Building and Environment 82 (2014) 726–739

Contents lists available at ScienceDirect

Building and Environment

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

A data-mining approach to discover patterns of window opening and closing behavior in offices

Simona D'Oca [a], Tianzhen Hong [b,*]

[a] Polytechnic of Turin, Energy Department, TEBE Group, Technology Energy Building Environment, Italy
[b] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA

A R T I C L E I N F O

Article history:
Received 1 July 2014
Received in revised form
12 September 2014
Accepted 23 October 2014
Available online 30 October 2014

Keywords:
Data mining
Behavioral pattern
Occupant behavior
Office buildings
Window closing
Window opening

A B S T R A C T

Understanding the relationship between occupant behaviors and building energy consumption is one of the most effective ways to bridge the gap between predicted and actual energy consumption in buildings. However effective methodologies to remove the impact of other variables on building energy consumption and isolate the leverage of the human factor precisely are still poorly investigated. Moreover, the effectiveness of statistical and data mining approaches in finding meaningful correlations in data is largely undiscussed in literature. This study develops a framework combining statistical analysis with two data-mining techniques, cluster analysis and association rules mining, to identify valid window operational patterns in measured data. Analyses are performed on a data set with measured indoor and outdoor physical parameters and human interaction with operable windows in 16 offices. Logistic regression was first used to identify factors influencing window opening and closing behavior. Clustering procedures were employed to obtain distinct behavioral patterns, including motivational, opening duration, interactivity and window position patterns. Finally the clustered patterns constituted a base for association rules segmenting the window opening behaviors into two archetypal office user profiles for which different natural ventilation strategies as well as robust building design recommendations that may be appropriate. Moreover, discerned working user profiles represent more accurate input to building energy modeling programs, to investigate the impacts of typical window opening behavior scenarios on energy use, thermal comfort and productivity in office buildings.

1. Introduction

To secure sustainable energy development in the building sector, occupant behavior needs to be modified towards a more efficient and conscious energy usage. The development of energy-conserving technologies is a necessary but incomplete step toward reduced energy consumption in buildings. Achieving energy conservation becomes a double challenge, partly technical and partly human, since energy consumption may vary largely due to how occupants interact with system controls and the building envelope. Currently, building simulation tools can only imitate some typical occupant activities in a rigid and pre-defined way (occupancy, use of windows, thermostat, shadings, and lighting). Nevertheless, occupant behavior and comfort is stochastic, complex, and multi-disciplinary therefore more realistic behavioral patterns need to be developed.

As a matter of fact, a deeper understanding of the relationship between occupant behavior and building energy consumption can be seen as one of the most effective ways to bridge the gap between predicted and actual energy consumption in buildings Several studies underlined that huge variability exists in terms of default settings and day-to-day use of control systems and appliances in buildings, where 'behavior' is central to consumption levels [1–3]. In this context, the 'dark side of occupant behavior on building energy use' was demonstrated by Masoso et al., in 2000 [4]. The work showed that more energy was used during non-working hours (56%) than during working hours (44%) in one office building. This arises largely from occupants' behavior of leaving lights and equipment on at the end of the day, and partly due to poor zoning and controls. In 2004 Bordass et al. [5] referred to this occurrence as the 'credibility gap', alluding to the loss of credibility when design expectations of energy efficiency and actual building consumption outcomes differ substantially. They suggest that credibility gaps arise not so much because occupants preform 'wrong', but because the assumptions often used are not well enough informed by what really happens in practice. In the last

* Corresponding author. Tel.: +1 510 486 7082; fax: +1 510 486 4089.
E-mail addresses: simona.doca@polito.it (S. D'Oca), thong@lbl.gov (T. Hong).

http://dx.doi.org/10.1016/j.buildenv.2014.10.021
0360-1323/

decades, a number of studies focused on overcoming this barrier, testing valid, applicable and robust methodologies and analysis techniques to predict building occupant behavior seriously [6–16]. Describing, predicting or influencing energy related individual behavior are challenging tasks that must start with the non-trivial understanding of the stochastic nature of human beings. In this view, the scientific community is addressing rising interest around the issue of energy efficient buildings and specifically toward the need of a more robust description of the motivations driving humans to interact with building envelope and control systems (fans, windows, thermostats, lights, etc.) in order to bring about desired comfort conditions [21].

The most important issue in between perceived indoor environmental quality and outdoors, in the built environment, is the building envelope [17]. As a consequence, window operation is one of the most relevant tools that allow occupants to bring about desired indoor thermal and air quality conditions, by moving air through the building. Further, since the building envelope is getting always more thermally efficient, ventilation and air infiltrations due to window opening are increasing their influence with respect to energy use, becoming the most dominant source of thermal loss of the heat balance mechanism. Fitting the Humphrey's adaptive principle that if a change occurs such as to produce discomfort, people react in a way which tend to restore their comfort [18] to the findings in literature [19,20], it is demonstrated that occupants in naturally ventilated buildings accepted and actually preferred a significant wider range of temperatures compared to users of mechanically ventilated buildings. As a matter of fact, naturally ventilated buildings allow occupants' a greater degree of control over indoor hydro-thermal conditions than air conditioned buildings that strongly influence their satisfaction with working spaces [19]. In 2004 de Dear and Brager [20] highlighted that the variation of indoor environmental conditions caused from a human operable control source such as windows lead occupants to a relaxation in expectations and higher tolerance of temperature excursions.

1.1. Statistical analysis of factors influencing occupant behavior in buildings

Statistical analysis techniques are extensively applied to discover associations and relationships among the various factors influencing building energy performance and occupant behavior in buildings. Different suitable user behavioral models were defined by means of statistical analysis (Markov Chain, Generalized Linear Models, etc …) [7–16,23–32]. An extensive review of these studies has been conducted in the context of Annex 53 – Total Energy Use in Buildings, under the International Energy Agency Energy in Buildings and Communities Program [21], in order to understand the correlation between window opening and the parameters, also called drivers, influencing users' interaction in buildings with natural ventilation. The parameters are divided into five categories of influencing factors:

- Physical (indoor and outdoor environment);
- Psychological (preferences, attitudes);
- Physiological (age, sex);
- Contextual (type of environment where the occupants are located);
- Social (income, lifestyle).

Specifically for window opening in office buildings, a literature review was carried out in 2012 by Fabi et al. [22] of more than 70 scientific papers, indicating that window operation was not only influenced by perceived thermal condition, but it was also seen as a response of sensed indoor air quality, external (outdoor temperature, solar radiation, wind speed, rain) and internal (indoor temperature) environmental conditions as well as contextual factors (window type, time of the day, season of the year) and personal and cultural preferences. In these studies, statistical analysis techniques were applied to identify the influential variables on user behavior in buildings. The strength of this methodology was the simplicity and widespread familiarity.

- Indoor and outdoor temperatures were found as paramount factors influencing window opening and closing by several studies [23–27]. For instance, Fabi et al. suggested that rising indoor temperatures might drive the opening of windows, but how long the window stayed open might depend more on outdoor temperature. More specifically, Andersen et al. [28] found that the CO_2 concentration was the most important driver for opening the windows, while the outdoor temperature was the most dominant driver for closing the windows.
- Solar radiation was found by Herkel et al. [29] to have little correlation with window openings. Solar radiation was a relatively small factor when compared with the correlation of indoor and outdoor temperatures
- Wind speed was reported by Roetzel et al. [30] as a driver for closing the windows when the sensation of draft was producing a predominant discomfort.
- Time of arrival and departure as well as the time of the day had been found having a strong correlation between window adjustments by several researches. [28,29,31]
- The season of the year was found by Herkel et al. [29] to have a strong correlation with window opening [6]. Usually, the interactivity with openings was higher in summer and during the midseason (autumn and spring) and lower in winter.
- The current state of the window was also underlined by several studies [30,32] as a key aspect to take into account when concerning user's willingness to open and close windows.

1.2. A data mining framework for behavioral pattern discovery

Currently, there is no comprehensive consensus about the way people interact with building controls or the motivating factors that influence their decisions. However, there is a substantial body of research that offers guidance on patterns of behaviors. Patterns are expressions describing typical behaviors or models applicable to a subset of the data to anticipate and replicate common actions. Moreover, patterns correlate repetitive behaviors and actions to user profiles. Guerra Santin [33] statistically determined behavioral patterns of HVAC system interactions and associated energy spent on heating. From this, household and building characteristics that could contribute to the development of energy-user profiles, were identified [33]. A study conducted by Van Den Wymelenberg [34] reviewed data from more than 50 buildings and identified patterns of occupant interaction with window blind controls. Moreover, Yun and Steemers [35,36] provided evidence of a statistically significant relationship between window-opening behavior patterns and clusters of indoor stimuli. In 1983 Van Raaij and Verhallen [37] carried out a study in 145 Dutch dwellings and defined five patterns of energy behavior (conservers, spenders, cool, warm and average) in relation to the use of heating systems and ventilation habits. Findings of this research showed that the energy uses of these five pattern groups differed considerably, up to 31% [37].

Data mining techniques to discover patterns of data are largely applied to research fields such as marketing, medicine, biology, engineering, medicine, and social sciences [38]. Even so, the application of data mining framework to building energy consumption and operational data is still under investigation and nevertheless could be potentially highly effective.