7 Conclusion

In spite of the technological advancement on building design and construction, actual energy use levels of dwellings are different than expected in several cases. Little is known about how occupants interact with their dwellings, what the background to this interaction is, as well as the resulting energy use. This research aimed at revealing the relationship between occupant behavior and energy consumption, both in terms of heating energy and electricity. The determinants of occupant behavior, the sensitivity of dwelling energy consumption to occupant behavior, and defining behavioral patterns/profiles are the main elements of this work. This thesis will help to understand the occupant related factors of energy consumption in dwellings, by this way designing better products, energy management systems, software, and achieving better regulations.

Research on energy consumption of dwellings covers thorough investigation of the behavioral performance during the occupancy process, as well as the aspects that are involved in the design and building processes. There has been extensive progress on the building physics aspects of energy consumption; concerning methods and practices for specification of building geometry, material properties, and external conditions. However, the resolution of input information regarding occupant behavior is still rather low. In order to respond to this, one of the research questions of this thesis has been: what is the sensitivity of dwelling energy consumption to occupant behavior? Secondly, the influence of lighting and appliance use on electricity consumption, as well as the determinants of electricity consumption in dwellings, and lastly, the behavioral patterns of energy consumption are investigated.

This study's methodological approach combined the deductive and the inductive methods, by considering both the determinants of behavior and the actual behavior itself. Deductive methods dissect energy consumption into its factors, such as household characteristics, dwelling characteristics, behavioral aspects, etc. On the other hand, inductive methods model actual behavior from bottom up experimenting and validating energy consumption levels.

In this thesis, occupant behavior was 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. This research looked at the building and household characteristics that determine occupant behavior, as well as habitual (surveyed) and actual (monitored) occupant behavior.

§ 7.1 Research Questions and Findings

This thesis deals with occupant behavior and actual energy consumption in the Dutch dwelling stock. Here, first the answers to the 4 sub-questions are presented in order to articulate the main research question, and then the response to the main research question is put forward.

§ 7.1.1 Research Q1: What is the sensitivity of a dwelling's heating energy consumption to occupant behavior? (Chapter 3)

- What are the existing models developed for the occupant behavior and energy performance relationship? and how different are the results of these models in terms of calculating the influence of occupant behavior on energy performance?
- How can behavior be modelled in order to assess the robustness of the energy performance in dwellings to occupant behavior?
- What is the weight of each behavioral aspect in terms of its influence on energy consumption?

In Chapter 3, our first hypothesis was proved: sensitivity analysis could be used as a method of evaluating the impact of occupant behavior on heating energy consumption. One important difference of our modeling method compared to existing research was that we did not assume presence as the initiating element of behavior, and nor as a precondition to behavior. There could be occupant behavior that has impact on heating energy consumption, while the occupant is not present in the space, such as preset thermostat and ventilation control behavior, etc.

Investigating our second research question about the weight of each behavior in terms of its influence on energy consumption, and which behaviors are more influential than others, we found that the energy consumption of a dwelling was the most sensitive to thermostat control, followed respectively by ventilation control and presence. We also found that ventilation at night or early in the morning had a great influence on the energy consumption of a dwelling.

Secondly, we found that presence in a space was not as closely related to heating energy consumption, but it was revealed as a strong element of electricity consumption.

Lastly, both heating energy consumption and indoor resultant temperature were the most robust to radiator control. Heating energy consumption was the most sensitive to thermostat settings, and the indoor temperature was the most sensitive to occupant presence. This could be because of the internal heat gain from presence.

§ 7.1.2 Research Q2: What is the influence of lighting and appliance use on the total electricity consumption in dwellings? (Chapter 4)

- What are the main direct and indirect determinants of electricity consumption? (Direct determinant: such as number of appliances and duration of appliance use … Indirect determinant: such as household size, dwelling size, dwelling type …)
- How much of the variance in electricity consumption in dwellings can be explained by direct and indirect determinants?

The number and duration of use of general appliances, cleaning appliances, food preparation appliances, and hobby appliances; number of standby appliances, battery chargers, light bulbs, energy-saving light bulbs were found to be significantly correlated to electricity consumption. Presence in room 1 (week – all day), room 2 (week – all day), bathroom (week – morning), room 3 (week – during day) were significantly correlated to electricity consumption.

In terms of household and dwelling characteristics, dwelling type, number of study/ hobby rooms, income of the household, yearly gas consumption, household size, years of residence in the current house, hours of working outside, age groups, dishwasher use, washing machine use, number of hot (90 °C) and cold washes, dryer use, number of baths and showers, duration of shower and lastly the heating system type appeared to be significantly correlated to the electricity consumption.

We found no correlation between the location of appliances, the duration of use of ventilation appliances, the number of energy saving light bulbs in the living room, or in the rest of the house, and electricity consumption. In addition, home ownership and electricity-inclusive rent did not emerge as significant predictors of electricity consumption. Gender, education, existence of elderly people and infants in the household, change in household composition in the previous year did not appear to influence electricity consumption either.

Similarly, no correlation was found between electricity consumption and mechanical ventilation systems, probably because these systems were seldom used in our sample (people disabled them or hardly used them at all). Similarly, there was no correlation between the use of extra ventilation appliances and electricity consumption, because their usage was too low (14% of the respondents said they had a fan). Lastly, we could not check the impact of renewable energy because of the insufficient response to the question (10%) in the survey.

Three regression models were built for the direct and indirect determinants, one based on the duration of appliance use (direct) and presence (indirect), one on the number of appliances (direct) and Dwelling, Household, Economic, and Social (DHES) characteristics (indirect), and one on the total duration of appliance use and DHES characteristics. We found that, in the first model, total duration of appliance use alone explained 37% of the variance in electricity consumption. Presence in rooms explained 14% alone and 37% in the combined model. This meant that hourly data on presence did not contribute to modeling electricity consumption in dwellings, when it was considered together with the total duration of appliance use. Study/hobby rooms emerged as important factors in the relationship between presence and electricity consumption, whereas living room and kitchen did not. In the second model, the number of appliances explained 21% of the variance in electricity consumption alone and 42% when combined with DHES characteristics. Household size, dwelling type, the number of showers, use of dryer and washing cycles appeared significant. The final (third) model explained 58% of the variance in electricity consumption, it may be possible to set up a model on occupant behavior and electricity consumption with duration of appliance use and DHES characteristics.

Although we found a strong relationship between number of showers taken per week and electricity consumption, the duration of shower did not appear to be significant. Number of bathing times per week and duration did not appear significant either. ‘Showers taken per week’ gave the clue of a comfort related aspect of electricity consumption, considering the evolution of personal cleaning habits from bathing to showering. It seems like changes in lifestyle preferences might have an increasing influence on consumption patterns.

§ 7.1.3 Research Q3: What are the behavioral patterns and profiles of energy consumption?

- What are the behavioral patterns of thermostat control? How do they relate to the household characteristics, revealing behavioral profiles? (Chapter 5)

We found that most households used Home Energy Management Systems (HEMS) mainly to control their thermostat settings. Also, the most constant thermostat control behavior was at night. This did not change between weekdays and weekends, or in March or April. 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.

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 was 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 have meant 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 could not have been reported in the questionnaire.

When partners managed heating together, they actually took more decisions towards energy conservation. Also, they checked the current and past energy consumption levels of gas and electricity. Dwellings that were bigger in size, higher in income level of the households, and owner occupied demonstrated more diverse and comfort oriented decisions of thermostat control behavior, which might have been because of the households' less interest in energy saving.

Our findings on the characteristics of households in relation to space heating control, mostly complied with literature in terms of household characteristics, in which age, household size, household composition, income, education, occupation, use of appliances. These characteristics come forward as significant characteristics that determine the behavioral profiles of heating energy consumption. Different than the existing research, in this study we found that 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 15), however, this behavioral attitude was in fact not only in 'comforty.' In this study, behavioral profiles were determined more heterogeneously.

In addition, different than the literature, we found that households with higher education were not necessarily often interested in energy saving, and that the elderly did not necessarily always preferred warmer temperatures.

- What are the behavioral patterns of electricity consumption? How do they relate to the household characteristics, revealing behavioral profiles? (Chapter 6)

This research aimed to analyze in detail the appliance use in the Dutch housing stock, and define behavioral patterns and profiles of electricity consumption. We analyzed survey data collected from 323 dwellings in the Netherlands on appliance ownership and use; presence; cleaning; household and dwelling characteristics. Descriptive, correlation and factor analyses were used to conduct the study. We created 4 groups with 'ICE', 'Cleaning', 'Food preparation' and 'Continuously used' appliances.

Most appliances were used in the morning (07:00-09:00) and the evening (18:00-20:00). Every household owning a dryer, an individual freezer pointed to the habits of cleaning and food preparation/ conservation. In addition, every household owning on average 2 TVs, 1 desktop computer, 1 laptop, 1 stereo system and 1 DVD player; some households 1 TV and 1 laptop per person; the total daily hours spent watching TV being 4 hours on average, PC use per day being approximately 2 and a half hours, and laptop use 3 hours suggested how central ICE appliances, especially TVs and computers were to our lives, and the importance of the improvement of energy efficiency of these appliances. As for cleaning appliances, a dryer was used 2 times per week and a washing machine 5 times. These numbers showed that almost every item of clothing was worn only once before it is washed. When this was considered together with the 17 minutes use of the iron per day and the once or twice showers per person per day, it might be telling about the occupations and/or the cleaning comfort preferences of the households. In terms of food preparation appliances per household (on average), the fact that there was a freezer in continuous use tell about food storing/eating habits. Perhaps less fresh food was being consumed and/or households might have been preserving food for winter/summer. The grill and microwave oven being used 24 minutes in total per day suggested that the main meals consisted of easy-to-prepare food. Lastly, a dishwasher was used 42 minutes per day on average, which meant that either the dishwasher was used on the quick cycle every day or the long cycle nearly 4 times a week. The numbers of ownership and duration of use in our sample were similar with the Dutch averages.

In order to derive the behavioral factors, patterns and profiles, first we conducted a correlation analysis between electricity consumption and the variables of occupant behavior, household and dwelling characteristics that could be related to electricity consumption. We selected the variables based on a literature review and our former paper (2). We found that total daily duration of use of continuously active, food preparation, (personal) cleaning, and ICE, battery charged appliances, as well as the number of stand-by appliances, and energy saving and halogen lamps (appliance use behavior); total weekly number of hot laundry cycles, baths, and duration of showers (behavior); total weekly hours of presence in rooms, kitchen, and bathroom (presence); household size, years of residence in the same house, presence of children or elderly in the household, monthly household income (household characteristics), type of dwelling and number of bedrooms (dwelling characteristics) were significantly correlated to electricity consumption. The variables of ownership of PV or solar panels, a member of the household having university or higher education, and hours spent outside the house for work were not found significantly correlated to electricity consumption, however they were still included in the factor analysis, since they might reveal insight about occupant behavior and electricity consumption and might contribute to building the behavioral patterns and profiles.

By using exploratory factor analysis, we found the behavioral factors and their underlying variables as total appliance use (total duration of use of continuous, cleaning, and food appliances), articulation of technology (duration of use of ICE, stand by and battery charged appliance use), spatial presence (active presence in rooms, bathroom, and living room and kitchen, number of halogen lamps), (personal) cleaning behavior (duration of shower, number of baths, number of hot washes, duration of use of dishwasher, number of dryer loads), and energy conservation (ownership of PV/solar panel, less use of dryer, hot washes, douche, and more number of energy saving lamps). In the following step, the 4 behavioral patterns were derived as the use of appliances, presence/ (personal cleaning), presence/technology, energy conservation.

While the use of ICE appliances created enough factor score to relate to a separate behavioral factor and pattern, the behavioral factor of presence appeared in two different behavioral patterns ((personal) cleaning and technology). The positive or negative behaviors of (personal) cleaning and use of halogen or energy saving lights also lead to two different patterns ((personal) cleaning and energy conservation). The correlation analysis revealed that the behavioral factors and patterns were significantly correlated to electricity consumption, and there was statistically significant difference between different factors and patterns. This might be explained by almost all variables (except for the ownership of PVs) being correlated with electricity consumption.

In terms of the behavioral profiles, we found that the behavioral factor 'appliance use' related to the profile 'family' considering the characteristics of dwelling typology (row house or middle level), household size (couple), higher working hours outside the house in some cases, and elderly household in some cases, slightly lower income (not statistically significantly correlated to the factor). The behavioral factor 'technology' related to the profile 'techie' considering the characteristics of higher income level, higher education level, and less hours of working outside in some cases. The behavioral factor '(personal) cleaning' related to 'comforty' considering the characteristics of dwelling typology (corner or freestanding), higher income level, bigger household size, and less hours of working outside. Lastly the behavioral factor 'energy conservation' related to the profile 'conscious' considering the characteristics of higher education level, working more hours outside, smaller household size, and top floor apartment or corner house in some cases. The factor of 'spatial presence' did not relate to a specific behavioral profile.

The higher or lower values of household size, income, education, working outside, number of bedrooms, and dwelling type were found to be related to different behavioral factors. For instance, the 'comforty' profile had bigger household size, higher income and number of bedrooms compared to 'family,' while it had lower working outside hours. The 'conscious' profile was found to have more hours of working outside, smaller household size, and higher education, compared to 'techie,' and was found to live in a house that gets more day light. The profile 'conscious' didn't necessarily correlate to income, but it had more income than profile 'family,' less income than 'comforty.' In our sample, considering the electricity consumption, the behavioral profiles did not relate to particular household stereotypes such as single, couple, elderly, etc., but to variables such as working hours, household size, education, and income.

We found that electricity consumption is closely related to occupants' presence. Besides, appliance use based on specific activities like cooking, washing, lighting, TV and PC use could be a good way to model occupant behavior and electricity consumption, and the related profiles. The use of ICE appliances (articulation of technology) determined a behavioral pattern on its own. Younger householders had the most appliances but also the most energy saving appliances (ESA). In our sample, the two groups had the most number of appliances were young singles, couples or families. Economic affluence had a strong influence in grouping the households according to electricity consumption. Income was one of the household characteristics that we used to determine the behavioral profiles, as well.

Finally, the overall question of this research is:

How much does the occupant behavior influence the energy consumption of dwellings in the Netherlands, and how could we identify the determinants of consumption, as well as the behavioral patterns and profiles?

The literature review shows that not achieving the calculated energy performance levels and significant energy consumption differences are observed in dwellings even with similar building characteristics. The variances between the calculated energy performance and the actual energy consumption of dwellings in energy efficient housing, i.e. energy performance gap, could stem from several reasons, such as unexpected occupant behavior, lack of comprehensive data of the whole building process, calculation drawbacks, the construction defects/mistakes in building construction. This thesis has been interested in determining occupant behavior in relation to energy consumption, claiming that the buildings' energy consumption can be validated in total, only during occupancy, when the design is tested on actual use.

This thesis brought together the occupant behavior that is habitual (questionnaire), and that is dynamic (monitoring). In addition, occupant behavior was included in this research both regarding presence, and regardless of it. Occupant behavior was considered as (presence patterns in a space, together with) the actual heating, i.e. thermostat setting and radiator control; and ventilation patterns, i.e. operation of windows, grids, and mechanical systems; and the use of lighting and appliances.

This thesis collected more detailed data on the determinants, and actual occupant behavior, both cross-sectional (surveyed) and longitudinal (monitored), and looked at the determinants of behavior, i.e. building and household characteristics that determine occupant behavior, as well.

Referring to the lack of research, this study combined the deductive (cross-sectional, macro data, macro level statistics) and the inductive methods (longitudinal data, detailed high frequency data, performance simulation), by considering both the determinants of behavior and the actual behavior itself. We found that deductive methods are much faster in calculating and dissecting energy consumption into its factors, such as household characteristics, dwelling characteristics, behavioral aspects, etc; and inductive methods model actual behavior from bottom up experimenting and validating energy consumption levels.

Applying sensitivity analysis in a large sample size of households/dwellings in relation to heating energy consumption, this research has found that the heating energy consumption of a dwelling is the most sensitive to thermostat control, followed respectively by ventilation control and presence. Both heating energy consumption and indoor resultant temperature are the most robust to radiator control. Calculating a regression model on the determinants of electricity consumption, this research has found that using the total duration of appliance use and parameters of household size, dwelling type, number of showers, use of dryer and washing cycles, and presence in rooms. This explained 58% of the variance in electricity consumption.

Introducing behavioral profiles and patterns contribute to the modeling of energy consumption and occupant behavior, this research revealed that household composition, age, income, ownership of dwelling, and education are the most important elements of behavioral profiling.

This research will help understanding the occupant related factors of energy consumption in dwellings, as well as the more accurate representation of occupant behavior, which will contribute to the better design of products, systems, dwellings, and achieving more advanced regulations.

§ 7.2 On the Limitations of the Research

One limitation of Dataset 1 (OTB dataset) was the low response rate to the questionnaire (5%). This might have been partly because the inhabitants were uncomfortable with personal questions about their lifestyles and income levels. It might have been related to the number and intricacy of questions, as well. The returned questionnaires being filled in completely showed that the interest/awareness of inhabitants in the subject matter was high.

In terms of the representation power of the dataset, general characteristics found to be representative of the Netherlands (validation dataset: WoON Database), except for the parameters of income and education, which were higher than the national average. In terms of heating and ventilation systems, the OTB dataset had a small number of dwellings with balanced ventilation and solar boilers; and no dwellings with heat pumps. The WoON Database included dwellings with heat recovery ventilation. One aspect to pay attention is the year of construction of the dwellings in these neighborhoods. The neighbourhoods were chosen on purpose, with the aim of working on new buildings with low EPC values. Potential deviations from the national averages might be caused by focusing on these two recently built neighborhoods. Here, it must be noted that similar sample sizes were observed in previous work on occupant behavior and energy consumption in dwellings (e.g. Jeeninga, 2001; Uitzinger, 2004). These studies claimed that a low response rate might not influence the accuracy of the results. Many results from early research are similar to the later ones (Curtin et al., 2000; Keeter et al., 2006).

Thirdly, even if the questions on presence and behavior are detailed on a weekly basis, respondents might have filled in the information based on remembering their habits, but not actual behavior. This could be a limitation on the one hand, but also a successful approach to obtain data on habits, on the other hand. The influence of Hawthorne effect (McCarney et. al., 2007) must also be mentioned, where the survey respondents' awareness of the goal of the survey might have directed them to fill-in the questionnaire different than the reality.

Another limitation of Dataset 1 was related to the tracking and recording system of electricity consumption in the Netherlands. Electricity providers ask occupants to send in their meter readings once a year. These providers actively check the meter readings as well, but they have different schedules. If the occupant fails to send in the meter readings, the electricity consumption is calculated based on the previous reading by the provider, which may be up to three years ago (more than 3 years is not allowed under the Dutch regulations). This reality could have created a bias in the accuracy of the electricity consumption data.

Dataset 2 had limitations resulting from monitoring. The real-time energy consumption figures recorded by the HEMS were not used, because of the inconsistency of the data. The most precise thermostat control data was collected in March and April 2011, out of 6 moths that the monitoring was made. Besides, there was a probability that thermostat behavior had not changed significantly in March and April, because of little outside temperature change.

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. Another limitation was that the data was collected from the consumers of one energy company. Being the subscriber of this company might have brought in essential differences between this group and the rest of the households in the country, in terms of awareness and lifestyle. In order to overcome this, the 61 households were chosen according to their characteristics matching with Dutch averages. Additionally, they did not have any specific affinity with energy consumption through their work at home. 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. .

§ 7.3 Relevance of This Research and its Contributions

The scientific contribution of this research is characterized by the combination of several domains, i.e. design for sustainability, policy and building regulations for energy efficiency, construction and management of buildings (developers, contractors, housing associations…), management of energy supply (energy companies) and behavioral studies. This research has sought for explaining heating energy and electricity consumption of dwellings in Dutch context, in relation to determinants of energy consumption, actual behavioral patterns, and the household behavioral profiles in detail.

Relationships between behavioral patterns, household and building characteristics in relation to electricity consumption have rarely been investigated in the Netherlands. However, there is no work on profiling households by their electricity consumption.

Our work contributes to the literature by (1) using (partially) continuous data on actual behavior as well as household and dwelling characteristics, (2) driving behavioral factors, patterns, and profiles, and linking them to each other, as well as looking for their relationship with electricity consumption.

Determining behavioral profiles could lead to more accurate prediction of electricity consumption in dwellings, as well as planning the targeted energy saving measures, and helping energy companies for better calculations. Considering that occupant behavior might be more visible in the newer dwellings, and that behavior might be revealed more precisely by analyzing 'electricity' consumption, this research might provide more detailed and articulated input on occupant behavior to research and policy, which focus on motivating/encouraging individuals' and households' towards more energy efficient behavior.

Our work on 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, revealed 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.

This identification is valuable because it combines several methods of data collection and analysis, and 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. However, they provide deeper insight into behavior, and they create the possibility to validate/compare the results of other research.

This research has provided a better understanding of thermostat control and relevant 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.

In particular for the design and engineering industry, and energy companies, this research means support for designing systems that are effective in reducing energy consumption, as well as influencing occupants towards energy efficient behaviors. Findings from this research could help in improving design of objects, systems and architectural design in order to reduce energy consumption by occupants at home.

The results presented in this thesis suggest directions on the more energy efficient use of thermostat control and appliances. Using the behavioral patterns, designers can facilitate and create opportunities for embedding thermostat control and home energy management systems in daily life and for better consideration of occupants' behaviors, practices and goals for a more efficient human–machine interaction in saving electricity.

For product and systems design, 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 followed up in a way that the field work includes all individuals that possibly use the HEMS. 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. 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.

For construction industry and design informatics (particularly simulation based energy performance assessment and design tools), this research illustrates the benefit of considering the occupant behavior in early phases of design in renovating existing housing stock and for new housing.

Claiming that changes in lifestyle preferences will have an increasing influence on consumption patterns, every household owning 1 wireless internet router in continuous use, on average 6 battery charged appliances in an average household emphasize the importance of improving these technologies. Through studying behavioral determinants and patterns, opportunities for embedding thermostat control behavior in design stage calculations can be explored.

Several studies display the 'energy performance gap' between the calculated and actual energy consumption levels of buildings, and explore the reasons to it. There is significant evidence to suggest that buildings do not perform as well when they are completed, as was anticipated when they were being designed. It's important to identify the source(s) of energy performance gap and bridge them, such as issues of communication, building commissioning, issues of calibration, accuracy, energy management systems development, metering in relation to weather data and occupant behavior.

This research focuses on occupant behavior and energy consumption in dwellings, and understanding how behavioral patterns relate to energy consumption. Sensitivity analysis as a methodology could contribute in the calculations and calibrations of energy performance and consumption of households, as well as in communication and commissioning of buildings. Sensitivity analysis would also contribute to the efforts of policy making (mentioned below) and energy companies (mentioned above).

For policy, this research could help in improving the models and calculations of occupant behavior in building regulations; hence the theoretical consumption levels could be more realistic. The behavioral patterns identified in this study could also contribute to more dynamic calculation and integration of occupant behavior in building regulations and policies.

Further research could utilize the knowledge produced in this research to increase the energy efficiency of dwellings. For a coherent and intact description of the occupants' thermostat control behavior and the significant differences among them, behavioral patterns were identified in this thesis. This study proves that exploring patterns requires a combination of deductive and inductive methodologies.

§ 7.4 Recommendations for Future Work

Recommendations on future work to this research are threefold. In subsection 4.1, the possible follow up research on occupant behavior and energy performance has been reported in short term and further, where the former could partially be realized with the same data set, and the latter requires new research proposals. Subsection 4.2 deals with recommendations for architectural and energy management systems and product design practice drawn from important findings regarding the role of occupant behavior in energy consumption. While household characteristics such as household size, number of children and elderly, their socio-economical and educational level have an indirect influence on energy consumption, presence, lighting and appliance use, and the use of energy management systems have a direct influence. Subsection 4.3 presents the recommendations for policy from the conclusions of the sensitivity analysis (Chapter 3), monitoring (Chapter 5) and determinants analysis (Chapter 6). In building the regulations, the energy performance of a building is calculated based on a standard formula of occupant behavior. More dynamic calculations are necessary to include occupant behavior in energy performance regulations, which can help to predict energy savings and performance more accurately.

§ 7.4.1 Research

Potential further research topics are listed below and some of them are addressed further in: '4.2. Energy management systems.'

- Modeling thermal comfort and indoor air quality could lead to results that would evaluate and explain the sensitivity of our model further. (Chapter 3)
- Further research is needed on the actual household appliance inventory, their powers and energy ratings in much larger samples. This would improve the regression model we set up in Chapter 5. The significant connection that was identified between electricity consumption and ground-floor dwellings points to the need for a detailed study on lighting.
- We have not collected enough data on stand-by appliances' energy consumption. Further research is needed on this topic using (Chapter 5). Understanding lighting and appliance use based on monitoring could reveal much more about electricity consumption.
- Every household owning 1 wireless internet router in continuous use and 6 battery charged appliances should be researched further in terms of a mobile 24/7 lifestyle and the addiction to being 'connected'. (Chapter 5-6)
- Personal cleaning behavior appeared to be an important factor both in the patterns and profiles in this research, which suggests a comfort related aspect of energy consumption. This aspect needs to be investigated in terms of the habits, motivations, frequencies, and consequences of the particular behavior.
- This research could be extended by specifically investigating the use of ICE appliances, food preparation (especially freezer, dishwasher) and (personal) cleaning (use of shower and bath, use of dryer and washing machine) based on specific activities like cooking, cleaning, or hobbies.
- Methodologies regarding monitoring occupant behavior need to be improved in terms of data collection frequency, calibration, modelling method, sampling of behavior data (is data size of 60 better to understand intricacies of household and behavior characteristics (as in Dataset 1), 300 (Dataset 2), or sample size of Dataset 3 (more than 4000 sample size representing the Dutch housing stock)?
- Whether we work with cross-sectional (questionnaire) or longitudinal data (monitoring), the research is still time-bound, meaning that there is a big possibility that different behavioral patterns will appear in a year, two years, and longer, depending on the changes in lifestyle, household composition, etc. Further research could explore longer time spans in monitoring and modelling in residences.

§ 7.4.2 Energy management systems and design

Energy efficiency of dwellings is influenced by climate, building, systems, lighting and appliances characteristics as well as household characteristics and behavioral patterns. There has been much advancement of building elements such as thermal insulation, fenestration, energy distribution system and their air tightness quality, which have significant direct impact on the energy consumption of dwellings. However, the same cannot be claimed considering occupant behavior. While household characteristics such as household size, number of children and elderly, their socio-economical and educational level have an indirect influence on energy consumption, presence, lighting and appliance use and energy management systems have a direct influence.

Our results showed that occupant behavior is very dynamic in terms of the duration and chosen thermostat setting, and occupants' use of spaces and HEMS may differ considerably, hence individualization and decentralization of energy management systems should be investigated. The individual and local comfort requirements could be responded by using demand-controlled, user centered energy management systems.

There is improvement in terms of research and design of climate and energy management products and occupant interaction; however, the user aspects of how the climate control systems integrate in architectural design has not been investigated at all.

Variation in the distribution of light, temperature and humidity generate microclimate zones. Indoor comfort management devices with different focus of field, capacity and effect could be used individually or in-combination in different rooms, in order to create the desired indoor climate in relation to energy performance. Indoor comfort and energy management systems could be controlled locally by devices with individual focus; this way these systems could independently be installed in dwellings for refurbishment purposes. These devices could be modular design and scalable.

Integrating large centralized climate/energy management systems may not be easy, especially in renovating existing buildings. However, if a decentralized, adaptive/responsive system is considered, different spaces and demands could be addressed separately. This possibility could help reducing consumption levels considerably.

Many studies agree on the key aspects of indoor climate and energy management and automation systems as: occupant being in control; enhanced information visualization and decision support; intuitive, interactive and upgradeable user interfaces & reliable automation. The findings of this research also support the arguments of the occupants being in control of the systems and products, and the interactive feedback systems.

The communication protocols among individual devices and/or systems could be designed in such a way that both the users and the control devices are active determinants of the indoor comfort and energy management. The internal heat gain from the occupants and the devices could be sensed by different sensors and stored in a dynamic dataset, where all energy management devices are connected real time. Our work on sensitivity analysis could hold a basis to develop such intelligent systems. Intelligence may include time schedules, occupancy control, feedback mechanisms, and demand response by automatically increasing/decreasing its capacity, or switching on/off.

Consequently, energy consumption control, management of active occupant (operation), smartness (sensor/automatic/simulation), comfort (air quality, thermal, acoustic, visual), decentral vs central, network (actively communicate with their immediate neighbours and environment), integrated into building compotents (wall, floor and skin), multiple sensors, distributed intelligent climate control could help to overcome problems such as unhealthy indoor climate, energy inefficiency and environmental impact.

§ 7.4.3 Building regulations and energy policies

The Energy Performance Building Directive (EPBD) demands all EU member states to apply performance-based energy requirements and label certification schemes towards lowering the building energy consumption levels since 2006. Energy consumption here covers space heating, cooling, ventilation; lighting; and water heating.

The EPC (energy performance coefficient) in the building regulations in the Netherlands is used as a constant displaying the overall building-related energy consumption; its calculation considers water heating, ventilation and lighting. These calculations mainly include the size of the dwelling, and then envelope quality, systems characteristics, etc. as well as, standard calculations for occupant-related parameters (indoor temperature, presence, air change). Better modeling of occupant behavior would improve the calculation of EPC. In addition, our results of sensitivity analysis and monitoring showed that occupant behavior is rather dynamic, especially in terms of the duration of a chosen setting. Therefore, an important future work on EPC would be to be able model this dynamism in the calculation, such as integrating a simulation software that could update the formula in a more dynamic way based on occupant behavior.

Another field of improvement could be to develop user profiles for energy use and use this as part of EPC formula, or the regulation. Precise energy prediction is not one of the goals of energy performance regulations in the Netherlands, but a better prediction of energy performance could help in understanding the capacity of energy saving of a building, as well as realizing the actual energy savings expected from the housing stock.

§ 7.5 Final Words

One of the goals of sustainable design is to maintain indoor comfort levels while reducing energy consumption and environmental impact. In addition to advanced research and labeling implementations in the field, building regulations on environmental impact and energy consumption both nationally and in EU level present the optimum thresholds that need to be achieved.

Understanding occupant behavior will be even more important in future for efficiency of electricity use. Findings from this research could help improving design of objects, systems and architectural design in order to reduce energy consumption by occupants at home. Including occupant behavior articulately in the product and system designs, as well as in the calculation tools and methods of building regulations will help in reaching the aimed energy performance levels. Unless done so, the levels set as goals might stay as abstract figures. Occupants' preferences and needs have an important influence on the energy efficiency of the buildings, but there is still little known about this, especially in terms of the actual behavior and the determinants of it.

Lastly, research efforts in this field are also important for the occupants to realize, and further understand how significant the impact of their decisions at home to its energy performance, through which their energy consumption expenses as well as their environmental impact could be reduced.