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Long term monitoring of window opening behaviour in Danish dwellings

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ABSTRACT: During the first eight months of 2008, measurements of occupant behaviour and eight environmental variables was carried out in 15 dwellings. Logistical regression was applied to infer the probability of open window as a function of the outdoor temperature. The results were compared with the findings in the literature. The measured variables just prior to an opening/closing event were compared to variables where no events occurred. Indoor air quality and solar radiation where found to be the main drivers in the occupants' determination of when to open a window. The indoor air quality and outdoor temperature affected when the window was closed and finally the time of day had an impact on the window opening behaviour of the occupants.

Keywords: Building controls, Behaviour, Thermal comfort, Adaptation, Building simulation

INTRODUCTION

Occupants who have the possibility to control their indoor environment have been found to be more satisfied and suffer fewer building related symptoms than occupants who are exposed to environments of which they have no control [1, 2, 3]. However, occupant behaviour varies significantly between individuals which results in large variations in the energy consumption of buildings [4, 5, 6]. Because of this, it is important to take occupant interaction with the control systems into account when designing buildings.

Most building simulation programs provide possibilities of regulating the simulated environment by adjusting building control systems (opening windows, adjusting temperature set-points etc.). However, discrepancies between simulated and actual behaviour can lead to very large discrepancies between simulation results and actual energy use [7]. Thus there is a need to set up standards or guidelines to be able to compare simulation results between cases. One way of doing this is to define standard behaviour patterns that can be implemented in building simulation programs. This would significantly improve the validity of the outcome of the simulations. A definition of such standard behaviours should be based on the quantification of real occupant behaviour.

Rijal et al. [8] conducted a longitudinal and a transverse study in 15 office buildings in the UK between March 1996 and September 1997. A survey of behaviour and adaptation was conducted by Haldi and Robinson in office buildings in Switzerland during the summer of 2006 [9]. Both Rijal et al. and Haldi and Robinson used logistical regression to derive a relationship between the proportion of open windows and the indoor and outdoor temperature. Also Andersen et al. used logistical regression to determine factors of importance for the behaviour of occupants [10].

Andersen et al. [11] quantified behaviour of occupants in Danish dwellings by means of a questionnaire survey. A definition of standard behaviour patterns was attempted, but a link to the indoor environment was missing due to undesired feedback between the behaviour of the occupants and the indoor environment. As a continuation of the questionnaire survey and to fill in this gap, simultaneous measurement of occupant behaviour, indoor and outdoor environment was carried out in 15 dwellings during the period from January to August 2008.

This paper examines the relationship between the outdoor temperature and the window opening behaviour.

In this paper we compare the results of measurements in Danish dwellings with the results obtained in the surveys described above [8, 9, 10] and attempt to find which variables could be drivers in determining the window opening behaviour.

METHOD

Andersen et al. found that a factor with influence on the behaviour of occupants in residences was the ownership status of the dwelling (rented, owned etc.) [11]. To be representative measurements were carried out in 10 rented apartments and 5 privately owned single family houses. Half of the apartments were naturally ventilated (apart form an exhaust hood in the kitchen) while the other half was equipped with constantly running exhaust ventilation from the kitchen and bathroom. Four of the single family houses were naturally ventilated while the other two single family houses were equipped with exhaust ventilation.

The measurements were carried out in one living room and one sleeping room in each dwelling.

The following variables were measured in 10 minute intervals in all 15 dwellings.

- Indoor environment factors
  - Temperature [°C]
  - Relative humidity [%]
  - CO2 concentration [ppm]
  - Illumination [lux]

- Outdoor environmental factors
  - Air temperature [°C]
  - Relative humidity [%]
  - Wind speed [m/s]
  - Solar radiation [W/m²]

- Behaviour
  - Window position (open/closed)

Ideally the temperature sensors should have been placed so they would not be hit by direct sunlight. Due to practicalities this was not always possible. In the cases where the temperature sensors were hit by direct sunlight the indoor illumination was used to correct the measured temperature. This was done by linear interpolation between measurements one hour prior to and one hour after direct sunlight fell on the sensor.

STATISTICAL METHODS

We have used logistical regression to derive the relationship between outdoor temperature and the state of the windows (open/closed). This method is governed by the equation:

$$log\left(\frac{p}{1-p}\right) = a + bt$$

Where

p is the probability that the window is open

a and b are constants

t is the temperature

This equation was fitted to the data and compared to the results of the three surveys [8, 9, 10].

To quantify the influence of the monitored factors on the window opening and closing behaviour, the value of each variable just before an opening/closing event was compared to measurements when no actions occurred. A t-test revealed if the differences in the average values were significant.

RESULTS AND DISCUSSION

Figure 1 shows the probability that the window was open as a function of the outdoor temperature for the measurements and for the surveys conducted by Andersen et al., Rijal et al., and Haldi and Robinson. It should be noted that curves 1 and 2 in figure 1 are based on data collected in dwellings while curves 3, 4 and 5 are based on surveys in office buildings.

Rijal et al. and Haldi and Robinson used both indoor and outdoor temperatures as explanatory variables in the logistical regression models and argued that this may be the most feasible approach since the indoor and outdoor temperature may be correlated. If they are correlated any impact from the outdoor temperature on the window opening behaviour could be attributed to an indirect influence of the indoor temperature.

We chose not to include the indoor temperature in the analysis because it is influenced by the state of the window. In a cold climate the indoor temperature is likely to drop when a window is opened. As a consequence, using the indoor temperature as an explanatory variable would lead to the illogical result that the inferred probability of having a window open would be higher at low indoor temperatures than at high indoor temperatures.

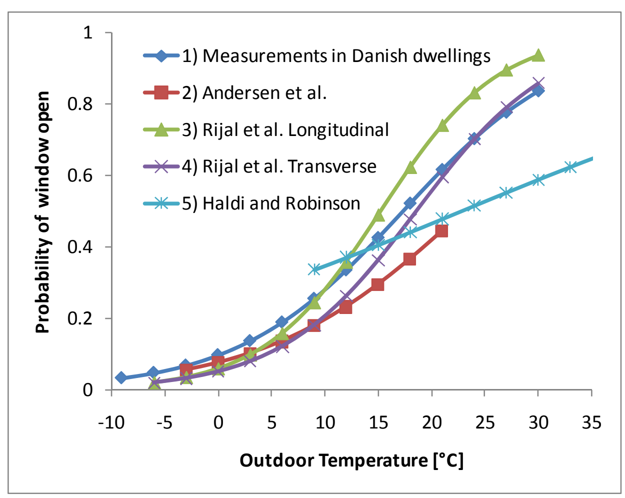

Figure 1: The probability of open window as a function of the outdoor temperature. The curves are a result of logistical regression

In table 1 values of the variables just before an opening event are compared to values obtained when the window was closed but no events occurred. Neither the indoor temperature nor the outdoor relative humidity before an opening event differed from the rest of the measurements. This indicates that the indoor temperature and outdoor relative humidity did not affect the occupants' decisions of when to open a window.
The CO_2 concentration, indoor relative humidity, outdoor temperature and solar radiation were higher before an opening event compared to the measurements when no events occurred.

Table 1: Differences in the average values of the measured variables, just before an opening event and when no opening event took place.

	open action	no action, window closed	p
indoor temperature [°C]	21.69	21.67	0.6362
CO2 concentration [ppm]	860.3	787.1	<0.0001
Indoor relative humidity [%]	41.6	40.9	<0.0001
Outdoor temperature [°C]	8.4	7.8	<0.0001
Outdoor relative humidity [%]	76.9	77.1	0.4662
Wind speed [m/s]	2.9	3	0.0102
Solar radiation [W/m²]	195.2	153.7	<0.0001

Table 2 compares the values of the monitored variables just before the window was closed with those when no events occurred. The indoor temperature and wind speed did not differ between the two situations. The CO_2 concentration, Indoor relative humidity, outdoor temperature and solar radiation were lower before the window was closed compared to measurements when the window stayed open.

Table 2: *Differences in the average values of the measured variables, just before a closing event and when no closing event occurred.*

	close action	no action, window open	p
indoor temperature [°C]	21.19	21.28	0.06753
CO2 concentration [ppm]	508.4	557.5	<0.0001
Indoor relative humidity [%]	39.3	42.3	<0.0001
Outdoor temperature [°C]	9.3	12.6	<0.0001
Outdoor relative humidity [%]	73	71	0.0005
Wind speed [m/s]	3.17	3.24	0.0750
Solar radiation [W/m²]	223.8	268.9	<0.0001

The fact that the CO_2 concentration and solar radiation before an opening event was higher than when the window remained closed indicates that air quality and sunshine may be drivers in the occupant's determination of when the window is opened. While other monitored variables showed significant differences these were small and it is unlikely that they impact the occupants' decisions of when to open a window.

The CO_2 concentration and outdoor temperature were both lower before the window was closed compared to when it stayed open, indicating that these variables affected the occupants' decision of when to close the window.

Figure 3 gives an overview of the time of day of the opening/closing actions. Most opening events occurred in the early morning while most closing events occurred later in the morning and in the afternoon.

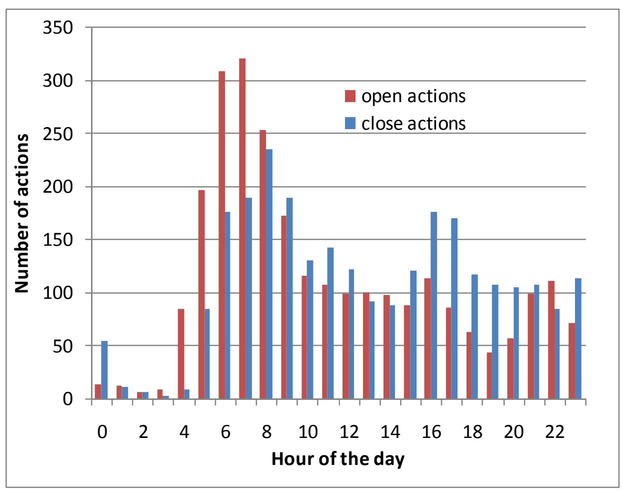

Figure 3: Histograms of the time of day for window opening and closing events.

CONCLUSION

Comprehensive measurements of window opening behaviour and environment were conducted in 15 dwellings in Denmark. Based on analysis of the results we found that:

- The probability that the window was open depended on the outdoor temperature in a similar way as others have reported.
- The indoor air quality and the solar radiation were the main drivers in the occupants' determination of when to open a window.
- The indoor air quality and the outdoor temperature affected when the window was closed.
- The time of the day had an impact on the window opening behaviour of the occupants.

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