1 Introduction

There is an increasing need for ensuring high energy savings throughout the building lifecycle, from the early design phases until post occupancy. Utility (services) and firmness (robustness) are principles of good design since Vitruvius, but sustainability was added as a new principle after 1980s, for a distinct understanding, evaluation and action development on energy consumption and environmental impact of buildings. Today, we are able to measure the consumption levels and environmental impact of our buildings, manage their indoor comfort, and combine this further with our personal desires.

Sustainability means decreasing waste and pollution, the demand for physical resources (energy, material…) and the impact on climate change, while maintaining the indoor comfort and health conditions in a building. Design decisions for sustainability include that of land use, microclimate management, form, spatial organization, building envelope, and managing water, waste, and energy systems. The essence of sustainability lies in designing all these factors with a holistic approach, while making sure that the building is usable for the occupant. Energy efficient housing requires less energy and uses renewable energy resources in the most efficient way for the energy needed during occupancy. Kim and Rigdon (1998) define the three basic principles of sustainable design as efficient use of resources (reduce, reuse, recycle); assessment of resource consumption during construction and use; and human centered design (the interaction between the human being and the environment). This research addresses the latter, the human aspect.

The buildings' energy consumption estimated by simulation software can be validated in total, only during occupancy, when the design is tested on actual use. For residential buildings, we know that sometimes the actual energy use levels are different than the expected/calculated (Lutzenheiser, 1992; Jeeninga et al., 2001; Guerra Santin, 2010; Majcen, 2013). A couple of reasons to this can be calculation drawbacks, incorrect construction applications and unexpected occupant behavior. Therefore, better understanding of the relationship between occupant behavior and energy consumption can enable more efficient design and operation of (residential) buildings, which are more suitable to the occupants' use considering thermal, acoustical, visual, environmental comfort, health and safety.

Policy on energy efficiency in buildings focuses mostly on building characteristics and mechanical systems like heating and ventilation. Although there is strong evidence for the influence of occupant behavior on energy consumption, the effort made to gain more insight to this relationship stayed behind for a long time. This study addresses the influence of occupant behavior on energy consumption for heating and electricity use for appliances and lighting, in residential buildings.

This research is conducted as a joint effort at Delft University of Technology, Faculty of Architecture, between the chair of Design Informatics; research program Computation and Performance, and the chair of Housing Quality and Process Innovation (HQPI). Chair Design Informatics, research program Computation and Performance aims to improve the performance of buildings by using computational methods for model generation and analysis, decision-making and design communication, in an interdisciplinary context. This research could contribute to the further development of computational model(s) and tools in support of user's decision-making processes. Furthermore, one of the research goals of chair HQIP is to understand the influence of occupant behavior to energy consumption in dwellings. The PhD research of Guerra Santin (2010) and Majcen (2016) of the chair HQIP specifically focus on occupant behavior and energy consumption. This research is built partially on the same datasets as Guerra Santin ('OTB dataset' and 'WoON survey'), with different research questions. Findings of Guerra Santin and Majcen's research are referred to, in the relevant sections of this thesis. Most of the research conducted under the title of this PhD was published between 2009 and 2013.

§ 1.1 Research Motivation

The building sector has a prominent share in energy consumption and environmental impact. Urban sprawl, over-consumption of energy and release of CO2 emissions, use of natural resources, excessive use of fossil fuels, and waste production damage the environment significantly. Residential buildings share 41% of final energy consumption at EU level (ODYSSEE, 2012); the construction and use of buildings account for 50% of natural resources consumption, 40% of energy and 16% of water use (Gauzin-Müller et al., 2002). Besides the impact on the environment, building and resource economy has a major share in the efforts towards sustainability, since energy independency is an advantage for all. Especially for the last 4 decades, improving energy efficiency in all sectors has been a major concern in the European context. Undoubtedly, this dedication requires long term involvement of all stakeholders in developing policy, mechanisms, measures, technology, monitoring, and re-evaluating.

Thanks to the accelerating effort on the energy performance regulations in member states, and on the EU level, and research focusing on passive and low to zero energy housing, residential buildings have incrementally improved in terms of their energy efficiency. However, the visionary goals seem not to be achieved, neither on EU level, nor on residential sector level (EC, 2012). Not achieving the calculated energy performance levels and significant energy consumption differences observed in dwellings even with similar building characteristics (e.g. Lutzenheiser, 1992; Jeeninga et al., 2001; Guerra Santin, 2010) raise curiosity to look into this variance. For instance, Guerra Santin (2010) found that the actual energy consumption for heating is half of the expected use in dwellings with low energy efficiency, and the actual energy use is even higher than the expected in very energy efficient houses. This finding is similar to others such as Tigchelaar et al., 2011 and Cayre et al., 2011. Lutzenheiser's research (1992) proves that actual energy consumption of households with similar characteristics in similar dwellings may differ by 3 times. Jeeninga (2001), who studied the theoretical energy consumption of dwellings with similar households, found a factor of 2. Majcen et al. (2016) found that the occupant behavior is crucial in actual energy consumption, accounting for as much as 50% of the variance in heating consumption. The potential variance of occupant behavior in dwellings with identical building characteristics suggests that its influence on energy consumption should be taken more seriously into consideration during calculations and design.

§ 1.2 Problem Areas

The variance of energy consumption in dwellings is expected to be based on design stage calculation drawbacks and incorrect construction applications in the implementation stage (Guerra Santin, 2010). In addition, ignoring occupant behavior in design processes, low resolution of the behavioral model in design stage, lack of knowledge on the determinants of occupant behavior and the rebound effect are the problems related with occupancy in the dwellings. Rebound effect is defined as occupant behavior reducing the potential energy savings, depending on their increased use of more efficient products, while replacing their inefficient products with more efficient ones (Terpstra, 2008). Today, most of the difference between the calculated/theoretical energy performance and actual energy consumption is defined as the energy performance gap, which is presented more in detail in Chapter 2.

§ 1.2.1 Calculation drawbacks, precision and sensitivity of calculation models

'Building' is a process that involves several professions, and parameters related to the decisions of the professions on design and construction. Collecting all the intense and specialized data, related to the whole process of building from design to post occupancy, is rather difficult, and requires many crosschecks among professions. The resolution and language of the data, including the data on occupant behavior, change significantly according to different fields, which also asks for calibration and optimization on different levels. The lack of comprehensive data of the whole process creates calculation drawbacks.

The ambiguity and several assumptions during conceptual design stage, the level of abstraction in modeling, the resolution of data, and the precision and sensitivity of the statistical model, software's built-in assumptions of energy management systems are the obstacles that might come across in regard to occupant behavior, when calculating energy performance through simulation based modeling (Judkoff et al., 1983). Statistical models (correlation, regression ...) are claimed to be faster and easier tools than simulation models to predict energy consumption in large sample size of dwellings (Schuler et.al. 2000; Pachauri, 2004; Freire et al. 2004). Indeed, the precision and sensitivity level of simulation tools might be too high to model occupant behavior in comparison to statistical models. However, simulation tools can help in modeling detailed aspects of behavior in a way that statistical models cannot, or ignore.

§ 1.2.2 Problems related to building construction and inspection

In addition to calculation drawbacks, the variance in energy consumption is expected to be because of construction defects/mistakes in thermal insulation, detailing, airtightness, and HVAC systems installations. Nieman (2007) showed that in a sample of 154 dwellings in the Netherlands, 25% did not meet the energy performance certificate requirements because of implementation being different than the expected. Gommans' (2007) monitoring in another sample proved that 25% of the heat pumps reached the expected efficiency, 40% of solar boilers functioned poorly. Exploring each of these issues will not only explain this variance in energy consumption but also emphasize the potential new fields of action for further energy efficiency.

§ 1.2.3 Occupant behavior

§ 1.2.3.1 Resolution of data on behavior

As also mentioned before, one of the first problems related with modeling the relationship between occupant behavior and energy performance is that there is not enough detailed data collected on occupant behavior (Mahdavi, 2011). Hence behavior is included in design process based on large assumptions of patterns, which many times do not reflect the real situation (e.g. Haas et al., 1998; Branco et al., 2004; Groot et al, 2006).

§ 1.2.3.2 Rebound effect

More and more our daily routines are equipped with appliances, complex systems and technologies in dwellings. We use smart control devices, real time feedback and smart meters to manage indoor comfort, and energy efficient appliances with the promise of saving energy and/or to manage our life at home easier, quicker and more efficiently. In some cases, it is proven that occupant behavior reduces the potential energy savings, depending on the occupants' increased use of more efficient products, while replacing their inefficient products with more efficient ones. This is called rebound effect. This leads to a reduction of the expected energy savings in dwellings. Berkhout (2000) explains part of the consumption difference between high and low energy efficient dwellings by rebound effect.

§ 1.2.3.3 Including occupant behavior in design / Designing for the user

One of the problems of the current building process is that the occupant is not known during the design phase. However, any system or product should meet users' needs and be usable (ISO, 1999) in order to obtain better performing buildings. This is very much related with the architectural design, as well. These buildings will have a better chance to be more energy efficient, since they will inherently reduce the miss-use related energy loss. As early as 1985, Gould and Lewis explain the elements of such design processes as early focus on occupants and tasks, empirical measurement, and iterative design. Haines (2014) lists those as the occupant behavior and its environment being studied, the occupants' characteristics being researched and designed for, the occupants being included in the design and development of building process. A user-centered design process would help to reduce the variance between the calculated and the actual levels of consumption. Several studies point out to the necessity to take occupant behavior into consideration in the design phase, and later on, for predicting their influence on energy consumption (Soebarto and Williamson, 2001; Dell'isola and Kirk, 2003; Yudelson, 2010; Azar and Menassa, 2012; Peschiera et. al., 2010).

§ 1.2.3.4 Determinants of behavior

In order to bring about a meaningful reduction in the energy consumed in the housing stock, we also need to know more about the underlying determinants of occupant behavior. In addition to occupant's interaction with systems and appliances, and determinants of energy consumption; perception of indoor comfort (thermal, acoustic, indoor/outdoor air quality) might vary considerably according to the characteristics of the dwelling and household (age, occupation, gender, income, etc.), which influences energy consumption, indirectly. How the household characteristics interact with building characteristics create the ground to explore further, for the reduction of energy consumption in dwellings.

§ 1.2.4 Occupant behavior and energy consumption

The advancements in energy performance regulations and various implementations in the field lead the way to reduce the energy consumption and the resulting environmental burden for buildings. However, the energy reductions might fall short of expectations. As mentioned before, occupant behavior, quality of the construction, and calculation drawbacks might be undermining the effect of the regulations. Little is known about how occupants interact with dwellings, what the background to this interaction is, and the resulting influence on energy consumption.

Developing insight into occupant behavior at home would improve the understanding of the effect of building regulations on energy consumption, which could further help to better integrate the calculation of user behavior's impact on energy consumption, in the energy regulations for buildings. This way, instead of assumptions about behavior, we can actually develop more adequate ways to model behavior in energy performance calculations.

The ability to make accurate predictions of the energy use of households is already an important issue for energy companies and will become even more important with the emergence of smart grids. Specifically, for electricity it is possible to make accurate predictions of the total consumption when the duration of use of each electrical appliance is known as well as its required power. Through the installation of smart meters and pattern recognition, the use of appliances and occupant behavior can be analyzed in individual homes. Unfortunately, as such data are difficult to collect by energy companies, especially at macro-level, therefore we need to establish more easily accessible parameters with an explanatory power to determine the level and variance of electricity consumption in households.

Calculating energy performance adopts a variety of tools. For instance, the EPC (Energy performance coefficient) calculation for energy consumption, is based on a standard number of people and behavioral patterns in the Netherlands. This instrument has been in effect since December 1995 in the country, and imposes the norm requirements on the energy performance of new buildings. It is a known fact that different methodologies for new buildings, like EPC, EPBD (Energy performance buildings directive), or other tools/methods calculate different levels of energy performance for the same building and the contribution of the occupant behavior to the energy performance levels. More exploration is necessary on the existing models of occupant behavior and energy performance, and their approaches of data collection, processing data, and so on. This topic is further elaborated in the Methodology sub-section.

Ultimately, it is interesting that the building regulations on energy consumption are formulated based on building and system characteristics and make assumptions of occupant behavior through a more static formula, while in essence, it is the people who dynamically cause energy consumption, not buildings. The growing number of households and size of dwellings, while the household size getting smaller, points to a future where inhabitants will have an even greater contribution to the energy consumption in housing.

The aim of this research is to reveal the relationship between occupant behavior and energy consumption, both in terms of heating energy and electricity used for lighting and appliances. The determinants of occupant behavior, robustness of dwelling energy consumption to user behavior, and defining user patterns/profiles are the main elements of this work. This research will help understanding the occupant related factors of energy consumption in dwellings, which will contribute to the better design of products, systems, dwellings, and achieving more advanced regulations.

§ 1.3 Research Questions

This thesis deals with occupant behavior and actual energy consumption in the Dutch dwelling stock. 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?**

In order to research this question, the sub-questions are formulated as follows:

1 **What is the sensitivity of a dwelling's heating energy consumption to occupant behavior? (Chapter 3)**

Research on energy consumption of dwellings covers thorough investigation of the behavioral performance during the use of the dwellings, 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 occupancy is still rather low. Recent research attempts to construct models for the effects of occupancy on building energy performance, and the physical and psychological descriptions of occupancy (Mahdavi, 2011).

The sub-questions are:

- a 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?
- b How can behavior be modelled in order to assess the robustness of the energy performance in dwellings to occupant behavior?
- c What is the weight of each behavioral aspect in terms of its influence on energy consumption?

2 **What is the influence of lighting and appliance use on the total electricity consumption in dwellings? (Chapter 4)**

This question aims to gain insight into the types of occupant behavior that influence electricity consumption. Discerning the determinants of behavior will help with the fields of action, to promote reducing energy consumption among inhabitants.

a. 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 …)
b. How much of the variance in electricity consumption in dwellings can be explained by direct and indirect determinants?

3 **What are the behavioral patterns and profiles of energy consumption? (Chapter 5-6)**

Following finding out the sensitivity of energy performance of dwellings to occupant behavior and its determinants, this question looks into exploring behavioral patterns of energy consumption. This will contribute to addressing occupant behavior in policies towards energy efficiency. Besides, determining how behavioral patterns relate to household characteristics will improve energy calculations and simulation programs for modeling occupant behavior more accurate as well as energy performance levels.

a. What are the behavioral patterns of thermostat control? How do they relate to the household characteristics, revealing behavioral profiles? (Chapter 5)
b. What are the behavioral patterns of electricity consumption? How do they relate to the household characteristics, revealing behavioral profiles? (Chapter 6)

§ 1.4 Research Approach and Methodology

The methodology for modelling the influence of occupant behavior on the energy performance of buildings follows two main approaches: The deductive and the inductive. This terminology refers to the data processing track and the hierarchy of data used in the analysis. The deductive approach utilizes the data on the characteristics of household and energy consumption and income levels to find statistical correlation between the energy use and occupant behavior, whereas the inductive approach calculates the energy consumption of a building based on actual occupancy and behavior patterns determined by presence, circulation, and operation of lighting, system control devices and appliances.

Inductive behavioral models focus on a single zone model based on one space in the building, or the whole building, or more zones with fewer details on use, and more articulation on movement. This underlines the gap of modelling occupant behavior in residences, in a manner that involves both the use of space and circulation patterns in relation to the dwelling energy performance. In terms of the kind of data used, the deductive approach works with household characteristics like age, education, hobbies, habitual use of systems and appliances, income and energy consumption levels based on energy consumption bills; whereas the inductive approach works with the actual behavioral data about presence, circulation and system operation patterns. The time frequency of the collected data may change from a period of 3 months, a year etc. in the deductive, to a period of a minute, an hour, etc. in the inductive approach. A survey (cross-sectional data) is the most common method of collecting data in deductive approach, however in the inductive approach, monitoring and/or observation of behavior (longitudinal data) are preferred. In terms of the analysis of the data, the deductive approach mainly uses statistical methods, and whereas the inductive approach might work with both statistics and simulation. Considering the differentiation of outputs; a big part of the research with deductive approach estimates the influence of behavior on energy use from 1 to 12% (e.g. Andersen, 2009; Vringer, 2005; Tommerup et. al, 2007), whereas the behavior models built up with the inductive approach calculate this impact as 20-50% (e.g. Page et al., 2008; Borgeois, 2005; Gaceo et al., 2009).

This study's methodological approach combines the deductive and the inductive methodologies, by considering both the determinants of behavior and the behavior itself. The details of the datasets, of which this thesis is concerned, are explained further in Section 1.4.1. Dataset 1 is analyzed with the deductive approach. The data collected is cross-sectional: a questionnaire applied at a certain time for once, on certain number of households, asking about the characteristics of the household and their behavior. Statistical methods such as regression and correlation applied. A test on Dataset 1 was made by modeling the sample with a dynamic simulation program, to see the sensitivity of dwelling energy consumption to occupant behavior. This test is a first attempt to bring together the deductive and the inductive methodologies, by using cross-sectional data in a dynamic energy performance simulation program. Dataset 2 is analyzed with inductive approach. Longitudinal data of Dataset 2 about thermostat control behavior of a sample monitored over 2 months is modeled by repeated measures, and cluster analyses.

In this study, behavior is considered as presence patterns in a space, together with the actual heating (thermostat setting and radiator control) and ventilation patterns (operation of windows, grids, and mechanical systems), and the use of lighting and appliances. Occupant behavior is claimed to be determined by household characteristics, lifestyle and cognitive variables such as motivation, values and attitudes. The interaction between the user and the systems, and thermal properties of the building are the other fields of exploration. This research looks at the building and household characteristics that determine occupant behavior, as well as habitual (surveyed) and actual (monitored) occupant behavior.

In addition, in this research 'energy performance' of a building is considered as the amount of energy consumption estimated to meet the different needs associated with a standardized use of the building (EC, 2002) and 'energy consumption' is considered as energy supplied to the final consumer's door for all energy uses (EU, 2016), which is about the actual occupant behavior. Robustness is "the ability of a system to resist change and to perform without failure under a wide range of conditions." (Wieland and Wallenburg, 2012)

PHASE	SENSITIVITY ANALYSIS	DETERMINANTS OF ELECTRICITY USE	BEHAVIORAL PATTERNS OF ELECTRICITY USE	BEHAVIORAL PATTERNS OF GAS USE (HEATING + HOT WATER)
CASE	WV & LR	WV & LR	WV & LR	WH
VALIDATION CASE	WV & LR & WoON	WoON		
METHOD	MONTE CARLO & MARKOV CHAIN	CORRELATION & REGRESSION	CORRELATION, FACTOR ANALYSIS, & ANOVA	CORRELATION & REPEATED MEASURES
	LITERATURE REVIEW			

FIGURE 1.1 Research phases, cases, and methods used that constitute the structure of the thesis (abbreviations: WV: Wateringse Veld; LR: Leidsche Rijn; WH: West Holland)

§ 1.4.1 Datasets

§ 1.4.1.1 Dataset 1: Wateringse Veld and Leidsche Rijn (OTB Dataset)

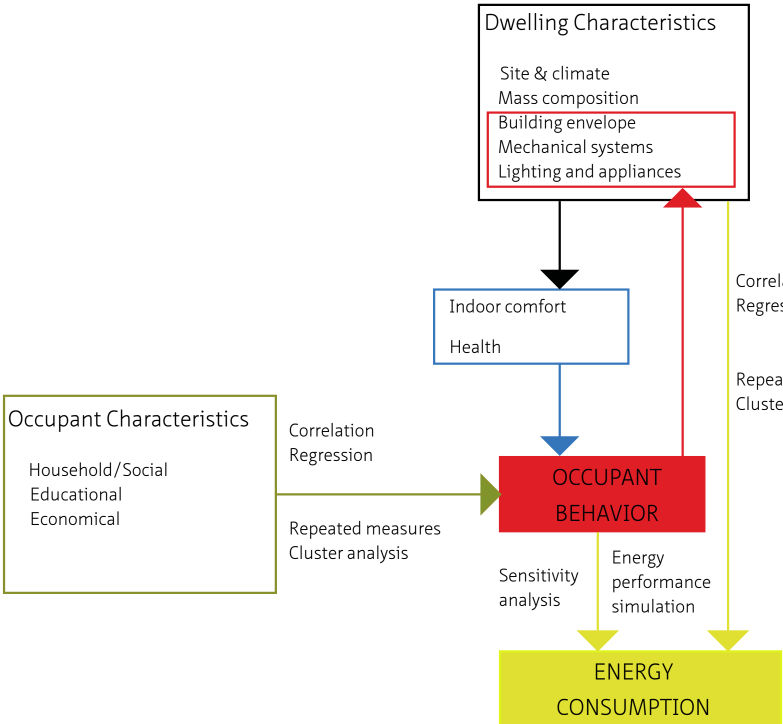

FIGURE 1.2 Explanation of research methods and data used in the research

Wateringse Veld (WV) , in the Hague is a neighborhood that started to be built in 1996. Leidsche Rijn neighborhood in Utrecht started to be constructed almost parallel to WV, in 1997 and is projected to be completed in 2025. Guerra Santin (2010) analyzed occupant behavior and heating energy consumption extensively in her research based on the OTB dataset. 6000 questionnaires were distributed in these two neighborhoods in The Hague and Utrecht. A response rate of 5% was achieved. The low rate can probably be explained by the fact that the inhabitants were uncomfortable with personal questions about their lifestyles and income levels, etc. The households were sent reminders to potentially increase the response rate.

The survey provided information on 323 dwellings that covered a range of topics in the questionnaire with regard to household characteristics, individual's characteristics, economic characteristics, energy consumption, presence, dwelling characteristics, heating behavior, ventilation behavior, appliance use, lighting devices, and others. All the dwellings in Wateringse Veld had individual central heating as opposed to Leidsche Rijn, where all but four had district heating. Dwellings with balanced ventilation was better represented in Wateringse Veld. There were far fewer maisonettes and detached houses in the sample than terraced houses, corner houses and flats. However, terraced and corner houses and flats are more common in the Netherlands. The questionnaire is provided in Appendix I.

<table>
<tr><th colspan="2" rowspan="2">DATA</th><th>CASE 1:
WATERINGSE VELD & LEIDSCHE RIJN</th><th>CASE 3:
WoON</th><th>CASE 2:
WEST HOLLAND</th></tr>
<tr><td>N: 323
2 neighborhoods built after 1995
data collection: in 2008
questionnaire</td><td>N: 4724
entire housing stock
data collection: in 2005
questionnaire</td><td>N: 61
random sampling
data collection: in 2011
questionnaire & monitoring</td></tr>
<tr><td rowspan="7">DWELLING CHARACTERISTICS</td><td rowspan="4">Layout</td><td colspan="2">dwelling size</td><td></td></tr>
<tr><td colspan="3">dwelling type</td></tr>
<tr><td colspan="3">dwelling location</td></tr>
<tr><td colspan="2">number of bedrooms</td><td></td></tr>
<tr><td>Envelope</td><td colspan="3">envelope design</td></tr>
<tr><td rowspan="2">Systems</td><td colspan="2">heating system type</td><td rowspan="2"></td></tr>
<tr><td colspan="2">ventilation system type</td></tr>
<tr><td rowspan="8">HOUSEHOLD CHARACTERISTICS</td><td rowspan="4">Household Characteristics</td><td colspan="3">household type</td></tr>
<tr><td colspan="3">education</td></tr>
<tr><td colspan="2">background</td><td></td></tr>
<tr><td colspan="3">income</td></tr>
<tr><td>Presence</td><td colspan="2">presence at home</td><td></td></tr>
<tr><td rowspan="3">Actual Behavior</td><td colspan="3">heating system use</td></tr>
<tr><td colspan="2">ventilation system use</td><td></td></tr>
<tr><td colspan="3">lighting/appliances use</td></tr>
<tr><td></td><td></td><td colspan="3">shower/bath frequency</td></tr>
<tr><td>ENERGY USE</td><td>Energy use</td><td colspan="2">energy consumption</td><td></td></tr>
</table>

FIGURE 1.3 Collected data in the three datasets

The actual energy consumption of households was asked to the respondents in the questionnaire, in the form of the energy consumption specified in their last available energy bill. Respondents living in dwellings with individual central heating reported their consumption in m3 of gas, while the ones with district heating in GJs. In the Netherlands, gas consumption in general includes space, water heating and cooking and electricity consumption includes mechanical ventilation, space cooling, lighting and appliances. In dwellings with district heating, heating energy is used for space and water, while electricity is used for cooking, mechanical ventilation, space cooling, lighting and appliances.

Characteristics			Behavior				
Household	Individual	Dwelling	Presence	Heating	Ventilation	Light & App	Consumption
Size	Age	Type	Nu of occupants	Thermostat type	Ventilation type	Nu/duration of domestic appliances use	Actual consumption figures
Composition	Gender	Room function	Duration of occupation at home	T. set point	V.T. previous h.		
Change in composition	Education	Number of rooms		T. set point duration w.day/w.end	Window operation: location/time/duration/angle	Nu of appliances in living room	Nu/power of solar panels
Years of residence	Occupation	Kitchen type	Duration of occupation in each room			Nu/duration of stand by appliances use	Nu/power of PV panels
Awareness of energy use	Hours spent outside house	Thermostat type		Shower &bath use	Grilles operation location/time/duration/angle	Nu of stand by appliances in living room	
Electricity tariff	Background	Ventilation type (V.T.)	Presence w.day/w.end & winter/summer	Comfort	Mechanical ventilation set point w.day/w.end duration	Appliance size & label	
Income	Health	V.T. in previous house				Washing mach. & dishwasher load & temper.	
Ownership	Smoking		Presence of pets		Comfort	Lighting appliances: location/nu/efficiency	

TABLE 1.1 Dataset 1, OTB sample, categories of collected data

§ 1.4.1.2 Dataset 2: The West of Netherlands Sample (WH)

A two months monitoring-pilot on a total of 61 dwellings in the Netherlands was conducted in 2011, by several commercial parties such as Eneco (an energy company in the Netherlands), to assess the effectiveness of a newly developed home energy monitor, and a follow-up study by researchers from Delft University of Technology.

The energy monitor includes a sensor, a sending unit, and a display (Figure 4). The sensor and sending unit are connected to the electricity and gas meters. The sending unit and the display communicates via the radio signal. The display has three settings, the standard one showing the consumption levels in real time (with a delay of up to 10 seconds). The display also indicates the daily consumption (over the past 24 hours), and compares daily consumption with a personal savings target. The daily target was corrected to the individual's fluctuations in consumption throughout the week. The monitor was designed to be simple to use, participation in the dataset-study was on a voluntary basis. The baseline consumption of the sample was 3614 kWh, the same as the Dutch average (which increased at an average rate of 1.1% per year between 1998 and 2008) (EnergieNed, 2009), while the household size of 2.4 was slightly above the Dutch average of 2.3. The large majority involved in the pilot were homeowners.

FIGURE 1.4 Smart thermostat display in Dataset 2

Occupant characteristics			Behavior
Household	**Individual**	**Dwelling**	**Heating**
Size	Age	Type	Thermostat setpoint day/night
Income	Gender	Floor area	
Electricity tariff		Insulation level	Lower temp. at night
Satisfaction with thermostat		Water-saving shower head	Lower temp. when absent
Selection of energy company		Nu of energy saving lamps	current thermostat program
		Double glazing	room temperature

TABLE 1.2 Dataset 2, West Holland dataset, categories of collected data

§ 1.4.1.3 Dataset 3: WoON (WoONonderzoek Nederland) Database

WoON Database of the Dutch Ministry of Housing (www.vrom.nl) includes 4500 cases and is assumed to be representative for the total housing stock of the Netherlands. The latest WoON used for this study was carried out in 2005. The dataset covers a household survey including occupant behavior, dwelling inspections and reports on energy consumption in the 4500 dwellings.

§ 1.4.2 Methods

This study applies a variety of statistical and simulation models, in relation to the deductive and inductive approaches.

Correlation and regression analyses are used on Dataset 1 (OTB Dataset), to model the relationship between occupant behavior and electricity consumption. This also revealed the determinants of electricity consumption. Later on principal component analysis and cluster analysis is applied to Dataset 1 for drawing electricity consumption behavior patterns and relevant user profiles. These cover the deductive methods of the work. Repeated measures analysis is used on Dataset 2 (WH Dataset) to reveal the users' thermostat management patterns over two months. Cluster analysis, afterwards, is used to generate user patterns for thermostat control. Applying building energy performance simulation tools and Monte Carlo analysis on Dataset 1 reveals the sensitivity of energy consumption of a dwelling to occupant behavior.

This thesis does not necessarily esteem the deductive or inductive methodologies; on the contrary, it tries to make us of both. The methods used to answer each research question are explained more in detail in relevant chapters.

§ 1.4.3 Limitations

One possible limitation of the Dataset 1 sample is the low response rate to the questionnaire (5%) and the other is that the survey was conducted in two similar neighborhoods, Leidsche Rijn and Wateringse Veld, from around similar periods of development.

The low response rate may be caused by the number and intricacy of questions. Except for the twelve blank forms, the returned questionnaires were filled in almost completely. The general characteristics of the sample were representative of the Netherlands (in comparison with Dataset 3: The National Survey: WoON Database) with the exception of income and education, which were higher than the national average. The Dataset 1 was representative for dwelling type, but not for HVAC systems used in the Netherlands. Another problem of the OTB dataset was the small number of dwellings with balanced ventilation and solar boilers; and no dwellings with heat pumps. Dataset 3 included dwellings with heat recovery ventilation.

Previous work on occupant behavior and energy consumption in dwellings use similar sample sizes, e.g. Curtin et al., 2000; Jeeninga, 2001; Uitzinger, 2004; Keeter et al., 2006. These studies claim that a low response rate might not influence the accuracy of the results. As far as the vintage of Wateringse Veld and Leidsche Rijn, these were chosen specially to be able to work on new buildings with low EPC values. The deviations from the national averages are caused by focusing on these two recently built neighborhoods.

Another limitation relates to the tracking and recording system for energy consumption in the Netherlands. Energy provider companies ask occupants to send in their meter readings once a year. These companies 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 on the basis of 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 could create a bias in the accuracy of the energy consumption data.

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

In Dataset 2, 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, based on income level, awareness level, availability of infrastructure, and further.

§ 1.5 Relevance of This Research and its Contributions

The scientific contribution of this research is characterized by the combination 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. The contribution of this research is new knowledge on heating energy and electricity consumption of dwellings in Dutch context, in terms of their determinants and patterns, in relation to occupant behavior. The relevance of this research and contributions is discussed more in detail in the Conclusion chapter of this thesis.

For the design and engineering industry, and energy companies, the knowledge gained through this research means support for designing systems that are effective in reducing energy consumption, in addition to influencing users towards energy efficient behaviors. For building 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. 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 knowledge produced with this research is reported for the improvement of energy policy and regulations, as well as advice to housing associations and energy companies. Furthermore, this thesis could contribute to the better design and implementation of management systems and products in new design. Further research could utilize this knowledge to increase the energy efficiency of dwellings.

§ 1.6 Thesis Structure

Chapter 2 provides a literature review of the field of energy consumption from urban to user scale, a review of energy performance modelling methods, a review of energy performance gap, and determinants of heating energy and electricity consumption. This review first helped to set up a reference point for the reasons to actual occupant behavior, how perception, lifestyle, norms, rules lead to various actions at home. Secondly, through the review, a framework for the relationship between occupant behavior and energy consumption is created (Figure 1 and Figure 2), based on the determinants of behavior, i.e. occupant characteristics (education, economy, social), and dwelling characteristics (envelope, systems, lighting and appliances…). This literature review sets the context and also the first steps of this research. The determinants found through this review hold the content and structure for the questions of the survey designed for OTB dataset.

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

Despite the efforts to improve the energy efficiency of electrical appliances, the growing population, the increasing number of households and the wider use of electrical appliances could be instrumental factors in the rising levels of electricity consumption. To bring about a meaningful reduction in the electricity consumed by the housing stock, we need to know more about the underlying determinants. Chapter 4 explores determinants of electricity consumption in Dutch dwelling stock.

Chapter 5 scrutinizes thermostat control behavior in Dutch dwellings, looking through data obtained by monitoring 61 dwellings during two months in Spring 2011. It also discusses monitoring as an approach towards understanding occupant behavior and energy consumption relationship. A smart thermostat was designed for dwellings, which will display and record the chosen thermostat settings, energy consumption, weather, and traffic conditions. This chapter reveals how the thermostat use pattern changes from day to day, weekdays to weekend, and between different weeks and months based on monitoring data. Following, households with similar patterns of thermostat use are identified, and these are related to other characteristics of household and/or thermostat use.

Creating user patterns and profiles of appliances and comparing them for electricity consumption is addressed in Chapter 6. This will provide better understanding of the behavioral aspects of electricity consumption. The ability to make accurate predictions of the electricity usage of households is already an important issue for energy companies and will become even more important with the emergence of smart electricity grids. It is possible to make accurate predictions of electricity consumption when the duration of use of each electrical appliance is known as well as its voltage. Unfortunately, as such data are difficult to collect by energy companies, especially at macro-level, therefore we need to establish more easily accessible parameters with an explanatory power to determine the level and variance of electricity consumption in households.

Chapter 7 is dedicated to the conclusions of this thesis.

References

Andersen, R. V. (2009). Occupant behavior with regard to control of the indoor environment. PhD thesis, Department of Civil Engineering, TU Denmark.

Berkhout, P.H.G., Muskens, J.C., Velthuijsen, J. W. (2000). Defining the rebound effect. Energy Policy, 28 (6–7), 425–432.

Bourgeois, D. (2005). Detailed occupancy prediction, occupancy-sensing control and advanced behavioral modeling with-in whole-building energy simulation. PhD Thesis, Universite Laval, Quebec.

Branco, G., Lachal, B., Gallinelli, P., Weber, W. (2004). Predicted versus observed heat consumption of a low energy multifamily complex in Switzerland based on long-term experimental data. Energy and Buildings, 36 (6), 543–555.

Cayre, E., Allibe, B., Laurent, M. H., Osso, D. (2011). There are people in this house! How the results of purely technical analysis of residential energy consumption are misleading for energy policies. Proceedings of the European Council for an Energy Efficient Economy (eceee) Summer School, 6–11.06.2011, Belambra Presqu'ıle de Giens, France.

Curtin, R., Presser, S., Singer. E. (2000). The effects of response rate changes on the index of consumer sentiment. Public Opinion Quarterly, 64 (4), 413-428.

Eames, M., Kershaw, T. & Coley, D. (2011). The appropriate spatial resolution of future weather files for building simulation. Journal of Building Performance Simulation, 5, 1-12.

EC (2002) Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings, 4.1.2003 Official Journal of the European Communities L 1/65 online at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:001:0065:0071:EN:PDF (last access: 26.11.2016)

EnergieNed (2009). Energieinformatiebank, Energy Dataset. http://www. energiened.nl/Content/Datasets/EnergieDataset.aspx?MenuItemID=9 (last accessed 20.05.2011).

EU (2016) EU energy in figures, Statistical Pocketbook 2016, Luxembourg: Publications Office of the European Union, 2016, online at: https://ec.europa.eu/energy/sites/ener/files/publication/pocketbook_energy-2016_epub-final_final.pdf (last access: 26.11.2016)

Euractiv, Energy efficiency (2016) The year of delivery? http://www.euractiv.com/section/energy/video/energy-efficiency-2016-the-year-of-delivery/?nl_ref=14169270 (last access: 05.06.2016)

Freire, R. Z., Oliveira, G.H.C., Mendes, N. (2004) Development of regression equation for predicting energy and hydrothermal performance of building. Energy and Buildings, 40, 810-820.

Gaceo, S.C., Vazquez, F.I., Moreno, J.V. (2009). Comparison of standard and case-based user profiles in buildings energy performance simulation, 11th International IBPSA Conference, Glasgow, Scotland (27-30.07.2009) 584-59.

Gauzin-Müller, D., Favet, N., Purver, K. (2002). Sustainable Architture and Urbanism: Concepts, Technologies, Examples. Princeton Architectural Press, USA.

Gommans, L.J. (2007). Energy performances of energy efficient buildings. (in Dutch) TVVL magazine, September 2008, 18-24.

Gould and Lewis (1985). Designing for usability: key principles and what designers think. Communications of the ACM 28, 3, 300-311

Groot-Marcus, J.P., Terpstra, P.M.J., Steenbekkers, L.P.A., Butijn, C.A.A. (2006). Technology and Household Activities. Book chapter in User Behavior and Technology Development: Shaping Sustainable Relations Between Consumers and Technologies. Springer Publications. Dordrecht, the Netherlands.

Guerra Santin, O. (2010). Actual Energy Consumption in Dwellings, the Effect of Energy Performance Regulations and Occupant Behavior. PhD Thesis, OTB Research Institute, Delft University of Technology, the Netherlands.

Haas, R., Auer, H., Biermayr, P. (1998). The impact of consumer behavior on residential energy demand for space heating. Energy and Buildings (27) 195-205.

Haines, V. (2014). The Role of User Centred Design in Domestic Energy Demand Reduction. PhD Thesis, Loughborough University, United Kingdom.

ISO (1999), nr. 13407, Human-centred design processes for interactive systems https://www.iso.org/standard/21197.html (last seen 8 November 2017)

Jeeninga, H., Uyterlinde, M., Uitzinger, J. (2001). Energieverbruik van energiezuinige woningen. ECN rapport: ECN-C-01-072.
Judkoff, R. Wortman, D. Burch, J. (1983) Measured versus predicted performance of the SERI Test House: A validation study. SERI/TP-254-1953, Solar Energy Research Institute.
Keeter, S., Kennedy, C., Dimock, M., Best, J., Craighill, P. (2006). Gauging the impact of growing nonresponse on estimates from a national RDD telephone survey. Public Opinion Quarterly, 70 (5), 759-779.
Kim, J.J. and Rigdon, B. (1998) Education, Sustainable Architecture Module: Introduction to Sustainable Design. Ann Arbor MI: National Pollution Prevention Center for Higher Education, University of Michigan.
Lutzenheiser, L. (1992). A question of control – Alternative patterns of room air conditioner use. Energy and Buildings (18), 193-200.
Mahdavi, A. (2011). The human dimension of building performance simulation. Proceedings of the 12th IBPSA Building Simulation Conference, 14-16.11.2011, Sydney, 16-33.
Majcen, D., Itard, L., Visscher, H. (2013). Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications. Energy Policy (54).
Majcen, D. (2016). Actual Energy Consumption in Dwellings, the Effect of Energy Performance Regulations and Occupant Behavior. PhD Thesis, OTB Research Institute, Delft University of Technology, the Netherlands.
Nieman, P. (2007). Final report housing quality indoor environment in new built dwellings. (in Dutch) report Wu060315aaA4.PK, Vrom inspectie Regio Oost, Arnhem.
ODYSSEE (2012). Energy efficiency trends in buildings in the EU, Lessons from the ODYSSEE MURE project: http://www.odyssee-indicators.org/publications/PDF/Buildings-brochure-2012.pdf
ODYSSEE-MURE (2012). Energy efficiency policies and measures in the Netherlands, Monitoring of EU and national energy efficiency targets:
http://www.odyssee-indicators.org/publications/PDF/netherlands_nr.pdf
Pachauri, S. (2004). An analysis of cross-sectional variations in total household energy requirements in India using micro survey data. Energy Policy, 32(15), 1723-1735.
Page, J., Robinson, D., Morel, N., Scartezzini, J. –L. (2008). A generalized stochastic model for the simulation of occupant presence. Energy and Buildings (40), 83-98.
Schuler, A., Weber, C., Fahl, U., (2000). Energy consumption for space heating of west-German household: Empirical evidence, scenario projections and policy implications. Energy Policy (28), 877-894.
Tigchelaar, C., Daniels, B., Maenkveld, M. (2011). Obligations in the existing housing stock: who pays the bill? Proceedings of the European Council for an Energy Efficient Economy (eceee) Summer School, 6–11.06.2011, Belambra Presqu'ıle de Giens, France.
Tommerup, H., Rose, J., Svendsen, S. (2007). Energy-efficient houses built according to the energy performance requirements introduced in Denmark in 2006. Energy and Buildings 39(10), 1123-1130
Uitzinger J. (2004). Analysis of EPC and energy use in dwellings (in Dutch). IVAM/SenterNovem report.
Vringer, K., Aalbers, T., Blok, K. (2007). Household energy requirement and value patterns. Energy Policy (35), 553–566.
Wang, L., Mathew, P., Pang, X. (2012). Uncertainties in energy consumption introduced by building operations and weather for a medium-size office building. Energy and Buildings (53), 152-158.
Wieland, A., Wallenburg, C.M. (2012). Dealing with supply chain risks: Linking risk management practices and strategies to performance. International Journal of Physical Distribution & Logistics Management 42(10).
De Wilde, P. and Coley, D. (2012). The implications of a changing climate for buildings. Building and Environment (55), 1-7.