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WinProGen: A Markov-Chain-based stochastic window status profile generator for the simulation of realistic energy performance in buildings

Davide Calì*, Mark Thomas Wesseling, Dirk Müller

Institute for Energy Efficient Buildings and Indoor Climate, E.ON Energy Research Center, RWTH Aachen University, Mathieustr. 10, 52074 Aachen, Germany

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ABSTRACT

New and retrofitted buildings often do not perform as expected. In fact, the real energy performance of a building depends on deterministic characteristics (e.g. building's structure and HVAC), and on stochastic elements (e.g. occupants' behavior). Probabilistic models of occupant behavior in the simulation of buildings' energy performance can help to bridge the gap between prediction and real energy consumption. With this aim, a stochastic window status profile generator (WinProGen) is introduced, validated (using the Markov chain Monte Carlo technique) through observations from field tests, and tested through dynamic building simulations. In WinProGen, we implemented three models for the generation of window state profiles, based on field test data, with a time resolution of 1 min. The profiles generated from model 1 depend on the time of the day and the daily average ambient temperature. The profiles generated from model 2 depend on the time of the day, on the daily average ambient temperature and on the day of the week (working day or weekend day). The profiles generated from model 3 depend on the time of the day, on the daily average ambient temperature of the actual day and on the daily average ambient temperature of the past day. The generated profiles can be used as an input to simulate dynamic building energy performance. Moreover, users can include in WinProGen their own field test data to generate own state profiles. The dynamic simulation of two demonstrator buildings with the generated window state profiles offers reliable predictions of buildings' energy performance.

1. Introduction

Buildings account for up to 40% of primary energy consumption in Europe. Much effort has been made in recent decades to build new energy-efficient buildings and to retrofit existing buildings. However, new or retrofitted buildings do not always perform as predicted: Field test studies all over Europe [1–15] show higher final energy consumption than expected. The reasons for this discrepancy can be grouped into engineering system issues (e.g. components with worse energy performance than expected or mistakes in thermal insulation installation) and issues with occupant behavior (e.g. elevated room temperatures in winter or inadequate behavior regarding the interaction with windows). In general, the energy performance of buildings depends on deterministic features such as building structure and HVAC systems, as well as stochastic (probabilistic) aspects such as weather and occupant behavior. While much effort has been spent on modeling the buildings as a whole, as well as on the generation of standard weather files for many regions in the world, only in recent years the importance of dynamic interaction between occupants and buildings has been recognized and investigated [16,17]. This is probably due to the fact that, as building standards improve, the impact of occupant behavior on building energy performance has grown [18]. Including the probabilistic aspects of occupant behavior in building energy performance simulation software (BEPS), could hence lead to better predictions of the buildings' final energy consumption [16,19,20]. In this work, we introduce a WinProGen, a Markov-Chain-Based Stochastic Window Status Profile Generator written in Python: the profiles generated through WinProGen describe the state of windows (distinguishing only opened/closed position) can be used as an input in BEPS, in order to take into account natural ventilation aspects when simulating the energy performance of buildings.

We define occupant behavior as the set of occupant-executed actions that modify the physical conditions of the built environment. Since occupants influence the indoor environment not only actively, but also passively (e.g. through the production of heat, vapor, CO_2, volatile organic compounds [VOCs]), a holistic and realistic model of occupant behavior should include the following:

1. periods of occupant presence and absence
2. occupants' interaction with, among other, heating set points,

* Corresponding author.
E-mail address: dcal@dtu.dk (D. Calì).

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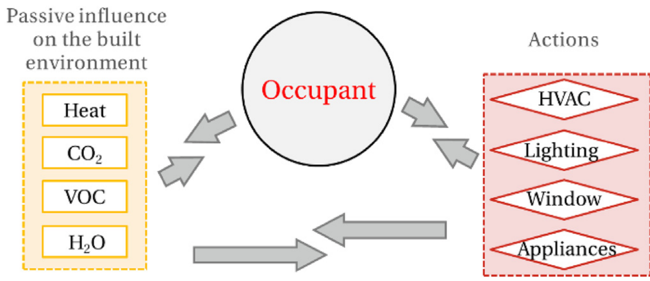

Fig. 1. General schema of occupants' impact on buildings (previously introduced in Ref. [25]).

windows and sun-blinds (as visualized in Fig. 1)

Nevertheless, at time of writing, to our knowledge, not enough data is available to create a consistent model of occupant behavior for residential buildings, based on a large database of observations. Hence, existing occupant behavior models can only focus on partial aspects. As pointed out in Ref. [21], studies where the presence of occupants was monitored, e.g. through the use of time-use survey and modeled [22–24], did not collect information about occupants' behavior. On the other hand, studies focusing on data collection for the evaluation and modelling of the occupant behavior, did not collect the presence of occupancy. To bridge this knowledge gap, the International Energy Agency started in 2014 the "IEA-EBC Annex 66 - Definition and Simulation of Occupant Behavior in Buildings" [17]. This annex had the aim to model and integrate the occupants' behavior in buildings' simulation software and hence bridge the gap between expected and observed energy performance of buildings.

As illustrated in Ref. [21], the architecture of a holistic occupant behavior model could consist of a core for the generation of presence patterns (e.g. based on Markov chain as in Refs. [22–24,26]), and a variable number of add on used to reproduce human activities (settings of the engineering system, change of state of windows, use of appliances, etc). It should be noticed that many models were developed in recent years for such occupant activities: A worthy literature review on occupant behavior models, up to 2013, is offered in Ref. [16]; Yan et al. [27] offers more recent review of state of the arts models of occupant behavior. Stazi et al. [28] offers an valuable literature review on both the driving factors and the contextual events that are influencing occupants' behavior in buildings.

One of the first attempts to mathematically model occupant behavior was made by Fritsch et al. [29] using a Markov chain process. Their model is based on measured window-opening angles recorded each half an hour for each window of four office rooms. Each window is modeled with six states transition probability matrices (TPMs), since the opening angles have been grouped into six opening classes and have been calculated for four different outdoor temperature ranges. The model simulates the windows always in a closed state at night and on the weekend, while the generation of the window state profiles starts at the beginning of each work day, ending at the end of the day. The authors argued for this configuration since the state of windows at night was, except for two cases, always closed over the entire observed heating period. However, we cannot apply this assumption to residential buildings, as shown in many field test studies [21,30–32]. Haldi [33] has presented several occupant behavior models based on observed data from offices, using logistic regressions, the Markov chain and the theory of survival analysis. The presented models require a presence profile as an input (the authors obtain realistic presence profiles with infrared sensors), while the probability of opening and closing windows is inferred differentially upon the arrival of occupants, their departure and during the hours in which they are present. In sum, as far as could be found in the literature, no occupant behavior models based on time inhomogeneous Markov chains (see section 2.1) account for parameters related to indoor air quality (e.g. CO_2 and VOCs). It should also be noted that the use of the Markov chain approach was widely adopted to model the presence patterns of occupants [22–24,34].

A deeper analysis of the literature review shows that the behavior of occupants, related to the opening and closing of windows, can be analysed and successfully modelled with linear regression analysis, as demonstrated in many projects. Andersen et al. [35] and Fabi et al. [20] developed logistic regression models for Danish dwellings, Yao et al. for Chinese dwellings [36], Calì et al. [21,32] for German dwellings, Haldi et al. [37–39] for office buildings in UK. Moreover, mixed regression models have been also widely used, for instance by Haldi et al. [40,41] for German and Danish dwellings, and for offices in UK.

Logistic regression models have the clear advantage to properly analyze the probability of a certain event (for instance the action "window opening/closing") depending on several explanation variables. Within a logistic regression models, all the measured variables could be included into the final window model. However, only explanatory variables with a significant impact on the probability function should be included (see Schweiker and Shukuya [42] for the selection process). Furthermore, mixed effects regression models allow modelling different windows in a unique model, since the diversity of occupants (and of the room typology) is incorporated in the random effect of each model. Regression models can be rigorously validated (e.g. through the K-Fold validation) and are useful also to identify which "drivers" (Fabi et al. [43]) play a bigger role on the behavior of occupants. It is important to notice how air quality and indoor air humidity are, de facto, among the major drivers for window opening and closing action [21,32,44,45] and are therefore often a fundamental input of those models. For this reason, however, regression models can hardly be included in BEPS, especially in residential case, where two main issues are encountered:

1. The production of CO_2 (from occupants) and water vapor (from occupants, and cooking and showers processes) is hard to determine, as this depends on the exact position of the occupant within the building and their exact activity;
2. The position of doors strongly influences the air flow within the building, hence influences the CO_2 concentration and relative humidity of the air in each room.

Andersen et al. [45] have the big merit to implement logistic regression models of window operations in a BEPS. However, in order to simulate the CO2 and indoor humidity production of the occupants, they have to make simplified assumption about the occupants. They consider the occupants to be "distributed evenly over the floor area with 0.05 occupants/m2". They also assume that "in unoccupied periods, all the windows were closed". Finally, Andersen et al. confirm that there is a poor correlation between the measured values (collected from two apartments) and the average simulated relative humidity values and CO2 concentrations: they explain this "could be a result of a mismatch between assumed and real production of CO_2 and water vapor" (what we indicate as first issue).

In this context, we propose a profile generator that takes into direct account only those variables, which are not affected by the presence of occupants. The presence of occupants, and therefore indoor air quality parameters and relative humidity are however indirectly and hence intrinsically taken into account, through the time dependency of the model, which is illustrated in the further sections. Furthermore, the use of a database with data recorded each minute, allow us to include also very short opening and closing processes of the windows. Hence, within this work, we illustrate the window state profile generator tool WinProGen, as introduced in the PhD Thesis "Occupants' Behavior and its Impact upon the Energy Performance of Buildings" [32]. WinProGen is written in Python and offers an intuitive graphical user interface (Fig. A1) and a large database based on monitoring data. The generation of window state (opening and closing) profiles is modeled with the