Simulation of the Effects of Occupant Behaviour on Indoor Climate and Energy Consumption

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SUMMARY

In this study the influence of occupant behaviour on energy consumption were investigated in simulations of a single room occupied by one person. The simulated occupant could manipulate six controls, such as turning on or off the heat and adjusting clothing. All control actions were carried out with the aim of keeping the PMV value within predefined limits in accordance with CR1752 [1]. An energy consuming and an energy efficient behavioural mode were simulated. A reference simulation was made during which the occupant had no control over the environment.

The occupant was able to keep the thermal indoor environment close to neutral when he/she had the possibility to manipulate the controls. The energy consumption was similar within each behavioural mode regardless of the PMV limits. However, the energy consumption in the energy consuming behavioural mode was up to 330 % higher than in the energy efficient behavioural mode.

INTRODUCTION

Buildings account for more than 40 % of the energy consumption in the EU member states and households are responsible for consuming more than 26 % [2]. Consequently, reductions of the energy consumption in buildings are instrumental to the efforts of alleviating the EU energy import dependency and comply with the Kyoto Protocol.

Indeed, occupant behaviour influences the amount of energy consumed to sustain a comfortable indoor environment. However, the extent to which occupant behaviour affects building energy consumption is largely unknown. The purpose of this study was to investigate the extent of this influence. This paper describes simulations of a naïve and a rational behaving occupant. The naïve occupant controlled the indoor climate using an energy expensive behaviour, while the rational occupant controlled the indoor climate in an energy efficient way.

METHODS

The simulations were carried out using a dynamic building simulation software [3]. The model consisted of a single room (4 m x 7 m) with a single occupant seated in the middle of the room. The room had one exterior wall (facing south) with a window and a heater underneath it. The building was placed in a suburban environment in Copenhagen, Denmark. All simulations were annual simulations using the Danish Design Reference Year for Copenhagen.

The simulated occupant could manipulate four different controls to adjust the environment (table fan, window opening, blinds, and heating) and two controls by which the occupant could adjust to the environment (clothing insulation and metabolic rate). All control actions were carried out with the aim of keeping the PMV value within predefined limits. Two behavioural modes were simulated. In the behavioural mode 1, the indoor environment was controlled in an energy expensive manner (naïve occupant), while the controls were operated in an energy efficient way in behavioural mode 2 (rational occupant). In both behavioural modes, three limits for the PMV index were set in accordance with the guidelines in CR1752 (+/-0.2, +/-0.5 and +/-0.7 for quality categories A, B, and C, respectively) [1], resulting in a total of six simulations. A seventh reference simulation was made during which the occupant had no control over the environment. In this simulation the occupant only controlled the clothing insulation and the metabolic rate.

Table 1: Setup of the simulations.

Criteria	Behavioural mode 1	Behavioural mode 2
A (-0.2<PMV<0.2)	Simulation 1A	Simulation 2A
B (-0.5<PMV<0.5)	Simulation 1B	Simulation 2B
C (-0.7<PMV<0.7)	Simulation 1C	Simulation 2C

In each simulation, all control actions were used to maintain PMV within the predefined limits. An example of the two behavioural modes for criterion A is given in Figure 1. Here it is seen that in behavioural mode 1, at increasing PMV, the table fan was turned on at PMV=0.03. If that did not stop the increase in PMV, the window was opened at PMV=0.06, blinds drawn at PMV=0.09, a clothing garment was removed at PMV= 0.11 and the metabolic rate was decreased to 1 met when PMV was higher that 0.14. Finally the heating was turned off when the PMV value increased beyond 0.17. When the PMV decreased below 0, the heating was turned on, the metabolic rate and clo value was increased, blinds opened, window closed and the fan was turned off, in that specific order.

In behavioural mode 2, the order of controls was inverted so the occupant turned off the heat as the first thing, when feeling warm – instead of turning on the fan.

In simulations B and C, the sequence of control actions at increasing or decreasing PMV were unchanged but the PMV value at which a control action was taken was increased according to the +/- 0.5 and +/- 0.7 criterion.

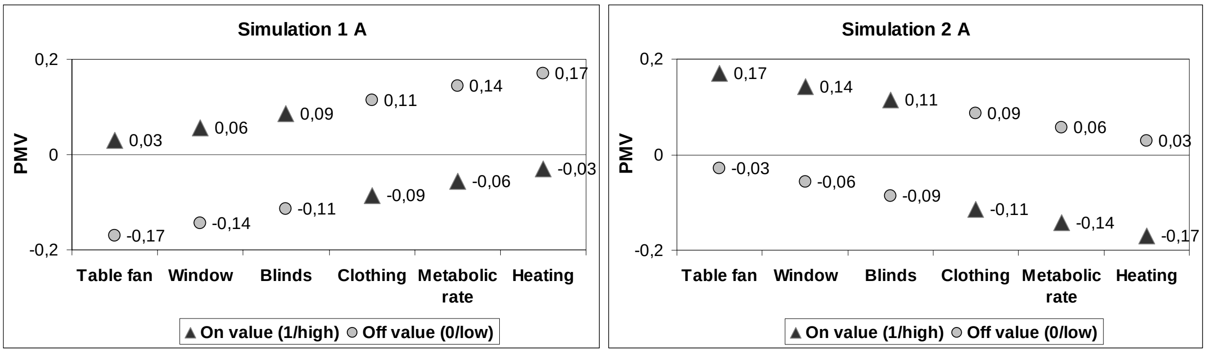

Figure 1: The control scheme for the energy consuming and the energy saving Behavioural modes for criterion A.

The occupant was constantly present in the room and was sleeping from 22:30 till 6:00 in the morning. During weekends the occupant slept from 24:00 till 8:00. During the sleeping periods the on and off values for the controls that adjusted the environment were multiplied by two to simulate that it takes a higher level of discomfort to act while sleeping than while being awake. The control of clothing and metabolic rate during the night is described below.

Table fan: When the fan was turned on the air speed at the occupant was increased by 1 m/s and the electric power consumption was increased by 50 W. These values were based on measurements using a normal table fan and a hot sphere manometer. During the measurements an average increase in air speed of approximately 1 m/s was detected when the fan was pointed directly at the occupant at a distance of 3 m. When the fan was pointed slightly to one of the sides of the occupant an airflow increase of 0.25 m/s was measured. Due to numerical problems in A simulations, the air speed was only increased by 0.25 m/s in simulation 1A and 2A. The power was kept at 50 W.

Window: The aerodynamic size of the window opening (corresponding to the size of a sliding window) was set each time the window was opened and remained unchanged until the window was closed. The opening size of the window depended linearly on the air change rate in the time step previous to the opening event. An air change rate of 0 h^{-1} in the time step prior to the opening event lead to an opening size of 0.6 m² while an air change rate of 2 h^{-1} in the time step prior to an opening event lead to an opening size of 0.12 m². When the air change rate with closed window exceeded 2.5 h^{-1}, the window was not opened even though PMV exceeded the window opening control value.

This was chosen because the air change rate depended on the wind speed outside the building. When there was a strong wind the air change rate was high and the window opening was small when the window was opened. When there was no wind the air change rate was small and when the window was opened it was opened completely

When the window was open the air speed at the location of the occupant was increased by:

$$V_{air} = 0.2 \cdot \frac{Q \cdot Vol}{A_{opening} \cdot 3600} \qquad (1)$$

Where

V_{air} is the air velocity at the occupant [m/s], Q is the air change rate [h^{-1}], Vol is the volume of the room, $A_{opening}$ is the aerodynamic area of the window opening.

The fraction in equation 1 is the air speed in m/s in the opening. The factor of 0.2 is multiplied because the airspeed decreased as a function of the distance to the window opening.

When the window was closed and the fan was off the air speed at the location of the occupant was 0.1 m/s.

Blinds: The binds were on/off controlled. They were external blinds that reduced the solar heat gain coefficient by a factor of 0.14 and reduced the direct energy transmission (short wave) by a factor of 0.09. The blinds were closed every night.

Clothing: The clothing insulation of the occupant could assume two values (Hi and Low), which were set each day at 6 o’clock in the morning on the basis of the outdoor temperature. This was done to model the action of taking on or off a piece of clothing. Both the time of day when the clothing insulation values were determined and the clothing insulation values were modelled according to [3] in the area of natural ventilation. The clothing insulation values were calculated using the following relation:

$$Clo_{Hi} = -0.024 \cdot T + 1.1 \qquad (2)$$

$$Clo_{Low} = -0.015 \cdot T + 0.83 \qquad (3)$$

Where *Clo* is the insulation of the occupants clothing [Clo], *T* is the outdoor temperature at 6:00 in the morning [°C].
During the night the clothing value was regulated continuously between 1.0 Clo and 2.5 Clo depending linearly on the PMV value. This was done to model a blanket or duvet that can be taken on or off in small increments while sleeping.

Metabolic Rate: The metabolic rate depended linearly on the PMV value assuming 1.0 Met at the PMV=off control value and 1.3 Met at the PMV=on control value. The metabolic rate of the occupant was 0.8 Met while sleeping.

Heating: The heating system comprised a water based radiator and a boiler with an efficiency of 66 %. The supply temperature to the radiator was 65 °C at outdoor temperatures below -12 °C and 20 °C at outdoor temperatures above 17 °C. Between -12 °C and 17 °C the supply temperature varied linearly with the outdoor temperature. The water flow through the heater was either on or off.

Infiltration rate: The simulated building had two cracks at different heights in each exterior wall. All cracks connected the interior of the building to the exterior environment. The local wind pressure coefficient of the faces of the building was determined according to [5]. The opening area of the cracks was determined by running a simulation with closed window and aiming for an average infiltration rate of 0.25 h^{-1}. In a study from 1985 [6] the average infiltration rate in 14 Danish dwellings ventilated by natural ventilation was measured. In this study, an average value of 0.19 h^{-1} was obtained, but it is stated that the 14 dwellings were among the most tightly sealed in the Danish housing mass.

Lighting: When the occupant was awake, the electrical lighting was turned on when if the daylight level dropped below 150 lux on a horizontal surface 0.6 m above the floor level at the location of the occupant (in the middle of the room). The light was only turned off when the occupant went to sleep, resulting in the light being on for the entire day if it was turned on in the morning.

RESULTS AND DISCUSSION

As seen in figure 2, the PMV index was close to neutral for a very large part of the year in all the simulations with active occupant behaviour. For the reference case with passive behaviour the PMV was far from neutral in a large part of the year (below -1 or above 1 during 72% of the year).
The PMV index was similar in the simulations with active occupant behaviour and attained values outside the control criteria for only small parts of the year. This means that the occupant was successful in controlling the environment within the comfort criteria.

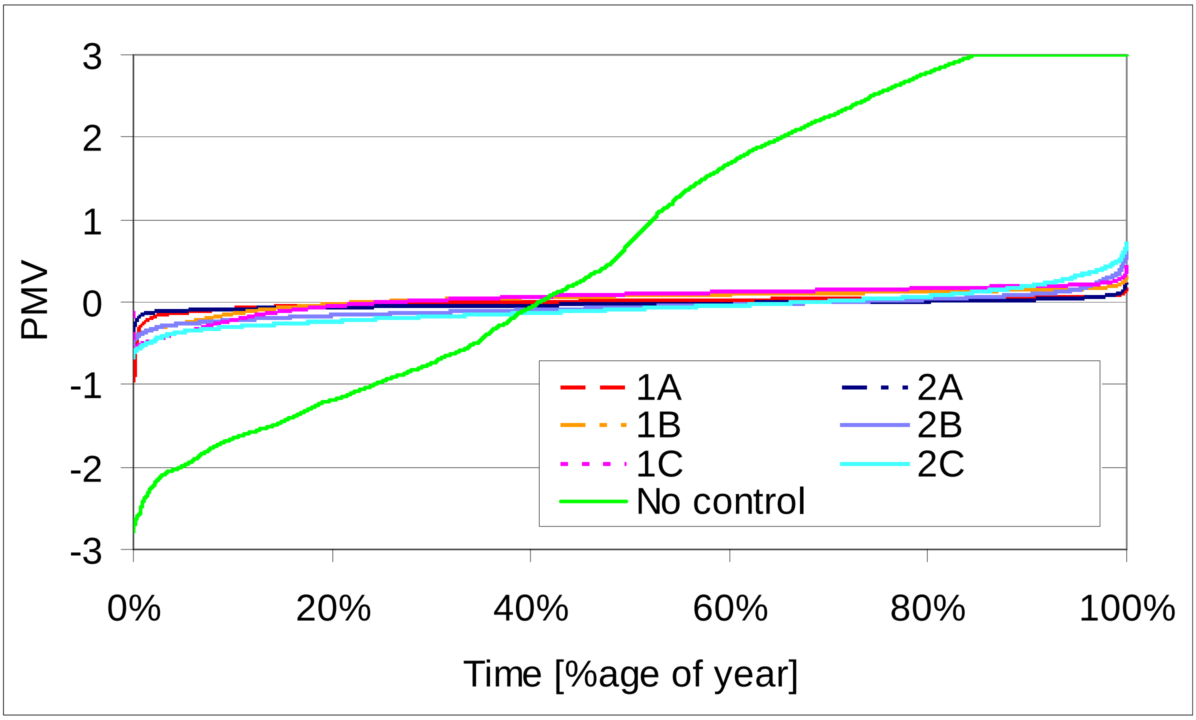

Figure 2: Duration curves for the PMV index in the 6 simulations and for the reference simulation. The figure shows how long time (in percentage of a year) the PMV index was below a certain value.

The total energy consumption refers to primary energy consumption. According to the Danish building code [7] this was calculated as the sum of all energy consumptions, where the electric consumptions were multiplied by 2.5. The highest primary energy consumption of 3948 kWh/year (simulation 1A) was 3.30 times higher than the lowest primary energy consumption of 1198 kWh/year (simulation 2C). Within each comfort control criteria the largest difference in primary energy consumption between the two behavioural modes was 324 % (3882 kWh/year simulation 1C was 3.24 times higher than 1198 kWh/year in simulation 2C). Within the two behavioural modes the largest difference in primary energy consumption was 117 % (1400 kWh/year in simulation 2A was 1.17 times higher than 1198 kWh/year in simulation 2C). This means that the comfort control criteria had much less impact on the primary energy consumption than the behavioural mode.

Table 1: Energy consumption in the simulations. The primary energy was calculated by multiplying electricity consumption by 2.5 according to the Danish building code. [7]

energy consumption pr. Year [kWh/year]	1A	1B	1C	2A	2B	2C	No control
Heating	2532	2372	2346	923	768	720	1812
Fan	380.1	423.6	431.0	1.4	0.3	0.1	0.0
Circulation Pump	13	13	13	3	2	2	13
Lighting	174	172	171	187	189	189	131
Primary energy for heating, ventilation and lighting	3948	3891	3882	1400	1246	1198	2171

Heating: The heating was turned on more often in Behavioural mode 1 than in Behavioural mode 2. Similarly, narrowing the control criteria resulted in higher energy consumption for heating.

Fan: A narrowing of the control criteria resulted in a decrease in the energy consumed by the fan in Behavioural mode 1. In Behavioural mode 2 this was opposite. In Behavioural mode 1 the fan was turned on as the first action when the occupant felt warm and turned off as the last control action when the occupant felt cold. In Behavioural mode 2 this was opposite meaning that the fan was turned on as the last control action when the occupant felt warm and was turned off as the first control action when the occupant felt cold. This meant that the fan was turned off more frequently as the control criteria narrowed in Behavioural mode 1. In Behavioural mode 2 the fan was turned on more frequently when the control criteria narrowed.

Circulation pump: In the behavioural mode 1 simulations, the heating was on for a longer period than in behavioural mode 2. This meant that the circulation pump was on for a longer period, which resulted in larger energy consumption in behavioural mode 1 than in behavioural mode 2.

Lighting: The differences in energy consumption for lighting are due to differences in daylight level. These differences were caused by differences in the use of blinds in the simulations.

CONCLUSIONS

Occupant behaviour affected the energy consumption in the building by up to 330 %. The behavioural mode affected the energy consumption in the room by up to 324 %, while the control criteria affected the energy consumption by up to 117 %.
All simulations with active occupant behaviour resulted in near neutral thermal sensation, compared to passive occupant behaviour.

The results of the study underline the importance of appropriate occupant behaviour for the consumption of energy to climatize buildings by quantifying the difference between a naïve and a rationally behaving occupant.

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