be strongly correlated with the *season* [34,39,74]: the percentages of open windows are lowest in winter, highest in summer and intermediate in autumn and spring, suggesting that the behaviour may be influenced by long-term experience.

Wind is a driver for closing the windows and occupants are likely to close windows if the sensation of draft in the office is producing a predominant discomfort: Roetzel et al. [63] reported an inverse linear correlation between wind velocity and window opening.

Researchers have found a strong correlation between window adjustment and time of arrival and departure [33,34,78]. Although these studies use this analysis to modify algorithms for predicting behaviours, one implication of their observations that is not further studied is that many window control actions could be a function of routine, habit or state of mind rather than simple environmental response. In fact, related research on thermostat control has found that major differences in control patterns were largely related to the habits and routines of households [77]. Warren [75], Yun [78], Herkel [34] and Haldi [33] found a strong link between time of day and the windows controls activities. During the night the percentages of completely open windows was around zero, and actions on windows mostly occurred on arrival of the occupants. In the survey conducted by Herkel [34], in 21 offices in Germany intermediate window switching during the day was found to be relatively low, so windows were usually left in the same position for long periods of time, till discomfort occurred. In naturally ventilated buildings, this behaviour could be interpreted as an avoidance of discomfort that has evolved to become a daily routine.

The current state of the window also plays a role in how likely it is to be adjusted. Several studies find that windows that are opened tend to stay that way [25,62,78]. Once the occupant has taken action, they usually will not revert back to the original state once comfort has been restored, but are more likely to wait until another crisis of discomfort is reached [45]. Moreover, this parameter was found significant in the context of night ventilation [63].

Type of windows influences the length of time the window is open. Herkel et al. [34] found that small openings were opened less frequently but remained open for longer periods of time, while large openings were opened more frequently, but generally closed after less than a working day.

The social dynamics of shared office space can also have a dramatic impact on window operating behaviour. As observed by Cohen et al. [14], manual controls (windows, blinds, lights) in open-plan offices tend to "lapse into default states that minimize conflict and inconvenience but are not optimal, e.g., 'blinds down, lights on." In part, this phenomenon points to differences in office inhabitants' natural disposition towards or awareness of their environment while they are working.

4.3. Identification of driving forces: key points

From the analysed studies it is clear that there is not a shared approach to the identification of driving forces for occupants' window opening and closing behaviour. In particular, it emerges how there is still a disagreement as to whether indoor or outdoor temperature or both are best predictors when simulating the actions on windows. Moreover, some parameters are not considered in any of the surveyed studies. There is a lack of understanding in the relationship between indoor air quality and the window opening behaviour of occupants. The behaviours of the occupants' towards night ventilation is generally poorly understood and the degree of openings are ignored in most studies, even though these are crucial for reliable air flow prediction.

In office buildings, almost all data were collected in buildings without ventilation systems and physiological (like gender or age) or psychological aspects are not investigated to the same degree at the physical drivers.

Moreover, the case of offices with several occupants is not specifically treated (single behaviour or shared behaviour).

Most studies focus on determining the most important drivers and put little emphasis on the variables that do not show up as drivers. However, highlighting variables found to have little or no impact on the occupants' window opening behaviour reveal contradictions between the studies and may help directing future research. Behind the parameters that are found to have an impact on occupant behaviour, Table 5 shows the variables that were included in the surveys, but found not to be drivers.

Table 5
List of variables that have been found not to drive window opening behaviour. The column 'Presence in "drivers tables" ' indicates if the variable has also been found to be a driver in other papers.

Parameter	Building type	Driver type	Presence in "drivers tables"
Wind speed	Residential	Physical Environmental	Yes
Wind direction	Office, Residential	Physical Environmental	No
Solar Radiation	Office, Residential	Physical Environmental	Yes
Rainfall	Office, Residential	Physical Environmental	No
Age	Residential	Physiological	Yes
Income	Residential	Social	No
Thermal sensation	Residential	Psychological	No
Day of week	Residential	Time	No
Wood burning stove	Residential	Building properties	No

From the table it appears clear that there are parameters that distinctly are not drivers, like wind direction or income, but there are other investigated variables which appear to have an impact on the window opening behaviour (Table 3 and Table 4) as well, indicating that they cannot be applied to models for any building, since they cannot be generalised. Unfortunately, the table is far from being exhaustive because many papers only report the variables that have an impact on the occupant behaviour.

From the table it appears evident that the following variables are clearly not drivers:

- Wind direction
- Rainfall
- Income
- Thermal sensation
- Day of week
- Wood burning stove

Haldi and Robinson [32] and Herkel et al. [34] in office building and Johnson and Long [40] in residential building did not observe any particular variations with wind direction and rainfall (which was correlated with relative humidity in the study of Haldi and Robinson [32]), thus they were not found to affect window opening behaviour significantly. Herkel et al. [34] reported a low correlation between wind direction and the percentage of open windows ($r = 0.16$).

Johnson and Long [40] reported in their survey that income (particularly related to poverty level, used in the investigation as an indicator of the socioeconomic level of Durham population) and the day of week (week day or weekend) were not found to impact the residential openness significantly.

With regard to thermal sensation, which is found not to be a statistical predictor for the interactions with windows in Andersen et al. [5], it is also explained in the paper that the reason could be the feedback mechanism occurring between the window opening and the thermal sensation. If a window was opened because the occupants felt too warm, it would probably stay open until they would start to feel cold. Because of this, occupants with open windows might have a thermal sensation anywhere between warm and cold.

The other parameters of Table 5 that appears not to be drivers are:

- Wind speed
- Age
- Solar radiation

Andersen et al. [5] found that age and wind speed did not affect the proportion of dwellings with open windows. These results are not coherent with other studies [18,21] where a significant decrease of open windows for high wind speed emerges. This inconsistency might be explained by the fact that Andersen et al. [5] used wind speed recorded at weather stations throughout the country at a height of 10 m above ground level, which may be different from local wind speeds. Herkel et al. [34] reported a low correlation between the percentages of open windows and wind speed ($r < 17$).

Regarding solar radiation, both Herkel et al. [34] in office buildings and Erhorn [21] in residential buildings cannot confirm a statistical significance for the correlation with solar radiation and the percentage of open windows. Herkel et al. [34] found that the correlation of window openings and solar radiation was small ($r < 0.5$) if compared to the correlation with temperatures both indoor ($r = 0.72$ for small windows and $r = 0.76$ for large windows) and outdoor ($r = 0.81$ for small windows and $r = 0.79$ for large windows). Erhorn [21] reported that while a strong influence appeared with solar radiation, it was not possible to determine a distinct dependence because the influences of outdoor air temperature and solar radiation were superimposed in the overall duration of window ventilation as function of daytime/night-time outdoor temperatures.

The aim of most existing studies is the window state instead of the action of opening and closing the windows (transition from one state to another). This is an important distinction, since the window state influences the indoor environment. If the indoor environmental variables are used to infer models of window state, the predictive variables are influenced by the state that they are trying to predict. In a cold climate low indoor temperatures would occur when the windows are open and not when they are closed. In such a case the result of the analysis would be that the inferred probability of a window being open increases with decreasing indoor temperature, with the illogical implication that the probability of opening a window would increase with decreasing indoor temperatures.

Another problem with focussing on the state rather than the transition is that the drivers for opening and closing windows might be different. Indeed, Andersen et al. [6] found that the CO_2 concentration was the most important driver for opening of windows, while the outdoor temperature was the most dominant driver for closing of windows.

The problems listed above are overcome, when the focus of the analysis is shifted from state to transition.

Further studies are then required focussing on the driving forces for the actions on windows (opening and closing) rather than keeping the state of the windows as the aim of the research.

5. Conclusions

This literature review highlights that what seems to be a simple task, to open or close windows, is in reality a task that is influenced by many factors, which interact in complex ways. It is evident that the window opening behaviour has a very big impact both on the indoor environment quality and on the energy consumed to sustain the desired indoor environmental quality level.

In this paper, we have reviewed the existing studies on the topic of window opening behaviour and elaborated a theoretical framework to deal with occupants' interactions with building controls, aimed at improving or maintaining the indoor environment. This approach is used to look into the drivers for the actions taken by the occupants (windows opening and closing) and to investigate the existing models in literature of these actions for both residential and office buildings. In general, the driving forces are multidisciplinary and can be categorised in five main categories (Physical Environmental, Contextual, Psychological, Physiological and Social). The analysis of the literature highlight how a shared approach on identifying the driving forces for occupants' window opening and closing behaviour has not yet been reached. Most studies focus on determining the most important drivers and put little emphasis on the variables that do not show up as drivers. However, the reporting of variables found not to be drivers may reveal contradictions in the obtained results and may be a significant tool to help direct future research.

Moreover, existing studies on window opening behaviour are aimed at investigating the state of the window itself instead of the transition from one state to another (opening and closing). This might be problematic, since the indoor environment is affected by the state of the window with the consequence that the predictive variables are influenced by the state that they are trying to predict. Further studies are required focussing on the driving forces for the transition of windows state (open and closing) rather than keeping the state of the windows as the aim of the research.

A significant effort should be addressed in the following years to better understand the dynamics of the relationship between indoor environment, occupant behaviour and energy consumption. More accurate, reliable and realistic occupant behaviour models need to be developed. The description of the dynamics regulating the relationship between occupant behaviour and energy consumption is still an unresolved problem. In this sense, it is fundamental to apply approaches in the interpretation of the phenomena shared as much as possible.

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