# 5 Analysis of thermostat control in dutch dwellings: occupants' behavioral profiles

## Introductory note

*In the previous Chapter we made a sensitivity analysis based on actual energy consumption and heating behavior, on the whole OTB sample using methods like Markov chain and Monte Carlo analysis. In this Chapter (Chapter 5) a deeper analysis of heating behavioral patterns is reported. The study included 61 houses randomly chosen from the Netherlands, monitored for 2 months during March and April 2011. The thermostat use patterns of households were studied as well as chosen maximum and minimum set points each day for the whole sample. Then these patterns were correlated with the household and dwelling characteristics of the sample. Unfortunately, the collected energy consumption data for this sample was not reliable to be included in the analysis.*

*This Chapter deals with the Research Question III-1 of this thesis:*
*(Chapter 1, Section 3, pg. 16-17)*
***" III. What are the behavioral patterns and profiles of energy consumption?***

*The sub-question is:*
*What are the behavioral patterns of thermostat control? How do they relate to the household characteristics, revealing behavioral profiles?"*

*The research reported in this Chapter was conducted by Bedir, borrowing the dataset of Sonja van Dam. The data was collected through monitoring, by and for Sonja van Dam for her PhD research, using ENECO's means of data collection. The analysis in this Chapter was done, and the paper was written by Bedir. The co-author has given permission to include this research in this thesis.*

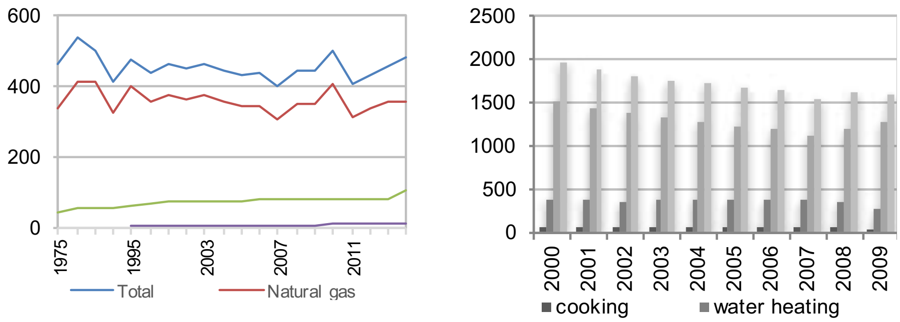
*This chapter is being prepared to be published as a scientific journal article. It was formerly published as a conference paper:*
*Bedir, M. Van Dam, S. (2013) Analysis of Thermostat Control Behavior in Dwellings: Evidence from monitoring in the Netherlands. Plea 2013, Proceedings of 29th Conference of Sustainable Architecture for a Renewable Future, Germany (CD)*

## § 5.1 Introduction

Heating energy consumption has the largest share in energy consumption of dwellings in the Netherlands. As the total yearly electricity consumption of Dutch dwellings slowly, but steadily increases between 1975 and 2014, the yearly natural gas consumption fluctuates, with an overall tendency of increase since 2007 (Figure 1-left (CBS, 2016)). Space heating, which is a function of thermostat control behavior, has by far the largest share (76%) of heating energy consumption in dwellings (Figure 1-right (SenterNovem, 2013)). Efforts in reducing the heating energy consumption have focused on improving thermal characteristics of the dwelling envelope, as well as the efficiency of systems and products. However, expected energy performance levels are not achieved, and significant energy consumption differences are observed in similar buildings. Occupant behavior is claimed to be one of the reasons for this variation (Jeeninga et al., 2001; Branco et al., 2004; Linden et al., 2006; Haas et al, 1998).

National programs on stimulating occupant behavior towards less use of heating energy have been put into effect, in addition to the several bottom up public and private initiatives (Jeeninga et al., 2001, and Guerra Santin et al., 2010). In addition, several studies have claimed that households can achieve more energy savings by changing occupant behavior (Papachristos, 2015; Ouyang et al., 2009; Wood et al., 2003; Darby, 2014; Røpke, 2012). Therefore, it is important to analyze the share of occupant behavior in energy consumption in detail.

Guerra Santin's study (2010) on the relationship between occupant behavior and heating energy consumption in dwellings reveals that the most important factor in energy use is the hours that the thermostat is at the highest chosen setting of the day. Following is the number of hours that radiators are turned on, and the number of bedrooms used as living area. These results go in-line with the findings of Jeeninga et al., 2001; Haas et al., 1998; Linden et al., 2006; Hirst et al., 1985; Harputlugil and Bedir, 2016. In existing research, factors related to energy conservation in dwellings have been identified, as well as the occupant characteristics that are related to higher levels of energy consumption. These studies point to the potential of energy consumption reduction, if energy efficiency policies are articulated according to different behavioral profiles (van Raaij et al., 1983; Poortinga et al., 2005; Guerra Santin, 2010; van Dam, 2013). More research on occupant behavior would help in analyzing and predicting behavioral patterns and profiles, and their relationship to heating energy consumption.




1 Total energy consumption (Pj/years)

2 Gas use in Dutch dwellings (m3/years)

FIGURE 5.1 Dutch averages for energy consumption and gas use

Existing research uses methodologies based on reported and/or monitored behavior data (Bedir et al., 2011; Vine et al., 1989), where the former has limitations on data being cross-sectional (collected once, at a certain time) and based on memory, and the latter has limitations on data collection being costly, time-inefficient, and requiring technological improvement. The other challenges of research on occupant behavior are further explained as the retrospective methods of data collection by the energy companies, the assumed usage patterns of systems and appliances in most calculation tools, the uncertainties in collecting and analyzing data, and the issues of energy performance gap (Guerra Santin, 2010; Dasa Majcen, 2016). More detailed investigation of thermostat control behavior is needed, in terms of the chosen temperature setting, the duration of the chosen temperature setting, but also how these preferences change over time and how they relate to household and dwelling characteristics, and behavioral attitudes. This means that a combination of different methods, collecting data via questionnaire, interview, and monitoring would be the most insightful when working on occupant behavior. However, the amount of this kind of research is small, and the resolution of data on occupant behavior is still rather low.

Our research investigates thermostat control behavior in 61 Dutch dwellings in detail, using an applied questionnaire on household and dwelling characteristics, and behavioral attitudes, as well as monitoring data on chosen thermostat settings collected by a home energy management system (HEMS) for two months in Spring 2011. The aim of our research is to (1) determine the behavioral patterns related to energy consumption for space heating, based on monitored thermostat control behavior, (2) find the household and dwelling characteristics and behavioral attitudes that are related with the behavioral patterns, based on data collected with questionnaire. This leads to determining the behavioral profiles. The paper also evaluates monitoring as a methodology for understanding the relationship between occupant behavior and energy consumption. The research covers data from 61 dwellings monitored for 2 months, hence our results would not be representative of the whole population. To deal with this limitation, we compare our findings with former research. In addition, comparisons with Van Dam's work (2013) are made, who researched the same sample using a questionnaire, interviews and focus group discussions.

The methodology of this research includes a descriptive analysis of thermostat control, followed by a repeated measures analysis to reveal how the thermostat control behavior have changed from day to day, weekdays to weekend, and between different weeks and months. Hierarchical cluster analysis is used to determine behavioral patterns of thermostat use. Patterns also refer to reliable acts, tendencies or other characteristics of a person or group. Based on this, the patterns that emerge in thermostat control need to be considered together with the characteristics of the occupant (Van Dam, 2013). Thus, behavioral profiles are determined based on the occupants' patterns of thermostat use; and the household characteristics, dwelling characteristics, and behavioral attitudes.

Our work contributes to the literature by: (1) combining different methods that brings together continuous data on actual behavior, and cross-sectional data like household and dwelling characteristics, and (2) deriving behavioral patterns and profiles and linking them to each other. Determining behavioral profiles using continuous actual behavior data could lead to more accurate prediction of energy consumption in dwellings, as well as planning the targeted energy saving measures, and helping energy companies for better calculations. In addition, this research could provide more detailed and articulated input to further research and policy, which focus on motivating/encouraging individuals and households towards more energy efficient behavior. Defining behavioral patterns and profiles could provide significant input to product/systems design and architecture.

Section 2 provides the literature related to the topic; Section 3 presents the research framework, methodology, and data; and Section 4 the results of the analyses. Section 5 and 6 are dedicated to the discussion and conclusions of this work.

## § 5.2 Literature Review

In this section, we present the studies that have focused particularly on occupants' heating behavioral patterns and profiles, in relation to household characteristics (Lutzenheiser, 1993; de Groot et al., 2008; Paauw et al., 2009), lifestyle (Poortinga et al., 2005; de Groot et al., 2008; Paauw et al., 2009; Assimakopoulos, et al., 1992; Tyler et al., 1990) cognitive variables such as values, motivations, attitudes (Poortinga, 2005; Vringer, 2007), and routines and habits (Gram-Hanssen et al., 2004; Gram-Hanssen, 2002; Shove, 2003). Lutzenheiser's (1993) theoretical evaluation based on a literature review on modeling household energy consumption analyzed the engineering, economical, psychological, sociological and anthropological models of energy consumption in US. He proposed a new cultural model, which is built on "recognizable lifestyles or cultural forms". In his work, these were classified under typologies such as retired working class couples, middle aged couples, low income rural families, suburban executive families, and young urban families.

In the Netherlands, van Raaij and Verhallen were the pioneers of energy profiling (1983). They identified 5 profiles (single inhabitant, couple, single-parent, family, and seniors) of energy behavior based on education, household size, and energy consumption among 145 households in the Netherlands and 5 patterns: Conservers (higher education, smaller household size), spenders, cool, warm (oldest group) and average. They found no differences regarding income and employment parameters. The research of Groot et al. (2008) and Paauw et al. (2009) developed 4 profiles of energy consumption: convenience/ease (comfort important, no interest in economic savings, energy, or the environment (EEE)); conscious (comfort important, interest in savings for EEE), cost (awareness of economy and hence energy and the environment); and climate/environment (concern for EEE). Raaij, Groot and Paauw's work found statistically significant differences in energy consumption among their groups.

Poortinga et al.'s survey (Poortinga et al., 2005) of 455 households in Dutch dwellings showed that seniors, single residents and low-income households were less willing to apply energy saving measures at home, and the acceptability of these measures varied among different socio-demographic groups. Vringer's work (2007) grouped households in the Netherlands according to income, age, education and household size. He found no significant differences in the energy consumption of groups of households with different value patterns, though he did establish that families that were least motivated to save energy used 4% more energy.

Guerra Santin's research (2010) on 319 dwellings about profiling household heating energy consumption revealed 5 groups according to the use of appliances, and heating and ventilation systems: (1) Spenders: use of more space, more use of electronics, more hours of heating, more hours of ventilation, no energy-saving concerns; (2) Affluent-cool: use of more space, more hours of ventilation; (3) Conscious-warm: use of more space, more use of electronics, more hours of heating, fewer hours of ventilation, energy-saving concerns; (4) Comfort: more use of electronics, more hours of heating, more hours of ventilation; (5) Convenience-cool: more use of electronics, more hours of ventilation.

In relation to the behavioral patterns of use of HEMS, literature reveals that there are big differences among households in the use of HEMS (Ueno et al., 2006). Van Dam et al. (2013) claimed that households who save energy, use the control systems more. Liikkanen (2009) identified three profiles of occupant behavior: the wisdom seekers, the detectives, and the judges, based on the consumption figures of an energy meter for individual devices that occupants used for one week. Van Dam's research (2013) focused on qualitative methods like interviews and focus group discussions over 50 households, and it categorized 5 groups of occupant patterns of HEMS: (1) Techies, who love gadgets and feel at home with products that look technical, who keep track of their energy consumption and see it as a hobby, are less motivated to save energy. (2) One-off occupants, who, like techies, are technically inclined and love gadgets, are interested in the consumption of individual appliances. (3) Managers, who do not necessarily have any affinity with technical things but like to keep a watchful eye out, may or may not go for energy saving consequently. (4) Thrifty spenders, who are like managers, but are motivated by money rather than altruism, have learned about thriftiness and energy saving ingrained in their behavior. (5) Joie de vivres, who enjoy living to the full, are not overly interested in energy or keeping track of their meter readings.

Research about occupants' behavioral patterns of thermostat control focus on behavioral characteristics of household size, composition, age, income, education, urban/rural background; and considerations of comfort, cost, energy, environment for behavioral patterns. In our work, we used these parameters in the analysis of behavioral patterns and profiles. Existing research uses two different methodologies that are based on cross-sectional vs longitudinal data collection, and very few have combined the two. Our work contributes to the literature by combining the two, and deriving behavioral patterns and profiles, and linking them to each other. This might provide deeper insight into reasons and motivations of behavior, in addition to the possibility of understanding long term behavioral changes. Determining behavioral profiles using continuous actual data on behavior could lead to more accurate prediction of energy consumption in dwellings, as well as planning the targeted energy saving measures. In addition, this research could provide more detailed and articulated input about occupant behavior in product and systems design, and architecture.

## § 5.3 Methodology

### § 5.3.1 Research Framework and Methods

In this paper, occupant behavior is considered as the actual behavioral patterns of thermostat control of the occupants. Patterns refer to a reliable sample of traits, acts, tendencies or other observable characteristics of a person, group or institution. This suggests that the patterns that emerge in thermostat control need to be considered together with the characteristics of the occupant (Van Dam, 2013). For a coherent description of the occupants' thermostat control behavior and the significant differences among them, the results of our analyses are clustered according to the types of behavior and types of occupants. Types of behavior are named as behavioral patterns; types of occupants are named as behavioral profiles. This paper also presents an evaluation of monitoring as a method for understanding the relationship between occupant behavior and energy consumption.

In order to determine the thermostat control patterns, we analyzed the quantitative data collected for 2 months in Spring 2011, from 61 dwellings by monitoring their use of home energy management systems, as well as the questionnaires filled in by households. Afterwards we compared our results with existing research, especially with Van Dam's work (2013) on the same sample, which had used the qualitative data collected with interviews and focus group discussions. Data collection and quality of data is further explained in Sub-section 3.2.

The maximum and the minimum thermostat settings were analyzed for the whole sample during the months of March and April 2011. The main chosen thermostat set points, and the durations of these set points were clarified during the morning (06.00-12.00), day (12.00-17.00), evening (20.00-22.00), and night (22.00-06:00) of everyday. Repeated measures analysis was conducted to reveal if and how the thermostat set points change in different cases from day to day, during two months. As a second step, (agglomerative) hierarchical cluster analysis was applied on the sample to see how the cases group in terms of their thermostat control behavior. This means that, the clusters were set up first based on the change of thermostat set point during the two months, and secondly based on selected thermostat set point temperature and duration. Correlation analysis was used to relate the thermostat control patterns to household, dwelling characteristics, and behavioral attitudes, which provided us with behavioral profiles (Figure 2 and 3). Lastly, the thermostat control patterns and profiles we found were compared former research.

The main questions of this research are:

- What are the thermostat control patterns derived by observing the long-term use of home energy management systems?
- How do the maximum and minimum chosen thermostat 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?
- How do these relate to the household, dwelling characteristics, and behavioral attitudes? and which behavioral profiles are revealed?

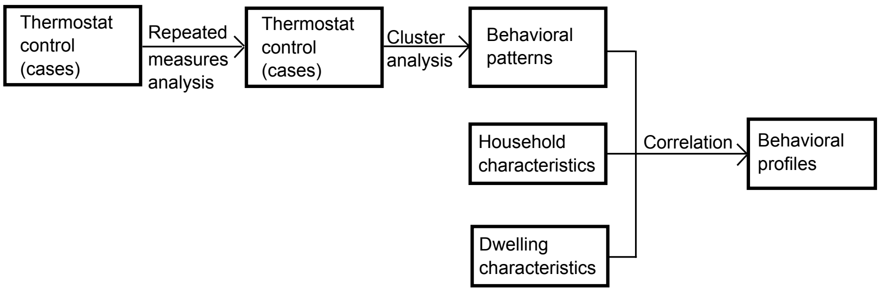



FIGURE 5.2 Research methodology

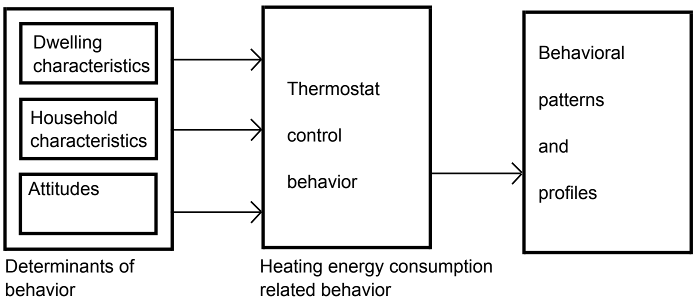



FIGURE 5.3 Research methodology: Research framework

## § 5.3.2 Data Collection

Data was collected from 61 dwellings in the Netherlands, during March and April 2011. The details of monitoring and questionnaire is explained in Table 1 and Figure 4. For selection of the households involved in the study, the client database of an energy company was used. A questionnaire was sent out to the households in the database with questions on the household's technical installations, demographics and environmental concerns, and participants were asked if they would accept to be part of a monitoring study. 61 households were included in the monitoring. Participants for monitoring were selected under the condition of forming a distributed mix of the Dutch population in terms of age, gender and education. Additionally, they did not have specific affinity with energy consumption through their work.

### § 5.3.2.1 Monitoring

The multifunctional HEMS consisted of an 8" touchscreen, 0–2 sensors for the gas and electricity meter, 1–2 transmitting units for the meters, an adapter and depending on the house 0–3 repeaters (to increase the signal strength of the wireless communication between transmitting unit(s) and the display). Communication between the parts happened by means of z-wave, but a wireless router was also installed for communications with the energy provider and the manufacturer. All households were to receive the same hardware, although there were variations in the peripheral devices to fit the different types of meters installed. A visualization of the HEMS can be found in Figure 4. The multifunctional HEMS was installed at the same location as the home's previous thermostat (because of the existing wiring infrastructure). This location was almost always the living/dining room and often near the entrance from the hallway, although the HEMS was occasionally installed in the hallway (Van Dam, 2013).

Monitored data was recorded with half a minute intervals. This data included thermostat set point temperatures, the time that thermostat set point was changed, the number of times that the thermostat screen was touched. Real time data on energy consumption was proved to be not reliable, therefore it was excluded from the analysis.

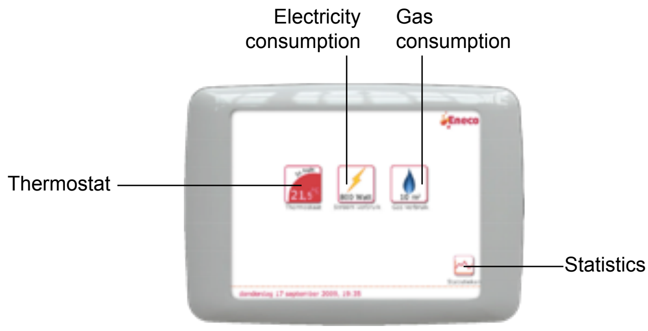



FIGURE 5.4 Multifunctional HEMS used to collect dataset 2

## § 5.3.2.2 Questionnaire

In addition to the monitored data, a questionnaire was applied over the whole sample, where respondents were asked about the dwelling type and size, energy tariff, household size, gender, year of birth, education and income level, day time and night time temperature preferences (based on how much they remember), who made energy related decisions in the household, energy saving measures, which time of the day/ daily activity thermostat control was related to, if the household had an understanding/awareness of their consumption, how much they followed their consumption from the previous and the current year, if they used a programmed thermostat setting, if they used, or got used to using some functions like continuous, free day, not at home, etc. (Table 1). The questionnaire was applied before the monitoring.

## § 5.3.3 Limitations

45 households' monitoring data was used over the sample size of 61. 8 households did not provide reliable data in March and April, and 8 cases for either March or April. Besides, 4 April and 12 April 2011 were the days that monitoring was problematic for all households. For minimum set point temperature, monitoring data of 19 and 21

April included outlier data. The measured energy consumption data by the HEMS was not reliable, therefore this study only explored thermostat control behavioral patterns, but could not research their relationship to energy consumption. Another limitation was that the data was collected from the consumers of one energy company. Being the subscriber of this company might mean essential differences between this group and the rest of the households in the country, in terms of values, attitudes, etc. Lastly, the Hawthorne effect (McCarney et al., 2007) must be mentioned, i.e. the participants of monitoring were aware that their heating thermostat control behavior and energy consumption was being observed and recorded.

| Group | Parameter | N | Mean | SD |
|---|---|---|---|---|
| Thermostat use | Number of set temperature change times | 45 | 3.89 | 1.03 |
| | Number of thermostat control touch times | 45 | 8.71 | 5.60 |
| | Monitored temperature day time (C degrees) | 45 | 18.8 | 1.70 |
| | Monitored temperature night time (C degrees) | 45 | 14.48 | 2.19 |
| | Reported temperature day time (C degrees) | 45 | 19.94 | 0.96 |
| | Reported temperature night time (C degrees) | 45 | 15.55 | 1.61 |
| Household characteristics | Household size | 45 | 5.25 | 1.25 |
| | Person decides on energy control in the house | 45 | 3* | 0.83 |
| | Gender | 45 | 1* | 0.42 |
| | Birth year | 45 | 1973 | 9.95 |
| | Education | 45 | 5* | 2.24 |
| | Total income (Euros) | 45 | 4* | 1.05 |
| | Day/night energy tariff | 45 | 1** | 0.46 |
| Dwelling characteristics | Dwelling size (m2) | 45 | 110 | 38.2 |
| | Owned/rented house | 45 | 1*** | 0.35 |
| | Type of house | 45 | 3** | 1.25 |

TABLE 5.1 Descriptive statistics of parameters about thermostat use, household and dwelling characteristics, reported attitude and behavior, during the two months monitoring continued.

| Group | Parameter | N | Mean | SD |
|---|---|---|---|---|
| Reported behavior (or attitude) | I change the thermostat when I get up | 45 | 1a | 0.75 |
| | I change the thermostat before I leave the house | 45 | 2b | 1.37 |
| | I change the thermostat when I get home | 45 | 1a | 0.31 |
| | I change the thermostat before I go to sleep | 45 | 1a | 0.96 |
| | I check current temperature and time | 45 | Y: 40 | N: 5 |
| | I adjust the temperature manually | 45 | Y: 34 | N: 11 |
| | I set up a thermostat program | 45 | Y: 32 | N: 23 |
| | I check electricity consumption | 45 | Y: 28 | N: 27 |
| | I check gas consumption | 45 | Y: 28 | N: 27 |
| | I set a saving target button | 45 | Y: 8 | N: 37 |
| | The number of energy saving measures I take | 45 | 53 | 1.33 |
| | I use 'continuous' button | 45 | 2c | .73 |
| | I use 'not at home' button | 45 | 2c | .83 |
| | I use 'free day' button | 45 | 2c | .69 |
| | I use 'holiday' button | 45 | 2c | .41 |

Notes:
3*: couples take energy-relevant decisions together
1*: male
5*: LBO
4*: 34.000-56.000 euros
1**: Day/night energy tariff
1***: owned house
3**: corner house
1a: everyday
2b: once a week
2c: sometimes

TABLE 5.1 Descriptive statistics of parameters about thermostat use, household and dwelling characteristics, reported attitude and behavior, during the two months monitoring continued.

## § 5.4 Results

Considering the whole sample over 2 months, the distribution of (1) chosen thermostat settings and (2) time of the day that those thermostat settings were chosen, seemed quite consistent (Figure 5); however, the duration that the chosen thermostat setting stayed active varied (Figure 6). In this section, first, the results of total monitoring data analysis on 45 households is presented, i.e. times of thermostat change vs screen touch; mean morning, day, evening, and night minimum and maximum thermostat setting preferences of the whole sample, and durations of chosen thermostat settings, per day. Secondly, the behavioral patterns that were found with hierarchical cluster analysis are explained. Lastly, the behavioral profiles created by relating the patterns (clusters) to household and dwelling characteristics, and behavioral attitudes are reported.

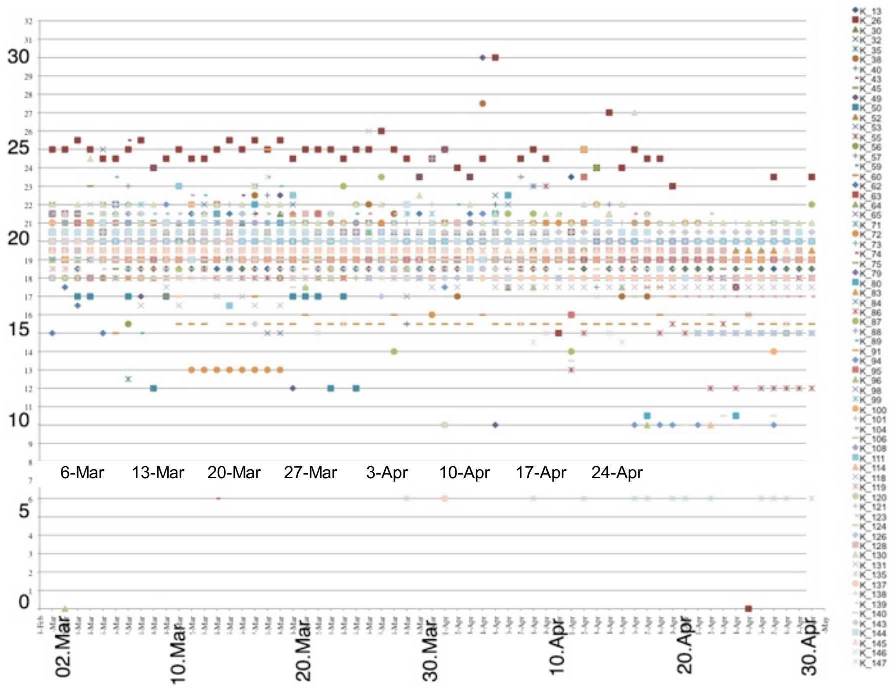



FIGURE 5.5 The distribution of maximum and minimum thermostat settings over two months (C degrees (vertical axis) /days (horizontal axis))

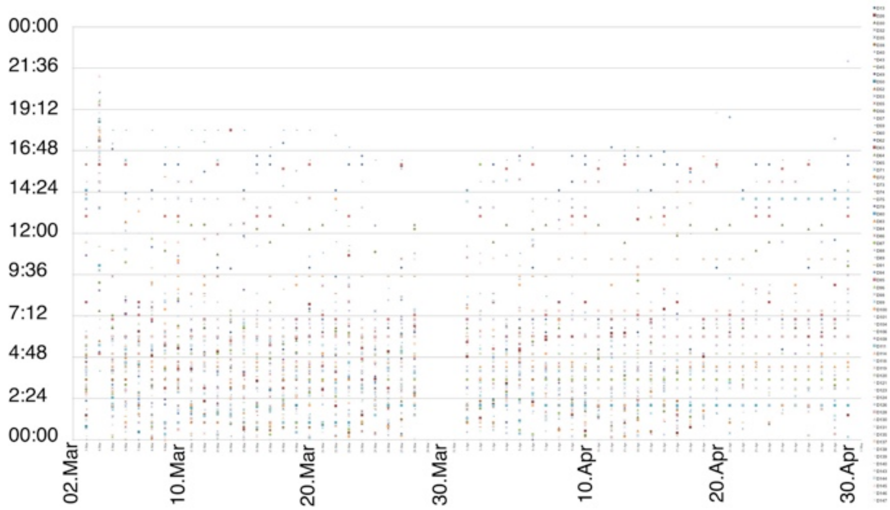



FIGURE 5.6 The distribution of duration of maximum and minimum thermostat settings (hours/days)

## § 5.4.1 Monitoring outputs of thermostat control, for the whole sample

While the touch screen of the HEMS was used between 4 times and 11 times per day, the times of actual thermostat setting change was between 2 times and 5 times on average. The difference could be because the other functions of the home energy management system were used as many times as the thermostat setting function (Figure 7).

For the entire sample, the average thermostat settings in the morning, during the day, in the evening, and at night were 17 C, 18.5 C, 17 C, and 15 C degrees, respectively. The duration of the chosen setting was on average 2 hours in the morning, 3:30 hours during the day, 4 hours in the evening, and 8 hours at night (Figure 8).

For the whole sample, the mean-maximum chosen thermostat set point was 21 C degrees, and was set between 14:30 and 19:00. The mean-minimum thermostat setting remained at 13 C degrees, during the night between 23:00 - 06:00 (Figure 9).

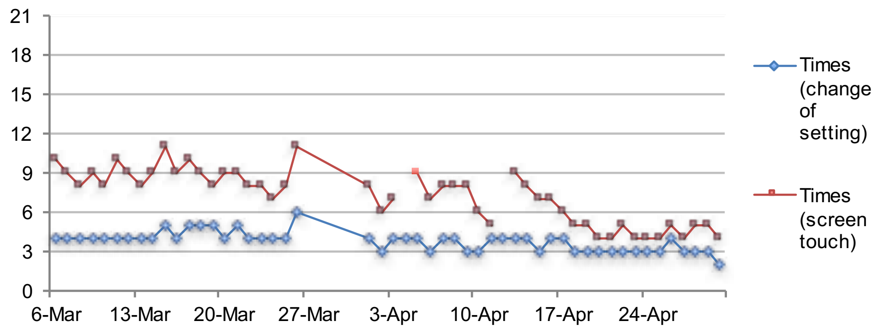



FIGURE 5.7 Times of thermostat setting change and screen touch for the whole dataset (number (vertical) / days (horizontal))

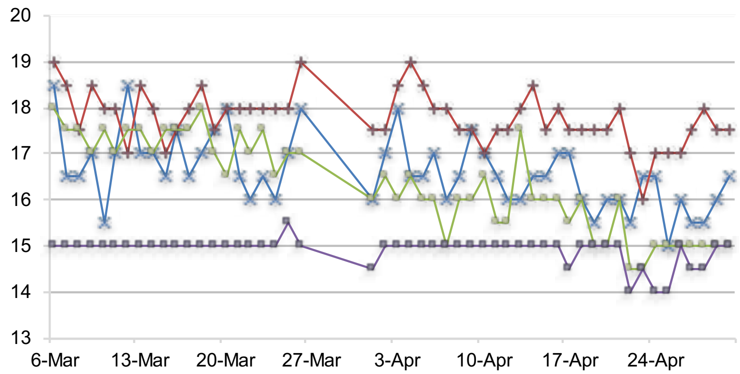



FIGURE 5.8 Average set temperature change during two months over the whole sample (C degrees (vertical) / days (horizontal))

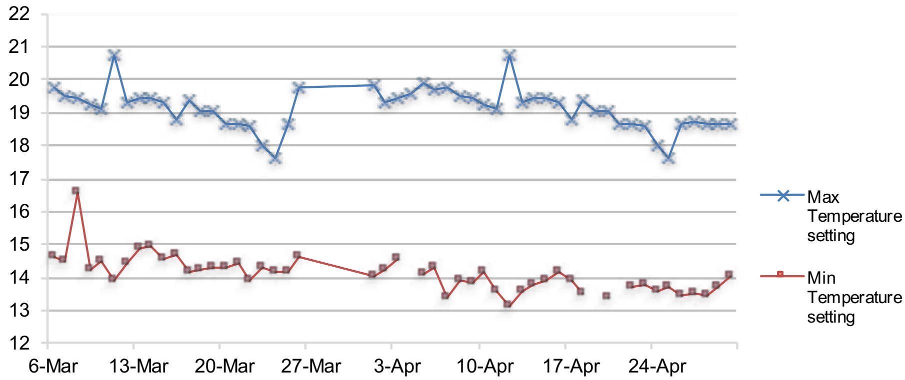



FIGURE 5.9 Maximum and minimum temperature setting change during two months over the whole dataset (C degrees (vertical) / days (horizontal))

## § 5.4.2 Thermostat control patterns

In this section, analysis results of the actual thermostat control behavior both from the questionnaire and from monitoring are presented. Thermostat screen touch times was found to be correlated with the temperature changing times (r=.48, p=<.01), and the number of households that changed the thermostat setting immediately when they arrived home (r=.67, p=<.01). This means that the HEMS was used for thermostat control as a major function, and occupants might be changing thermostat setting prior to major shift of behavior in daily life, and occupancy of the house.

Monitored night time temperature setting was correlated with that of the reported (r=.55, p=<.01), however, there was no correlation between the reported and monitored day time temperature (Figure 10). Reported night time temperature setting was correlated with the use of 'continuous' setting (r=-.52, p=<.05). These together might mean that most of the time questionnaires report the behavior that the occupant remembers, and not the actual one. It is easier to remember the night time thermostat setting because it's a single, continuous period of the day and not interrupted with activities, the same cannot be claimed for the day.

Reported night time temperature setting was correlated with specific thermostat use pattern (r=.42, p=<.05), and with the number of households that changed their thermostat setting when the occupant arrives at home (r=-.52, p=<.05). In addition, the use of 'not at home' setting was found to be correlated with the use of 'free day' setting (r=.61, p=<.01). These meant that the set programs, free day/continuous/not at home settings were usually activated when there would be an undivided activity at home, i.e. sleeping (night time), or when the occupants knew that the house would be unoccupied for a period. In addition, the function settings of ‘free day’ ‘not at home’ ‘continuous’ were possibly used interchangeably.

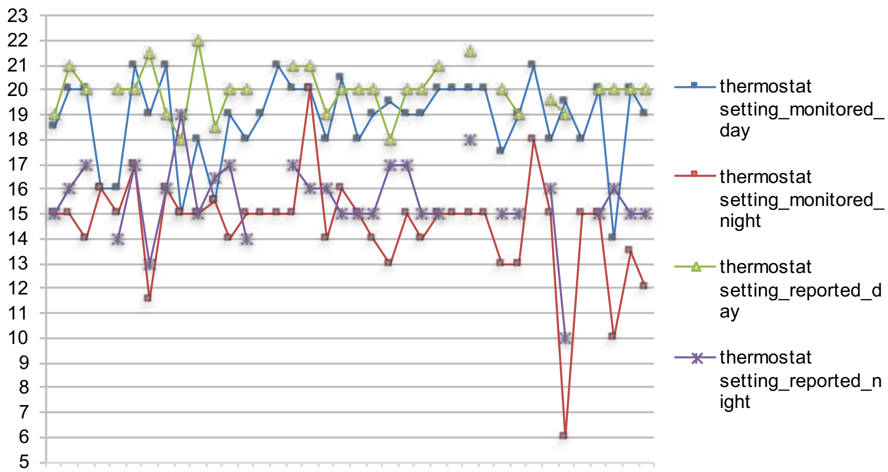



FIGURE 5.10 Monitored vs Reported day and night time thermostat settings (C degrees (vertical) / days (horizontal))

## A Repeated measures analysis

We applied repeated measures analysis for every household in the sample, for the chosen morning, day, evening, and night time settings and durations.

For 7 households, Mauchly’s test indicated that the assumption of sphericity was violated (X2(5)= 10.23, p=0.45). We did not make a correction for the degrees of freedom in the repeated measures analysis, because our aim was to only explore the significant change in thermostat set point temperature and duration. We interpreted this as the thermostat set point temperature and its duration being different for 7 households, for morning, day time, evening, and night, in the consequent days of March and April 2011.

This left us with a group of 38 households. For the morning thermostat set point and duration (for 26 households), sphericity was not violated, as displayed in the Mauchly's test ($F=1.79$ $p=0.65$, and $F=2.54$ $p=0.55$, respectively). For a group of 12, sphericity was violated in the repeated measures test for the morning and evening set point durations ($X2(4)= 9.12$, $p=0.049$ and $X2(5)= 8.47$, $p=0.044$). This meant that this part of the group had no duration pattern for the morning and evening periods. For the chosen day, evening, and night thermostat settings, the assumption of sphericity was not violated in any tests ($F=1.55$ $p=0.065$; $F=1.62$ $p=0.056$; $F=1.45$ $p=0.059$, respectively). For the chosen day, evening (for 26 households), and night set point durations, sphericity was not violated in any tests ($F=2.42$ $p=0.062$; $F=2.39$ $p=0.071$; $F=1.29$ $p=0.062$, respectively). This meant that each case had a pattern of thermostat control behavior for 2 months, coherent with itself for the mentioned periods.

Afterwards, we started reading the data in detail, the preferred thermostat settings and the durations, for each household, every day. The common patterns that were immediately visible were that some households preferred a single thermostat setting and duration per part of the day, every day; while others had different choices for different days of the week continuous in March and April. We continued to analyze the sample of 38 houses based on the morning/day/evening/night set points and durations, and we used cluster analysis for this.

## B Hierarchical cluster analysis

We sought to build a hierarchy of clusters from the cases in the sample. We used agglomerative strategy, i.e. each observation started in its own cluster, and pairs of clusters were merged as one moved up the hierarchy, with a "bottom up" approach. We used Ward's method, aiming to join cases into clusters such that the variance within a cluster is minimized (Field, 2000). The clusters were set up first based on the long-term thermostat control change. Afterwards, within each cluster, the thermostat set point temperature preference and the duration were considered. Behavioral patterns observed on the 38 households based on cluster analysis were: (1) 11 cases/ single thermostat setting throughout two months and one duration for each part of the day (one-off), (2) 12 cases/ different thermostat setting and duration patterns for different days of the week (comforty), (3) 15 cases/ different patterns between the days of the week and during March and April (controller).

## § 5.4.2.1 Single thermostat setting and duration: One-Off

One-off's were households that chose one set point temperature and one duration for the chosen thermostat setting, for each part of the day, during the entire data collection period. 11 cases picked a single set point temperature with a certain interval. In this group, the most chosen thermostat setting was 18 C degrees in the morning, 20 during the day, 19 in the evening and 15 at night (Figure 11). The highest and lowest chosen thermostat settings were 20 C/ 16 C degrees in the morning, 21 C/ 15 C during the day, 21 C/ 15 C in the evening, and 18 C/ 10 C at night. The maximum and minimum durations for the chosen thermostat settings were between 3 and 5 hours in the morning, between 1 and 5 hours during the day, between 1 and 5.30 hours in the evening, and 8 hours at night. This group's selected thermostat temperatures were more constant in the morning and at night, and more diverse during the day and evening. It was also possible to observe a 'One-off-warm' group (set points above 17 C degrees), and 'One-off-cool' group (below 17 C degrees).

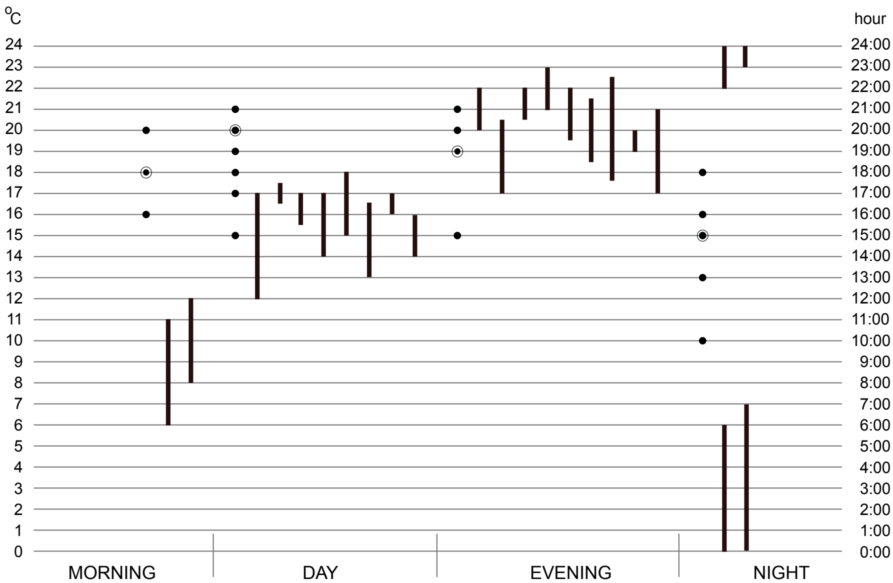



FIGURE 5.11 Clustering of households that chose one set point temperature and one duration for the chosen thermostat setting in March and April. The dots represent the chosen thermostat set point temperatures, and the stripes represent the duration of chosen thermostat settings in morning, day, evening and night. The circled dots mark the most chosen thermostat set points in the sample, for each part of the day.

## § 5.4.2.2 Different thermostat settings for different days of the week: Comforty

12 cases displayed different thermostat set temperatures or periods during the week for each part of the day, but with a certain pattern that repeated weekly, during March and April (Figure 12). This group had no duration pattern for the morning and evenings, and they preferred higher temperatures compared to the other two groups. We could follow a pattern for the morning, day, evening, and night thermostat settings, and a pattern of duration of chosen thermostat setting for the day and night time in this second group. The temperature preferences were between 16 and 21 C degrees in the mornings; between 16 and 20 C degrees during the day; between 16 and 19 C degrees in the evening, and at night, for different days. In terms of the hours of chosen thermostat setting, the maximum and minimum duration of chosen settings were between 2.30 and 5 hours during the day; and between 6.30 and 10 hours at night.

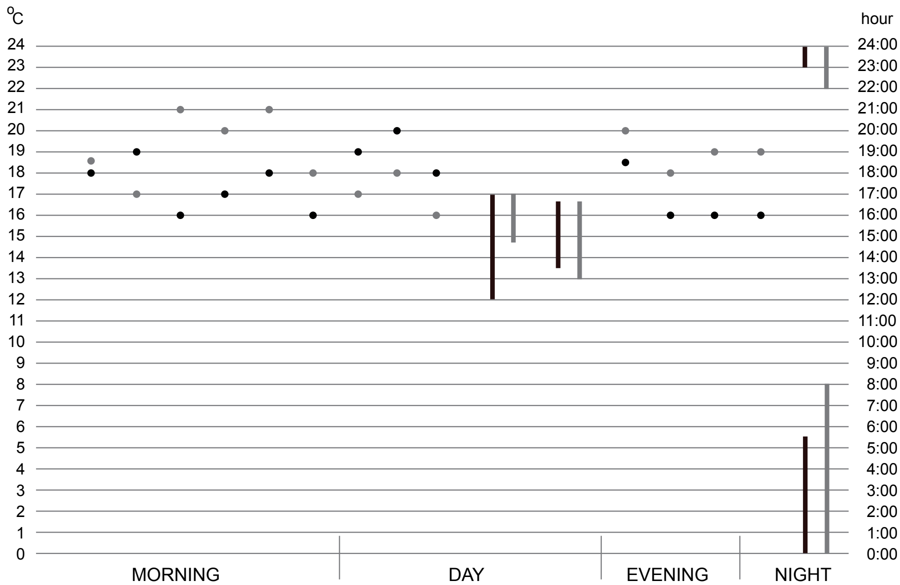



FIGURE 5.12 Clustering of households that use one or more thermostat settings and durations (with a pattern) in different days of March and April. The dots represent the chosen thermostat set point temperatures, the stripes are the intervals of set points chosen in morning, day, evening and night.

## § 5.4.2.3 Different settings for different parts of the week and different months: Controller

15 cases displayed different thermostat set temperature and periods during different parts of the day, between weekdays and weekends, and March and April (Figure 13 and 14). In this group, the morning time thermostat set points changed between 12 and 19, day time set points between 12 and 20, evening time set points between 12 and 19.5, and night time set points between 10 and 15 C degrees. Duration for the morning set point was between 1 hour and 6 hours, day set point was between 1 hour and 5.30 hours, evening set point was between 1 hour and 3.30 hours, and night set point was 4 and 7 hours. Participants of this group preferred lower thermostat set points. The duration of chosen thermostat setting varied a lot within the group, but there was a readable pattern.

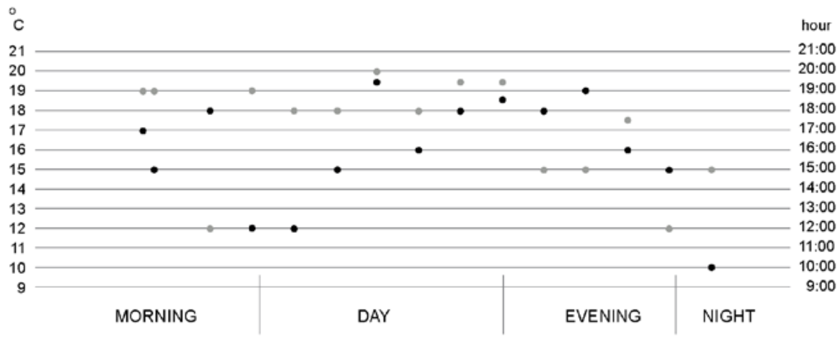



FIGURE 5.13 Clustering of households that use different thermostat setting (with a pattern) for weekdays and weekends, through both March and April. The dots represent the chosen thermostat set point temperatures in the morning, day, evening and night.

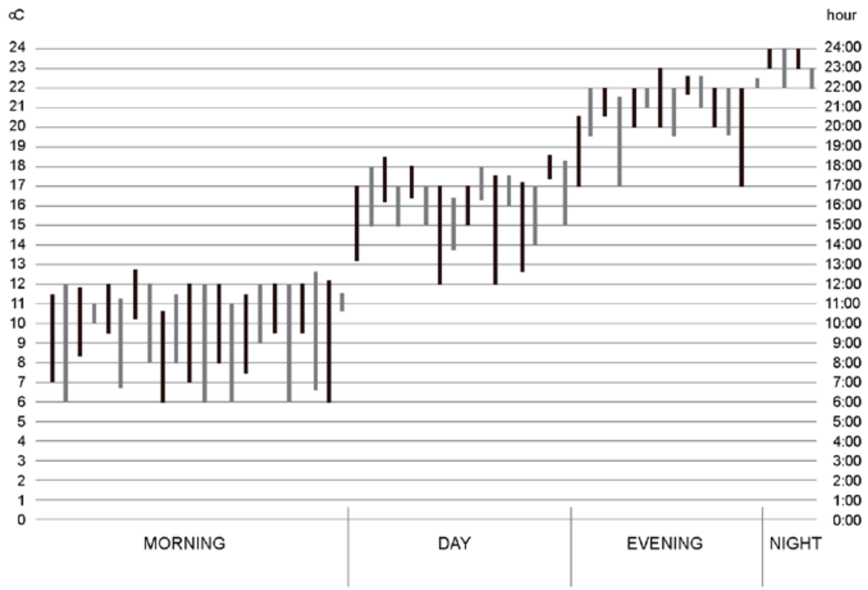



FIGURE 5.14 Clustering of households that use different intervals (with a pattern) for weekdays and weekends, through March and April. The stripes represent the intervals of set points chosen in the morning, day, evening and night..

## § 5.4.3 Thermostat patterns in relation to household and dwelling characteristics, behavioral attitudes

In this section, thermostat control patterns are analyzed in relation to their determinants of behavior (with cross-sectional data from the questionnaire), such as dwelling and household characteristics, and behavioral attitudes (see Table 1). Using the day-night tariff was found to be correlated with household size (r=-.48, p=<.01), and having a specific thermostat pattern (r=.45, p=<.01). The use of continuous thermostat setting function was correlated with the number of energy saving measures (r=.60, p=<.05), and the education level of the household (r=.54, p=<.05). Setting a thermostat program was correlated with the dwelling size (r=-.56, p=<.05), the income level of the household (r=.63, p=<.01) and if the dwelling was owned or rented (r=.59, p=<.01).

Monitored day (r=.62, p=<.01) and night time (r=.55, p=<.01) thermostat set point temperatures were correlated with the household having an energy saving target. Having an energy saving target was correlated with the household size (r=.59, p=<.05), with checking the current (r=.62, p=<.01) and past (r=.59, p=<.01) energy consumption levels of gas and electricity. The number of energy saving measures was correlated with who made the decision of thermostat control in the household (r=.40, p=<.05). These correlations, as well as the behavioral patterns were used to set up the behavior profiles (Table 2).

| Name | Behavioral pattern | Behavioral profile |
|---|---|---|
| One-off | - single temperature and duration per period during 2 months<br>- 'one-off-cool' and 'one-off-warm' groups based on temperature preference | - gadget lover<br>- thermostat controlled by higher educated males<br>- high frequency of HEMS touch screen use (for part of the group lower frequency).<br>- no interest in energy saving |
| Comforty | - varied temperature and duration for different days<br>- no morning and evening duration pattern<br>- warmer temperature preference | - comfort lover<br>- owners<br>- bigger size dwellings<br>- higher income<br>- no interest in energy saving |
| Controller | - varied temperature and duration for different days with a pattern<br>- cooler temperature preference | - keeps control of the thermostat set point and duration<br>- has an energy saving agenda<br>- families where the parents/couples take energy related decisions together<br>- part of the group includes the elderly |

TABLE 5.2 Behavioral patterns and profiles of thermostat use explained

## § 5.4.3.1 Behavior profile: 'One-Off'

This group was dominated by higher educated males, who made the decisions of thermostat control in the house. The group also had a high frequency touch screen use of the home energy management system, even if the behavioral pattern was single temperature/period every day. The monitored night time thermostat setting was found to be correlated with the use of 'free day' setting and with the use of 'continuous' setting, which might mean that the chosen night time setting was used when the household was not at home or when the household did not want to make a new adjustment in the temperature.

In this group, the use of continuous thermostat setting was negatively correlated with the number of energy saving measures. This might mean that this group's occupants mostly enjoyed following the temperature and the other features of the home energy management system as a gadget, but they were not necessarily interested in energy saving.

Part of the group had a high frequency of touch screen use of the home energy management system throughout the two months, while the frequency of use for part of the group reduced towards April. This might also be a sign that the group was not actually interested controlling their thermostat setting temperature and or their energy consumption, so as they started to get used to the device, they stopped using it.

Van Dam (2013) explained two patterns that seem to explain further about this group: (1) Techies and (2) One-off's. "Techies like products that look technical and checking their energy consumption is a hobby. They are data analysists, less motivated to save energy, often male and sole occupants of home energy management systems and their feedback. One-off occupants have many similarities with techies regarding their background, interests and use of energy. However, keeping track is not a goal, they are more interested in the consumption of individual appliances. They utilize the HEMS as a very informative but short-term tool to discover where they can save energy and to be able to implement technical solutions or adapt their behavior based on that."

### § 5.4.3.2 Behavior profile: 'Comforty'

This group were mostly owners, had bigger size dwellings, and higher income. Their 'not at home' setting was the same as 'free day,' in contrast to the former group, who used the 'continuous' set point. This group used higher thermostat set point temperatures, compared to the other two groups.

Van Dam (2013) explained this group as 'Joie de vivre,' who enjoyed living to the full and are not overly interested in energy or keeping track of their meter readings. "A desired application of a control system, for this group would be as 'suspicion checker', for being able to discover what the cause of their energy consumption was."

### § 5.4.3.3 Behavior profile 'Controller'

This group was not found to be gadget-lovers, as in One-Off group, i.e. playing with a gadget for learning and interest in technology, but it was obsessed with keeping control of the thermostat set point and duration. In this group, the monitored day and night time thermostat settings were significantly correlated with the household having an energy saving target. Also, the households in this group set the thermostat when they arrived and left home. They also used the day/night tariff of the energy company. It seemed energy saving was seriously in the agenda of this group.

Part of the group was comprised of families, where the parents took energy related decisions together. Also, they checked the current and past energy consumption levels of gas and electricity. The families reported not only the use of day-night tariff, but also the use of a specific thermostat program. The other part of the group included the elderly, where the couples took energy related decisions together. This group used the night thermostat for continuous setting, and checked their energy consumption levels regularly.

Monitored day ($r=.62$, $p=<.01$) and night time ($r=.55$, $p=<.01$) thermostat set point temperatures were correlated with the household having an energy saving target. This meant that households that have an energy saving target are careful with their thermostat control behavior. Having an energy saving target was correlated with the household size ($r=.59$, $p=<.05$), with checking the current ($r=.62$, $p=<.01$) and past ($r=.59$, $p=<.01$) energy consumption levels of gas and electricity. The number of energy saving measures was correlated with who made the decision of thermostat control in the household ($r=.40$, $p=<.05$).

What we defined as 'controller,' based on the monitored thermostat control behavior, was defined in two groups by Van Dam (2013) as 'managers' and 'thrifty spenders.': "Managers are often parents with school-age children, who do not necessarily have any affinity with technical things but take a more behavioristic approach instead. Their goal is to regularly keep a watchful eye out for appliances that are left on unnecessarily. 'Thrifty spenders' have some characteristics similar to those of managers, but they are motivated by money rather altruism. Thrifty spenders are often middle-aged or older. Old lessons learned about thriftiness and turning lights and appliances off are now ingrained in their behavior."

## § 5.5 Discussion

### § 5.5.1 Thermostat control patterns and profiles

Among 61 households, this research has identified 4 groups of occupants, 7 households with no pattern, and 38 households with pattern: one-off (11 households), comforty (12 households), and controller (15 households). The last 3 were explored more in detail in this paper. The research brought together the household and dwelling characteristics, behavioral attitudes, and actual thermostat control behavior to set up these groups. Thermostat set point temperature, the duration of chosen setting, household size and composition, education, age, income, dwelling size, frequency of use of the thermostat were the parameters that were used to define the groups. This identification is valuable because it provides a representation for this group of occupants and suggests directions on the more energy efficient use of thermostat control systems. However, this research does not have a high capacity of representation, since the sample size is rather small.

7 households with no pattern of thermostat control should be studied much more in detail to understand the particularities of their behavior and characteristics. In these houses, we found evidence that the thermostat might not have been controlled by just one person, which meant that there were more occupant characteristics that were not identified within the current method of data collection/analysis. The other possibility is that there might have been technical issues in monitoring, with calibration or recording the data.

The no-correlation between reported and monitored day time temperature might mean that people have reported the temperature as they remembered or felt at the time of the questionnaire, however the actual thermostat setting was a different one. This shows the importance of monitoring, i.e. longitudinal data collection in behavioral studies. The same argument could be asserted based on the frequency of touch-screen use, being much more intensive in March and less in April, a fact that was visible with monitoring, but wasn't reported in the questionnaire.

Occupants might have used 'continuous' 'free day' 'not-at-home' buttons interchangeably for the thermostat control. The correlation between monitored night time temperature setting and 'free day' or 'continuous' setting was probably because people picked a certain setting for the lowest occupancy condition and left it at that chosen setting for a long time. This result might be telling about the occupant's preference to manage the thermostat based on work day/non-work day, or if the households is staying at home longer at the weekend. These results go in line with Van Dam's research (2013) on the same sample based on interviews and focus group discussions.

When partners manage heating together, they actually take more decisions towards energy conservation. Dwellings that are bigger in size, higher in income level of the households, and owner occupied demonstrate a more diverse and comfort oriented decisions of thermostat control behavior, which might be because of the households' less interest in energy saving.

In this research, we were not able to use the monitored energy consumption data, because it was not reliable. More measurements and analysis including energy consumption would provide better insights into the behavioral profiles and their relation to energy consumption.

## § 5.5.2 Comparison with literature

Besides Van Dam's research (2013), which was used for one-to-one comparison, our findings mostly comply with literature in terms of household characteristics, in which age (Raaij et. al., 1983a; Poortinga et. al., 2005; Tyler et. al., 1990; Vringer et. al., 2007), household size (Raaij et. al., 1983a; Guerra Santin, 2010; Raaij et. al., 1983b; Vringer et. al., 2007), household composition (Raaij et. al., 1983a; Poortinga et. al., 2005; Guerra Santin, 2010), income (Poortinga et. al., 2005; Lutzenheiser, 1993; Vringer et. al., 2007), education (Raaij et. al., 1983a; Vringer, 2007), occupation (Lutzenhiser, 1993), use of appliances (Guerra Santin, 2010; Van Dam, 2013) come forward as significant characteristics that determine the behavioral profiles of heating energy consumption. In our research, even if the household characteristics were used to define different profiles, they didn't appear as the only major elements that determine the variance among groups. For example, 'one-off's were composed of higher educated respondents, but this did not mean that there was no representation of high education in the profile 'controller'; but it meant that education was a defining characteristic for 'one-off's, but not for group 'controller.' Similarly, we saw that 'comforty' group cared more about thermal comfort (as in Raaij et. al., 1983a), however, this behavioral attitude was in fact not only in 'comforty.' In this study, behavioral profiles were determined more heterogeneously. Our research is close in attitude to the work of Raaij and Verhallen (Raaij et. al., 1983a).

In addition, unlike Raaij and Verhallen (Raaij et. al., 1983a), Poortinga et al. (2005), and Vringer and Blok (2007), we found that households with higher education were not necessarily often interested in energy saving, and that the elderly did not necessarily always prefer warmer temperatures.

We used Van Dam's analysis (2013) for one to one comparison, since she worked with interviews and focus group discussions with the same group. She categorized 5 groups of occupant patterns of energy management systems: (1) Techies, who love gadgets, but less motivated to save energy; (2) One-off occupants, who love gadgets, and are interested in the consumption of appliances; (3) Managers, who like to keep a watchful eye out, may or may not go for energy saving; (4) Thrifty spenders, who are like managers, but motivated by money; and have learned about thriftiness and energy saving ingrained in their behavior; (5) Joie de vivres, who enjoy living to the full, are not overly interested in energy or keeping track of their meter readings. The profiles we found were complementary to Van Dam's groups, where our first group (One-off's) covered techies and one offs, our second group (Comforty) complemented with joie de vivres, and our third group (Controller) covered managers and thrifty spenders. Our research could complement that of Van Dam's, since we provided the preferred thermostat set temperatures and durations for the profiles. For instance, 'comforty' was the most comfort-preferring group compared to the other two, and chose the highest temperatures. Also, 'one-off's included two groups within, 'warm' and 'cool' group, based on the temperature preferences. This might also explain the behavioral pattern variation between one-off's and techies in Van Dam's grouping. The 'controller' group was the one that used the thermostat control the most, which complies with Van Dam's findings of managers and thrifty spenders.

### § 5.5.3 Methods and limitations

In the literature section, we quoted two methodologies on occupant behavior and energy consumption research (Bedir et. al., 2011; Vine et. al., 1989), where longitudinal and cross-sectional data collection and related methods for analyses were applied on smaller samples, or large populations. In this research, we tried to combine the two methodologies, analyzing continuous data (collected by monitoring) on actual behavior, and cross-sectional data (collected by questionnaire) like household and dwelling characteristics. By doing these, we derived behavioral patterns and profiles, and linked them to each other.

Major issues to deal within the former methodology are on data collection and working with big data; for instance, calibration of the data collected with monitoring, checking the reliability of the data collected (in our case, crucial data on energy consumption was not usable). In addition, existing research using this methodology, including ours, does not have a representation capacity on the whole population, because of their small sample size. However, they provide deeper insight into behavior, and they create the possibility to validate/compare the results of other research.

We used 45 households' monitoring data over the sample size of 61. 8 households did not provide reliable data in March and April, and 8 cases for either March or April. Besides, 4 April and 12 April 2011 were the days that monitoring was problematic for all households. Another limitation was that the data was collected from the clients of one energy company. Being the subscriber of this company might have brought in essential differences between this monitoring group and the rest of the households in the country, based on cognitive variables like attitudes, values, etc. In order to overcome the limitation of representation this might have created, participants for monitoring were selected under the condition of forming a distributed mix of the Dutch population in terms of age, gender and education. Additionally, they did not have specific affinity with energy consumption through their work. In addition, to decrease the impact of the limitations of the research on the quality of the outputs, other published research was consulted to compare and validate the results.

Even if the data obtained during 2 months revealed about behavioral patterns more precisely, it is still time-bound, which means there is a big possibility that different patterns will be observed in a year, two years, and longer on the sample, depending on the changes in lifestyle, household composition, etc. of the households.

Van Dam (2013) discussed the problems of conducting research in collaboration with the industry, stating that the interests of the industry might differ from those of the scientific researchers, and that researchers should be careful about it since the tendency for such collaborations is on the increase: "The difference of interests might result in different priorities for parties, and the merits of scientific research can be assessed differently. Privacy and sharing of data may be interpreted in articulated viewpoints, which might have negative influence on the monitoring process and available data for scientific research." She also reported that finding participants for monitoring might take more effort than expected. Similar challenges were reported in former research, for instance with technical barriers (Nye et. al., 2010) and participants (Hutton et. al., 1986). This shows that preparing good research protocols, especially defining the procedures of sharing and assuring privacy, the involvement of households for monitoring, and the use of data are crucially important.

## § 5.6 Conclusion

This paper investigated thermostat control behavior in 61 Dutch dwellings in detail, using an applied questionnaire on household and dwelling characteristics, and behavioral attitudes, as well as the HEMS recording data on chosen thermostat settings in March and April 2011. The paper analyzed the thermostat control patterns and profiles of the households, and evaluated monitoring as a method for understanding the relationship between occupant behavior and energy consumption.

We found that most households used HEMS mainly to control their thermostat settings. Also, most occupants changed their thermostat setting as part of their main daily activities, when they came home, when they got up in the morning, before going to bed, when they left home, etc. It is also worthy to note that we identified the patterns and profiles of behavior, but this did not mean that these were perfectly homogenous. There were always cross-overs between groups. Gadget obsession, care for comfort, and care for control were the main visible characteristics of the three different profiles.

4 occupant groups were identified, where the group of 'no pattern' required detailed investigation of the behaviors, household and dwelling characteristics to understand the context to the behavior. The other three were (1) 'one-off' households with a single set point per time of the day and interval of thermostat use, composed of higher educated males, gadget lovers, and not necessarily interested in energy saving; (2) 'comforty' households with thermostat use of more than one set point and interval with high temperature preferences in different days of the week, composed of home owners with high income, who had bigger size dwellings, not interested in energy saving and preferred higher temperatures; and (3) 'controller' households with single or double set point temperatures and intervals with low temperature preferences in different days of the week, as well as during March and April, composed of households with energy saving in agenda, who are mostly families, and sometimes the elderly, where the parents/couples took energy related decisions together.

In this study, we covered 2 months of data collection on thermostat use, however the period of data collection were March and April, where the weather conditions were not extreme in terms of temperature. It would be important to repeat/continue monitoring the same sample during Summer and/or Winter. In addition, any research on occupant behavior is inevitably time-bound. Hence, it would be interesting to re-visit the households to see the change in behaviors in the long run. Behavioral patterns regarding thermostat control and energy use could change in the long run. Lastly, this research does not have a representation capacity on its own, because of its small sample size. However, it provides deeper insight into behavior, and creates possibilities for validating its results from other literature.

This research has provided a better understanding of thermostat control and regarding behavioral patterns. By considering these insights, energy performance regulations could be articulated, better design of thermostat control devices could be achieved, more efficient infrastructural implementations could be developed by energy companies, the targeted energy saving measures could be better planned. Using the behavioral patterns, designers could facilitate processes for embedding HEMS in daily life. Energy management systems could be integrated more with thermostat control; this kind of combination might provide more efficient use.

Considering the heterogeneity of the behavioral patterns and profiles, and the possibility that more than one person might be managing thermostat, HEMS could be designed flexible enough to suit various possible activities/conditions at home. In this respect, this research could be furthered in a way that the field work includes all individuals that possibly use the HEMS. The technical issues in measuring and monitoring, as well as calibrating data remain as obstacles to deal with. It is important to emphasize that more consideration should be given to occupant behavior, for a more efficient user–machine interaction, and energy preservation.

## Acknowledgement

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