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Analysis of occupants' behavior related to the use of windows in German households

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A B S T R A C T

Real energy performances of buildings depend not only on deterministic aspects, such as building physics and HVAC systems, but also on stochastic aspects such as weather and occupants' behavior. Typically, occupant behavior is not adequately considered when calculating the expected performance. As a result, field test studies all over Europe have shown discrepancies between real and expected energy performance of buildings. In order to bridge this gap, stochastic occupants' behavior models could be embedded into building energy performance simulation software. In order to make such models, there is a need for a better understanding of occupants' behavior and in particular the reasons of their adjustments of building controls such as window opening, heating set points, etc. The purpose of this paper was to analyze window opening behavior in residential buildings, investigate which drivers lead occupants to interact with windows and how these actions can be modeled. A method to analyze the probability of a state change of the windows, based on logistic regression, was applied to monitored data (measured each minute) from two refurbished demonstration buildings. The weather and the five rooms of the 60 apartments located in the buildings were monitored in terms of air quality and thermal environment (presence of occupants was not monitored) during four years.

The most common driver to open a window was the time of the day, followed by the carbon dioxide concentration. The most common driver to close a window was the daily average outdoor temperature, followed by the time of the day.

1. Introduction

During the last decades, a big effort has been made to build new energy efficient buildings and make energy retrofits to the existing building stock. However, new or retrofitted buildings do not always perform as predicted: field test studies all over Europe [1–14] show higher final energy consumption than predicted. The reasons for this discrepancy can be grouped into engineering system issues (e.g. components not performing as expected or wrongly installed, wrong installation of the insulation, bad insulation of thermal bridges, tightness, etc.), weather data as well as occupants' behavior issues (differences in modeled and real behavior regarding the interaction with windows and engineering systems).

The real energy performances of buildings depend in general on deterministic aspects, like building physics and the HVAC systems, as well as stochastic (probabilistic) aspects, such as weather and occupants' behavior. While a lot of effort has been spent on deterministic modeling of the buildings as a whole, as well as on the generation of standard weather files (known as test reference years) for many regions in the world, only in the last decade the importance of the dynamic interaction between occupants and buildings has been recognized and researched. A reason for this can be connected to the fact that the relative impact of the occupants' behavior on the building energy performance seems to increase when building standards require lower energy use [15]. Including the stochastic aspects of occupants' behavior into building energy performance simulation software, could hence lead to better predictions of the buildings' final energy consumption, especially for new low energy buildings or energy retrofitted buildings.

In order to improve the energy performance forecasts, there is a

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need to focus on occupants' behavior, defined as *the set of actions, executed by occupants, modifying the physical conditions of the built environment*. Occupants also influence the indoor environment passively through their presence (e.g. through the production of heat, water vapor, carbon dioxide, and volatile organic compounds); thus, a holistic model of the occupants' behavior should include:

1. Periods of presence and absence of occupants
2. Occupants' interaction with, among others, thermostats/valves, windows and sun-blinds (as schematized in Fig. 1)

A consistent stochastic model of occupants' behavior in residential buildings based on a large database of observed data has not been developed yet, mostly due to lack of data. In fact, in studies where the presence of occupants was monitored (e.g. through the use of time-use survey) and modeled [17,18], no information about occupants' behavior was recorded. Vice versa, in studies focusing on the evaluation and modeling of occupants' behavior, based on monitoring data, reliable information about real occupancy profiles is missing. In this context, in 2014, the International Energy Agency started the "IEA-EBC Annex 66 – Definition and Simulation of Occupant Behavior in Buildings" [19]: this aims to bridge the gap between expected and observed energy performance of buildings, by modeling and integrating the occupants' behavior in buildings' simulation software.

The architecture of a holistic occupants' behavior model could consist of a core for the generation of presence patterns (e.g. based on Markov chain as in Refs. [17,20,21]), and, on top of this, of a variable number of add ons to reproduce human activities, (e.g. related to settings of the engineering system, change of state of windows, use of appliances, etc.). Many models have already been developed for reproducing occupants' activities: A plenary literature review on occupants' behavior models, up to 2013, is offered in Refs. [22]; a more recent review of state of the art models of occupants' behavior is offered in Yan et al. [23].

In the European Union (EU28), space heating [24], which is influenced by the ventilation rate, accounts for more than two thirds of residential buildings' energy consumption. As such, the energy consumption in residential buildings is under heavy influence of the occupants' window opening behavior and any attempt to realistically model indoor environment and energy consumption in residential buildings should include realistic models of the window operation. In order to construct such models, basic knowledge of the reasons for opening and closing windows, is needed.

In 2012 Fabi et al. [25] analyzed more than 70 papers to investigate why occupants opened and closed windows. In addition to the literature review, the authors define the concept of drivers: "Factors influencing occupant behavior, both external and individual, that could be named with the general term "Drivers", are the reasons leading to a reaction in the building occupant and suggesting him or her to act (they namely "drive" the occupant to an action)". From the analyzed literature review, Fabi et al. conclude that:

1. Window opening behavior has a strong impact on both the indoor environmental quality and the energy performances of buildings,
2. There is not a commonly agreed upon approach among scientists about the driving forces of occupants' window opening and closing behavior,
3. Most of the existing studies analyze the position of windows instead of the transition from state "Open" to state "Closed" and vice versa, and this might be problematic since the status of the windows influences the indoor environment,
4. More efforts should be made to better understand and model occupants' behavior.

One of the first attempts to mathematically model the occupants' behavior related to natural ventilation was made by Fritsch et al. [26]. They use a Markov Chain process and their model is based on the measured window opening angles recorded each half hour for four windows in four office rooms. Each window is modeled with transition probability matrices with six states respectively (the opening angles are grouped into five opening classes plus a class for the closing status) and adjusted for four different outdoor temperature ranges. The model considers the windows to be closed at night and on weekends, and the generation of the window state profiles starts at the beginning of each working day (and ends therefore at the end of the day). Fritsch et al. [26] argue that the state of windows during night has, except for two cases, always been closed over the entire observed heating period. However, this consideration is not valid for residential buildings, as shown in many field test studies [25], [27].

With their work "Interactions with window openings by office occupants" [28], Haldi et al. set a milestone in the modeling of occupants' behavior related to window operation in office buildings. For seven years, the authors monitored temperature, window position (open/closed, no distinction between opening angles), and presence of occupants (with passive infra-red sensors) of 14 offices in a building, and the outdoor environmental conditions through a weather station located 8 km away from the building. They modeled the behavior following several approaches based on logistic probability distributions, Markov chains, continuous-time random processes, and hybrid combinations of those models. They concluded that "[s]upported by rigorous cross-validation, [they] have demonstrated the superiority of a discrete-time Markov process approach and its strong added value compared with existing models". Further, they wrote: "[f]actors related to indoor air quality (e.g. CO_2 or pollutant concentration) should also be treated".

A further contribution to the occupants' modeling for natural ventilation is done by Andersen et al. within several works [27,29,30]. In the last paper, the authors introduce a model for the transition of the state of windows (open to close and vice-versa close to open) based on observations collected from 15 dwellings located in Denmark. Contrarily to previous window operation (or state) models introduced by 2013 and only based on thermal conditions, the authors also monitored indoor carbon dioxide concentration as an indicator for indoor air quality. The models – one for the opening and one for the closing of the windows – are based on the results of logistic regression analysis. The conclusion of the manuscript is that indoor CO_2 concentration and outdoor temperature are the two single most important variables (drivers) determining the window opening and closing probability respectively.

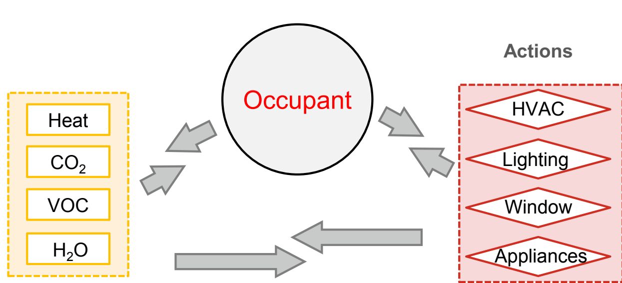

Fig. 1. General schema of occupants' impact on buildings (previously introduced in Ref. [16]).