EXPLORING ROBUSTNESS OF ENERGY PERFORMANCE OF DWELLINGS TO OCCUPANT BEHAVIOUR: RENOVATION AND POST OCCUPANCY

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Abstract

In this paper, we focus on the influence of occupant behaviour on the energy performance of dwellings, before and after renovation process. In this context, 'ventilation control pattern', 'maintenance', and 'heating energy demand' are selected as the key parameters of the study. The aim is to reveal the sensitivity of energy performance of a dwelling to occupant behaviour, considering the pre and post-renovation process. Sensitivity of dwelling energy performance to occupant behaviour is analysed using Monte Carlo method. This method is one of the most commonly used methods to analyse the approximate distribution of possible results on the basis of probabilistic inputs. The inputs are selected as: window and grid operation, and mechanical ventilation set for ventilation control. The data used about occupant behaviour is gathered from OTB Survey [2008]. The Dutch reference building is used as a generic building to test the behavioural patterns. The result shows that a renovated [maintenance] dwelling is more robust to ventilation behaviour of the occupant.

Keywords: occupant behaviour, ventilation, renovation, energy performance, sensitivity analysis.

INTRODUCTION

It has long been known that energy efficiency improvements in the building stock cannot be furthered, unless strategies for renovation of existing dwellings are developed. Moreover, occupant behaviour has been a growing research interest, since the expected energy performance levels have not been achieved with low energy design, and occupant behaviour could be a reason [GuerraSantin and Itard, 2010]. This study focuses on the behavioural aspects of energy performance in renovation of dwellings. The aim is to reveal the sensitivity of occupant behaviour to the energy performance of a dwelling, considering the pre and post-renovation process. Main research question is: Is there an occupant behaviour threshold that defines a significant difference on the energy performance, considering renovation process?

Following, this paper's approach towards the domains of 'renovation' and 'behaviour' are explained:

Kohler defines 'simple renovation' such as insulating walls or replacing single glazing with double glazing, and states that this is only possible if the quality of the existing dwelling is sufficient to fulfil current needs [Kohler, 2006; Itard and Klunder, 2007] redefines simple renovation as 'maintenance'; and furthermore, provide the terms 'consolidation' and 'housing transformation' as steps between simple renovation, demolition and new construction [redevelopment]. In their paper, consolidation is explained as improvements of the building shell [such as insulation, without any change in the floor plan of the house or housing block]. Transformations are improvements or interventions in a housing block or complex that go beyond an individual house. Examples of this are joining houses together horizontally or vertically. Housing transformation requires that at least the loadbearing structure will be preserved when the remaining components are renewed. The scope of this study includes 'maintenance', namely the improvements in the building shell.

In this paper, occupant behaviour is considered as: presence patterns in a space, together with the actual heating [thermostat setting and radiator control] and ventilation patterns [operation of windows, grids, and mechanical systems], and the use of lighting and appliances.

METHODOLOGY

Method

The research methodology is based on sensitivity analysis, which is the study of how the variation in the output of a model can be apportioned, qualitatively or quantitatively, to different sources of variation. In sensitivity analysis, a mathematical model is defined by a series of equations, input factors, parameters, and variables aimed to characterize the process being investigated. Input is subject to many sources of uncertainty including errors of measurement, absence of information and poor or partial understanding of the driving forces and mechanisms. This uncertainty imposes a limit on the confidence in the output of the model [Hamby et al, 1994; Helton et al, 2006; Saltelli et al, 2006]

There are several possible procedures to perform sensitivity analysis. The most common sensitivity analysis practice works based on sampling. Several sampling strategies are available, including random sampling, importance sampling, and Latin hypercube sampling. In general, a sampling-based sensitivity analysis is one in which the model is executed repeatedly for combinations of values sampled from the distribution [assumed known] of the input factors. There are several examples of the application of sensitivity analysis in building thermal modelling [Spitler et al, 1989; Corson, 1992; Lam, 1996; Fulbringer and Roulet, 1999; McDonald, 2004; Westphal and Lamberts, 2005; Harputlugil et al, 2009]. For sensitivity of energy simulation models, a set of input parameters and their values are defined and applied to a building model. The simulated energy consumption of the model is used as a base for comparison to determine how much the output [here measured in terms of energy use per year] changes due to particular increments of input values [Corson, 1992]. Consequently the results show which parameters can be classified as "sensitive" or "robust". Sensitive parameters are the parameters that by a change in their value cause effective changes on outputs [in this case heating energy demand]. Contrarily, change of robust parameters causes negligible changes on outputs.

The sensitivity of occupant behaviour; which is considered here as factors influencing energy use by behaviour; are analysed using Monte Carlo method. The Monte Carlo method is one of the most commonly used methods to analyse the approximate distribution of possible results on the basis of probabilistic inputs [Lomas and Eppel, 2007; Hopfe et al, 2007]. In this research, the inputs [parameters] include use of ventilation system, and resulting air change rates. The steps of the analysis are as follows [Figure-1]:

- Pre-processing survey data [see next section] within statistical analysis program [the mean and standard deviations [SD] of the input parameters are determined]
- Gathering Latin-Hypercube samples from SimLab [SimLab] pre-processor
- Simulating each sample by a dynamic simulation program to collect output data. The simulations are made with 'one at a time' approach. Each input is perturbed in turn while keeping all other inputs constant at their nominal value.
- Combination of inputs and outputs in post-processor of SimLab to get Monte-Carlo
- Interpretation of the results

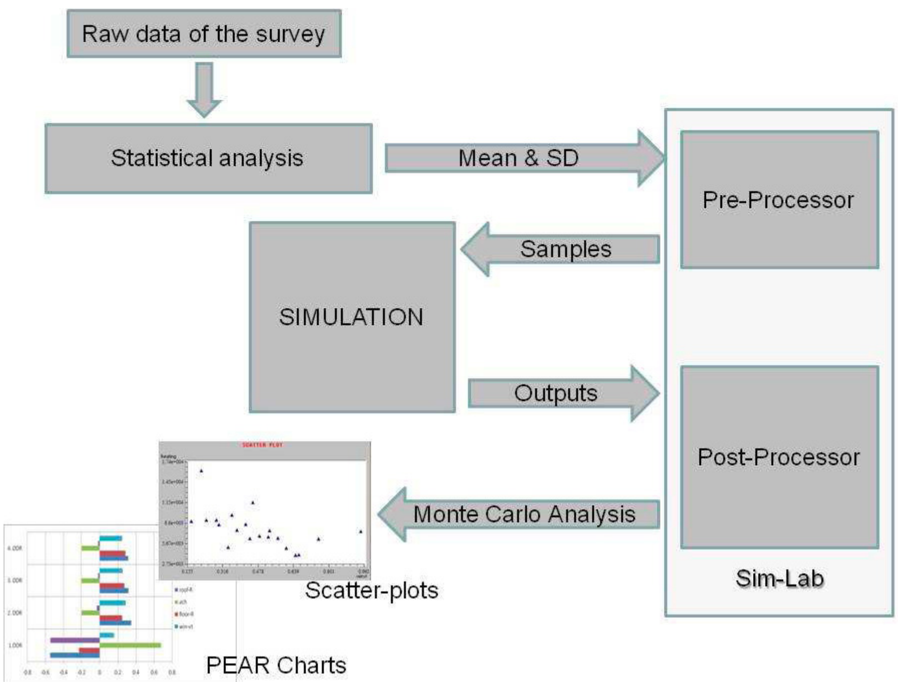


Figure 1. *Experiment/Computation/Observation*

Data

Dutch reference row house [Referentie woning, 2010] is modelled using the simulation software. The characteristics of the dwelling is explained below.

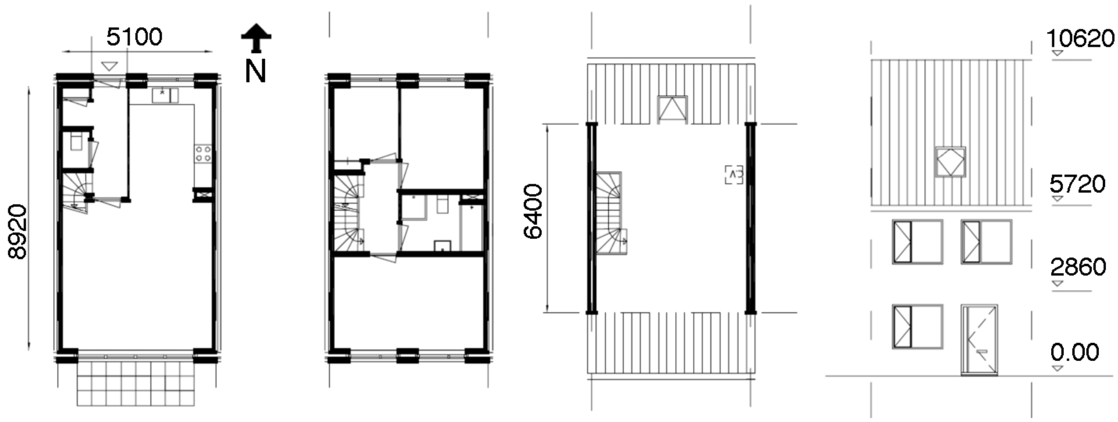


Figure 2. *Plans and sections of the reference row house*

Envelope properties of the non-renovated case [common row house of 1946 [Itard, 2006]] and the renovated case [contemporary row house [NEN 5128]] are displayed in Table 1.

Table 1. *Envelope characteristics and Energy use of sample dwellings*

Characteristics		Row house [contemporary] [renovated]	Row house [1946] [non renovated]
Dimension	Width [m]	5,1	
	Depth [m]	8,9	
	Height [m]	2,6	
	Floor area [m^2]	45,4	
	Volume [m^3]	118,0	
Envelope properties	Rc façade [m^2K/W]	3,0	0,58
	Rc roof [m^2K/W]	4,0	0,42
	Rc ground floor slab [m^2K/W]	3,0	0,38
	U window [W/m^2K]	1,8	5,1
	U front door [W/m^2K]	2,0	3,5
Energy use	EPC value [NEN 5128]	0,78	-
	Yearly energy use	359 MJ/m^2 [NEN 5128]	596 MJ/m^2 [Itard, 2006]

For calculating the *total ventilation rates*, Dutch standard for ventilation: NEN 1087 values are assumed [Table 2].

Table 2. *Dutch standards for ventilation*

	Living room	Bedroom	Kitchen	Bathroom +WC	WC only
Netherlands [NEN 1087]	1,0 $dm^3/s/m^2$ floor area	1,0 $dm^3/s/m^2$ floor area	21 dm^3/s	14 dm^3/s	7 dm^3/s

The following formula and the physical descriptions of the dwelling model provide the air change values for each room, listed below.

Supply Air Rate [AC/h] = Volume Flow Rate [m^3/h] / Room Volume [m^3]

Living room: 1,25 ach
Bathroom: 1,26 ach
Attic: 1,47 ach
Bedroom 1: 1,26 ach
Bedroom 2: 1,26 ach
Bedroom 3: 1,15 ach
Entrance: 1,26 ach
Circulation: 1,26 ach

Data about *ventilation behaviour* is collected in two neighbourhoods, that began to develop in 1996, in the Netherlands. The survey was conducted in Winter 2008, in 319 dwellings. Number of row houses in the sample is 117 [37%]. The data collected through the survey is about dwelling characteristics, household characteristics, energy consumption figures, actual behaviour about heating and ventilation behavioural patterns and use of lighting and equipments. In the scope of this research, data used about behaviour from the survey include: hourly ventilation behaviour changes: use of windows, and grids in each room, and hourly set point adjustment of mechanical ventilation.

In the survey, respondents were asked to fill in tables, mentioning if they open/don't open windows and grids in each room, each hour; and if they turn on/off mechanical ventilation each hour, during the week and the weekend. These tables are converted to values for further mathematical calculations [1: open window/grid, mechanical ventilation on, 0: closed window/grid, mechanical ventilation off]. Then, these values are used to calculate the air change per hour values [ach] of each room, when there is/not natural and/or mechanical ventilation present.

All 117 dwellings from the survey database have open kitchens. Therefore, reported data on ventilation behaviour in living room and in kitchen is combined. In addition, entrance, bathroom and circulation zones' natural ventilation patterns reported in the survey database are not simulated, because the reference dwelling model did not propose natural ventilation through windows, in these rooms.

Using the ach value assumptions calculated from the NEN standard and the reference row house, and the converted/quantitative ventilation behaviour data [from the survey database], air change rates of each room during the day are calculated. Afterwards, descriptive statistical analysis is applied to be able to obtain the mean and the standard deviations of ventilation patterns. These values [Table 4] are processed in SimLab pre-processor for gathering the generic 50 samples of ventilation patterns [see Pre-processing survey data step, in previous section]. As this study only focuses on ventilation behaviour, the remaining behavioural patterns are kept constant and taken from the NEN 5128 [Table 3].

To calculate average internal heat-gain from lighting, assumption for 1 m^2: 6,0 W For this study, 50 samples of ventilation rates are generated with SimLab.

Table 3. *Indoor temperature settings [NEN 5128]*

	07.00-17.00		17.00-23.00		23.00-07.00	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
Living area thermostat setting	19 °C	19 °C	21 °C	21 °C	16 °C	16 °C
Sleeping area thermostat setting	16 °C	19 °C	16 °C	21 °C	14 °C	16 °C

Table 4. *Mean and Standard deviations of ach values per hour*

	Living room		Attic		Bathroom		Bedroom 1		Bedroom 2		Bedroom 3	
Hours	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
01.00-02.00	1,12	0,56	0,49	0,70	0,23	0,11	0,87	0,58	0,76	0,62	0,59	0,58
02.00-03.00	1,12	0,56	0,49	0,70	0,23	0,11	0,87	0,59	0,77	0,62	0,58	0,58
03.00-04.00	1,12	0,56	0,49	0,70	0,23	0,11	0,87	0,59	0,77	0,62	0,58	0,58
04.00-05.00	1,12	0,56	0,49	0,70	0,23	0,11	0,87	0,59	0,77	0,62	0,58	0,58
05.00-06.00	1,12	0,55	0,49	0,70	0,24	0,14	0,88	0,58	0,78	0,61	0,58	0,58
06.00-07.00	1,15	0,58	0,49	0,70	0,27	0,18	0,89	0,58	0,79	0,61	0,58	0,58
07.00-08.00	1,21	0,54	0,49	0,70	0,30	0,19	0,99	0,52	0,89	0,58	0,62	0,58
08.00-09.00	1,21	0,54	0,52	0,71	0,27	0,18	1,03	0,49	0,94	0,55	0,62	0,58
09.00-10.00	1,18	0,54	0,53	0,71	0,25	0,14	1,05	0,47	0,94	0,55	0,63	0,57
10.00-11.00	1,19	0,52	0,56	0,72	0,24	0,12	1,03	0,49	0,96	0,54	0,64	0,57
11.00-12.00	1,18	0,53	0,57	0,72	0,24	0,12	1,04	0,48	0,94	0,55	0,64	0,57
12.00-13.00	1,20	0,52	0,56	0,72	0,24	0,12	1,03	0,49	0,92	0,56	0,64	0,57
13.00-14.00	1,19	0,52	0,56	0,72	0,24	0,12	1,05	0,47	0,94	0,55	0,64	0,57
14.00-15.00	1,19	0,52	0,56	0,72	0,24	0,12	1,04	0,48	0,94	0,55	0,64	0,57
15.00-16.00	1,18	0,54	0,55	0,71	0,25	0,14	1,04	0,48	0,94	0,55	0,64	0,57
16.00-17.00	1,21	0,55	0,55	0,71	0,30	0,21	1,05	0,47	0,96	0,54	0,65	0,57
17.00-18.00	1,34	0,61	0,53	0,71	0,40	0,29	1,05	0,48	0,94	0,55	0,65	0,57
18.00-19.00	1,34	0,61	0,55	0,71	0,45	0,31	1,00	0,51	0,86	0,59	0,62	0,58
19.00-20.00	1,16	0,61	0,53	0,71	0,33	0,24	1,00	0,51	0,84	0,60	0,61	0,58
20.00-21.00	1,07	0,61	0,52	0,71	0,29	0,20	1,00	0,51	0,82	0,60	0,60	0,58
21.00-22.00	1,07	0,59	0,51	0,70	0,27	0,17	0,97	0,53	0,81	0,61	0,59	0,58
22.00-23.00	1,08	0,58	0,49	0,70	0,26	0,17	0,95	0,55	0,81	0,61	0,59	0,58
23.00-24.00	1,10	0,58	0,51	0,70	0,24	0,13	0,89	0,58	0,78	0,61	0,59	0,58
24.00-01.00	1,10	0,57	0,51	0,70	0,23	0,11	0,87	0,59	0,76	0,62	0,58	0,58

Based on the 50 samples generated from pre-processor of SimLab, heating energy demand for each sample during the Dutch heating season [assumed as 01.October-01.April] is calculated with 'one at a time' approach [see previous section], using a dynamic building simulation program. Both renovated and non-renovated reference building models are simulated with the 50 samples of ventilation behaviour, and the analysis of the results is conducted using the Monte Carlo statistical analysis method, in the post-processor of SimLab. Results are discussed in the next section.

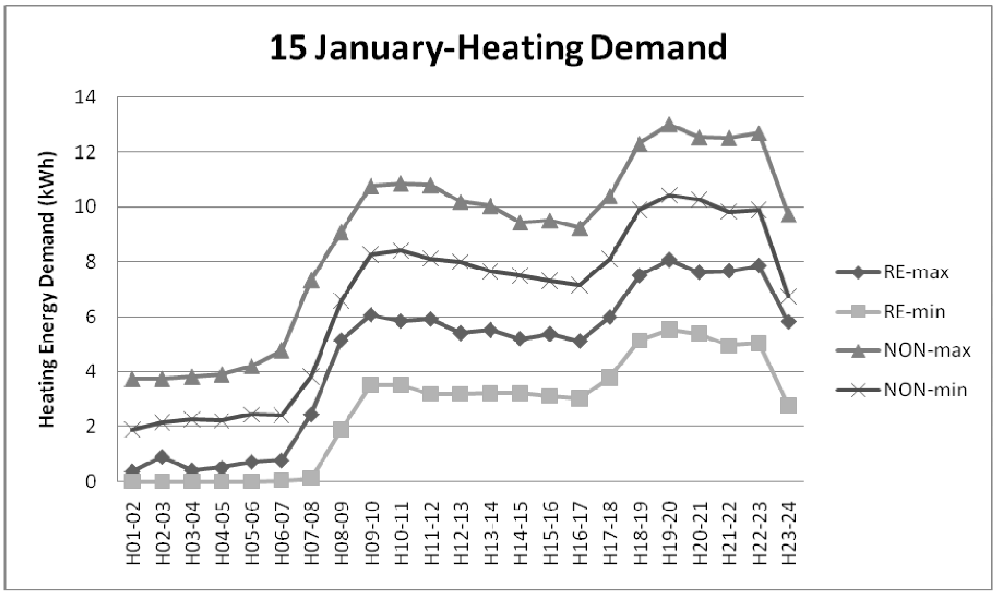
RESULTS AND DISCUSSION

Considering the great amount of hourly input and output data produced, representative days within the heating season are selected to facilitate interpretation of the results: 15.October, 15.January and 15.March. Discussion of the results, focusing on the comparison of the renovated and the non-renovated, is covered through: [1] comparison of the influence of the variations in daily ventilation behaviour on daily heating energy demand, and [2] on seasonal heating energy demand.

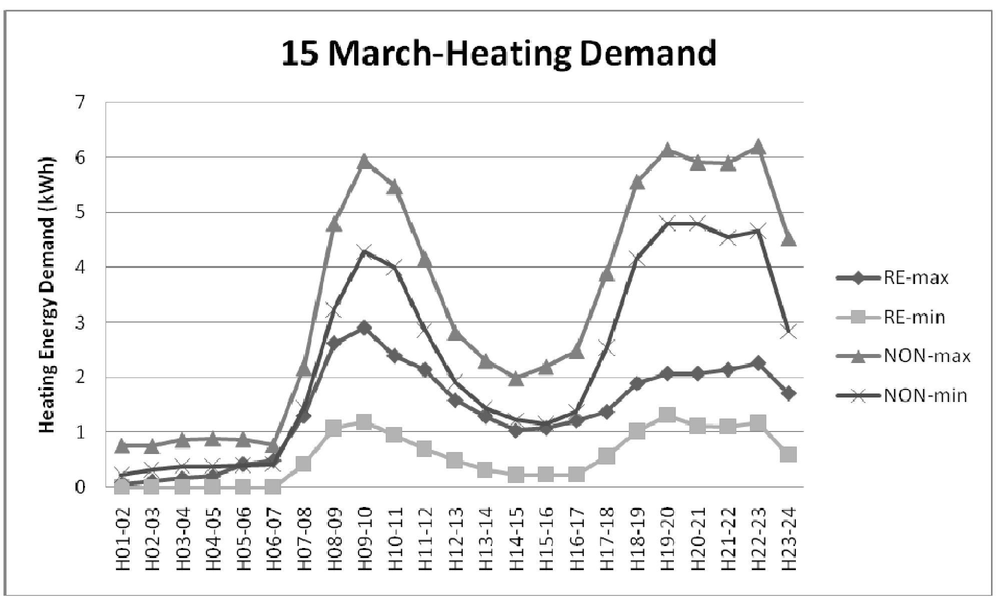
Daily heating energy demand of both renovated and non-renovated cases, regarding hourly ventilation behaviour of the occupants in each room showed that: On 15.January [Figure 3] heating energy demand of the non-renovated case is much higher than the renovated one. However, the changes in ventilation patterns seem not to be directly related with the resulting heating energy demand, occurring each hour. Similar non-relation could be seen on 15.March [Figure 4] and 15.October [Figure 5].

Heating energy demand of the renovated case displays the inference of heat conservation during early hours of the day, when occupants are present. However, this should not be interpreted as heating energy demand would be less during occupancy, than non-occupancy, because during evening hours presence results in increasing heating energy demand. For further evaluation, Monte Carlo analysis was conducted over the outputs of 50 samples. The results of Monte Carlo showed that:

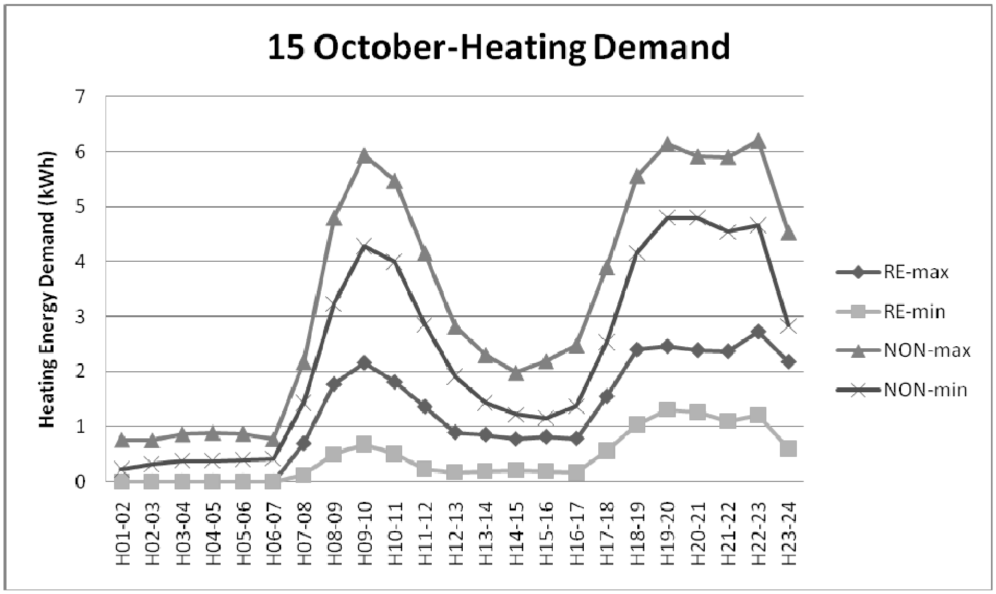
Based on the ventilation behaviour of 24 hours in living room, the hours that have the biggest impact on heating energy demand on 15th January, 15th March and 15th October differ in renovated and non-renovated cases. In non-renovated cases the biggest impact period is between 8 and 9 am. However, in renovated cases, the biggest impact periods are 11 and 12 am for 15 January, 8 and 9 am for 15 March, and 9 and 10 am for 15 October [Figure 3,4,5-Table 5].



[Re-: Renovated case, NON-:Non-renovated case]
Figure 3. *15.January daily heating energy demand change*



[Re-: Renovated case, NON-:Non-renovated case]
Figure 4. *15.March daily heating energy demand change*



[Re-: Renovated case, NON-:Non-renovated case]
Figure 5. *15.October daily heating energy demand change*

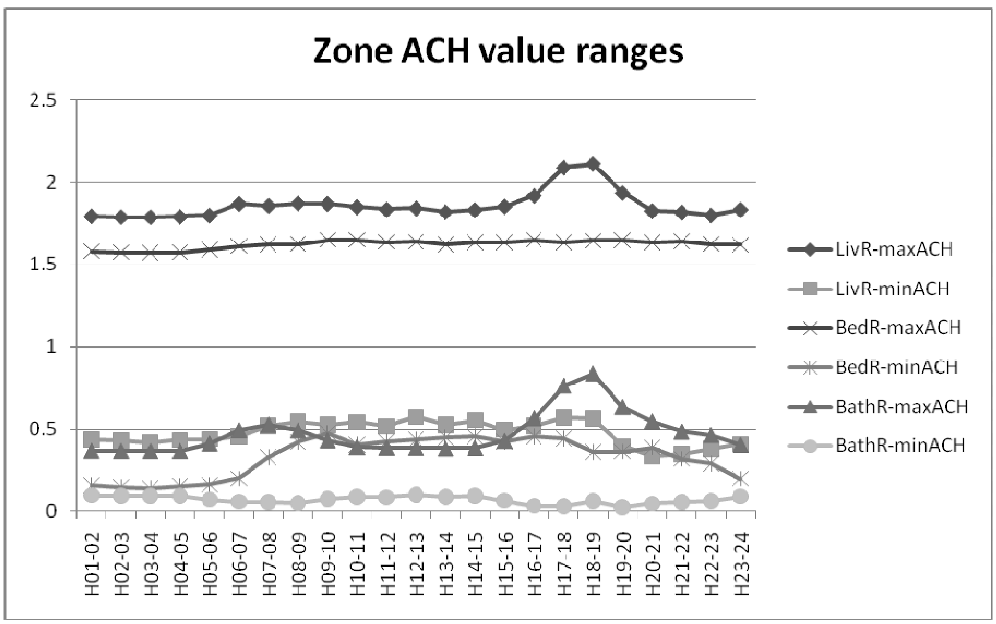


Figure 6. *Room ach values, minimum and maximum*

The seasonal heating energy demand analysis has been executed as well [Figure 7-8, Table 5]. The hours, that the ventilation behaviour influences the heating energy demand most are the same with the non-renovated case daily values, namely 8:00AM and 9:00AM. On the other hand, the values of correlation coefficients [PEAR] are closer to each other in the renovated cases than the non-renovated cases. This shows that, non-renovated dwellings are more sensitive to ventilation behaviour, considering the heating energy demand.

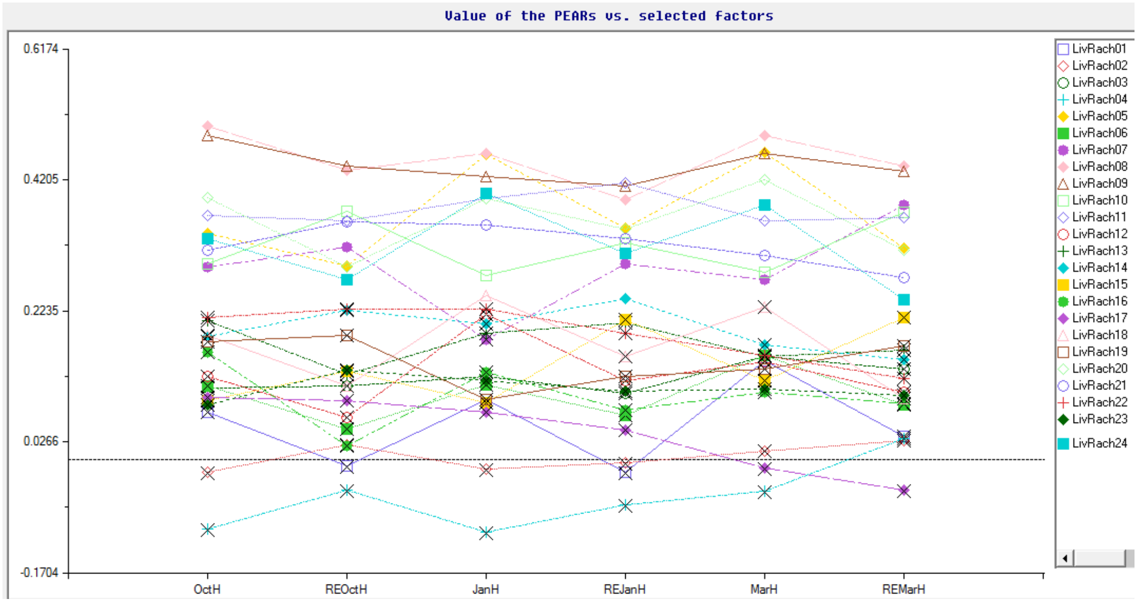


Figure 7. *PEAR factors for seasonal heating energy demand [non-renovated case]*

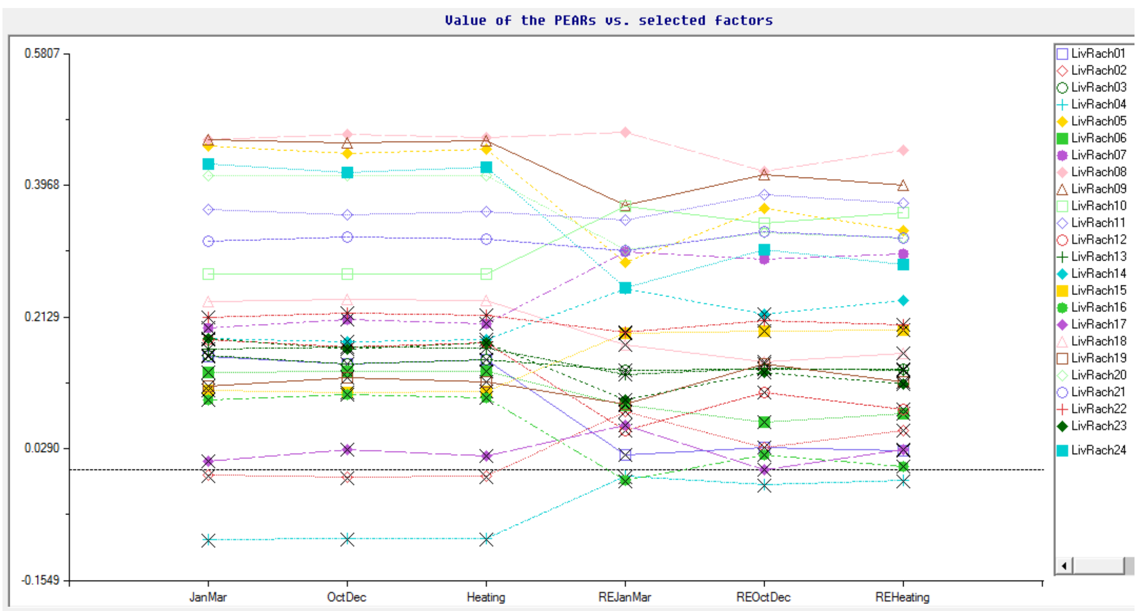


Figure 8. *PEAR factors for seasonal heating energy demand [renovated case]*

Table 5. *First five hours, ventilation behaviour is most influential on heating energy demand*

Rank	Non-Renovated Case						Renovated case					
	Daily heating energy demand PEAR values and related hours											
	15 October		15 January		15 March		15 October		15 January		15 March	
	Hours	PEAR	Hours	PEAR	Hours	PEAR	Hours	PEAR	Hours	PEAR	Hours	PEAR
1	08-09	0,502	08-09	0,461	08-09	0,487	09-10	0,441	11-12	0,417	08-09	0,442
2	09-10	0,487	05-06	0,460	05-06	0,463	08-09	0,435	09-10	0,411	09-10	0,435
3	20-21	0,394	09-10	0,425	09-10	0,460	10-11	0,374	08-09	0,390	07-08	0,383
4	11-12	0,368	24-01	0,401	20-21	0,421	11-12	0,359	05-06	0,348	10-11	0,373
5	05-06	0,341	11-12	0,393	24-01	0,384	21-22	0,358	20-21	0,346	11-12	0,364
	Heating season, heating energy demand PEAR value											
	Hours			PEAR			Hours			PEAR		
1	08-09			0,465			08-09			0,446		
2	09-10			0,459			09-10			0,397		
3	05-06			0,448			11-12			0,372		
4	24-01			0,422			10-11			0,359		
5	20-21			0,411			05-06			0,334		

CONCLUSION

In this paper, we focused on exploring the sensitivity of energy performance of a dwelling to occupant ventilation behaviour, considering the pre and post-renovation process. Results of this preliminary study showed that there is a correlation between occupant behaviour and heating energy demand of dwellings, and the more energy conservative the dwelling gets, the less it is sensitive to occupant behaviour.

However, this conclusion covers only ventilation behaviour, and it is necessary to include presence, and heating behaviour in further analysis. Energy performance simulations are conducted with one-at-a-time approach. In this case, only ventilation behaviour for each hour of the heating season was changed, while the rest of the behavioural variables left constant. This conclusion also directs us for further investigation.

In order to reveal the interrelations among different behavioural patterns, and their influence on the heating energy demand of dwellings, a further analysis is still under progress with 250 samples and three behavioural variables as presence, ventilation, and thermostat settings.

ACKNOWLEDGEMENT

This paper forms one part of Gülsu Ulukavak Harputlugil`s six months post-doc research in OTB Research Insititute for Built Environment/ Delft University of Technology, which is funded by Scientific and Technical Research Council of Turkey [TUBITAK].

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