Main physical environmental drivers of occupant behaviour with regard to space heating energy demand

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SUMMARY
Several studies have highlighted the significant gap between the predicted energy performance of buildings and their measured actual performance. Uncertainties regarding behaviour of building occupants are one of the key factors limiting the ability of energy simulation tools to accurately predict real building energy requirements.

The paper focuses on the particular topics of space heating energy demand related to the occupants habits of adjusting heating set-points. The parameters influencing the user interaction with the heating control system are analyzed in literature for residential buildings, and the resulted influencing factors are illustrated.

Statistical analysis of data coming from measurement carried out in Danish dwellings are performed to infer the probability of adjusting the thermostatic radiators valves and to determine the relationship between the (indoor and outdoor) environmental conditions and the occupants’ heating set-point preferences. The paper aims at providing a reliable basis for a more accurate description of control action models in performance simulation applications.

KEYWORDS

1 INTRODUCTION
Real energy consumption in dwellings depends on several factors as the location, design and construction of the buildings, the specification of heating systems and their controls together with the efficiency of appliances. But it is mostly dependent on the behaviour of occupants (Seligman et al., 1977-78). It was demonstrated that the total energy consumption in dwellings can be reduced by 10–30% by changing occupants’ behaviour alone (Cordes, 1990, Mullaly, 1998). The number of occupants and their age influences energy consumption, for example, households where there are no children or where couples work consumes less energy than a household with children or older people (Guerra Santin et al. 2009). Dwelling size, family size, climate, appliance ownership, lifestyle and behaviour are all defining factors of households’ energy consumption patterns. Therefore, the energy demand of dwellings varies greatly between households and with time on an hourly, monthly and yearly basis according to the “user profile”. This variability and the uncertainties related to the occupant behaviour are one of the key factors limiting the ability of energy simulation tools to accurately predict real building performance, causing the significant discrepancy between the predicted energy performance of buildings and the real final energy consumptions. The reason of the discrepancy between simulated and real energy use in buildings lies in the fact that simulation tools are only able to describe control actions deterministically e.g. following predefined,
fixed and consequently unrealistic schedules. Models of human behaviour are generally described by statistical algorithms which predict the probability of a state or an action while simulation tools are based on deterministic equations and mimic user behaviour in a very static way. It is therefore necessary to increase the capability in taken into account occupant’s interactions in order to obtain values that are closer to real energy use. In modelling, there is a need to move toward a probabilistic approach (Fabi et al., 2011). In order to do this, equations describing human behaviour need to be implemented in simulation programs and methods for a better prediction of energy demands have to be defined.

In this paper we will focus on heating set-point adjustments and their effects on energy demand for a residential building typology. The simple action of adjusting the thermostatic radiator valve is influenced by many factors that interact in complex ways. Differences in users’ attitudes, preferences in thermal comfort and reactions to the indoor environment bring great variations in energy consumptions. An investigation of consumption of energy for heating in 290 similar houses revealed that there was considerable variation between houses (Henningsen, 1999). Since the houses were identical (apart from orientation for some of them) the variation was largely due to the way the houses were used. As a consequence there is an urgent need to take into account the role of occupants’ interactions with control systems in buildings.

In this work a first phase will take into account the existing results of a literature survey of heating behaviour research highlighting the main driving forces for occupants to interact with heating system. Afterwards, a probabilistic approach in building energy modelling is presented with the purpose of defining user type patterns to be implemented in simulation tools.

2 METHODS
The present work undertakes a theoretical and empirical study of the uncertainty of energy consumption assessment related to occupants’ behaviour in residential buildings. A literature survey is addressed to derive the most dominating driving forces useful for a more accurate description of occupant behaviour related to the habits adjusting the heating set point. Thus, based on measurements in 15 Danish dwellings, the probability of adjusting thermostatic radiator valves (TRVs) (the probability of turning up/down the heating control) has been inferred as a function of several indoor and outdoor variables separately.

Literature survey of investigation on heating behaviour in residential buildings
The simple action of adjusting the thermostatic radiator valve is influenced by many factors that interact in complex ways. Occupants’ behavioural influencing factors, called with the general term “Drivers”, represent the reason leading the building occupant to a certain reaction and suggest him/her to operate an action (Fabi et al., 2011). “Drivers” have been investigated by several researchers and have been grouped into “external” factors connected with indoor/outdoor conditions (Seligman et al., 1977-78, Nicol, 2001, Schweiker et al., 2009, Andersen et al., 2009) and “internal” factors connected with the field of social science (Ajzen et al. 2005, Refsgaard et al., 2009).

Drivers influencing heating and cooling behaviour include physical, psychological, social and contextual factors. In particular, variables influencing energy use for heating are mainly related to household characteristics, regarding both social and physiological and contextual drivers.

According to several papers (Sardianou, 2008 Guerra Santin et al., 2009, Andersen et al., 2009), people age is an important characteristic determining energy use: in general, the presence of elderly people or children is related to more hours of use of radiators. Gender
differences in the adjustments of thermostat set point have been found in the use of thermostat. Results (Karjalalainen, 2007, Andersen et al., 2009) have shown that females are less satisfied with room temperatures than males and preferred a higher set point, but males adjust the thermostat set point more often than females.

Household income has proven to be an important factor in determining energy use for heating. In a study based on the expenditure and energy use of 2800 households in the Netherlands, Vringer (2007) found that a 1% increase in income results in a 0.63% increase in energy use. Biesiot and Noorman (1999), using data from household budget surveys, energy prices and the primary energy requirements of goods in the Netherlands, found an almost linear relationship between expenditure and energy use, confirming that the higher the disposable yearly income, the higher the energy requirements.

Psychological drivers are related to the occupant preferences on indoor temperature. Results of a survey conducted in a student house in Japan (Schweiker et al. 2009), including people coming from several countries, have shown that also the “thermal background” of occupants, related to climate region of origin, and the “behavioural background”, related to the habits in childhood, are drivers leading to different heating behaviour.

Dwellings size (Sardianou 2008), type and ownership are contextual parameters found to be drivers of heating behaviour. Guerra Santin’s investigations (2009) lead to the result that single-family houses are connected with highest chosen temperature and more hours with radiators on. Andersen (2009) found that the heating tended to be on more often in rented dwellings compared to those which are owner-occupied.

The type of thermostat is an important aspect in the determination of how occupants interact with thermostats: households with programmable thermostat were associated with higher temperature settings during the night and with more hours with radiators on (Guerra Santin et al., 2009). Shipworth et al. (2010) found that in dwellings with thermostats, the mean temperature setting is slightly lower than in dwellings without a thermostat. They also found that households with a programmable thermostat keep the heating system on for longer than households with manual thermostats.

The most influential parameter physical environmental on the heating set-point is the indoor temperature. Several studies (Haas et al., 1998, Guerra Santin et al., 2009, Schweiker et al., 2009, Andersen et al., 2009) have indicated strong evidence for a linear relationship between space heating energy demand and indoor temperature.

Outdoor temperature, wind speed, solar radiation and outdoor relative humidity have an impact on the heating behaviour. They have been found to be negatively correlated with the heating set-point on Thermostatic Radiator Valves (TRV) (Andersen et al., 2011), indicating that heating set-point increases when these variables decreased.

Mean outdoor temperature of the foregoing night has been found (Schweiker et al., 2009) to have a major impact on occupant behaviour during the summertime (cooling behaviour regarding the AC usage), but a minor one in wintertime.

Table 1. Driving forces for energy-related behaviour with respect to heating set-point adjustments.

<table>
<thead>
<tr>
<th>biological</th>
<th>psychological</th>
<th>Social</th>
<th>physical environment</th>
<th>building/equipment properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>Indoor environmental preferences</td>
<td>Annual income</td>
<td>Outdoor temperature</td>
<td>Dwelling type</td>
</tr>
<tr>
<td></td>
<td>in terms of temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>Thermal background</td>
<td>User presence</td>
<td>Indoor temperature</td>
<td>Dwelling size</td>
</tr>
<tr>
<td></td>
<td>Behavioural background</td>
<td>Wind speed</td>
<td>Room type</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solar radiation</td>
<td>Temperature control Type</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ownership</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The field survey in Denmark
A monitoring campaign of indoor and outdoor climate variables and occupant’s control actions was conducted in 13 Danish dwellings in the period from March to August 2008 in Copenhagen. Measurements were carried out in 10 rented apartments and 5 privately owned single family houses. Half of the apartments were naturally ventilated while the other half were equipped with constantly running exhaust mechanical ventilation in the kitchen and in the bathroom. Three single family houses were naturally ventilated while the other two were equipped with exhaust ventilation. A series of variables concerning indoor and outdoor environmental conditions were monitored and meteorological data were obtained from two Danish meteorological stations in the dwellings proximity. Occupants’ adjustments of heating set-points temperatures, were monitored by measurement of the setting of one TRV in the bedroom and one in the living room of each dwelling.

The dwellings were divided into three groups selected by inhabitants frequency of TRVs manipulation: the three groups were named active, medium and passive users types.

In the analyses the probability of turning up/down the heating was inferred for the three behavioural models. Set-point dependency on indoor and outdoor environment and users control actions was deduced by mean of logistic regression with interaction between selected variables accordingly to the following equation:

\[
\log \left( \frac{P}{1-P} \right) = a + b_1 \cdot x_1 + b_2 \cdot x_2 + \ldots + b_n \cdot x_n + c_{12} \cdot x_1 \cdot x_2 + c_{13} \cdot x_1 \cdot x_3 + \ldots
\]  

(1)

Backward and forward selection based on the Akaike information criterion was used to reduce the models. The results were models that predict probabilities of turning up and down the set-point. A model that predicts the size of the set-point change was inferred using linear regression. The statistical analyses were performed using the statistical software “R”.

3 RESULTS
The probability of turning up or down the heating set-point temperature was deduced as a function of the indoor and outdoor climate on the basis of occupant’s actions on controls. Findings of the statistical analysis are presented in Table 2 in the form of coefficients of the logistical regression and the linear model for all the variables that had a statistically significant impact on heating set-point adjustment. Indoor relative humidity, outdoor temperature, solar radiation, wind speed and time of the day were the variables that influenced mostly the set-point temperatures.

Table 3  Results of the models of the TRVs set-point for different user type.

<table>
<thead>
<tr>
<th>User type</th>
<th>Variable</th>
<th>Coefficient</th>
<th>Max-Min</th>
<th>Magnitude*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active users</td>
<td>Model up</td>
<td>Intercept</td>
<td>-4.286</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Indoor relative humidity</td>
<td>-0.085</td>
<td>50.117</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time of the day</td>
<td>Morning</td>
<td>3.6596</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Day</td>
<td>3.4470</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Afternoon</td>
<td>3.4197</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Evening</td>
<td>2.1425</td>
</tr>
<tr>
<td></td>
<td>Outdoor temperature</td>
<td>-0.1441</td>
<td>363</td>
<td>5.2337</td>
</tr>
<tr>
<td></td>
<td>Model down</td>
<td>Intercept</td>
<td>-3.514</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar radiation</td>
<td>-0.0194</td>
<td>849</td>
</tr>
<tr>
<td>Midium users</td>
<td>Model up</td>
<td>Intercept</td>
<td>-7.6356</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outdoor temperature</td>
<td>-0.2284</td>
<td>363</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind speed</td>
<td>0.3699</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>Model down</td>
<td>Intercept</td>
<td>-22.8446</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time of the day</td>
<td>Morning</td>
<td>17.6847</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Day</td>
<td>16.7473</td>
</tr>
</tbody>
</table>
The magnitude of the variable is a measure of the maximum impact of the variable in the probability of turning up/down the heating.

Statistical analysis revealed that for active users the most important variables in determining the probability of turning up the set-point were indoor relative humidity, time of the day and outdoor temperature. An increase in solar radiation resulted in a decrease in the probability turning down the heating. This is probably a result of the relation between solar radiation and time of the day and may indicate that some occupants decreased the heating set-point before going to bed. For medium users outdoor temperature and wind speed were negatively correlated with the TRV set-point indicating that the heating set point was increased when these variables decrease while the time of the day was the most influential variable in the determination of turning down the heating.

The model for passive users showed no significant variable influencing the probability of increasing the heating set-point whereas wind speed was positively correlated with the probability of turning down the heat, indicating that an increase of wind speed increased the probability of turning down the heating.

As shown in Table 2, indoor temperature is not considered as an influencing variable. That is because heating set-point and indoor temperature are inter-correlated and affect each other. Due to this interaction indoor temperature is not always included in investigations of many researcher.

4 DISCUSSION
The analysis is based on logistic regression to infer the probability of an adjustment of the TRV’s setting. Using this method, we have assumed that the probability function looks like equation (1). Additionally, we have assumed that all observations were independent of each other. This assumption is questionable as the observations were gathered in 15 dwellings. Essentially the assumption would hold true if all inhabitants of the dwellings reacted similarly to the conditions they were subjected to. In any other case the observations in each dwelling will be influenced by the habits of the inhabitants of the individual dwelling and, as a result, they would not be independent from each other. This problem is dealt with by using the number of the individual dwelling as a factor in the model. In this way the variance between dwellings due to the habits of the inhabitants is accounted for in the model and the observations can be regarded as being independent.

5 CONCLUSIONS
By means of measurements carried out in 15, dwellings the relationship between users behaviours and the most influencing variables in adjusting heating set-points have been found. Based on the measurements, a probabilistic approach of occupants’ interactions with heating controls was developed. The approach is based on inference of models form measurements and predicts the probability of increasing/decreasing the set-point on a thermostatic radiator valve for three different user patterns named active, medium and passive. The data analysis showed the variable that mostly influencing the set-point temperatures were indoor relative humidity, outdoor temperature, solar radiation, wind speed and time of the day. The most influential physical environmental variables for the occupant to interact with the heating system found to be drivers in this study fit perfectly with the results existing in literature.
6 REFERENCES


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