Analysis of Thermostat Control Behaviour in Dwellings
Evidence from monitoring in the Netherlands

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ABSTRACT: Thermostat control behaviour is claimed to be an important aspect of energy consumption in dwellings. Relevant literature applies a variety of methods, mostly built on cross-sectional data. Although longitudional data possibly has a greater potential to explain the relationship between occupant behaviour and energy consumption, this sort of research is quite rare. This paper presents a first evaluation on the thermostat control behaviour in Dutch dwellings, based on monitoring data. The methodology includes a descriptive and a repeated measures analysis to reveal how the thermostat control pattern changes from day to day, weekdays to weekend, and between different weeks and months. Data was collected by monitoring 61 dwellings in the west Netherlands, for 2 months in Spring, 2011. The results of the study shows that, during two months, the thermostat control behaviour displays a significant varience.
Keywords: occupant behaviour, thermostat control, energy consumption, dwellings, monitoring

INTRODUCTION
The insight into the relationship between occupant behaviour and energy consumption has been advancing, especially for the last two decades. Relevant literature has approached the topic covering several perspectives, from defining behavioural patterns to finding determinants of consumption, exploring modelling potentials of occupant behaviour, and simulating it, in relation to different types of end use energy and environmental impact. Claiming that thermostat control behaviour is one of the most crucial aspects of energy consumption in dwellings [e.g. 1; 2], national programs on stimulating behaviour towards less use of heating energy have been put into effect, in addition to the several bottom up public and private initiatives, and research.

Existing research on understanding the relationship between occupant behaviour and energy consumption has utilized a variety of methodologies: Deductive: macro level, using cross-sectional data on dwelling, system, economical, energy consumption characteristics; and Inductive: bottom up, applying monitoring, using actual data on behaviour patterns of heating, ventilation, lighting and appliance use. It is well known that inductive and deductive research display a significant variance in explaining the sensitivity of energy consumption to occupant behaviour [For further reading: 3].

This paper scrutinizes thermostat control behaviour in Dutch dwellings, looking through data obtained by monitoring 61 dwellings during two months in Spring 2011. It also discusses monitoring as an approach towards understanding occupant behaviour and energy consumption relationship. A smart thermostat was designed for dwellings, which will display and record the chosen thermostat settings, energy consumption, weather, and traffic conditions. The methodology includes a descriptive analysis, followed by a repeated measures analysis to reveal how the thermostat use pattern changes from day to day, weekdays to weekend, and between different weeks and months.

LITERATURE
In this section, a summary of the important aspects of occupant behaviour and energy consumption, in relation to thermostat control behaviour are presented.

Energy Consumption in Dutch dwellings
Figure 1 and 2 display the gas and electricity consumption in Dutch Dwellings between 2000 and 2009. As electricity consumption slightly and steadily increases from 3230 kWh to 3558 kWh [average: 3384 kWh], yearly gas consumption decreases between 2000 and 2007, with a tendency of increase recently [average: 1725 m3]. As for gas use in detail, gas use for cooking reduces to half in 2009 [average 61 m3; 3% of total gas use], gas use for hot water and space heating reduces until 2009 with an average of 368 m3; 21% of the total gas use and an average of 1297 m3; 76% of the total gas use, respectively. These figures show that space heating, which is a function of thermostat control behaviour has by far the largest share [76%] of energy consumption in dwellings [4].

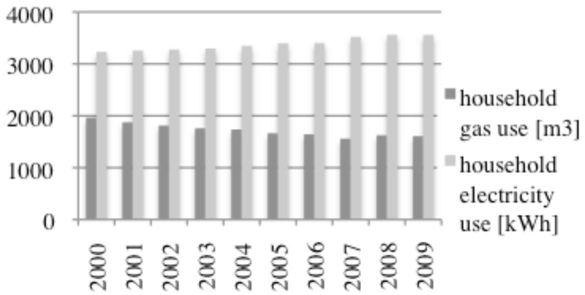

Figure 1: Gas and Electricity use in Dutch Dwellings [years]

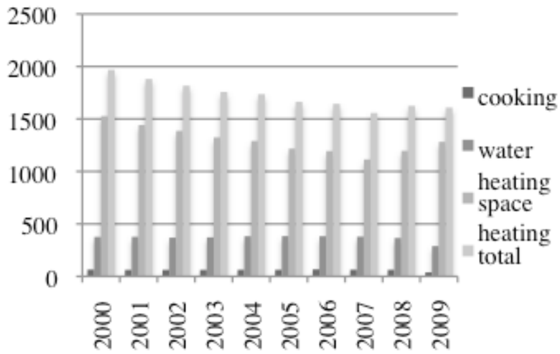

Figure 2: Gas use in Dutch Dwellings [m3/years]

Occupant Behaviour and Energy Consumption

Two main aspects of energy consumption in dwellings cover household and dwelling characteristics, which directly influence energy consumption, and indirectly influence energy consumption via occupant behaviour. Table 1 displays a review of the relevant literature [for further reading 5; 6; 7; 8].

Table 1: Characteristics affecting occupant behaviour [related with indoor comfort/health – energy performance]

Occupant characteristics				
Household [Social]	Educational		Economical	
-Age -Occupation -Culture -Lifestyle -Hobbies -Habits	-Awareness -Knowledge -Realization -Attitude -Motivation -Sensitivity		-Ownership -Energy use pattern -Income level	
Building characteristics				
Site-Climate	Building Envelope	Mass composition	Mechanical systems	Lighting-Appliances
-Urban layout -Weather: Solar radiat. Wind -Site: Noise Odour	-Air tightness -Material use -Insulation	-Floor heights -Window design -Special design elements	-Heating -Ventilation -Water heating	-Efficiency -Power -Smartness -Special design features

Guerra Santin's study [2] on the relationship between occupant behaviour and energy consumption in dwellings reveal that; the most important factor in energy use is the hours that the thermostat is at the highest chosen setting. Following is the number of hours that radiators are turned on and the number of bedrooms used as living area. These results go inline with the findings of Jeeninga et al., 2001; Haas et al., 1998; Linden et al., 2006; Hirst and Goeltz, 1985 [1; 9; 10; 11]. A more recent study also proves that heating energy consumption is the most sensitive to thermostat setting [12].

Existing research points to the necessity of more detailed investigation on thermostat control behaviour, in terms of the chosen temperature setting, the duration of the chosen temperature setting, but also how these preferences change over time.

Heating Behavioural Patterns

Energy Research Center of the Netherlands [ECN] and Research and Consultancy of Sustainability [IVAM] registered energy use in 180 dwellings and applied 2 questionnaires in 2000. The behavioural characteristics that influence energy use were found to be: The bandwidth in heating demand is mainly determined by set point heating temperature; When the participant keeps a record of their energy use, the set point heating temperature turns out to be lower; Preferred set points are not influenced by type of thermostat [programmable or analogue]; Participants with an analogue thermostat tend to more often adjust the temperature set point to a lower temperature, in case of a longer period of absence, than participants with a programmable thermostat [1].

User profiles and their behavioural patterns related to energy consumption for space heating have been defined with household characteristics such as household composition, income, age, education, and household size [13; 14; 15] and coginitive variables such as values, motivations, needs, and attitudes [15; 16; 17; 18]. In addition, Hens discusses habitual behaviour and reboud effect in relation to energy consumption, extensively [19]. Raaij and Verhallen [20] found that 5% of the variation in energy consumption could be explained by energy-related attitudes that could be categorized under price, environment, energy concern, health concern, and personal comfort.

In a recent study by TNO-ECN [20; 21] five groups of households were studied on the basis of consumption: Single inhabitant, couple, single-parent, family, and seniors. Four profiles were built: convenience/ease [comfort is of priority, saving money, energy or the environment is not a consideration], conscious [comfort is of priority, while environment and cost consideration appears], cost [awareness of energy costs, and saving money], climate/environment [concern for the environment].

Methodologies Used in Existing Research

Research about the influence of occupant behaviour on the energy performance of dwellings, have two different approaches: Deductive and inductive. The deductive approach deals with the problem in a macro level, considering household characteristics, income, rent, and energy consumption figures. This approach collects data by survey, and establishes correlative, regressive, etc. statistical models to explain the relationship. Frequently, these models estimate the influence of occupant behaviour on the energy performance of dwellings around 10%. The inductive approach, however, builts up on actual behaviour of heating, ventilation, lighting and appliances. It's bottom up models include simulation of probabilities, and consider presence as a precondition of behaviour. Data collection methods of this approach are mostly diary, and monitoring. Data processing techniques of this approach are generally more componental, such as Monte Carlo, Markov chain, S curve, probabilistic. These models suggest a greater influence of occupant behaviour on the energy performance of a dwelling [3].

In their early study, Vine e al. [22] mention about the difference between reported and monitored thermostat settings. Indeed, the limitation of the research conducted based on reporting behaviour, such as questionnaire, interview, self-reporting, etc. is that, it is based on how the occupant remembers their activity, which may be different than the actual. Besides, the data is cross-sectional, i.e., reported at one time about a continuous activity. Monitoring and observation seem to provide more precise, frequent, longitudional data, which fits better with the nature of behaviour; however, it is costly, time-inefficient, and its data collection technology needs further improvement.

This research follows an inductive approach, where actual behaviour and longitudional data collection is in focus.

METHODOLOGY

This paper covers 61 dwellings in the West of Netherlands. A smart thermostat was designed, to display weather and traffic data, in addition to the thermostat setting, indoor temperature, gas and electricity consumption. The smart thermostat has a function of recording past consumption figures, and could be managed both by programing and manually [Figure 3].

The recordings of thermostat setting during the months of March and April, 2011 are analysed for this paper. A descriptive analysis, followed by a repeated measures analysis are conducted to reveal how the thermostat use pattern changes from day to day, weekdays to weekend, and between different weeks and months.

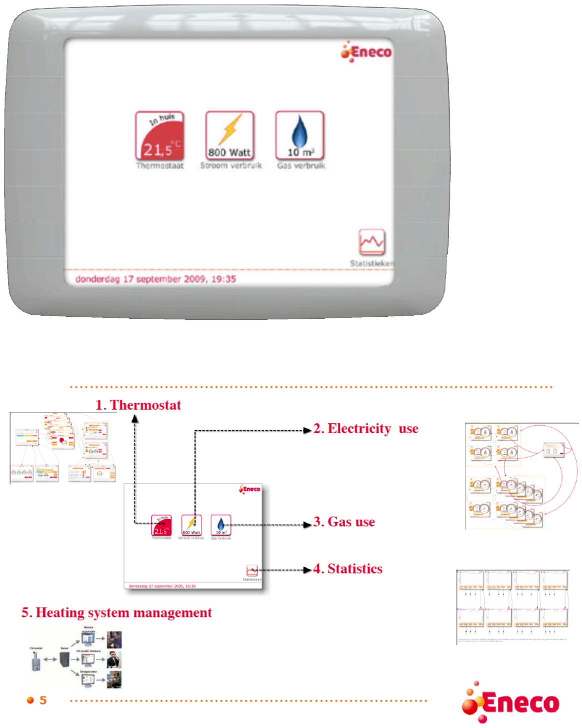

Figure 3: Smart thermostat front view and display functions

Main questions that are included in the scope of this paper:
- How do participants control their thermostats for one day? In different days? Between weekdays and weekends?
- How does the maximum and minimum chosen temperature settings change, in terms of the temperature, the time of the day, and the duration of the chosen setting?
- Are there common temperature preferences for certain parts of the day?

The descriptive analysis is conducted over the entire sample, and the repeated measures analysis on one of the dwellings [Dwelling code 13, D13].

RESULTS

Descriptive Analysis

Considering the whole sample size over 2 months, the distribution of chosen thermostat settings and the time of the day that those thermostat settings are chosen seem quite consistent [Figure 4]. However, the duration that the chosen thermostat setting stays active varies significantly [Figure 5]. For the entire sample, the average thermostat settings in the morning, during the day, in the evening, and at night are 18 C, 20 C, 20 C, and 16 C, respectively. The chosen maximum thermostat setting differ between 18 C and 21 C degrees. The maximum thermostat setting is chosen between 14:30 and 19:00 over the whole sample. The minimum thermostat setting remain constant at 15 C degrees [during the night between 23:00 and 06:00].

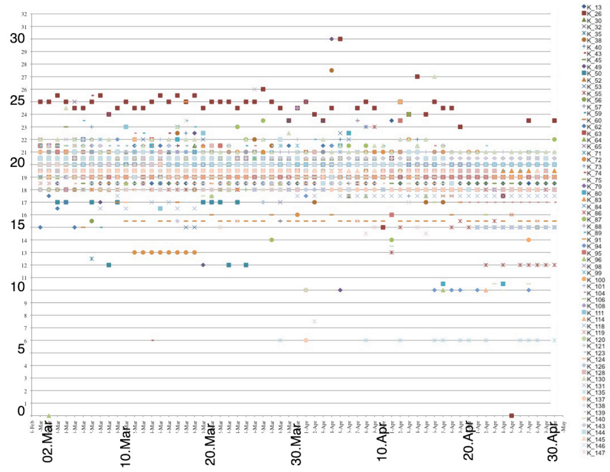

Figure 4: The distribution of maximum thermostat settings for all dwellings during March and April 2011

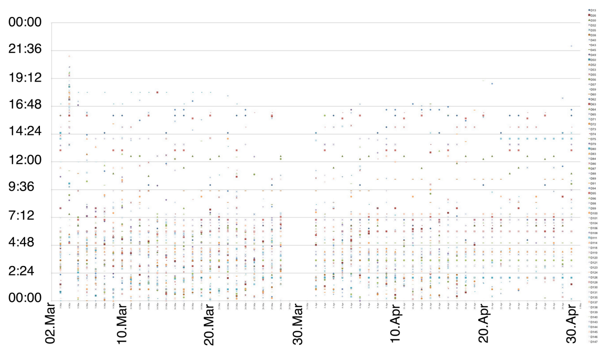

Figure 5: The distribution of duration of maximum thermostat settings for all dwellings during March and April 2011

In order to give an example, dwelling code 13 [D13] will be analysed in detail, here. Looking at the change over 2 months in the preferred maximum and minimum thermostat setting of D13, there is a significant change on 5 random days for the maximum, and 8 random days for the minimum thermostat setting. The main thermostat setting preferences are 18 and 15, respectively [Figure 6].

Both in March and April, between Monday and Thursday, the morning thermostat setting is 19 C degrees, and the day thermostat setting is 15 C degrees. From Friday to Sunday, the chosen thermostat setting in the morning and during the day is 15 C and 19 C, respectively [Figure 7].

Looking at the evening and night thermostat settings, during March and April, the preferred evening thermostat setting remains on 18 C degrees on average; in March at the weekends, the setting drops down to 15 C in the evenings, whereas in April the preference is an increase to 19 C in the evenings, at the weekends. As for the night thermostat setting, the preference is 15 C, constant [Figure 8].

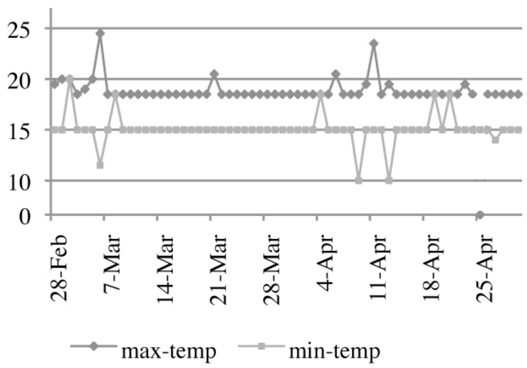

Figure 6: Maximum and minimum thermostat settings [D13]

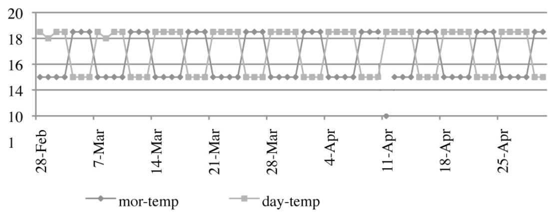

Figure 7: Morning and day thermostat settings [D13]

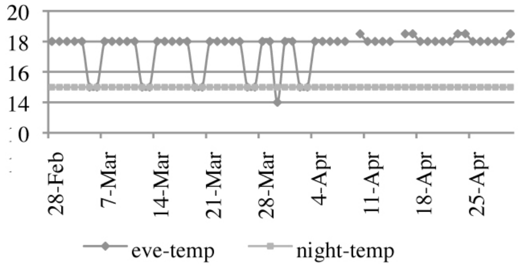

Figure 8: Evening and night thermostat settings [D13]

Repeated Measures Analysis

The results of the repeated measures analyses are:

Maximum thermostat setting: Mauchly's test indicated that the assumption of sphericity is not violated. F=1.63 p=.04 [p<.05]. March 5 and 7, 12 and 14, 19 and 21, 26 and 28 are found to be significantly different than the previous day. These days are the Saturdays and Mondays of March, which are also found to be different in the descriptive analysis [within subject contrasts test].

The time of the day the maximum thermostat setting is chosen: Sphericity is not violated, as displayed in the Mauchly's test. F=1.79 p=.002 [p<.05]. Besides, only 7 March maximum thermostat setting is found to be significantly different than 8 March. The rest of the days are likely to be related to each other**.**

Duration of the chosen maximum thermostat setting is active: Mauchly's test indicated that the assumption of sphericity is not violated. F=2.54 p=.45 [p<.05]. Test of within subject contrasts shows that almost everyday is significantly different than the other in terms of the thermostat setting.

Morning, day, evening, and night thermostat settings chosen: The assumption of sphericity is not violated in any tests. F=1.45 p=.005 [p<.05]; F=2.42 p=.02 [p<.05]; F=2.39 p=.043 [p<.05]; and F=1.29 p=0.037 [p<.05], respectively. The morning and day temperatures show significant difference on 4 and 7, 11 and 14, 17 and 20, 23 and 26, 29 March and 1 April, 4 and 7, 10 and 13, 16 and 19, 22 and 25, and 28 April. These are the Mondays and Fridays of every week. In terms of the evening temperature, significant differences are observed at the weekend-evenings in March.

DISCUSSION

Results of descriptive analysis on the whole sample and in D13 show that: The most constant thermostat control behaviour is, very predictably, at night [15 C, 23:00 and 06:00]. This does not change between weekdays and weekends, or in March or April. The maximum/minimum chosen thermostat settings differ between weekdays and weekends, probably because some households spend more time at home during the weekdays and some at the weekends; however, these settings do not change between March and April. This could be because of household habits or the stable weather conditions. Further research could be conducted for a correlation analysis between weather and thermostat control behaviour. Most importantly, it seems like, inhabitants do have a habit on the first change of setting, such as getting up in the morning, coming back home from work, going to bed at night, but how long the setting will be kept at the chosen temperature changes during the day and between different days.

The household D13 seem to have 4 day work-weeks. Their thermostat control behaviour is rather constant during the mornings and day time both in March and April. However, the evening thermostat setting preference seem to change from March to April between the weekdays and the weekends. They seem to have spent more time outside in the weekend-evenings during March, and at home at the weekend-evenings during April. Being at home or outside created a 3-4 C degrees change in the thermostat setting preference.

The results of the repeated measures analysis goes inline with the descriptives. Based on these results, the time of the day the maximum thermostat setting is chosen, we could claim that the variation we found in descriptive analysis is acceptable, therefore the household has a consistent behavioural pattern of thermostat control, in terms of the maximum thermostat setting.

CONCLUSION

This paper presents a first evaluation on the thermostat control behaviour in Dutch dwellings, based on monitoring data. It is important to scrutinize occupant behaviour using monitored data, because the variety of methods mostly built on cross-sectional data might not completely explain the continuous nature of behaviour.

Our results show that during two months, the thermostat control behaviour displays a significant varience, especially in terms of the duration of chosen thermostat setting. Together with the other results we found from maximum and minimum thermostat setting, the morning, evening and night settings, it seems likely that inhabitants have a habit of the first thermostat temperature they choose, after getting up, or just before going to sleep, but the duration of chosen setting is random. We did find a pattern for maximum/minimum and morning/day thermostat setting change between weekdays and weekends, and for weekend-evening thermostat setting between the months of March and April.

These results emphasize how different the reported behaviour could be different than the actual behaviour, and the details that longitudional data might reveal about occupant behaviour. Future work to this study will be about clustering thermostat control behaviour and correlating it to weather and energy consumption data for all seasons.

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