MODELLING OCCUPANTS' HEATING SET-POINT PREFFERENCES

Rune Vinther Andersen, Bjarne W. Olesen, and Jørn Toftum
International Centre for Indoor Environment and Energy, department of Civil Engineering, Technical University of Denmark

ABSTRACT

Discrepancies between simulated and actual occupant behaviour can offset the actual energy consumption by several orders of magnitude compared to simulation results. Thus, there is a need to set up guidelines to increase the reliability of forecasts of environmental conditions and energy consumption. Simultaneous measurement of the set-point of thermostatic radiator valves (trv), and indoor and outdoor environment characteristics was carried out in 15 dwellings in Denmark in 2008. Linear regression was used to infer a model of occupants' interactions with trvs. This model could easily be implemented in most simulation software packages to increase the validity of the simulation outcomes.

INTRODUCTION

Occupants who have the possibility to control their indoor environment have been found to be more satisfied and suffer fewer building related symptoms than occupants who are exposed to environments of which they have no control [Leaman and Bordass, 1999, Paciuk, 1989, Toftum, 2009]. Consequently, giving the occupants possibilities to interact with building controls will result in better building performance in terms of occupant satisfaction. However, occupant behaviour varies significantly between individuals which results in large variations in the energy consumption of buildings. Because of this, it is important to take occupant interaction with the control systems into account when designing buildings.

Most building simulation programs provide possibilities of regulating the simulated environment by adjusting the building control systems (opening windows, adjusting temperature set-points etc.). However, discrepancies between simulated and actual behaviour can lead to a large off-set between simulation results and actual energy use [Bishop and Frey, 1985]. Indeed, Andersen et al., 2007a showed that differences in occupant behaviour might lead to differences in energy consumption higher than 300 %. Thus, there is a need to set up standards or guidelines to enable comparison of simulation results between simulation cases. One method that can provide this is to define standard behaviour patterns that can be implemented in building simulation programs. This would significantly improve the validity of the outcome of the simulations. A definition of such standard behaviours should be based on the quantification of real occupant behaviour.

An important parameter that influences the energy consumption in dwellings is the indoor temperature. In a Scandinavian climate like the Danish, mechanical cooling is rarely used and heating is a major contributor to the total energy consumption. During the winter season, the indoor temperature is controlled mainly by the heating set point. As a result, the heating set-point is very important in the determination of the total energy consumption of a building in Denmark.

METHOD

Andersen et al 2009. quantified behaviour of occupants in Danish dwellings by means of a questionnaire survey. A definition of standard behaviour patterns was attempted, but a link to the indoor environment was missing due to the effects of behaviour of the occupants on the indoor environment. As a follow up to the questionnaire survey and to fill this gap, simultaneous measurement of occupant behaviour, indoor and outdoor environment was carried out in 15 dwellings during the period from January to August 2008.

Measurements

The following variables were measured continuously in all 15 dwellings.

Indoor environment factors measured every 10 minutes

- Air temperature in °C
- Relative humidity (RH) in %
- Illumination in Lux
- CO2 Concentration in ppm

Outdoor environment acquired from meteorological measuring stations in 10 minute intervals [Danish Meteorological Institute]

- Air temperature in °C
- RH in %
- Wind speed in m/s
- Global Solar radiation in W/m²

Behaviour

- Window position (open/closed)
- Heating set-point on thermostatic radiator valves in °C.

Figure 1: Pictures of the instruments used to measure the indoor environmental variables and temperature set-point of the thermostatic radiator valves.

The indoor environment measurements were carried out with Hobo U12-012 data loggers. The CO_2 concentration was measured using a Vaisala GMW22 sensor connected to the Hobo logger as depicted in figure 1. Both the CO_2 sensors and the Hobo data loggers were newly calibrated from the factory. The CO_2 sensors were tested against a newly calibrated Innova mulitgas analyser both before and after the measuring period. The temperature sensors in the hobo data loggers were also tested before the measurements. The Outdoor environmental variables were obtained from the Danish meteorological institute. Data from the meteorological station closest to each of the dwellings was used. The closest meteorological stations did not measure precipitation and since local wind direction is very sensitive to local conditions it was decided not to include the direction of the wind.

All dwellings were equipped with a heating system in which the supply water temperature was controlled based on outdoor conditions (weather compensation) while the flow through the heaters was controlled by thermostatic radiator valves (trv). As such, the trv position represented the heating set-point. This was measured using custom made thermostatic radiator valves. The trv's were equipped with a variable electric resistance attached so that the electrical resistance varied with the set-point of the trv. The electrical resistance was measured using Hobo U12-012 [Onsetcomp] data loggers. All trv's were calibrated before the measurements. The loggers that measured the electrical trv resistance also measured temperature. These measurements were used to check corrections made to the primary temperature measurements due to direct sunlight on the sensor. This is described in further detail in section 3

Pictures of the measuring instruments are displayed in figure 1.

Generally, all measurements were carried out in one living room and one bedroom in each dwelling. However, in some of the dwellings the residents stated that they never turned on the heating in the bedroom. In these cases, both thermostatic radiator valves were installed on radiators in the living room. The window sensors were installed on windows that inhabitants used most often when ventilating the dwelling.

Table 1: description of dwellings and residents.

DWELLING NUMBER	TYPE	MECHANICAL VENTILATED	FLOOR AREA [m²]	YEAR OF CONSTRUCTION (AND RENOVATION)	NUMBER OF RESIDENTS	AVERAGE AGE OF RESIDENTS	DISTANCE TO METEOROLOGICAL MEASURING STATION [km]
1	House	Yes	126	1994	2	65	4.7
3	House	No	145	1928	2	57	10.3
4	House	No	130	1956 (1976)	2	70	1.7
5	Apartment	Yes	83	1981 (2001)	1	76	8.5
6	Apartment	No	86	1945	2	78	5.2
7	Apartment	Yes	83	1981 (2001)	2	63	8.5
8	Apartment	No	109	1945	2	55	5.2
9	Apartment	No	87	1945	3	35	5.2
11	Apartment	No	77	1945	1	71	5.2
12	Apartment	No	109	1945	2	64	5.2
13	Apartment	Yes	80	1981 (2001)	1	60	8.5
14	Apartment	Yes	85	1981 (2001)	3	28	8.5
15	Apartment	Yes	84	1981 (2001)	2	60	8.5

The dwellings

Measurements were carried out in 10 rented apartments and 3 privately owned single family houses. Half of the apartments were naturally ventilated (apart form an exhaust hood in the kitchen) while the other half was equipped with constantly running exhaust ventilation from the kitchen and bathroom. Two single family houses were naturally ventilated while the other was equipped with exhaust ventilation.

All dwellings were located less than 25 km from Copenhagen.

Features of the dwellings are described in Table 1.

All apartments were located in two complexes, one with natural ventilation and one with mechanical exhaust ventilation.

All dwellings used waterborne radiators/convectors and natural gas boilers as a primary means of heating and none of the dwellings had auxiliary heating installations such as wood burning stoves.

Processing and preparation of data

The indoor environment sensors were placed on internal walls at a height of roughly 1.8 m above the floor. We attempted to place the sensors so that they would not be hit by direct sunlight, but due to acceptance of the occupants in the dwellings and other practicalities, this was not always possible. In the cases when direct sunlight fell on the sensors, the temperature measurements were corrected for the heating of the sensor. This was done in periods when the measured illumination level was larger than 1000 lux. In these cases the temperature was corrected by linear interpolation between temperature measurements 30 minutes prior to and one hour after direct sunlight fell on the sensor. The trv set-point loggers were placed behind the heaters and were never hit by direct sunlight. The temperature measurements from these loggers were used to make sure that the temperature corrections on the primary temperature sensors followed the same profile as the trv sensors. Due to the close proximity of the trv sensors to the heaters, only cases with the heater turned off were used.

The CO2 concentration was used as an indicator of the occupancy of the rooms where the measurements took place. If the CO2 concentration was below 420 ppm and the window was closed the room was classified as being unoccupied. Furthermore, if the CO2 concentration was higher than 420 ppm, but decreased and continued to decrease until reaching values below 420 ppm and the window was closed in the entire period, the room was classified as unoccupied during the period of concentration decay.

The room was classified as occupied if the window was open. This classification was based on a questionnaire survey conducted by Andersen et al. 2007b, who found that the statement 'I had to leave the dwelling' was often mentioned as a reason for closing windows.

If the bedroom and the living room were both unoccupied, the dwelling was classified as unoccupied. Periods when the dwelling was unoccupied were not taken into consideration in the analysis.

Meteorological data was obtained from the weather station closest to each dwelling. The following variables were obtained in 10 minute intervals: Outdoor temperature, outdoor relative humidity, wind speed at 10 m above ground level, solar radiation on a horizontal surface, the number of minutes with sunshine in a day. The meteorological data was merged with the indoor environment observations and the behaviour observations to form one database.

Statistical method

Linear regression was used to infer the set-point of the trvs based on the observed variables. The full model consisted of all major variables and interaction terms between selected variables. The analyses were based on backward selection meaning that interaction terms and variables that did not have a significant impact on the set-point were removed from the full model. The variable with the highest p-value was removed from the full model and the model was run again without that variable. The variable with the highest p-value was then removed from that model and so forth. In this way, all interaction terms with p-values greater than 0.1 were removed from the model. Variables with p-values greater than 0.1 were removed unless they interacted significantly with other variables. The analysis resulted in a model that was too complex for the current standard of simulation programs. To lower the level of complexity the data was reanalysed with evaluation of only interaction terms between continuous and nominal variables, e.g. indoor temperature and day of week.

In the interpretation of the coefficients, the sign, the size and the scale of the corresponding variable have to be taken into account. E.g. a wind speed coefficient (during daytime) of -0.2 might seem to impact the set-point more than an outdoor relative humidity coefficient of -0.063. However, when the scales of the two variables (Wind speed: from 0 m/s to 13 m/s, Outdoor relative humidity: from 30 % to 100 %) are taken into account the picture changes. To get an indication of the magnitude of the impact from each variable, the absolute value of the coefficients for each variable was multiplied with the range of the variable. In the example described above the magnitude of the impact was abs(-0.2) · (13-0) = 2.6 and abs(-0.063) · (100-30) = 4.4 for the wind speed and the outdoor relative humidity respectively, indicating that the wind speed had a larger impact on the trv set-point that the outdoor relative humidity had.

RESULTS

The heating set-point was monitored by measuring the set-point of two trvs in 13 dwellings. The set-points' dependency on indoor and outdoor environment was deduced using multivariate linear regression with interactions between selected variables.

Table 2: Analysis of variance for the linear regression model of trv set-point. All non-significant terms were removed from the full model by backward selection. The R^2 for the model was 0.86

VARIABLE	DF	P-VALUE
Indoor temperature [°C]	1	<0.0001
Indoor RH [%]	1	<0.0001
CO2 concentration	1	<0.0001
Time of day [night, morning, daytime, afternoon, evening]	4	<0.0001
Weekday [workday, weekend]	1	<0.0001
Outdoor temperature [°C]	1	<0.0001
Wind speed [m/s]	1	<0.0001
Outdoor RH [%]	1	<0.0001
Solar radiation [W/m²]	1	<0.0001
Hours of sunshine [h]	1	<0.0001
Room [living room, bedroom]	1	<0.0001
Dwelling number	12	<0.0001
Indoor temp : time of day	4	<0.0001
Indoor temp : Weekday	1	<0.0001
Indoor temp : Wind speed	1	<0.0001
Indoor temp : Solar radiation	1	<0.0001
Indoor temp : Sunshine hours	1	<0.0001
Indoor temp : Room	1	<0.0001
Indoor temp : dwelling number	12	<0.0001
Daytime : Weekday	4	0.0004
Daytime : Outdoor temp	4	<0.0001
Daytime : Wind speed	4	<0.0001
Daytime :Solar radiation	4	<0.0001
Daytime : Sunshine hours	4	<0.0001
Daytime : Room	4	<0.0001
Daytime : dwelling number	48	<0.0001
Weekday : Outdoor temp	1	<0.0001
Weekday : Wind speed	1	<0.0001
Weekday : Solar radiation	1	<0.0001
Weekday : sunshine hours	1	<0.0001
Weekday : dwelling number	12	<0.0001
Outdoor temp : Wind speed	1	<0.0001
Outdoor temp : Solar radiation	1	<0.0001
Outdoor temp : sunshine hours	1	<0.0001
Outdoor temp : Room	1	<0.0001
Outdoor temp : dwelling number	12	<0.0001
Wind speed: solar radiation	1	<0.0001
Wind speed: sunshine hours	1	<0.0001
Wind speed : Room	1	<0.0001
Wind speed : dwelling number	12	<0.0001
Solar radiation : Room	1	<0.0001
Solar radiation : dwelling number	12	<0.0001
Sunshine hours : Room	1	<0.0001
Sunshine hours : dwelling number	12	<0.0001
Room : dwelling number	8	<0.0001

As table 2 shows, the trv set-point was affected by almost all the measured variables and by many of the interaction terms. Both the number of the dwelling, the room and almost all interaction terms including these affected the trv set-point significantly. In fact, the R^2 decreased from 0.86 to 0.45 when the variable 'number of the dwelling' and all its' interaction terms were removed from the model. This means that the occupants' trv set-point behaviour differed from one dwelling to another and even between bedroom and living room within a dwelling

Because the results of table 2 are too complex for most simulation programs, the data was reanalysed with a reduced number of interaction terms in the full model.

Table 3: Results of the less complex model of the trv set-point with few interaction terms. The R^2 for the model was 0.31

VARIABLES	TIME OF DAY	UNIT	COEFFICIENTS	MAGNITUDE
Intercept during workdays	morning	-	23.76	-
	day		24.82	
	evening		23.99	
	night		23.29	
Intercept during weekends	morning	-	23.80	-
	day		24.86	
	evening		24.02	
	night		23.32	
CO2 concentration	-	ppm	0.00048	0.8
Outdoor temperature	morning	°C	-0.30	12.5
	day		-0.32	
	evening		-0.33	
	night		-0.31	
wind speed during workdays	morning	m/s	-0.08	2.6
	day		-0.20	
	evening		-0.06	
	night		0.02	
wind speed during weekends	morning	m/s	-0.01	1.7
	day		-0.13	
	evening		0.01	
	night		0.09	
outdoor relative humidity	-	%	-0.063	4.4
Solar radiation	-	W/m²	-0.0006	0.6

Essentially, the indoor temperature was affected by the temperature set-point and then the variables were not independent, which is a requirement of this analysis. As a consequence it is not a suitable predictor of the trv set-point and was removed from the model.

The outdoor temperature, solar radiation and outdoor relative humidity were negatively correlated with the trv set-point indicating that the heating set-point was increased when these variables decreased. The magnitude indicates that the most important variables in the determination of the trv set-point were the outdoor temperature, outdoor relative humidity and the wind speed.

DISCUSSION

The results from the analysis with a limited number of interaction terms provide a possibility of defining behaviour patens for simulation purposes. The results presented in table 3 can be used to determine the heating set-point of thermostats in simulations.

An implementation of the model into a simulation program would significantly improve the validity of the simulation results in two ways: First of all, it would enable comparability of results from different models, since they would be based on the same behaviour patterns. Secondly, because the behaviour in the model is based on real behaviour it has a better chance of mimicking the behaviour of the occupants in the building and thus getting the indoor environment and energy consumption correct.

Occupancy

The occupancy of the dwellings was determined using the monitored CO2 concentration. This method was better than not considering the occupancy but may have lead to uncertainties since short changes in the occupancy may have passed unnoticed. Since most of the periods without occupancy were removed, any correlations between behaviour and CO2 concentration indicate relationships between air quality and behaviour.

Statistical approach

We have used linear regression to infer the heating set-point of the trvs. In using this method, we have assumed that relationship between the explanatory variables and the trv set-point is linear. Additionally we have assumed that all observations were independent of each other. This assumption is questionable as the observations were gathered in 13 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. We have dealt with this problem 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.

In the more simple model described in table 3, the number of the dwelling was removed which means that the assumption of independence between variables no longer holds true. The consequence of this is that variables that in reality do not impact the probability significantly will show up in the model as being significant. However, the simple model described in table 3 was derived from the more complex model, which included the dwelling number and only had significant variables.

Seasonal variations

The measurements were made during the winter, spring and summer. Consequently, the results in this paper are only valid for these seasons. There is however no evidence that the behaviour of occupants depends differently on the measured variables in the autumn than in other parts of the year. This means that the results can be assumed to representative of the entire year.

Variations in individual behaviour patterns

The difference in trv set-point behaviour from dwelling to dwelling could be a result of differences in the occupants' sensitivities to the variables governing their behaviour. It could however also be a result of misunderstandings in function of the thermostats. The findings of Sami Karjalainen (2007) support this. He analysed the understanding of room thermostats in Finnish offices by means of a qualitative interview survey and found a variety of usability problems. Also Rathouse and Young (2004) found usability problems and misunderstandings of thermostats which could lead to great variation in the use of thermostats. Wheil and Gladhart (1990) found that the thermostat control patterns varied greatly amongst households but were stable within each household. This is consistent with our findings and would indeed lead to stable energy consumption within each dwelling and to variations between dwellings as observed by Hackett and Lutzenhiser (1991) and Seligman et al. (1977/78).

CONCLUSIONS

Measurements of heating set-point behaviour, indoor and outdoor conditions were carried out in 13 dwellings near Copenhagen, Denmark.

The results indicated that the behaviour was governed by different but distinct habits in the 13 dwellings.

Correlations between environmental variables and set-point on the thermostatic radiator valves were found using linear regression. The most influential variables in the determination of the trv set-point were the outdoor temperature, outdoor relative humidity and the wind speed.

Based on the measurements a definition of occupant behaviour patterns in building simulation programs was proposed. When implemented into simulation programs, this definition will significantly increase the validity of the simulation outcome.

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