Evaluation of the impact of window use on the heating energy use and IEQ in dwellings based on simulations

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ABSTRACT

Window opening behaviour can have an important impact on residential energy use, especially in energy efficient dwellings. A few studies indicated that the window use may be a habitual behaviour, meaning that the behaviour is performed without conscious thought as a consequence of frequently repeating this action. Verbruggen et al. (2021a) developed an event-based residential occupant behaviour model (EROB) based on habits as present in Belgian dwellings, including a window opening model. This habit-based approach has some advantages such as the prediction of inter-occupant diversity, easy implementation in Building Energy Simulation (BES) and the prediction of realistic actions that fit in the occupants' day-to-day life.

However, for application purposes it can be questioned if the inclusion of these habits makes a significant impact on the energy use and indoor climate. Therefore, this paper explores the impact of the habit-based occupant behaviour model on the energy use and indoor climate predictions in dwellings.

First, the modelling approach is introduced. One of the nearly zero energy houses (NZEB) in a case study neighbourhood has been modelled in the simulation environment Dymola-Ideas. In addition to the actual situation with NZEB performance, the house has also been modelled with a design reflecting a medium and poor energy performance. The library components and modelling assumptions are explained.

The simulations are carried out for 30 different household profiles, generated using the EROB-model. The evaluation of the impact of user behaviour is based on three criteria: the net energy use for space heating, the CO2-concentration as a measure for IAQ, and overheating as a measure for thermal discomfort. The simulations are carried out for both the overall model and for a base-model including only one type of occupant behaviour, to evaluate which has the largest influence. Additionally, the importance of predicting realistic window use actions, one of the intrinsic characteristics of the habit-based approach, is assessed.

The simulation results show a significant impact on the energy use and indoor climate predictions due to the inclusion of occupant behaviour, especially by the window use and especially in energy efficient buildings.

KEYWORDS

Occupant behavour, Window opening, Building energy simulation, IEQ, Heating energy use

1 INTRODUCTION

In residential buildings the energy use is defined by numerous aspects such as the building envelope, installed systems, climate, but as well the occupant behaviour. The building user can perform a wide set of actions that can have an effect on the energy use, such as opening or closing windows, using appliances, adapting the heating set-points. To predict the residential energy use more accurately, occupant behaviour models have been developed. The current approach towards occupant behaviour modelling is predominantly based on the assumption that occupant behaviour is deliberative, with many models relating the occupant behaviour to environmental and time-dependent variables. However, behavioural studies indicate that not all actions are deliberative, and that especially in a stable context such as a residential building, the actions are often performed without conscious thought, out of habit. By including habits in occupant behaviour models the behavioural predictions and corresponding energy use and indoor environmental quality simulations can be improved.

Verbruggen et al. (2021a) developed a window use model based on data collected in an online survey in Belgium, an initial classification of households according to the habit-coherence across rooms in winter and a seasonality coherence. These predicted habits are coupled to an occupancy and activity model to predict window use profiles. Next, the window use habit model is combined with other types of occupant behaviour in an event-based residential occupant behaviour (EROB) model. This model based on time use data allows to predict the occupancy and activity profiles of households and linked to that the window use, heating set-points, domestic hot water use, electricity use, internal heat gains and CO2-production. This habit based model can be easily implemented in building energy simulations (BES) and allows for fast computation as it is not using (simulated) indoor environmental variables as inputs.

However, for application purposes it can be questioned if the inclusion of these habits makes a significant impact on the energy use and indoor climate. Therefore, this paper explores the impact of the habit-based occupant behaviour model on the energy use and indoor climate predictions in dwellings.

2 OCCUPANT BEHAVIOUR (OB) MODEL

Results of an online survey conducted with near 500 Belgian households revealed that almost all occupants habitually interact with at least one window. Some household and building characteristics were related to the presence of certain habits. However, this impact was rather small in comparison to the impact of the habits of other rooms. These insights were utilized for the creation of a window use habit model. The model starts by assigning a winter household-habit to each household. The different household winter window habits were generalised to five different categories:

- All windows closed (24.6%)
- All windows shortly opened (20.5%)
- Bedroom window opened more than the windows in other rooms (25.6%)
- Clear distinction between habits in the day-zone and night-zone (20.3%)
- Clear distinction between habits in the most occupied zones (living room, bedrooms) and in the less occupied zones (kitchen, bathroom) (9.0%)

The assignment of these habits is based on multinomial logistic regression with the following buildings and household characteristics as inputs: the type of ventilation system in the house, the year of built, the type of family, the presence of children and the employment types of the household members.

In the next step, the seasonality coherence is determined. The room-habits in summer are determined based on this seasonality coherence and the room habits in winter. The household-habits are for some households extended throughout the year, while others reveal other window opening behaviours in summer:

- Windows use is the same as in winter (18.0%)
- All windows opened more (46.6%)
- Windows in the dayzone opened more (25.3%)
- Windows in the nightzone opened more (10.0%)

Finally, these habits are coupled to stochastic occupancy and activity profiles, to predict the window use per time step. In this case the occupancy and activity model as present in the StROBe-model is applied (Stochastic Residential Occupant Behaviour Model, Aerts et al. 2014, Baetens and Saelens 2016). The StROBe-model generates three-state occupancy profiles (away, asleep, active) for the individuals of each household based on their employment type.

Activity probabilities are applied to determine the performance of specific energy consuming activities. The translation of the habits to discrete window use sequences is straightforward, since the habits relate the window use purely to changes in occupancy state and the performance of activities. Since the occupancy and activity profiles are stochastic, the resulting window use profiles are variable as well, and do not represent fixed schedules.
A comparison between this new window use habit model and four different window use models from literature indicated that the latter models underestimate the inter-individual diversity (Verbruggen et al. 2021b).

This window opening model was integrated in a new Event-based Residential Occupant Behaviour model (EROB) using the modelling approach of the StROBe-model. In first instance the occupancy and activity profiles of the household and its individual members are defined, based on some characteristics of the household. The other types of occupant behaviour (electricity use, heating behaviour, internal heat gains, domestic hot water use and window use) are subsequently linked to these profiles. The modelling of each of these steps and the adaptations compared to the StROBe-model is described in detail in the work of Verbruggen (2021).

3 MODELLING APPROACH

A mulizone building energy simulation model was created in the object-oriented modelling language Modelica, created based on components of the Modelica 3.2.3 and the IDEAS 2.1.0 library (Jorissen et al. 2018) within the simulation environment Dymola.
The model is based on one of the houses from a NZEB case-study neighbourhood (Janssens et al. 2017). It represents a 2-storey terraced house with 3 bedrooms, with a total floor area of 100 m², north-south orientation, and operable windows in all rooms. In the model an ideal heating system is applied which directly compensates the heating demand to the given set-point profiles. The model is coupled to climate data from Uccle, Belgium. Figure 1 shows the floorplan of the house. The building structure components exist of 9 zones representing the different rooms. Three building designs with different energy performance levels were created:

- NZEB – Highly insulated and airtight building envelope (v_{50} = 1 m³/h/m²), balanced mechanical ventilation system with heat recovery (80% effectiveness), summer bypass and constant flow rate (122 m³/h dwelling flow rate).
- E100 - Medium energy performance: building envelope compatible to energy performance standards of 2006, at the start of the EPB regulations in Flanders, medium airtightness (v_{50} = 5 m³/h/m²), demand-controlled exhaust ventilation system (room flow rate is reduced from 100% of design flow rate to 20% when CO_2-concentration in a room is lower than 800 ppm). Total dwelling design flow rate is 240 m³/h.
- Y70 - Poor energy performance: building envelope compatible to building practices in the 1970's. This means limited or no insulation, simple double glazing, a poor airtightness (v_{50} = 12 m³/h/m²), and no ventilation system.

The flow rate due to window airing is calculated with the equation of Phaff for single sided ventilation which is based on the temperature difference and wind speed (Dubrul 1988), assuming a tilted window as this was the most common window state according to the online survey. This approach was chosen over the use of the window/door-airflow component of IDEAS, since it results in faster simulations. The flow rate by infiltration is simulated per zone as a constant value based on the zone airtightness.

To assess the impact of occupant behaviour and window use on the energy use and IEQ, the outputs of the EROB-model are used as inputs in the Modelica model of the dwelling. Since the EROB model is stochastic, 30 households were simulated to get a representative result sample. For each of the households, first the occupancy and activity-profiles are created. Based on the number of persons present in each zone, the metabolic heat gains and CO_2-production are determined. Additionally, the heating set-points in each zone and the demand of domestic hot water is given to the heating system. Identical profiles are used for each of the three building designs, except for the window use as it is dependent on the installed ventilation system in the EROB model. A high diversity in window use is observed between the simulated households, as shown in Figure 2.

Figure 1: Ground and first floor of terraced house

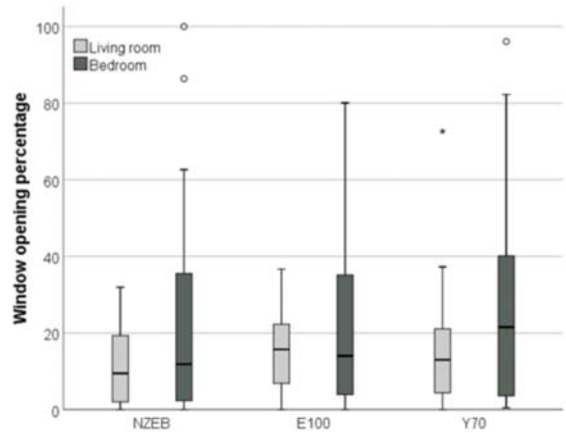

Figure 2: Window opening percentage for the different households in the living room and bedroom

4 IMPACT OF OCCUPANT BEHAVIOUR

To assess the influence of including the different types of OB, the simulations were carried out for each type of behaviour separately (occupancy/activity, heating behaviour, and window use) and for the combination of all OB types. The DHW and electricity use were not considered in this comparison as they do not have an influence on the energy use for space heating or indoor environmental quality. For the comparison only the behaviour under review was changed while the other types of behaviour remained fixed as in a base-model. The base-model represents a simple OB-model by assuming default settings:

- The heating set-point is always 20°C in all rooms.
- The windows are always closed.
- An average occupancy and activity profile is selected to account for the internal heat gains.

4.1 Impact on heating energy use

The results of the simulations for the energy use for space heating are given in Figure 3. The base-model predicts a yearly energy use for space heating of 1683 kWh/year, 5609 kWh/year and 13991 kWh/year, for respectively the NZEB-building, E100-building and Y70-building (surface area is 100 m²). The inclusion of different occupancy profiles and associated internal heat gains leads to a limited change and variation compared to the base profile. As can be expected, the introduction of heating behaviour (varying set-points) has a larger influence on the total heating energy demand. The average heating energy use is significantly lower compared to the base-model for all buildings. This can be attributed to the choice of a uniform heating set-point of 20°C in the base-model, while the EROB-model often predicts unheated bedrooms and bathrooms, and therefore a lower heating demand.

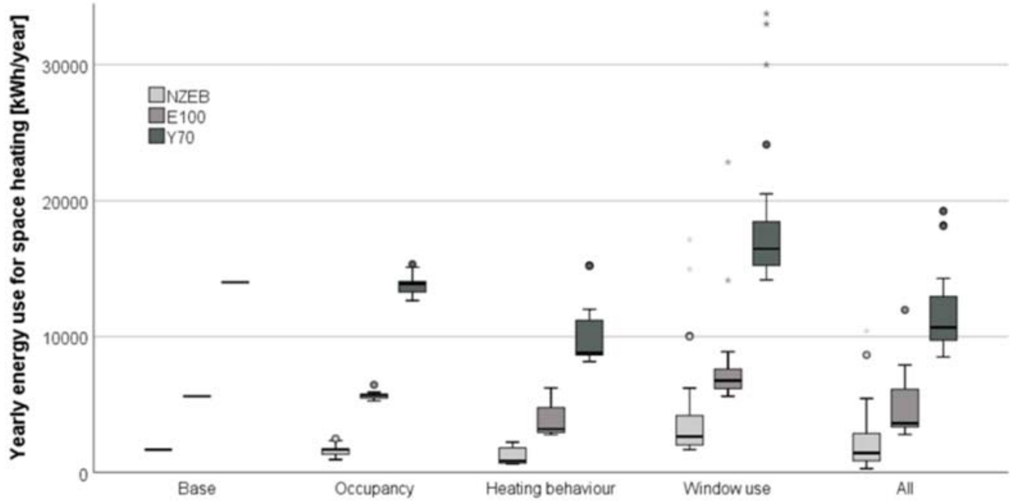

Figure 3: Variation of yearly energy use for space heating across 30 different households for three different dwelling performance levels and for the different types of occupant behaviour.

The inclusion of the window opening behaviour results in the highest variability in heating energy use. It is observed that the impact of including window use is proportionally smaller and leads to a smaller variation in the E100-building compared to the other buildings. Since the opening of windows reduces the CO_2-concentration the demand controlled ventilation system operates less in boost-mode, reducing the ventilation flow rates of the ventilation system and with that the heating demand. The inclusion of the window use without including other types of OB leads to the highest average energy use for heating. This can be explained by the fact that in this case the heating set-point remains 20°C even when windows are opened.
The average heating energy use when all types of OB are jointly considered is respectively 2314 kWh/year, 4740 kWh/year and 11768 kWh/year for the different performance levels. This average energy use is higher than the base-model load for the NZEB-building, and lower for the E100 and Y70-building. This difference can be attributed to the combination of the heating behaviour and window use. While the inclusion of the window use increased the energy use compared to the base-model, the lower heating set-points reduced the energy use. Since the heating behaviour has a smaller impact in the NZEB-building the average energy use increased, while for the other buildings the average energy use decreased. As a consequence, the expected energy use reduction between E100 and NZEB is smaller when occupant behaviour diversity is considered compared to the base case.

In the previous simulations the different types of OB were simulated separately. While the connection between the occupancy and the other behaviours is taken into account, the heating set-point profiles are independent of window use profiles. In reality window use is possibly interrelated with the heating behaviour, as many occupants will close the window when turning on the heating or the other way around. To assess the impact of the combination of different types of behaviours, the complete model as discussed above is compared with a similar model but including the restriction that the heating is turned off in a room when the window is opened. The results of these simulations are shown in Figure 4. Obviously the heating energy use decreases when the heating is turned off with window opening. The average heating energy use is respectively 1977 kWh/year, 4583 kWh/year and 10272 kWh/year for the different performance levels. While the median energy use decreased only slightly, the households with very high energy use were reduced more significantly, with that reducing the range of the heating energy use. The difference with the base case is even more pronounced, specifically for the Y70 case. This also illustrates the importance of further research on OB relations.

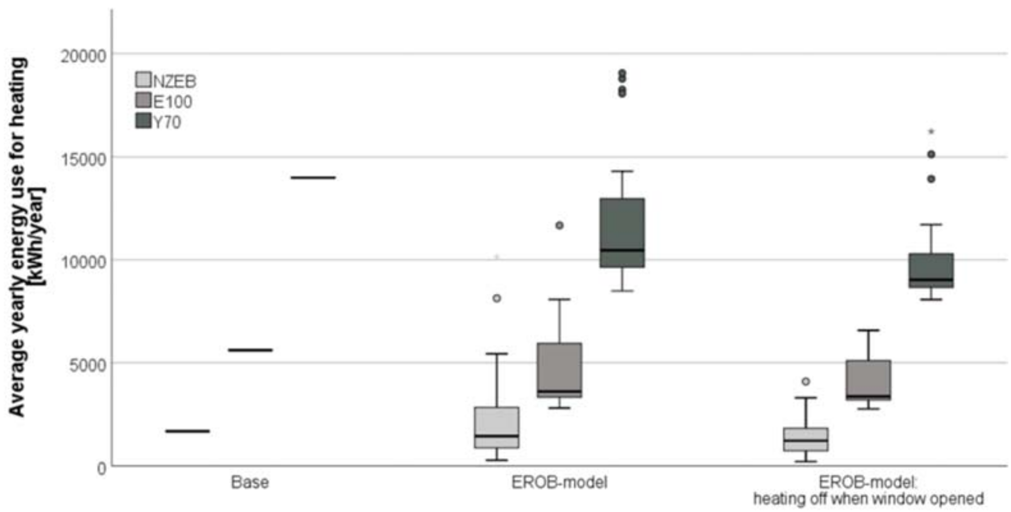

Figure 4: Variation of yearly energy use for space heating across 30 different households for three different dwelling performance levels for the combination of all OB and for the combination of all OB assuming the heating in a room is switched off when a window is open.

4.2 Impact on Indoor Air Quality (IAQ)

The impact of OB on IAQ is assessed using the CO_2-concentrations as evaluation criteria. The average yearly CO_2-concentrations as simulated for the master bedroom is shown in Figure 5 as an illustration of typical results.

The type of ventilation system and building envelope airtightness have an important influence on the average CO_2-concentration in the rooms. The average yearly CO_2-concentration is the highest for the Y70-building, followed by the NZEB-building and the E100-building. This finding applies both for the base case and for the cases with variations in OB. The constant flow rate of the balanced ventilation system in the NZEB-building (50% of the design flow rate to account for manual control settings) is not always sufficient leading to higher CO_2-concentrations compared to the demand driven ventilation system (E100) for which the flow rate is increased to the design flow rate when the threshold of 800 ppm is exceeded. The Y70-building is the least airtight, but has no ventilation system, resulting in the highest CO_2-concentrations.

The inclusion of different occupancy profiles results in wide variations in yearly average CO_2-concentrations per household, especially in the NZEB and Y70-building. Due to the demand controlled ventilation system, the variation in CO_2-concentration is more limited in the E100-building. The window use impacts the average CO_2-concentration as well. While the maximum CO_2-concentration is observed for the base-model (all windows closed), it was significantly reduced by the opening of windows. The effect is most pronounced in the seventies building, as the efficient use of the windows can reduce the CO_2-concentrations to similar levels as in buildings where ventilation systems are installed.

4.3 Impact on overheating

Finally an assessment is made of the impact of OB modelling on the overheating predictions by including OB in the building simulations. The overheating is expressed in Kelvin hours above 26°C (operative temperature). Figure 6 shows the overheating for the living room.

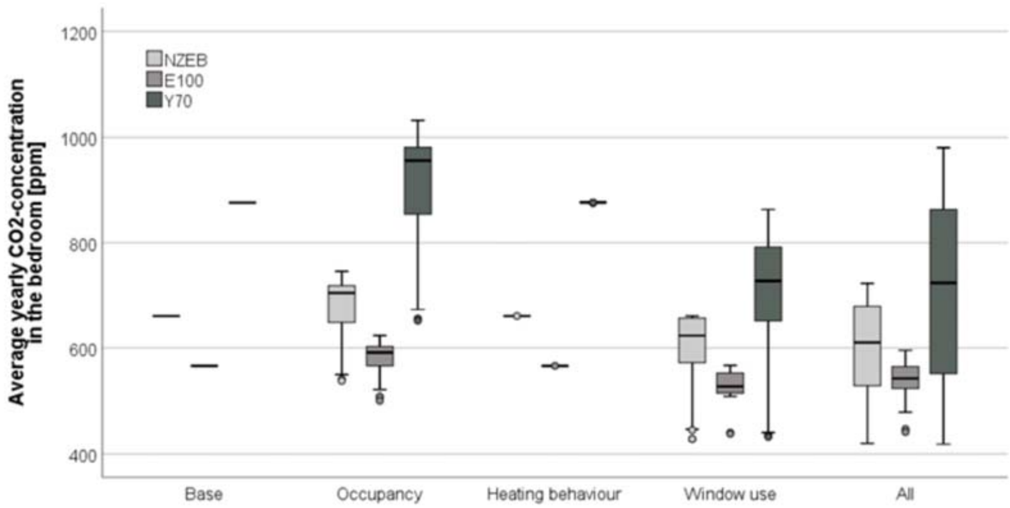

Figure 5: Variation of the yearly average CO_2-concentration in the master bedroom, as a measure for the indoor air quality, across 30 different households, for three different dwelling performance levels and for the different types of occupant behaviour.

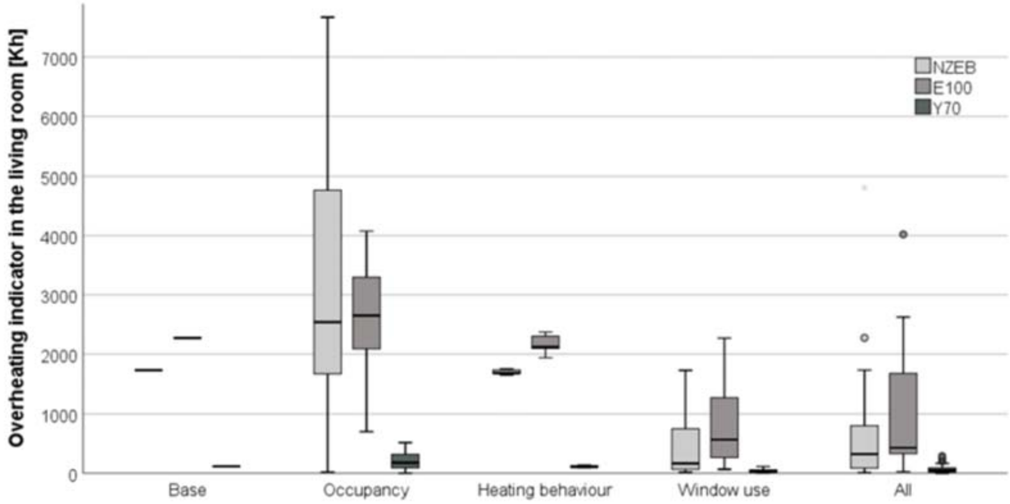

Figure 6: Variation of the overheating indicator in the living room across 30 different households, for three different dwelling performance levels and for the different types of occupant behaviour.

Overheating is more common in the NZEB and E100-buildings due to the well insulated building envelope, especially in the living rooms. In the E100-building overheating is even more prevailing than in the other two cases because of the lower ventilation rate as a result of demand control during times with low CO_2-concentrations, when nobody is present in the room. The variation in occupancy profiles has a significant impact on the overheating prediction, especially in the energy efficient buildings. The internal heat gains due to persons and appliances lead to more overheating, but as well larger variations in the overheating indicator, with some households experiencing rarely any overheating. Again the window use has a significant impact on the overheating prediction, with the maximum overheating when the windows are always closed and no overheating at all when the windows are frequently used. The distribution of the overheating due to the varying window use is strongly skewed to the lower end, even though the window use itself is only slightly skewed for the NZEB-building and normally distributed for the other buildings. This indicates that even window use profiles with limited window opening are already sufficient to lower the overheating significantly.

5 CONCLUSIONS

The results revealed that occupant behaviour is important to take into consideration, not only for energy use predictions but as well for assessment of overheating and IAQ, especially in more energy efficient buildings. The use of the EROB-model does not only benefit the energy use predictions but as well the design and control of different systems such as for ventilation or cooling.

Of all OB-types window use had the most important influence on the three evaluated metrics, emphasising the importance of including window use in BES. While the inclusion of the window use led to an increase in the energy use, it led to a decrease in overheating and CO_2-concentration, and thus in better assessed IEQ. The average energy use of the high performance NZEB-building increased when the OB-model was included compared to the base-model, while it decreased for the other two less energy efficient dwelling performance levels, revealing a similar trend as often observed in performance gap research. This indicates that occupant behaviour may be an important part of the explanation of the performance gap. To further improve the OB-models, research on the combination of different behaviours is necessary.

6 ACKNOWLEDGEMENTS

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