Building and Environment 69 (2013) 101–113

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Window opening behaviour modelled from measurements in Danish dwellings

Rune Andersen [a,*], Valentina Fabi [b], Jorn Toftum [a], Stefano P. Corgnati [b], Bjarne W. Olesen [a]

[a] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark
[b] Department of Energy, Polytechnic of Turin, Italy

ARTICLE INFO

Article history:
Received 8 January 2013
Received in revised form
4 July 2013
Accepted 8 July 2013

Keywords:
Occupant behaviour
Building controls
Adaptation
Window opening
Building energy performance simulation
Air quality

ABSTRACT

A method of defining occupants' window opening behaviour patterns in simulation programs, based on measurements is proposed.

Occupants' window opening behaviour has a strong effect on indoor environment and the energy consumed to sustain it. Only few models of window opening behaviour exist and these are solely based on the thermal indoor/outdoor environment. Consequently, users of simulation software are often left with little or no guidance for the modelling of occupants' window opening behaviour, resulting in potentially large discrepancies between real and simulated energy consumption and indoor environment.

Measurements of occupant's window opening behaviour were conducted in 15 dwellings in Denmark during eight months. Indoor and outdoor environmental conditions were monitored in an effort to relate the behaviour of the occupants to the environmental conditions. The dwellings were categorized in four groups according to ventilation type (natural/mechanical) and ownership (owner-occupied/rented) in order to investigate common patterns of behaviour. Logistic regression was used to infer the probability of opening and closing a window.

The occupants' window opening behaviour was governed by different but distinct habits in each dwelling. However, common patterns were also identified in the analysis: Indoor CO_2 concentration (used as indicator of indoor air quality) and outdoor temperature were the two single most important variables in determining the window opening and closing probability, respectively.

The models could be implemented into most simulation programs, which would enable a better chance of mimicking the behaviour of the occupants in the building and thus simulating the indoor environment and energy consumption correctly.

1. Introduction

Occupants who have the possibility to control their indoor environment have been found to be more satisfied and suffer from fewer building related symptoms than occupants who occupy environments in which they have no control [1–4]. These studies emphasize the significance of providing occupants with rich opportunities of interacting with building controls. In doing so, the control of the building is to some extent left in the hands of the occupants. However, occupant behaviour varies significantly between individuals which results in large variation of the indoor environment and energy consumption of buildings [5–9]. Because of this, it is important to take occupants' interactions with building controls into account when designing buildings.

Most building simulation programs provide possibilities of regulating the simulated environment by adjusting building controls (opening windows, adjusting temperature set-points etc.). However, discrepancies between simulated and actual behaviour can lead to very large offset between simulation results and actual energy use [10,11]. Indeed, Andersen et al. showed that differences in occupant behaviour might lead to differences in energy consumption of over 300% [12]. Thus, there is a need to set up standards or guidelines to enable comparison of simulation results between simulation cases. One method that can provide this is to define typical 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 typical behaviours should be based on the quantification of real occupant behaviour.

* Corresponding author. Tel.: +45 4525 4029; fax: +45 4593 2166.
E-mail addresses: rva@byg.dtu.dk, rune.v.andersen@gmail.com (R. Andersen).

0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.07.005

Table 1
Overview of referenced studies of window opening and ventilation.

Reference	Sample size	Geographical location	Duration of measurement
[13]	One single family house	Virginia, USA	One year
[14]	Two single family houses	California and Virginia, USA	One year
[15]	9 apartments and 19 single family houses	Denmark	One week
[16]	500 dwellings	Denmark	2.5 nights (only nights)
[17]	15 office buildings, Transverse questionnaires from 890 subjects and longitudinal questionnaire and measurements from 219 subjects	UK	Transverse: 1 day each month for one year. Longitudinal: 3 months
[18]	60 subjects from several office buildings	Switzerland	3 months
[19]	One office building (21 offices)	Germany	13 months
[20]	2 office buildings (6 offices)	UK	3 months
[21]	2 office buildings (6 offices)	UK	3 months
[22]	Surveys and spot measurements from 846 people in 33 office buildings	Pakistan	1 questionnaire each month for 16 months
[23]	One office building (14 offices)	Switzerland	7 years
[24]	Three apartments and 39 student dormitory rooms	Switzerland and Japan	Apartments: 1 year. Dormitory: 1 month
[25]	1 office building (4 offices)	Switzerland	One winter
[26]	Repeated questionnaire in 933 (summer) and 636 (winter) dwellings	Denmark	2 questionnaires
[27]	1100 dwelling	North Carolina, USA	72 survey sessions, consisting of 2 observations of 1100 dwellings
[28]	Literature review	–	–
[29]	Literature review	–	–
[34]	24 dwellings	Scotland, UK	Daily visits and spot measurements for 7 months
[35]	Summary report of 22 studies in dwellings. Sample size: from 5 to 3000	Germany, The Netherlands, Switzerland, UK and Belgium	Questionnaires, observations, continuous measurements
[36]	Repeated questionnaire in 933 (summer) and 636 (winter) dwellings	Denmark	2 questionnaires

Two important parameters influencing energy consumption in dwellings are indoor temperature and air change rate. Wallace et al. measured air change rates in a house during one year and found that the opening and closing of windows had the largest effect on the air change rate [13]. Also Howard-Reed et al. found that opening of windows produced the greatest increase in air change rates compared with temperature differences and wind effects [14]. Kvistgaard and Collet [15] measured air change rates in 16 Danish dwellings and noted that there was considerable difference in the total air change between individual dwellings. As the basic air change[1] was similar, it was concluded that the behaviour of the occupants caused these large differences. Also Bekö et al. [16] concluded that the occupants' behaviour had the largest effect on air change rates, in their measurements of air change rates in 500 bedrooms. In Danish dwellings, mechanical cooling is almost never used, which means that the indoor temperature depends on the heating set point in winter and on the air change rate in the summer. As a consequence, window opening behaviour and heating set point behaviour of occupants play an important role in determining the energy consumption and indoor environment of a household.

Recently, the effect of indoor and outdoor temperature on the window opening behaviour in offices has been investigated by means of logistic regression [17–24]. The general trend has been to infer the probability of the window state as a function of indoor and outdoor temperature, while some have investigated the probability of opening a window (change from one state to another) as a function of temperature [20,21,23]. Haldi and Robinson argued that the indoor temperature would be a better predictor than the outdoor temperature because indoor temperature is a driver for opening and closing windows to a much larger extent than outdoor temperature [18]. In a later paper Haldi and Robinson addressed the differentiation between indoor and outdoor stimuli for openings and closings and tested several modelling approaches [23]. Since indoor environmental parameters are influenced by the state of the windows, it is problematic to infer the latter based on indoor parameters e.g. indoor temperature. 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.

Another problem with this approach is that the driving forces for opening and closing a window might be different. The window might be opened due to bad air quality or high humidity and closed because of low indoor temperature. We have overcome these problems by inferring the probability of opening and closing windows (change from one state to another) rather than modelling the state of the window itself. When using this approach, the predictive variables are not influenced by the state of the window and the most dominating drivers were inferred separately for each action (opening and closing the window).

Most recent studies have been limited to the investigation of thermal stimuli [17–22,25] although other studies have found that many other stimuli play an important role in determining the window opening behaviour [26–29]. Table 1 provides information on sample size, measuring duration and building type of the referenced studies on window opening and ventilation.

The objective of this study was to quantify the influence of environmental factors on occupants' window opening behaviour in Danish residential buildings.

2. Method

Andersen et al. [26] quantified behaviour of occupants in Danish dwellings by means of a questionnaire survey. A definition of

[1] With all windows and doors closed.