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Occupants' behaviour in office building: stochastic models for window opening.

V. Fabi[1], V. Maggiora[1], SP. Corgnati[1] and Rune Andersen[2]

[1] TEBE Research Group, Department of Energetics, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[2] ICIEE, Department of Civil Engineering, Technical University of Denmark, Nils Koppels Allé Building 402, 2800 Kgs. Lyngby, Denmark)

Abstract

The interactions between building occupants and control systems have a high influence on energy consumption and on internal environmental quality. In the perspective of a future of "nearly-zero" energy buildings, it is crucial to analyse the energy-related interactions deeply to predict a realistic energy use during the design stage. Since the reaction to thermal, acoustic or visual stimulus is not the same for every human being, monitoring the behaviour inside buildings is an essential step to assert differences in energy consumption related to different interactions. Based on measurements in eight offices in Prague, seven models concerning occupants' window opening behaviour in office buildings were proposed. The dataset was gathered through a monitoring campaign lasting 11 months, from February 2012 until January 2013. Indoor and outdoor environmental conditions were collected in eight south-west exposed rooms, mechanically ventilated and heated through radiators. Two rooms were used by two people while the other six were single offices. Seven models for opening and closing windows were inferred using multiple logistic regression.
The model's outputs were probabilities of a window opening and window closing event within the next five minutes. Implementing all the models into dynamic energy simulation software would lead to different simulated behaviour patterns and consequently different demands and uses of energy, representing a more reliable variability of energy consumption due to building occupants'.

Keywords: Occupant's behaviour; window opening; stochastic modelling

1 INTRODUCTION

Probabilistic models of occupants' behaviour require an important step: observing the real interaction between dwellers and building; several existing models are based on empirical data (Nicol et al. 2007, Mahdavi and Pröglhöf 2009, Bourgeois and Reinhart 2004) although these only include thermal stimuli. This step is the starting point of a path that leads to a better understanding of the links between building, energy consumption and users passing through the study of human behaviour in relation to environmental stimuli.

Pioneering investigations (Dick and Thomas, 1951; Brundrett, 1979; Warren and Perkins,1984) mostly aimed to find a correlation between the use of the window and the external temperature. Logically if the perceived temperature is increasing then the opening action is more likely to happen. However, temperature is not the only physical environmental parameter influencing occupants' window opening behaviour. Brundrett (1979) and Warren and Perkins (1984) were among the first to demonstrate that also external radiation and wind speed could be considered as predictors of an opening/closing action and (Schweiker, 2010) later noted that "Occupants' behaviour is not only related to thermal, visual and acoustic stimuli but is a complex system that involve also physiological, psychological and social aspects”. The relation between these factors is soft and does not always lead to a certain action. The variation in occupants’ behaviour can lead to differences in consumption. As a consequence, measurements of internal and external physical conditions and surveys are essential to understand factors influencing an interaction between the occupant and the building. In this paper we have investigated the effects of certain Volatile Organic Compounds (VOCs) on occupants’ window opening behaviour. Some VOCs have certain scents and according to Jones (1999) VOCs have been associated with irritation of the mucus membrane. As such, VOC may be a better predictor of the air quality associated drivers for window opening behaviour.

Many papers have used different mathematical method to infer the probability of an action occurring in order to define behavioural models for opening and closing of windows (Fritch, 1990; Nicol, 2001; Haldi and Robinson, 2008; Herkel et al, 2008; Yun and Steemers, 2010; Schweiker, 2012; Andersen et al, 2013).

This paper describes occupants’ behaviour models related to the window opening and closing in offices based on measurements. The statistical analysis was applied separately for each office room in order to take advantage of the variety of monitored data (different in each room) and evaluate which of them could be related to the actions on windows.

2. MEASUREMENTS

Measurements were taken in eight different offices of the Department of Micro-environmental and Building Services Engineering, located in the second floor of a sixteen-storey building. The environmental data collection was part of the EU FP7 project ClearUp and started on February 2012 and ended on January 2013. Figure 1 shows a picture and floor plan layout with indication of rooms. All the rooms are south-west exposed and seven of them have an area of 15 m^2 (3m x 5m) while room R8, has an area of 30 m^2 (6m x 5m). The rooms R3 and R6 were shared by two people, while the others are single offices.

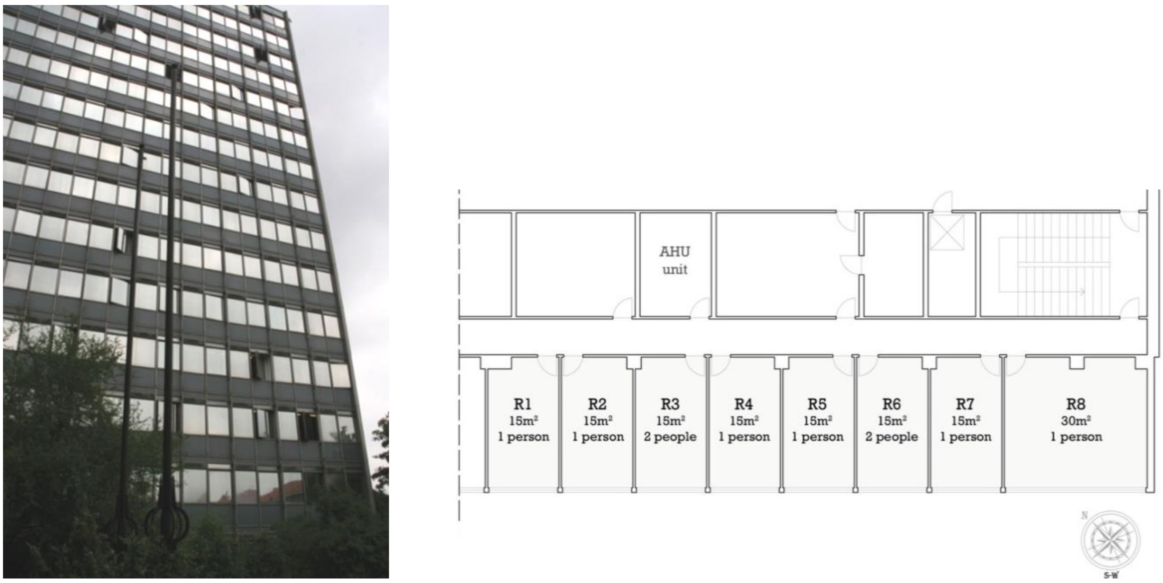

Figure 1. Czech Technical University in Prague building (left) and the second floor plan (right).

The offices were heated by radiators placed below a book case; users had the possibility to change the heating set-point through valve actuators and within pre-set boundaries. The ventilation was controlled by an air handling unit (AHU) placed on the same floor with a pre-set flow rate of 30 m^3/h. Users could interact with the ventilation system in pre-set mode according to flow rate values (20,35,50 m^3/h). Mechanical ventilation and set-point temperature schedule were constantly active but subordinated to the manual control. For each office natural ventilation was enabled by one of two windows characterised by a rotating frame around a central pivot. The inner roller blinds were both manual and automatic; if the window was open only manual mode was possible. According to the season, the system worked following an algorithm that gave a different position of the blinds for collecting or rejecting solar gains. Users' interaction was always possible but after one hour, the automatic mode resumed. The following variables were measured at 5 minute intervals in all 8 offices:

• *Indoor environment parameters*

- Temperature [°C]
- Set-point temperature [°C]
- Relative humidity [%]
- CO_2 concentration [ppm]
- VOC concentration [ppm]
- Illuminance (in the middle of the room, on desk, at window)

Outdoor environment parameters

- Air temperature [°C]
- Relative humidity [%]
- CO_2 concentration [ppm]
- VOC concentration [ppm]
- Wind speed [m/s]
- Rain (yes, no)
- Wind speed [m/s]

• *Window state (open/closed)*

• *Door position (open/closed)*

• *Contextual Factors*
- Moment of the day (morning, day, afternoon, evening, night)
- Season (winter, spring, summer, autumn)
- Presence measured by PIR sensor (arrival the first 15 min, intermediate, departure the last 15 min.)

3. STATISTICAL ANALYSIS

The probability of an opening and closing event was inferred using multivariate logistic regression with interactions between selected variables (equation 1). The statistical software R was used for all data analysis and modelling.

$$\mathrm{Log}\frac{p}{1-p} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + c_{12}x_1x_2 + c_{13}x_1x_3 + \cdots \quad (1)$$

Where:

p is the probability of an switching on/off event

β_0 is the intercept

β_{1_n} are coefficients

x_{1_n} are explanatory variables such as indoor room temperature, relative humidity, …

c_{12_nm} are interactions coefficients

To reduce the complexity of the model, only interactions terms between environmental and contextual factors (moment of the day, weekdays, seasons) were considered. Through the statistical software R, the Akaike information criterion (AIC) was used individually for each room database to select the predictive variables among the ones monitored during the campaign. This criterion tests one by one the variables in order to find the combination with the lower AIC value (forward and backward selection). In considering the AIC of room R8, an infinite value was found and it was not possible to apply the regression. In the interpretation of the coefficients, the sign, the size and the scale of the corresponding variable have to be taken into account. The scales of the variables should be taken into account: Schweiker and Shukuya (2009) suggested to multiply the scale of the variable with the coefficient, to get an indication of the magnitude of the impact from each variable.

4. RESULTS

Since temperature is generally correlated to seasons and time of day, the whole day was divided into different periods. Since it was demonstrated (Warren et al. 1984) that occupants' window actions occur mostly when occupants arrive or leave the workplace, and windows are mainly closed at the end of the working day. For rooms with presence detector was possible to split up the presence time into arrival, the first 15 minutes, and departure, the last 15 minutes. From the analysis of each room, the relation between the arrival and the open act appears clearly.

A comparison between the hours of presence and the actions on the window gave the number of opening actions (relative frequency) per day for each room ; the mean value of the relative frequency was considered as a threshold to define passive users (number of opening per day lower than the threshold) and active users. These numbers were compared to their mean value equal to 0.15 ACH (Figure 2).

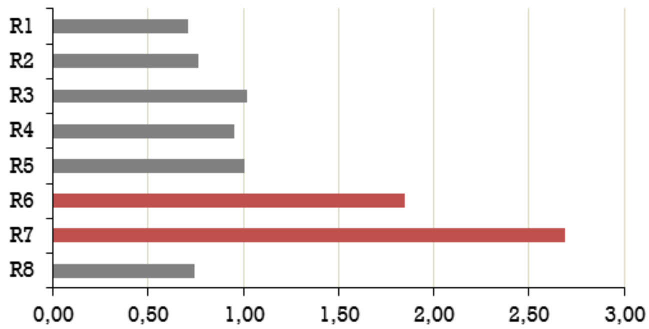

Figure 2. Relative frequency of the opening acts in each room and the determination of active (red) and passive (grey) users

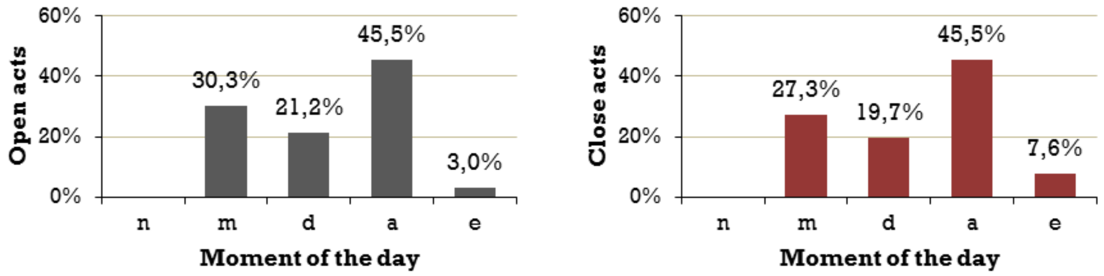

Figure 3. Distribution of opening and closing acts spread throughout the moment of the day [**n**=night (from 23 to 5 a.m.); **m**=morning (from 6 to 8 a.m.); **d**=day (form 9 to 12 a.m.); **a**=afternoon (from 13 to 17); **e**=evening (from 18 to 22)] for room R1

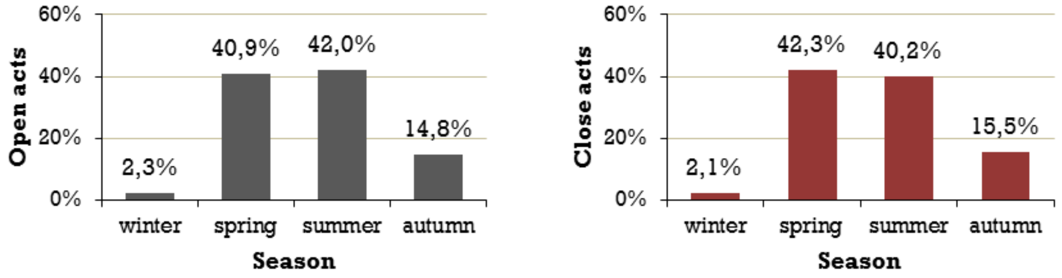

Figure 4. Distribution of opening and closing acts spread throughout the season for room R3.

The main influencing factors for the seven different models were presented in table 1 and in table 2 with their magnitudes. Table 1 is aimed at highlighting the parameters obtained by applying the Akaike information criterion and resulted to be influencing on the actions of opening and closing the windows within all the factors investigated in the case studies. In Table 2 is shown the magnitude of each influencing factor gained by multiplying the regression coefficient for the difference between the maximum and minimum value of the measured parameter.

Table 1. Influencing factors for window opening/closing behaviour for the investigated offices.

	Open windows							*Close windows*						
Investigated variables	***R1***	***R2***	***R3***	***R4***	***R5***	***R6***	***R7***	***R1***	***R2***	***R3***	***R4***	***R5***	***R6***	***R7***
Time of day	X	X					X		X					X
Season	X				X			X					X	
Arrival/intermediate/Departure		X			X	X	X							X
Indoor Temperature		X		X										X
Outdoor Temperature	X							X			X	X	X	X
Indoor Relative humidity			X		X	X								
Outdoor Relative humidity														
Indoor CO_2 Concentration	X		X		X					X				
Outdoor CO_2 Concentration											X			X

Indoor VOC Concentration	X	X
Outdoor VOC Concentration		
Door position	X X	
Illuminance in the room		
Illuminance on desk		
Illuminance at window	X	X
Rain		
Wind speed		

Table 2. Magnitudes of resulting influencing factors for energy-related behaviour with respect to window opening/closing for the investigated offices.

	Open windows							***Close windows***						
Investigated variables	***R1***	***R2***	***R3***	***R4***	***R5***	***R6***	***R7***	***R1***	***R2***	***R3***	***R4***	***R5***	***R6***	***R7***
Indoor Temperature[°C]		12.3		3.57										3.4
Outdoor Temperature[°C]	3.9							9.6			3.8	6.7	2.8	5.33
Indoor Relative humidity [%]			4.4		4.8	2.1								
Indoor CO_2 Concentration[ppm]	0.001		0.7		0.001					0.6				
Outdoor CO_2 Concentration[ppm]											0.5			0.8
Indoor VOC Concentration[ppm]							1,07					0.0004		
Illuminance in the room[lux]														
Illuminance on desk[lux]														
Illuminance at window[lux]			1.4							0.5				

The different rooms had different predictors for opening and closing actions (Table 1). Three of the seven behaviour models for window opening were influenced by the indoor relative humidity. This variable had the highest magnitude value in the single room model. The CO_2 was found to be a common predictor for three rooms, but its weight in the models was lower than the other influencing factors. The arrival/departure division was related to the opening actions as a single influence in rooms R2 (figure 5) and R6, but it also interacted with the relative humidity in room R5 and in R7 with the VOC. Furthermore, the moment of the day was more relevant than the season because it was an influencing factor for rooms R1 and R2, and also in the R7 with an interaction with the VOC.

Season also resulted having an impact on the occupants' window opening behaviour in two of the seven analysed room, both for the probability of opening and closing the windows. Since also outdoor temperature affected the window opening behaviour, the seasonal effect is linked to the change of the temperature itself.

In the closing models, a more general influence of outdoor temperature was found in five of the seven rooms, while for the other variables the paths are split. No generalized pattern was found for the contextual factors. . The presence and moment of the day had an influence on the closing probability in room R7 as an interaction with the outdoor temperature (figure 6), and in room R2. In the other analysed rooms both the presence and the moment of the day has not been recongnized as influencing factors for opening or closing windows probabilities. In the following figures two main examples of resulting probabilities as function of indoor temperatures (figure 5) and outdoor temperature (figure 6) are represented.

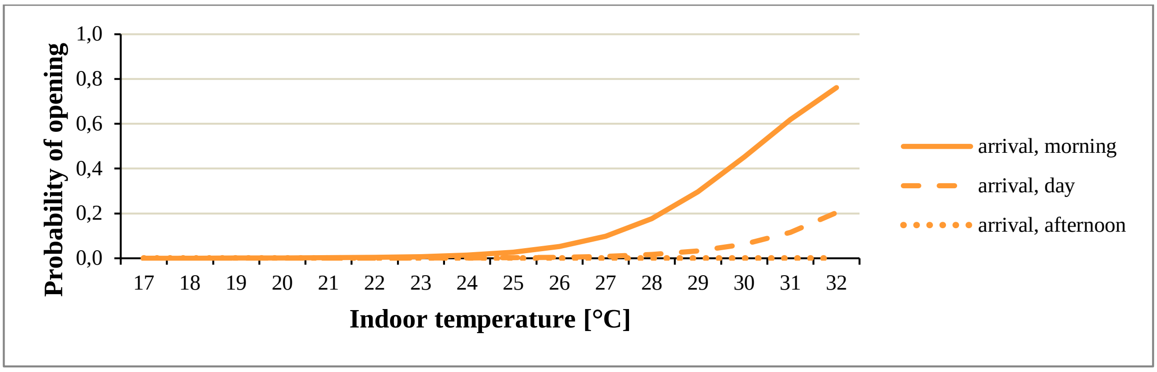

Figure 5. Probability of opening windows for different times of day and indoor temperature for one analysed office behavioural model (R2).

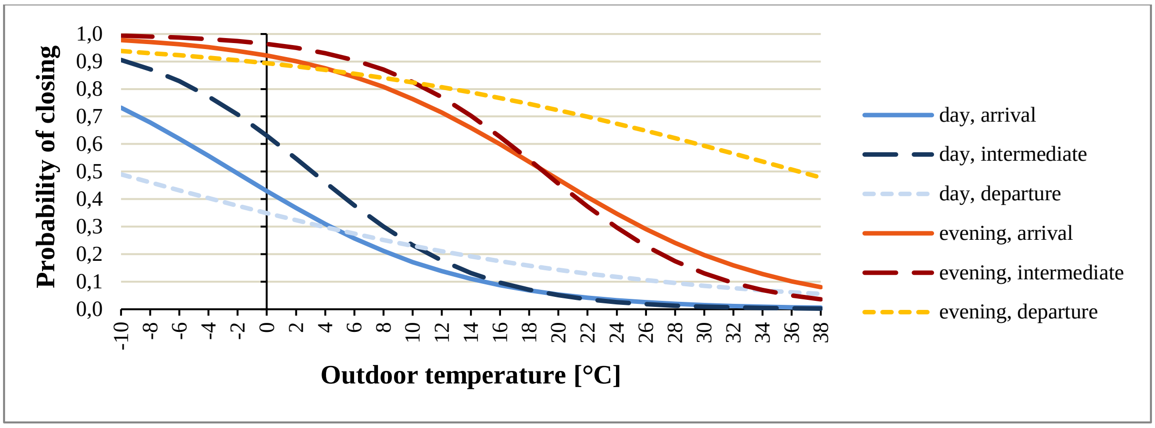

Figure 6. Probability of closing windows for different times of day and office occupancy patterns as a function of the outdoor temperature for one analysed office behavioural model (R7).

5. DISCUSSION

We inferred the probability of opening or closing a window (change from one state to the other) rather than the probability of an open window (state). This approach has its root in a study by Herkel et al. (2005) about the opening actions on a window in office buildings. They used separated probabilistic sub-models for opening and closing at arrival, departure and intermediate presence considering outdoor temperature as a predictor. The relation between a window interaction and the outside temperature was investigated by Rijal et al. (2007), Nicol and Humphreys (2004), Warren et al. (1984) and Fritsch et al. (1990) who all found a positive correlation between open windows and temperature.
Fabi et al. (2012) found that internal variables (such as indoor temperature) may influence occupants' window opening behaviour and should be included in models of occupants' window opening behaviour. Indoor environmental conditions are a consequence of the window state, thus interference may occur between predictors that are internal variables (e.g. internal temperature) and the state of the window that is trying to predict. Furthermore the driving forces that can lead to open a window may be different from to one for closing it.

To implement the results of the statistical analysis in a building energy simulation software, it is necessary to obtain a generalized occupant behaviour model. This work was developed starting from a database that provided many variables both indoor and outdoor to improve the knowledge about the factors influencing the occupants to perform an action. The first step was to find if variables which are generally not taken into account in behavioural research, like concentration of VOC, could have an impact on the opening and closing behaviour in offices. Since some variables were only monitored in some rooms, it was not possible at the beginning to merge rooms in for example active/passive users. However, the results of the regression analyses showed a tendency towards more classical parameters, such as indoor relative humidity, CO_2 concentration and outdoor temperature, which were monitored in all rooms.

As a second step, a division between active and passive users could be applied by merging data from rooms and deleting some not shared variables of the rooms, creating a passive and an active user model. Furthermore, it is also interesting to see if rooms with one occupant have a different common behaviour towards the one with two occupants.

Considering the results of the regression analysis (see table 1 and table 2) the opening and closing probabilities can be inferred by picking the rooms with the common predictors. For example, the room R3, R5 and R6 can be merged to see if the relative humidity can be considered as a reliable predictor in a more general opening behaviour. R1, R3 and R5 are useful to infer the CO_2 influence. For the closing probability, it could be interesting to have a complete database which comprises all the rooms in order to see if the outdoor temperature is a reliable predictor.

Considering that a logistic regression applied on a single room is not enough to depict an overall correlation between the air conditioner, the door switching and the window opening, the analysiswill be only hypothesis of a possible implementation of the model into simulation software.

Moreover, the current research trend about occupants' behaviour is mainly focused on the analysis of the single device whereby users could interact. If we think about our daily behaviour in indoor environment, we realize that our reactions to thermal, visual or acoustic stimuli are sometimes correlated. For example, if we feel hot our direction could be to open a window or perhaps to turn on the air conditioner. Taking this into consideration, an integrated approach where probabilistic behavioural models define all the possible interactions between users and building controls (such as use of the window, heating and cooling set point adjustments, use of lighting and equipment), would be very useful. Furthermore this approach would help to get closer to a truthful evaluation of users' influence in modifying the energy performances of the building by considering probabilistic all the objects that imply human interaction.

6. CONCLUSIONS

The indoor temperature, indoor relative humidity and outdoor temperature had the highest influence on the window opening probability. The outdoor temperature influenced the closing probability in five of the seven rooms and had the highest magnitude in all five rooms. Contextual variables such as time of day and season also affected occupants' window opening behaviour. The VOC concentration had an effect in two of 4 rooms, but this effect was small compared to other factors. The occupancy state (arrival/intermediate/departure) had an effect on opening probability in four out of seven rooms while it only affected the closing probability in one room.

The variables indoor and outdoor temperature, indoor relative humidity and contextual variables such as occupancy state, turned out as the best predictors of occupants' window opening behaviour. As such any attempt to realistically model occupants' window operation in office buildings should be based on monitoring campaigns including measurements of at least these variables.

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