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Verification of stochastic behavioural models of occupants' interactions with windows in residential buildings

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ABSTRACT

Realistic characterisation of occupants' window opening behaviour is crucial for reliable prediction of building performance by means of building energy performance simulations. Window opening behaviour has been investigated by several researchers, leading to a variety of logistic regression models expressing the probability with which actions will be performed. But only very few attempts have been made to investigate the reliability of the models. In this paper, data from a measurement campaign in 15 apartments was used to estimate the predictive accuracy of four sets of models of window opening. Initially three models from literature were investigated by comparison of predicted probabilities and the actual measured state of the windows.

Data from one of the papers was reanalysed to create new models, based on measurements from single dwellings. These models were used to predict window transition probabilities using data from the field survey. The output was then compared to the measured transitions.

Results showed that the models which most accurately predicted both the state of the window (open or closed) and the number of actions on windows had certain characteristics in common: A positive correlation between the probability of opening and CO_2 concentration and illumination values and a negative correlation with sun hours and illumination level for closing windows.

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1. Introduction

Dynamic building energy performance simulation (BEPS) programs are increasingly used to develop efficient solutions for predicting and optimising energy and environmental performance of buildings. However, some key processes are often not taken into account in the use of these tools, leading to potentially large errors. Most noteworthy is the influence of building occupants, whose actions, such as the use of windows and shading devices, have an important impact on the indoor environment and the overall energy performance of a building [1].

Window opening behaviour has been investigated by several researchers [2–9]. This has led to a variety of stochastic models based essentially on thermal environment and occupancy patterns, thus expressing the probability with which actions will be performed on windows, as a function of indoor temperature, outdoor temperature or both. Studies with the purpose of implementing realistic models of human behaviour in simulation tools (BEPS) have generally been conducted in offices [4,10,11]. However, a number of dedicated studies have been performed using questionnaire surveys, monitoring campaigns in conjunction with different statistical approaches [9,12–21]. Some of these papers have resulted in stochastic models of behaviour. This leads to the natural question – how accurate are the models? Which criteria should be used to choose amongst models to be implemented in a building energy performance simulation tool (BEPS)?

Generally, with only few exceptions, the published models of occupant's behaviour were not validated, meaning that the predictive power has not yet been tested against measurements. This means that currently, models are applied in BEPS tools without knowing the accuracy of the predicted results [22].

So far, only few papers about validation of behavioural models have been published [4,23,24], regarding both office buildings and residential buildings.

In 2009, Haldi and Robinson [4] proposed a cross-validation procedure to perform the evaluation of the predictive power of window opening behaviour models developed for office buildings.

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Cross-validation [25–28] is one of the most commonly used methods of evaluating predictive performances of a model, which is given a priori or developed by a modelling procedure. Basically, based on data splitting, part of the data is used for fitting each competing model and the rest of the data is used to measure the predictive performances of the models by the validation errors, and the model with the best overall performance is selected.

Haldi and Robinson [4] assessed the predictive power of the models by checking four main aspects called "Discrimination Criteria": based on these criteria they have retained the best performing model. Results of this validation procedure were compared with a Bernoulli random variable with constant probability (a random guess based on observed overall opening proportion). This simulation procedure consists of a statistical comparison of the calculated window opening probability with a random number in each time step. In particular, Haldi and Robinson have performed 20 repeated simulations of window position using 5 min time steps for the whole period with available measurements.

Applying these validation criteria, Schweiker et al. [23] tested the accuracy of window opening behaviour models using different datasets in a double-blind way.

Langevin et al. [24] validated an agent-based model of occupant behaviour using data from a field study in an air-conditioned office building applying the validation approach of Haldi and Robinson [4].

Although these papers represent important milestones on the way of assessing the predictive accuracy of stochastic models of occupants' interactions with the built environment (in particular with windows), a considerable space for further research remains. Schweiker et al. [23] stated that the procedure proposed by Haldi and Robinson [4] and used by Ref. [23] validated the predicted state of the window, without taking the transition probabilities into account (window opening action and window closing action). Since the procedure only validated the state of the window, the consequences for the indoor environment were not taken into account by the models. The problem is that a transition event (e.g. opening a window) will result in changed indoor environment (e.g. reduction of temperature or CO_2 concentration) in the measured data. Consequently, a comparison of states rather than transition events could lead to false results. If the model fails to correctly predict a transition event, there could be a mismatch between the predictions and measurements. For example, in a cold climate, the indoor temperature will drop when the window is opened. Assuming a negative correlation between indoor temperature and opening probability, the drop in measured temperature (input to the model) will result in a reduction in the predicted window opening probability. If the model fails to predict the transition at the correct moment, the predicted window position will most likely remain closed, due to the low predicted transition probability resulting from the drop in the measured temperature (input of the model).

In this paper, the authors propose and demonstrate a verification procedure in which transition probabilities are compared to the measured data (rather than the state), to avoid the problem described above.

Data from a measuring campaign was used to test the accuracy of window opening models from three papers [4,20,23]. Data from Andersen et al. [20] was re-analysed to create new models, based on measurements from single dwellings. Initially, the procedure proposed by Ref. [4] was used. The authors then propose another verification procedure. This procedure is demonstrated on transition probabilities and it will be described in Section 2.4.2.

2. Method

The present study compared the logistic regression models of window opening behaviour in their ability to predict occupants' window opening and closing actions. The verification process applied was primarily a way of measuring the predictive performance of the statistical models.

Four sets of models (described in Section 2.1) derived from three datasets were tested against a fourth dataset (described in Section 2.3).

2.1. Validated window opening models

The predictive performance of the following window opening and closing behaviour models were evaluated using the procedure proposed by Haldi and Robinson [4] and [23]. Four sets of models (three from literature [4,20,23] and one developed in this paper) were evaluated, using the same dataset for testing their accuracy. The four sets of models originally came from different datasets as described in Table 1. Their main difference is related to the outcome of the used logistic regression. In the case of model sets number 1 and 2, logistic regression is used to predict the probability that a certain action will occur (window opening action or window closing action): this is a Markov model. In model sets number 3 and 4, the main outcome is related to predict the state of the window (window is in the state open or window is in the state closed): this is a Bernoulli model.

Model sets number 1 and number 2 were both derived from data obtained in a monitoring campaign described in Ref. [20]. "Models belonging to model set number 2 were specifically developed within this paper.". In the monitoring campaign of [20], measurements of window opening and closing behaviour along with indoor and outdoor environmental variables were conducted in 15 dwellings located in the area of Copenhagen, Denmark. Measurements took place for eight months (January–August) in 2008. During this period, environmental variables were measured in the main bedroom and living room at 10-min intervals in all 15 dwellings. The dwellings were categorized into different groups depending on the ownership (owner-occupied or rented) and on the type of ventilation (natural or mechanical) in the following way (model set number 1):

a) Group 1 (M1, NatOw): Owner-occupied, natural ventilation.
b) Group 2 (M2, MechOw): Owner-occupied, mechanical ventilation.
c) Group 3 (M3, NatRent): Rented-occupied, natural ventilation.
d) Group 4 (M4, MechRent): Rented-occupied, mechanical ventilation.

Andersen et al. [20] used this grouping to develop four models from mixed data from several dwellings. The dwellings were grouped due to the high complexity and large variety between the individual dwellings, but by merging the dwellings in groups, inner dynamics of a single dwelling may have been lost and the specific behaviour could have been flattened in the groups. In this paper, the same dataset was used to obtain another set of models (model set number 2). This set consisted of 15 models: each of them is based on data from a single dwelling. These models are reported in the Appendix 1 and could be randomly simulated in order to obtain a better representation of variability in the occupants' behaviour.

The predictive performance of the Bernoulli models proposed for residential buildings by Schweiker et al. [23], (model set number 3, Neuchàtel, and model set number 4, Tokyo), were also evaluated. Both models applies only thermal environment (indoor temperature, outdoor temperature or both) to predict the state of the windows, and not the actions (transition) on them. The database for model set number 3 was collected in three apartments in two buildings with a monitoring campaign of six months (long-

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