1 Introduction

§ 1.1 Energy consumption in residential buildings

One of the most important European and worldwide topics of the post war era has been the energy use. The rapidly increasing world energy consumption, from the 1950ies and on, has raised concerns on the security of supply, energy resources exhaustion and the environmental impacts on the ozone layer, global warming and climate change. The oil crisis of 1973 and 1979 made governments and policymakers to intensify the efforts of promoting energy conservation.

Final energy consumption is usually divided in three major sectors: industry, transport and 'other'. In the category 'other' one can find the sectors of agriculture, services and residential. A great part of the energy consumption of the industry, agriculture and services is related to buildings, which makes the total of energy consumption in EU due to the built environment approximately 40% [1]. Population growth, the increase in complexity and size of building services, the continuous strife for more comfort, and the increase in time spent inside buildings have made energy consumption for the built environment similar to the consumption of transport and industry. The world energy consumption due to industrial purposes in 1973 was 39%, in 2004 it was 30% and in 2040 according to the IEA optimistic scenarios is about to reach 31.4%. However, the consumption classified to the 'other' sectors has increased from 36% in 1973 to 42% in 2004 mainly due to buildings [2,3].

In 2014, energy consumption in EU due to residential buildings was 24.7%% of total consumption, almost matching that of the industry, while consumption due to transport was 32% [4]. According to the reference case scenario of the IEA in 2016, the total world energy consumption in buildings will be increasing by an average of 1.5% per year from 2012 to 2040. Until then, the world energy use in homes will be the 13% of the world delivered energy consumption showing an increase of 48% mainly due to increasing demand for housing in the non-OECD countries [5]. The above-mentioned numbers have made policy makers in EU (and elsewhere) to take action in order to promote energy efficiency and savings strategies in the building sector. The European Energy Performance of Buildings Directive (EPBD) [6] is an example towards this direction.

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The intensification of HVAC (Heating, Ventilation, and Air-Conditioning) energy consumption as well as the demand for increased thermal comfort, at levels that were considered a luxury not long time ago, have been crucial in the increase of energy use in the residential buildings. It is the largest energy end use for both the residential and non-residential sectors and it consists of the energy for heating, cooling, ventilation and air conditioning, which could be 30-57% of the total [7]. HVAC energy consumption represents on average, for old and new dwellings, approximately half the total energy consumption, more than double to that for domestic hot water, lighting or appliances [6].

§ 1.2 Background and scientific relevance

One way to reduce energy consumption is to improve the built environment's end-use energy efficiency. For the residential building sector, a series of options can be considered such as improving the envelope characteristics of the dwellings, replacing outdated and inefficient HVAC equipment, appliances and lighting, and improving the demand response (metering, pricing, end-use load management). Additionally, switching to less carbon intensive fuels for space and water heating would further contribute to the reduction of energy consumption.

The implementation of the above-mentioned measures resulted in a reduction of energy consumption increase in the residential sector but still substantial differences can be found between the energy consumption of similar dwellings [7,8,9]. Energy consumption between dwellings occupied by similar households have showed variations up to a factor of 3 [9]. Furthermore, the actual energy consumption of households was differing from the theoretical energy performance (as defined by the national guideline described in ISSO 82.3 [6]) by a factor of 2 [8].

The reasons for these discrepancies are believed to be the misunderstanding or underestimation of occupancy behavior [10,11,12], the quality of the construction [13,14] and rebound effects [15,16]. Therefore, there are plenty of opportunities for research and implementation of solutions towards the above-mentioned reasons, which could lead to a more efficient and sustainable residential built environment. Policy makers so far have been focusing their efforts in energy savings via technical measures that targeted the building envelope and HVAC. Although there is strong evidence that the final energy consumption of the residential built environment is strongly influenced by household characteristics, lifestyles and occupant behavior [7,66,67], few attempts have been made in order to quantify and analyze the effects of these factors.

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Another very important boundary condition when it comes to designing dwellings is that the indoor thermal comfort should not be compromised by energy savings. This necessitated a rational concept for the engineering and management of indoor climate in order to provide the proper levels of thermal comfort for the occupants, while minimizing the energy consumption. Thermal comfort standards have thus evolved in order to fulfill these increasing needs for comfort, and to improve the thermal acceptability of indoor environments. Although the specification of thermal comfort remains one of the most controversial topics in building science [17], two thermal comfort standards were developed since the 1970ies. The first one is the PMV (predicted Mean Vote) or heat balance model, which was primarily developed for the HVAC industry by P. O. Fanger [18]. During the model's development, Fanger used college students in controlled climate chambers that were exposed in various environmental conditions and developed heat balance equations that assumed that the human body's thermoregulatory system strives to maintain a constant internal body temperature [18]. Eventually he created a 7 point thermal comfort scale (-3 cold, -2 cool, -1 a bit cool, 0 neutral, +1 a bit warm, +2 warm, +3 hot) and a comfort equation that could predict when people could feel neutral based on the following parameters: mean radiant temperature, air temperature, relative air velocity, metabolic activity, clothing insulation and humidity. The PMV model in general works well in buildings with HVAC installations, mainly public buildings and offices. However, only a small fraction of residential dwellings has mechanical ventilation, the majority of those dwellings rely on natural ventilation. Furthermore, for these naturally ventilated dwellings the predicted indoor temperatures, which are considered comfortable, are significantly warmer than the ones predicted by Fanger's PMV model in warm climates and colder in cold climates [19,20]. Another criticism of the heat-balance approach was its static nature and the fact that it does not allow variations in the activity levels, the clothing or control of occupants over their thermal environment (opening or closing windows, turning up or down the thermostat). This could be explained by the fact that the PMV model, as already mentioned, was developed for the HVAC industry, which was mainly servicing the commercial building sector. In office buildings, usually there is a specific dress code with little deviation from it, metabolic activity is uniform, and the ventilation and temperature are centrally controlled by the HVAC.

This is not the case in the residential sector (and even in a big part of office buildings, nowadays, people can use windows or alternative dressing codes as well as working while standing up in specially developed office desks). Therefore another model was needed that could address these adaptive notions of the occupants which was the adaptive model for thermal comfort. According to the principles of this model people are not passive recipients of a constant thermal environment but constantly interacting with and adapting to it. When something is happening that upsets their neutral thermal sensations people tend to adapt in order to restore this initial balance of neutrality. Therefore three types of adaptation were introduced, physiological, behavioral and psychological [21].

Physiological adaptation, defined as the changes in the physiological responses that result from exposure to thermal environmental factors, and which lead to a gradual diminution in the strain induced by such exposure [19]. It can be distinguished into two categories: genetic adaptations, which have become part of the genetic heritage of a group of people and can go on for multiple generations, and acclimatization within the lifetime of individuals [68]. Acclimatization is considered an unconscious feedback loop mediated by the autonomic nervous system and is not likely to play a role in occupants' thermal comfort due to the moderate range of thermal conditions in the built environment [68]. Psychological adaptation is mostly related to social, cultural and cognitive variables and describes to what extent habits and expectations might influence occupants' perception of thermal environment [22]. Finally, behavioral adaptations are by far the most influential adaptation towards thermal comfort. Actions like adjusting the clothing levels, the metabolic activity, opening or closing windows and using the thermostat affect greatly the thermal comfort and consequently the energy consumption of the dwellings [23].

Field studies that were conducted with the adaptive thermal comfort in mind, led to a significant correlation between the indoor neutral temperature (T_n) and the corresponding mean outdoor temperature (T_o) [19,24,25]. For naturally ventilated buildings, the correlations between T_n and T_o indicated that more than 90% of the variations in T_n could be explained by the changes in T_o while for buildings with HVAC the correlations were much looser [22]. The strong correlations show that when heating or cooling is used, the neutral temperature may vary within a wide bandwidth dependent on the external temperatures. This variation was attributed to the behavioral adaptations such as clothing, metabolic activity, and actions towards thermal comfort (opening or closing the windows, using the thermostat etc.) as well as psychological adaptations in the form of shifting expectations [68].

The introduction of the adaptive model and the demonstration of a wide zone of indoor temperatures for thermal neutrality created space for potential implications on energy savings. If people by adapting to their thermal environment could feel neutral in a wide range of temperatures, then one could think what could be the potential energy savings if the indoor temperature is always closer to the lower margin of this bandwidth, minimizing the heating costs (for the colder climates where energy is primarily spent for heating). The same could be implied for the hot climates where energy is primarily spent for cooling. If people could feel comfortable in a range of indoor temperatures then air conditions could be programmed to operate in the highest temperatures of this range, thus, minimizing the cost of electricity used for cooling [26].

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However, there has been much criticism to the adaptive model, for example it has been suspected of pushing the thermal zone of building occupants to the critical boundary. Besides Nicol and Humphreys had warned that a low energy standard which increases discomfort would be as unsustainable as a standard that encourages energy use [25]. Furthermore, attitudes and beliefs could increase the forgiveness factor towards comfort conditions [19] and people might be deterred from doing actions that are deemed "too different and troublesome, and too much associated with a 'greeny segment' or associated lifestyle" [69] meaning that environmental concerns are not always translated into actions. Moreover comfort should not be compromised to that extent so it hinders productivity. Finally one can doubt if the realization of thermal comfort, which is a complex issue and depended on so many different parameters, by adjusting only a single parameter (temperature) is possible. De Dear himself has acknowledged this, suggesting for this reason the concept of alliesthesia [70].

Summing up, there are two prevailing models for predicting thermal comfort in the built environment. Validation of scientific models is usually coming from field data and large-scale measurement campaigns. The data needed to validate the PMV model is a combination of quantitative data (radiant temperature, air temperature, humidity) but also subjective data such as metabolic activity and clothing. The adaptive model is mathematically formulated only on quantitative data (indoor and outdoor temperatures) but all the adaptations (quantitative data such as actions towards thermal comfort, clothing adjustments etc.) are hidden in the bandwidth of indoor temperatures in which people feel neutral [27]. However, although both these models are widely used in building simulation models by practitioners to estimate and assess the comfort in individual dwellings, there are doubts about their validity and applicability range. It has to be noted here, that although indoor comfort in residential dwellings is also related to light, noise (and other aspects such as cooking, washing, gaming, watching television etc.) the focus of this thesis was on the parameters related to thermal energy, as this has the main share in energy consumption, and therefore to thermal comfort.

Various field studies have taken place over the years in the scientific field of thermal comfort in the built environment which differ in methods used, the length of the monitoring period and the season that the measurements took place. Temperature sensors with recording intervals of 15, 30, 45 and 60 minutes have been used [28,29,30,31,32,33,34,35,36,37,38]. The duration of the measurements varied between one to four weeks [33,34,35,36,37,38] in some studies while in others it covered the whole heating period [28,39]. In one study the occupants were provided a temperature sensor with its operating manual and were prompted to install it themselves which could hinder the accuracy and credibility of the measured data [34]. Furthermore, in all the above-mentioned studies data were gathered locally and had to be retrieved manually. Other studies used diaries and questionnaires where tenants could fill in the temperatures at specific times of the day as well as other relevant information [40,41]. This probably led to large uncertainty as no measurements were performed by measuring equipment and all the data were heavily dependent on the occupants' answers.

Apart from the problem of improving our knowledge on the actual energy consumption of the residential sector and the factors that affect it such as the building envelope, the heating and ventilation installations and the occupancy behavior, building scientists, designers and policy makers face another challenge. Building performance simulation has been established as the most common method in order to assess the theoretical energy consumption of dwellings that are under renovation or will be built from the start. Despite the growing sophistication and complexity of simulation tools for the built environment there are also shortcomings. The reasons for these shortcomings could be technical such as false assumptions made by researchers, designers or engineers who perform the simulations [10,43]. Furthermore, there could be limited information on materials of the building's envelope (especially for very old buildings). Another very important reason is related to misunderstanding or underestimation of the role of occupant's behavior [10,11,12]. Better prediction for the theoretical energy performance of buildings is tightly related to taking proper account of occupant behavior [10,11,43,44,45] leading to the need for understanding it better.

The EPBD directive is operational across Europe since 2009, however, little is known about the actual efficiency of this policy. There is a lack of publicly accessible databases containing the information on the energy label certificates together with the actual energy consumption of the dwellings [42]. Studies towards this direction, performed in the Netherlands, found that there are discrepancies between the theoretical and actual energy consumption of the residential building sector. Particularly, it was found that the most efficient dwellings were actually consuming more energy for heating than the energy predicted by their energy label while the least efficient dwellings were consuming less than the actual prediction of the label [7,42].

In order for the EPBD to become more efficient and more effective, it is imperative that the theoretical energy consumption of dwellings is predicted as accurately as possible. Furthermore, there should be detailed knowledge on the factors that affect the real energy consumption. Energy savings will not be realized if there is lack of in depth knowledge of the parameters that are causing the energy consumption in the first place. Especially for newly built dwellings, in which all the materials used and installations are known in detail, the most critical factor that remains in order to have a clear view on the actual energy consumption is occupancy, and particularly presence patterns and comfort which are in turn related to energy consumption. These last mentioned parameters are completely ignored in performance certification in the built environment, which is focused mainly on materials and installations [42].

§ 1.3 Problem definition

Therefore, research should focus on two directions. The first should be dedicated in research on the parameters that affect both actual energy consumption and comfort in residential dwellings. There is significant potential for research on occupancy behavior; little is known on how people interact with the thermostat, what are their indoor temperature preferences, which are their clothing and ventilation patterns. New smart built environments equipped with sensors could be providing information (as frequently as one minute) on environmental parameters such as indoor temperatures, CO_2, humidity, local air speed, and motion. Furthermore, sensors could provide data on clothing patterns, metabolic activity, actions towards thermal comfort (turning thermostat up or down, opening or closing windows, having warm showers or having a hot or cold drink etc.). This type of detailed data, measured in real time, will enable scientists to test further the validity of the comfort models in the residential environment, which up to now was very difficult to realize.

The second direction of research should be dedicated to the improvement of simulation software delivering the theoretical energy of buildings. Already simulation software have undergone huge improvements since they were first introduced. Dynamic simulation engines (Energy+, ESP-r, TRYN-SYS etc.) have replaced the older, static calculation models, which are still used by most of the EU member states in order to calculate the theoretical energy consumption of dwellings. The most important input parameters (physical or behavioral) that are affecting the calculated energy consumption in the residential environment should be identified and focused on. The dynamic software already provide more opportunities for more complex input files with more detailed occupancy profiles which are related to presence, thermostat, hot water, appliances and lighting use. However, these profiles are generally set up using common sense and/or the own perception of the engineer doing the simulation and lack proper validation. Furthermore the effect of comfort has not been fully incorporated yet as the big data from the future smart environments could be analyzed by appropriate algorithms and machine learning applications such as a-priori algorithms and neural networks [47].

§ 1.4 Aim of the study

The focus of this study is to contribute towards both the above-mentioned directions of research. The first aim is to test the sensitivity of the parameters that affect energy consumption and comfort in the residential built environment in a theoretical basis. The second aim is to investigate if it would be possible, with the help of a sensor rich environment, to validate both prevailing models for indoor comfort, the PMV and adaptive model, and explore the dynamics between occupancy behavior, indoor comfort and energy consumption in the built environment. Sensor rich environments in the residential sector are not present yet in large scale; therefore, this study investigates a small, but still significant, sample of dwellings. The aim is not to achieve representativeness for the complete residential building sector but to research if the methodology of using sensors to gather quantitative and subjective data (related to thermal comfort, occupancy behavior, and energy consumption) is promising enough and could lead to potential energy savings without compromising the indoor comfort of occupants.

The main research question that this thesis will try to answer is:

“Are the existing indoor comfort models appropriate for use in the residential built environment of the Netherlands? How can advances in sensor technology and big data gathering contribute to the improvement of the existing models and the balance between indoor thermal comfort and energy consumption in the residential sector?"

§ 1.5 Research questions

This section introduces the five main research questions and sub-questions defined for this study.

1 Q1: What are the most critical parameters relating to the building's physical properties and the thermal behavior of occupants on predicting the energy consumption and the thermal comfort?

The energy models that are widely used to predict the theoretical energy consumption of buildings are sensitive to particular input parameters. The most sensitive parameters should be modeled with detail in order to represent the building as accurately as possible [48,49] In order to improve the prediction quality and accuracy of building energy performance it is imperative to understand the effect that each parameter has, as well as the effect of the synergies between parameters, in the energy consumption of a building and the predicted comfort of occupants. Several studies in the past have dealt with sensitivity analysis on the effects of physical parameters on the energy consumption of buildings [50,51]. However, parameters related to occupancy behavior and energy consumption or predicted comfort have rarely been studied in the context of the residential built environment.

The following sub-questions have emerged from the above research question and will all be handled in chapter 2:

- Which are the most critical (physical and behavioral) parameters that influence heating energy use in the residential built environment according to dynamic building simulation software?
- Which are the most critical parameters that influence the PMV comfort index?
- How do the most important parameters for heating and PMV relate to each other? Is the sensitivity different for dwellings with different physical qualities and different energy classes?
- What do the results mean for the modelling techniques for predicting the energy consumption in dwellings (simple versus more complicated models)?

2 Q2: How to perform in-situ and real time measurements of subjective and quantitative data related to indoor comfort and occupancy behavior in an easy unobtrusive way in the residential built environment, and how do actual comfort parameters relate to each other's and to the reported thermal sensation?

To answer this research question the hardware and the methodology during the Ecommon (Energy and Comfort Monitoring) measurement campaign that took place as part of this PhD study under the funding of SusLab [52], Monicair [53] and Installaties2020 [54] projects will be explained first. The project demonstrated a long period of non-intrusive, in-situ, and real time measurements of quantitative (air temperature, relative humidity, CO_2 levels and motion) and subjective (thermal sensation, metabolic activity, clothing, actions during last half hour related to thermal comfort) parameters that affect thermal comfort.

The following sub-questions will be answered:

- What are the temperature levels, reported thermal sensations, clothing levels, reported actions towards comfort, and activity levels in the sample and do they differ according to energy rating of the building and heating system (chapters 3, 4 & 5).
- What is the occupants' temperature perception in relation to the energy rating, the ventilation and heating systems of the dwellings? (chapter 3)
- What is the most common type of clothing worn by the occupants and what is their activity level in relation to their thermal sensation? (chapters 3 and 5)
- Is there a relationship between type of clothing /metabolic activity and the thermal sensation? (chapters 3 and 4)
- Is there a relationship between type of clothing /metabolic activity and the indoor operative temperature? (chapter 3)

3 Q3: Are the results from the in-situ and real time measurements in agreement with already existing insights from the PMV theory?

Comfort has rarely been researched on site and in actual conditions and in other ways than surveys or diaries. The main research question and its sub-questions will try to provide insight in the existing models of thermal comfort, particularly the PMV, and its success in the prediction of occupants' thermal comfort in the residential built environment.

The following sub-questions will be answered in chapter 3:

- Which are the neutral temperatures calculated by the PMV method and how do they compare to the neutral temperatures derived from the measurements of thermal sensation?
- To what extent does the PMV comfort index agree with the thermal sensation reported by the tenants?

4 Q4: Are the results from the in-situ and real time measurements in agreement with already existing insights from the adaptive comfort theory?

For this research question the in-situ and real time measurement of quantitative and subjective data gathered during the Ecommon measurement campaign (see Q2) are used. This research question and its sub-questions will try to provide insight in the adaptive model theory, and its success in the prediction of occupants' thermal comfort in the residential buildings. As the adaptive model has been incorporated into international standards (ASHRAE Standard 55 and EN15225) and is widely used to assess the comfort in individual buildings, it is important to know how far the results of the model are from the reported thermal sensation of occupants of dwellings.

The following sub-questions have emerged by the above research question and will be handled in chapter 4:

- How successfully does the adaptive model predict occupants' thermal sensations in the residential dwellings that participated in the monitoring study?
- To what extent do outdoor temperatures affect indoor temperature set points, clothing and metabolic activity?
- Which are the most common behavioral adaptations/actions taken by occupants to achieve thermal comfort, and how do these relate to the tenants' thermal sensations?

5 Q5: Could a pattern recognition algorithm using subjective and quantitative data from a sensor rich environment, be able to predict occupancy behavior related to thermal comfort and energy consumption, and how does the use of these actual patterns impact the energy consumption calculated by building energy simulation software?

This last research question investigates a methodology for predicting occupancy behavior related to indoor thermal comfort and energy consumption in residential buildings. The Generalized Sequential Pattern recognition algorithm, developed originally for the retail industry, has been applied on the Ecommon data in order to discover frequently occurring sequences between thermal sensations, actions towards improving thermal comfort, clothing, metabolic activity, and indoor temperatures. The algorithm was implemented for a period of three hours in the morning and in the evening in order to discover possible differences between morning and evening behavior. Finally, the Ecommon data were used in dynamic simulations and the results were compared to the results of simulations with default occupancy schedules provided by the software.

The following sub-questions have been formulated and are handled in chapter 5:

- Can we implement an unsupervised algorithm as a data driven model for the prediction of occupant behavior related to energy consumption and thermal comfort in order to:
  - discover the most frequently recorded thermal sensations, actions towards thermal comfort, and metabolic activity and clothing levels based on the tenants' recorded data?
  - discover the most frequent occurring sequences among the above mentioned items?
  - discover if there are different patterns of behavior at different times of the day?
- Estimate how building energy simulations can be improved by this methodology.

§ 1.6 Research outline and methods

The first research question (chapter 2) was answered by performing a Monte Carlo sensitivity analysis based on a series of simulations using the dynamic simulation software Energy+ in which the input data was varied using random sampling. Sensitivity analysis is a widely accepted method for the determination of the most influential parameters concerning the energy consumption and comfort in the built environment [55]. Its biggest advantage compared to other sensitivity analysis techniques is that it also takes into account possible synergies between the various parameters, which is very important especially in complex systems such as residential buildings that require hundreds of input parameters in order to make a relatively accurate simulation. The novelty of this study is related to the parameters that were studied in the sensitivity analysis. Quantitative parameters (related to the building envelope, indoor environment, heating system, ventilation patterns, and electricity consumption) and subjective parameters (related to PMV such as clothing, metabolic activity, and actions towards thermal comfort such as the thermostat use) were used simultaneously in the Monte Carlo analysis, revealing the most influential parameters for energy consumption and comfort (simulated as PMV). The post process analysis took place in SPSS and ranked regression analysis was further used in order to obtain the coefficients that show the importance of each parameter in the heating energy consumption and thermal comfort (PMV).

Chapters 3, 4, and 5 deal with the data from the Ecommon measurement campaign. Quantitative data (temperature, relative humidity, CO_2 and motion) were gathered wirelessly every five minutes for a period of six months. Furthermore, subjective data were gathered for a period of two weeks with the use of an apparatus especially developed for this campaign, called the “comfort dial”, Fig. 2. Occupants could record their thermal sensation at any time of the day with this device and add additional information about their activities and clothing in a logbook in paper form. Each data record was time stamped and time coupled with the quantitative data. In that way we knew the exact time for each thermal sensation record and the corresponding indoor temperature, humidity and CO_2 levels, as well as in which room did this record took place.

In the fifth chapter, a concept initially developed for the retail industry, in the field of market basket analysis, was implemented to be used with the data of the Ecommon measurement campaign. The data were fed in an unsupervised (apriori) algorithm and the most frequently occurring sequences of thermal sensations, indoor temperature, actions towards thermal comfort, metabolic activity, and clothing levels were discovered.

§ 1.7 Data

§ 1.7.1 Ecommon campaign set up

The sample used in the Ecommon monitoring campaign was restricted to social housing due to data availability and prior and ongoing research in the field by the author’s research group [59]. Social housing in the Netherlands represents approximately one-third of the total residential housing stock and is quite representative of the residential housing stock as a whole [60,61,62]. Furthermore, housing associations have the energy rating of all their housing stock determined, which is not the case with individual owners. The sample had to be divided into A-rated and F-rated dwellings, in order to address issues of current energy rating models. In fact, A-rated and B-rated dwellings were selected at one extreme and F-rated dwellings at the other. F-rated dwellings were selected in preference to G-rated ones, since previous studies [60,63] had shown that there are few dwellings in the Netherlands with a G energy rating.

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The method used to calculate the energy rating is described in Dutch building code ISSO 82.3 [64] which rates each dwelling on a scale from ‘A++’ (the most efficient) to ‘G’. The categories are determined with reference to the energy index, which is calculated based on the total primary energy demand (Q_{total}); this represents the primary energy consumed for heating, hot water, pumps/ventilators and lighting, after subtracting the energy gains from PV cells and/or cogeneration.

We sent a letter to more than 2,000 addresses, inviting the occupants to participate in the study. The response rate was 8.6%, and a careful selection had to be made among the households willing to participate in order to maximize the amount of useful data that could be collected. We used the SHAERE database developed by Aedes [65], the federation of Dutch housing associations, to select respondents based on their energy rating and heating system. Fifty-eight dwellings were selected. Finally, due to limitations in the monitoring equipment, 32 dwellings were monitored over a 6-month period, from October 2014 to April 2015. The final sample is described in Table 1.1. The A-rated and B-rated dwellings were divided into those with an electrical heat pump coupled with low hydronic floor heating and those with condensing gas boilers. The F-rated dwellings all had their old inefficient boilers replaced by new condensing gas boilers, apart from three that were still equipped with old gas stoves connected to the radiators in the various rooms to provide a central heating system.

The dwellings were also classified based on their ventilation systems. Eight had balanced ventilation, 10 had completely natural ventilation (supply and exhaust) and 14 had natural air supply and mechanical exhaust (usually in wet rooms and kitchens). Details of the ventilation systems of the various dwellings are also given in Table 1.1.

TABLE 1.1 Dwellings participating in the Ecommon campaign

NO.	ENERGY RATING	HEATING SYSTEM	VENTILATION SYSTEM	NO. OF ROOMS	NO. OF OCCUPANTS	AVERAGE AGE
W001	F	Condensing gas boiler	Natural supply Mech. Exhaust	6	1	67
W002	F	Condensing gas boiler	Natural supply Mech. Exhaust	5	3	39
W003	A	Heat pump	Balanced Vent.	4	2	73
W004	A	Heat pump	Balanced Vent.	4	2	67
W005	A	Condensing gas boiler	Balanced Vent.	4	1	92
W006	A	Condensing gas boiler	Balanced Vent.	3	2	77
W007	A	Heat pump	Balanced Vent.	4	4	31
W008	A	Heat pump	Balanced Vent.	4	2	25
W010	A	Condensing gas boiler	Natural supply Mech. Exhaust	7	2	29
W011	A	Condensing gas boiler	Natural supply Mech. Exhaust	7	2	69
W012	F	Condensing gas boiler	Natural Vent.	5	4	40.5
W013	F	Condensing gas boiler	Natural Vent.	5	3	53
W014	F	Gas stove	Natural Vent.	5	1	83
W015	B	Condensing gas boiler	Natural supply Mech. Exhaust	3	2	25
W016	B	Condensing gas boiler	Natural supply Mech. Exhaust	4	2	70
W017	B	Condensing gas boiler	Natural supply Mech. Exhaust	3	1	66
W018	B	Condensing gas boiler	Natural supply Mech. Exhaust	3	1	61
W019	F	Condensing gas boiler	Natural Vent.	5	3	29
W020	F	Condensing gas boiler	Natural Vent.	6	2	74
W021	F	Condensing gas boiler	Natural supply Mech. Exhaust	4	2	73
W022	F	Condensing gas boiler	Natural supply Mech. Exhaust	3	2	64
W023	F	Condensing gas boiler	Natural Vent.	4	2	66
W024	F	Condensing gas boiler	Natural supply Mech. Exhaust	5	1	72

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TABLE 1.1 Dwellings participating in the Ecommon campaign

NO.	ENERGY RATING	HEATING SYSTEM	VENTILATION SYSTEM	NO. OF ROOMS	NO. OF OCCUPANTS	AVERAGE AGE
W025	F	Gas stove	Natural Vent.	5	3	43
W026	F	Condensing gas boiler	Natural Vent.	4	4	21
W027	F	Gas stove	Natural Vent.	5	1	67
W028	F	Condensing gas boiler	Natural supply Mech. Exhaust	6	2	72
W029	F	Condensing gas boiler	Natural supply Mech. Exhaust	3	1	62
W031	F	Condensing gas boiler	Natural supply Mech. Exhaust	6	3	43
W032	B	Condensing gas boiler	Natural supply Mech. Exhaust	4	3	39

§ 1.7.2 Data acquisition and equipment

§ 1.7.2.1 Honeywell equipment used to collect indoor climate data

The system used to collect temperature (T), relative humidity (RH), CO_2 level and presence data was a custom-built combination of sensors developed by Honeywell. The temperature, humidity and CO_2 sensors were all mounted in a single box that was installed in up to four habitable rooms (living room, bedrooms, study and kitchen) in each house participating in the measuring campaign. The type, model and accuracy of the sensors are shown in Table 1.2. The T, CO_2 and RH sensors were not battery powered and therefore had to be plugged into a wall socket. The PIR movement sensor, on the other hand, was battery powered. Figure 1.1 gives an impression of the arrangement of the sensors.

The measuring frequency of all sensors was 5 minutes. The value recorded for each 5-minute interval was the average of the readings during that interval. Temperatures were measured in °C, relative humidity in percentage (%) and CO_2 levels in ppm (parts per million). The PIR sensor data were in binary form (0 and 1), zero means that no movement was detected during the 5-minute interval in question while one means that movement was detected at least once during the interval. The presence sensors had an automatic correction for pets.

TABLE 1.2 Types, models and accuracy of sensors used during the Ecommon measurement campaign

SENSOR TYPE	MODEL	ACCURACY
CO_2	GE Telaire	400 – 1250 ppm: 3% of reading 1250 – 2000 ppm: 5% of reading
Relative Humidity	Honeywell HiH5031	+/- 3%
Temperature	KT Thermistor	1% per °C
Movement	Honeywell IR8M	11 x 12 m (range at 2.3 m mounting height)

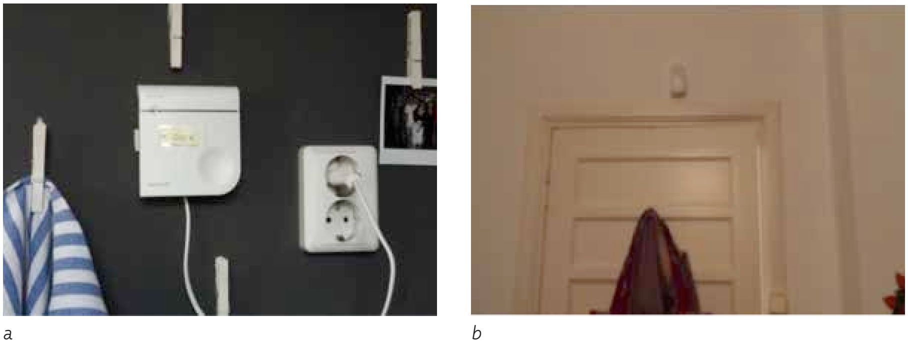

a
b

FIGURE 1.1 T, CO2, RH box (a) and movement sensor (b) as used during the Ecommon measurement campaign

§ 1.7.2.2 Subjective data: comfort dial and log book

The Ecommon measurement campaign collected subjective as well as quantitative data. Data on perceived comfort levels were collected with the aid of a device developed by Delft University of Technology's Department of Industrial Design under the umbrella of the European Interreg project Sustainable Laboratories North West Europe (SusLab) [52]. This wireless device, called "comfort dial" (Figure 1.2), allowed the tenants to digitally record their perceived thermal comfort level at any time of the day on a 7-point scale, from -3 (cold) via 0 (neutral) to +3 (hot). This digital record was afterwards time-couple to the Honeywell data.

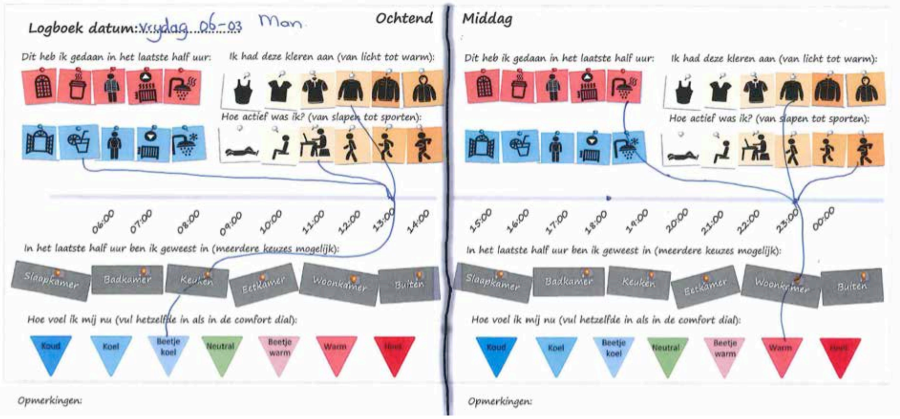
FIGURE 1.2 Comfort Dial used to capture perceived comfort levels of tenants during the Ecommon measurement campaign

Tenants also received a paper logbook, shown in Figure 1.3. This logbook, like the comfort dial, was developed by Delft University of Technology's Department of Industrial Design. It was initially intended to be in online format so that people could log on to their computer, smart-phone or tablet and fill in various subjective data such as:

- Perceived comfort level on the above-mentioned 7-point scale.
- The room they are occupying when filling in the log (kitchen, living room, bedroom etc.)
- Clothing combination worn: a choice of six combinations from very light to very warm clothing is available; see Figure 1.3 and Table 1.4.
- Actions taken during the past half hour relating to comfort and energy consumption, such as opening or closing the windows, drinking a cold or hot drink, taking clothes off or putting them on, raising or lowering the thermostat setting and having a hot or cold shower.
- Activity level: lying /sleeping, relaxed sitting, doing light deskwork, walking, jogging, running. These activities can then be related to the metabolic rate.

However, we finally used a paper version of the logbook due to a combination of financial limitations (not enough tablets available to provide all occupants of the 32 dwellings with one) and the fact that many participants were elderly and not well acquainted with digital technology.

The occupants of the houses were given the comfort dial for a 2-week period in March and early April 2015. The main respondent was asked to use it as often as he or she wanted, but at least three times a day (preferably in the morning, midday and evening). They also had to fill in the paper log, at least when they were using the comfort dial.



Logboek datum: Vrijdag 06-03 Mon

Ochtend

Dit heb ik gedaan in het laatste half uur:

Ik had deze kleren aan (van licht tot warm):

Hoe actief was ik? (van slapen tot sporten):

06:00 07:00 08:00 09:00 10:00 11:00 12:00 13:00 14:00

In het laatste half uur ben ik geweest in (meerdere keuzes mogelijk):

Slaapkamer | Badkamer | Keuken | Eetkamer | Woonkamer | Buiten

Hoe voel ik mij nu (vul hetzelfde in als in de comfort dial):

Koud | Koel | Beetje koel | Neutral | Beetje warm | Warm | Heet

Opmerkingen:

Middag

Dit heb ik gedaan in het laatste half uur:

Ik had deze kleren aan (van licht tot warm):

Hoe actief was ik? (van slapen tot sporten):

15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 00:00

In het laatste half uur ben ik geweest in (meerdere keuzes mogelijk):

Slaapkamer | Badkamer | Keuken | Eetkamer | Woonkamer | Buiten

Hoe voel ik mij nu (vul hetzelfde in als in de comfort dial):

Koud | Koel | Beetje koel | Neutral | Beetje warm | Warm | Heet

Opmerkingen:

FIGURE 1.3 Paper logbook for entry of subjective data

Furthermore, tenants had to fill in a questionnaire during the installation of the monitoring equipment, and all dwellings participating in the study were inspected at the same time. These two measures provided extra data in household characteristics, heating and ventilation patterns and perceived comfort levels.

§ 1.7.2.3 Data storage and management

The data collected by the Honeywell sensors were managed by software developed by Honeywell. This software made it possible to select measurement frequency of 1, 5, 10 or any other number of minutes at any moment. A measurement frequency of 5 minutes was chosen for this project.

All the data were wirelessly transmitted from the sensors to a locally installed mini-PC on which the Honeywell software was installed. The data were regularly copied from this mini-PC to our SQL database at Delft University of Technology. This set-up allowed the data to be stored both locally, on the hard drive of the mini-PC, and centrally in the database at Delft. Another point worth mentioning is that each Honeywell sensor box (containing the temperature, relative humidity and CO_2 sensors) also acted as a wireless transmitter for the adjacent sensor box, so that one mini-PC could collect data from neighboring dwellings. This reduced overall equipment costs for the project. Data from the comfort dial were transmitted to the database at Delft University of Technology via a connect port and the local internet connection or a 3G network, if available.

§ 1.7.2.4 Occupant survey and inspection list

Occupants were asked to fill in a questionnaire during installation of the sensors in their home. The questions asked fell into three categories: 1) general information on the participating households, such as household composition, income, age, education level; 2) the occupants' heating, showering and ventilation habits; and 3) overall perception of the comfort of the dwellings, see appendix A.

Furthermore, each dwelling was inspected during the installation of the monitoring equipment. The inspection covered the following items, which were relevant to the present study: the type of space heating system, type of glazing, the types of ventilation present in the dwelling (extraction point in the kitchen, other mechanical ventilation usually present in the kitchen or bathroom and balanced ventilation) and information on the thermostat: type of thermostat, settings and control program.

The information mentioned in this section appear again in each of the later chapters of this thesis as part of the respective published articles in scientific journals.

§ 1.8 Limitations

Like in almost all field studies, the Ecommon measurement campaign had its limitations. The selection of the dwellings took place by sending more than 2000 letters to occupants inviting them to participate in the measurement campaign. Despite the reasonable response rate from the tenants (8.6 %), limitations in monitoring equipment allowed us to install the sensors in only 32 dwellings. The software developed by Honeywell for the management of the quantitative sensors' data could accommodate the sensors of up to six dwellings as long as these dwellings were adjusted to each other. In that case, each sensor could also act as a transmitter and bounce its data from sensor to sensor until they reach the local mini PC for storage. However, the selection of dwellings, did not take place via a housing association that could bring on board dwellings that were all sited in the same neighborhood or in the same block. The dwellings that responded positively to our plea were scattered all over the Den Haag region and rarely two of them were next to each other. The mini PCs that acted as local storage depot (before they were wirelessly transmitted to our database) could therefore not be used for more than one house. We had in our disposal 32 mini PCs that could accommodate the sensors for 192 dwellings if these were close to each other. Instead, we were able to gather data from only 32 dwellings.

Another limitation had to do with the collection of the subjective data. Initially a smartphone/tablet application had been developed in order to capture data on thermal sensation, actions towards thermal comfort, clothing and metabolic activity. However, due to financial limitations, there were not enough tablets to be handed in to the tenants and, furthermore, many of the tenants were old and not so familiar with new technology. Therefore, a paper version had to be devised (paper logbook) in order to gather the subjective data. This approach of course was crude especially in terms of timing. The data recorded by the smartphone application could be easily time coupled with the internal timer of the Honeywell sensors that provided the quantitative data. On the other hand, in the paper logbook occupants were prompted to fill in the time of their data records by drawing a line in the logbooks timeline (Figure 1.3).

§ 1.9 Structure of the thesis

Table 1.3 summarizes the questions and sub-questions that were researched in this thesis. For the first question the analysis and results were based on simulated data produced by the Energy+ dynamic simulation software and DesignBuilder, which is a graphic interface built for Energy+ and supports many of the simulation engine's features. The rest of the questions and sub questions were answered with the data gathered during the Ecommon measurement campaign.

RESEARCH QUESTION

Q1: What are the most critical parameters relating to the building's physical properties and the thermal behavior of occupants on predicting the energy consumption and the thermal comfort?

Sub questions	Data	Chapter
1) Which are the most critical (physical and behavioral) parameters that influence heating energy use in the residential built environment according to dynamic building simulation software?	Simulations (Energy+, DesignBuilder, jEplus)	2
2) Which are the most critical parameters that influence the PMV comfort index?	Simulations (Energy+, DesignBuilder, jEplus)	2
3) How do the most important parameters for heating and PMV, relate to each other? Is the sensitivity different for dwellings with different physical qualities and different energy classes?	Simulations (Energy+, DesignBuilder, jEplus)	2
4) What do the results mean for the modelling techniques for predicting the energy consumption in dwellings (simple versus more complicated models)?	Simulations (Energy+, DesignBuilder, jEplus)	2

RESEARCH QUESTION

Q2: How to perform in-situ and real time measurements of subjective and quantitative data related to indoor comfort and occupancy behavior in an easy unobtrusive way in the residential built environment, and how do actual comfort parameters relate to each other's and to the reported thermal sensation?

Sub questions	Data	Chapter
1) What are the temperature levels, reported thermal sensations, clothing levels, reported actions towards comfort, and activity levels in the sample and do they differ according to energy rating of the building and heating system?	Ecommon	3,4, 5
2) What is the occupants' temperature perception in relation to the energy rating, the ventilation and heating systems of the dwellings?	Ecommon	3
3) What is the most common type of clothing worn by the occupants and what is their activity level in relation to their thermal sensation?	Ecommon	3, 5
4) Is there a relationship between type of clothing / metabolic activity and the thermal sensation?	Ecommon	3, 4
5) Is there a relationship between type of clothing / metabolic activity and the indoor operative temperature?	Ecommon	3

RESEARCH QUESTION

Q3: Are the results from the in-situ and real time measurements in agreement with already existing insights from the PMV theory?

Sub questions	Data	Chapter
1) Which are the neutral temperatures calculated by the PMV method and how do they compare to the neutral temperatures derived from the measurements of thermal sensation?	Ecommon	3
2) To what extent does the PMV comfort index agree with the thermal sensation reported by the tenants?	Ecommon	3

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RESEARCH QUESTION		
Q4: Are the results from the in-situ and real time measurements in agreement with already existing insights from the adaptive comfort theory?		
Sub questions	**Data**	**Chapter**
1) How successfully does the adaptive model predict occupants' thermal sensations in the residential dwellings that participated in the monitoring study?	Ecommon	4
2) To what extent do outdoor temperatures affect indoor temperature set points, clothing and metabolic activity?	Ecommon	4
1) Which are the most common behavioral adaptations/actions taken by occupants to achieve thermal comfort, and how do these relate to the tenants' thermal sensations?	Ecommon	3

RESEARCH QUESTION		
Q5: Could a pattern recognition algorithm using subjective and quantitative data from a sensor rich environment, able predict occupancy behavior related to thermal comfort and energy consumption, and how can does the use of these actual patterns impact the energy consumption calculated by building energy simulation software?		
Sub questions	**Data**	**Chapter**
1) Can we implement an unsupervised algorithm as a data driven model for the prediction of occupant behavior related to energy consumption and thermal comfort in order to: a) discover the most frequently recorded thermal sensations, actions towards thermal comfort, and metabolic activity and clothing levels based on the tenants' recorded data? b) discover the most frequent occurring sequences among the above mentioned items? c) discover if there are different patterns of behavior at different times of the day?	Ecommon	5
2) How does the use of actual behavioral patterns affect the simulated energy use?	Ecommon	5

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