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Stochastic behavioural models of occupants' main bedroom window operation for UK residential buildings

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ABSTRACT

This paper presents the development of stochastic models of occupants' main bedroom window operation based on measurements collected in ten UK dwellings over a period of a year. The study uses multivariate logistic regression to understand the probability of opening and closing windows based on indoor and outdoor environment factors (physical environmental drivers) and according to the time of the day and season (contextual drivers). To the authors' knowledge, these are the first models of window opening and closing behaviour developed for UK residential buildings. The work reported in this paper suggests that occupants' main bedroom window operation is influenced by a range of physical environmental (i.e. indoor and outdoor air temperature and relative humidity, wind speed, solar radiation and rainfall) and contextual variables (i.e. time of day and season). In addition, the effects of the physical environmental variables were observed to vary in relation to the contextual factors. The models provided in this work can be used to calculate the probability that the main bedroom window will be opened or closed in the next 10 min. These models could be used in building performance simulation applications to improve the inputs for occupants' window opening and closing behaviour and thus the predictions of energy use and indoor environmental conditions of residential buildings.

1. Introduction

In UK residential buildings, space heating accounts for around two thirds of energy consumption [1]. The energy required for space heating in buildings is dependent on the balance between six heat flows: heat from the heating system; heat transmission through the building's façade; external and internal heat gains; heat stored in or released from thermal mass; and heat from ventilation and infiltration [2]. As dwellings typically have a higher degree of direct control by the occupants than non-domestic buildings, the latter heat flow from ventilation is greatly influenced by the occupants' window opening and closing behaviour [3,4]. Consequently, any attempt to predict the space heating demand and indoor environmental conditions of residential buildings using dynamic building energy performance simulation (BEPS) programs requires realistic models of the occupants' window operation [5–7].

The sophistication of BEPS has made significant progress during the last decades and is increasingly used to predict and optimise the energy and environmental performance of buildings. However, the stochastic aspects of occupant behaviour (e.g. window and shading operation, adjusting temperature setpoints, etc.) are often poorly defined in simulation tools [8]. In addition to a wide number of other contributing factors throughout the building lifecycle, from planning and design to operation, discrepancies between simulated and actual behaviour can lead to significant differences between the predictions of building energy use at the design stage and actual use in operation. This is referred to as the “energy performance gap” [9,10]. For a detailed review of all the root causes of the energy performance gap, see de Wilde [9]. Improving the model inputs for the representation of occupants and their behaviour has only recently been identified and researched [11–15]. Accordingly, in 2014, the International Energy Agency launched IEA-EBC Annex 66 – Definition and Simulation of Occupant Behaviour in Buildings [16], which aims to help close the energy performance gap through the modelling and integration of occupants' behaviour in building simulation software. Of particular relevance to the current paper is

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Subtask B: Occupant action models in residential buildings.

As a result, the modelling of occupant's behaviour in buildings has steadily increased in the last few years, however, as early as 1990, Fritsch et al. [17] using a Markov Chains process modelled window opening angles in office buildings for four different outdoor temperature ranges. In 2009, Haldi and Robinson [18] set a milestone in the modelling of window operation in office buildings using data collected over a period of seven years. They modelled window position (open or closed) using several modelling approaches including, Bernoulli process, discrete time random (Markov) process and continuous random process and hybrid combinations of those techniques. In 2013, Andersen et al. [19] using multivariate logistic regression proposed the first window opening (closed to open) and closing (open to closed) models for domestic buildings based on observations from 15 dwellings located in Denmark.

Providing modellers with typical occupant behaviour patterns is one method to improve model inputs and thus the accuracy of simulation outputs. Constructing models of typical occupant behaviour requires the quantification of real occupant behaviour measured in real buildings, combined with an understanding of the underlying "drivers" of the behavioural action. Fabi et al. [20] define drivers as *"the reasons leading to a reaction in the building occupant and suggesting him or her to act (they namely "drive" the occupant to action)"*.

Previous studies have identified the key factors that influence occupants' window opening behaviour in buildings (e.g. Refs. [17–19,21–34]). A detailed international review and discussion of these factors is provided by Fabi et al. [20]. In their review, the "drivers" of window opening behaviour in residential buildings were categorised as: (1) physiological drivers (age and gender); (2) psychological drivers (perceived illumination and preference in terms of temperature); (3) social drivers (smoking behaviour and presence at home); (4) physical environmental drivers (outdoor and indoor temperature, solar radiation, wind speed and CO_2 concentration) and (5) contextual drivers (dwelling type, room type, room orientation, ventilation type, heating system, season and time of day).

The review concluded that: (1) window operation has a strong impact on the energy use and indoor environmental conditions of buildings; (2) there remains a lack of consensus as to which drivers actually influence occupants' window operation; (3) the majority of previous studies analyse window state (open or closed) rather than change of state (open to closed; closed to open) and (4) significant further effort is required to understand the dynamics of the relationship between indoor environment, occupant behaviour and energy consumption, as well as the development of more accurate, reliable and realistic occupant behaviour models.

Furthermore, as Fabi et al. [20] reviewed window interaction studies in both domestic and non-domestic buildings, it was evident that most previous analyses have focused on office buildings (e.g. Refs. [17,18,35–41]) and there is a lack of studies related to residential buildings. Stochastic models of occupants' window interactions developed based on measurements in office buildings can provide useful inputs for modelling large buildings or clusters of buildings (city scale) with many occupants. In addition, Schweiker et al. [27] have shown that window operation models developed from data collected in office environments can also be used to reliably predict window usage in the residential context and vice-versa.

This paper presents stochastic models of occupants' main bedroom window operation behaviour based on measurements collected in ten UK dwellings over a period of a year. The study uses multivariate logistic regression to understand the probability of opening and closing windows (change from one state to another) based on a range of indoor and outdoor environment factors (physical environmental drivers) and according to the time of the day and season (contextual drivers). This work is a pilot study of window operation behaviour for UK domestic buildings, replicating the methodology previously used in the studies by Andersen et al. [19] and Fabi et al. [24].

This study specifically targets an understanding of the drivers of main bedroom window operation behaviour, as it is the room most often used for ventilation in domestic buildings. Previously, Brundett [42] found that open windows were most commonly found in bedrooms, in particular the main bedroom, and Dubrul [32] identified that bedrooms were the main ventilation zones in dwellings. In addition, the living rooms of the ten dwellings investigated had French doors, instead of windows, onto either an exterior patio or balcony and were therefore excluded from the analysis.

The data used in this study were collected as part of a larger Post-Occupancy Evaluation (POE) to assess the actual operational performance of the dwellings [43,44], rather than a specific study of occupants' window behaviour, therefore the range of indoor and outdoor environment factors used for modelling (i.e. indoor air temperature and relative humidity; outdoor air temperature and relative humidity; wind speed; global solar radiation; and rainfall) were those available to the researchers. Similarly, the monitoring system installed only allowed data to be collected about the window state rather than the position. It should be noted that there are other possible drivers of window interactions that were not captured in this study and further research on these for the UK domestic sector would be beneficial (e.g. removal of odours from smoking or pets, presence at home, CO_2 concentration, metabolic activity, clothing insulation, etc.). The analysis undertaken does however partition the data to account for variations in window opening according to the time of day and season.

The dwellings investigated in this study are new-build properties and should therefore achieve current standards for airtightness as set by the building regulations. This means that the models developed in this work may better capture occupant's window operation behaviour in new homes or those which have undergone refurbishment (i.e. the future housing stock), as it could be imagined that window opening behaviour studies undertaken in older dwellings may well be affected by the higher air leakage rates.

To the authors' knowledge, these are the first stochastic models of window opening and closing developed for UK residential buildings. Previously, Rijal and Stevenson [45] proposed a window state model (open or closed) for autumn only, based on data collected in a single UK dwelling and for one potential driver: outdoor temperature. Window state models are problematic as the predictive indoor environment variables are affected by the window state itself. By modelling the change of window state (open to closed; closed to open) rather than the window state, this work overcomes this limitation and also allows the important drivers of window opening and closing to be inferred separately.

The development of national models of occupant behaviour is important as occupants' living patterns and behavioural practices vary internationally [46–48]. Nicol [49], albeit for offices, previously identified differences in window opening behaviour between occupants of buildings in the UK, other European countries and Pakistan. The research identified that the proportion of open windows in European offices was generally lower than in the UK at any given temperature. In addition, Pakistani office workers were observed to use windows less than their counterparts in Europe and the UK. This behaviour was attributed to the hot dry conditions in Pakistan, whereby opening windows has little advantage and may even increase indoor temperatures.

The objective of this work was to develop stochastic models of window opening and closing behaviour for UK residential