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Influence of Occupants' Behaviour on the Energy Consumption of Domestic Buildings

Henrik Brohus[1], Per Heiselberg[1], Allan Simonsen[1] and Kim C. Sørensen[1]

[1]Aalborg University, Denmark

Corresponding email: hb@civil.aau.dk

SUMMARY

The present work undertakes a theoretical and empirical study of the influence of occupants' behaviour on energy consumption of domestic buildings. The calculated energy consumption of a number of almost identical domestic buildings in Denmark is compared with the measured energy consumption considering the influence of occupants' behaviour. The sensitivity and uncertainty related to occupants' behaviour – among other parameters - are determined by means of stochastic modelling based on input distributions found by literature study, industry guidelines, measurements and simple assumptions. A high number of parameters are investigated and ranked in terms of variance and importance to determine which ones contribute the most to the overall level of uncertainty. It is found that the temperature set point and occupant heat load are substantial contributors to the uncertainty. The major part of the variance can be assigned to the occupants' behaviour.

INTRODUCTION

It is important to be able to assess the energy consumption of buildings to a certain level of accuracy. In order to assess the influence of energy reduction initiatives, to determine the expected annual cost, to calculate life cycle cost, emission impact, etc. it is crucial to assess the energy consumption reasonably accurate. However, several investigations reveal significant uncertainties in the estimation of energy consumptions in buildings. Deviation between the calculated energy consumption and the actual energy consumption may exceed 100 % in extreme cases. At the same time it is reported that occupants' behaviour may contribute substantially to the variance.

METHODS

The present work undertakes a theoretical and empirical study of the uncertainty of energy consumption assessment of domestic buildings related to occupants' behaviour. The calculated energy consumption of eight Danish buildings is compared with the measured energy consumption. Furthermore, the uncertainty is determined by stochastic modelling.

Building description

The building case applied for the measurements and simulations comprises eight almost similar red-bricked semi-detached houses located in the western part of Denmark, Figure 1. The conditioned area is 149.2 m^2 with 0.35 m cavity walls (0.11 m bricks - 0.125 m thermal insulation – 0.11 m bricks). Room height is 2.37 m. The *U*-values for ceiling, floor and walls are 0.19, 0.36 and 0.32 W/(m^2K), respectively. The buildings are naturally ventilated and heated by means of district heating.

Figure 1. Top, left: area around the eight domestic buildings. Top, right: surroundings. Bottom, left: close-up of one of the buildings. Bottom, right: sectional view.

Measurements

A number of detailed measurements are made on the buildings both to obtain detailed knowledge on the building constructions, occupants' behaviour and actual energy consumption, but also to be able to model the buildings properly.

The building leakage is determined by means of a standard blower door pressure test with pressure differences of 50 Pa. The blower door test is combined with tracer gas measurements to supplement the knowledge of the overall leakage area with an investigation of the leakage distribution. The leakage information is used to determine the air infiltration and natural ventilation.

Internal temperature is measured to assess the occupants' preferences and determine the heating set-point. The temperature is measured at several locations as a function of time to obtain information on daily variation and general temperature swings. Time-dependent temperature measurement may also reveal information on window and door opening.

Weather data are collected by local external temperature measurements and also by collecting data from the nearest local meteo station: wind speed, wind direction, external air temperature, relative humidity, atmospheric pressure, cloud cover and global solar radiation.

A questionnaire survey is used to collect information on occupant number and age, occupied period, bathing habits, use of computers, TV, appliances, etc. This is combined with a registration of the use of district heating, water and electricity (readings of the meters in each house). Table 1 provides some statistics on selected main findings.

Table 1. Results from measurements (8 buildings). μ is the mean value and, σ is the standard deviation. Conditioned space 149.2 m^2. 2005 is reported to be a "typical year" according to the occupants. Meteo data is from the local weather station.

Measurement	Unit	μ	σ
Infiltration (leakage)	$l/(s \cdot m^2)$ @ 50Pa	3.00	0.23
Internal air temperature set-point	°C	22.19	1.03
Internal heat load, appliances	W/m^2 (time average)	2.93	1.21
Internal heat load, occupants	W/m^2 (time average)	1.11	0.56
Airing, number	Airings per day	1.21	0.50
Airing, duration	Minutes per airing	10.88	8.72
2005 external air temperature	°C	9.3	7.6
2005 wind speed	m/s	4.6	2.5
2005 total water consumption	m^3/year	125.3	41.2
2005 electricity consumption	$kWh/(m^2 \cdot year)$ (kWh/year)	27.3 (4,079)	11.4 (1,697)
2005 district heating consumption	$kWh/(m^2 \cdot year)$ (kWh/year)	73.0 (10,886)	16.6 (2,480)

Simulations

The building simulations including the determination of the energy consumption are made by means of the hygrothermal building simulation programme *BSim* (version 2007) which is developed by the Danish Building Research Institute [1], Figure 2.

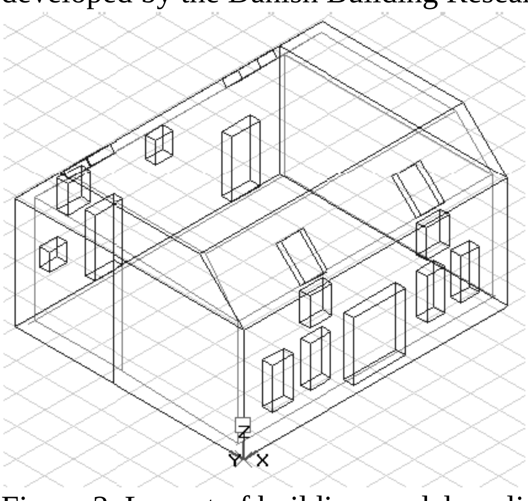

Figure 2. Layout of building model applied for the hygrothermal building simulations.

To include a proper description of the natural ventilation and air infiltration Computational Fluid Dynamics and multizone modelling are applied [2].

To determine what parameters to treat stochastic and what to consider deterministic, an initial screening sensitivity analysis is performed. After the screening analysis a more elaborate quantitative sensitivity analysis is undertaken for the most important parameters to apportion the output variability on the input parameters.

The screening method of Elementary Effects [3,4] is applied in this work. The method determines the mean value and standard deviation of the so-called elementary effects providing information on importance and possible correlation or non-linearity of the input parameters.

In the screening sensitivity analysis input distributions are established for 13 input parameters applied in the building simulation and energy calculations. The distributions are determined using a combination of measurements, questionnaires, literature, theoretical considerations, and also educated guesses depending on the accessibility of material in each case (Table 2):

- Set-point of space heating is detemined from the temperature measurements
- Occcupied period is found by questionnaires
- Appliances heat load is found by questionnaires and literature survey
- Occupant heat load is found by questionnaires regarding number, age and sex combined with literature regarding heat output per person
- Natural ventilation is found by a combination of questionnaires and a simplified calculation method (all purpose provided natural ventilation including window opening, door opening, etc. is covered by the “natural ventilation” parameter in this case; in the screening sensitivity analysis correlation with wind and temperature is ignored)
- Solar shading factor is taken from local building survey and literature
- *U*-value for windows and doors is taken from local building survey and literature
- *U*-value for walls is determined from calculated theoretical value taken as a minimum value which is increased according to literature in the interval of 0 – 40 % using a truncated lognormal distribution
- Glass *g*-value is taken from local building survey and literature (correlation with *U*-value for doors and windows)
- Building orientation is taken from location according to map and building drawings
- Infiltration is determined by blower door test results at 50 Pa corrected to normal pressure conditions
- Building heat capacity is assumed and the spread is related to furniture part of total heat capacity

Due to lack of information the input parameters are assumed to be independent, i.e. uncorrelated. This assumption is discussed later on.

Table 2. Screening sensitivity analysis of yearly heating energy consumption with input distributions based on 140 samplings according to the method of Elementary Effects [4]. Type N is a truncated normal distribution, L is a truncated lognormal distribution, and D is a discrete distribution. Interval defines distribution boundaries, μ^* is mean value and σ is standard deviation of the elementary effects (EE).

Input parameter		Distribution		EE [kWh/year]		
Name	Unit	Type	Interval; μ; σ	Rank	μ^*	σ
Wholly occupant behaviour related parameters:						
Set-point space heating	°C	N	21 - 24; 22; 0.71	1	2850	656
Occupied period	h/day	D	10 – 18; see NOTE 1	2	1500	376
Appliances heat load	W	N	215 – 730; 437; 100	3	1290	510
Occupant heat load	Occ. No.	N	0.522 – 2.861; 1.594; 0.5	7	741	218
Partly occupant behaviour related parameters:						
Natural ventilation	m^3/s	N	0.0386 – 0.0433; 0.041; 0.001	8	587	473
Solar shading factor	-	N	0.5 – 1.0; 0.8; 0.1	9	472	49
Building related parameters:						
U-value windows	W/m^2K	N	1.1 – 2.9; 2.4; 0.4	4	1280	439
U-value doors	W/m^2K	N	2.2 – 3.3; 2.9; 0.2	5	940	666
U-value walls (optimal value increase)	%	L	0 - 40; 2.5; 0.7 (0.267 – 0.376 W/m^2K)	6	782	501
Glass *g*-value	-	N	0.59 – 0.76; 0.67; 0.04	10	362	47
Building orientation	°	D	21 – 291; see NOTE 2	11	261	236
Infiltration	$l/(s \cdot m^2)$	N	0.20 – 0.24; 0.215; 0.008	12	71	9
Building heat capacity	Wh/m^2K	N	120 - 144; 132; 4	13	58	158
NOTE 1, data format (occupied period [h/day], relative frequency): (10,0.0526; 11,0.1053; 12,0.0526; 13,0.1579; 14,0.1053; 15,0.1053; 16,0.2105; 17,0.1579; 18,0.0526)						
NOTE 2, data format (building orientation [°], relative frequency): (21,1/3; 111,1/3; 291,1/3) [0° = North]						

Based on the results from the screening analysis a reduced number of stochastic input parameters are chosen for further investigation, see Table 3. In the screening analysis infiltration and natural ventilation are treated rather simplified, thus, even though they are not ranked as the highest they are included in the quantitative analysis using a somewhat more detailed model in *BSim*, see formula (1), that considers the influence of wind and temperature

$$n = n_0 + c_t \cdot (t_i - t_e)^{t_p} + c_v \cdot v \qquad (1)$$

where n is the air change rate [h^{-1}], n_0 is the basic air change rate [h^{-1}], c_t is the temperature factor [1/(h·K)], t_i is the internal temperature [°C], t_e is the external temperature [°C], t_p is the temperature exponent [-], c_v is the wind factor [s/(h·m)], and v is the wind speed [m/s] [1].

As to weather data the Danish DRY (Design Reference Year) is applied. Multizone modelling using input from the local meteo station from 2005 and 2006, respectively, are compared with models using the Danish DRY. It is found that the DRY provides a reasonable good description of the infiltration and natural ventilation in this case.

The detailed distributions are mainly based on a Danish database on 50,000 households containing information on electricity consumption, heat consumption and water consumption as well as socio-economic data [5]. Other results are found in Statistics Denmark (national institution producing offical statistics). Values are related to the category of semi-detached houses. Infiltration and natural ventilation is found in a combination of local measurements (blower door and tracer gas) and modelling (*BSim*, CFD and multizone modelling), see Table 3:

- Set-point space heating [5]
- Infiltration and natural ventilation (measurements and modelling)
- Occupied period (Statistics Denmark)
- Occupant heat load [5]
- Appliances heat load [5]

Table 3. Input distributions for the detailed sensitivity and the uncertainty analysis. Type N is a truncated normal distribution and E is a truncated exponential distribution. Interval defines distribution boundaries of the 99% confidence interval, μ is mean value and σ is standard deviation (Normal distribution) and *d* is a positive displacement of the distribution (Exponential distribution)

Input parameter		Distribution	
Name	Unit	Type	Interval; μ; σ *or d*
Set-point space heating	°C	N	20 - 25; 22.27; 0.75
Infiltration / Nat. vent. Basic air change rate, n_0 Temperature exponent, t_p Wind factor, c_v	 1/h - s/(h·m)	 N N N	 1.0 - 1.2; 1.1; 0.033 0.5 – 0.6; 0.55; 0.017 0.034 – 0.064; 0.058; 0.007
Occupied period	h/day	N	12 – 18; 14.9; 0.95
Occupant heat load	W/m^2 (Occupants)	E	0.68 – 6.00; 1.10; 0.68 (1.01 – 8.95; 1.64; 1.01)
Appliances heat load	W/m^2 (kW)	E	1.62 – 6.00; 0.70; 1.62 (0.24 – 0.90; 0.10; 0.24)

RESULTS

The results of the *screening* sensitivity analysis are presented in Table 2 where each input factor is shown as a function of mean value and standard deviation of the elementary effects and ranked according to importance.

The *quantitative* sensitivity analysis is based on regression analysis. PEAR (Pearson product moment correlation coefficient) and SRC (Standardised Regression Coefficient) and their rank transformations SPEA (Spearman coefficient) and SRRC (Standardised Rank Regression Coefficient) are applied. Whereas PEAR is suited for linear models, SPEA is a good measure of correlation in case of non-linear models. Especially, the SPEA coefficient is assumed to work well in this case and taken as the most reliable quantitative measure of the sensitivity, i.e. how the output uncertainty is apportioned on the input parameters [4]. Table 4 and Figure 3 present the results.

Table 4. Results from quantitative sensitivity analysis.

Input parameter	SPEA		PEAR		SRC		SRRC	
	%	Rank	%	Rank	%	Rank	%	Rank
Set-point space heating	36.9	1	38.0	1	34.7	1	41.1	1
Occupant heat load	22.6	2	22.8	2	25.5	2	22.1	2
Appliances heat load	15.7	3	20.7	3	15.6	4	19.3	3
Basic air change rate, n_0	14.6	4	4.7	5	16.0	3	6.2	5
Occupied period	5.9	5	6.8	4	5.6	5	7.7	4
Temperature exponent, t_p	2.4	6	3.0	7	0.3	7	0.8	7
Wind factor, c_v	2.0	7	3.9	6	2.4	6	2.9	6

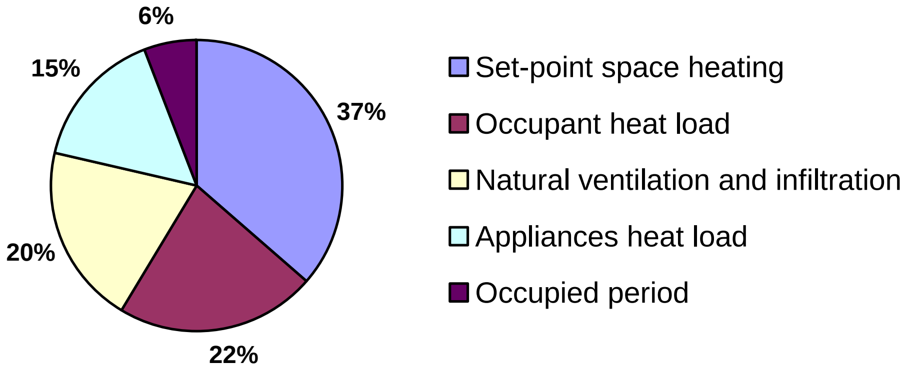

Figure 3. Visualisation of parameter sensitivity indicating the relative contribution of stochastic input parameters to total output (energy consumption) uncertainty. Based on the Spearman coefficient (SPEA).

In Figure 4 results from the uncertainty analysis are presented. The uncertainty is determined via the cumulative distribution function for the yearly district heating energy consumption found by means of Monte Carlo analysis and Latin Hypercube sampling. Latin Hypercube sampling is applied to ensure that the ensemble of random numbers is representative of the real variability [4].

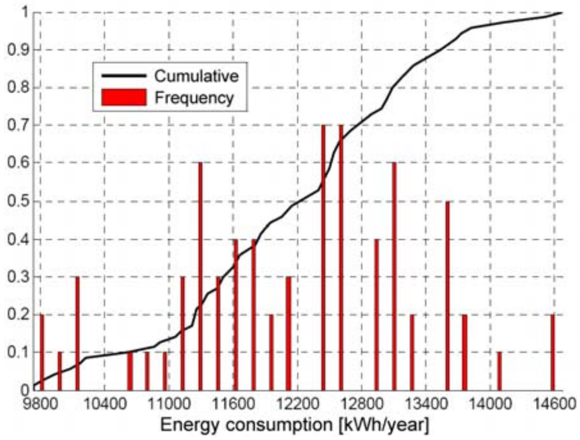

Figure 4. Frequency and cumulative distribution function for the uncertainty analysis of the heating energy consumption (district heating). The analysis is based on 70 realisations using Monte Carlo analysis and Latin Hypercube sampling.

For the 70 realisations the following statistics are found: mean value μ = 12,008 kWh/year, median x_m = 11,925 kWh/year, standard deviation σ = 1,294 kWh/year and, thus, the coefficient of variation δ = 10.8 %.

DISCUSSION

The measurements reveal a substantial variance of several parameters like the internal heat load related to appliances and occupants. The energy consumption coefficient of variance is approximately 0.2. It is found that the internal temperature corresponds well with the thermal comfort requirements in international standards like [6].

Measurements and simulations are found to correspond reasonably well; however, it is also found that significant differences may occur between calculated and measured energy consumption due to the spread and the fact that the result can only be determined with a certain probability (coefficient of variation of approximately 0.1 – 0.2). The standard deviation of the measurements (δ ~ 0.2) is twice as high as for the simulations (δ ~ 0.1). This may partly be due to the low number of samples for the measurements (8 buildings) and additional sources of variance not reflected in the simulation approach like model uncertainties.

Ranking of input parameter is performed using sensitivity analysis. The purpose of the ranking is to be able to select the most important input parameters for further stochastic modelling assuming that the rest are deterministic. In that way a reduced set of stochastic parameters may be identified and facilitate practical application of Monte Carlo simulation and focus of resources when the knowledge of distributions is to be expanded.

Using regression coefficients the variability of the energy consumption may be apportioned to the relevant input parameters. For instance, it is found that more than 1/3 of the variability is due to the set-point of space heating.

Correlation of input parameters is ignored due to lack of information and, as a consequence, the input parameters are assumed statistically independent. The quality of this assumption may be questioned to some extent. Yet, in general it is felt that the assumption does not violate the overall conclusions. More research including measurements is needed to provide sound and detailed evaluation of the correlation issue.

It is found that the most important (sensitive) parameters are related to occupants' behaviour. Even the natural ventilation and infiltration, which is influenced by weather data to a great extent, is also influenced by occupants by window and door opening, airing habits, etc. In general the influence of occupant behaviour is not well understood and more research should be undertaken to investigate this topic to be able to understand and to predict building energy consumption. This point will be even more important when the permitted energy consumption is further reduced in future due to the fact that a relatively higher proportion of the consumed energy is related to user behaviour including hot water consumption.

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