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Summary

Residential buildings account for a significant amount of the national energy consumption of all OECD countries and consequently the EU and the Netherlands. Therefore, the national targets for CO_2 reduction should include provisions for a more energy efficient building stock for all EU member states.

National and European level policies the past decades have improved the quality of the building stock by setting stricter standards on the external envelope of newly made buildings, the efficiency of the mechanical and heating components, the renovation practices and by establishing an energy labelling system. Energy related occupancy behavior is a significant part, and relatively unchartered, of buildings' energy consumption. This thesis tried to contribute to the understanding of the role of the occupant related to the energy consumption of residential buildings by means of simulations and experimental data obtained by an extensive measurement campaign.

The first part of this thesis was based on dynamic building simulations in combination with a Monte Carlo statistical analysis, which tried to shed light to the most influential parameters, including occupancy related ones, that affect the energy consumption and comfort (a factor that is believed to be integral to the energy related behavior of people in buildings). The reference building that was used for the simulations was the TU Delft Concept House that was built for the purposes of the European project SusLab NWE. The concept house was simulated as an A energy label (very efficient) and F label (very inefficient) dwelling and with three different heating systems.

The analysis revealed that if behavioral parameters are not taken into account, the most critical parameters affecting heating consumption are the window U value, window g value, and wall conductivity. When the uncertainty of these parameters increases, the impact of the wall conductivity on heating consumption increases considerably. The most important finding was that when behavioral parameters like thermostat use and ventilation flow rate are added to the analysis, they dwarf the importance of the building parameters in relation to the energy consumption. For the thermal comfort (the PMV index was used as the established model for measuring indoor thermal comfort) the most influential parameters were found to be metabolic activity and clothing, while the thermostat had a secondary impact.

The simulations were followed by an extensive measurement campaign where an in-situ, non-intrusive, wireless sensor system was installed in 32, social housing, residential dwellings in the area of Den Haag. This sensor system was transmitting

quantitative data such as temperature, humidity, CO_2 levels, and motion every five minutes for a period of six months (the heating period between November to April) and from every room of the 32 dwellings that participated in the campaign. Furthermore, subjective data were gathered during an initial inspection during the installation of the sensor system, concerning the building envelope, the heating and ventilation systems of the dwellings. More importantly though, subjective data were gathered related to the indoor comfort of the occupants with the use of an apparatus that was developed specifically for the SusLab project. This gimmick, named the comfort dial, allowed us to capture data such as the occupants' comfort level in the PMV 7 point scale. In addition further comfort related data like the occupants' clothing ensemble, actions related to thermal comfort, and their metabolic activity were captured with the use of a diary. The subjective data measurement session lasted for a week for each dwelling. These data were time coupled real time with the quantitative data that were gathered by the sensor system.

The data analysis focused on the two available indoor thermal comfort models, Fanger's PMV index and the adaptive model. Concerning the PMV model the analysis showed that while the neutral temperatures are well predicted by the PMV method, the cold and warm sensations are not. It appears that tenants reported (on a statistically significant way) comfortable sensations while the PMV method does not predict such comfort. This indicates a certain level of psychological adaptation to occupant's expectations. Additionally it was found that although clothing and metabolic activities were similar among tenants of houses with different thermal quality, the neutral temperature was different. Specifically in houses with a good energy rating, the neutral temperature was higher than in houses with a poor rating.

Concerning the adaptive model, which was developed as the answer to the discrepancies of Fanger's model related to naturally ventilated buildings (the majority of the residential sector), data analysis showed that while indoor temperatures are within the adaptive model's comfort bandwidth, occupants often reported comfort sensations other than neutral. In addition, when indoor temperatures were below the comfort bandwidth, tenants often reported that they felt 'neutral'. The adaptive model could overestimate as well as underestimate the occupant's adaptive capacity towards thermal comfort. Despite the significant outdoors temperature variation, the indoor temperature of the dwellings, as well as the clothing of the tenants, were largely constant. Certain actions towards thermal comfort such as 'turning the thermostat up' were taking place while tenants were reporting thermal sensation 'neutral' or 'a bit warm'. This indicates that either there is an indiscrimination among the various thermal sensation levels or alliesthesia, a new concept introduced by the creators of the adaptive model, plays an increased role. Most importantly there was an uncertainty on whether the neutral sensation means at the same time comfortable sensation while many actions are happening out of habit and not in order to improve one's thermal comfort. A chi^2 analysis showed that only six actions were correlated to thermal sensation in thermally poorly efficient dwellings, and six in thermally efficient dwellings.

Finally, the abundance of data collected during the measurement campaign led the last piece of research of this thesis to data mining and pattern recognition analysis. Since the introduction of computers, the way research is performed has changed significantly. Huge amounts of data can be gathered and handled by evermore faster computers; the analysis of these data a couple of decades ago would take years.

Sequential pattern mining reveals frequently occurring patterns from time-ordered input streams of data. A great deal of nature behaves in a periodic manner and these strong periodic elements of our environment have led people to adopt periodic behavior in many aspects of their lives such as the time they wake up in the morning, the daily working hours, the weekend days off, the weekly sports practice. These periodic interactions could extend in various aspects of our lives including the relationship of people with their home thermal environment. Repetitive behavioural actions in sensor rich environments, such as the dwellings of the measurement campaign, can be observed and categorized into patterns. These discoveries could form the basis of a model of tenant behaviour that could lead to a self-learning automation strategy or better occupancy data to be used for better predictions of building simulating software such as Energy+ or ESP-r and others.

The analysis revealed various patterns of behaviour; indicatively 59% of the dwellings during the morning hours (7-9 a.m.) were increasing their indoor temperature from 20 ^{o}C< T< 22 ^{o}C to T> 22^{o}C or that the tenants of 56% of the dwellings were finding the temperature 20 ^{o}C< T< 22 ^{o}C to be a bit cool and even for temperatures above 22 ^{o}C they were having a warm shower leading to the suspicion that a warm shower is a routine action not related to thermal comfort.

Such pattern recognition algorithms can be more effective in the era of mobile internet, which allows the capturing of huge amounts of data. Increased computational power can analyse these data and define useful patterns of behaviour that could be tailor made for each dwelling, for each room of a dwelling, even for each individual of a dwelling. The occupants could then have an overview of their most common behavioural patterns, see which ones are energy consuming, which ones are related to comfort and which are redundant, and therefore, could be discarded leading to energy savings. In any case the balance between indoor comfort and energy consumption will be the final factor that would lead the occupant to decide on a customised model of his indoor environment.

The general conclusion of this thesis is that the effect of energy related occupancy behaviour on the energy consumption of dwellings should not be statistically defined for large groups of population. There are so many different types of people inhabiting so many different types of dwellings that embarking in such a task would be a considerable waste of time and resources.

The future in understanding the energy related occupancy behaviour, and therefore using it towards a more sustainable built environment, lies in the advances of sensor technology, big data gathering, and machine learning. Technology will enable us to move from big population models to tailor made solutions designed for each individual occupant.

Samenvatting

Woningen hebben een substantieel aandeel in het nationale energiegebruik van alle OECD-landen, en dus ook van EU-landen, waaronder Nederland. Alle EU-lidstaten moeten hun nationale doelstellingen voor CO_2-reductie daarom ook richten op het vergroten van de energie-efficiency van de woningvoorraad.

Het nationaal en Europees beleid van de afgelopen decennia heeft bijgedragen aan de verbetering van de kwaliteit van de woningvoorraad door strengere standaards vast te leggen voor de gebouwschil van nieuwe gebouwen, het rendement van verwarming en mechanische systemen, de praktische uitvoering van renovaties en door het tot stand brengen van een energielabellingsysteem. Het aandeel van bewonersgedrag in het energiegebruik speelt een belangrijke rol maar is nog niet echt goed in kaart gebracht. Dit proefschrift richt zich op het beter begrijpen van de invloed van bewonergedrag op het energiegebruik in woningen door gebruik te maken van simulaties en experimentele data verkregen, uit een omvangrijke meetcampagne.

Het eerste deel van het proefschrift is gebaseerd op dynamische gebouwsimulaties in combinatie met een statistische Monte Carlo-analyse. Hierin is geprobeerd de parameters - inclusief parameters gerelateerd aan bewoning en gedrag - te identificeren die de grootste invloed hebben op energiegebruik en comfort (comfort is een factor die wordt verondersteld integraal deel te zijn van het energiegerelateerd gedrag van mensen in gebouwen). Voor deze simulaties is als referentiewoning het TU Delft Concept House gebruikt, dat werd gebouwd in het kader van het Europees project SuslabNWE. Het Concept House is in verschillende varianten gesimuleerd, als energielabel A-woning (zeer efficiënt), als energielabel F-woning (zeer inefficiënt) en met drie verschillende verwarmingssystemen.

De analyse heeft laten zien dat wanneer gedragsparameters niet worden meegenomen, de U-waarde en de g-waarde van de ramen en de warmtegeleidingscoëfficiënt van de buitenmuren de meest kritische parameters zijn voor de verwarmingsenergie. Bij toename van de onzekerheid over deze parameters neemt de invloed van de warmtegeleiding in de muren sterk toe. De belangrijkste bevinding is dat wanneer gedragsparameters zoals thermostaatgebruik en ventilatiedebieten worden toegevoegd aan de analyse, het aandeel van gebouwparameters op het energiegebruik sterk afneemt. Wat betreft het thermisch comfort (de PMV-index is gebruikt als goed geaccepteerd model om het thermisch binnencomfort te meten), zijn metabolische activiteit en kleding de parameters met de grootste invloed gebleken, terwijl de thermostaat in mindere mate invloed had.

Na de simulaties is een extensieve meetcampagne gestart waarin een in-situ, niet-intrusief en draadloos sensorsysteem werd geïnstalleerd in 32 sociale woningen in de regio Den Haag. Met dit sensor-systeem is iedere vijf minuten kwantitatieve data verzameld zoals temperatuur, vochtigheid, CO_2-niveau en beweging gedurende een periode van zes maanden (tijdens de verwarmingsperiode van november tot en met april), in iedere kamer van de 32 woningen die meededen aan de campagne. Er zijn bovendien data verzameld tijdens een initiële inspectie toen het sensorsysteem werd geplaatst. Deze data betroffen de gebouwschil en het verwarmings- en ventilatiesysteem van de woning. Nog belangrijker, data over het binnencomfort van de bewoners zijn verzameld met een apparaat speciaal ontworpen voor het Susab-project. Met deze gadget, genoemd 'comfort dial', kunnen de bewoners hun comfortniveau registreren overeenkomstig de 7 punten van de PMV-schaal. Bovendien werden extra data relaterend aan comfort zoals kleding, acties in relatie met thermisch comfort en metabolische activiteit verzameld met een dagboek. Deze comfortmetingen hebben plaatsgevonden gedurende een week, in elke woning. Deze data werden ook real time geregistreerd en konden zo worden gekoppeld aan de data uit het sensorsysteem.

De focus tijdens de data-analyse lag bij de twee bestaande thermischcomfortmodellen: de PMV-index van Fanger en het adaptief model. Betreffende het PMV-model heeft de analyse laten zien dat terwijl de neutrale temperaturen goed voorspeld worden door de PMV-methode, dat niet het geval is voor de perceptie van koud en warm. De bewoners rapporteerden (op een statistisch significante manier) een comfortabel gevoel terwijl de PMV-methode dat niet voorspelde. Dit is een indicatie voor een bepaald niveau van psychologische adaptatie , in termen van verwachtingsmanagement door de bewoner.

Bovendien is geconstateerd dat, ondanks het feit dat kleding en metabolische activiteiten van bewoners gelijk waren ongeacht de thermische kwaliteit van de woning, de neutrale temperatuur anders was in woningen waarvan de thermische kwaliteiten verschilden. In het bijzonder in woningen met een goed energielabel was de neutrale temperatuur hoger dan in woningen met een slecht energielabel.

Voor het adaptief model, dat is ontwikkeld als antwoord op de onvolkomenheden van het model van Fanger in gebouwen met natuurlijke ventilatie (die in meerderheid zijn in de woningvoorraad), heeft de data-analyse aangetoond dat, terwijl de binnentemperaturen binnen de comfort-bandbreedte bleven zoals aangeven door het adaptief model, de bewoners comfortpercepties rapporteerden die niet neutraal waren. Bovendien rapporteerden bewoners een neutraal gevoel, terwijl de binnentemperaturen onder de bandbreedte bleven. Het adaptief model kan dus de capaciteit van adaptatie richting thermisch comfort evengoed overschatten als onderschatten. Ondanks significante buitentemperatuurvariaties veranderden de binnentemperatuur en de kleding van de bewoners vrij weinig. Sommige thermischcomfortgerichte acties zoals ‘thermostaat omhoog zetten’ werden waargenomen, terwijl de bewoners als thermisch gevoel ‘neutraal’ of ‘een beetje warm’ rapporteerden. Dit geeft aan dat de bewoners geen verschil kunnen maken tussen de verschillende thermische sensaties, dan wel dat alliesthesia (een nieuw concept geïntroduceerd door de auteurs van het adaptief model), een grotere rol speelt dan gedacht. Het is bovendien onzeker of een neutraal gevoel als een comfortabel gevoel geïnterpreteerd kan worden en of de acties ondernomen worden uit gewoonte of met als doel de verbetering van het thermisch comfort. Een chi²-analyse heeft laten zien dat alleen zes typen acties zijn gecorreleerd met de thermische sensatie in woningen met een slecht energielabel, en zes (waarvan alleen 3 dezelfde als in woningen met een slecht label) in woningen met een goed energielabel.

Voor dit proefschrift is tijdens de meetcampagne een grote hoeveelheid data verzameld, die zicht leent voor datamining en patroonherkenning. De manier waarop onderzoek verricht wordt is sinds de introductie van computers sterk veranderd. Een enorme hoeveelheid data kan verzameld en verwerkt worden door steeds sneller wordende computers. De analyse van deze data zou twintig jaar geleden jaren hebben gekost.

Sequentiële patroonherkenning brengt frequente patronen aan het licht uit tijdgeordende datastromen. Een groot deel van de natuur toont een periodisch gedrag, en deze sterke periodische elementen uit onze omgeving hebben ernaar toe geleid dat de mens ook een periodisch gedraag vertoont in vele aspecten van zijn leven, zoals de tijd waarop hij ’s ochtends wakker wordt, de dagelijkse werkuren, verlofdagen in het weekend of wekelijks sporten. Periodisch gedrag kan zich ook uitstrekken tot verschillende aspecten van onze levens zoals de relatie van bewoners met de thermisch omgeving in hun huis. Zich herhalende gedragsacties in omgevingen met veel sensoren, zoals de woningen tijdens de meetcampagne, kunnen geobserveerd en in patronen gekarakteriseerd worden. Deze bevindingen zouden de basis kunnen vormen voor een model van bewonersgedrag. Dat zou kunnen leiden tot een zelflerende automatiseringsstrategie of tot betere bewoningdata om betere voorspellingen te kunnen maken in gebouwsimulatiesoftware zoals Energy+ en ESP-r.

Er zijn verschillende gedragspatronen geïdentificeerd. Zo werd bijvoorbeeld in 59% van de woningen gedurende de ochtenduren (7-9 a.m.) de binnentemperatuur verhoogd van 20ºC< T< 22ºC tot T> 22ºC en de bewoners in 56% van de woningen vonden de temperatuur in de bandbreedte 20ºC< T< 22ºC een beetje koud en zelfs met temperaturen boven de 22ºC namen ze een warme douche, wat leidt tot de verdenking dat een warme douche nemen een routine-actie is die niet relateert aan thermisch comfort.

Zulke patroonherkenningsalgoritmen worden efficiënter in deze tijd van mobiel internet, waarmee enorme hoeveelheden data verzameld kunnen worden. De toegenomen rekenkracht kan helpen bij de analyse van deze data en het definiëren van nuttige gedragspatronen die toegesneden zouden kunnen worden op iedere woning, op iedere kamer in een woning, en zelfs op ieder individu in de woning. De bewoners zouden dan kunnen beschikken over een overzicht van hun meest alledaagse gedragspatroon en zouden dan kunnen zien welke van deze patronen energiegebruik veroorzaken, welke gerelateerd zijn aan comfort en welke onnodig zijn en zouden achterwege gelaten kunnen worden zodat energie bespaard kan worden. Hoe dan ook zal de balans tussen binnen-comfort en energiegebruik de beslissende factor zijn in de afweging van de bewoner over een afgestemd model van zijn binnenmilieu.

De algemene conclusie van dit proefschrift is dat het effect van energiegerelateerd bewoningsgedrag in woningen niet statistisch bepaald zou moeten worden voor grote populaties. Er zijn zo veel verschillende soorten mensen, wonend in zo veel verschillende soorten woningen dat zo'n exercitie een aanzienlijk verlies van tijd en middelen zou zijn.

De toekomst in het begrijpen van energiegerelateerd bewoningsgedrag, en dus in het gebruik van die kennis voor een duurzamere gebouwde omgeving, moet gevonden worden in de vooruitgang op het gebied van sensortechnologie, het verzamelen van big data en machine learning. Technologie zal het mogelijk maken om over te stappen van modellen voor grote groepen naar op maat gemaakte oplossingen ontworpen voor afzonderlijke bewoners.

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.

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.

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].

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.

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 OC-CUPANTS	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

>>>

TABLE 1.1 Dwellings participating in the Ecommon campaign

NO.	ENERGY RATING	HEATING SYSTEM	VENTILATION SYSTEM	NO. OF ROOMS	NO. OF OC-CUPANTS	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.

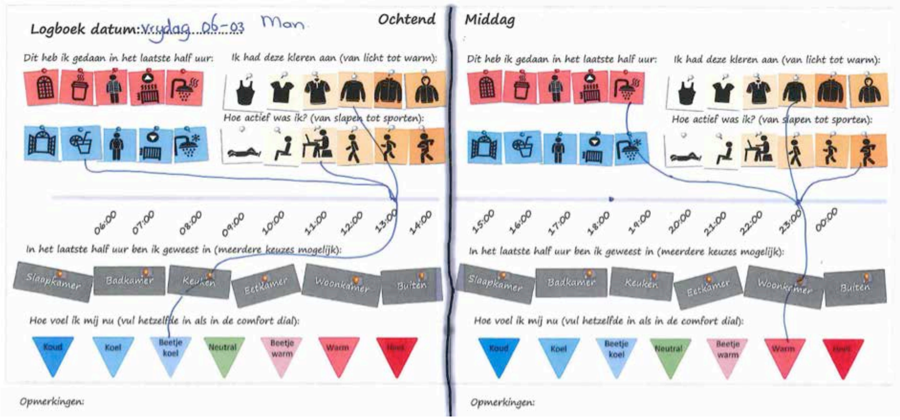

FIGURE 1.3 Paper logbook for entry of subjective data

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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2 Energy Performance and comfort in residential buildings

Sensitivity for building parameters and occupancy[1]

Abstract
Energy performance simulation is a generally used method for assessing the energy consumption of buildings. Simulation tools, though, have shortcomings due to false assumptions made during the design phase of buildings, limited information on the building's envelope and installations and misunderstandings over the role of the occupant's behavior. This paper presents the results of a Monte Carlo sensitivity analysis on the factors (relating to both the building and occupant behavior) that affect the annual heating energy consumption and the PMV comfort index. The PMV results are presented only for the winter (heating) period, which is important for energy consumption in Northern Europe. The reference building (TU Delft Concept House) was simulated as both a Class-A and Class F dwelling and with three different heating systems. If behavioral parameters are not taken into account, the most critical parameters affecting heating consumption are the window U value, window g value and wall conductivity. When the uncertainty of the building-related parameters increases, the impact of the wall conductivity on heating consumption increases considerably. The most important finding was that when behavioral parameters like thermostat use and ventilation flow rate are added to the analysis, they dwarf the importance of the building parameters. For the PMV comfort index the most influential parameters were found to be metabolic activity and clothing, while the thermostat had a secondary impact.

§ 2.1 Introduction

Building performance simulation has been established as a widely accepted method of assessing energy consumption during the design process for buildings that are either due to be renovated or are going to be built new. Modern buildings are highly complex and have high performance requirements relating to sustainability, making simulations a necessity.

Building simulation tools have shortcomings and are unreliable at predicting the energy performance of buildings. The reasons for these failings could be technical, such as weather variations and false assumptions during the building design phase [1, 2]. Also limited information on the building's envelope and installations (especially

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when the buildings are very old and there are no records of the materials used) may also play an important role in the discrepancies between simulated and actual energy use. As a result, large differences are observed between predicted and actual energy performance, ranging from 30% up as far as 100% in some cases [1-6]. In Majcen and Santin [3-5], it was also shown that predictors are much worse for buildings with a lower energy class (generally older stock) than those with a higher energy class (generally the more recently built stock). Another important reason is related to a misunderstanding or underestimation of the role of the occupant's behavior [1, 6, 7]. Current simulation software fails to take into account the energy-related behavior of the occupant and his behavior towards indoor comfort. There are numerous studies that emphasize the need to take proper account of the occupant's behavior during the design phase, or even during the refurbishment stage, in order to generate better building energy performance predictions [1, 2, 6, 8, 9].

The energy models that are used to predict the energy performance of buildings are sensitive to specific input parameters. These most sensitive parameters should be modelled with care in order to represent the building as accurately as possible [10-12]. Accordingly, in order to improve the quality of the prediction of building energy performance, it is important to understand its sensitivity to the various input parameters, and in this particular case, changes in a combination of the building envelope and the occupancy behavior parameters. This can be done through sensitivity analysis and specifically using the method of Monte Carlo analysis (MCA) [13].

Several studies can be found in literature with sensitivity analysis performed on the effects of technical and physical parameters on the energy consumption of buildings [12-18]. However, occupancy-related parameters that could reflect the behavioral pattern of occupants have rarely been studied and moreover, the majority of studies have involved commercial or office buildings and not residential buildings, which are the main object of the present study.

The international standard ISO 7730 is a commonly used method for predicting the thermal sensation (PMV) and thermal dissatisfaction (PPD) of people exposed to moderate thermal environments. The PMV model predicts the thermal sensation as a function of activity, clothing and the four classical thermal environmental parameters: air temperature, mean radiant temperature, air velocity and humidity. Activity means the intensity of the physical activity of a person and the clothing is the total thermal resistance from the skin to the outer surface of the clothed body. Many widely used building simulation programs such as ESP-r, TRYNSYS and Energy+ use ISO 7730 [19] to calculate comfort levels inside a building. One main criticism of the PMV/PPD method is that it disregards the effect of adaptations, the changing evaluation of the thermal environment due to changing perceptions. There are three different forms of adaptation, which are all interrelated and affect one another [20]. Psychological adaptation relates to a person's thermal expectations based on his past experiences and habits [21-23]. Physiological adaptation (acclimatization), relates to how an individual adapts to a thermal environment over a period of some days or weeks and behavioral adaptation relates to all modifications or actions, which an individual might make consciously or unconsciously, and changes in the heat and mass fluxes governing the body's thermal balance [20]. These modifications may be personal [24-26], technological, or environmental adjustments [27].

The environment inside a residential dwelling is not as constant as that of an office and the range of behavior of occupants and their interactions with building components is wider than in office buildings. All forms of thermal adaptation can be applied in residential dwellings: changing the level of activity and clothing, adjusting the thermostat, opening or closing windows and window shades, etc. It is suspected that user behavior plays a much more important role in determining the comfort range, which may also be much wider than in office buildings, which are often more uniformly conditioned by HVAC and individuals have much less potential for changes and adaptations.

There is a significant gap in the literature when it comes to sensitivity analysis of physical, technical and occupancy parameters in the residential sector of areas with a maritime climate such as the Netherlands. Few studies have evaluated these parameters with a complete sensitivity analysis method, which reflects the occupant's energy-related behavior such as ventilation and thermostat settings as well as physical parameters for heating consumption and comfort index.

This paper presents the results of a sensitivity analysis study that was performed for a single residential housing unit in the Netherlands. The analyses were performed for the technical/physical properties of the building only- i.e. the thermal conductivity of the walls, floor and roof, window U and g values, orientation, window frame conductivity and indoor openings. The simulations were carried out with the following variations: multi-zone and single-zone versions of the building; two different grades of insulation; three different types of HVAC services; the occupant's behavioral characteristics (thermostat level, ventilation behavior, metabolic rate, clothing and presence that in simulation terms is the heat emitted by people). The sensitivity of the above-mentioned parameters was gauged for the yearly total heating demand of the building and the hourly PMV comfort index. The present paper focuses on the heating period, which is of importance in the Netherlands.

§ 2.2 Methodology

The goal of the study is to make recommendations for

1 the effect of the accuracy of measurements relating to the building's physical properties on predicting the energy consumption of the building;

2 We will seek to answer the following questions:
- Which are the most critical parameters (physical and behavioral) that influence energy use in residential dwellings for heating according to whole building simulation software?
- Which parameters have the most critical influence on 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)?

First, a sensitivity analysis will be carried out to determine the most important physical parameters for the energy consumption of the dwelling. Next, the behavioral parameters (heat emission due to tenants' presence, thermostat and ventilation) are added to the sensitivity analysis in order to compare the effect of the physical parameters and the behavioral parameters on the total energy consumption for heating. At the same time, another sensitivity analysis will be carried out in order to assess the most important parameters for the thermal comfort index (PMV). Possible overlap between the most influential parameters for the total energy consumption and the comfort index could reveal possibilities for improvement that could lead to reduced energy consumption and higher comfort levels.

§ 2.2.1 Sensitivity Analysis

The technique of sensitivity analysis is used to assessing the thermal response of buildings and their energy consumption [13]. The goal of a sensitivity analysis is to study the response of the model simulated by EnergyPlus with respect to the variations of specific design parameters.

In general, a sensitivity analysis is able to determine the effect of a building's design variable on its overall performance (for example, the demand for heating or cooling) of the building. It can be used to assess which set of parameters has the greatest influence on the building performance variance, and at what percentage.

Sensitivity analyses can be grouped into three classes: screening methods, local sensitivity methods and global sensitivity methods. Screening methods are used for complex, computationally intensive situations with a large number of parameters, such as in sustainable building design. This method can identify and rank in subjective terms the design parameters that are responsible for the majority of the output variability e.g. energy performance. These methods are called OAT methods (one-parameter-at-a-time) and the impact of changing the values of each parameter is evaluated in turn (partial analysis). A performance estimation using standard values is used as control. For each design parameter, two extreme values are selected on either side of the standard value. The differences between the results obtained by using the standard value and the extreme values are compared in order to evaluate which parameters would affect the energy performance of the building the most [28].

Local sensitivity analysis methods are also based on an OAT approach, but the evaluation of output variability is based on the variation of one design parameter between a certain range (and not only on extreme values) while the rest are maintained at a constant level. This method is a useful way of comparing the relative importance of various design parameters. The input-output relationship is assumed to be linear and the correlation between design parameters is not taken into account [28].

In global sensitivity methods, output variability due to one design parameter is evaluated by varying all the other parameters at the same time, while also taking account of the effect of range and shape of their probability density function. Randomly selected design parameter values and their calculated outputs are the means for determining the design parameters' sensitivity. The influence of other design parameters is very important in a sensitivity analysis because the overall performance of the building is determined by all these parameters and how they interact. Distribution effects are relevant because parameter sensitivity depends not only on the range and on distribution of the individual parameter but also on other parameters, that building performance is sensitive to. Design parameter sensitivity often depends on the interaction and influence of all the design parameters [28]. The method used in the present study is the Monte Carlo analysis; this is a variance-based method and a form of global sensitivity analysis.

§ 2.2.1.1 Monte Carlo Analysis

There are several mathematical methods for sensitivity analysis that can be found in the literature [11,13,18,29-32]. The Monte Carlo analysis (MCA) method was chosen for the purposes of this study. The use of MCA in the field of thermal modelling was proposed by the employees at the SERI [33] and the Los Alamos National Laboratory [34]. Under MCA, all the uncertain parameters are assigned a definite probability distribution. For each simulation, a value is selected at random for each input based on the probability of its occurrence. For inputs that are distributed with a Gaussian (normal) distribution, a value close to the modal value is more likely to be selected than an extreme value. The predictions that are produced by this unique set of parameter values are saved and the process is repeated many times, using a different and unique set of values for each parameter every time. When the process reaches an end, all the values for the predicted parameter (e.g. energy performance or PMV) that have been calculated from each simulation are recorded. At the same time, all the values for each of the design parameters for every simulation are also recorded [13].

The accuracy of the method is based on the number of simulations that have taken place and not on the number of the uncertain input parameters. This means that given enough computational power, the effect of a large number of parameters could be assessed simultaneously with MCA. Figure 2.1 shows that irrespective of the number of parameters, only marginal improvements can be obtained after 60-80 simulations [13].

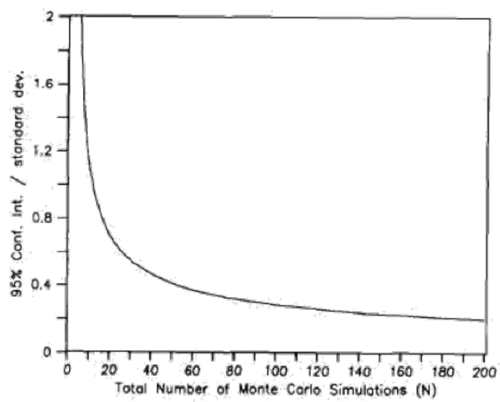

FIGURE 2.1 Relationship between normalized confidence interval and number of MC simulations *(From Lomas and Eppel, 1992)*

Since all the inputs are perturbed simultaneously, the method takes full account of any interactions between the inputs and, in particular, any synergistic effects. Moreover any non-linearity effects in the input/output relationships are fully accounted for [13].

§ 2.2.1.2 Sampling

Three sampling techniques are relevant to Monte Carlo analysis: simple random, stratified and Latin Hypercube Sampling (LHS). Random sampling is the most basic sampling technique and works by generating a random number and scaling it to the target variable via its probability distribution [35]. The stratified sampling method is an improvement on simple random sampling that force the sample to conform to the whole distribution that is being analyzed. In order to achieve this, the probability distribution of the target variable is divided between several strata of equal probability and finally, one value is chosen at random within each stratum. Latin hypercube sampling method is a further improvement on the stratified sampling method. It works by dividing the input into strata and then generating samples so that the value generated for each parameter comes from a different stratum [36]. However, stratified sampling can introduce unknown bias into the results of the analysis [37, 38] and varying degrees of success are encountered with the use of Latin hypercube sampling [29]. A study by McDonald [35], which compared all the above sampling techniques for Monte Carlo analysis, suggests that the best combination for MCA in typical building simulation applications is simple random sampling with 100 runs. For the present study, simple random sampling was therefore chosen with, for the sake of accuracy, 200 simulation runs.

§ 2.2.1.3 Statistics

The post-processing took place in SPSS [39] after each of the 200 simulation sets was finished and the results were recorded. The use of the regression analysis enabled us to calculate the sensitivity ranking based on the relative magnitude of the regression coefficients. The parameters that were used in the simulations have different units and relative magnitudes and for that reason, a standardization process was needed. For this study, the standardization of the regression analysis took place in the form of transformation by ranks [40]. Moreover, the ranking of the raw data allowed the exploration of non-linear relationships between predictors and dependent variables. The regression analysis was then performed on the rank transformed data rather than the raw original ones. The beta value that was produced by the regression analysis is the standardized rank regression coefficient (SRRC). The SRRC values that were obtained are the sensitivity indicator for each parameter and describe the effect that this parameter has on the dependent variables (energy consumption for heating and PMV). Only statistically significant parameters are presented in the results, with the significance level being 0.05. The higher the value of the SRRC, the more sensitive the parameter is and thus the more impact it has on the heating energy or the PMV. A positive SRRC means that an increase in the parameter leads to an increase in the value of the dependent variables; a negative SRRC means that an increase in the parameter leads to a decrease.

§ 2.2.2 Tools

The initial modelling of the reference building was carried out using the simulation software DesignBuilder, which is a user interface for the Energy+ [41, 42] dynamic thermal simulation engine. Energy+ is a dynamic simulation software for energy analysis in buildings, which is based on transient heat conduction equations and combined heat, and mass transfer in construction elements. The building file was exported in the form of an Energy+ file and uploaded to the main Energy+ editor for the simulation of the installations. The parametric simulations for the Monte Carlo analysis took place with an Energy+ add-on that was created for that purpose, the jEPlus [43, 44].

§ 2.2.3 Reference Building

The reference building for the simulations was based on a real building, the Concept House built by TU Delft in Rotterdam. Two variations of the concept house were initially chosen as reference cases based on their energy class, which represents the amount of energy consumed per m^2 in kWh/year. Two buildings were used (external envelope materials) corresponding to a Class-A building and a Class-F building, according to the Dutch building code ISSO 82.3 [45]. The dwelling consists of a living room with kitchen, two bedrooms, a bathroom, a storage room and a hallway. The floor area of the house is $86.2m^2$ and its height is 2.7m. The shading system of both dwellings consists of blinds with high reflectivity slats, positioned outside the window system. The blinds are open while the occupants are awake and closed when they are asleep or absent. The blinds therefore also act as window insulation.

§ 2.2.4 Independent variables and predictor parameters

The output (dependent) variables selected for this study were the total annual heating demand and hourly PMV. The first part of the study is about the first dependent variable, the annual heating. The reference building was modelled in two ways, as a single zone and as a multi-zone (three zones: kitchen/living room, bedroom 1 and bedroom 2 were the heated areas in this case). Each single zone and multi-zone model was modelled as a Class-A and Class-F buildings based on the Dutch energy labels for buildings ISSO 82.3 [45], according to European directive 2010/31/EU [46] on the energy performance of buildings.Furthermore, modelling was carried out for three different heating systems: ideal loads, high efficiency boiler with radiators and floor heating coupled with a heat pump.

The most important parameters needed for a building's thermal simulation are the thermo-physical properties of the construction materials (conductivity, specific heat, density), the casual gains associated with occupancy and appliances and infiltration/ventilation rates. Without those parameters, a reliable model could not have been created [37]. Previous studies have demonstrated that in simulations, the most sensitive parameters affecting the heating consumption are the conductivity of the external construction components, the outdoor temperature (as described by a weather file), equipment heat gains and the infiltration/ventilation rate [18, 37]. Furthermore occupancy could play a major role in households' demand for energy and that the presence of a thermostat is a major factor in the demand for heating [47]. In our study, we did not consider sensitivity to outdoor temperature, as we were mainly interested in explaining the differences in sensitivity in different types of dwellings that are all located in the same climate area: the Netherlands. Furthermore, in the multi-zone model we did not take into account the air exchange between zones.

The predictor parameters for the present study were chosen in such a way that they cover all four of the parameters mentioned above, which are essential for the thermal modelling of a building. The Class-A (thermally efficient) and Class-F (thermally inefficient) reference building was simulated once with predictor variables: walls, roof and floor conductivity, window glazing U and g values, window frame thickness, building orientation. The second time, the two classes were simulated with the same set of predictor variables plus the occupant behavior related parameters of ventilation, thermostatic level and the heat emitted due to the presence of the occupant.

Figure 2.2 shows a complete picture of the simulations and combinations of the type of buildings, class of buildings and parameters used for this study. Each of the parameters was assigned a base case value and a normal probability distribution based on which, the parameter value was randomly changing. Normal distribution maximizes the information entropy among all distributions with a known mean and standard deviation. The standard deviation was 5% of the base case value for each parameter [18, 37]. Moreover, in old buildings the accuracy of the U-value is very different from new buildings. For ventilation, it is the same. Preliminary analysis of the data justified the choice of 5%. We can guess that conductivity of walls/floor/roofs, thermostat, ventilation& infiltration, and heat emitted due to people (which as input in the simulation is translated as number of people present) have the highest standard deviation (of all parameters of Table 2.1, they are the most difficult to estimate accurately, especially in older buildings) while orientation is easy to determine. However, even when we keep the standard deviation low (5%) these parameters still appear to be the most influential. Therefore increasing their standard deviation will lead to the same trend in the results with even more influence. Table 2.1 shows the base case values (mean) of the parameters, the standard deviation and the amount of samples. Ventilation and infiltration are presented together as one number, which is the same for both reference buildings (Class-A and Class-F), because the sum of infiltration and ventilation flow rates was chosen to ensure enough fresh air. In the first case, infiltration is much lower and ventilation much greater because the Class-A building is new and airtight while in the Class-F building infiltration is higher and ventilation lower because building is older and less airtight.

TABLE 2.1 Mean, std. deviation and number of samples for the predictor parameters for total heating and cooling

PARAMETERS	CLASS A			CLASS F		
	mean	std. deviation	samples	mean	std. deviation	Samples
Orientation (degrees angle)	245	14.5	10	245	14.5	10
Wall Conductivity [W/(m-K)]	0.048	0.0024	10	0.25	0.0125	10
Roof Conductivity [W/(m-K)]	0.048	0.0024	10	0.3	0.015	10
Floor Conductivity [W/(m-K)]	0.048	0.0024	10	0.3	0.015	10
Window Glazing U value [W/(m^{2}K]	0.96	0.064	10	6.121	0.3	10
Window Glazing g value	0.5	0.03	10	0.81	0.04	10
Window Frame Thickness [m]	0.045	0.003	10	0.045	0.003	10
Thermostat [°C]	20	1	10	20	1	10
Ventilation+ Infiltration (flow rate) [m^3/s]	0.1	0.005	10	0.1	0.005	10
People present (heat emitted by people)	2	0.1	10	2	0.1	10

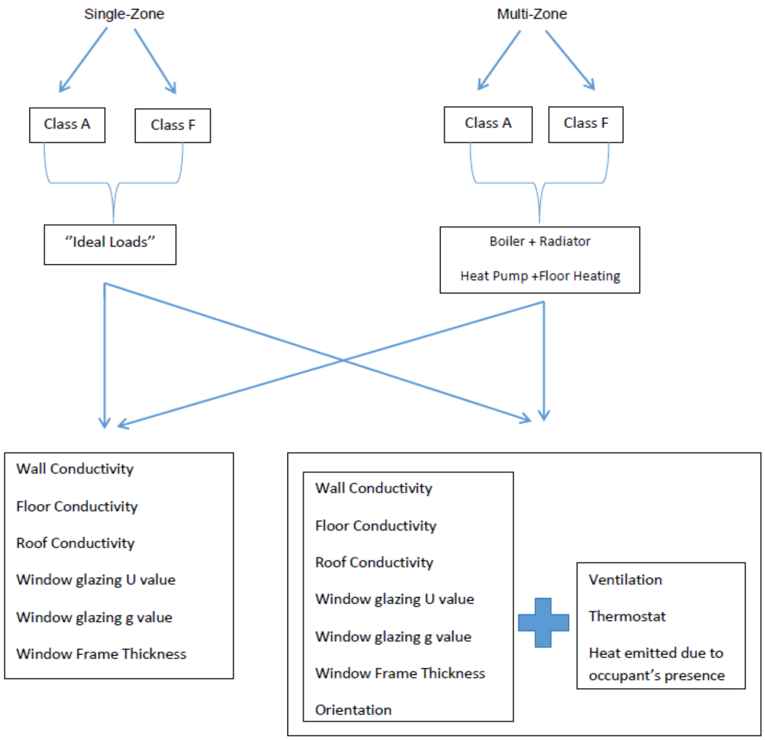

FIGURE 2.2 Schematic representation of simulations between building types and parameters

The second part of the study related to the second dependent variable, the hourly PMV. The predictor variables used were the thermostat setting, metabolic activity, clothing, and ventilation (airflow rate), while the air speed in the rooms was held constant (0.14 m/sec). The reason for the choice of these variables was that they represent the factors that affect the thermal comfort index (PMV) most closely. The PMV model predicts the thermal sensation as a function of metabolic activity, clothing and air temperature, mean radiant temperature, air velocity and humidity [19]. In reality, air temperature and radiant temperature related to the thermostat setting, while humidity and air speed related to the ventilation of the building. However, in Energy+ the local air speed of the rooms that affects comfort is not dynamically calculated from infiltration and ventilation; instead it can only be defined using a schedule, which means that detailed and reliable comfort calculations can only take place if an extensive file with air speed patterns (produced from empirical data or from CFD calculation) is available [41, 42].

Each simulation in the first part of this study was performed for each hour of a whole year. For the second part of the study, each simulation was performed for a whole day in the fall, the winter, the spring and summer. The reason for this was that it makes no sense for the dependent variable to have a yearly PMV value. The PMV value can change many times in a day, even within one hour, and cannot be aggregated to a yearly value. Moreover, a yearly PMV value says nothing meaningful about the occupants' feeling of comfort. Figure 2.3 shows a complete picture of the simulations and combinations of type of buildings, class of buildings and parameters that took place in the second part of this study. As in the first part of the study, each of the parameters was assigned a base case value and a normal probability distribution, based on which the parameter value changed randomly. Table 2.2 shows the base case values (mean) of the parameters, the standard deviation (10% around the mean) and the number of samples [18].

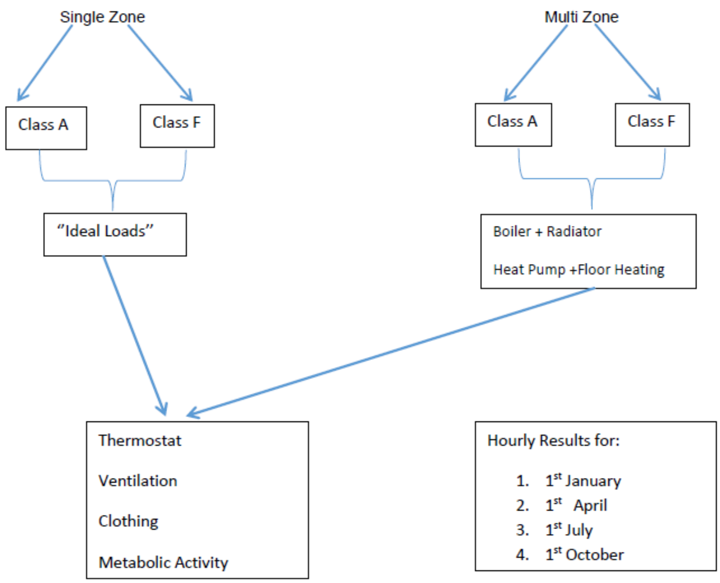

FIGURE 2.3 Schematic representation of simulations and combinations between buildings types and parameters

TABLE 2.2 Mean, std. deviation, and number of samples for the predictor parameters for hourly PMV

PARAMETERS	CLASS A			CLASS F		
	mean	std. deviation	samples	mean	std. deviation	Samples
Clothing (clo)	1	0.1	10	1	0.1	10
Metabolism (W/person)	100	10	10	100	10	10
Thermostat [°C]	20	1	10	20	1	10
Ventilation-Bedroom [m^3/s]	0.015	0.0015	10	0.015	0.0015	10
Ventilation-Living room [m^3/s]	0.04	0.004	10	0.04	0.004	10

§ 2.2.5 Heating Systems

Both Class A and F dwellings were simulated with three different heating systems. The first heating system was based on the model of ''Ideal Loads Air System''. This model can be thought of as an ideal unit that mixes the air at the zone exhaust condition with the specified amount of outdoor air and then adds or removes heat and moisture at 100% efficiency to produce a supply air stream with the properties specified [41]. The second heating system is based on the model ''Low Temperature Radiant: Constant Flow'' of Energy+. This low temperature radiant system (hydronic) is a component of zone equipment that is intended to model any radiant system where water is used to supply/remove energy to/from a building surface (wall, ceiling, or floor). The low temperature radiant system is supplied with warm water from a water-to-water heat pump. The supply side of the heat pump is connected to a ground heat exchanger and the circulation pump is a constant speed pump [41, 42]. This system will henceforth be referred as the floor heating system, which includes a heat pump.

The third heating system is a high temperature radiant system (gas-fired) that is intended to model any ''high temperature'' or ''high intensity'' radiant system where electric resistance or gas-fired combustion heating is used to supply energy (radiant heat) [41]. In this model, the user is allowed to specify the fraction of heat that leaves the heater as radiation, latent heat and heat that is lost. The user can also specify the fraction of radiant heat (0.4 for this study) that reaches the occupants and the zone surfaces, which is later used in the thermal comfort calculations. Moreover, the radiant fraction of energy that reaches the occupants and the zone surfaces always sums up to unity; although every fraction of radiant energy affects the occupants in a zone, it automatically affects the zone surfaces as well. As such, there are no ''losses'' from the perspective of zone air temperature and the surfaces heat balance. This system will henceforth be referred as the Radiator system, which includes the gas boiler.

§ 2.2.6 Natural Ventilation

The natural ventilation for each of the thermal zones of the base case scenario is calculated from the directions given by the Dutch NEN 1087 standard. The NEN standard provides the required flow for each room. The ACH when the rooms are not occupied is set to 15% of the ACH when the room is occupied and the air exchange between zones has not been modelled. Infiltration was calculated based on the Dutch NEN 1087 [48] standard and added to the ventilation. Table 2.3 shows all the data related to the natural ventilation calculations.

TABLE 2.3 ACH (including ventilation and infiltration) per room when the space is occupied and unoccupied

	AREA (m2)	NEN 1087 FLOW Standard ($m^3/h/m^2$)	VOLUMETRIC AIR Flow Q (m^3/h)	ROOM Vol (m^3)	ACH_{OCC} (Q/Vol)	ACH_{UNOCC} (15% of ACH_{occ})
Bedroom 1	13.8	3.3	45.5	37.2	1.22	0.18
Bedroom 2	12.9	3.3	42.6	34.8	1.22	0.18
Bathroom	6.9	50	345	18.7	18.5	2.77
Living Room	37.1	3.3	122.4	100.1	1.22	0.18

§ 2.2.7 Heating and Ventilation Controls

For all three systems, the temperature control type was the mean air temperature of the zone. The thermostatic control set point defines the ideal temperature (i.e. setting of the thermostat) in the space. During daytime and occupied periods, this heating set point is set to 20 °C for all rooms and for the whole year [49, 50]. Every time the mean air temperature falls below 20 °C the system is providing heat to the zone, if it is above 20 °C then the system will stop. The setback set point temperature, which is the temperature during the night and unoccupied periods, is set to 16 °C. The thermostatic control set point determines whether or not there is a heating load in the space and thus whether the systems should be operating.

In the ideal loads system, the control is only through the thermostatic control set point. Heating control in the high temperature radiant system (radiator + boiler) takes place with two additional parameters: the heating set-point temperatures and the throttling range. The throttling range specifies the range of temperature, in degrees centigrade, over which the radiant system throttles from zero heat input to the zone up to the maximum. The heating set-point temperature specifies the control temperature for the radiant system in degrees centigrade and controls the flow rate to the radiant system [41, 42]. This set point is different from the thermostatic control set point for the zone. In our study, the heating set point temperature was set to 20 °C and the throttling range to 1 °C.

The control for the low temperature radiant system takes place with four additional parameters: heating high and low control temperatures and heating high and low water control temperatures. The zone mean air temperature is compared to the high and how control temperatures at any time. If the mean air temperature is higher than the high temperature, then the system will be turned off and the water mass flow rate will be zero. If the mean air temperature is below the low temperature, then the inlet water temperature is set to the high water temperature. If the mean air temperature is between the high and low value of the control temperature, then the inlet water temperature is linearly interpolated between the low and high water temperature value [41]. In our study, the heating high and low control temperatures were 21 °C and 18 °C and the heating high and low water temperatures were 35 °C and 10 °C.

§ 2.2.8 Activity

§ 2.2.8.1 Clothing and Metabolic Rate

There were two occupants in the dwelling, a man and a woman. The density (people/m^2) was thus 0.0232. The metabolic rate of the two tenants was chosen to be ''Standing Relaxed'' during the occupancy periods, which corresponds to 100 W/person. Moreover, the metabolic factor accounts for physical size and is 1 for men and 0.85 for women. In our case, the average metabolic factor (0.90) for a man and a woman (which were assumed the occupants of the concept house) was used for the simulations.

The clothing factor (clo) was set to 1 for the whole year. Usually 0.5 is the clo value for the summer period but preliminary simulations showed that the comfort index in the Netherlands during the summer period at 0.5 clo is low, which means that the occupants would feel cold. In addition, the clothing habits of people in the Netherlands during the summer months resemble a factor closer to 1 clo than 0.5. Clothing with factor of 1 clo corresponds to: trousers, long-sleeved shirt, long-sleeved sweater, underwear T-shirt. Summer clothing of 0.54 clo corresponds to knee-length skirt, short-sleeved shirt, panty hose, sandals [51]. Table 2.4 shows the input that was used for the simulation for the base case scenario.

TABLE 2.4 Occupancy simulation assumptions for the base case scenario

Density (people/m²)	0.0232
Metabolic Rate (W/person)	100 (Standing relaxed)
Metabolic Factor	0.90
Clothing factor (clo)	1

§ 2.2.8.2 Occupancy

The occupancy schedules vary according to the type of the thermal zone. In Table 2.5 we can see the occupancy for the living room/kitchen and in Table 2.6 the occupancy for the bedroom.

TABLE 2.5 Occupancy Schedule, Living Room/Kitchen

OCCUPANCY SCHEDULE--LIVING ROOM/KITCHEN	MORNING	EVENING
Weekdays	7:30-9:00	18:00-22:00
Saturday	9:30-11:00	18:00-22:00
Sunday	9:30-11:00	17:00-22:00

TABLE 2.6 Occupancy Schedule, Bedroom

OCCUPANCY SCHEDULE--BEDROOMS	NIGHT	EVENING
Weekdays	24:00-7:00	22:00-24:00
Saturday	24:00-9:00	22:00-24:00
Sunday	24:00-9:00	22:00-24:00

A half-hour gap in the occupancy of the bedrooms and living room-kitchen can be observed between 7:00 a.m. and 7:30 a.m.; this is because the occupants are assumed to use the bathroom for half an hour in the morning. The bathroom belongs to the non-heated zone.

During occupied periods, the living room and the bedrooms were assumed to have two people. For the sensitivity analysis, the number of people in the rooms was varied around the mean of two people with 0.1 (0.5% of the mean).

§ 2.2.8.3 Heat Gains

The internal gains in the dwellings for the base-case simulation scenario are due to occupancy (the heat that a person emits while in the room), a refrigerator, a computer, a monitor, a wireless router, and a television set which are all placed in the living room. Lighting is also a major contributor to the internal gains, which are set at 5 W/m^2 for the whole house but with different schedules for the operation for every room. In Table 2.7 the internal gains are summarized.

TABLE 2.7 Internal heat gains: people, equipment and lighting

TYPE OF INTERNAL GAIN	ACTIVITY	TOTAL HEAT	UNITS
Person	Light Activity	126	W/person
Refrigerator	Always on	3.24	W/m^2
Computer + Monitor	18:00-22:00	3.78	W/m^2
Television	18:00-22:00	6.75	W/m^2
Router	Always on	0.35	W/m^2
Lighting	Occupancy	5	W/m^2

§ 2.3 Results

The mean and standard deviation of the total annual consumption for the various configurations of the dwellings, is displayed in Figure 2.4. The heating consumption for the ideal loads--single zone model and the multi-zone boiler/radiator model is similar for both the Class A and Class F dwellings. The consumption of the heat pump system though, appears to be much higher on both classes. The reason for that is the way that the systems are controlled. The ideal loads and radiator systems availability follows the occupancy schedules mentioned in section 2.8.2 and the rest of the hours the system is shut off or in set-back temperature during the night. The floor heating system on the other hand is operating around the clock without intermission, and during the night, there is a setback temperature of 16 °C. This amounts to 168 hours per week compared to the 49 hours of operation for the other two systems. The consumption for the ideal loads system is the total demand for a whole year, for the radiator system it includes the gas boiler combustion efficiency, which was set to 1 (high efficiency boiler) and for the floor heating system it includes the coefficient of performance that was 2.47. The high efficiency of the floor heating system compensates for a large part the higher number of hours of operation. Finally, the high consumption of the floor heating in Class F is explained in section 3.1.4. Note that a heat pump would probably never be installed in a Class F dwelling.

The results of these simulations correspond with the findings that energy savings by using air/water heat pumps are, in the Netherlands at least, often disappointing, which has among others to do with the fact that no set back temperature settings are used to avoid long periods of warming (floor heating is a slow system) that lower comfort levels [49].

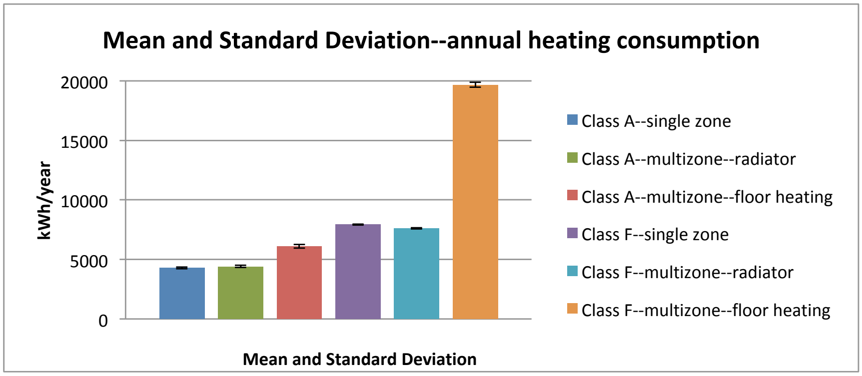

FIGURE 2.4 Mean and Standard Deviation for the annual heating consumption of the various heating systems

§ 2.3.1 Heating Sensitivity Analyses

§ 2.3.1.1 General Trends

Figures 2.5, 2.6, 2.7 and 2.8 show the results for the Class A and Class F buildings with and without the behavioral parameters, for both the single and multi-zone models and for three types of heating systems. Only the parameters that were found to be significant are displayed in the results. For the Class A configuration of the reference building and for all three different types of heating systems that were modelled, the most influential parameter with a positive effect (the higher the value of the parameter, the more energy is needed for heating) that affects the annual heating consumption, is the window U value (Figure 2.5). The results of the sensitivity analysis for the concept house (Figure 2.6) modelled as a Class F dwelling, showed that the window U value was not the most influential parameter. In fact, the window U-value has a very small impact on the floor heating and the ideal loads configurations, but it is insignificant for the radiator system. Wall conductivity, window g value and orientation are the most critical parameters in the Class F dwelling. Window frame thickness is insignificant in all cases.

§ 2.3.1.2 Behavioral Parameters

The introduction of three new parameters that are closely related to the tenant's energy behavioral patterns completely change the results of the sensitivity analysis since the new behavioral parameters dominate the effects on heating consumption. For the Class A simulations (Figure 2.7) of the radiator and ideal loads systems, the ranked regression coefficient for the thermostat use was 0.934 and 0.945. For the floor heating system, the parameter of the thermostat was not statistically significant (see further explanation in 3.1.4). Figure 2.8 shows the results for the reference building simulated as a Class F dwelling. For the ideal loads and radiator systems, the thermostat is also the parameter that dominates the effect on the heating consumption. Consequently, the other parameters for these two systems have a very small impact in the total heating consumption.

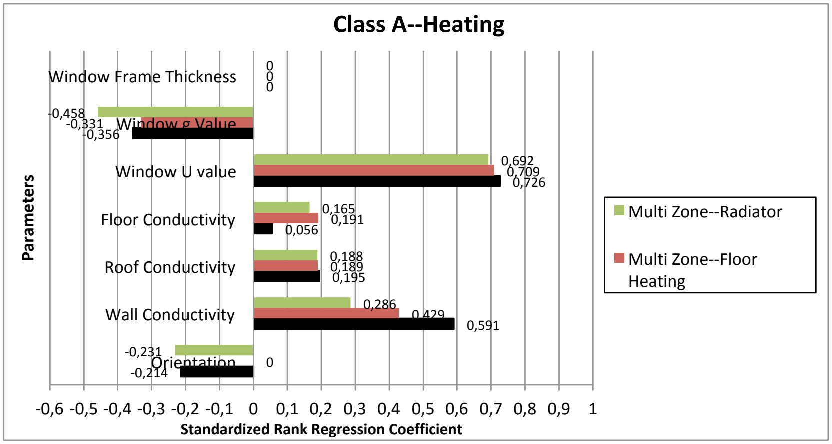

FIGURE 2.5 Class A--Heating sensitivity analysis

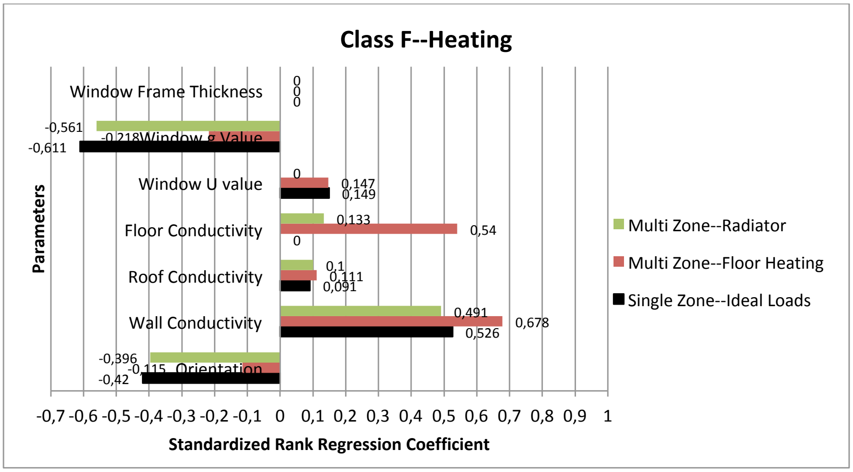

FIGURE 2.6 Class F--Heating sensitivity analysis

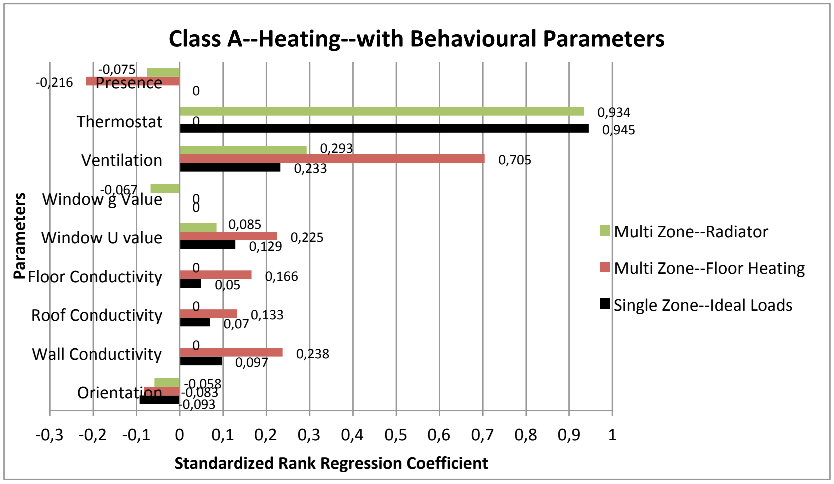

FIGURE 2.7 Class A--Heating sensitivity analysis with behavioral parameters

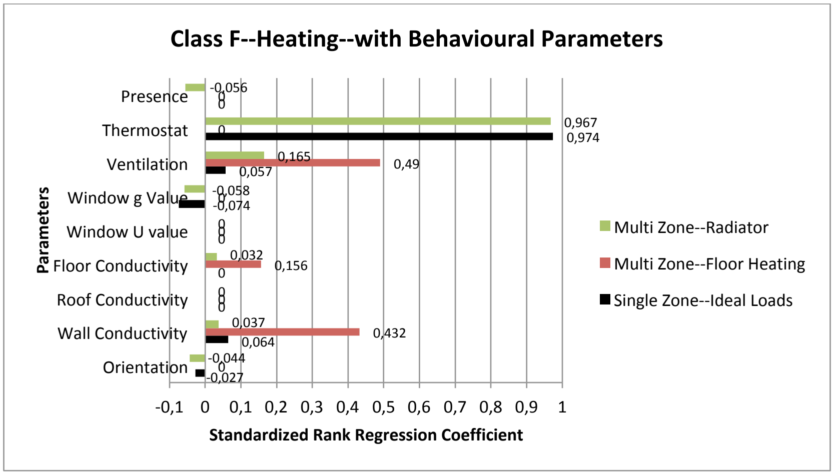

FIGURE 2.8 Class F--Heating sensitivity analysis with behavioral parameters

Figure 2.9 shows the amount of variance in the dependent variable, in this case annual heating consumption, which can be explained by the independent variables (heat emitted due to people, thermostat, ventilation, window g value, window U value, floor, wall and roof conductivities and orientation). For all the configurations and different heating systems, the proportion of variance in the heating that is explained by the parameters is higher than 70%, and in some cases reaches 98%) for all cases with the sole exception of the combination of Class F with behavioral parameters and floor heating as the heating system. In that case, 46% of the variance can be explained by the parameters since only three of them were found to be significant in this configuration.

§ 2.3.1.3 Comparison between Class-A and Class-F buildings

Without behavioral parameters

As mentioned previously, for the Class A building the most influential parameters on the heating are the Window U and g values and the conductivity of walls. Since the wall area is larger than the roof and floor areas it is logical that the influence of wall conductivity is larger than that of the roof and floor.

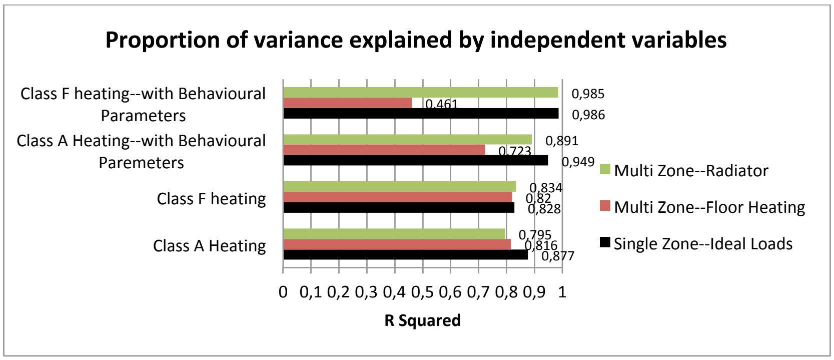

FIGURE 2.9 Proportion of variance in Heating Consumption explained by the independent variables

The parameters with the least impact are Floor and Roof Conductivity and Orientation. It has to be noted here that the alterations in the orientation only affect the Multi Zone-radiator and the Single Zone-ideal loads. Any effect on the Multi Zone-floor heating combination was found to be statistically insignificant.

For the Class F reference building, the influence of the window U-value decreases drastically compared with the Class A dwelling and is replaced by the larger influence of window g value, wall conductivity and orientation. This can easily be explained by the fact that in a house where the walls are well insulated (Class A dwelling), transmission losses take place mainly through the windows, while most of these losses occur through the walls when they are poorly insulated (Class F dwelling).

For the floor heating system, the most influential parameter on the total heating consumption is Wall Conductivity followed by Floor Conductivity, which increased by almost three times compared to that of the Class A dwelling. The reason for that is that the Class A dwelling has a very highly insulated thermal envelope and the Class F dwelling is poorly insulated. In this case, the floor heating system produces a higher floor temperature, which causes much more heat losses through the floor.

With Behavioral Parameters

As mentioned, the introduction of behavioral parameters considerably alters the results of the sensitivity analysis. For both Class A and Class F and for all heating systems, thermostat and ventilation dominate the sensitivity analysis. For the radiator and ideal loads systems, the thermostat has by far the biggest impact, well over 0.9, for both Class A and Class F. For the floor heating system, Ventilation followed by Conductivity are the most important parameters for both classes. However, in Class A, the influence on heating is divided among all the parameters while in Class F, Ventilation, Wall and Floor Conductivity are the only significant parameters. The thermostat has no influence on the floor heating system (see explanation in 3.1.4). The influence of heat emitted by people is not very high, and is even insignificant in some cases which can be explained by the fact that, for the heating consumption sensitivity analysis, the metabolic rate of the people is stable and set to ''standing relaxed'' (126 W/person). This means that a slight deviation from the mean (0.5 %) of 2 persons per room does not add much to the heat gains for the room.

§ 2.3.1.4 Comparison between heating systems

The results for the three different systems when behavioral parameters are not taken into account are quite similar, except for the fact that the orientation is insignificant for the floor heating system in Class A, which relates to the higher significance of other parameters. In the Class F building, the exception is the absence of significance for floor conductivity for the ideal loads system and of significance of window U-value for the multi-zone radiator. Again, this relates to the higher significance of other parameters.

When behavioral parameters are taken into account, the most important parameters for Class A and F are the Thermostat, followed by Ventilation for the ideal loads and radiator systems. However, for the floor heating system, the thermostat is insignificant which relates to the control system.

In the sensitivity analysis, the standard deviation was 1 °C around 20 °C for 10 samples. The radiator and ideal loads systems operate according to the deviation of the zone air temperature from the set point. When the zone air temperature drops below the set point, the heating systems immediately start to consume more energy in order to condition the zone to the fixed set point temperature. For more information on the control of the floor heating system, see section 2.7. The high and low control temperatures were set to 21 °C and 18 °C, respectively, which offsets the thermostatic control temperature of 20 °C.

The heating system is installed inside the layers of the floor, above the insulation layer and close to the dwelling's interior. When the insulation layer is similar to the one in Class A, the heat does not escape through the ground. It is instead directed back into the interior. However, in the Class F dwelling, where the initial value of the conductivity of the floor's insulation layer is much higher (and fluctuates around that higher level), the impact on the total energy consumption is significantly greater. This is because much of the thermal energy from the floor escapes through the ground and more energy is needed to heat the dwelling, which explains the high-energy consumption seen in Class F, Figure 2.4.

The most important parameter for the floor heating system is ventilation for the Class A dwelling and window U value followed by ventilation for the Class F dwelling. The importance of the ventilation and window U value for the floor heating system can be explained by the fact that the thermostat that dominates the two other systems has no impact on the radiant floor system. The rest of the parameters have a zero or minimal impact on the dwellings' heating consumption.

§ 2.3.1.5 Increased uncertainty results

One of the most important problems when it comes to simulating building energy consumption is the lack of reliable information on the building envelope and user behavior. Especially for older buildings, represented in this study by the Class F dwelling, information on the external envelope is limited. U and g values for glass can be determined easily but the U values for the walls, roof and floor, as well as ventilation flow rates are very difficult to determine precisely. Houses built in the 1960s and earlier, provide little information about their thermal characteristics. For this reason, a sensitivity analysis was carried out for the Class F concept house with the standard deviation of the parameters set to 30% instead of the 5% that was initially used. The results can be viewed in Figures 2.10 and 2.11.

For the analysis without behavioral parameters (Fig. 2.10), the sensitivity outcome follows the same pattern as the results when 5% standard deviation was used for each parameter. Wall conductivity is the most influential parameter for all three systems. The second most important parameter for the ideal loads and radiator system is window g value followed by the orientation. For the floor heating system, the second most influential parameter for the heating consumption is floor conductivity followed by window g value and the orientation.

The major difference is that the impact of wall conductivity increased significantly for all three systems at the expense of the rest of the parameters, the impact of which is reduced. This may be the cause of major uncertainties when calculating the heating consumption of older buildings.

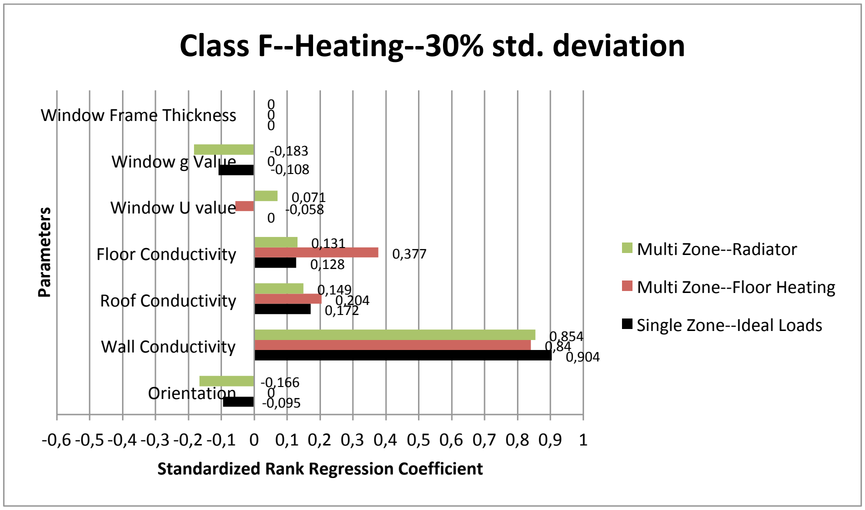

FIGURE 2.10 Class F--Heating sensitivity analysis--30% standard deviation

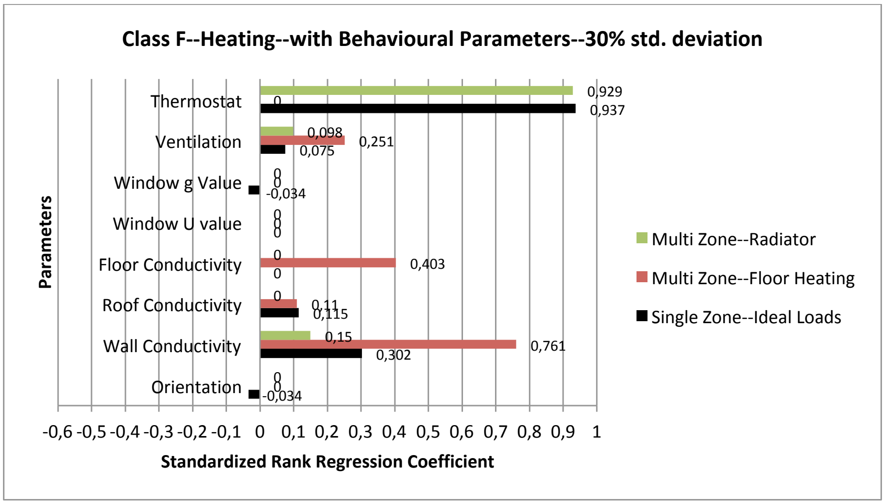

FIGURE 2.11 Class F--Heating sensitivity analysis with behavioral parameters--30% standard deviation

Figure 2.11 shows the analysis that included behavioral parameters. For the radiator and ideal loads systems, the thermostat remains the most influential parameter (in both cases with a value greater than 0.9). The influence of wall conductivity increases for all three systems and it is the second most influential parameter while the impact of window g value and the orientation declines or is found to be insignificant. Floor conductivity, for the floor heating system, is the last parameter that has a substantial influence, which also has a mild increase in value.

§ 2.3.2 Comfort Sensitivity Analysis

This section shows the results for the first day of January. The results for October and April do not lead to different conclusions and the results for July refer to summer conditions where no heating is needed and as such falls outside of the scope of this paper.

§ 2.3.2.1 General Trends

The results from the sensitivity analysis on the comfort index show (see Figures 2.12 to 2.21) that in all simulation configurations, the metabolic rate is one of the most important parameters, together with clothing and thermostat level. The impact of metabolic rate was found to be higher in the Class F building that the Class A building.

Ventilation plays a minor role, and is often insignificant. However, this comes as a consequence of the modelling approach. Dynamic simulation software cannot dynamically calculate air velocity from ventilation, more specialized software like CFD modules are need for that. In that sense, air speed was constant in all cases. Changes in the ventilation flow rate produce changes in the room's humidity and temperature. The temperature is controlled via the heating system, so that every time temperature deviates from the set point the heating system starts working until the room temperature matches the set point temperature. Humidity though is not regulated in residential dwellings and thus ventilation affects the comfort index. Clothing and thermostatic settings alternate between the second and third most influential parameters depending on the configuration. The thermostat is more influential in simulations where the heating system is ideal loads or radiators, which was to be expected because that heating system's controls are more directly connected to the thermostatic use (see previous section). On the contrary, for the floor heating system, as already explained, thermostat control has no real impact and the only parameters that affect the PMV are metabolic rate and clothing. The proportion of variance that was explained by the four parameters remained above 90% for all the possible configurations that were analyzed.

§ 2.3.2.2 Single Zone, Ideal Loads

Figures 2.12 and 2.13 show the results of the sensitivity analysis on the values of the PMV comfort index, for the first day of January, for the Single Zone configuration of the concept house, with the ideal loads heating system for Class A and Class F. For the Class A dwelling, the influence of the thermostat follows the heating schedule: after 22:00 the heating stops and the influence of the thermostat decreases constantly until 9:00 and starts increasing again at 10:00 when the heating has already been on for half an hour and until 11:00 when the heating stops again. From 11:00 till 17:00, the impact of the thermostat drops continuously and at 17:00 it starts to increase again until 22:00 when the heating stops again. An interesting observation is that the impact of the thermostat in Class A never drops below 0.4 (with the only exception is at 9:00 in the morning, when the dwelling has been in the setback setting for the longest period of the day), even when the heating is off. This is because the simulated dwelling is Class A with very good insulation and heat loss is very small.

Most of the heat, which is regulated from the thermostat, stays in the dwelling even when the heating is off and thus the influence of the thermostat never drops below 0.4. The factor with the biggest influence in the PMV index is the metabolism, which follows the opposite pattern of that of the thermostat. When the heating is off the impact of the metabolism starts to increase, from 23:00 to 9:30, after which it drops for two hours while the heating is on and increases again until 17:00 when the heating starts to operate again; then the impact of metabolism drops until 23:00 when the heating switches off again. The third most influential parameter is clothing which follows the same pattern as metabolism and the opposite to that of the thermostat.

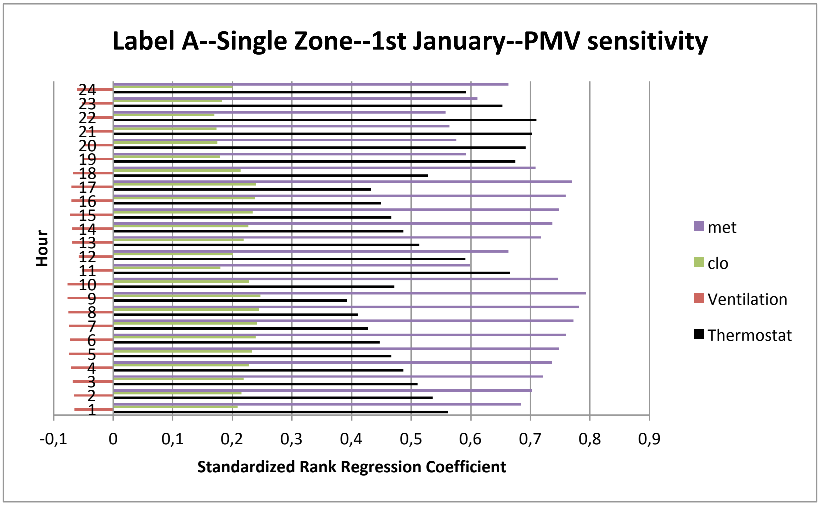

FIGURE 2.12 Label A--Single Zone--Ideal Loads--PMV sensitivity per hour for the first day of January

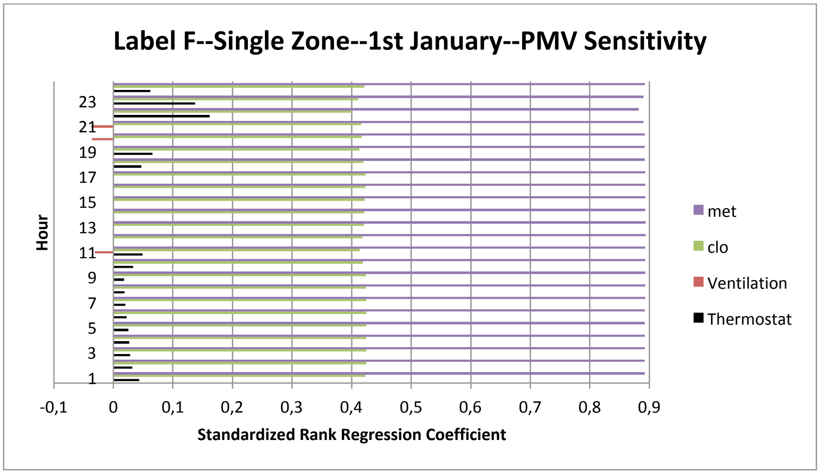

FIGURE 2.13 Label F--Single Zone--Ideal Loads--PMV sensitivity per hour for the first day of January

For the Class F dwelling, metabolism and clothing are the most influential parameters, with the thermostat having a very small influence compared to the Class A dwelling. This result was not expected, however, it can be explained using the comfort theory. The comfort zone depends heavily on the relationship between the radiation temperature (the average of all walls/floor/ceiling temperatures) [52]. In a Class A dwelling, the wall temperature is quite high because of the good insulation. Small variations in air temperature +/- 1 °C (thermostatic level) may then be enough to produce large changes in PMV. In an F-dwelling, the wall temperature will be low because of the lack of insulation and this will dominate the PMV: small variations in air temperature (thermostatic level) will not be able to compensate for the low wall temperature. Clothing has a more significant impact on comfort, almost double during all 24 hours of the day. Metabolic activity also has a bigger impact in Class F dwellings, although not as great as clothing. While in the Class A dwelling the metabolic activity's impact ranges from 0.55 to 0.79, in Class F it is above 0.89 all the time. Ventilation was found to be insignificant for comfort for most of the hours compared to the Class A dwelling.

Figures 2.14 and 2.15 display the hourly temperature, humidity and PMV for the 24 hours of the Class A and F simulations. Both the graphs show that the PMV index follows the same pattern as the mean temperature and the opposite of the indoor humidity. It also shows that according to the PMV, all dwellings should be found too cold by occupants (negative PMV). However, a temperature of 20 °C is very common in Dutch houses, which poses the problem of whether the PMV, which was initially developed for offices, can be used to estimate comfort in dwellings. The Class F dwelling is a much colder dwelling; the thermostatic set point temperature of 20 degrees is not enough to condition the space at the desired level. Of course, this is because of the colder temperature of the walls, floor and ceiling due to poor insulation.

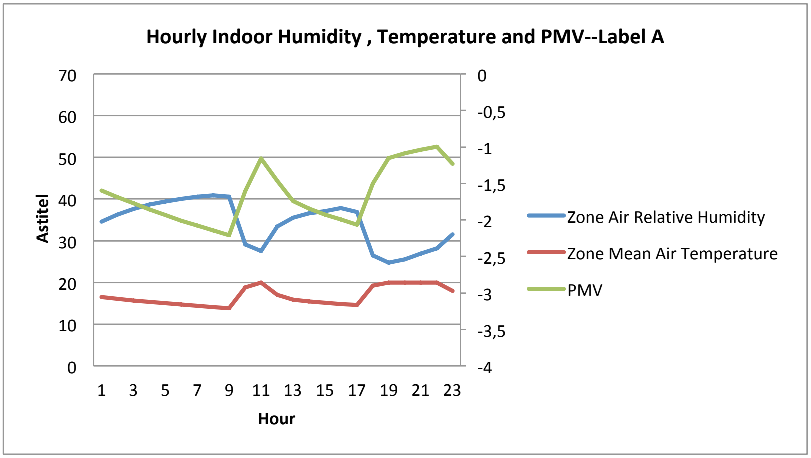

FIGURE 2.14 Hourly Indoor Temperature, Humidity and PMV for 1st of January--Label A

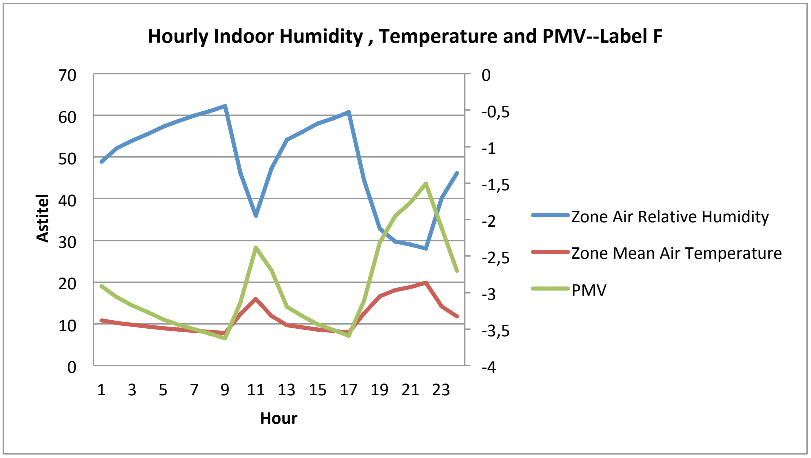

FIGURE 2.15 Hourly Indoor Temperature, Humidity and PMV for 1st of January--Label F

Figures 2.16 and 2.17 show the results of the sensitivity analysis for comfort, with ventilation being kept constant but the air speed in the indoor space being varied in the range 0.16 +/- 0.016. Air speed is significant in both cases this time. For the Class A dwelling, the most influential parameter is still metabolic activity. The effect of the thermostat has diminished while that of clothing has increased. The thermostat is no longer the second most influential parameter for all hours (Figure 2.12), although it is still the second most influential parameter during the hours that the dwelling is heated.

For the Class F dwelling, metabolic activity is again the most influential parameter and clothing, despite the fact that its impact diminishes compared to Figure 2.13, is the second most influential parameter for almost all the hours of the day. The thermostat has a larger effect, especially in the evening. Between 21:00 and 23:00, it even surpasses clothing as the second most important parameter, but for the rest of time it alternates with air speed as the least influential parameter.

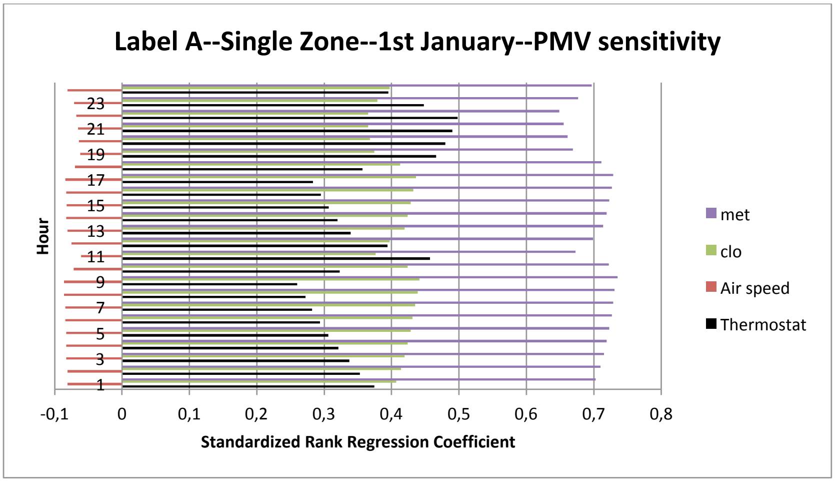

FIGURE 2.16 Label A--Single Zone--Ideal Loads--PMV sensitivity for January with Air Speed instead of Ventilation

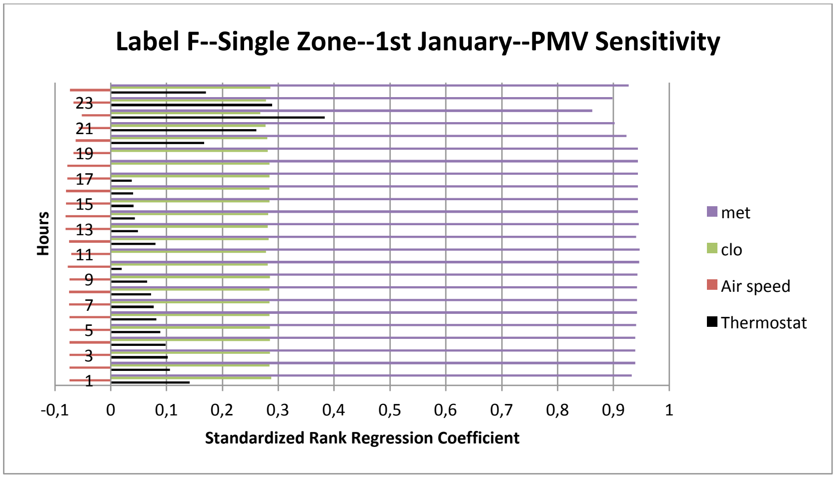

FIGURE 2.17 Label F--Single Zone--Ideal Loads--PMV sensitivity for January with Air Speed instead of Ventilation

§ 2.3.2.3 Radiator heating system

The multi zone simulations with the boiler/radiator heating system showed that, for the colder month of January and for the Class A building, the thermostat is the most influential parameter for comfort, followed by the metabolic rate. The results are very similar to the results for the ideal load system, which was expected because of the similarity between both control systems. As mentioned already, the radiator system controls, which are immediately connected to the thermostat, and the thermally tight Class A building result in a greater impact on the comfort index from the thermostatic use (Figure 2.18). The results are given for the living room below; the results for the bedroom are similar.

The results for the Class F dwelling are also in accordance with the findings of the ideal loads system. Figure 2.19 shows that metabolic rate and clothing are the most influential parameters for comfort. The thermostat in the cold month of January has no impact on comfort at all in the living room and bedrooms. Small adjustments in the thermostat do not increase the comfort of the occupants due to the bad insulation of the building, results in cold walls. In October and April on the other hand, due to higher ambient temperatures, small adjustments on the thermostat do affect comfort.

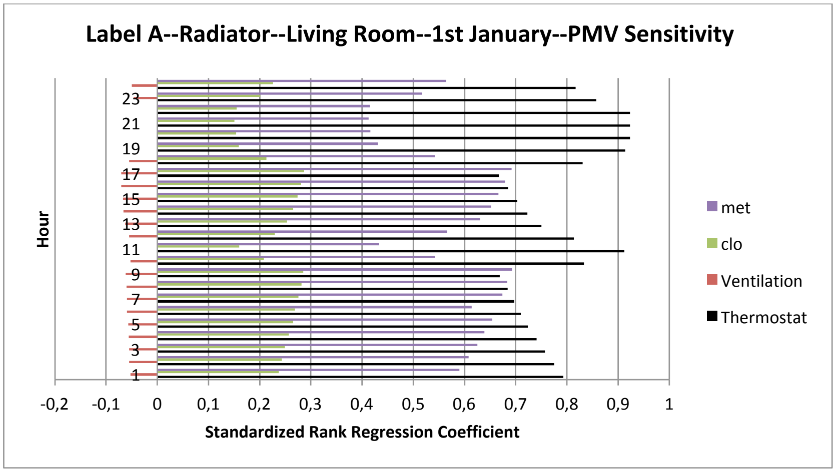

FIGURE 2.18 Label A--Radiator--Living Room--PMV sensitivity for January

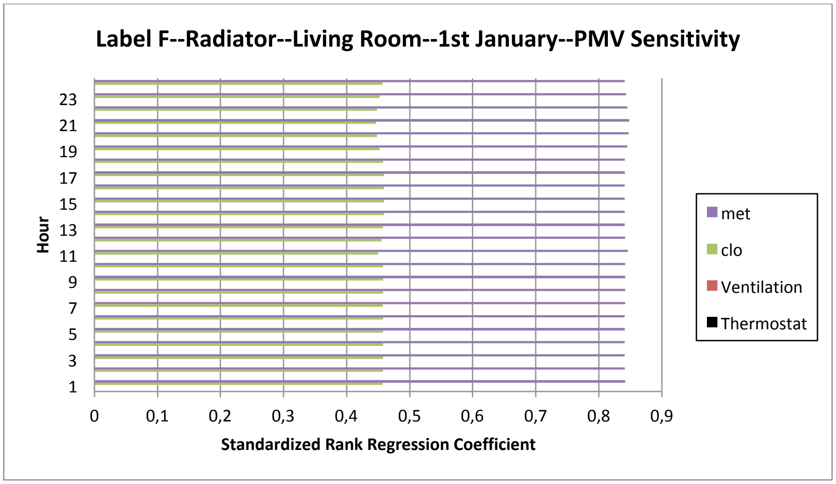

FIGURE 2.19 Label F--Radiator--Living Room--PMV sensitivity for January

§ 2.3.2.4 Floor heating system

The results of the sensitivity analyses for the floor heating system were the most straightforward. The thermostat, due to the way in which the system is controlled from the simulation software (see section 2.7), does not influence the comfort index at all. Moreover, the low temperature hydronic system coupled with heat pump performs at its best when in continuous operation in a pre-set temperature. The thermal lag of such a system is big and especially with thicker better insulated floor [49,53,54]. In that sense, small variations of thermostat will not affect comfort immediately as in other heating systems. The notion of turning the thermostat a bit higher and get immediately or after a few minutes extra heat in the space is not applicable in the low temperature hydronic floor with heat pump. That is why hydronic systems are set in a fixed mode to ensure that thermal conditions in the space are as uniform as possible.

The most influential parameter is always metabolic rate, while SRRC is always higher than 0.8, followed by clothing for both the Class A and Class F reference buildings. Figures 2.20 and 2.21 show the results for the Class A and Class F reference buildings for the month of January in the living room. The results for the bedroom are similar.

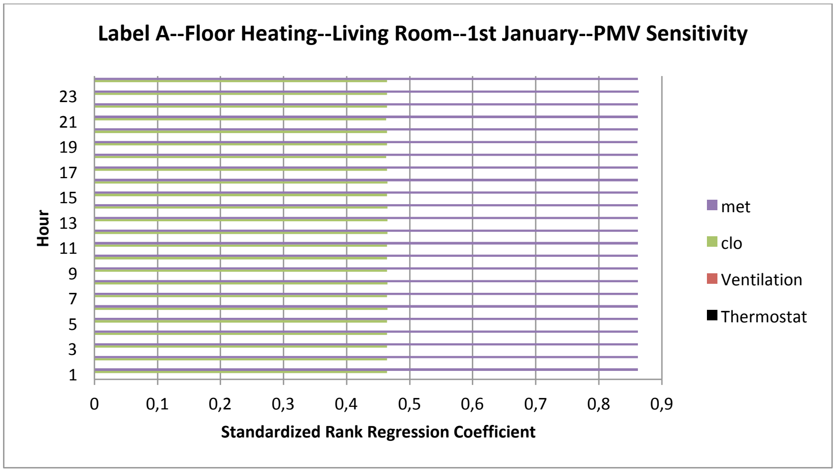

FIGURE 2.20 Label A--Floor Heating--Living Room--PMV sensitivity for January

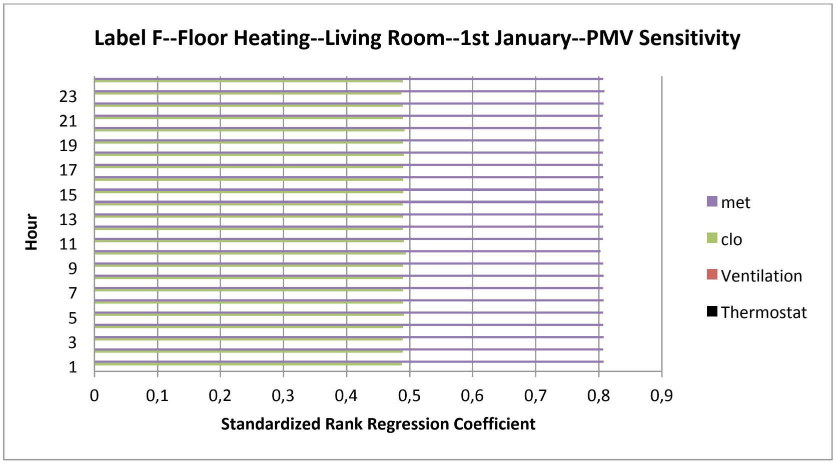

FIGURE 2.21 Label F--Floor Heating--Living Room--PMV sensitivity for January

§ 2.4 Conclusions and discussion

§ 2.4.1 Most critical parameters that affect energy use in residential dwellings for heating according to whole building simulation software.

When the behavioral parameters were not taken into account, the most critical parameters (defined as those that have the highest standardized rank regression coefficient) were the window U-value, window g value and wall conductivity in the Class A building. These three parameters were the most critical in the single zone-ideal loads model as well as the multi-zone models for both radiator and floor heating systems. The order of importance of these parameters varies between the different configurations but these three are always the most important.

In the Class F building, the results were less clear: two parameters (window g value and wall conductivity) were found to be the most important for the single zone-ideal loads and the multi-zone radiator systems. The third most important parameter was the orientation of the building, instead of the window U-value. For the floor heating system, the most critical parameters were wall conductivity, floor conductivity and window g value, which can be explained by the importance of the heat flux through the floor in floor heating systems.

It was also found that the relative importance of the wall conductivity for heating consumption increases when the standard deviation of all the parameters that was carried out in the sensitivity analysis was set to 30% instead of 10%. This may indicate that the more inaccurate the information on parameters there is during building simulations, the more important it becomes to determine the conductivity of walls accurately. A larger standard deviation around the mean of the parameters that were assessed in the sensitivity analysis for the Class F concept house (without behavioral parameters) resulted in wall conductivity being by far the most influential parameter for all three heating systems. A larger degree of deviation around the mean of a parameter can recreate the lack of information that we might have for various components of a building. Especially in older houses in the lower energy classes because they were built forty or fifty years ago, this problem is very common. The information on the U values of the building's thermal envelope are usually limited, and as the sensitivity analysis reveals, these U values are the most crucial factor in accurately calculating the energy consumption of the building. The analysis including the behavioral parameters that was performed with larger standard deviations showed also an increase in the influence of the parameters that are related to the conductivity of the building's thermal envelope.

Another finding was the non-negligible effect that the orientation had on heating. However the orientation of the reference building (the direction of the façade with the largest glass surface area) is north/north-east, which is far from the optimum (for heating), which is a south facing orientation. So any positive deviation from the orientation (which in this case means that the building faces more south) resulted in a decrease in heating consumption.

The most important result is the predominance of behavioral parameters in the sensitivity analysis. When these parameters are introduced, in particular, thermostat setting and ventilation flow rate, they reduce the explanatory power of the physical parameters considerably.

Another important finding is the importance of how the heating system is controlled. If the control related to the thermostat setting in a straightforward way, as in the case of the boiler coupled with radiators, then the thermostat settings have major explanatory power. On the other hand, if the control system tends to ensure a constant temperature throughout the whole day all over the house, which is generally the case with a heat pump system coupled with floor heating, the influence of the thermostat is nil.

§ 2.4.2 Most critical parameters that influence the PMV comfort index.

The most important parameter in determining the PMV during the heating season was, by a long way, metabolic rate (meaning the occupants' level of activity), followed by clothing (clo values). Small variations in the metabolic rate (10% around 100 met, which corresponds to standing relaxed) can explain a very large proportion (up to 95%) of the variance in PMV.

In addition to the metabolic rate, the thermostat setting and clothing were found to be important to a relatively similar extent. However, it is noticeable that the thermostat settings were almost insignificant in the Class F building, which can be explained by the small variations, which could not compensate for the cold walls. For the same reasons as before, the thermostat has no influence on the PMV for the floor heating system.

It was also shown that, according to the simulation results on the PMV index, the reference building was too cold during the heating season, even the well-insulated Class A dwelling. This poses a question about the validity of the PMV index, since the air temperature was 20 °C, a temperature that is generally accepted as being comfortable in the Netherlands. Even at this temperature, the PMV index did not exceed the threshold of -0.5 at all (the comfort zone according to the PMV theory is between -0.5 and +0.5), but was constantly below -1.

§ 2.4.3 Parameters that influence both heating and PMV

Obviously, the thermostat settings push both energy consumption and PMV upwards, except for the low temperature hydronic floor heating system, for which the thermostat settings are offset by the control systems and the fact that the response time in such a system could be very long. A critical aspect of predicting the energy consumption of a dwelling is the behavior of the tenants, about which we have limited information. The parameter that influences heating the most is the use of the thermostat, which at the same time plays a minor role in the thermal comfort of the occupants. People may be trying to regulate their comfort by adjusting the thermostat, which could result only in an increase in heating consumption but will not produce an increase in the occupants' comfort levels.

However, the above conclusions may be case dependent, there are various heating systems installed in the residential sector and in this paper, only three of them were assessed. Furthermore, specific assumptions were made for the simulation of these three systems, which have an impact on the results.

§ 2.4.4 Sensitivity of dwellings with different physical quality and different energy classes

There are indeed differences between the sensitivity analysis of the Class A and Class F buildings. The former were highly sensitivity to the window U-value, whereas in Class F dwelling this was not a very influential factor. Furthermore, in the Class F building, wall conductivity gains importance, and for both types of building thermostat and ventilation remain the most important.

§ 2.4.5 Interpreting the results and reflecting on the modelling techniques used (simple versus detailed models)

The results for a single zone/ideal loads and multi-zone/radiator are quite similar. This is because the control system used in both systems is similar. Modelling the building as multi-zone or single zone does not seem to produce large variations (see also Figure 2.4). Despite fact that no Energy+ Airflow network was used in order to simulate the air exchange between zones, the two extremes cases that were used (Single Zone and Multi Zone with fixed ventilation rates according to the Dutch standard) didn't reveal great differences between them. Every other configuration with air exchange between zones would fall between these two extreme cases. Moreover, this may be because the unheated zone in the multi-zone model is very small (15%) compared to the total heated surface. However, when it comes to the floor heating system coupled with the heat pump, the results are quite different. It seems that simply modelling the heat pump with the use of COP values that are multiplied by the heating demand (as is done with the EPA modelling or when making simple calculations) will lead to an underestimation of the heat consumption in F-dwellings, even if this is corrected for the number of operational hours. On the other hand, in A-dwellings this is does not produce any problems.

A second point is the importance of the thermostatic control loop. Predicting heating energy consumption for existing dwellings or buildings that are in the design phase can stray somewhat from reality. The reasons for this include a lack of information for specific components of the building like the U values of walls and floors, or the exact way that a heating system, such as a heat pump, is simulated and controlled by the simulation software. A heat pump loop is a complex system and a lack of specific information concerning its operation and control can lead to rather misleading predictions concerning the energy consumption of a dwelling.

The third point concerns orientation: we generally define orientation by approximating to the nearest of the eight primary compass points, e.g. south, south-west, south-east etc. According to the results of this study, such an 8-point approximation may lack precision because even small differences in the orientation of a building (14.5°) can affect annual heating consumption.

§ 2.4.6 Recommendations

As already mentioned, conclusions presented in this paper may be case dependent, due to the variety of heating systems installed in the residential sector, the specific modelling assumptions that were made for the simulation of the three systems that were chosen for this study and inputs like the standard deviation of the parameters. All these have an impact on the results. Further research could add valuable information in the present study.

Based on the findings of the present study, it is very important to know (or be able to measure) the exact U-values of walls, assuming determining the U-values and g values for windows is not a problem. This problem was also pointed out by Majcen (2013) after using a completely different approach. Given the fact that most of the time it is very difficult to find information on the building characteristics of older dwellings, a new method has to be developed for the fast and reliable in situ determination of the U-values for walls, floors, roofs or other building surfaces.

A further step in improving the reliability of the results of whole building simulation software is to integrate variance into the simulation results. Since the thermostat and ventilation have a very high impact but at the same time cannot be determined precisely, energy consumption should be shown as bandwidth, particularly for design purposes. Furthermore, in simulations for energy labelling the average heating set-point temperature of the whole building stock should be used. This average heating set-point temperature should be determined by a measuring campaign with sensors across all the classes of the building stock.

Future research should address the influence of various simulation models and assumptions on the results. The reference building should be modelled as a multi-zone with the Energy+ Airflow Network module, which simulates the air exchange between zones, and the results should be compared with the ones presented in this paper.

Another important issue that has to be studied is the effect of air speed on the PMV. A CFD model of the reference building has to be created and hourly air speed profiles have to be obtained which will later be loaded to Energy+. This will enable the inclusion of air speed in the parameters of the sensitivity analysis for the PMV.

In addition, despite the fact that existing literature suggests 5% and 10% standard deviations for most of the parameters assessed in this paper, a detailed study should be performed with a range of standard deviations for specific parameters and simulation models. Moreover, apart from average heating set-point temperature the variations should be measured too in order to facilitate information on general variance.

Finally the effects of the blinds on the heating and PMV, should be studied in modes other than on/off.

In this paper, we assumed that the schedule of occupancy was fixed and only the number of people present in the dwelling (total amount of heat emitted to the space by human presence) was varied. However, we know (Guerra Santin, 2010) that the hours of occupancy in the dwelling are also very important for the energy consumption, especially if people are heating their homes during these hours. Extra heating hours in a dwelling would significantly alter the results and for that, detailed profiles for the Dutch residential building sector should be determined by using empirical data on occupants' behavior relating to energy use, obtained by a measuring campaign.

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3 In-situ and real time measurements of thermal comfort and its determinants in thirty residential dwellings in the Netherlands.[2]

Abstract

Reducing energy consumption in the residential sector is an imperative EU goal until 2020. An important boundary condition in buildings is that energy savings should not be achieved at the expense of thermal comfort. However, there is little known about comfort perception in residential buildings and its relation to the PMV theory. In this research, an in-situ method for real time measurements of the quantitative and subjective parameters that affect thermal comfort as well as the reported thermal comfort perception was developed and applied in 30 residential dwellings in the Netherlands. Quantitative data (air temperature, relative humidity, presence) have been wirelessly gathered with 5 minutes interval for 6 months. The thermal sensation was gathered wirelessly as well, using a battery powered comfort dial. Other subjective data (metabolic activity, clothing, actions related to thermal comfort) were collected twice a day using a diary. The data analysis showed that while the neutral temperatures are well predicted by the PMV method, the cold and warm sensations are not. It seems that people reported (on a statistically significant way) comfortable sensation while the PMV method does not predict it, indicating a certain level of psychological adaptation to expectations. Additionally it was found that, although clothing and metabolic activities were similar among tenants of houses with different thermal quality, the neutral temperature was different: in houses with a good energy rating, the neutral temperature was higher than in houses with a poor rating.

Keywords

in-situ measurement, PMV, thermal comfort, clothing, metabolic activity, thermal sensation, occupancy behavior, energy consumption, residential dwellings, wireless monitoring

§ 3.1 Introduction

The built environment is responsible for about 40% of total energy use in Europe. Of this 40%, 63% is related to residential energy consumption [1]. European and national regulations like the Energy Performance of Buildings Directive EPBD and specific parts

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of national building codes aim to reducing the energy consumption of buildings in order to achieve the goals set for emissions and resource consumption by 2020.

The prediction and assessment of the energy consumption of residential dwellings is an important means to this end. Building performance simulation is a widely accepted method for this purpose. Buildings are highly complex systems in their own right. Both new buildings and renovated ones that are equipped with new heating and ventilation systems have high performance requirements that are closely related to EU sustainability goals for 2020. Increasing the reliability of building performance simulations can make an important contribution to reduction of the energy consumption of residential building stock.

The need for increased reliability of building simulations is also closely related to the discrepancy between actual and predicted energy use in the residential building sector. Researchers in the Netherlands and elsewhere have found a substantial gap between actual and predicted energy use in residential dwellings, with the worst dwellings (those with an energy rating of F or G) consuming significantly less energy than expected while dwellings with a higher energy rating consume more [2]. One reason for this discrepancy could be limited information on the building's thermal envelope and installations (more obvious in older dwellings where no records are available on the materials used). Another important reason is related to a misunderstanding or underestimation of the role of the occupant's behavior [3,4,5]. Simulation software in its current form has very limited capabilities for taking the energy-related behavior of the occupant into account. There is a clear need to take this behavior into account during the design phase of new residential buildings or the renovation phase of older ones [3,4,6,7].

An important requirement both for new dwellings and for the refurbishment of older ones is that thermal comfort should be maintained or improved. Many commercially available simulation packages for the calculation of the energy consumption of buildings such as ESP-r, TRNSYS and Energy+ use the ISO 7730 method [8] for the assessment of occupants' thermal comfort. This seems to work well for office buildings, but not for residential buildings [9]. The ISO 7730 method, developed by P.O. Fanger, predicts perceived thermal comfort as a function of metabolic activity, clothing level and the four classical environmental parameters air temperature, mean radiant temperature, air velocity and humidity. Although Fanger's formulations were based on a sound physical model, the general validity of the statistically derived parameters is doubtful [9]. The thermal responses of occupants of residential and office buildings recorded in various countries differ from the predicted values [10,11,12,13,14,15] though Humphreys showed, in a world-wide data set of 16,762 cases with various settings, that the perceived thermal comfort agreed quite well with the model's predictions [15]. This means that it is very difficult to draw general conclusions for specific local settings, despite the model's strong physical basis.

Residential dwellings, unlike office buildings, include zones with variable thermal comfort requirements, are characterized by less predictable activities. Therefore, provide more ways for the tenant to adapt to his thermal environment in order to reach the desired comfort level [16]. These conditions in these residential settings differ greatly from those applying in the climate chamber Fanger used to develop the PMV thermal comfort index.

Temperature levels and profiles in dwellings are expected to have an important effect on the energy consumption for heating and tenants' thermal comfort [17,18,19]. Furthermore, the operative temperature is a critical component of the PMV comfort index.

Various studies have derived indoor temperature profiles for the residential built environment but they differ in the methods used, the length of the monitoring period and the season when measurements were made. In many cases, temperature sensors with data recording intervals of 15, 30, 45 or 60 minutes were used [20,21,22,23,24,25,26,27,28,29,30]. The duration of the measurement campaign in some studies varied from 1 to 4 weeks [25,31], while in others it covered the whole heating period (December to April in a northern European country, Belgium) [31]. A study in one southern Mediterranean country (Greece) [24] also covered the whole heating period –one that is much shorter than northern European countries like the Netherlands or Belgium. In another study, the tenants were given the temperature sensor together with the operating manual and were invited to install it themselves [26], which could lower the accuracy of the measured data. In all these studies, the data were collected locally in data loggers and had to be retrieved manually. Other studies used questionnaires or diaries for recording the temperatures where the tenants had to fill in the required information [32,33]. This probably led to large uncertainties, as no measurements were performed.

The aim of the present paper is to provide information on a kit for in-situ real-time measurement of the quantitative and subjective parameters that affect thermal comfort on the reported tenant's thermal sensation and finally to present the resulting analysis of energy-related occupant behavior (in particular the parameters that affect the PMV comfort index). This is important because thermal comfort may affect largely occupant behavior, which relates to energy consumption and which in turn is an important factor for the discrepancy between actual and theoretical energy consumption in the residential dwellings.

The results presented here are taken from the Ecommon (Energy and Comfort Monitoring) campaign, which took place in the Netherlands as part of the Monicair [34], SusLab [35], and Installaties2020 [36] projects. Thirty-two residential dwellings (classified by energy rating and types of heating and ventilation system) were monitored for a 6-month period, from October 2014 to April 2015, which is the heating season for north Western Europe. Quantitative data (air temperature, relative humidity, CO_2 level and movement) for each room in the dwellings (living room, kitchen, bedroom 1 and bedroom 2 or study) were collected wirelessly at 5-minute intervals. In addition, subjective data (thermal sensation, metabolic activity, clothing, actions during the previous half hour related to thermal comfort) were collected over a 2-week period by two different methods, wirelessly and by entries in a manual log (see section 2.3.2). The wireless device used to capture the thermal sensation of the tenants was time-coupled with the sensors for the quantitative data. This allowed the thermal sensation of the tenants at any given time to be time-coupled with the exact atmospheric conditions (temperature T, relative humidity RH and CO2 level), which could improve the reliability of the PMV calculations (see section 2.3.1). All data (quantitative and subjective) were available for inspection and analysis in real time throughout the whole campaign via a remote desktop application.

The next chapter describes the research questions, the design of this study, the way the campaign was set up, the data acquisition equipment and the data management system. The results follow in chapter 3, which first presents the neutral operative temperatures, per room type, derived from the PMV calculations and the recorded thermal sensation of the tenants. Furthermore, the relationship between the reported thermal sensation and the calculated PMV is explored to validate further the ability of the PMV index to predict the tenant's real thermal sensation. The next two sections (3.4 and 3.5) describe the clothing and metabolic activity of the tenants during the measurement campaign against the operative temperature and thermal sensation. Further, the clo and met values that correspond to the neutral thermal sensation of the tenants were calculated and the effect of the inaccuracy of these values was researched. Finally, a section with discussion, conclusions and recommendations conclude the present study.

§ 3.2 Study design

Comfort has seldom been researched on site in actual conditions, and even more rarely has been measured in other ways than using surveys. The main research questions in this paper aim to determine whether it is possible to make such measurements and how the results of these measurements compete with already existing insights from PMV theory.

§ 3.2.1 Research Questions

The goals of this study are:

1. To perform in-situ real-time measurement of quantitative and subjective data on comfort and occupant behavior and their underlying parameters in an easy, unobtrusive way, in a residential environment.
2. To determine the tenants' temperature perception in relation to the energy rating and the ventilation and heating systems used in the dwellings.
3. To determine the type of clothing worn by the tenants and their activity levels in relation to the thermal sensation of the occupants.
4. To determine the neutral temperature levels calculated by the PMV method and to compare them to the neutral temperatures derived from the measurements thermal sensation.
5. To determine to what extent the PMV comfort index agrees with the thermal sensation reported by the tenants.
6. To determine if there is a relationship between the type of clothing and metabolic activity with thermal sensation and the indoor operative temperature.

§ 3.2.2 Ecommon campaign set-up

The original design of the study was to have stratified random sampling. The dwellings were grouped according to the various heating systems, to their energy label and their ventilation system. However, for practical reasons we deviated from that. Furthermore, this is why we do not claim universality in our results but we instead show the methods that can be applied in order to measure in situ the subjective and quantitative parameters of the PMV.

The sample used in the Ecommon monitoring campaign was restricted to social housing, in order to match the present study with a previous one in which most data were collected for social housing[37]. 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 [2,38,39]. Furthermore, housing associations have the energy rating of all their housing stock determined, which is not the case with all 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 [2,37] had shown that there are few dwellings in the Netherlands with a G energy rating.

The method used to calculate the energy rating is described in Dutch building code ISSO 82.3 [40]. The energy survey used as a basis for the energy performance certificate (EPC) 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 them to participate in the study and the response rate was 8.6%. Surveys that are intended for external audiences usually have a return rate of 5-10%. Considering the long length of the measurement campaign, the amount of equipment that had to be placed in each dwelling, the frequent intrusion of TU Delft personnel into the tenants' privacy (installing the equipment, handing over and retrieving the comfort dial, calling tenants to restart the data gathering mini pc, retrieving the equipment), and finally the fact that the data gathered could compromise the tenants' privacy and potentially their security (tenants were notified for all these issues in the initial letter they received), the return rate of 8.6% is considered very successful. Furthermore, compensation was offered to the participants for the electricity costs of the equipment for the period of the six months, two gift cards of 20 euros each was offered to them and the feedback we received for this present was very positive.

TABLE 3.1 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

>>>

TABLE 3.1 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

A careful selection had to be made from among the households willing to participate in order to maximize the amount of data that could be collected. We used the SHAERE database developed by Aedes [41], the federation of Dutch housing associations, to select respondents based on their energy rating and heating system. A total of 58 dwellings were selected. Finally, due to limitations in the monitoring equipment used, 32 dwellings were monitored over a 6-month period, from October 2014 to April 2015. The final sample may be seen in Table 3.1. 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 efficient 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). Dwellings 9 and 30 have been excluded from the analysis due to unavailability of data. Technical reasons related to the wireless transmission of the temperature, humidity and CO_2, resulted in complete loss of data for these two dwellings. Details of the ventilation systems of the various dwellings are also given in Table 3.1.

§ 3.2.3 Data acquisition and equipment

§ 3.2.3.1 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 CO_2 data were not required for the scope of the present paper, and therefore, not reported. 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 3.2. 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 3.1 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 % and CO_2 levels in ppm (parts per million). The temperature sensor is fully compliant with the ISO 7726 standard for type C, measurements carried out in moderate environments approaching comfort conditions (comfort standard) specifications and methods. The humidity data were displayed as relative humidity (%) which was derived by the voltage output of these capacitive sensors and in terms of accuracy complies fully with the ISO 7726 [56].

TABLE 3.2 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 3.1 T, CO2, RH box (a) and movement sensor (b) as used during the Ecommon measurement campaign

The PIR sensor data were in binary form (0 and 1), 0 means that no movement was detected during the 5-minute interval in question while 1 means that movement was detected at least once during the interval. The PIR sensor had 11m x 12mm detection range, which was enough for all the rooms they were installed in. They had selectable pet immunity (0.18-36 kg) a patented look down mirror in order to detect movement exactly below the sensor, front and rear tampers and operative temperature range between -10 °C and 55 °C. The battery life was 4.5 years, which was exceeding by far the period of this project and was ensuring that the data would be safely stored in case of wireless transmission problems. Finally, they were compliant with the NEN standard for alarm systems [55].

§ 3.2.3.2 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) [35] This wireless device, called "comfort dial" (Figure 3.2), 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).

FIGURE 3.2 Comfort Dial used to capture perceived comfort levels of tenants during the Ecommon measurement campaign

The comfort dial is portable and relatively small and therefore tenants could carry it with them anywhere in the dwelling. That is why the data of the comfort dial had to be coupled to the PIR sensor data in order to determine the location of the tenant that particular moment.

Tenants also received a paper logbook, shown in Figure 3.3. 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 3.3 and Table 3.4.
- 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 and comfort logbook for a 2-week period in March and early April 2015. The logbook was given to them in 45 copies, 3 per day for the period of the two weeks that the tenants had to use the comfort dial. They had been instructed to use it at least 3 times per day (it was equipped with a time line, see Figure 3.3) together with the comfort dial. The comfort dial on the other hand could be used as often as they wanted throughout the whole day.

The data from the comfort dial were wirelessly and in real time recorded to our database while the data from the comfort logbook as well as the equipment (comfort dial) were retrieved in the end of the 2 weeks period. In that way we managed to obtain thermal sensation data (comfort dial), subjective data related to the PMV (clothing and metabolic activity), and quantitative data related to the PMV (temperature and humidity) all universally time stamped. This enabled us to make calculations on the PMV with precision of 5 minutes, which was the interval of the sensor quantitative data.

The main respondent (only one person per household was asked to use the comfort dial and log book) 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.

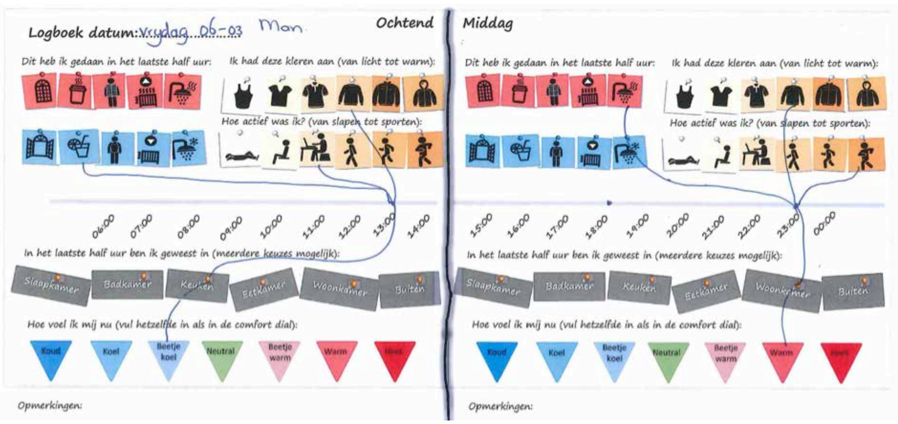

FIGURE 3.3 Paper logbook for entry of subjective data

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.

§ 3.2.3.3 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.

§ 3.2.3.4 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. The questionnaire was taken from an existing template that has been used in past projects, with different scopes, prior to Ecommon [57].

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

§ 3.3 Results

§ 3.3.1 Perceived dwelling temperature in relation to the energy rating and ventilation system

This section presents the results of this study starting with the tenant's overall perception of the dwelling temperature. The following part (3.2.3) presents the calculation of the neutral operative temperature, per room type and energy rating, according to the calculated PMV and the thermal sensation recorded by the tenants. In the two sections that follow (3.4 and 3.5) the clo and met values are displayed, for the living room, versus the recorded thermal sensation of the tenants and the operative temperature. Subsequently, a statistical analysis follows in order to determine the extent of possible bias in the calculations from potential mistakes in the gathering of the clo and met data.

Figure 3.4 shows the answers to the question ''How do you feel about the temperature of the dwelling during the winter?'' as a function of the energy rating of the dwelling and the type of ventilation system used. It will be seen that the proportion of occupants who regard the dwelling as being too cold increases as we move from energy-efficient class A dwellings to class F dwellings, which have a poor energy performance. This finding is in agreement with the results reported by Majcen et al. [38], and is probably related to the insulation level and air-tightness of the dwellings.

The tenants of dwellings with balanced ventilation had the highest percentage (85.7%) of responses in dictating that the indoor temperature during the winter was all right. It should be noted that all these dwellings had energy rating A or B. In that sense, these results could be expected and relate more to the energy rating than to the ventilation system.

As may be seen from Table 3.1, some dwellings with mechanical exhaust ventilation had energy rating A/B, while others were F-rated. Figure 3.4 shows that the proportion of ''too cold'' responses increases from A/B-rated dwellings to F-rated ones. Occupants of dwellings with completely natural ventilation were less likely to find the indoor temperature acceptable (55.6%). All dwellings with natural ventilation had energy rating F. It is noteworthy that this group included three dwellings with an old gas stove. The occupants of all three stated that they found the indoor temperature to be acceptable.

It might be expected that temperature perception during the winter is more closely related to the energy rating than to the type of ventilation. This was not however found to be the case in all dwellings with natural ventilation and mechanical exhaust. Some occupants of energy-efficient dwellings in this category stated that they felt too cold in the winter, while some occupants of less energy-efficient dwellings were satisfied with the indoor temperature. Further investigation of the actual energy consumption in these dwellings is required to determine whether these responses are related to excessive energy use in dwellings with low energy efficiency or very low consumption in the more energy-efficient dwellings.

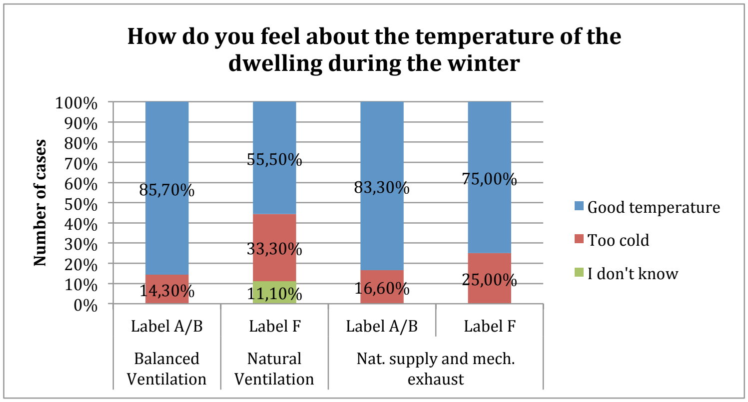

FIGURE 3.4 Temperature perception in the winter per energy rating

§ 3.3.2 Neutral temperatures in relation to PMV and reported thermal sensation

Fanger's method [14, 42] for calculation of the predicted mean vote (PMV) is used worldwide to estimate the thermal comfort levels than can be achieved under various hydro-thermal conditions. This method uses the following parameters: air temperature (T_{air}), mean radiant temperature (T_{mrt}), air velocity (v), relative humidity (RH) and two parameters related to the thermal resistance of occupants' clothing [clo] and their metabolic activity [met]. During the present study, data for most of the above-mentioned parameters were collected with the aid of the sensors, the comfort dial and the logbook. The parameters for which no direct data had been gathered were the mean radiant temperature T_{mrt} and the air speed; the latter in particular is a very difficult parameter to record since it has a very strong topical effect and its value may vary significantly from place to place in a given room. Energy Plus simulations as described below were performed in order to estimate $T_{mrt,}$ sensitivity analysis for T_{mrt} and air velocity has been included in all further analyses in this paper.

§ 3.3.2.1 Estimation of mean radiant temperature (T_{mrt}), indoor air speed, clo values and metabolic activity rates

A reference dwelling, with a surface area of 75 m^2 divided in two zones (living room and bedroom), was simulated using the weather data for The Hague, the Netherlands, for the whole month of March 2015. This month, tenants were provided with comfort dials in order to record their thermal sensations, clothing values, actions aimed at modifying thermal sensation, and metabolic activity. The size and characteristics of the reference dwelling were similar to the types of dwellings that were found in the sample of the Ecommon campaign. The dwelling was simulated in Energy Plus in 3 different ways. As an A-rated dwelling with a condensing gas boiler for the heat generation and radiators for heat distribution in the rooms, as an A rated dwelling with a water-to-water heat pump, a ground heat exchanger, and ground floor heating, and finally as an F-rated dwelling with condensing boiler and radiators. These three configurations cover all the dwellings used in the Ecommon measurement campaign.

Occupancy schedules, commonly available in simulation software libraries and adjusted to Dutch habits, were used for the simulations of the living room (presence early in the morning, and from 5 pm until midnight) and bedroom (presence/sleeping during the night hours). The number of people occupying the reference dwelling was set to 2 and the thermostat settings were 18 °C during daytime occupancy and 12 °C at night. The thermal transmittance (U) values used for A-rated dwellings were 0.251 W/m^2-K for the external walls, 0.346 W/m^2-K for the roof and 0.232 W/m^2-K for the ground floor. The corresponding values for F-rated dwellings (which were very poorly insulated) were 2.071 W/m^2-K for the external walls, 1.54 W/m^2-K for the roof and 3.11 W/m^2-K for the ground floor. Glazing for both configurations was set to standard double-glazing with 6 mm glass thickness and 13 mm air filling with a U value of 2.7 W/m^2-K set in wooden window frames with a U value of 3.3 W/m^2-K.

The reason why the same double-glazing was used for both A-rated and F-rated dwellings is that our inspection revealed that all F-rated dwellings had had their outside glazing upgraded to double. Similarly, all the simulations made use of the same condensing boiler (variable flow, nominal thermal efficiency 0.89, maximum loop temperature 100 °C) and radiators with a constant water temperature of 80 °C, since nearly all the F-rated dwellings had had new condensing boilers installed. In both cases, the infiltration was set to 0.5 air changes per hour while the ac/h due to window natural ventilation was set to 3. The windows covered 30% of the wall and the lighting gains were set to 5W/m^2-per 100 lux.

Table 3.3 presents the averages of the hourly simulation results for March 2015, the month when tenants used the comfort dials to record comfort-related data. It will be seen that the difference between the radiant and air temperatures in A-rated dwellings with a boiler was only about 0.3 °C, appreciably less than the respective standard deviations. It was therefore decided that the radiant temperature for these dwellings could be set equal to the air temperature recorded by the sensors.

Table 3.3 further showed that the difference between the average radiant and air temperatures in F-rated dwellings with condensing boilers was about 4 °C. Finally, the simulated radiant temperature for A-rated dwellings with heat pumps and under floor heating was about 1.2 °C higher than the air temperature, due to the radiant heating effect of the hydronic floor heating system. The instantaneous value of T_{mrt} for these dwellings was therefore calculated as T_{air} – 4 °C and T_{air} + 1.2 °C respectively. Thus, the Energy Plus simulations made it possible to estimate the radiant temperature based on the sensor readings of air temperature.

TABLE 3.3 EnergyPlus simulation results for March 2015, hourly average indoor air, radiant and operative temperatures

	A-RATED--BOILER		F-RATED--BOILER		A-RATED--HEAT PUMP	
	Average	St. dev	Average	St. dev	Average	St. dev
Air Temperature (°C)	20.45	1.05	20.12	0.15	20.98	1.08
Radiant Temperature (°C)	20.09	2.16	16.21	1.48	22.20	1.46
Operative Temperature (°C)	20.27	1.54	18.17	0.77	21.59	1.22

Furthermore, two values of the indoor air speed were chosen for the PMV calculations, a low one of 0.1 m/sec and a higher one of 0.3 m/sec [8, 40].

Table 3.4 presents the values used to calculate the effects of clothing and metabolic activity, taken from the manual of the American Society of Heating, Refrigeration and Air Conditioning Engineers, (ASHRAE) [43]. Tenants were asked to note the clothes they were wearing and the metabolic activities they performed in the logbook at regular intervals. All clothing ensembles include shoes, socks and briefs or panties. The insulating effect of chair (0.15 clo) was neglected.

TABLE 3.4 Range of clothing and metabolic activities available, in connection with entries in the comfort logbook during the Ecommon measurement campaign and the values used to calculate their thermal effects

CLOTHING ENSEMBLE	CLO VALUE	METABOLIC ACTIVITY	MET VALUE
Very light (Sleeveless T-shirt, icon in Fig. 3)	0.5	Lying/sleeping	0.7
Light (Normal T-shirt, icon in Fig. 3)	0.55	Sitting relaxed	1
Normal (Knit sport shirt, icon in Fig. 3)	0.57	Light desk work	1.1
Rather warm (Long-sleeved shirt, icon in Fig. 3)	0.61	Walking	2
Warm (Long-sleeved shirt plus jacket, icon in Fig. 3)	0.91	Jogging	3.8
Very warm (Outdoor clothing, icon Fig. 3)	1.30	Running	4.2

§ 3.3.2.2 PMV and reported thermal sensation as functions of the operative temperature

As mentioned above, tenants were asked to fill in the comfort logbook at least 3 times a day to provide information about their clothing and the metabolic activities they performed. They also had to record how hot or cold they felt at the same time. All this information was time stamped and time coupled with the quantitative data collected by the sensors at 5-minute intervals. This interval is assumed large enough to ensure that the comfort level is not related to prior comfort levels and conditions. An adaption time of approximately 4 minutes when people are submitted to temperature step changes was reported in the studies of Zhang et al. (2004) and Xiuyuan et al. (2014) [44,45], which implies that the comfort sensation may be assumed to have reached a steady state after 4 minutes under the same conditions.

The PMV was calculated for each room in the dwelling for all 5-minute intervals for which a complete set of data was available. Further analysis of the data points (metabolic activity, clothing, actions, quantitative data etc.) was only performed if motion was detected in the room in question at any given time. This selection procedure resulted in a total of 194 data points for the 2-week period in which the tenants were provided with the comfort dial and the log book. The radiant temperature was derived from the EnergyPlus simulations (see section 3.4.1), while, calculations were performed for two air speeds, 0.1 m/sec and 0.3 m/sec. The calculated PMV values and the reported thermal sensation were plotted against the operative temperatures, and regression analysis was used to determine the data trend line.

As most data were available for the living room, Figures 3.5 and 3.6 show the scatter plots of the operative temperature versus the PMV (calculated for an air speed of 0.1 m/sec) and the reported thermal sensation for the living rooms of A/B-rated and

F-rated. The samples used for determination of the PMV and for the reported thermal sensation are of different sizes because more records of quantitative parameters from the sensors were available than records of thermal sensation made with the aid of the comfort dial. Furthermore, the number of cases for "All dwellings" is slightly different from the sum of cases for A/B and F dwellings. This is because in the regressions for the different rooms and energy labels, different outliers had to be excluded each time and because for the A/B dwellings kitchen and living room data were put together in the same regression.

Regression analysis showed significant correlation between the operative temperature and the PMV or reported thermal sensation (RTS) in both A/B-rated and F-rated dwellings. Significance levels of p=0.01 and p=0.04 respectively were found in A/B-rated dwellings, and p=0.02 and p=0.001 respectively in F-rated dwellings. It may be noted that the kitchen and living room were treated as a single room for the purposes of regression analysis on A/B-rated dwellings, since the kitchen and living room in these dwellings were in one continuous space with no doors or walls separating them. The basic statistical data for all regression lines are given for each room in Tables 3.5 and 3.6.

TABLE 3.5 Basic statistical data for the regressions between operative temperature (OT) and PMV (significant results in blue), and calculated neutral operative temperature (see section 3.2.3)

Room	Neutral OT--all dwellings	p value	Number of cases	R^2	Neutral OT--A/B-rated dwellings	p value	Number of cases	R^2	Neutral OT—F-rated dwellings	p value	Number of cases	R^2
0.1 M/SEC AIR SPEED												
Kitchen	19.47	0.010	34	0.189	23.08	0.025	37	0.149	18.78	0.04	23	0.19
Living Room	21.67	0.003	79	0.105					20.3	0.02	48	0.086
Bedroom 1	–	0.280	32	0.007	23.11	0.005	10	0.655	–	0.88	18	0.001
Bedroom 2	18.61	0.003	21	0.223	–	–	–	–	18.29	0.02	19	0.265
0.3 M/SEC AIR SPEED												
Kitchen	19.61	0.008	32	0.211	23.4	0.038	37	0.117	18.99	0.01	21	0.302
Living Room	21.81	0.020	78	0.068					20.78	0.04	45	0.094
Bedroom 1	–	0.655	26	0.008	–	–	–	–	–	0.68	16	0.003
Bedroom 2	18.77	0.031	21	0.221	–	–	–	–	18.4	0.02	19	0.265

TABLE 3.6 Basic statistical data for the regression between operative temperature (OT) and reported thermal sensation (RTS) (significant results in blue), and calculated neutral operative temperature (see section 3.2.3)

Room	Neutral OT--all dwellings	p value	Number of cases	R2	Neutral OT--A/B dwellings	p value	Number of cases	R2	Neutral OT--F dwellings	p value	Number of cases	R2
Kitchen	19.1	0.040	40	0.106	22.5	0.04	34	0.125	18.2	0.03	27	0.169
Living Room	23.2	0.001	89	0.121					20.4	0.001	57	0.175
Bedroom 1	18.1	0.006	39	0.188	22.5	0.04	10	0.429	16.3	0.01	25	0.136
Bedroom 2	–	0.578	24	0.014	–	0.30	3	0.797	–	0.92	21	0.000

As expected, both PMV and the reported thermal sensation increase when the operative temperature increases. The same trend was observed when the PMV calculation was carried out with an air speed of 0.3 m/sec, both for label A/B-rated and F-rated dwellings. It is noteworthy, however, that the full range of both PMV values and reported thermal sensations (from -4 to +3) is observed in A/B-rated dwellings at temperatures between 20 °C and 26 °C and in F-rated dwellings at temperatures between 14 °C and 24 °C. PMV and reported thermal sensation seem to be closer to each other in the F dwellings than in the A/B dwellings. The R^2 values are low (12.6% and 10.9%), meaning that the operative temperature explains only 12.6 and 10.9 % of the variance in PMV or RTS.

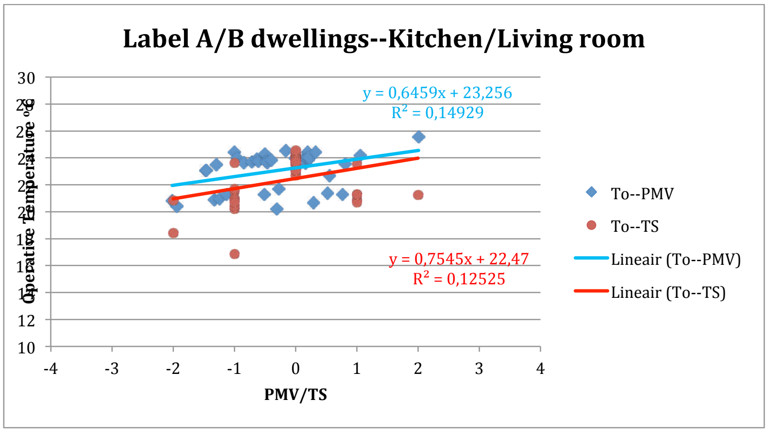

FIGURE 3.5 Operative temperature versus PMV and RTS (reported thermal sensation) scatter plot and regression analysis trend line for the kitchen/living rooms of A/B dwellings at an air speed of 0.1 m/sec

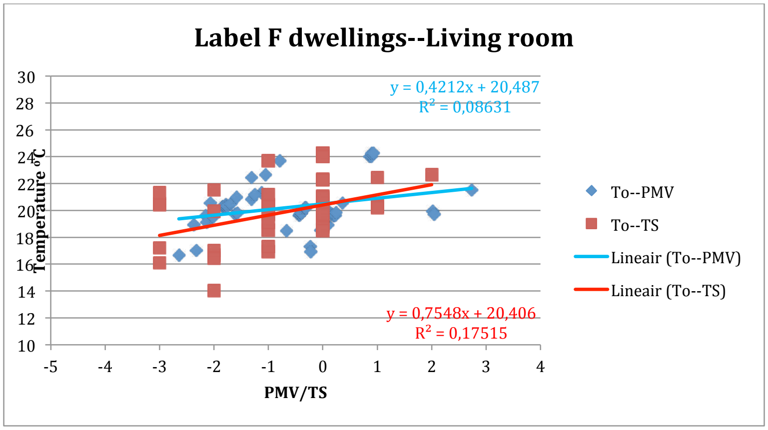

FIGURE 3.6 Operative temperature versus PMV and RTS scatter plot and regression analysis trend line for the living rooms of F dwellings at an air speed of 0.1 m/sec

In order to explore if there are significant differences between the neutral temperatures for the living room between the label A/B and F dwellings an analysis of variance was performed. The operative temperatures (per room type) of the A/B and F dwellings while the tenants' recorded neutral thermal sensation were gathered and an ANOVA was performed. The results were highly significant: for the living rooms p=4.66E-10, F=61.87 and F_{crit}=4.05 while for the bedrooms p=7.22E-06, F=56.25 and F_{crit}=4.74 and they are displayed in Figure 3.7 and show that there are significant differences between the neutral temperatures of the living rooms of A.B and F rated dwellings.

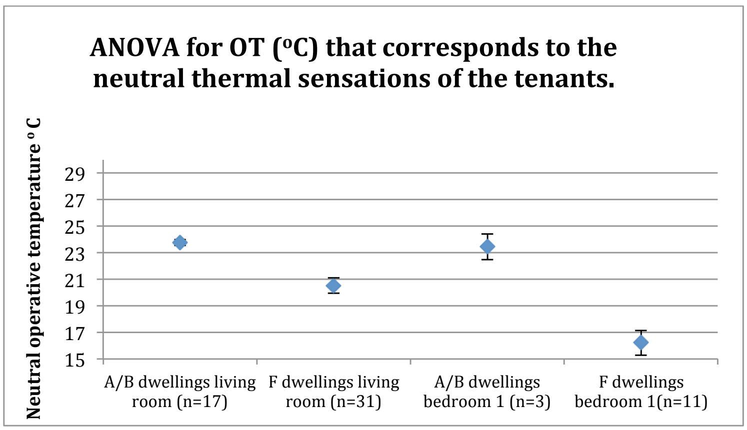

FIGURE 3.7 ANOVA single factor for the operative temperatures that correspond to the neutral thermal sensations of the tenants

§ 3.3.2.3 Neutral operative temperature (T_o) according to PMV and reported thermal sensation

The neutral temperature, the temperature at which occupants feel neither hot nor cold, can be estimated by solving the regression equations of section 3.2.2 for neutral thermal sensation. Solution of the equations in Figures 3.5 and 3.6 for PMV=0 or for RTS=0 thus permits comparison of the neutral operative temperatures based on reported thermal sensation and on PMV index.

Only the significant regression lines (as indicated in Tables 3.5 and 3.6) were taken into account. Two of the regressions, for bedroom 2 in A/B dwellings were found not to be significant, because of, the very small amount of data points (only three) involved in both case.

Figure 3.8 shows the neutral operative temperatures for all room types and energy ratings derived from the calculated PMV and the thermal sensation reported by the tenants. Despite the uncertainties in the parameters needed to calculate the PMV (air speed and operative temperature), which were determined indirectly on the basis of assumptions and simulations, the neutral temperature (T_o) in both A/B and F dwellings is well predicted by the PMV model. In addition, it closely matches the neutral temperatures obtained using the reported thermal sensation of tenants in different rooms of dwellings with different energy ratings. However, when all dwellings are considered together, the neutral temperature is less well predicted by the PMV model, especially for the living room. A/B and F dwellings give noticeably different results here. The average neutral temperature for the kitchen and bedroom 2 calculated for all dwellings is quite similar to that calculated for F dwellings only (the regressions for A/B dwellings were found not to be significant in this case, as explained above). On the other hand, there are marked differences between average neutral temperatures in the kitchen, living room and bedroom of A/B and F dwellings at both air speeds.

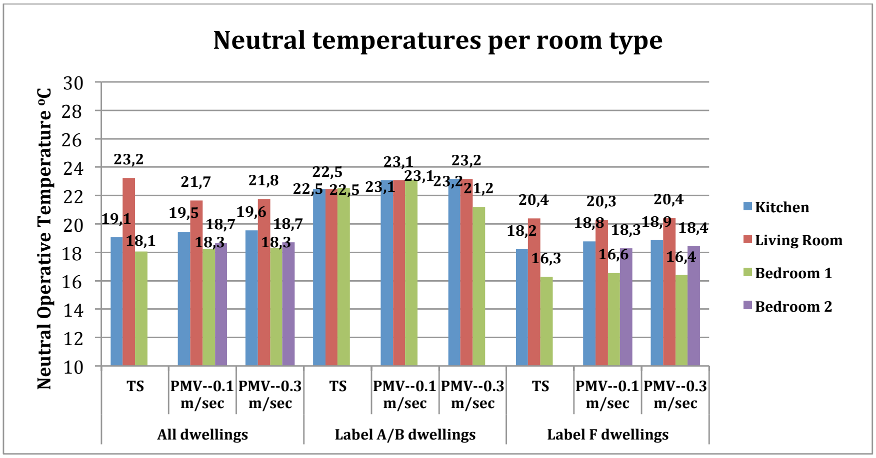

FIGURE 3.8 Neutral operative temperatures calculated from RTS and PMV regressions for all room types and energy ratings

The regression predicts a neutral temperature for the living rooms of A/B dwellings that is about 3 ºC higher than that for the living rooms of F dwellings. The difference is even bigger for bedroom 1, about 4 ºC.

The lower neutral temperatures in F dwellings could indicate that air velocities are lower in these dwellings (this is possible, because the balanced and mechanical ventilation systems used in A/B dwellings are known to give higher air velocities). Other possible explanations are that people in F dwellings may wear warmer clothes or have higher metabolic activity. Finally, this difference could be attributed to different thermal expectations or age or gender differences between the tenants of A/B and F dwellings. The last-mentioned explanation seems unlikely, however, since the average age of the tenants of the A/B and F dwellings is 56 and 57 years respectively, and men and women were equally distributed between the two dwelling types.

§ 3.3.3 Relationship between reported thermal sensation and PMV

To validate further the PMV index and its ability to predict tenants' real thermal sensation, all thermal sensation values collected during the campaign were compared with the calculated values of the PMV. The PMV values for all energy ratings, types of rooms and air speed scenarios were grouped in sub-sets around each integer value of PMV. For example, the sub-set around a PMV of -1 includes all PMV values between -1.5 and -0.5. The reason for this was that tenants were asked to record their thermal sensation on a scale of integer numbers from -3 to +3. The PMV calculations, on the other hand, lead to non-integer numbers. Furthermore, each PMV value between -0.5 and +0.5 is considered to be neutral. Values between -1.5 and -0.5 correspond to a rather cool thermal sensation, and so on. Figure 3.9 show the plots of reported thermal sensation against PMV for all A/B and F dwellings, and for air speeds of 0.1 m/sec and 0.3 m/sec. The line on which RTS equals PMV separates the thermal sensation points that are warmer than the PMV points (above the line) from those that are cooler (below the line). The best-fit lines are shown in red.

The prediction success of the PMV model never exceeds 30%. When the PMV fails to predict the thermal sensation correctly, it usually underestimates it especially at higher air speeds. These findings are in agreement with other studies from various countries [9,46,47] and are similar for each type of room (see Figure 3.10 for a breakdown of the results by room). However, the PMV method never claimed to give accurate predictions on a case-by-case level, but only at a statistical level. The R^2 values given in Figure 3.9 show that only less than 1.7 % of the variations in the reported thermal sensation can be explained by the PMV; it follows, therefore, that the PMV cannot be considered as an accurate predictor of the actual thermal sensation and that other parameters must play a role.

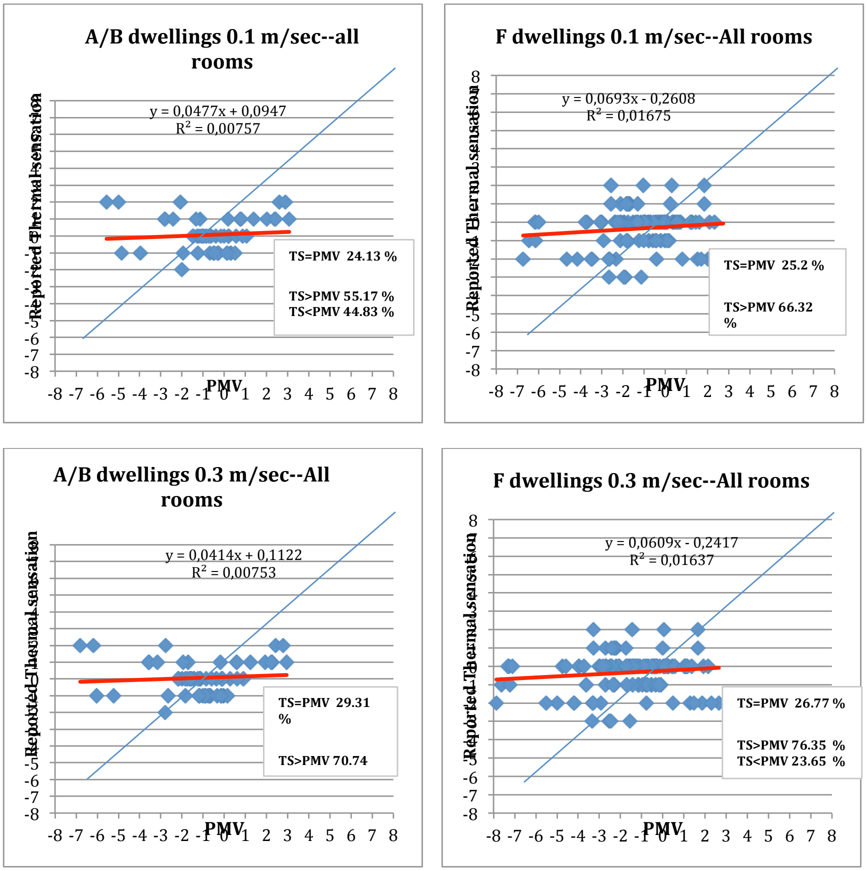

FIGURE 3.9 Plots of reported thermal sensation against PMV for A/B and F dwellings, at air speeds of 0.1 m/sec and 0.3 m/sec (blue line TS=PMV, red line=regression line)

However, the best-fit lines in all four graphs cross the RTS=PMV line around the neutral level, which shows that neutrality is well predicted. Furthermore, the best-fit line for A/B dwellings, is within the comfort band (corresponding to PMV values between -0.5 and +0.5) at all times, while it is somewhat lower in F dwellings. This shows either that the PMV does not perform well outside the climate chamber, or that people adapt to cooler conditions and take action to improve their thermal comfort. Another possibility that the clo and metabolic activity values used in our calculations were not accurate enough, due either to incorrect assumptions (wrong values attributed to subjectively recorded clo values and activity levels from ASHRAE tables), or to inaccurate recording by the tenants. These possibilities are explored in sections 3.6 and 3.7.

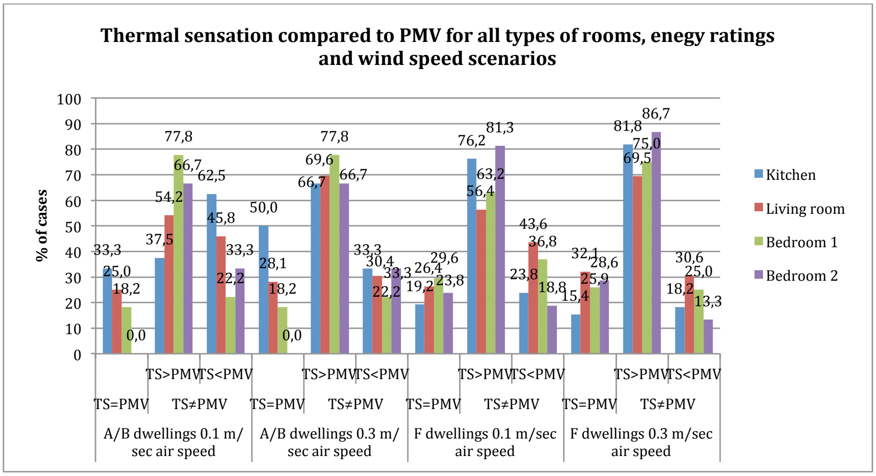

FIGURE 3.10 Thermal sensation compared to PMV for all types of rooms, energy ratings and wind speed scenarios

§ 3.3.4 Clothing and reported thermal sensation

Figure 3.11 shows the clothing types worn by tenants in A/B dwellings for each reported thermal sensation, while Figure 3.12 gives the corresponding results for F dwellings. The different types of clothing are color-coded, while the numbers in each segment represent the number of times the type of clothing in questions is worn (total n=94 for A/B dwellings and n=155 for F dwellings).

These stacked graphs show first that no tenants in A/B dwellings reported feeling “cold” (in agreement with the thermal sensation graphs of Figure 3.10), while 8 tenants in F dwellings made this observation. No tenants from either type of dwelling reported feeling “hot”. The most preferred clothing ensemble for both types of dwellings is the warm ensemble, as defined in, Table 3.4. When tenants feel warmer, they replace the warm ensemble by lighter ensembles. The only instances when tenants report wearing the outdoor warm ensemble were in A/B dwellings, generally when they had just come in from outside and immediately filled in the comfort app/log book. They usually reported feeling rather warm or warm in these cases, probably because of the lower outdoor temperature.

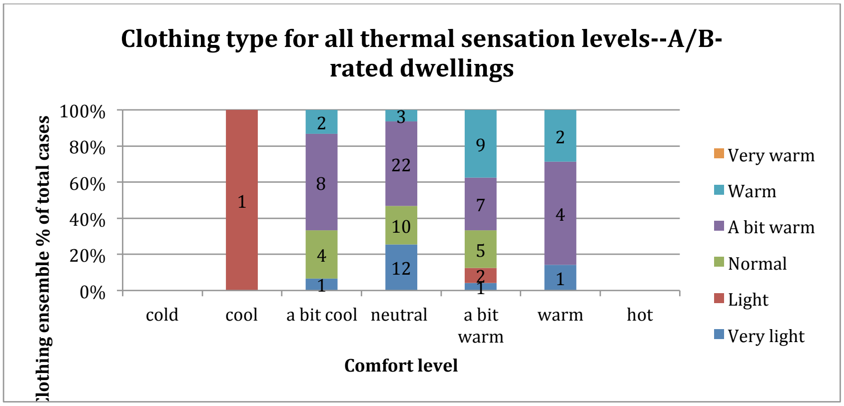

FIGURE 3.11 Clothing types worn at all thermal sensation levels in A and B dwellings (n=94)

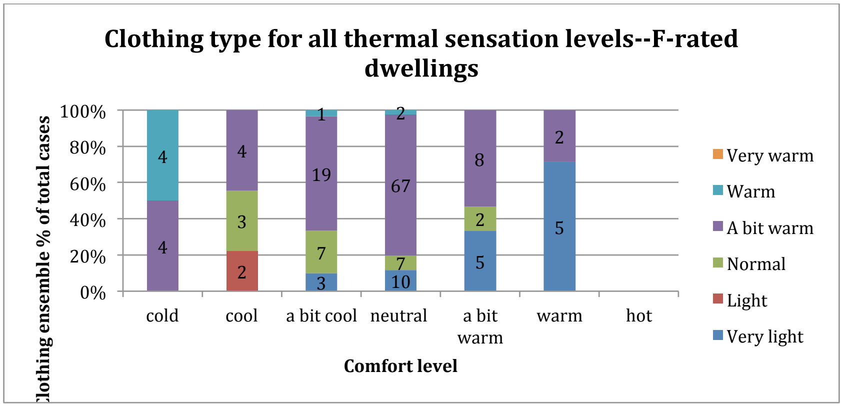

FIGURE 3.12 Clothing types worn at all thermal sensation levels in F dwellings (n=155)

The clo value corresponding to neutral thermal sensation can be determined by plotting the clo value against the reported thermal sensation and applying regression analysis to the resulting graph. Table 3.7 gives the basic statistical data for the regression calculation, and Figure 3.13 shows the scatter plots and trend lines for the living rooms of A/B and F dwellings. Both regressions were significant with p=0.02 and the total number of cases was 31 and 62 respectively. The regressions for bedroom 1 of A/B dwellings and bedroom 2 of F dwellings were found not to be significant.

TABLE 3.7 Basic statistical data for the regressions between TS and clo values (significant results in blue), and calculated clo values for neutral thermal sensation

Room	Average clo value all dwellings	p value	Average clo value A/B-rated dwellings	p value	Average clo value F-rated dwellings	p value
Kitchen	0.58	0.050	–	0.119	0.59	0.019
Living Room	0.61	0.040	0.60	0.027	0.60	0.021
Bedroom 1	0.57	0.043	–	0.907	0.56	0.047
Bedroom 2	0.60	0.013	0.60	0.017	–	0.686

Although the spread of the data is large, especially in A/B dwellings, the clo value was found to decrease with increasing thermal sensation in both cases. This confirms that clothing is an adaptive behavioral feature exercised in order to feel more comfortable. According to the regression analysis, 15.7% of the variance in clo relates to the thermal sensation. We see a fall in clo value from a little above 0.7 (warm ensemble) to somewhat below 0.5 (light ensemble) in A/B dwellings as the thermal sensation rises from -2 (cool) to +2 (warm. A similar effect is observed in F dwellings, though the drop in clo value on going from a thermal sensation of -2 (cool) to +2 (warm) is slightly smaller.

The data collected in this measurement campaign indicate that the tenants of both A/B and F dwellings seem to wear much the same type of clothing, which means that clothing does not seem to be the reason for the lower neutral temperatures found in F dwellings (see section 3.2.3). The same trend was found for the other types of rooms (kitchen, bedroom 1 and 2) as the living room.

Table 3.7 displays the calculated clo values corresponding to neutral thermal sensation (zero on the horizontal axis of Figure 3.13) for each type of room. Identical values were found for the living room (the room for which most data were recorded) in both A/B and F dwellings.

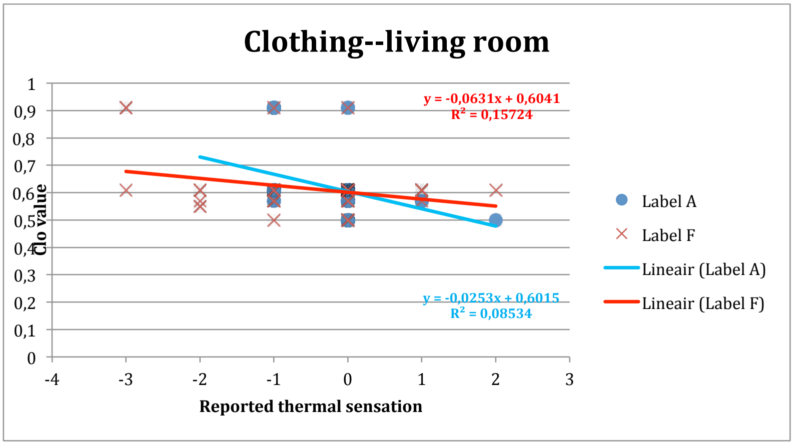

FIGURE 3.13 Clo value versus thermal sensation scatter plot and regression analysis for the living rooms of A/B and F dwellings

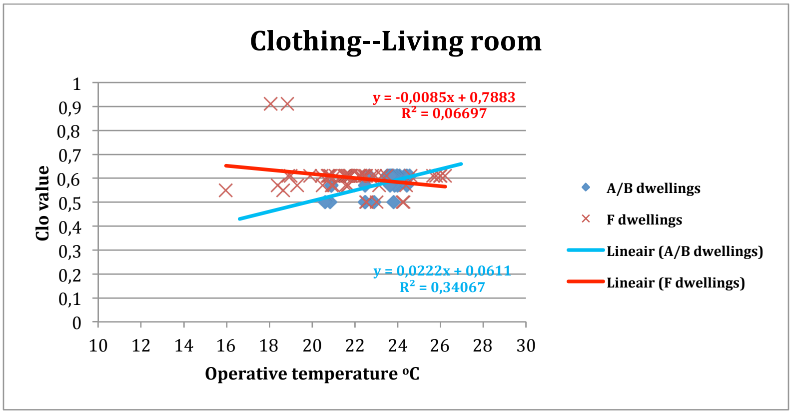

FIGURE 3.14 Clo value plotted against operative temperature for the living rooms of A/B and F dwellings

Figure 3.14 shows the clo value plotted against the operative temperature for the living rooms of A/B and F dwellings. Both regressions were significant, with p=0.0009 and p=0.047 respectively. The trend line for the A/B dwellings is slightly ascending while for the F dwellings it is slightly descending. However, a closer look at the results for temperatures between 20 ºC and 24 ºC shows that the clo value for A/B dwellings starts around 0.5 (very light clothing) and ends around 0.6 (rather warm clothing). In F dwellings, the clo value is already 0.6 at 20 ºC and ends up slightly below 0.6 at 24 ºC. In other words, people in A/B dwellings actually tend to wear somewhat warmer clothing as the operative temperature rises from 20 °C to 24 °C, while people in F dwellings wear lighter clothing; the clo values converge at a temperature of 24 ° C. In both cases, the slope of the trend line is very shallow and the value of R^2 is small. At operative temperature below 23 °C, the occupants of F dwellings seem to be wearing warmer clothes compared to their counterparts in A/B dwellings. The rising trend for A/B dwellings is counter intuitive. However, it could be related to the higher air speed of the balanced ventilation system. Intuitively this could mean that when tenants turn up the ventilation in such cases to deal with temperature rises, the higher air speeds may cause then to wear warmer clothing.

The following procedure was used to gain an insight into the effect of the inaccuracy in clo values on the PMV: The reported RTS values and the calculated PMV values were collected and split into two groups, one for A/B dwellings and the other for F dwellings. The difference PMV-RTS, which is the most logical indicator of the quality of the PMV calculation, was then calculated and assigned to 5 groups by clo value. (Since no data were recorded for very arm clothing, the clo value 1.30 given in Table 3.4 was omitted). A one-way analysis of variance was then used to calculate the 95% confidence interval of the difference PMV-RTS within the various clo categories. If the 95% confidence intervals of two categories overlap, this means that the quality of the prediction (PMV-RTS) cannot be assumed to differ significantly between the two clo categories. If the 95% confidence intervals do not overlap, this indicates significant differences in the quality of prediction; in other words, there are good reasons to suspect a bias relating to clo value in the behavior of the PMV [15]. Figures 3.15 and 3.16 display the mean difference PMV-RTS and the 95% confidence interval for each clo value category the closer to the zero line, the more accurate the prediction of the thermal sensation.

The confidence intervals of (PMV-TS) for A/B dwellings overlap in the categories clo=0.5, 0.57 and 0.61, meaning that the quality of the TS prediction by the PMV is probably not different in these clo categories. The results for clo=0.91 do however differ significantly from those for other categories.

There seem to be two groups of clo categories for F dwellings with no difference in the quality of prediction. One is the group for clo=0.5 and clo=0.55 and the other for clo≥0.57. The quality of the prediction is worse in the lower clo categories than in the higher. It might be though at first sight that this is because the low clo values were not accurately determined. Previous studies indicate that it is difficult to determine clo values precisely in situ [48,54].

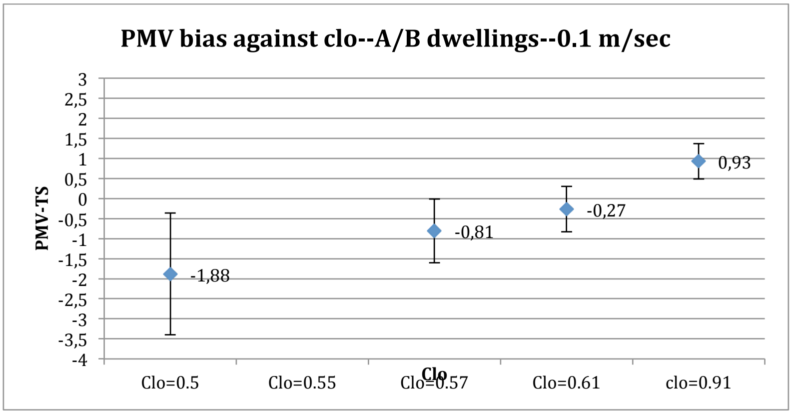

FIGURE 3.15 Predictive bias (PMV-TS) of the clo value against the PMV for A/B dwellings

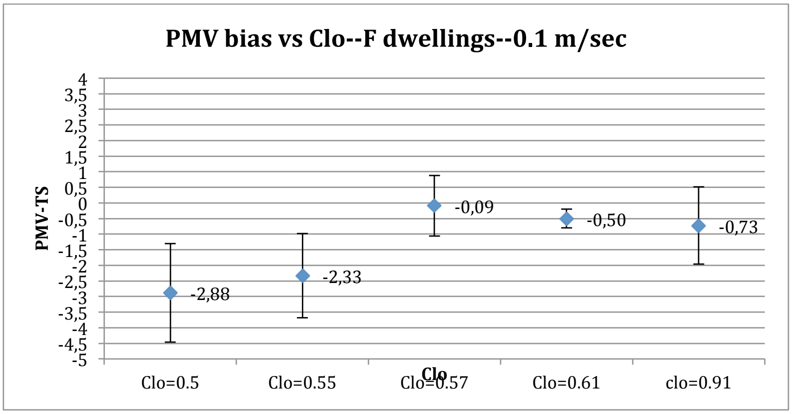

FIGURE 3.16 Predictive bias (PMV-TS) of the clothing value against the PMV for F dwellings

However, closer examination of the above graphs does not reveal any evidence that the problem lies in the clo value. In order to reduce the possible bias at low clo values in Figure 3.16, the average PMV-RTS value for the lower clo category would have to move vertically upwards towards the zero line. Since RTS has a fixed value reported by the tenants, this means that PMV (and hence the clo value) would have to increase: for example, the category clo=0.5 might move up to 0.61 for A/B dwellings and 0.57 for F dwellings if the clo values were measured accurately. This is unlikely, however, since it would have the result of moving all clo categories closer together so that it would be impossible to distinguish between them.

Alternatively, the problem may not lie in the PMV calculation and the poor determination of the clo value but in the reported thermal sensation. We used the widely accepted 7-point scale, but this scale may be too detailed for the range of operative temperature found in the buildings that were monitored. People are accustomed to keeping their home as a comfort zone; in other words, they are used to a neutral operative temperature indoors but not to other comfort levels especially at the colder end of the scale. It may be impossible for people to make a real distinction between 'cold', 'cool', and 'slightly cold', or the results would have been different if they had been exposed to cold outdoor temperatures before using the comfort dial. In line with this, Figure 3.9 shows that PMV ranges from -8 to +3 while RTS ranges only from -3 to +2.

The same technique (Anova: single factor) was used to determine if there are any significant differences between the clo value between A/B and F rated dwellings. The Anova was performed for the clothing level that corresponded to the neutral votes of thermal sensation of the tenants. The result was highly insignificant with p=0.993 and F=6.23E-05 and F_{crit}=3.94 which means that we cannot reject the null hypothesis that the clo values in the living room for neutral thermal sensation between A/B and F rated dwellings are equal (Figure 3.17).

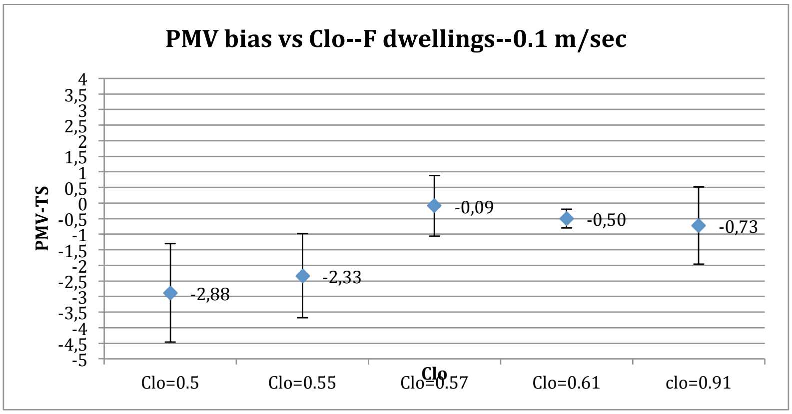

FIGURE 3.17 ANOVA single factor for the clo values in the living rooms for neutral thermal sensations of the tenants

§ 3.3.5 Metabolic activity and thermal sensation

Figure 3.18 displays the metabolic activity for each thermal sensation level recorded by tenants of A/B dwellings with the aid of the comfort dial and the comfort logbook, while Figure 3.19 gives the corresponding results for F dwellings. The metabolic activity shown here is the average activity level as defined in Table 3.4 reported for the half hour before use of the comfort dial. The activity levels are color-coded, while the superimposed numbers represent the frequency of reporting each type of metabolic activity (in total n=147 for A/B dwellings and n=206 for F dwellings).

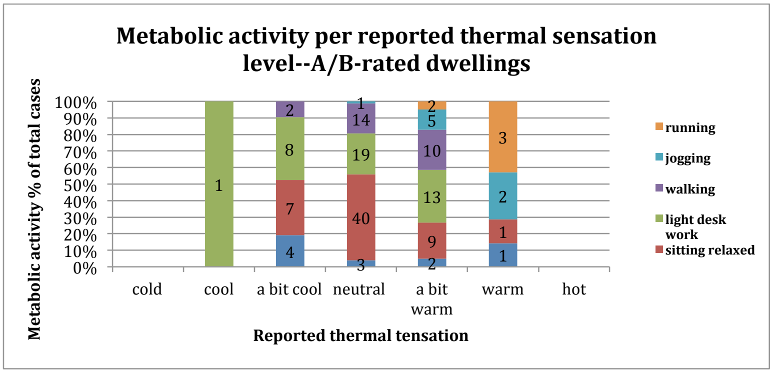

FIGURE 3.18 Metabolic activity reported at various comfort levels in A/B dwellings (n=147)

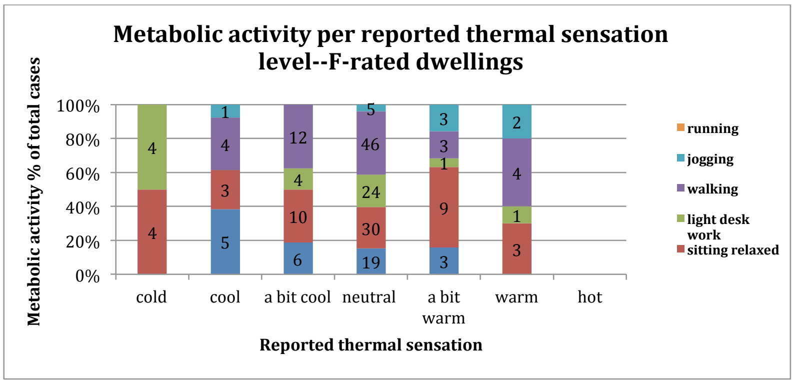

FIGURE 3.19 Metabolic activity reported at various comfort levels in F dwellings (n=206)

The metabolic activity most often reported in both A/B and F dwellings was ''relaxed sitting''. This was followed by "light desk work" and then "walking" in A/B dwellings. ''Walking'' was recorded than ''light desk work'' in F dwellings.

''Lying/sleeping'' was the fourth metabolic activity level for both types of dwellings. The metabolic activity of the tenants can be calculated as a function of the reported thermal sensation, in much the same way as was done for the clo value above. Figure 3.20 shows the scatter plots and trend lines for the metabolic activity value plotted against reported thermal sensations for the living rooms of the A/B and F dwellings. Both regressions were significant with p=0.008 and p=0.04 respectively, and the total number of cases was 56 and 82 respectively. The RTS explains 12% of the variance of metabolic activity in A/B dwellings, but only 5% in F dwellings. The statistical significance values for each regression are given in Table 3.8.

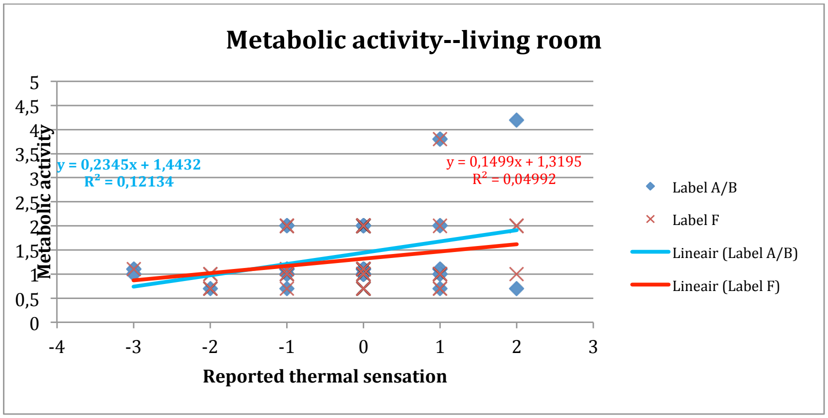

FIGURE 3.20 Metabolic activity versus reported thermal sensation scatter plot and regression analysis trend-line for the living rooms of A/B and F dwellings

TABLE 3.8 Basic statistical data for the regressions between TS and met values (significant results in blue), and calculated met values for neutral thermal sensation

Room	Average met value all dwellings	p value	Average met value A/B-rated dwellings	p value	Average met value F-rated dwellings	p value
Kitchen	1.53	0.002	1.88	0.01	1.38	0.01
Living Room	1.41	0.039	1.44	0.008	1.32	0.043
Bedroom 1	1.46	0.048	1.28	0.050	1.90	0.040
Bedroom 2		0.286		0.069	1.45	0.048

The regression for bedroom 2 was only significant in F dwellings. The regressions for all other types of room were significant at $p \le 0.01$. The metabolic activity in the kitchen of A/B dwellings is appreciably higher than in the living room and bedroom 1, which is to be expected since the kitchen is where dinner is prepared and where people usually have breakfast in the morning before they leave home. Both those common activities for kitchens are associated with higher metabolic activity levels. Furthermore, A/B dwellings all had their kitchens and living rooms combined in a single large space. This is likely to make for a more frequent movement between the two halves of the space for example; breakfast may be prepared in the kitchen and eaten at the table in the adjacent living area, unlike the case with separate kitchens containing a breakfast table. Similar considerations apply to the metabolic activity levels in the kitchens and living rooms of the F dwellings. The metabolic activity is higher in the kitchen than in the living room, but a lot less than in A/B dwellings.

All the F dwellings in this study had separate kitchens, and the confined space could lead to lower metabolic activity. The highest metabolic activity for neutral thermal sensation was observed in the bedroom 1 of F dwellings. The data points for A/B dwellings in this case were for 3 dwellings; two of those belonged to elderly people who used the bedroom only for sleeping while the third house belonged to a young couple who also used the bedroom only for sleeping since they had a second bedroom that they used as a study. The F dwellings on the other hand provided enough data points for accurate calculation of the regressions; these households all had young family members (from small children up to teenagers) who used the rooms actively during the daytime, not just for sleeping.

Apart from the special cases analyzed in the previous paragraph, similar levels of metabolic activity were found in the living room in both types of dwellings; this type of room was used in the same way in both A/B and F dwellings, and provided most of the data points for the regression analysis. This is also evident from Figure 3.20, where the reported thermal sensation ranges from -3 to +2 in both cases and the metabolic activity usually varies from 0.75 to 1.5.

Figure 3.21 displays the metabolic activity as a function of the operative temperature for the living rooms of A/B and F dwellings. As in the case of the clo value discussed in section 3.6, the trend line is rising for A/B dwellings and falling for F dwellings, converging to the same levels of metabolic activity as the temperature rises from 18 °C to 24 °C. Furthermore, the slope of the trend lines is very shallow and the R^2 values are even lower than for the clo trend lines. The increase in the metabolic activity of the tenants in A/B dwellings as the operative temperature rises may be due to the design of these dwellings. Most of them have the kitchens and living rooms combined in one continuous space. Cooking causes the temperature of the space and the level of metabolic activity to rise, since it requires more activity than typically found in the living room, which is normally associated with more relaxed activities such as watching TV, reading a book or listening to music. People who were recording their metabolic activity in the living room were more likely to be in a relaxed state, sitting on a couch or in a chair, while people recording their metabolic activity in the kitchen would be more active (cooking, using the dishwasher etc.).

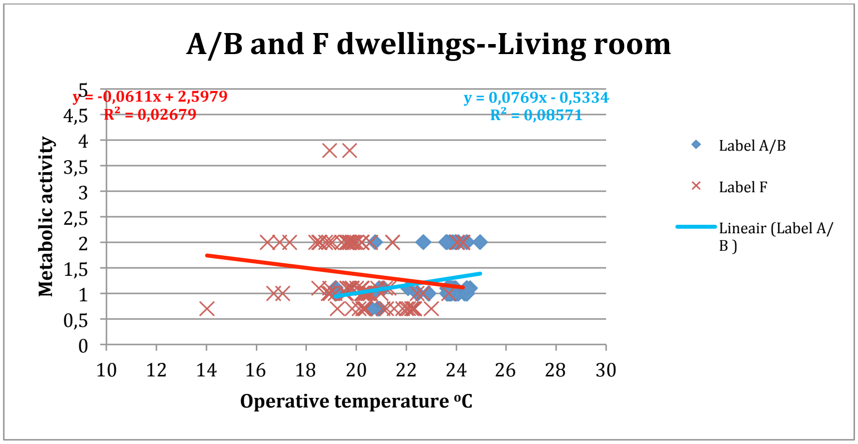

FIGURE 3.21 Metabolic activity (met value) plotted against operative temperature for the living rooms of A/B and F dwellings

As in the previous section, we explored the effect that inaccuracy in determination of the values of metabolic activity might have on the calculated PMV. The difference PMV-RTS was once again determined, grouped by the energy rating of the dwellings and categorized by metabolic activity value into 7 groups as defined in Table 3.4. One-way analysis of variance was again used to test whether the different mean discrepancies for the various groups could be attributed to chance. Figures 3.22 and 3.23 display the mean discrepancy (predictive bias) plotted against the met value (met value of 1.5 appears in the graph despite its absence in Table 3.4. This is because tenants many times recorded more than one type of metabolic activity for the past half hour and so an average met value of those activities was used), together with the 95% confidence interval for each category. If the PMV were free from bias relating to the met value, the confidence intervals of all categories would overlap.

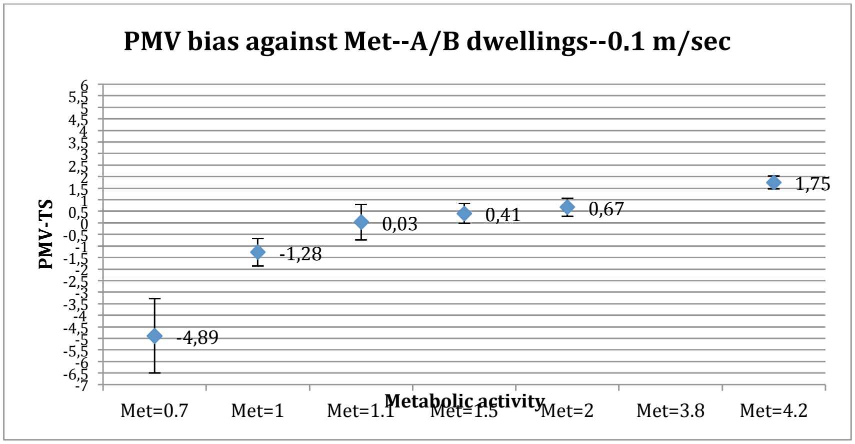

FIGURE 3.22 Predictive bias of the met value against the PMV for A/B dwellings

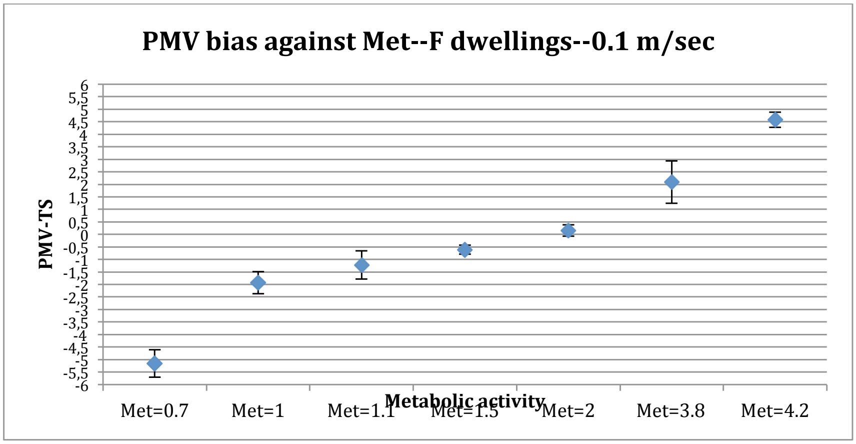

FIGURE 3.23 Predictive bias of the met value against the PMV for F dwellings

It was found that the discrepancies were not attributable to chance and were highly significant at $p<0.001$. A/B dwellings showed substantial bias for met=0.7 (lying/ sitting), met=1 (relaxed sitting) and met=4.2 (running), though the bias is much smaller in the last two categories. The PMV is however free from serious bias for met values of 1.1 (light deskwork), 1.5 and 2 (walking).

The discrepancies in F dwellings were also not attributable to chance and were highly significant at $p<0.001$. The bias in these dwellings was more substantial than in A/B dwellings. All categories of metabolic activity showed marked bias, apart from met=1.5 and met=2.

Anova: single factor was used to determine if there are any significant differences between the metabolic activity value between A/B and F rated dwellings. The Anova was performed for the metabolic activity level for the living rooms that corresponded to the neutral votes of thermal sensation of the tenants for both A.B and F dwellings. The result was highly insignificant with $p=0.488$ and $F=0.483$ and $F_{crit}=3.91$ which means that we cannot reject the null hypothesis that the metabolic activity values in the living room for neutral thermal sensation between A/B and F rated dwellings are equal (Figure 3.24).

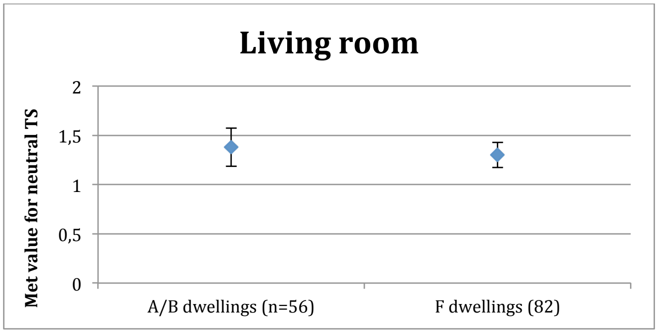

FIGURE 3.24 ANOVA single factor for the metabolic activity values in the living rooms for neutral thermal sensations of the tenants

§ 3.4 Discussion

Despite limitations on materials and equipment, the Ecommon measurement campaign successfully collected adequate quantitative and subjective data on comfort and occupant behavior in a relatively easy and unobtrusive way in the residential environment. The tenants were very interested in the comfort dial, and used it much more often than the requested minimum three times a day. The high frequency (every 5 minutes) of the sensor measurements of quantitative parameters, the unobtrusive wireless method used to collect thermal sensation data and the remote management of the entire sensor system ensured minimal data loss over the whole six months of the measurement campaign.

Furthermore, the reported thermal sensation data used for the comfort calculations were collected electronically for the first time with a time stamp linked to the quantitative sensors; this approach compares favorably with the questionnaire tenants had to fill in by hand in previous monitoring campaigns. The precision of data collection is much higher in this approach: tenants no longer had to write down the exact time they filled in the comfort logbook, and the 5-minute interval used for quantitative data collection ensured that the quantitative data, entered in the comfort logbook, could be precisely linked with the subjective data. At the same time, the motion sensors helped to identify where the tenants were when they were filling in the comfort logbook, thus allowing the appropriate room type to be linked with the corresponding data entry.

One of the issues that arose during the analysis of the campaign data was the possible effect of direct solar radiation on tenants' thermal preferences. Energy Plus accounts fully for the effects of direct and diffused solar radiation in the interior of a building when simulating air, radiant and operative temperatures [49]. However, these simulations were based on a reference building (described in section 3.2.1) which may differ in architecture (placement, size and orientation of the windows) from the real buildings dealt with in the campaign. Furthermore, while the average hourly radiant temperature in each flat was approximated in detail in Energy Plus simulations, we have no way of knowing whether tenants were sitting in front of a window while they recorded their thermal sensation. The Netherlands may not be the sunniest country in the world and monitoring did take place during the winter, but direct solar radiation could still have played a role in determining tenants' thermal sensation. Besides, the radiant temperature at a given time may differ from the average hourly value obtained from Energy Plus simulations. However, Table 3.3 shows that the highest standard deviation found for the air temperature was 1.08 °C while that for the radiant temperature was 2.16 °C. In order to estimate the effect of temperature variations, the PMV equation was subjected to sensitivity analysis with reference values of 20 °C for air and radiant temperature. The maximum effect on PMV produced when the air and radiant temperatures were varied in 0.5 °C steps from 18 °C to 22 °C (in order to cover the entire possible range of twice the standard deviation) was 0.7. It follows that possible deviations of the radiant temperature from the average at a given time should not have a dramatic effect on the PMV.

Another point of discussion is related to the 7-point scale used for the PMV. This scale was developed in climate chamber experiments where subjects were exposed to a variety of climatic conditions. It was validated by determining the regression between the calculated PMV values and tenants' reported thermal sensations. There is however, no guarantee that a thermal comfort level of -3 reported by a Dutch subject corresponds to -3 on the PMV scale. Greater robustness could be achieved by collecting large-scale data sets for a wide variety of subjects and areas in the Netherlands and using these data to define the PMV scale for the Netherlands together with the thermal sensation scale for Dutch subjects. It is claimed that the PMV model can be applied irrespective of climate and social convention, way of life and kind of clothing, though some distinction needs to be made between winter and summer [13]. In contrast with this, previous thermal comfort studies found that subjects' thermal sensations varied from individual to individual and were dependent on race, climate, habits and customs [50,51].

Furthermore, the thermal sensations recorded by the tenants in the present study ranged mainly between -2 and +2. Comfort levels of -3 (cold) were recorded very infrequently (only 9 cases out of 192, all in F dwellings), while comfort levels of +3 (hot) were never recorded. Most reported comfort levels were between -1 and +1. As discussed in section 3.6, the PMV shows little bias for clo and met values that are close to those for neutral comfort levels. These facts reflect the possible effect of psychological adaptation on the tenants in the present study. Thermal adaptation can cause people to perceive, and react to, sensory information differently based on experience and expectations [52]. Personal comfort set points are far from thermostatic, and expectations may be relaxed in a way that resembles the habituation found in psychophysics [53,54] where repeated exposure to a constant stimulus leads to a diminishing evoked response [52]. The tenants who participated in the Ecommon campaign might not even have a clear feeling of what a thermal sensation of -3 means. They are always in their own personal space, which they always try to keep as comfortable as possible, and this feeling of comfort is what they know and what they associate with their home. It follows that their response are more accurate around the neutral comfort level and less accurate at more extreme comfort levels approaching -3 or +3, which correspond to thermal sensations to which they are much less accustomed in their own homes. Similarly, our analysis of the bias in PMV due clo and met values showed that bias was low around the neutral point, but could be substantial at lower and higher clo and met vales.

§ 3.5 Conclusions and proposals for further research

The PMV model predicts neutral temperatures for the various room types well, in line with those derived from the thermal sensations reported by tenants.

The thermal sensation reported by tenants ranged from -3 (cold) to +2 (warm), while the PMV calculations showed thermal comfort levels ranging from -8 to +3. This means that people feel more comfortable than indicated by the predictions. The PMV model underestimates the thermal comfort of the tenants in residential dwellings. Furthermore, people seem to have better perception of thermal comfort around neutrality. This could indicate a certain level of psychological adaptation and expectation since each person's home is associated with comfort, relaxation and rest, in contrast to office buildings for example that are associated with work and higher levels of stress, effort and fatigue.

Tenants of A/B and F dwellings seem to show no differences in clothing and metabolic activity patterns, even though, F-rated dwellings had lower neutral temperatures. Age and gender also seem to have no effect on neutral temperature levels, which leaves the indoor air speeds and psychological adaptation and expectations as possible explanatory factors for the difference in neutral temperatures between A/B and F dwellings.

Further research could include up scaling of the Ecommon project, with improvement in the equipment and data collection. The high level of automation of the quantitative and subjective data collection tools has already made the data collected more reliable, robust and time accurate, though in the future it would be better to have everything on an app and not partly on paper. Moreover, data collection should be expanded to incorporate information on the thermal expectations of tenants during the measurement campaign. Improved equipment could ensure the collection of more solid data (in particular clo and met values), which could further help to eliminate measurement bias and lead to more accurate calculation of PMV. Further research on the actual energy consumption of the dwellings is also needed in order to discover the effect of the reported thermal sensation on the energy consumption in the dwellings. For example, do tenants in F dwellings turn up the thermostat before reporting "good" thermal sensation?

Finally, extended data collection from a variety of Dutch subjects with different demographic characteristics such as sex, age, income, and ethnicity, different housing typologies (standalone houses, row houses, apartments), and different geographical locations in the Netherlands is needed as a basis for development of a national thermal sensation index. This would lead to a better prediction model that could supplement or replace PMV.

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4 In-situ real time measurements of thermal comfort and comparison with the adaptive comfort theory in Dutch residential dwellings.[3]

Abstract

Indoor thermal comfort is generally assessed using the PMV or the adaptive model. This research presents the results obtained by in-situ real time measurements of thermal comfort and thermal comfort perception in 17 residential dwellings in the Netherlands. The study demonstrates the new possibilities offered by relatively cheap, sensor-rich environments to collect data on clothing, heating, and activities related to thermal comfort, which can be used to improve and validate existing comfort models. The results are analyzed against the adaptive comfort model and its underlying assumptions. Data analysis showed that while indoor temperatures are within the adaptive model's comfort bandwidth, occupants often reported comfort sensations other than neutral. Furthermore, when indoor temperatures were below the comfort bandwidth, tenants also often reported that they felt 'neutral'. The adaptive model could overestimate as well as underestimate the occupant's adaptive capacity towards thermal comfort. Despite the significant outdoors temperature variation, the indoor temperature of the dwellings and the clothing were observed to remain largely constant. Certain actions towards thermal comfort such as 'turning the thermostat up' were taking place while tenants were reporting thermal sensation 'neutral' or 'a bit warm'. This indicates that either there is an indiscrimination among the various thermal sensation levels or alliesthesia plays a role and the neutral sensation is not comfortable, or many actions are happening out of habit and not in order to improve one's thermal comfort. A chi^2 analysis showed that only six actions were correlated to thermal sensation in thermally poorly efficient dwellings, and six in thermally efficient dwellings.

Keywords

in-situ measurement, adaptive model, thermal comfort, clothing, metabolic activity, thermal sensation, occupancy behavior, energy consumption, residential dwellings, wireless monitoring

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§ 4.1 Introduction

Reducing energy consumption in the residential sector is a major EU goal. Buildings should become more efficient but this cannot happen at the expense of thermal comfort. Indoor thermal comfort is generally assessed using the much-criticized PMV model, especially when it comes to naturally ventilated dwellings, which has led to the development of the adaptive comfort model. For both models, collection of data is a major issue. Measurements in a climate chamber do not account for the adaptation and psychological aspects of indoor comfort in homes, while in situ measurements are expensive, intrusive, and time consuming. However, recent developments in home automation and wireless sensor-rich environments, offer growing possibilities for cheaper and more extensive in-situ measurements, which could improve the existing comfort models. This paper reports the results of a study in which a wireless sensor network was placed in 17 houses to measure thermal sensations and comfort parameters. In Ioannou and Itard (2017) [1] the results were assessed against the PMV model, while the present paper focuses on the adaptive model. It is true that the adaptive model was originally developed for non-conditioned spaces and most of its experimental substantiation was realized with data from countries with a warm season. However, building simulation software often use conventional thermal comfort theories to make decisions. Therefore, Peeters et al. [26] extracted acceptable temperature ranges and comfort scales for residential dwellings based on a prior study by Van der Linden et al. [7] who developed adaptive temperature limits for the Dutch official purposes. Since the adaptive model for thermal comfort in residential dwellings is accepted as a standard in the Dutch residential sector, it is useful to be assessed with experimental data.

In section 2, a brief state of the art concerning the adaptive model is proposed, along with its limitations. Section 3 presents the research questions, the methods, and tools used for the collection and data analysis. Section 4 presents the results and Section 5 contains a discussion, the conclusions, and suggestions for future research.

§ 4.2 Brief State of the art of adaptive models

The adaptive model [2, 3] created to circumvent problems encountered in the PMV model, has gained increasing support among researchers in the field of indoor environment and comfort [4-8] and has been incorporated into two internationally used standards: the ASHRAE Standard 55 [9] for North America and the European EN 15251 [10]. The Netherlands is among the European countries that has incorporated the adaptive model into their regulations [11, 12]. This model is able to assess the indoor thermal environment of naturally ventilated buildings in which the occupants have the freedom to open or close the windows, adjust their clothing and generally perform activities that improve their thermal comfort.

§ 4.2.1 Basic assumptions of the adaptive model

The basic assumption is that people take action to improve their thermal comfort by utilising various adaptive opportunities [13]. The adaptive approach relies on field studies where the thermal comfort of occupants was measured in situ [14] and relates the indoor neutral operative temperature to a single variable, the mean monthly outdoor temperature, defined as the arithmetic mean of the daily maximum and minimum temperatures during the month considered. It does not actively deal with the effect of thermal comfort factors described by Fanger [15, 16] and used in the PMV model. According to Nicol and Humphreys, the reason for ignoring parameters such as clothing (clo value) is that they are related in various ways to the outdoor temperature [3]. However, other parameters used in the Fanger model (metabolic activity, mean radiant temperature, and air velocity) are not directly associated with outdoor temperatures [16].

According to the adaptive model, contextual factors and past thermal history modify occupants' thermal expectations and preferences. Adaptation is defined as the gradual lessening of occupants' response to repeated environmental stimulation and may be behavioural (clothing, windows), physiological (acclimatisation), or psychological (expectations) [17]. Based on the expectation theory of the adaptive approach [18], people will tend to expect and accept lower temperatures in the winter, or in cold climates, and higher temperatures in the summer, or in hot climates. Scientists supporting this model clearly state that occupants are free to adapt, primarily through clothing adjustment, to the variable indoor climate in naturally ventilated buildings [19].

McIntyre has acknowledged the role of expectations in relation to thermal comfort, stating that an individual's response to temperature depends on his expectations, personality, and whatever he is doing at that time [20]. According to Fountain, changes in expectations occur when a tenant is used to the cycles and variations of the indoor environment, which in turn may follow diurnal or seasonal outdoor climate patterns or even longer term climatic changes. After long-term exposure to variations in environmental conditions, an individual's expectations in relation to those conditions may become more relaxed and even anticipatory of temporal changes [18].

§ 4.2.2 Limitations of the adaptive model

Evidence from field studies around the world has shown that thermal conditions in fully mechanically air-conditioned spaces (hotels, offices) often deviate from the comfort zone [16]. If the expectation hypothesis is true, then most people who complain about discomfort in their work environment should eventually stop doing so since this recurring discomfort should make them increasingly tolerant. Chronic discomfort should lower their expectations and help them accept the current reality. People might thus stop complaining, but there is no information if this really happens, or if they do so because they have come to terms with their discomfort, or because no one is offering a solution. Furthermore, naturally ventilated buildings offer their occupants a greater degree of thermal control compared to fully mechanically air-conditioned buildings. This enhanced control of thermal comfort leads to the relaxation of expectations and greater tolerance of temperature excursions [17]. Intuitively, it would make sense that when someone has greater control over his thermal environment he would exercise this control in order to achieve the best possible thermal comfort. Thus, it is possible that occupants of naturally ventilated dwellings do not develop more relaxed expectations and greater tolerance, related to thermal comfort, but make full use of the control opportunities. The fact that they have potential control and can always adjust the temperature to suit their personal needs could lead to exactly the opposite conclusion to Brager and de Dear. Rather than their expectations being lower, they expect they will be able to meet their comfort preferences by exercising more control over their thermal environment [16]. Residential tenants may have a specific thermal comfort level in mind, which is related to the quality of their dwelling, the comfort that it can provide, and various personal parameters that might affect thermal comfort. Therefore, it could be that the tenants of these dwellings are used to the performance of the dwelling with respect to the outdoor conditions and know how to gain the most from it.

Another limitation of the adaptive theory relates to the phenomenon of alliesthesia, which points out that feeling neutral does not necessarily means feeling comfortable, people may feel comfortable while feeling cold or warm [22]. Last, and most important, it should be noted that while the original model was made to explain seasonal and regional differences in temperature preferences, it has been used more and more as a basis for building design and assessment of the thermal comfort of existing buildings [9, 10]. It is therefore questionable if the adaptive model as it is used in national guidelines [9, 10] is able to accurately assess and predict comfort in existing dwellings.

§ 4.3 Methodology

This study, considering only 17 houses, makes no attempt to claim representativeness at the housing stock level or to conclude on the original adaptive model, in which seasonal average indoor temperatures were used. As mentioned in section 2, the adaptive model has been used often to assess the hourly values of indoor operative temperatures against the reference outdoor temperature in order to conclude on the indoor thermal comfort at individual dwelling level. This paper reports on the quality of this assessment in 17 dwellings.

This paper is a follow-up to that by Ioannou and Itard (2017) [1]. The main finding of that analysis was that the PMV model is a good predictor of neutral temperatures for the various room types and in line with the temperatures derived from the recorded thermal sensations. However, the PMV model was found to underestimate the thermal comfort of tenants. Occupants felt comfortable while the PMV model predicted they should feel cool or a bit cool. Furthermore, no difference in clothing levels and metabolic rates between A/B and F-labelled dwellings were found, despite the latter having lower neutral temperatures.

The main objective of the present paper is to compare the results obtained with the adaptive comfort model and to further test the hypothesis underlying this model in order to get more insights into the advantages and drawbacks of the use of the adaptive comfort model for design and assessment of thermal comfort.

§ 4.3.1 Research questions

1. How successfully does the adaptive model predict occupants' thermal sensations in the 17 residential dwellings that participated in the monitoring study?
2. To what extent do outdoor temperatures affect indoor temperature set points, clothing and metabolic activity?

3 What are the most common behavioural adaptations/actions taken by occupants to achieve thermal comfort, and how do these relate to the tenants' thermal sensations?

4 What is the impact of clothing level and metabolic activity on tenants' thermal sensations?

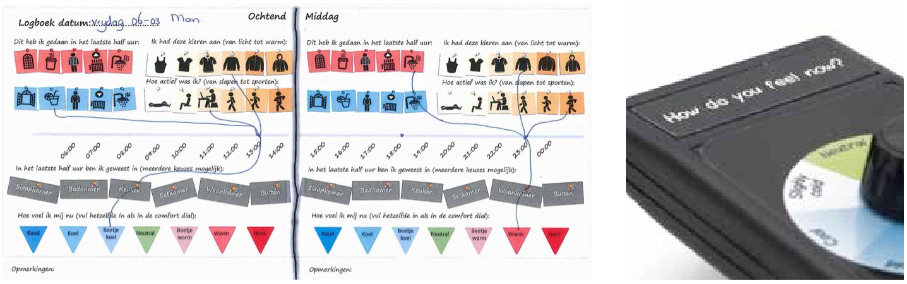
§ 4.3.2 Set up of the monitoring campaign

The measurements were part of the Ecommon (Energy and Comfort Monitoring) study of residential dwellings in the Netherlands. The Ecommon project was part of the Monicair [23], SusLabNWE [24] and Installaties2020 [25] projects and monitored 32 dwellings (classified by energy rating, types of heating and ventilation systems) for a six-month period from October 2014 to April 2015, which is the heating season for north-western Europe. Quantitative data (air temperature, relative humidity, CO_2 and movement) for each room (living room, kitchen, bedroom 1 and bedroom 2 or study) were collected wirelessly at five-minute intervals. In addition, subjective data (thermal sensation, metabolic activity, clothing, actions during the previous half hour related to thermal comfort) were collected in 17 dwellings over a two-week period in March using two different methods, wirelessly and through entries in a manual log. The wireless device used to capture the thermal sensation of the tenants was time-coupled with the sensors for the quantitative data. This allowed the reported thermal sensation of the tenants, at any given time, to be coupled with the exact atmospheric conditions (temperature, relative humidity, and CO_2).

The occupants' thermal sensation was recorded with the help of a wireless device called the 'Comfort Dial' (Figure 4.1) that allowed tenants to record their perceived thermal comfort at any time of the day on a seven-point scale, from -3 (cold) through 0 (neutral) to +3 (hot). Furthermore, tenants also made use of a hard copy log book (Figure 4.1). The data recorded in the log book concerned:

- Thermal sensation on the above-mentioned seven-point scale.
- The room being occupied when filling in the logbook (kitchen, living room, bedroom, etc.).
- Clothing combination worn: a choice of six clothing ensembles from very light to very warm (Figure 4.1 and Table 4.1).
- Actions taken during the past half hour relating to comfort and energy consumption, such as opening and closing the windows, drinking a cold or hot drink, putting clothing on or taking it off, turning the thermostat up or down, and having a cold or hot shower.

– Activity level: lying/sleeping, relaxed sitting, doing light desk work, walking, jogging, and running (activities related to occupants' metabolic rate). Both comfort dial and comfort log book were developed by the TU Delft Industrial Design Department [23].



a *b*

FIGURE 4.1 Hard copy logbook for entry of subjective data (a)and Comfort Dial (b) used to capture perceived comfort levels of tenants during the Ecommon study

TABLE 4.1 Range of clothing and metabolic activities available for selection, in connection with entries in the Comfort Log Book during the Ecommon study and the values used to calculate their thermal effects

CLOTHING ENSEMBLE	CLO VALUE	METABOLIC ACTIVITY	MET VALUE
Very light (Sleeveless T-shirt, icon in Fig. 3)	0.5	Lying/sleeping	0.7
Light (Normal T-shirt, icon in Fig. 3)	0.55	Sitting relaxed	1
Normal (Knit sport shirt, icon in Fig. 3)	0.57	Light desk work	1.1
Rather warm (Long-sleeved shirt, icon in Fig. 3)	0.61	Walking	2
Warm (Long-sleeved shirt plus jacket, icon in Fig. 3)	0.91	Jogging	3.8
Very warm (Outdoor clothing, icon Fig. 3)	1.30	Running	4.2

The quantitative data were used to calculate the comfort zone defined by the adaptive model. The subjective data were subsequently used to assess various aspects of the adaptive model and its hypothesis. For more details about the quantitative data collection see section 3.1 and Ioannou and Itard (2017) [1].

The dwellings that participated in the measurement study were part of the Dutch social housing stock. The sample was divided into energy A/B-labelled (thermally efficient dwellings) and F-labelled dwellings (poor thermal efficiency). The final sample of the dwellings in which thermal sensations were collected is described in Table 4.2.

TABLE 4.2 Dwellings participating in the Ecommon study

NO.	ENERGY RATING	HEATING SYSTEM	VENTILATION SYSTEM	NO. OF ROOMS	NO. OF OCCUPANTS	AVERAGE AGE OF HOUSEHOLD (sample average: 59 years)
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
W010	A	Condensing gas boiler	Natural Supply, Mech. Exhaust	7	2	29
W012	F	Condensing gas boiler	Natural Vent.	5	4	40.5
W013	F	Condensing gas boiler	Natural Vent.	5	3	53
W016	B	Condensing gas boiler	Natural Supply, Mech. Exhaust	4	2	70
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
W025	F	Gas stove	Natural Vent.	5	3	43
W026	F	Condensing gas boiler	Natural Vent.	4	4	21
W028	F	Condensing gas boiler	Natural Supply, Mech. Exhaust	6	2	72
W031	F	Condensing gas boiler	Natural Supply, Mech. Exhaust	6	3	43
W032	B	Condensing gas boiler	Natural Supply, Mech. Exhaust	4	3	39

The dwellings with heat pump are equipped with a subfloor low temperature hydronic system. The system uses no gas and the total costs are translated in electricity use for the pumps that are constantly circulating the hot water in the hydronic system. The dwellings equipped with condensing boilers are having hot water radiators in each room while the dwellings with gas stoves are heated only locally I the spaces where the gas stove is installed. Both these two systems use gas.

§ 4.3.3 Calculation of the neutral, upper and lower temperature limits for the adaptive model

The adaptive temperature limits were calculated using the Dutch official guidelines in which $T_{e,ref}$ is calculated according to Van der Linden et al. [11].

$$T_{e,ref} = \frac{(T_{today} + 0.8T_{today-1} + 0.4T_{today-2} + 0.2T_{today-3})}{2.4} \qquad (1)$$

where $T_{e,ref}$ is the reference external temperature (°C), T_{today} is the average of the day's maximum and minimum outside temperatures (°C) and $T_{today-1}$, $T_{today-2}$, and $T_{today-3}$ are the average of maximum and minimum outside temperatures (°C) for yesterday, two and three days before, respectively [26].

For the calculation of the neutral temperatures in each room of each dwelling, the equations by Peeters et al.[26], set up for different types of rooms in Belgium, very close to the Netherlands, were used:

$$T_n = 20.4 + 0.06 * T_{e,ref} \qquad \text{for } T_{e,ref} < 12.5\ {}^{o}\text{C} \qquad (2)$$

$$T_n = 16.63 + 0.36 * T_{e,ref} \qquad \text{for } T_{e,ref} \geq 12.5\ {}^{o}\text{C} \qquad (3)$$

The upper and lower temperature limits in the most commonly used standards are symmetrical around the neutral temperature [9,10,11]:

$$T_n \pm \alpha \qquad \text{Where } \alpha \text{ is a constant } ({}^{o}\text{C}) \qquad (4)$$

The constant α is independent of the season and the comfort band around the neutral temperature is thus considered to have a constant width [26]. To account for both the enhanced sensitivity to cold versus heat and the non-seasonal dependence, we used the equations recommended by Peeters et al. (2009) [26] for the upper and lower temperature limits:

$$T_{upper} = T_n + wa \tag{5}$$

$$T_{lower} = \max\left(T_n - w\,(1 - a), 18\right) \tag{6}$$

with T_{upper} (°C) the upper limit, T_{lower} (°C) the lower limit of the comfort band and *w* the width of the comfort band (°C). The value of *w* for 90% acceptability was 5 °C and for 80% acceptability 7 °C. Furthermore, the width of the comfort band was not split symmetrically around the neutral temperature, rather a 70-30% split was used as recommended by Peeters and al., which resulted in an α equal to 0.7 [11,26,27].

§ 4.3.4 Estimation of mean radiant temperature (T_{mrt}) and indoor operative temperature

Unfortunately, it was not possible to measure directly the radiant temperature or the operative temperature during the measurement campaign. These temperatures were therefore estimated using simulations, following the procedure described by Ioannou and Itard (2017) [1]. For the sake of clarity, this procedure is summarized below.

Dynamic simulations, performed with Energy+, showed that the difference between air and radiant temperature during March in a typical F-labelled dwelling with a condensing boiler and radiators was about 4 °C. For a typical A/B-labelled dwelling with heat pump and floor heating, the radiant temperature was 1.2 °C higher than air temperature due to the radiant heating effect of the hydronic floor heating system. The instantaneous values for the mean radiant temperature (T_{mrt}) of F and A/B- labelled dwellings were thus calculated as T_{air} -4 °C and T_{air} +1.2 °C, respectively. For the A/B-labelled dwellings with condensing boilers and radiators instead of heat pumps, the air temperature was slightly higher (0.3 °C) than the radiant temperature and appreciably less than the respective standard deviations. Therefore, it was assumed that the radiant temperatures for A/B-labelled dwellings with condensing boilers could be set as equivalent to the air temperatures recorded by the sensors. The operative temperature T_{op}, is defined as,

$$T_{op} = \gamma\, T_{mrt} + (1-\gamma)\, T_{air} \tag{7}$$

Where, γ = is the radiative fraction, T_{MRT} = is the mean radiant temperature for the thermal zone, and $T_{drybulb}$ = is the mean zone air temperature.

For air velocities below 0.2 m/s, which is a reasonable number for indoor residential dwellings, a typical value of γ is 0.5. For a more detailed description of the methodology and a sensitivity study concerning the qualities of these assumptions, refer to Ioannou and Itard (2017) [31] and Niu and Burnett (1998) [28].

§ 4.4 Results

§ 4.4.1 Evaluation of the prediction success of the adaptive model in the sample of residential dwellings

The two weeks of measurements in March were quite cold, with an average temperature of 6.2 °C, average minimum of 1.9 °C, and average maximum 9.6 °C. These temperatures are representative for the average heating period in the Netherlands.

§ 4.4.1.1 Reported thermal sensations and the adaptive model

Table 4.3 presents an overview of the total number of thermal sensation scores recorded per dwelling, their percentage breakdown into scores on the colder, neutral and warm sides of the ISO 7730 [29] seven-point scale, as well as whether they were recorded before or after midday. The majority of the thermal sensation scores were recorded after 12.00 noon. In total, 465 thermal sensation points were recorded during the two weeks and they were time-coupled to indoor comfort parameters and outdoor temperatures. However, these thermal sensations were not equally distributed between A/B and F-labelled dwellings. In the F-labelled dwellings, 322 thermal sensations were recorded by 11 respondents, while in the A/B-labelled dwellings only 143 thermal sensations were reported by 5 respondents. It should also be noted that in the A/B-labelled dwellings, 75% of the scores were given by the respondent of W032. In the F-labelled dwellings, the respondent of W031 is also over-represented, with 40% of the scores. Both of these dwellings were occupied by a middle-aged couple with one child.

TABLE 4.3 Overview of thermal sensation scores recorded for each dwelling

		% TS			TS < 0		TS = 0		TS > 0	
	No. of RTS	TS < 0	TS = 0	TS > 0	% before 12.00 noon	% after 12.00 noon	% before 12.00 noon	% after 12.00 noon	% before 12.00 noon	% after 12.00 noon
A/B-labelled dwellings										
W032--B	107	6.5	34.6	59.9	42.9	57.1	32.4	67.6	38.1	61.9
W016--B	9	44.4	55.6	0	25	75	60	40	0	0
W010--A	9	33.3	0	66.6	66.7	33.3	0	0	33.3	66.7
W006--A	13	7.7	84.6	7.7	100	0	36.36	63.63	100	0
W005--A	3	0	33.3	66.7	0	0	0	100	50	50
W004--A	15	20	66.7	13.3	33.3	66.7	60	40	50	50
F-labelled dwellings										
W031--F	128	24.2	42.2	33.6	58.1	41.9	31.5	68.5	32.6	67.4
W028--F	59	23.7	62.7	13.6	57.1	42.9	48.6	51.4	12.5	87.5
W026--F	6	83.3	0	16.7	40	60	0	0	0	100
W025--F	5	40	60	0	50	50	66.7	33.3	0	0
W024--F	6	50	33.3	16.7	0	100	50	50	100	0
W023--F	5	20	80	0	100	0	0	100	0	0
W022--F	19	10.5	89.5	0	50	50	29.4	70.6	0	0
W021--F	10	30	70	0	100	0	57.1	42.9	0	0
W020--F	29	20.7	75.9	3.4	16.7	83.3	59.1	40.9	0	100
W013--F	46	37	39.1	23.9	58.8	41.2	50	50	9.1	90.9
W012--F	39	17.9	33.3	48.7	85.7	14.3	15.4	84.6	21.1	78.9

The adaptive model limits were plotted based on the formulas presented in Subsection 3.3, and outdoor temperature data were obtained from the Royal Dutch Meteorological Institute at a location close to the measured dwellings. The graphs display the 90% acceptability neutral bandwidth and the results presented are for the living room, as most measurement points were obtained for this room. The graphs are presented for each label category by ascending order for thermal sensation, from 'cold' to 'warm' (when data were available). The tenants did not record any 'hot' thermal sensation scores during the measurement period. For the A/B-labelled dwellings, there were very few data points for the comfort levels 'cold' and 'cool' and, therefore, only the graphs from 'a bit cool' to 'warm' are presented.

§ 4.4.1.2 A/B-labelled dwellings

Figure 4.2 displays the neutral temperature bandwidth of the adaptive model, the indoor operative temperatures for the living rooms and the reported thermal sensations. For people who reported feeling 'a bit cool', 69% of the data points are in the neutral bandwidth, which means that according to the adaptive model the tenants should have taken appropriate measures to feel neutral (such as wearing a sweater). Despite this adaptive hypothesis, the tenants still reported that they felt 'a bit cool'. Furthermore, the indoor temperatures for dwellings W004 and W016 (A/B-labelled) were adjacent to the upper limit (the warmer side) of the adaptive model.

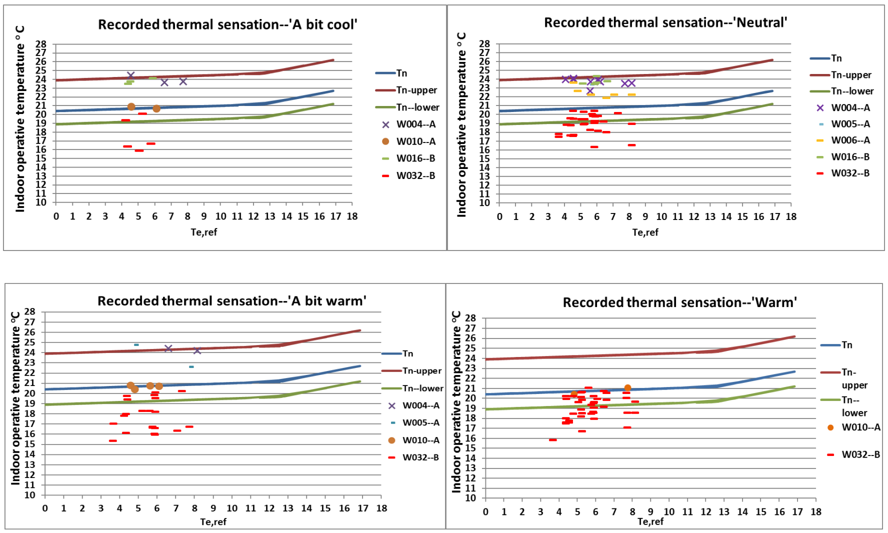


FIGURE 4.2 Adaptive thermal comfort model and indoor operative temperatures for the thermal sensations recorded in A/B-labelled living rooms

For 'neutral' thermal sensation, 73% of the data points are within the adaptive model's bandwidth, while the points that are not in the comfort band are below it. As we move further towards the warmer side of thermal sensation ('a bit warm' and 'warm'), we see the same trend, with some of the data points lying between the neutral temperature line and the lower limit of the comfort bandwidth, but the majority lying below the comfort band. It is noticeable that each dwelling remains in the same area of the graphic: for instance, WO32 is always at the lower side, while WO4 is always at the upper side.

Dwelling W004, at any level of recorded thermal sensation, had an indoor temperature in the upper limit of the adaptive model. W004 is a new dwelling with floor heating coupled to a heat pump and its tenants were elderly. The indoor temperatures of this dwelling constantly hovered around 24 °C to 25 °C for the whole day due to the continuous operation of the low hydronic system, and logically the adaptive model assumes that these people do or should feel neutral.

The comfort scores for dwelling W032 (a B-labelled dwelling with a natural gas boiler heating localized radiators, occupied by middle-aged tenants) show the opposite pattern to that of W004. For all levels of recorder thermal sensation, the corresponding temperatures are outside the comfort zone of the adaptive model (the occupants should feel too cold), while the temperatures that are within are all concentrated at the lower end of the comfort zone. The total number of reported thermal sensations recorded in this case was 107 and 95% were either neutral (35%) or at the warmer end of the seven-point comfort scale (60%), Table 4.3. The majority of both neutral and warmer scores were recorded after midday. Operative temperatures in this dwelling ranged between 16 °C and 21 °C.

The same trends would have been observed if an 80% acceptance level (approximately 1 °C wider at the lower and upper limits) was chosen as the comfort bandwidth, rather than the 90% we used here. While a few more data points would be in the 'neutral' zone, the graphs would not look much different.

§ 4.4.1.3 F-labelled dwellings

Similar tendencies to the A/B-labelled dwellings are observed for the F-labelled dwellings, Figure 4.3. Starting from the comfort perception of 'cool', 66% of the data points are below the comfort bandwidth, while the rest are within it. The more we move towards warmer thermal sensations, the more data points appear in the neutral bandwidth, with most of them in the graph for 'neutral' comfort sensation. The data points that are not in the comfort bandwidth are below the lower 90% neutrality limit, similarly to the A-labelled dwellings.

We see the same effect in dwellings W013 (46 scores) and W031 (128 scores) as in dwelling W032 (see A/B-labelled dwellings subsection). These dwellings had more evenly distributed reported thermal sensations between neutrality and the colder and warmer sides of the seven-point scale. The majority of the thermal sensations reported at the cold side were given before midday, while the majority of the neutral or warmer reported thermal sensations were given after midday.

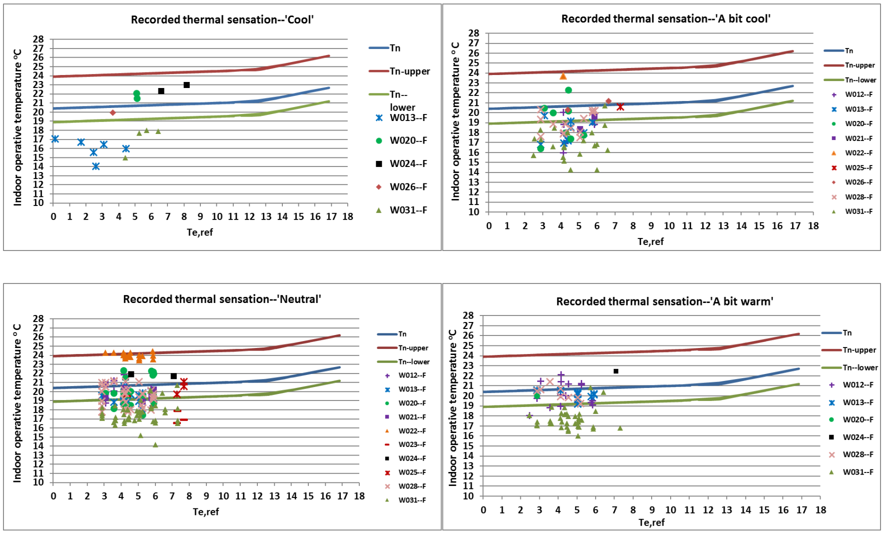


FIGURE 4.3 Adaptive thermal comfort model and indoor operative temperatures for the thermal sensations recorded in F-labelled living rooms

As mentioned above, the most important underlying assumption of the adaptive model is that people will take action to improve their thermal comfort by utilizing various adaptive opportunities. In Figures 4.2 and 4.3 we see elements that contradict this adaptive hypothesis. In all of the non-neutral thermal sensation graphs, there are many indoor temperature data points that are inside the adaptive model's comfort bandwidth. According to the model, these individuals have already taken the necessary action and should feel neutral. However, the participants felt 'cool', 'a bit cool', 'a bit warm' or 'warm'. Not feeling neutral might lead the tenants to further actions aimed to improve their thermal sensation, which could lead to additional energy consumption. It could also be that they feel more comfortable at these thermal sensations, than at a neutral thermal sensation, as already pointed out by de Dear [22]. When the people were asked in the initial survey how they feel in general about the indoor temperature during the winter, they characterized it as ‘good temperature’. This means that the occupants of W032 feel comfortable at temperatures that are deemed as non-neutral.

Both Figures 4.2 and 4.3 show that people still differentiate in their thermal sensation regardless of the indoor and the outdoor average temperature. This differentiation of their comfort seems to be due to other parameters than temperature such as metabolic activity, clothing, air speed, and physical or psychological tiredness. It may be that people control the temperature in such a way that they feel most comfortable (leading for instance to high temperatures in W004 and to lower temperatures in W032), but it may also be that people just get used to the temperature in their house (for instance the people in W004 had little control on the temperature). However, the small number of total scores recorded (15) does not allow for concrete conclusions on this matter. Further research and larger field experiments are required.

For all reported thermal sensations, cold or warm, the data points that are not in the neutral bandwidth are on the lower side of the graphs. This indicates that the adaptive model appears to predict better the colder side of thermal sensations but strongly underestimate the thermal sensation on the warmer side (tenants feel warm while the theory predicts they should feel cool).

§ 4.4.1.4 Conclusions about predicted and reported thermal sensations

Thus, the adaptive model seems to both overestimate and underestimate the adaptive capacity of tenants in relation to their thermal comfort. On the one hand, many of the reported thermal sensations that were neutral were not in accordance with the adaptive model. On the other hand, many of the reported thermal sensations that were non-neutral also contradicted the adaptive model, which predicted they should be neutral. The subjects of the Ecommon study had all the options at their disposal to improve their thermal comfort (clothing, actions such as having a hot or cold drink, control over thermostats and windows) and probably used many (if not all) of these options. It may be that the non-neutral sensations reported are experienced as completely acceptable by the occupants, belonging to a normal range of differing sensations. Therefore, these non-neutral sensations would not require any further adaptations, as they were considered comfortable. It is equally possible that the neutral sensations reported could have been experienced as uncomfortable, necessitating some adaptation. Such phenomena have already been mentioned by De Dear [22], and in our previous paper [1], we considered the possibility of indiscrimination between the thermal sensations of 'a bit cool', 'neutral' and 'a bit warm', which can also be seen in the ASHRAE RP884 database [30].

Another important finding is that if the adaptive comfort model had been used to assess whether the dwellings were comfortable, it would have led to conclusions not shared by the occupants. In response to the question, 'How do you feel about the indoor temperature of your apartment during the winter?' during the initial survey, almost all of the occupants of the 17 dwellings, with the exception of dwellings W012 and W013, thought it was a 'good temperature'. As mentioned in the introduction, one point of criticism of the adaptive model is that all of the parameters used by Fanger were condensed into indoor and outdoor temperatures. In the data for the above-mentioned dwellings, we see many discrepancies between actual and predicted data, leading to the suggestion that temperature alone might not be sufficient to predict accurately the comfort levels of tenants. Furthermore, this could be an indication of an inaccurate estimation of the tenants' adaptive capacity with respect to thermal comfort, or an overestimation of the thermal sensations occupants discriminate between, or it may relate to the fact that 'neutral' does not mean 'comfortable'. It might also be that the thermal sensations of 'a bit cool' and 'a bit warm', in the eyes of the occupants, are simple observations that do not suggest any wish for improvement.

§ 4.4.2 Adaptive model and indoor temperature

It was already apparent in Figures 4.2 and 4.3 that the indoor temperatures of specific dwellings were quite constant across the different thermal sensation levels reported. Figures 4.4 and 4.5 show the hourly outdoor temperature plotted against the hourly indoor temperature of a few of the A/B and F-labelled dwellings for the two weeks of measurement in March. The results for the other dwellings are similar. For an outdoor temperature range between -3 °C and 16 °C, the linear trend lines for the indoor temperatures of A/B dwellings showed a slight inclination while the ones from the F-labelled group show a bigger trend line slope. In line with the findings of Peeters [26], the slope at temperatures below 12,5 °C is very low, generally between 0.06 and 0.17. Additionally, and most important, Figures 4.4 and 4.5 show that the explanatory power of outdoor temperature on indoor temperature is very low: the R^2 values are low, meaning that the outdoor temperature is only for a marginal part responsible for the variance in indoor temperature. This in turn means that the indoor temperatures chosen by the occupants only marginally relate to the outdoor temperature.

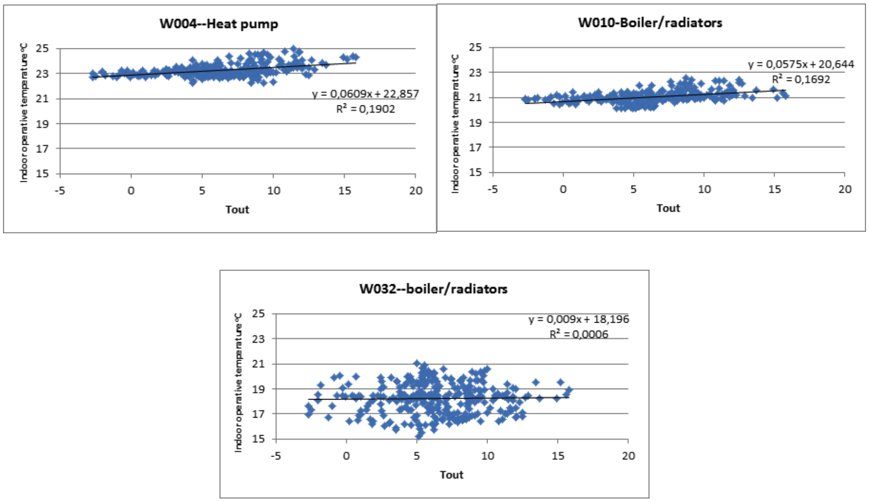


FIGURE 4.4 Indoor vs outdoor temperature for the A/B-labelled dwellings and corresponding regression line

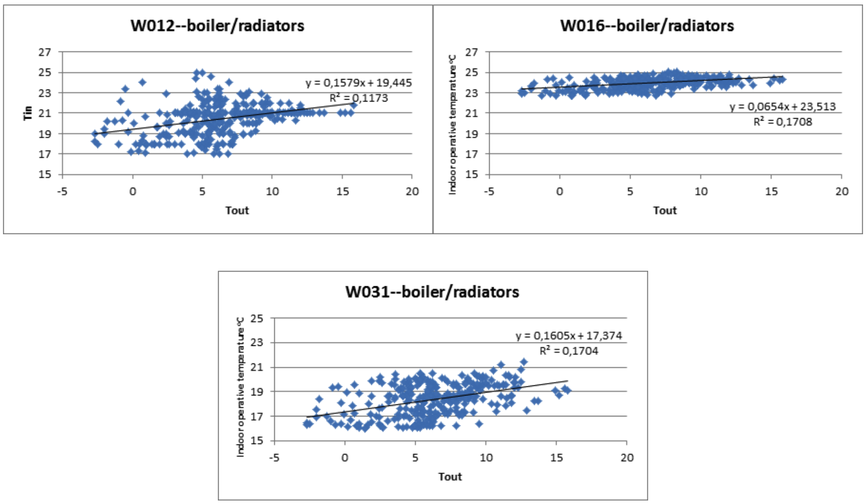
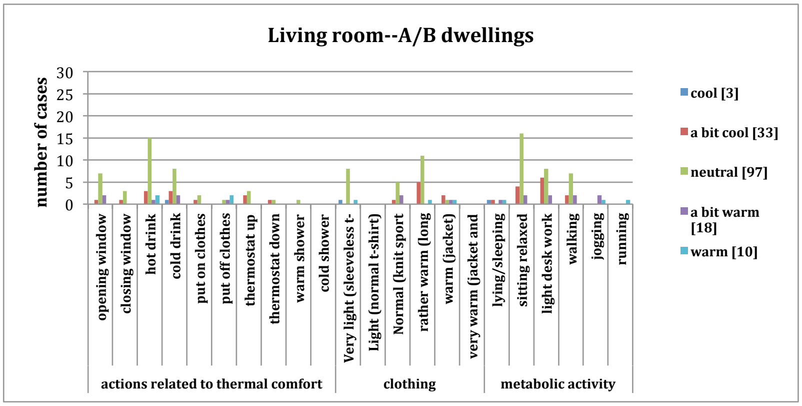


FIGURE 4.5 Indoor vs outdoor temperature for the F-labelled dwellings and corresponding regression line

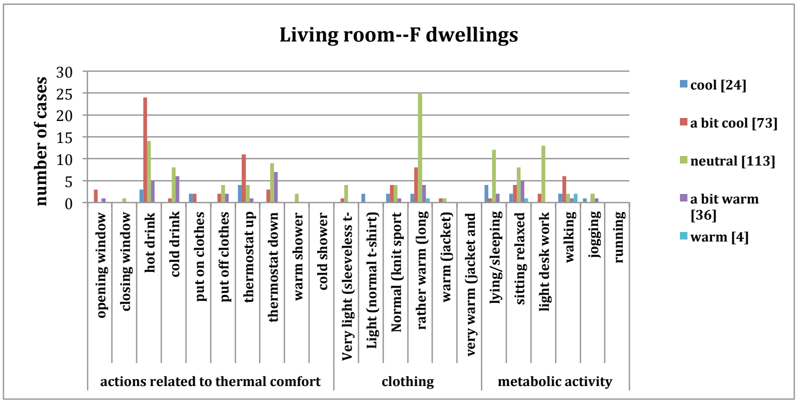
§ 4.4.3 Adaptive model and behavioral adaptations

As explained in Subsection 3.2, in addition to using the Comfort Dial, the tenants were also asked to note in a logbook the actions they had taken in the past half hour when registering their thermal sensation. Figure 4.6 presents an overview of the actions that could possibly influence thermal comfort, including clothing levels and the metabolic activity of the tenants. The legend of Figure 4.6 presents the total number of recorded data points per thermal sensation. It appears that tenants turned their thermostat up more often while feeling 'a bit cool' than when they were feeling 'cool' (which might be evidence of the difficulty in discriminating between 'a bit cool' and 'cool' thermal sensations). Furthermore, they turned their thermostat up when feeling 'neutral' and even when feeling 'a bit warm', which offers additional evidence of the habitual use of the thermostat. Having a hot drink was another popular action, with tenants doing so while reporting all of the four thermal sensations mentioned above, and the number of times they did this was higher for 'a bit cool' and 'neutral' than for 'cool'.

This could be an indication that tenants undertake specific actions, wear specific clothing or maintain specific metabolic activities due to habits developed over the long term, regardless of their reported thermal sensation; for example, having a coffee in the morning to wake up or after lunch to avoid afternoon sleepiness. The results presented in Figure 4.6 come from our relatively small sample of 17 dwellings. To go further than a simple description of this sample and attempt to detect whether there are any significant differences (at population level rather than sample level) in actions undertaken for different groups of reported thermal sensations, chi^2 tests were performed to explore possible habitual connections between actions aimed to create thermal comfort and the various levels of thermal sensation.



a



b

FIGURE 4.6 a+b: Overview of actions towards thermal comfort, clothing worn and metabolic activity of A/B and F-labelled dwellings for various thermal sensations

To perform the chi^2 analysis, categorical variables had to be converted into numerical values. The chi^2 for each action, clothing level, and metabolic activity was calculated by creating three categories for each test. The first category concerns the number of cases for each particular situation (the combination of an action, e.g. hot drink, and the reported thermal sensation). The second category indicates whether the person performed the specific action or not (1 if they had and 0 if not), while the third indicates the RTS (1 = warm, 2 = a bit warm, 3 = neutral, 4 = a bit cool, 5 = cool; the missing thermal comfort levels hot and cold are due to a lack of data for the respective RTS). The three categories were weighted based on the number of cases and then a chi^2 test was performed. Since many of the resulting chi^2 tables had more than 20% of cells with an expected count of less than five, Fisher's exact test was used instead of chi^2. Significance below 0.05 means that differences in action/ clothing/ metabolic activity between different RTS do not happen by accident. Figure 4.7 shows the results of the Fisher's tests.

TOC

A label	Actions and p value	0,114	0,245	0,01	0,038	0,279	0,884
		Thermostat up	Thermostat down	Hot shower	Very light clothing	Light clothing	Normal clothing
		0,068	0,23	1	0,067	-	0,266
		Rather warm clothing	Warm clothing	Lying sleeping/relaxed	Sitting relaxed	Light desk work	Walking
		0	0,209	0,012	0,001	0	0,065
		Jogging					
		0,195					
F label	Actions and p value	Opening window	Closing window	Hot drink	Cold drink	Put on clothing	Take off clothing
		0,062	1	0	0,419	0,004	0,94
		Thermostat up	Thermostat down	Hot shower	Very light clothing	Light clothing	Normal clothing
		0	0,624	1	0,65	0,004	0,11
		Rather warm clothing	Warm clothing	Lying sleeping/relaxed	Sitting relaxed	Light desk work	Walking
		0,224	0,511	0,013	0,297	0,072	0
		Jogging					
		0,303					

FIGURE 4.7 Chi2 tests performed to explore correlations between actions, clothing level or metabolic activity and RTS

Concerning the actions aimed towards thermal comfort, no correlations were found between the RTS and 'opening' or 'closing the window', 'take off clothing', 'turn the thermostat down' or 'having a hot shower' for both A/B and F label dwellings, which is a good indication that these actions are habitual and therefore not related to thermal comfort. Concerning clothing levels, no correlations were found between the RTS and wearing a very light, normal and warm combination of clothes while for metabolic activity, only jogging was unrelated to the RTS. Furthermore, the differences between labels A/B and F are conspicuous; only having a hot drink and lying sleeping/ relaxed are correlated with RTS on both labels. In A/B label dwellings, the only actions, clothing or metabolic activity that correlate to RTS are 'having a cold drink', wearing a 'rather warm clothing' ensemble (long-sleeved sweatshirt), 'sitting relaxed' and doing 'light deskwork'. In F label dwellings 'put on clothes', 'thermostat up', wearing 'light clothing' (T-shirt) and 'walking' correlate to the RTS. This indicates that in the A/B dwellings the conditions during the heating season are so good (e.g. operative temperature, air velocities) that people do not feel the need to undertake any additional action. In F buildings, which generally have a poorer thermal envelope, these actions are needed to increase comfort. It may also be that in the A/B-labelled dwellings, which are well insulated and air-tight, the temperature can only be adjusted very slowly and the tenants of these dwellings know that changing the thermostat set point will have no immediate impact on their comfort.

'Opening the window', which is another factor that could affect the energy consumption of a dwelling, was not related to the reported thermal sensation level for either the A/B or F-labelled dwellings. Thus, people probably open the window out of habit to ventilate the room, regardless of their thermal sensation. However, turning the thermostat up was related to the reported thermal sensation level in the F-labelled dwellings. The tenants of these dwellings used the thermostat to improve their thermal sensation, but this occurred more often when they felt 'a bit cool' rather than 'cool'.

Turning the thermostat down was not related to the RTS, therefore, we can assume that tenants turned the thermostat down out of habit.

For the clothing combinations, only the wearing of rather warm (long-sleeved sweatshirt) was related to the RTS and the majority of the cases were recorded for 'neutral' thermal sensation, followed by 'a bit cool'. This means that there were significantly more people wearing a long-sleeved shirt in the categories of 'neutral' and 'a bit cool' than in other categories. Finally, for the metabolic activity, 'lying sleeping/relaxed', 'sitting relaxed' and 'light desk work' were found to be significantly related to the RTS. For 'neutral' thermal sensation, the majority of the tenants said they were just 'sitting relaxed', followed by 'light desk work'.

§ 4.4.3.1 Clothing in relation to outdoor temperature

To further study whether clothing worn inside the dwelling relates to outdoor temperature, the clothing and metabolic activity levels recorded by the tenants were plotted in relation to the outdoor temperature as well as the thermal sensation for each data point. Figure 4.8 shows the plot between outdoor temperature and clothing for the F-dwellings. The results for the A-labelled dwellings are similar. The outdoor temperatures are presented on an hourly basis, as it was the smallest granularity available from the Royal Dutch Meteorological Institute. The clothing level at a given moment (for example at 2.35 p.m.) was plotted against the corresponding hourly outdoor temperature for that data point (in this case against the hourly value for outdoor temperature between 2 p.m. and 3 p.m.). During the non-sleeping hours in which tenants recorded their clothing levels (clo), the outdoor temperatures varied between 2.5 °C and 15 °C. Indoor temperature for A/B-labelled dwellings varied between 19 °C and 25.5 °C, while for F-labelled dwellings it was between 16 °C and 25.5 °C. The clothing level for both A/B and F-labelled dwellings was between 0.5 and a little over 0.6 clo. The outliers (heavier clothing values) that appear further away from the major clusters probably reflect clothing people were wearing when they were outside the dwelling, having only recently returned, and not due to low indoor temperatures. This means that for this period of two weeks in March, regardless of the thermal quality of the dwelling and the indoor temperature, people had a consolidated clothing pattern, which did not change despite the 13 °C difference in outside temperature. This does not mean that the indoor clothing patterns do not relate to the outdoor temperature at seasonal level. However, when the adaptive model is used to assess the performance of houses, which generally can only be done using a shorter period of measurements, one cannot assume that clothing is dependent on outdoor temperature, even if the temperature range is high.

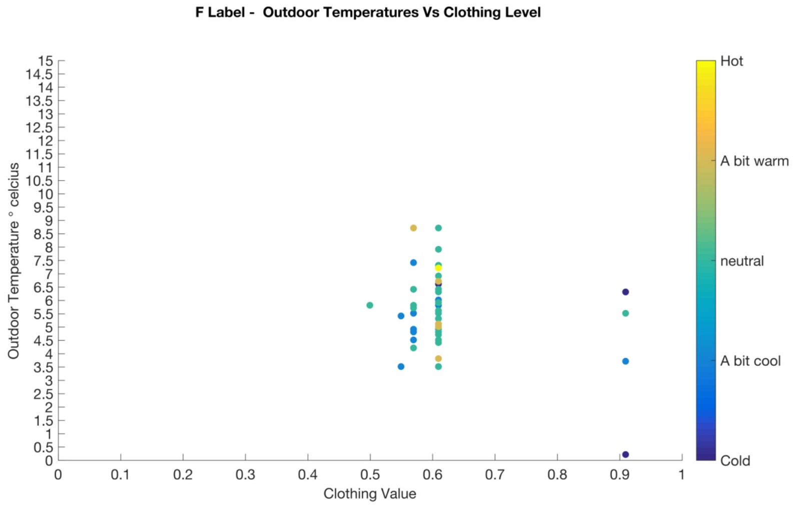


FIGURE 4.8 Clothing level versus hourly outdoor temperature for A/B and F-labelled dwellings per RTS

§ 4.5 Discussion, conclusions and recommendations

In our sample, the adaptive model predicted that tenants would have thermal sensations at the cold end, while the tenants themselves recorded sensations at the warmer end such as 'a bit warm' or 'warm'. While many data points were inside the comfort band of the adaptive model, the thermal sensation scores corresponded to comfort levels other than 'neutral'. At the same time, many tenants recorded 'neutral' thermal sensations when the indoor temperatures were below the lower limits of the adaptive model. The model might thus be both overestimating and underestimating tenants' adaptive capacity in relation to achieving thermal comfort. It was also found that the explanatory power of outdoor temperature on indoor temperature was very low, and that clothing did not related to outdoor temperatures.

A limitation of this study was its short time span, by which it does not allow to refute or validate the adaptive model, as described by de Dear [2] which was aimed at modelling seasonal and regional differences. However, this model has been used since as a design and assessment guideline in which hourly values of the operative temperature are plotted against the reference outdoor temperature. The use of the adaptive model for the dwellings of this study would lead to considering some of them as being out of the comfortable zone in March, while occupants reported feeling 'neutral'. Although our sample, by its small size and its characteristics, cannot claim to be representative for all dwellings in the Netherlands, it has been possible, by using the Fisher's test, to indicate which actions can be considered habitual or do relate to thermal sensation. Extending the study to more dwellings, our measurement method, by which the reported thermal sensation is measured many times a day and coupled to physical data, will allow the collection of more accurate data on actual comfort. Furthermore, the MRT and air velocities were not measured in situ. This was compensated by building simulations with Energy+ [31], but these parameters should be measured in further studies.

De Dear [18,22] mentions that the adaptive model does not really provide any insight into why certain conditions will be comfortable or acceptable, other than a broad generalization that they conform to occupants' expectations. The indoor temperatures would lead the adaptive model to assume that the tenants were comfortable, having already performed the adaptive actions aimed to create thermal comfort and a 'neutral' thermal sensation. Yet, this was not the case, and the tenants' non-neutral feelings might lead them to perform additional acts, which could come at the expense of energy consumption, especially because the tenants in the monitoring study reported that economic factors played no role in their energy consumption.

The expectation aspect of the adaptive model relative to outdoor temperature lacks a solid foundation, a finding supported by several other studies [3,16]. The proposition of this study is that elements of expectations should also be explored with respect to the ideal indoor conditions and the thermal comfort level that tenants have consolidated in their minds. Furthermore, local behavioral, social and psychological aspects should be explored to create a robust expectation factor for residential dwellings, which can subsequently be validated by field experiments similar to the Ecommon study. However, one should keep in mind that the technical systems installed in residential dwellings might induce self-fulfilling prophecies. If the dwellings are equipped with constant temperature systems, the occupants will take this for granted and no adaptability to outdoor temperature will be observed, while such adaptability might exist and demonstrated by studies of dwellings that do have this adaptation possibility. The fact that in our sample (see our preceding paper [1]) the indoor temperatures in the A/B-labelled dwellings are higher than in the F-labelled dwellings and that there were not more people feeling non-neutral in the F dwellings indicates this adaptation possibility.

Finally yet importantly, a rethinking of the theoretical background of the adaptive model is required if it is to be applied to residential buildings. Despite the fact that they account for a very large share of energy consumption in the EU, residential buildings have been treated up to now if they were similar to office buildings when it comes to thermal comfort models. The equations used are developed based on office buildings, while it is clear that the use of space, the activities undertaken, clothing worn, and actions aimed to improve thermal comfort differ in these two types of buildings. Future research must aim to develop and validate new equations that take the specific qualities of residential buildings and their inhabitants into account.

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5 Behavioral patterns relating to thermal comfort and energy consumption

§ 5.1 Introduction

Since the introduction of computers, the way research is performed has changed significantly. A huge amount of data can be gathered and handled by a computer, compared to the situation before these machines were commonly available to scientists and households. Every interaction with a computer system or sensor can be recorded, resulting to an abundance of data that has already surpassed the human capability to analyze and understand them. Computers are not only used for monitoring, creating and recording data but also they have become the tool to analyze these data with the use of certain automations that otherwise would make the data analysis take years.

This abundance of data has led to a new field in research, related to scientific methods and processes aiming at extracting knowledge from data in various forms [24], known as data mining. Data mining techniques have been developed to perform sequential pattern mining by processing time-ordered input streams and discover the most frequently occurring patterns [1] in applications such as healthcare, education, web usage, text mining, bioinformatics, telecommunications and other applications [17]. When data contain temporal information then they may hide additional interesting characteristics such as periodicity. A great deal of nature behaves in a periodic manner, the orbit of earth around the sun, the spinning of the planet around its axis and further on division of this periods into years, days, hours and so on. These strong periodic elements of our environment have led people to adopt periodic behavior in many aspects of their lives such as the time they wake up in the morning, the daily working hours, the weekend days off, the weekly sports practice, watching your favorite sports events or fiction series on TV every week at the same time. These periodic interactions could extend in various aspects of our lives including the relationship of people with their home thermal environment. What are the periodic elements in people's lives concerning the temperature inside their dwelling, their clothing and metabolic activity patters, their actions towards improving thermal comfort such as opening or closing windows, having a hot or cold drink or having a hot or a cold shower? These periodic elements could probably exist and are waiting to be found if a huge amount of data could be recorded and was available for analysis. Computers nowadays are powerful enough and new mathematical methods have been developed to take advantage of this rise in computational power. Therefore, data collected by system of sensors and computers, related to the interactions of people and their residential environment could contain patterns that exhibit periodic behavior.

Recently there has been extensive research on the development of smart built environments. The goal was to reduce the energy consumption of dwellings and at the same time maintain the maximum possible comfort level for the occupants. Occupant behavior in buildings has large impact on energy consumption (space heating or cooling, ventilation demand, lighting and appliances) [2]. A number of studies have been published using stochastic models in order to model occupant presence and its interaction with space appliances and equipment.

However, all these studies were either tested in a single person office or were focused only on a specific application (occupancy [3,5,7,8], lighting [5,6,8], ventilation [4,8] etc.). Most of these works are based on the 'supervised' approach, which means that machine learning occurs by providing a set of data, and for each input value, the user provides also the output value. An (supervised) algorithm is then used to train the model and produce an inferred function, which can predict the output data when new input data is used. This method requires ground truth input data in order to be successful. For example, when talking about occupancy prediction models, the data are often based only on motion sensor readings, which could fail to detect occupants that are sitting or standing still [9]. A more complicated sensor network that includes CO_2 and humidity sensors is needed in order to have more robust occupancy and behavior detection in the residential environment than motion sensors alone [26]. The unsupervised approach on the other hand is a machine-learning task in which the user provides only input and no output data. The algorithm then is able to find the structure or relationships between the different inputs.

A smart environment, in the built environment context, is defined as an environment that is able to acquire and apply knowledge about the tenants and their physical surroundings in order to improve the tenant's experience [10] and in our case to provide insights that could lead to potential energy savings. Such an experimental network of smart environments was created during the Ecommon (Energy and Comfort Monitoring) measurement campaign, which took place in the Netherlands as part of the Monicair [11], SusLab [12] and Installaties 2020 [13] projects. Thirty-two residential dwellings were monitored for a 6-month period, from October 2014 to April 2015, which is the heating season for north Western Europe.

This study is a continuation of the work made by Ioannou et al. [14,15] under the Ecommon measurement campaign. In the above-mentioned studies, the authors used the subjective and quantitative data related to thermal comfort to test the prediction success and the underlining assumptions of the two models widely used in this field, the PMV and the adaptive model. According to the adaptive model's main hypothesis, people are expected to perform the necessary actions, when feeling uncomfortable, that will bring them to neutral comfort sensation. Many tenants, however, had recorded "neutral" thermal sensation while the indoor temperatures were below the lower limit of the adaptive model. Furthermore, while many data points were inside the comfort band of the adaptive model, the thermal sensation votes recorded by the tenants showed comfort levels other than "neutral". Could the adaptive model be poorly estimating the tenants' adaptive capacity in relation to thermal comfort? Despite the fact that they had all kinds of options in their disposal (adjusting clothing, metabolic activity, opening or closing windows, turning up or down the thermostat, having a hot shower etc.) and the temperature was inside the comfort bandwidth, they still voted for comfort sensations other than "neutral". It could be that they exercised their adaptive options at their disposal and these were just not enough to make them feel comfortable because other parameters such as psychological ones could have a great impact. It could be the case that they did not do any of those actions. In both cases the indoor temperatures were leading the adaptive model to assume that the tenants were comfortable, having already done their adaptive actions towards thermal comfort and having "neutral" thermal sensation. But tenant's non- "neutral" feeling might lead them to take extra actions which could always come at the expense of energy consumption (especially when the tenants in the monitoring campaign answered that the economic factor plays no role in their energy spending) [14,15].

Furthermore, a statistical analysis was made with chi^2 tests between the various actions towards comfort and the thermal sensations recorded by the tenants during the monitoring campaign in order to find out which of these actions took place habitually and which were aimed towards improving thermal comfort. For example, the indoor temperature during the morning hours in some dwellings was above 20 ^{o}C, however, tenants were waking up and as a first thing they were turning up the thermostat. Moreover, other habitual actions, such as having a hot shower and opening the window, were found to be unrelated to thermal comfort and related to increased energy consumption.

The aim of this paper is to go a step further in this direction. Repetitive behavioral actions in sensor rich environments, such as the dwellings of the Ecommon measurement campaign, can be observed and categorized into patterns through data mining techniques. These discoveries could form the basis of a model of tenant behavior that could lead to a self-learning automation strategy [16] or better occupancy data to be used for better predictions of building simulation software such as Energy+ or ESP-r and others.

§ 5.2 Study design

Heierman et al. [1] described a sequential pattern mining approach that was borrowed from economics [18] and applied in the context of the built environment. An example of a sequential pattern mining application in economics is used by major supermarket chains. These supermarkets monitor the purchases of their clients (usually by a discount card in which supermarkets store information) and by applying pattern mining they try to find at a specific time of the day, which are the purchase patterns of the customer. For example, at 13:00 when the customer A is buying cheese it is most likely that he will also buy bread and orange juice. Specific patterns can be defined for the various times of the day. The same customer during the early morning hours could have a specific purchase pattern, buying for example croissants and orange juice while during the evening hours he could be buying vegetables and chicken. In the context of the built environment, the customer A can be substituted by a specific dwelling. The products that the customer can buy can be substituted by quantitative data like specific ranges in temperature (for example 18 °C $<T_{in}<$20 °C or $T_{in}>$20 °C) or by subjective data (clothing and metabolic activity levels and actions such as opening or closing a window, having a hot shower or a hot drink).

In this study, real time data obtained by a seasonal monitoring campaign on the built environment will be implemented on the above-mentioned methodology in order to gain insights in the occupant behavior related to energy consumption of the residential sector. The main aim of this study is to demonstrate if such a pattern recognition algorithm is suitable for discovering meaningful patterns of occupancy behavior. Furthermore, this study will try to explore how these patterns can be used to improve the energy simulations for the prediction of energy consumption in the built environment.

§ 5.2.1 Research Questions and goals

The research questions and sub-questions are formulated as follows:

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:

- 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?

2 Estimate how building energy simulations can be improved by this methodology.

§ 5.2.2 Ecommon Campaign set-up

Detailed information on the Ecommon campaign set-up, the data acquisition set, and the subjective and quantitative data gathered during the campaign can be found in the previous chapter of this thesis.

The dwellings that participated in the measurement campaign were part of the Dutch social housing stock which represents about one third of the total residential units and it is quite representative of the residential stock as a whole [27]. The sample was divided into energy A/B-rated and F-rated dwellings (Ioannou and Itard, 2017 [14]) and the final sample of the dwellings is described in Table 5.1. Finally, only seventeen dwellings were included in the analysis due to data limitations.

TABLE 5.1 Dwellings participating in the Ecommon campaign

	NO.	ENERGY RATING	HEATING SYSTEM	NO. OF OCCUPANTS	AVERAGE AGE OF HOUSEHOLD	NO. OF DATA POINTS	
						Morning hours	Evening hours
	W004	A	Heat pump	2	67	135	167
	W005	A	Condensing gas boiler	1	92	109	61
	W006	A	Condensing gas boiler	2	77	166	157
	W010	A	Condensing gas boiler	2	29	96	80
	W016	B	Condensing gas boiler	2	70	173	131
	W032	B	Condensing gas boiler	3	39	8	16
Total A/B dwellings	–	–	–	2	62.33	687	612

>>>

TABLE 5.1 Dwellings participating in the Ecommon campaign

	NO.	ENERGY RATING	HEATING SYSTEM	NO. OF OCCUPANTS	AVERAGE AGE OF HOUSEHOLD	NO. OF DATA POINTS	
						Morning hours	Evening hours
	W012	F	Condensing gas boiler	4	40.5	295	482
	W013	F	Condensing gas boiler	3	53.3	291	332
	W014	F	Gas stove	1	83	35	26
	W020	F	Condensing gas boiler	2	74	323	258
	W021	F	Condensing gas boiler	2	73	118	273
	W022	F	Condensing gas boiler	2	64	171	301
	W024	F	Condensing gas boiler	1	72	89	105
	W025	F	Gas stove	3	43	67	70
	W026	F	Condensing gas boiler	4	21	65	85
	W028	F	Condensing gas boiler	2	72	174	190
	W031	F	Condensing gas boiler	3	43	958	1924
Total F dwellings	–	–	–	2.5	58	2586	4046

§ 5.3 Sequential Pattern Mining

Sequential pattern mining methods have applications in many fields. A very common goal when using sequential mining is the discovery of the most frequent patterns [18,19]. The more frequent an event, the more important it is and more likely to be a pattern. During the analysis of time-stamped data it is important to know if event (a), event (b) and event (c) occurs frequently but it is more intriguing to know how often the event (a, b), (a, c) or the event (a, b, c) occurs. Furthermore, knowledge on the most frequent combinations of events over time, adds even more value to the analysis.

In market research, this would mean not only knowledge on which are the most common product combinations that a customer buys in his visits to the shop, but also knowing in which part of the day these occur. Customers usually buy different things in the morning and different ones in the evening and in that way shops can create tailor made marketing strategies to increase sales. In the context of the built environment this would mean that instead of tracing combinations of events that might occur in a dwelling in a whole day (which could have limited use in terms of improving thermal comfort and reducing energy consumption), now we can target specific hours and see the behavior of tenants in different periods of the day.

The algorithm that was used for the mining of sequential patterns in this study is the Generalized Sequential Pattern (GSP) algorithm [21], which is an enhanced version of the a *priori* algorithm suggested by Agrawal and Shrikant [20]. The methodology for the application of the specific technique in the context of the built environment has been described by Heierman et al. [1] but it lacked any experimental demonstration. The Ecommon campaign provided enough built environment related data that could be implemented in the above-mentioned methodology.

Input parameters

The time parameter and the customer id are inputs to the algorithm. With this pair of parameters, the algorithm is generating a sequence per customer containing every transaction made in a specific time. Then the algorithm searches sequential patterns such as: if customer A bought the item (a) and item (b) in a transaction, he bought item (c) in the next one.

Another input parameter is the *minimal support*, which describes how many customers must support a pattern in order for the algorithm to regard it as frequent. It takes values between 0 and 1 with 1 being the 100% of the customers. If we set for example the minimal support to 0.9 the algorithm will *prune* all the patterns that are supported by less than 90% of the customers.

Furthermore, three remaining input parameters are defining how transactions are handled. These are the *min-gap*, the *max-gap*, and the *window-size*. The *window-size* defines the period within successive transactions could be considered as a single transaction. For example, if a customer bought some products (a, b, c) but forgot to buy the product (d) and comes back after 10 minutes to buy this remaining product then the question is: will this transaction be treated as a completely new one or it will be added to the previous one? In order to avoid this issue the *window-size* determines how long a subsequent transaction is treated as the same transaction. In the above example if the *window-size* is larger than 10 minutes then buying the product (d) will be treated as part of his initial transaction when he bought (a, b, c).

The *max-gap* parameter is used in order to filter out large gaps in data sequences. For example, a customer bought the product (a) and despite that he is within the specified *window* there is a very large gap between buying the product (b) which is his new transaction. For a business owner this huge gap, even if it is inside the *window size*, might still make the customer uninteresting. Therefore, this is an extra tool of the GSP algorithm when seeking supported sequences. The *max-gap* parameter causes sequences not to support a pattern if the transactions containing this pattern are time-wise too widely separated. The same applies for the *min-gap* parameter for the sequences that belong to transactions that time wise appear too near.

The concepts of the *window-size*, *min-gap* and *max-gap* parameters were the most important upgrades of the apriori algorithm, introduced by Agrawal and Shrikant [18], and led to the GSP algorithm [21]. These concepts helped to overcome important weaknesses of the apriori algorithm such as the absence of time constraints and the rigid definition of a transaction. The apriori algorithm has no time constraint, which means that the data source is a time ordered input sequence with no natural points that indicate the start or stop of the pattern. Furthermore, the user cannot specify a minimum or a maximum time gap for two adjacent elements of a sequential pattern. For example, if we were applying the apriori algorithm in the transactions of a library where a person borrowed the book (a) and then he borrowed another one after three years the algorithm would still show (a, b) as a potential pattern if the window size was three years. However, such a pattern has such a major gap between the transactions that it does not really add substantial knowledge to the library concerning the borrowing patterns of people. Setting the minimum or maximum gap into, for example, three months will automatically prune all the patterns that are not supported from this time gap and are not of interest to the library.

The rigid definition of the transactions as mentioned above is related to the *window-size*. This parameter sets the time window within successive transactions to be treated as a single transaction. For example, a person that borrows book (a) from a library, book (b) next week and book (c) the week after. If the user sets the *window-size* to three weeks then the supported pattern for that person would be (a, b, c). If the window size was two weeks then the supported patterns would be (a, b) and (c). This concept adds greatly to the flexibility of the analysis and offers much more options to the user that is mining for sequential patterns.

§ 5.3.1 Sequential pattern mining in the context of the built environment

In order to make use of an algorithm developed for the retail industry in the context of the built environment first all the input parameters have to be defined in the respected context. Furthermore, the data have to be transformed into the right format in order to be handled by the algorithm.

Input data

In the retail context the customer buys various products (transactions) in specific hours and based on his frequent combinations transaction patterns are mined. In our case, the transactions are called *events* and our customers are the people of the seventeen, dwellings that participated in the monitoring campaign. The various 'products' that our 'customer' (dwelling) can 'buy' are temperature range, recorded thermal sensation, actions towards thermal comfort, clothing, and metabolic activity levels.

Temperature Range: Houses of A/B and F label have usually a temperature range from 18-24°C which for the purposes of the pattern mining was broken down into bins of 2 °C (18 °C – 20 °C, 20 °C – 22 °C and 22 °C – 24 °C) at a given time.

- Recorded thermal sensation: is the vote casted by the occupant according to his thermal sensation at a given time of the day. It can be distinguished into 'cold', 'a bit cool', 'neutral', 'a bit warm' and 'hot'.

- Actions towards thermal comfort: Several actions that the occupants could choose towards the improvement of their thermal comfort were predefined in the comfort logbook. The options were opening or closing a window, having a hot or cold drink, put on or put off clothes, turning the thermostat up or down, having a warm or cold shower.

- Clothing: Tenants could choose from a set of predefined clothing items, which were closest to the clothing ensemble that he/she was wearing at a specific moment. The options were sleeveless t-shirt, t-shirt, knit sport shirt, long sleeved sweatshirt, jacket, jacket and hood (Table 5.2).

- Metabolic activity: occupants could also choose from a set of predefined metabolic activity levels. These levels were lying/sleeping, sitting relaxed, light deskwork, walking, jogging, running (Table 5.2).

All the above answers were given by the occupants every time bearing in mind the last 30 minutes.

All the input data for the GSP algorithm have to be binominal (nominal with two possible values, true or false). This means that the data, quantitative and subjective, had to be properly transformed to be compatible with the GSP algorithm input requirements. As already mentioned in section 2.2, the quantitative data (temperature, humidity, and CO_2) are real numbers obtained by a set of sensors with a 5-minute interval for a period of six months between October and April. For the purposes of this study, the temperature was the quantitative measurement that was used in the GSP calculations. In order to transform the temperature into binominal data the following process took place: the 5-minute interval data were aggregated into hourly values for the whole period of two weeks and then three bins of temperatures were defined (18<T<20, 20<T<22, T>22). If the temperature in a specific hour was, for example, between 18 °C and 20 °C then the 18<T<20 bin would take the value TRUE (for this specific hour) and the rest of the bins would take the value FALSE. The procedure is repeated until all the hourly values under the four temperature bins are transformed into TRUE or FALSE. The reasons for the hourly aggregation of the data were that the previous research of the authors [11,14,15] was based on hourly aggregation of the data due to their large volume. Furthermore, the hourly time-step is a very common time-step during building simulations and one of the major goals of the Ecommon, Monicair and Installaties2020 projects was the improvement of the prediction quality of the simulation software for the built environment. Therefore, for consistency between our goals and results so far we chose to use the hourly aggregation of the data also in this study. Furthermore, only the data that were accompanied by recorded motion data were used for the analysis in this study.

The subjective data were transformed in similar way with the difference that the bins in this case were the subjective data themselves. Thermal sensations, actions towards thermal comfort, clothing, and activity level are categories that can take binominal values for each hour of the day. For example, if a tenant has recorded that he feels 'neutral' within the 5-minute interval between 13:30 and 13:35 then for the 13th hour the value under 'neutral' bin would be TRUE while the value under all other thermal sensations would be FALSE. The same applies for the clothing, activity levels, and actions towards thermal comfort. If within the 5-minute interval between 13:30 and 13:35 of a day a tenant recorded that he wears 't-shirt' and is 'sitting relaxed' then the value under the 't-shirt' and 'sitting relaxed' bins for the 13th hour of that day would be TRUE and all the other clothing and metabolic activity options would take the value FALSE. Also, if during the 5-minute interval of an hour an occupant recorded that he has opened the window, or turned the thermostat on then at that specific hour the values of 'open window' and 'thermostat up' would be TRUE and all the rest of the actions would be false.

One limitation of this approach was, as mentioned already, that tenants were instructed to fill in the subjective data based on what they did the previous half an hour. The recording of the thermal sensation is not affected by this directive, when an occupant recorded that he felt 'neutral', 'a bit cool' or 'cool' he was recording his instantaneous thermal feeling. However, for the rest of the subjective data such as actions towards thermal comfort, clothing, and activity levels recorded data at the 13:15 hours could mean that some of these actions such as 'close window' or 'open window' could have occurred before 13:00 hours. For the clothing it is more likely that tenants recorded what they were wearing at that exact moment with the exception of 'jacket' which indicated most of the times that people were outside and came home with in the last half hour. Nevertheless, the actions towards thermal comfort could have a delay up to half an hour. The general assumption for the purposes of this study was that during the hourly aggregation when an action, clothing or metabolic activity appeared within a specific hour's 5-minute interval then it was eventually assigned in this hour. The reason for this was that we had no way to determine the exact time an action, clothing or activity levels took place from the time it was recorded and the previous half hour. This problem could have been even more evident if we had not aggregated the data into hourly values. As already mentioned, prior research has taken place in hourly values and hourly values is a very common time step for simulation software. With hourly aggregation every action, clothing and metabolic activity recorded with timestamp in the second half hour (for example after 13:30) it had most chances to have occurred within this hour rather than before 13:00.

Finally, for the analysis not all the hours of the day were used partly because that would require a very big data file and slow computational time and partly because not all the hours of the day are of the same importance. As already mentioned only the data points with motion were kept for the analysis. Further filtering removed all the data points that had no subjective data recorded. Hourly data of thermal sensation, actions towards thermal comfort, clothing and metabolic activity that had only FALSE values were removed from the analysis. Each hourly value in order to be used for further analysis should have at least one TRUE value in the subjective parameters.

From occupant behavior related to thermal comfort point of view the most interesting hours of the day are the early morning hours when people wake up and the early evening hours when people return from work. In that sense, the morning hours between 7-9 a.m., for each day of the two weeks that occupants were given the comfort dial, were chosen for the morning analysis and the 5-7 p.m. were chosen for the evening analysis. In Table 5.2, we can see a data set example with all the necessary transformations that was used by the GS algorithm for the purposes of this study.

TABLE 5.2 Example of input file for (morning hours) sequential pattern mining with the use of the GSP algorithm in the context of residential built environment

			TEMPERATURE RANGE			THERMAL SENSATION			ACTIONS TOWARDS THERMAL COMFORT			CLOTHING			METABOLIC ACTIVITY		
Customer id (dwelling number)	DAY	TimeStamp (hour)	T<18	18<T>20	....	cold	A bit cool	....	Open window	Thermostat up	....	t-shirt	jacket	....	Sitting relaxed	Light desk work	....
5	1	7	TRUE	FALSE	...	TRUE	FALSE	...	FALSE	TRUE	...	TRUE	FALSE	...	FALSE	FALSE	...
5	2	7	FALSE	TRUE	...	FALSE	FALSE	...	FALSE	TRUE	...	FALSE	FALSE	...	FALSE	FALSE	...
5	3	7	TRUE	FALSE	...	FALSE	FALSE	...	FALSE	TRUE	...	TRUE	FALSE	...	FALSE	TRUE	...
5	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
5	1	8	TRUE	FALSE	...	FALSE	FALSE	...	FALSE	FALSE	...	FALSE	TRUE	...	TRUE	TRUE	...
5	2	8	FALSE	TRUE	...	FALSE	FALSE	...	FALSE	FALSE	...	FALSE	FALSE	...	TRUE	TRUE	...
5	3	8	FALSE	TRUE	...	FALSE	FALSE	...	FALSE	FALSE	...	FALSE	FALSE	...	TRUE	TRUE	...
5	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
5	1	9	FALSE	FALSE	...	FALSE	TRUE	...	TRUE	FALSE	...	FALSE	TRUE	...	TRUE	TRUE	...
5	2	9	TRUE	FALSE	...	FALSE	FALSE	...	FALSE	TRUE	...	FALSE	FALSE	...	TRUE	TRUE	...
5	3	9	FALSE	TRUE	...	FALSE	FALSE	...	FALSE	FALSE	...	TRUE	FALSE	...	FALSE	FALSE	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
8	1	7	FALSE	TRUE	...	FALSE	FALSE	...	TRUE	FALSE	...	FALSE	FALSE	...	TRUE	FALSE	...
8	2	7	TRUE	FALSE	...	TRUE	FALSE	...	FALSE	FALSE	...	FALSE	FALSE	...	FALSE	FALSE	...
8	3	7	TRUE	FALSE	...	TRUE	TRUE	...	TRUE	FALSE	...	FALSE	FALSE	...	FALSE	FALSE	...
8	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
8	1	8	TRUE	FALSE	...	FALSE	FALSE	...	FALSE	FALSE	...	FALSE	TRUE	...	TRUE	TRUE	...
8	2	8	FALSE	TRUE	...	FALSE	FALSE	...	FALSE	FALSE	...	FALSE	FALSE	...	TRUE	TRUE	...
8	3	8	FALSE	TRUE	...	FALSE	FALSE	...	FALSE	FALSE	...	FALSE	FALSE	...	TRUE	TRUE	...
8	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
8	1	9	FALSE	FALSE	...	FALSE	TRUE	...	TRUE	FALSE	...	FALSE	TRUE	...	TRUE	TRUE	...
8	2	9	TRUE	FALSE	...	FALSE	FALSE	...	FALSE	TRUE	...	FALSE	FALSE	...	TRUE	TRUE	...
8	3	9	FALSE	TRUE	...	FALSE	FALSE	...	FALSE	FALSE	...	TRUE	FALSE	...	FALSE	FALSE	...

The customer id, as mentioned already, denotes the dwelling under monitoring, the timestamp shows the hour under consideration (e.g. 7 means the 7th hour of the day between 6 a.m. and 7 a.m.) and the rest of the columns show the quantitative and subjective parameters that have been transformed into binominal values for the GSP algorithm simulation. In the end, there is one input string per dwelling per day per timestamp. Temperature range and thermal sensation can have only one value that can be true for each timestamp while for the rest of the parameters more than one is possible. Furthermore, in Table 5.3 we can see the taxonomy that was used for this analysis. The analysis took place for the A/B and F dwellings for the morning and evening hours respectively.

Input Parameters

The *Customer-id* is the first input parameter. Originally, this would be the customer of a retailer as already mentioned. For the purposed of this study the customers are the seventeen respondents of each of the seventeen dwellings that were monitored during the campaign.

The *timestamp* would be the time that a retail customer would make a transaction. In our case, the quantitative data that were gathered by the wireless sensors had a granularity of 5 minutes. The data were aggregated into hourly values and so the *timestamp* could get a value between one and twenty-four with one being the first hour of the day between 00:00 and 1:00 am and 24 being the last hour of the day between 23:00 pm and 00:00.

The *minimal-support* that was used for our analysis was adjusted for each simulation until we were able to find the highest support between dwellings that was giving meaningful patterns. We started with 0.9 (which means that 90% of the dwellings support a pattern) and run one simulation each time reducing the minimal support by 0.1 at a time until meaningful patterns were revealed.

The *window-size* was assumed zero, which means that the three hours of the morning (7-9 a.m.) period and evening period (5-7 p.m.) were treated as a single time window. The reason for this choice was that for the purposes of this study we were not interested in what is happening in each hour specifically but for the morning and evening periods as a whole.

The *min-gap* and *max-gap* values were assumed to have a value of 1. The reason for this was again that we wanted to find frequent patterns in an hourly basis. By setting the *min-gap* and *max-gap* to one, we assure that all frequent patterns will be contained in the hourly basis that we have been aiming.

§ 5.3.2 Building simulations

In order to demonstrate how the sequential pattern recognition methodology can improve the energy consumption calculations for the built environment, we had to perform simulations with a whole building simulation software (Energy+). The dwellings that participated in the measurement campaign had various typologies and it was not possible to perform exact energy simulations for each one of those dwellings. However, we had abundance of data concerning the daily temperature profiles for each type of room of these dwellings, their heating system, the insulation level of their windows, and their walls (assumed from the energy label of each dwelling and the year of construction), the number of people and their occupancy profiles (derived from the motion sensors). Therefore, we used the Delft University of Technology Concept House [23] as the reference building in order to perform the simulations for the dwellings that participated in the measurement campaign. The typology of the Concept house and the dwellings was not the same, however, all other aspects of the simulation (heating system, U values for walls and windows, occupancy schedules, hourly temperature profiles for each type of room, number of people) were based on realistic data gathered during the campaign. Some of the simulation parameters were adjusted to the energy label and age of the dwellings (such as infiltration and ventilation) and others such as electricity consumption for lighting and appliances were assumed the same for all dwellings.

The heating control for each dwelling was simulated with three different ways. First, the heating set point temperature was corresponding to the indoor air temperature, followed by the indoor operative temperature and finally the PMV comfort level. The indoor temperatures for each room of each dwelling were provided by the measurement campaign's data while the PMV was set to be between the comfort levels of -0.5 and +0.5.

§ 5.4 Results

Sections 4.1 until 4.5 present the temperatures, recorded thermal sensation, actions towards thermal comfort, clothing, and activity levels for the data points that were used in the GSP analysis. Section 4.6 shows the results of the GSP analysis and 4.7 the results of the Energy+ simulations.

§ 5.4.1 Temperature

Figures 5.1 and 5.2 display the morning and evening temperatures of all dwellings for the total data points that were used for the simulations with GSP.

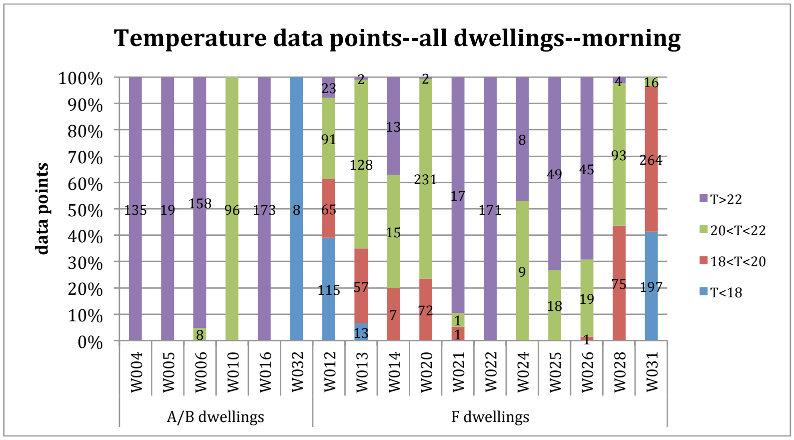


FIGURE 5.1 Morning temperatures of all dwellings for the total data points used in GSP analysis

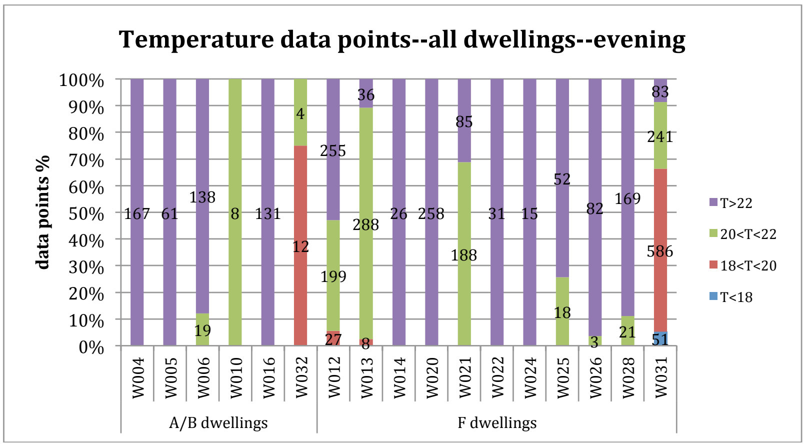


FIGURE 5.2 Evening temperatures of all dwellings for the total data points used in GSP analysis

For A/B labelled dwellings, Figure 5.1, all temperatures during the morning hours (7-9 a.m.) were above 20 °C and four out five dwellings had temperatures above 22 °C. For F dwellings, the majority of morning temperatures are above 20 °C, however, significant increase is observed in temperatures below 18 °C or between 18 °C and 20 °C. The thermal envelope of A/B dwellings could have played a significant role in this respect apart from potential occupant behavior.

For the A/B dwellings during evening hours, Figure 5.2, the temperatures of 95% of the data points were above 22 °C and the rest between 20 °C and 22°C (dwelling W010). In terms of temperature there seem to be no great differences between morning and evening hours for the A/B label dwellings. The majority of temperatures for the F labeled dwellings, approximately 75% of the data points, were above 20 °C. Compared to the morning hours there is a significant increase (more than double) in the percentage of temperatures above 22 °C and a decrease in temperatures below 20 °C, Figure 5.3. This shows clearly that occupants prefer their dwellings to be warmer in the evening than in the morning hours. In A/B labeled dwellings there is an increase in temperatures above 22 °C and a decrease in temperatures between 20 °C and 22 °C. Therefore, A/B and F label dwellings are warmer in the evening hours than in the morning hours.

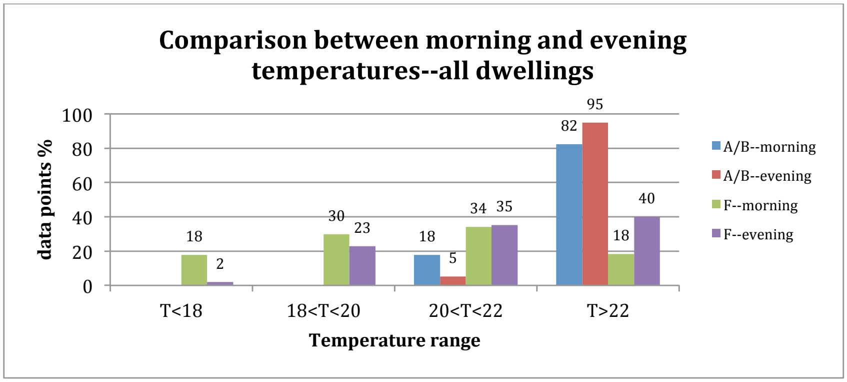


FIGURE 5.3 Comparison between morning and evening temperatures of all dwellings for the total data points used in GSP analysis

§ 5.4.2 Reported thermal sensation

Figures 5.4 and 5.5 display the total amount of reported thermal sensation scores for the data points during used for the GSP simulation.

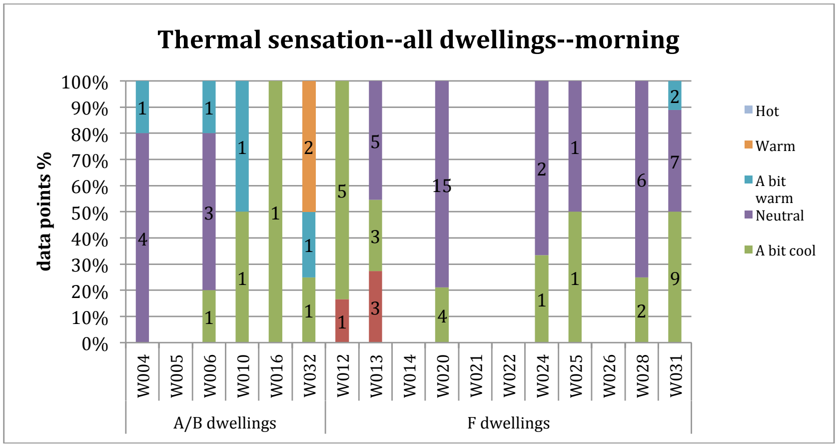


FIGURE 5.4 Morning thermal sensation scores of all dwellings for the total data points used in GSP analysis

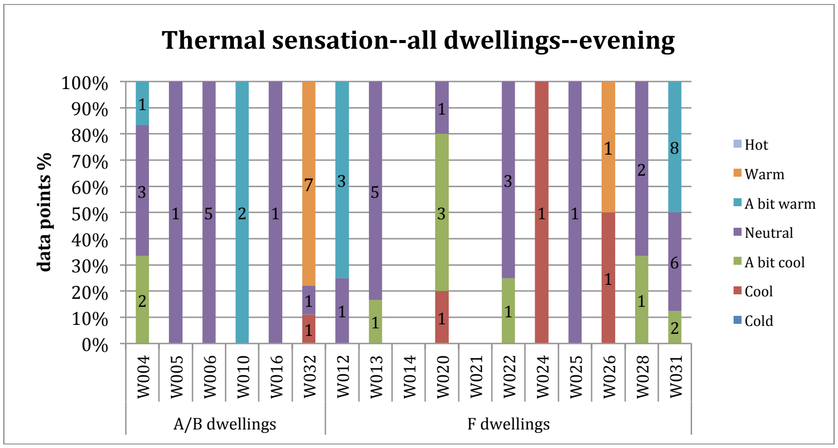


FIGURE 5.5 Evening thermal sensation scores of all dwellings for the total data points used in GSP analysis

The reported thermal sensation for the morning hours are not enough to draw conclusions, however, it is still surprising that despite the high indoor temperatures, occupants of A/B dwellings recorded thermal sensations such as 'a bit cool'. For the F labeled dwellings there were more thermal sensations reported and the majority of those were 'neutral' despite the lower indoor temperatures.

On the one hand, this could be a result of the occupants' difficulty in discriminating between the various thermal sensations [14]. The seven-point thermal sensation scale, developed in climate chambers, provides no guarantee that a specific thermal comfort level reported by a Dutch occupant corresponds to the PMV scale. Furthermore, studies have found that people's thermal sensations vary between winter and summer, from individual to individual, and are dependent on race, climate, habits and customs [29,30,31]. On the other hand, this could as well be a sign of the effect of psychological expectations. Adaptation is defined as the gradual lessening of the occupants' response to repeated environmental stimulation and can be behavioral, physiological and psychological [28]. The majority of the thermal sensations recorded in this measurement campaign were between -1 (a bit cool) and +1 (a bit warm). Analysis of these data in a prior study showed that the PMV model predicted well the thermal comfort of the occupants for thermal sensations between -1 and +1 while the prediction was getting less accurate approaching -3 or +3 [14]. These dwellings are the personal space of the occupants, a place they always try to keep a comfortable as possible, and comfort is part of what people associate with the notion of home. Occupants of the F dwellings may be aware of the lesser thermal capabilities of their homes and used to the lower indoor temperatures of their dwellings and have adapted to these conditions. If this is true, then despite the fact that these people might have lowered their thermal comfort standards, it is beneficial for the environment and energy efficiency of the housing sector because occupants could have just been using more energy in order to increase their comfort instead of adapting. All occupants in this campaign said they have no problem paying their energy bills, which they found easy to pay, despite the fact that their income ranged between half and one and a half time the Dutch median [32].

The comfort votes of the A/B dwellings during evening hours have shifted to more 'neutral' and 'a bit warm', which is logical based on the indoor temperatures. For F labeled dwellings the effect of increased temperatures during evening hours does not seem to be translated into more comfortable thermal sensation votes although still the majority of thermal sensations are between 'a bit cool' and 'a bit warm'. However, the amount of data is not sufficient to draw concrete conclusions.

§ 5.4.3 Actions towards thermal comfort

Figures 5.6 and 5.7 display the actions towards thermal comfort for the morning and evening hours used for the GSP simulation. For the morning hours, the occupants of the F labelled dwellings recorded having a 'hot drink', having a 'warm shower' and 'thermostat up' as the most common actions which seem intuitively sensible given the lower temperatures of their dwellings. These actions seem to be genuinely performed in order to improve thermal comfort. The occupants of the A/B labelled dwellings, however, have used various actions in a more erratic way. For example, W004 had morning temperatures above 22 °C for the whole period of analysis and the tenants still recorded having a warm shower and a warm drink every morning while feeling 'neutral'. Obviously, these actions in this particular case are not related to thermal comfort. Dwelling W006, with similar indoor temperatures as W004, recorded having a 'hot drink' and even turning the 'thermostat up' while thermal sensations were mainly 'neutral'. This occupant behavior could be led by behavioral reasons and could have an impact in energy consumption of a dwelling with no significant benefit to indoor comfort.

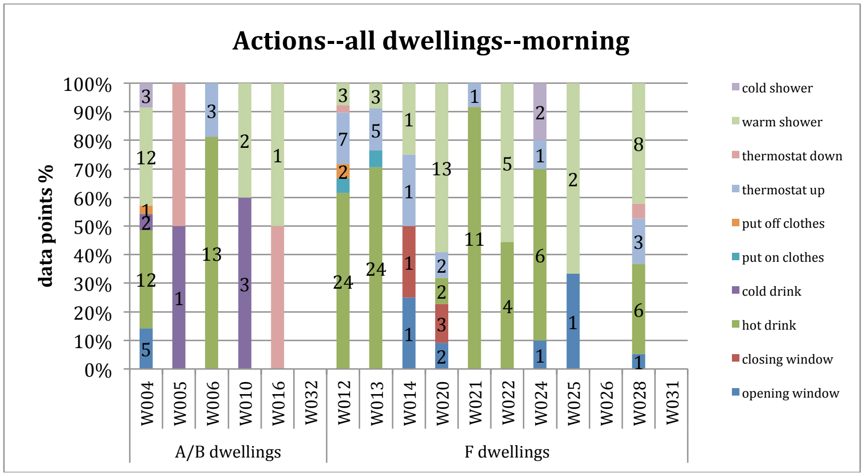


FIGURE 5.6 Morning actions toward thermal comfort scores of all dwellings for the total data points used in GSP analysis

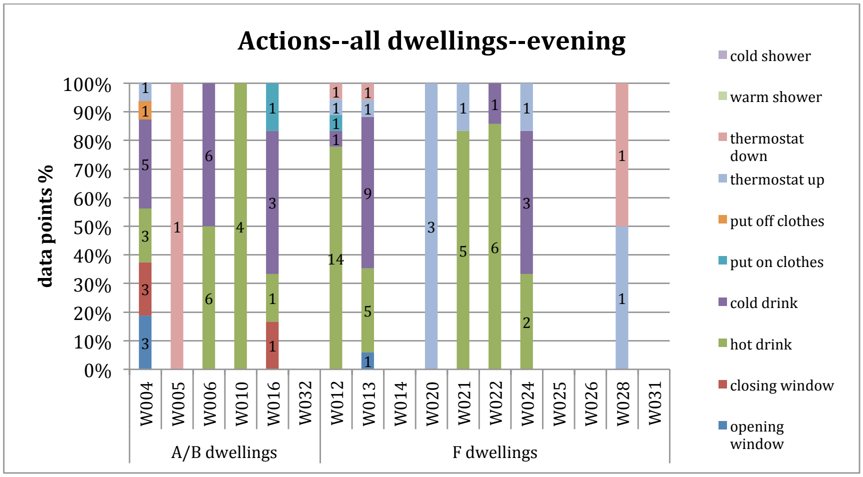


FIGURE 5.7 Evening actions toward thermal comfort scores of all dwellings for the total data points used in GSP analysis

During the evening hours, all F label dwellings that recorded 'thermostat up' had temperatures above 20 °C. However, only dwellings W020 and W024 had recorded majority of thermal sensations 'a bit cool' or 'cool', which could explain the action of thermostat up. All other F labelled dwellings had temperatures above 20 °C and the majority of thermal sensations were 'neutral' followed by 'a bit cool', to a lesser extent, while dwelling W012 even had thermal sensations of 'a bit warm'. Regardless of the recorded thermal sensations, the level of indoor temperatures is very high to substantiate an action such as 'thermostat up', which affects energy consumption. Compared to the morning actions, for F labelled dwellings, 'cold drink' has been substituted with 'warm shower'. This action in A/B labelled dwellings has substituted 'closing the window'.

§ 5.4.4 Clothing

Figures 5.8 and 5.9 display the clothing levels for the morning and evening hours used for the GSP simulation.

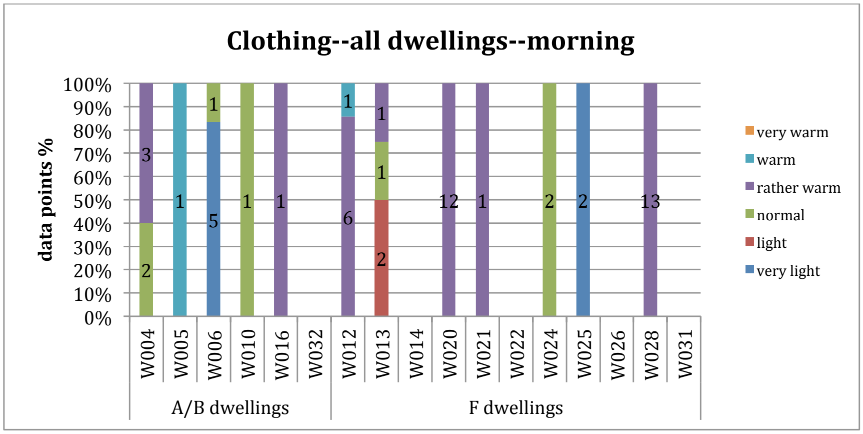


FIGURE 5.8 Morning clothing scores of all dwellings for the total data points used in GSP analysis

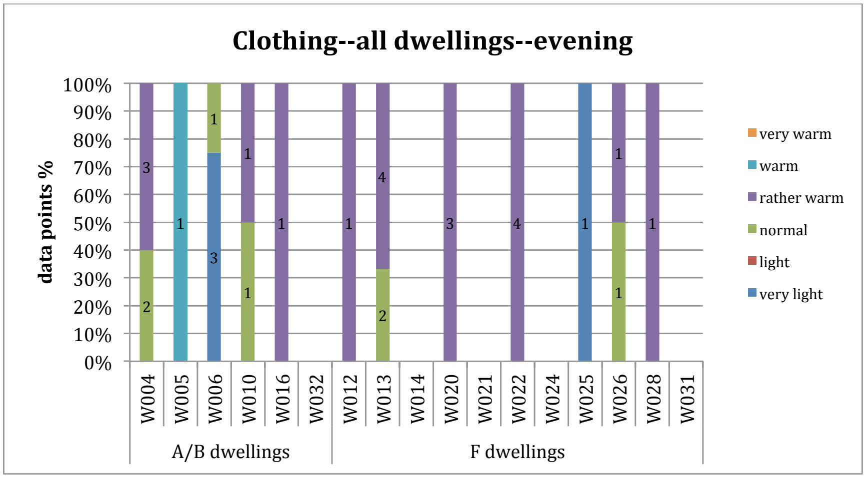


FIGURE 5.9 Evening clothing scores of all dwellings for the total data points used in GSP analysis

During the morning hours, for the F labeled dwellings, we see the majority of clothing being rather warm 'long sleeved sweat shirt'. Take dwellings W020 and W028, for example. The majority of hours between 7-9 a.m. have temperatures between 20 ^{o}C < T< 22 ^{o}C and the occupants mainly feel 'neutral' and a few times 'a bit cool'. The seemingly consolidated 'long sleeved sweat shirt' clothing pattern for F labeled dwellings could be part of the psychological adjustment mentioned earlier. The worst (compared to A/B dwellings) thermal conditions in these dwellings are compensated by a higher clothing level which is a good practice concerning energy conservation. As we can see in Figure 5.10, from the 41 data points on actions towards thermal comfort recorded for W020 and W028, only 5 times there was an increase in thermostat levels during the morning hours. Occupants have adjusted themselves in order to feel neutral by means of clothing and other actions such as 'hot drink' or 'warm shower'. Temperature conditions in A/B dwellings are always above 22 ^{o}C, which allows for a variety of clothing ensembles.

For the evening hours, clothing seems similar for all dwellings with the 'long sleeved sweat shirt' being the most frequently used garment. If we compare the morning and evening clothing patterns there seems to be no significant difference. In the evening, there is a complete absence of t-shirt, but still sleeveless t-shirt (which provides even lower thermal protection) is present in A/B and F labelled dwellings. More data are needed in an extended measurement campaign in order to establish detailed clothing patterns of occupants based on the time of the day, their age, sex and health conditions.

§ 5.4.5 Metabolic activity

Figures 5.10 and 5.11 display the metabolic activity levels for the morning and evening hours used for the GSP simulation.

The metabolic activity data during the morning hours show that for the A/B dwellings the most common activity level is 'sitting relaxed' followed by 'lying/sleeping'. For the F labeled dwellings, the most common activity was 'walking' followed by 'light desk work'. Despite the small number of data, which does not allow definite conclusions, the increased metabolic activity (just as with the increased clothing levels), which results in more comfortable thermal sensations, could be another evidence of adjustment for the occupants of the F dwellings.

For the evening hours, the most common metabolic activity of the occupants of A/B labelled dwellings was 'sitting relaxed', while for the F labelled dwellings it was 'walking'. Just like for the morning hours this could be a sign of adjustment to the thermal sensation for the F labelled dwellings' occupants. Two of the three dwellings that recorded 'cool' for thermal sensation had also recorded 'walking' as a metabolic activity despite the fact that indoor temperatures were almost identical for all dwellings. However, the metabolic activities could be related more to the established routines of occupants in the dwellings rather than thermal sensation and further research with increased amount of recorded data is needed.

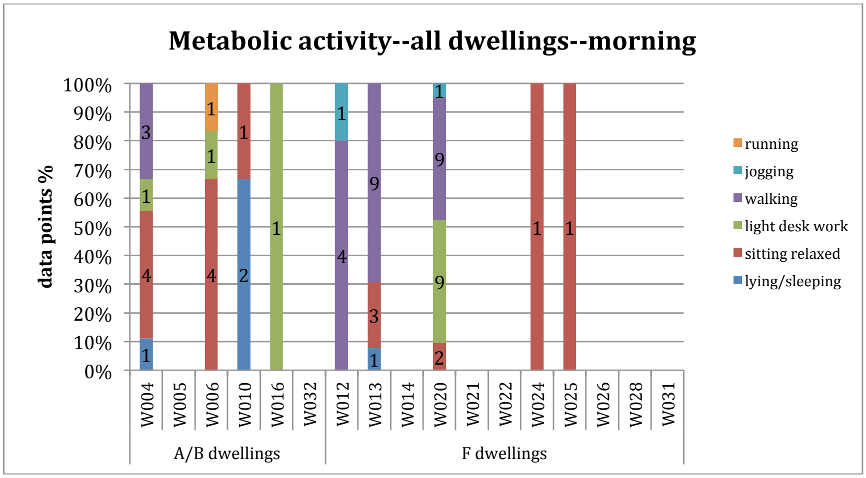


FIGURE 5.10 Morning metabolic activity scores of all dwellings for the total data points used in GSP analysis

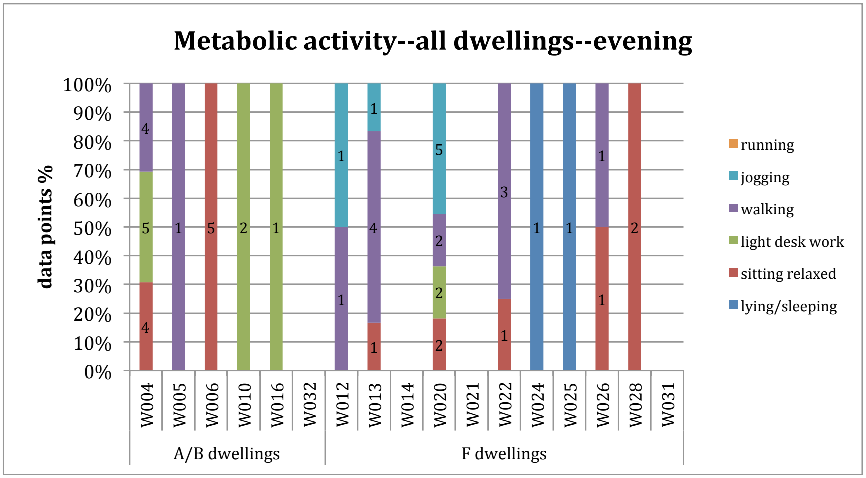


FIGURE 5.11 Evening metabolic activity scores of all dwellings for the total data points used in GSP analysis

§ 5.4.6 Generalized sequential pattern recognition (GSP)

The analysis of the data so far gave us an insight in the cumulative data scores on thermal sensation, indoor temperatures, actions towards thermal comfort, clothing and metabolic activity. However, this analysis is not dynamic, it does not take into account, for example, the exact hour at which an action took place, and what other action, temperature, clothing, and metabolic activity or a combination of the above was recorded at the same hour. Such time combinations between the above-mentioned parameters could also shed light in the causality of certain actions, clothing preferences or metabolic activity patterns. For example if actually metabolic activity is used as an adjustment factor for lower thermal sensations or if warmer clothing is actually used as an adjustment for low temperatures, or if having a warm shower and a hot drink is not related to any of those things and are happening out of pure habit. Moreover, the GSP analysis could lead to patterns supported by all dwellings, which means that with the accumulation of enough data, patterns supported by greater population groups would be possible to be defined.

The data set described in Table 5.2 was fed to the GSP algorithm with the purpose of defining significant sequential patterns. The software that was used for the analysis was rapidminer [22]. The GSP analysis took place for the morning hours between 7-9 a.m. and the evening hours between 5-7 p.m. for all dwellings and for A/B and F label dwellings separately. There is one input string per dwelling per day per timestamp, but the sequences are aggregated on the three morning hours and the three evening hours.

§ 5.4.6.1 Most important sequences

The results of the GSP algorithm concerning the most important sequences discovered for the morning and evening hours are presented in Tables 5.3, 5.4, and 5.5. The events' combinations with the highest support and the smaller amount of events are presented first in the tables. There were many combinations of events that were supported by all dwelling days (Table 5.3), A/B dwelling days (Table 5.4), and F labeled dwelling days (Table 5.5), especially in lower support values such as thirty or twenty per cent. In this study we choose to present results that were supported by minimum of 40% of the dwelling days. In this work, 100% support means that the sequence is found in all dwelling days (meaning in turn that for all days of all dwellings this specific sequence was found between 7 and 9 o'clock.

The sequences (combination of events) are presented as a, b, c etc. meaning that, a was the first event, followed in time by b (although b could also takes place at the same hour as a), followed in time by c (although c could also takes place at the same hour as b).

When all seventeen dwellings were participating in the GSP simulation, for the morning hours, the highest support was found to be 0.59 and the events combination was $20<T<22$, $T>22$. This means that 59% of the dwelling days between 7-9 a.m. have their temperature increased from a value between 20 °C and 22 °C to a temperature above 22 °C. This combination of events is also the most supported (82%) among the F labeled dwellings. For the evening hours, and for all dwellings participating in the simulation, the most supported sequence (65%) was $T>22$, Neutral. The same sequence is supported the most by A/B dwellings (67%) and F dwellings (65%). This shows that regardless of the energy label of the dwelling, during the early evening hours, residential dwellers in our sample seem to agree that neutrality is accompanied by temperatures above 22 °C. F label dwellings, however, should consume considerably more energy to reach the same level of indoor comfort.

TABLE 5.3 GSP results from the morning and evening simulation of all dwellings

SUPPORT	EVENTS COMBINATION--MORNING	SUPPORT	EVENTS COMBINATION--EVENING
0.59	20<T<22, T>22	0.65	T>22, Neutral
0.53	20<T<22, A bit cool	0.47	20<T<22, T>22
0.53	T>22, hot drink	0.47	T>22, hot drink
0.53	T>22, warm shower	0.47	T>22, rather warm clothing
0.47	18<T<20, 20<T<22	0.41	20<T<22, Neutral
0.47	20<T<22, thermostat up	0.41	T>22, cold drink
0.47	T>22, A bit cool	0.41	T>22, thermostat up
0.47	T>22, thermostat up	0.41	T>22, sitting relaxed
		0.41	T>22, walking
0.47	20<T<22, T>22, thermostat up	0.41	Neutral, rather warm clothing
		0.41	hot drink, cold drink
0.41	18<T<20, T>22	0.41	T>22, Neutral, rather warm clothing
0.41	20<T<22, Neutral	0.41	T>22, hot drink, cold drink
0.41	20<T<22, hot drink		
0.41	20<T<22, warm shower		
0.41	T>22, Neutral	0.35	T>22, A bit cool
0.41	T>22, rather warm clothing	0.35	A bit cool, Neutral
0.41	A bit cool, Neutral	0.35	Neutral cold drink
0.41	A bit cool, warm shower	0.35	Neutral, sitting relaxed
0.41	hot drink, thermostat up	0.35	rather warm clothing, sitting relaxed
0.41	18<T<20, 20<T<22, T>22	0.35	20<T<22, T>22, Neutral
0.41	20<T<22, T>22, A bit cool	0.35	T>22, A bit cool, Neutral
0.41	20<T<22, T>22, hot drink	0.35	T>22, Neutral, cold drink
0.41	20<T<22, A bit cool, Neutral	0.35	T>22, Neutral, sitting relaxed
0.41	20<T<22, hot drink, thermostat up	0.35	T>22, rather warm clothing, sitting relaxed
0.41	T>22, hot drink, thermostat up		

TABLE 5.4 GSP results from morning and evening simulation of A/B labeled dwellings

SUPPORT	EVENTS COMBINATION--MORNING	SUPPORT	EVENTS COMBINATION--EVENING
0.5	T>22, light desk work	0.67	T>22, Neutral
0.5	A bit cool, A bit warm	0.67	T>22, hot drink
0.5	A bit warm, normal clothing		
0.5	A bit warm, sitting relaxed	0.5	T>22, cold drink
0.5	normal clothing, sitting relaxed	0.5	Neutral, cold drink
		0.5	hot drink, cold drink
0.5	A bit warm, normal clothing, sitting relaxed	0.5	hot drink, normal clothing

>>>

TABLE 5.4 GSP results from morning and evening simulation of A/B labeled dwellings

SUPPORT	EVENTS COMBINATION--MORNING	SUPPORT	EVENTS COMBINATION--EVENING
		0.5	rather warm clothing, light desk work
		0.5	T>22, Neutral, cold drink
		0.5	T>22, hot drink, cold drink

TABLE 5.5 GSP results from morning and evening simulation of F labeled dwellings

SUPPORT	EVENTS COMBINATION--MORNING	SUPPORT	EVENTS COMBINATION--EVENING
0.82	20<T<22, T>22	0.64	20<T<22, T>22
		0.64	T>22, Neutral
0.73	18<T<20, 20<T<22	0.55	T>22, rather warm clothing
		0.55	T>22, thermostat up
0.64	18<T<20, T>22		
0.64	20<T<22, A bit cool	0.45	20<T<22, Neutral
0.64	20<T<22, thermostat up	0.45	T>22, A bit cool
0.64	T>22, hot drink	0.45	T>22, hot drink
0.64	T>22, thermostat up	0.45	T>22, sitting relaxed
0.64	T>22, warm shower	0.45	T>22, walking
		0.45	A bit cool, Neutral
0.64	18<T<20, 20<T<22, T>22	0.45	Neutral, rather warm clothing
0.64	20<T<22, T>22, thermostat up	0.45	rather warm clothing, sitting relaxed
		0.45	20<T<22, T>22, Neutral
0.55	18<T<20, thermostat up	0.45	T>22, A bit cool, Neutral
0.55	20<T<22, Neutral	0.45	T>22, Neutral, rather warm clothing
0.55	20<T<22, hot drink	0.45	T>22, rather warm clothing, sitting relaxed
0.55	20<T<22, warm shower		
0.55	T>22, A bit cool		
0.55	A bit cool, Neutral		
0.55	hot drink, thermostat up		
0.55	18<T<20, 20<T<22, thermostat up		
0.55	18<T<20, T>22, thermostat up		
0.55	20<T<22, T>22, A bit cool		
0.55	20<T<22, T>22, hot drink		
0.55	20<T<22, T>22, warm shower		
0.55	20<T<22, A bit cool, Neutral		
0.55	20<T<22, hot drink, thermostat up		
0.55	T>22, hot drink, thermostat up		
0.55	18<T<20, 20<T<22, T>22, thermostat up		
0.55	20<T<22, T>22, hot drink, thermostat up		

Clearly, there are much more variations (events combinations) in F labeled dwellings than in A/B ones. This could however, result from the significantly higher number of data points related to the F label dwellings.

§ 5.4.6.2 Occupancy Behavior patterns

Such pattern recognition of important sequential events in buildings aims at shedding light in occupancy behavior, related to thermal comfort, which in turn is connected with energy consumption. Having this in mind, we categorized the above combinations of events in two groups that are related to energy consumption, energy and non-energy consuming events, for the morning and evening hours, Table 5.6. Furthermore, the two main categories were further categorized into thermal sensation related and surprising events, which are denoted by superscripts as shown in Table 5.6. By 'energy consuming', we mean all the events that could relate directly to an increase in energy consumption. 'Non energy consuming events' are the events that are not related to an increase in energy consumption. For example the event (18<T<20, 20<T<22) shows an increase in temperature, which is expected to lead to an increase in energy consumption. Another example are the thermal sensation related events (20<T<22, Neutral) and (T>22, Neutral). It is logical to expect (despite the numerous parameters that affect thermal comfort) that for temperatures above 20 °C people would have many chances to feel neutral. 'Surprising' were the events that were counter intuitive, having in mind that people would try to maximize their thermal comfort even at the expense of increased energy consumption. For example the events (20<T<22, T>22), (20<T<22, thermostat up) or (T>22, A bit cool) describe combinations that are counter intuitive, especially when temperatures are above 22 °C and occupants say they are 'a bit cool' or they turn their thermostat up. Such combinations have more chances to lead to rebound effects and unnecessary energy consumption.

TABLE 5.6 Categorization of combination events in groups related to energy consumption for the morning and evening hours of all dwellings

SUPPORT	MORNING		SUPPORT	EVENING	
	Energy consuming events	Non energy consuming events		Energy consuming events	Non energy consuming events
0.59	20<T<22, T>22 [SE]		0.65		T>22, Neutral [TS]
0.53		20<T<22, A bit cool [TS]	0.47	20<T<22, T>22	
0.53		T>22, hot drink	0.47		T>22, hot drink [SE]
0.53	T>22, warm shower [TS]		0.47		T>22, rather warm
0.47	18<T<20, 20<T<22		0.41		20<T<22, Neutral [TS]
0.47	20<T<22, thermostat up [SE]		0.41		T>22, cold drink
0.47		T>22, A bit cool [TS, SE]	0.41	T>22, thermostat up [SE]	
0.47	T>22, thermostat up [SE]		0.41		T>22, sitting relaxed
0.47	20<T<22, T>22, thermostat up [SE]		0.41		T>22, walking
0.41	18<T<20, T>22		0.41		Neutral, rather warm [TS]
0.41		20<T<22, Neutral [TS]	0.41		hot drink, cold drink
0.41		20<T<22, hot drink [SE]	0.41		T>22, Neutral, rather warm [TS]
0.41	20<T<22, warm shower [SE]		0.41		T>22, hot drink, cold drink [SE]
0.41		T>22, Neutral [TS]	0.35		T>22, a bit cool [TS]
0.41		T>22, rather warm	0.35		A bit cool, neutral [TS]
0.41	A bit cool, warm shower [TS]		0.35		Neutral, sitting relaxed [TS]
0.41	hot drink, thermostat up		0.35		rather warm, sitting relaxed
0.41	18<T<20, 20<T<22, T>22		0.35	20<T<22, T>22, Neutral [TS]	
0.41	20<T<22, T>22, A bit cool [TS, SE]		0.35		T>22, A bit cool, Neutral [TS, SE]
0.41	20<T<22, T>22, hot drink [SE]		0.35		T>22, Neutral, cold drink [TS]
0.41		20<T<22, A bit cool, Neutral [TS]	0.35		T>22, Neutral, sitting relaxed [TS]
0.41	20<T<22, hot drink, thermostat up [SE]		0.35		T>22, rather warm, sitting relaxed
0.41	T>22, hot drink, thermostat up [SE]				

TS: thermal sensation related event / SE: surprising event

The most populous category was the 'energy consuming events' with 15 event combinations, followed by 'Surprising events' with 13 event combinations. Even more discouraging, in terms of energy efficiency, is the fact that the energy consuming and surprising events share 10 common events. These unexpected events are mostly related to jumping from already high indoor temperatures to even higher ones. These events are tightly connected with energy consumption and their effectiveness towards thermal comfort is doubtful, given the already very high indoor temperatures. Furthermore, there is a complete absence of alternative ways to improve one's thermal comfort such as clothing, or increased metabolic activity. The GSP algorithm found only one sequence (supported by 41% of the dwelling days nonetheless) for which people feeling 'a bit cool' took a 'warm shower'. However, this is more likely related to a habitual event, since many people have a warm shower in the morning in order to start their day. The combinations of events towards the improvement of thermal comfort showed a prevalence of conventional means such as increase of indoor temperature and turning the thermostat up while actions such as hot drink or warm shower were deemed more as habits rather than actions towards comfort. We have to mention again that the data we had were not exhaustive and that there is a great room for improvement, especially for the gathering of the subjective data such as actions, clothing and metabolic activity.

The GSP simulation for the evening hours showed rather different results compared to the morning hours. The energy consuming combinations were significantly reduced mainly because of the absence of temperatures below 20 °C and having a warm shower. Usually dwellings are not heated during the night and temperatures could fall below 20 °C and even below 18 °C, therefore, it would not be surprising that occupants are trying to increase indoor temperature in the morning hours. Having a warm shower on the other hand seems to be a daily routine more than an action towards comfort. This finding is supported by the results of the chi^2 tests that are shown in Table 5.4 of chapter 4, according to which for both A/B and F label dwellings, having a "warm shower" was found entirely unrelated to the reported thermal sensation. The 'energy consuming' combinations were reduced to 3 while the 'surprising events' were only 5 and only one of them was shared with the 'energy consuming' category.

§ 5.4.7 Energy+ simulation results

First, the concept house was simulated with the commonly available occupancy profiles and set point temperatures that are predefined in almost every building simulation software such as Energy+, Design Builder, and ESPr. Therefore, the temperature heating set point was 20 °C for all rooms, and the heating system's availability was matching the occupancy schedule; the heating system was on from 7-9 a.m. when people were waking up and getting ready to go to work. Then it was off until 17:00 when people were absent from the dwelling and on again from 17:00 until 24:00 when people were going to sleep.

Subsequently, the concept house was simulated with the actual hourly temperature profiles and occupancy schedules that we obtained from the measurement campaign. Ioannou and Itard (2015) showed with a Monte Carlo sensitivity analysis, with the same Concept House as the reference building, that using the thermostat and altering the indoor temperature, can explain more than 90% of the variance in the total heating consumption of the dwelling. Therefore, actual hourly heating profiles could improve simulation accuracy compared to business as usual simulations that are taking place with schedules and heating points based on assumptions that may not reflect actual ones

This was done by using the hourly heating profiles of three different types of dwellings that participated in the campaign in order to model a reference dwelling. The dwellings used were A and B label, with gas boiler and radiators as the heating system, A label and heat pump coupled with hydronic underfloor heating, and F label with gas boiler and radiators. As already mentioned in section 3.2 the simulations were repeated three times, one time with the control of the heating system corresponding to the indoor air temperature (T_{air}), one time corresponding to the indoor operative temperature (T_{oper}), and one corresponding to the PMV thermal comfort index. The reason for performing the simulations with the above three different set points was to compare the energy consumption, the indoor temperatures, and the comfort index between these configurations. This approach allows the comparison of the performances of these three control strategies of the heating system.

Because the control set points were not known from the measurement campaign, and only the indoor air temperature was known, the following model calibration procedure was applied:

The actual hourly air temperature profiles from the measurement campaign were fed to the model and the control set points (T_{air} and T_{oper}) were iteratively adjusted up to the moment where the hourly air temperature profiles, resulting from the simulations, were matching the actual ones (the ones obtained during the measurement campaign). When the PMV was used as the control, it was set between -0.5 and +0.5, which corresponds to the neutral comfort level of the PMV scale and the resulting hourly air temperature profile from the simulation is presented in the results and compared to the profiles obtained for T_{air} and T_{oper} as the control set points. The simulations took place for the period between 1st March and 7th March which is the period that the tenants were handed the comfort dial.

For the reference simulation (standard profile) the T_{air} and T_{oper} were assumed to be 20 °C, during the hours that the dwelling was occupied, which is a common approach among engineers when simulating residential dwellings.

§ 5.4.7.1 A/B label dwellings with boiler and radiators

Figure 5.12 shows the annual heating consumption of the concept house, simulated as an A label dwelling with gas boiler and radiator, with first business as usual schedules and heating set points, and then simulated with the actual hourly heating profiles and occupancy schedules of dwellings W010 and W032. These two dwellings were chosen because they were both in the A/B label category and their actual hourly temperature profiles were above 22 °C and around 20 °C respectively. Figure 5.13 shows the indoor temperature T_{air} and the PMV resulting from the simulations for the living room of those dwellings.

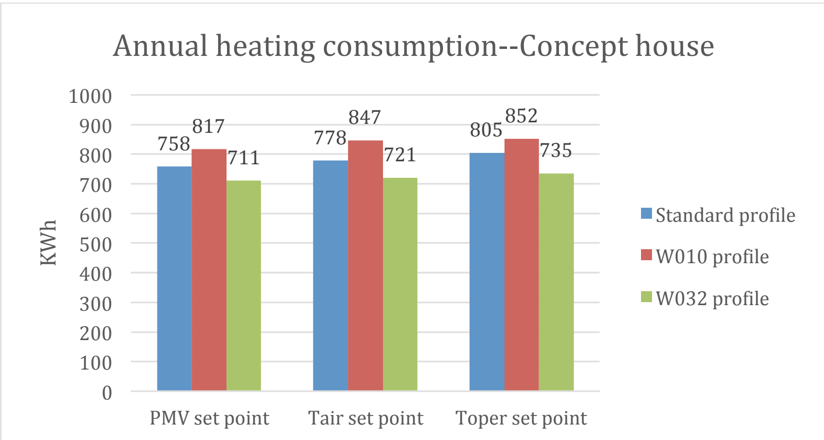
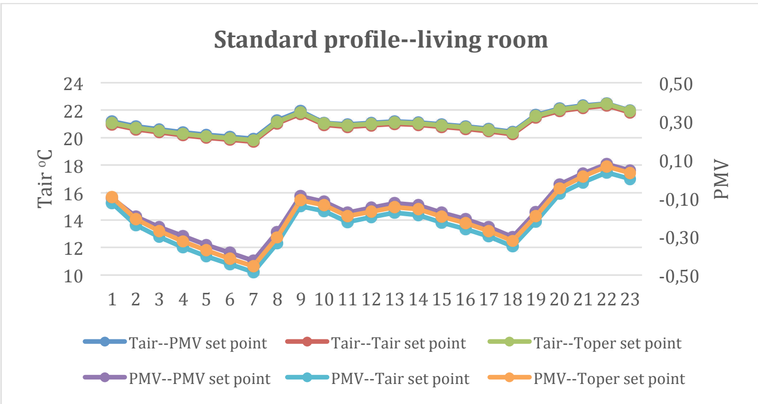


FIGURE 5.12 Annual heating consumption simulated for three different heating set points for the Concept House and dwellings W010 and W032

When heating set point corresponds to the T_{air} (which is the way the majority of thermostats are controlled) or T_{oper}, all profiles lead to higher energy consumption. This clearly relates to the indoor temperatures, Figure 5.13. W010 has the highest indoor temperature profile, the highest energy consumption, and the most comfortable PMV index, which suggests that the tenants of W010 strive for higher comfort in the expense of energy consumption. However, if the indoor temperature is controlled by the PMV we see that the simulated PMV of tenants is significantly lower (but still within the comfort range) and the indoor air temperature is 1.5 °C to 2 °C lower. This could lead to significant energy savings. This effect, in the presented dwellings, seems to be more obvious when the indoor temperatures of the dwelling are higher. This can be seen in the comparison between W010 and W032. W010 that has the highest indoor temperatures records the greatest drop in the PMV level (and indoor air temperature) when control is switched from T_{air} and T_{oper} to PMV. This effect is smaller (but still significant) in W032.



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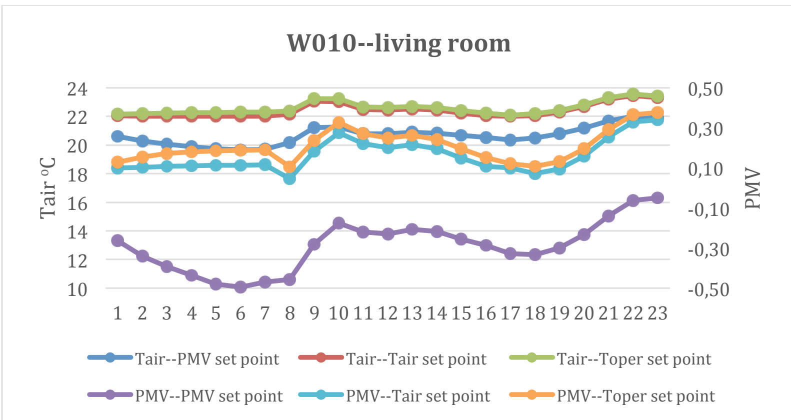

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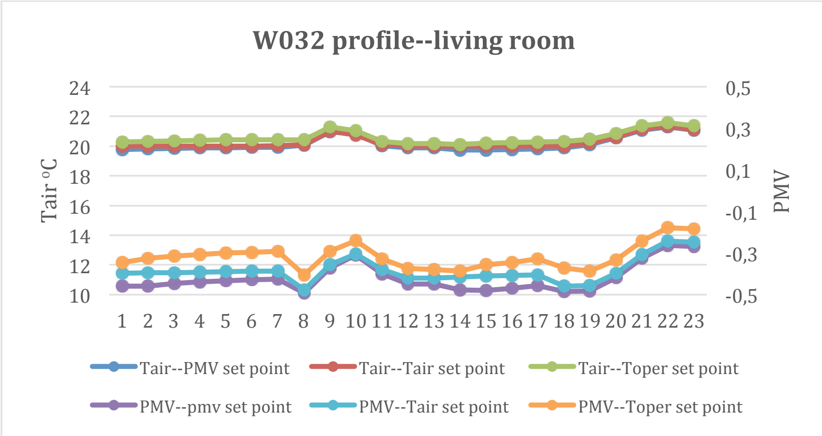

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FIGURE 5.13 Indoor Tair and PMV simulated for the Concept house (well insulated and HR boiler) with three different heating set points and occupancy profiles

§ 5.4.7.2 A label dwellings with heat pump and underfloor hydronic heating

Figure 5.14 shows the annual heating consumption of the concept house, simulated as A label dwelling with heat pump and hydronic underfloor heating system, with business as usual schedules and heating set points, and with the actual hourly heating profiles and occupancy schedules of dwellings W003 and W004. Figure 5.15 shows the indoor T_{air} and PMV for the living room of those dwellings.

The effect of the different heating set points is not visible in this case of dwellings due to the continuous operation of this heating system and the big amount of time needed for specific changes in the thermostat to be felt in the indoor environment of the dwelling. The differences in the annual energy consumption between the dwellings is because of the different hourly temperature profiles that we obtained during the measurement campaign. In the standard profile the concept house was simulated with 20 °C heating set point for the whole day, while W003 and W004 had an average of 26 °C and 24 °C in the living room respectively. The PMV for all dwellings was within the comfort limits and only for concept house, which had the lowest heating set point, the PMV drops slightly below the comfort limits during evening hours. This is due to the undersized heating element that was used for the simulation of each thermal zone of the dwellings (3000 Watts).

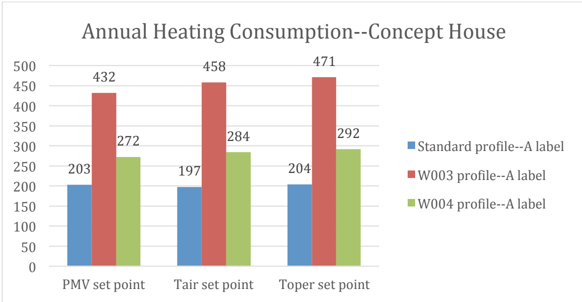
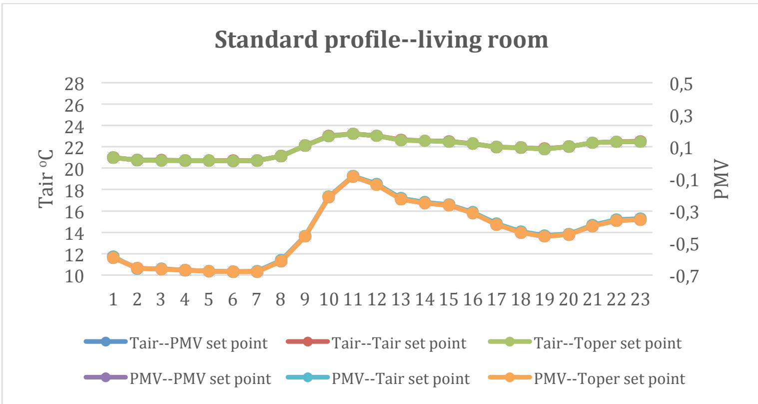


FIGURE 5.14 Annual heating consumption simulated for three different heating set points for the Concept House and dwellings W003 and W004



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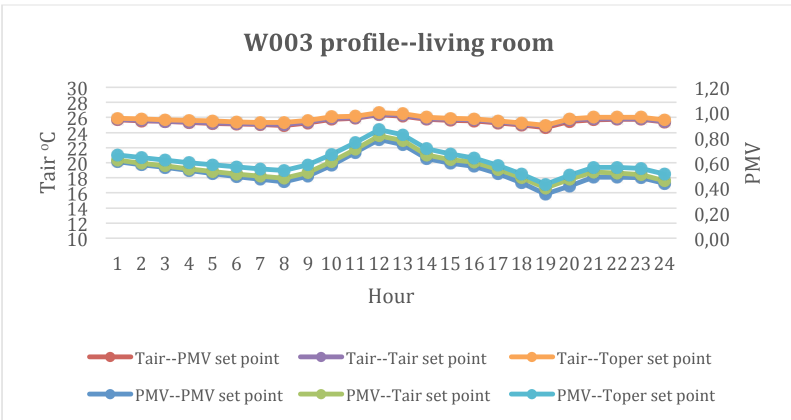

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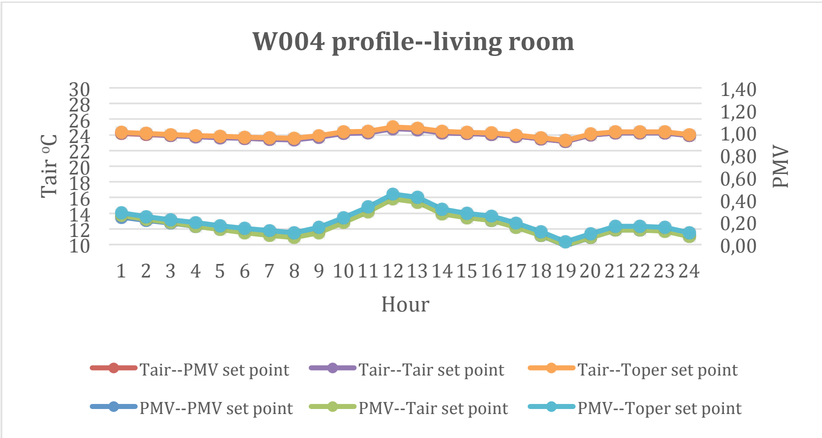

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FIGURE 5.15 Indoor Tair and PMV simulated for the Concept house (well insulated, heat pump, and underfloor heating) with three different heating set points and occupancy profiles

§ 5.4.7.3 F label dwellings with boiler and radiators

Figure 5.16 shows the annual heating consumption of the concept house, simulated as an F label dwelling, with gas boiler and radiator, with business as usual schedules and heating set points, and simulated with the actual hourly heating profiles and occupancy schedules of dwellings W013, W022, W026, and W031. Figure 5.17 shows the indoor T_{air} and PMV for the living room of those dwellings.

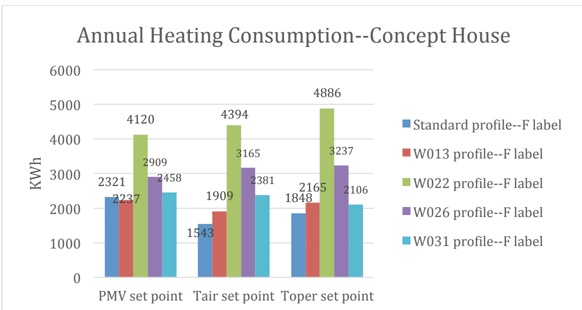
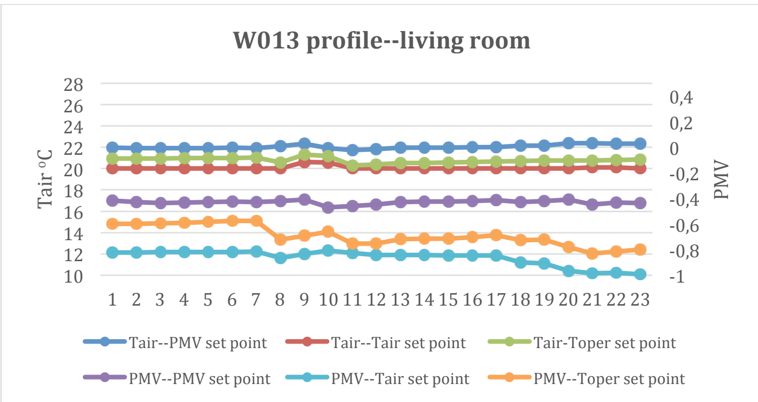


FIGURE 5.16 Annual heating consumption simulated for three different heating set points for the Concept House and dwellings W013, W022, W026, and W031

Using the PMV set point as the corresponding value for the operation of the heating system results in the lower energy consumption in W022 and W026. The reason for this is, similar to the case of A label dwellings (Figures 5.12 and 5.13), the unusual high temperature profiles preferred by the tenants of these dwellings, Figure 5.17. As we can see in the graph for dwelling W022 the indoor air temperatures are above 24 °C for the whole day, while for maintaining an hourly comfort level of -0.5, only 22 °C are needed, Figure 5.17. In contrast, W013 has lower indoor temperatures for the whole day and the PMV calculations show that tenants are not supposed to be felling neutral. In this case, switching to PMV as the set point will result to increased energy consumption, which, however, will bring the tenants within the comfort zone of the PMV index. Nonetheless, during the evening hours the tenants of W013 reported neutral thermal sensations just like their W022 counterparts. This suggests that they might have adjusted their thermal comfort levels to a lower level compared to the tenants of W022 or that the later are more comfortable than they need, utilizing a rebound effect on comfort. Therefore, using the PMV as the set point temperature could result to either an increase or decrease in the energy consumption, depending in the indoor temperature that the tenants prefer. In any case, the comfort of the tenants in this case will be brought within the comfort zone of the Fanger model. But as we saw for the example of W013, this could not be the desired comfort level of the tenants.



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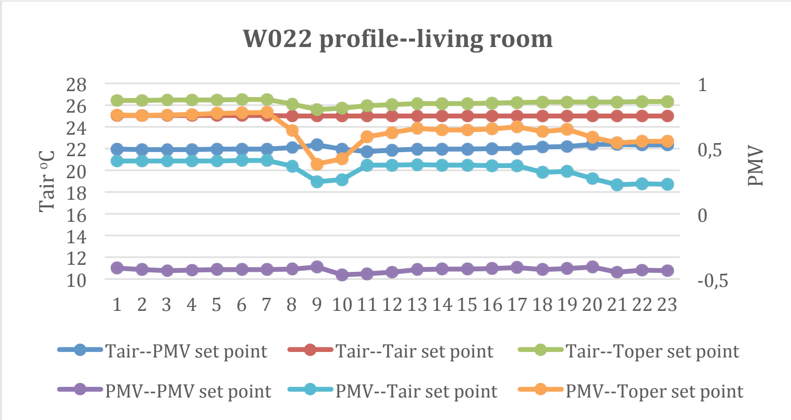

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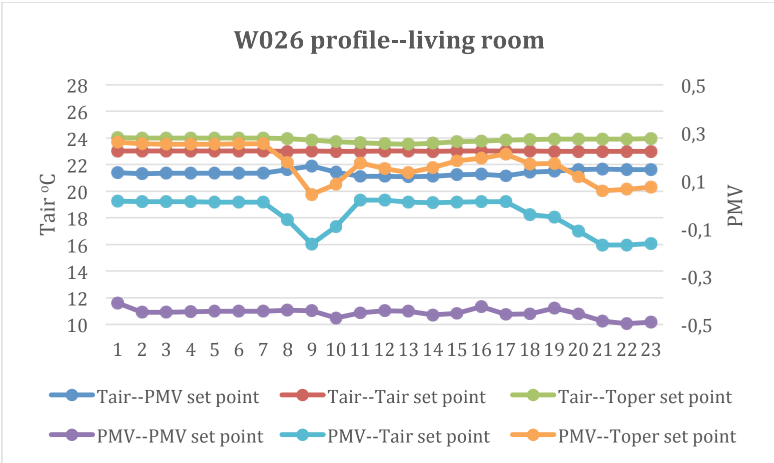

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FIGURE 5.17 Indoor Tair and PMV simulated for three different heating set points for the Concept House and dwellings W003 and W004

Majcen et al. [27] demonstrated the discrepancy between actual and calculated energy consumption in energy labelled residential dwellings in the Netherlands. Furthermore, Santin [33] and Page et al. [2] showed the importance that occupancy behavior might have in the energy consumption of a dwelling. From a building simulation perspective, Ioannou and Itard [23] showed that behavioral parameters such as the use of the thermostat affects greatly the total energy consumption and the PMV of the tenants. Therefore, if the tenants of a residential dwelling command their indoor environment based on their comfort levels, the components of building simulation software related to the PMV must be improved.

In order to calculate the PMV index, values from six parameters are needed; clothing, metabolic activity, mean radiant temperature, air speed, air temperature, and relative humidity. In a smart built environment, it would be easy to gather the quantitative data related to the PMV with the use of an extensive network of sensors. However, clothing and metabolic activity are more difficult to capture, but a mobile or tablet application incorporating the features of the comfort dial and log book, could give a solution to this problem. Gathering enough subjective data and simulating them with the GSP algorithm could lead to hourly clothing and metabolic activity profiles that would improve greatly the simulation components related to the PMV, thus, improving the accuracy of the simulated energy consumption of residential dwellings.

§ 5.5 Conclusions

Using big data, from a sensor rich environment in residential dwellings, into a data driven model such as the GSP algorithm could lead to the prediction of occupancy behavior patterns. Even grouping all dwellings together, regardless of the energy label, provided high enough support (% of dwelling days that are following a pattern in a specific hour) for occupancy patterns that were revealed by the simulation. For example, in 59% of dwelling days in the morning hours the temperatures between 7-9 a.m. were increasing from 20 °C< T< 22 °C to T> 22°C. Furthermore, in 56% of them the temperature 20 °C< T< 22 °C was found to be a bit cool and even for temperatures above 22 °C occupants were reporting having a warm shower leading to the suspicion that a warm shower is a routine action not related to thermal comfort. For the evening hours between 5-7 p.m. the simulation for all dwellings showed that in 65% of the dwelling days temperatures higher than 22 °C were found to be neutral and in half of them the temperature was increased from 20 °C < T< 22 °C to T>22 °C. For only the A/B label dwellings, GSP showed that in 80% of the dwelling days temperatures above 22 °C were experienced as being neutral. Furthermore, in the F labeled dwellings in 64% of the dwelling days T > 22 °C was found to be neutral and the temperature was increased from 20 °C < T< 22 °C to T>22 °C. This shows that tenants of lower labeled dwellings do not compromise their comfort by heating less than the tenants of A/B label dwellings. This will lead of course to higher energy consumption. This is in agreement with some of the findings of the initial questionnaire given to the tenants. To the question "do you find it difficult to pay you monthly energy bills?" all tenants replied "no" despite the fact that the household incomes ranged between 700 to 4.5 thousand euros.

Furthermore, the sequential pattern analysis revealed patterns of occupancy behavior that were categorized as energy consuming, non-energy consuming, thermal sensation related, and surprising. The common notion in building simulations, reflected in the premade models of occupancy available in simulation software, is that during the night the heating is switched off, temperature drops and therefore in the morning hours when people wake up they try to bring the temperature to the desired comfort level. However, the hourly air temperature profiles of the specific dwellings mentioned in this study suggest otherwise since the temperature profiles during the night were very stable and most of the time above 20 °C. If the "energy consuming" patterns are due to habitual reasons then a GSP algorithm could reveal these patterns and feed them back to the tenants leading to potential energy savings, as long as of course these patterns do not compromise their comfort levels.

Finally, the GSP pattern recognition could be proven beneficial in the improvement of the building simulation process. Subjective parameters that are very difficult to capture and transform into hourly profiles, to be used in simulations, can be fed to the GSP algorithm, via information technology applications for mobile phones or tablets, and can be processed into hourly profiles. These customized profiles can afterwards be used to predict more accurately the energy consumption of a specific dwelling. If common patterns are found between large groups of dwellings then profiles that are more generic can be created for larger groups of dwellings based on their energy label, heating system or other categories.

Propositions for further research include the development of a more detailed application for smartphones or tablets for the tenants. The more data are fed into the algorithm, the more its precision will improve and therefore a more exhaustive, non-obligatory, selection of choices should be available. Furthermore, a challenging task would be how the findings of the GSP algorithm could be used. Some people might be interested in reducing their energy consumption while others might interested in maximizing their comfort, or some might be interesting in finding a balance between the two. The findings of the GSP could be used to attempt to alter tenants' behavior by introducing a teaser function in order to save energy, or they could just be used for tenants to help them find the appropriate levels of indoor parameters to maximize their comfort. Moreover, the customized profiles obtained by the GSP algorithm should be used in an attempt to close the gap between the simulated and actual heating consumption in residential dwellings.

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6 Conclusions and recommendations

§ 6.1 Introduction

The broader aim of this thesis was to contribute towards a more sustainable built environment, by first looking at how to seek ways to improve the existing simulation software's ability to predict the energy consumption of residential dwellings by identifying the most important parameters that affect energy consumption and indoor comfort, which is tightly related to energy consumption.

The second aim of this study was to compare the results of both PMV and adaptive models with data obtained with the use of a sensor rich smart environment. Such environments in the residential sector are still in their infancy but improvements in information technology, sensor miniaturization, software development, and analysis techniques (such as pattern recognition methods) will result to a smarter built environment in the future.

Existing thermal comfort models have been developed either for centrally conditioned spaces, with the help of steady state conditions climatic chambers, or for non-conditioned and naturally ventilated spaces with statistical data from mostly warm countries. Although none of these two models seems suitable for the residential sector of the Netherlands (mostly naturally ventilated dwellings in a relatively cold climate), they have been extensively used by engineering companies, architects, and developers. In addition, the adaptive model has been modified by the work of Van der Linden et al. [1] and Peeters et al. [2] for the Dutch official purposes and is used as a standard for indoor comfort in residential dwellings. There is therefore a huge need for further validation of these models, and the present study is a step in this direction.

Finally, the significant amount of subjective and quantitative data, gathered by the Ecommon measurement campaign, were not used only for the validation of the existing indoor thermal comfort models. They were also used by a pattern recognition algorithm in order to discover useful patterns of occupancy behavior, which could in turn be transformed into input data for simulation software, thus improving the quality of their predictions.

§ 6.2 Research Questions

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?

Building simulation analysis of newly built or refurbished buildings is a common practice among engineers, designers, developers, and public authorities. Furthermore, the complexity of simulation software has been improved over the years and more simulation modules have been added to the software to cover all possible aspects of a building. However, some of the hundreds of parameters participating in a building simulation are more important than others, with regard to the energy consumption and indoor thermal comfort. Therefore, improving the prediction quality and accuracy of building simulation software is closely related to understanding the effect that each parameter has on the energy consumption and thermal comfort.

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?

Without Behavioral parameters

In A labeled dwellings, the most critical parameters, when behavioral parameters were not taken into account, were the window U-value, window g value, and wall conductivity. Moreover, these three parameters were the most critical in both simple (single zone, ideal loads) and the more complicated models (multi-zone) for both heating systems, radiator and floor heating. The order of importance of these parameters varies between the different configurations but these three were the most important in every case. Furthermore, the relative importance of the wall conductivity for heating consumption increases when the standard deviation of all parameters that took part in the sensitivity analysis was set to 30% instead of 10%. Therefore, the more inaccurate the information on parameters during building simulations, the more important it becomes to determine the conductivity of walls as accurately as possible.

In F labeled dwellings the results were less clear. Window g value and wall conductivity were found to be the most important for the simple (single zone, ideal loads) and complex models (multi-zone, radiator). The third most important parameter was the orientation of the building, instead of the window U-value. For dwellings with a floor heating system (which is anyway a highly unlikely scenario that an F labeled dwelling will be equipped with a floor heating system), the most critical parameters were wall conductivity, floor conductivity, and window g value, which can be explained by the increased heat losses of bad insulated dwellings. A larger standard deviation around the parameters mean for label F dwellings resulted in wall conductivity being by far the most influential parameter for all types of heating systems. A larger degree of deviation around the mean of a parameter resembles the lack of information on the components of a building. Especially in older dwellings, in the lower energy labels, which were built more than forty or fifty years ago, this is a common problem. There are limited information on the U values of a building's thermal envelope, which according to the sensitivity analysis, are the most crucial factor in accurately calculating the energy consumption of the dwelling.

In addition, orientation had a non-negligible effect on heating. However, the orientation of the reference building (the direction of the façade with the largest glass surface area) is north/north-east, while the optimum orientation is facing south. Therefore, any positive deviation from the orientation (which in this case means that the building faces more south) resulted in a decrease in heating consumption.

With behavioral parameters

The most important result obtained from the Monte Carlo sensitivity analysis was the predominance of behavioral parameters. When these parameters were included, such as the thermostat setting and the ventilation flow rate, the importance of the physical parameters on the heating was significantly reduced. When the analysis took place with larger standard deviations, the results showed an increase in the influence of the parameters that are related to the conductivity of the building's thermal envelope.

Another important finding is the importance of how each heating system is controlled. If the thermostat controls the heating system in a straightforward way, as in the case of the boiler coupled with radiators, then the thermostat settings have major explanatory power. However, if the control system tends to ensure a constant temperature throughout the whole day all over the house, which is generally the case with a heat pump system coupled with floor heating, the influence of the thermostat is nil. Low hydronic underfloor systems for example constantly circulate low temperature warm water in the floor of a dwelling. The heat slowly passes through the floor and warms up the house. When a tenant uses the thermostat, the circulating water has to be heated first, circulate in the floor, and then the heating has to pass through the floor resulting in a delay of several hours, which in turn explains the non-influence of the thermostat in such cases.

2 Which are the most critical parameters that influence the PMV comfort index?

The most important parameter in determining the PMV during the heating season was the metabolic rate (meaning the occupants' level of activity), followed by clothing (clo values). Small variations in the metabolic rate (10% around 100 met, which corresponds to standing relaxed) can explain up to 95% of the variance in PMV.

In addition to the metabolic rate, the thermostat setting was found to be important to a relatively similar extent. However, the thermostat settings were almost insignificant in F label buildings, which is explained by the fact that the variations in the sensitivity analysis could not compensate for the cold walls and increased heat losses. For the same reasons as before, the thermostat has no influence on the PMV for the floor heating system.

Furthermore, the simulation results on the PMV index showed that the reference building was too cold during the heating season, even the well-insulated Class A dwelling. This poses a question about the validity of the PMV index, since the air temperature setting was 20 °C, which is a generally accepted comfortable temperature in the Netherlands. However, even at this temperature, the PMV index did not exceed the threshold of -0.5 at any case (the comfort zone according to the PMV theory is between -0.5 and +0.5), and was constantly below -1. This was also observed in the results of the measurement campaign that showed that people felt more comfortable than the PMV predictions indicated and that the PMV model underestimates the thermal comfort of occupants.

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?

Increased thermostat settings push both energy consumption and PMV upwards in dwellings with heating systems such as boilers and radiators, local and integrated (moederhaard) gas stoves, with the exception of the low temperature hydronic floor heating systems. As already explained, in such a system the thermostat settings are offset by the controls and the response time is very long. Another critical aspect of predicting the energy consumption of a dwelling is the behavior of the tenants, for which we have limited information. The parameter that influences heating the most is the use of the thermostat, which at the same time plays a minor role in the thermal comfort of the occupants. People may be trying to regulate their comfort by adjusting the thermostat, which could result only in an increase in heating consumption but will not improve their comfort levels. The results of the measurement campaign showed that the A/B labeled dwellings did not use the thermostat as much as their counterparts of F dwellings. On the one hand the A/B labeled dwellings had 3 °C higher temperatures and some of them were equipped with subfloor heating systems, with the tenants having observed that adjusting the thermostat has no immediate effect on their indoor temperature and comfort. On the other hand, the F dwellings had lower indoor temperatures and tenants have been using the thermostat more often in order to regulate their comfort.

There are indeed differences between the sensitivity analysis of the A and F label buildings. The former were highly sensitive to the window U-value, whereas for F label dwellings this was not an influential factor. Furthermore, in the F label buildings, wall conductivity gains importance, and for both types of buildings thermostat and ventilation remain the most important parameters.

4 What do the results mean for the modelling techniques for predicting the energy consumption in dwellings (simple versus more complicated models)?

The results for the simple (single zone/ideal loads) and more complicated models (multi-zone/radiator) were quite similar mainly due to the similar control system used for both models. Modelling the building as multi-zone or single zone does not seem to produce significant differences. Despite fact that no Energy+ Airflow network was used to simulate the air exchange between zones, the two cases (Single Zone and Multi Zone with fixed ventilation rates, according to the Dutch standard) did not reveal great differences between them. Every other configuration with air exchange between zones would fall between these two cases.

However, the results are quite different for the floor heating system coupled with the heat pump. Modelling the heat pump with COP values that are multiplied by the heating demand (in accordance to the EPA modelling or when making simple calculations) leads to an underestimation of the heating consumption in F label dwellings, even if this is corrected for the number of operational hours. In A label dwellings this is does not produce any problems.

Another important point is the importance of the thermostatic control loop. Predicting the heating energy consumption for existing dwellings or buildings in the design phase might not produce accurate results. The reasons for this are the lack of information such as the U values of walls and floors, or the exact way that a heating system, such as a heat pump, is simulated and controlled by the simulation software. A heat pump loop is a complex system and the lack of specific information on its operation and control can lead to rather misleading predictions concerning the energy consumption of a dwelling.

Finally, we generally define orientation by approximating to the nearest of the eight primary compass points, e.g. south, southwest, southeast etc. According to the results of this study, such an 8-point approximation may lack precision because even small differences in the orientation of a building (14.5°) can affect the annual heating consumption.

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?

The aim of this research question is to present the hardware and the methodology for 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 in residential dwellings. Furthermore, it aims to provide insights into the PMV thermal comfort model, and its success in the prediction of occupants' thermal comfort in the residential built environment, especially since comfort has rarely been researched in actual conditions on site and in other ways than surveys or diaries.

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?

The neutral temperature levels in the living rooms of the A/B label dwellings, as already mentioned, were found to be 3 °C higher than the living rooms of the F label dwellings. Consequently, the reported thermal sensations of the F label dwellings were more to the colder end compared to the ones of the A/B dwellings because the result of the neutral temperatures was obtained by a regression analysis of all the reported thermal sensations against indoor temperature.

The clothing (rather warm) and activity levels (sitting relaxed and performing light desk work) did not have significant differences between the A/B and F label dwellings. These two categories play a very important role for the thermal comfort of the occupants. Comfort wise, this could be compensated by increased energy consumption, which could be filling in for the increased thermal losses of the F label dwellings. However, given the lower neutral temperatures of the F label dwellings this could be an indication of adaptation of these occupants to a lower comfort level.

The analysis for the actions towards thermal comfort showed that the occupants of the F label dwellings have the tendency to increase the indoor temperature compared to the occupants of A/B dwellings, which could be explained by the increased heat losses of the F label dwellings. A rather popular action was having a hot drink, which was undertaken by both occupants of A/B and F label dwellings. However, this action was reported for all types of thermal sensations, which leads to the conclusion that it is taking place mostly due to habit rather for the improvement of one's thermal comfort.

2 What is the occupants' temperature perception in relation to the energy rating and heating systems of the dwellings?

The proportion of occupants who regard the dwelling as being too cold increases as we move from A label to F label dwellings. This finding is in agreement with the results reported by Majcen et al. [3], and is related to the insulation level and air-tightness of the dwellings. The tenants of dwellings with balanced ventilation (A and B label dwellings) had the highest percentage (85.7%) of responses that the indoor temperature during the winter was all right. These results could be expected and relate more to the energy rating than to the ventilation system. However, when it comes to natural ventilation with mechanical exhaust, some dwellings were A/B label while others F. The proportion of ''too cold'' responses increases from A/B label dwellings to F label ones. Occupants of dwellings with completely natural ventilation were the least likely to find the indoor temperature acceptable (55.6%). All dwellings with natural ventilation had energy rating F. Temperature perception during the winter is more closely related to the energy rating than to the type of ventilation. This was not however found to be the case in all dwellings with natural ventilation and mechanical exhaust. Some occupants of more efficient dwellings stated that they felt too cold in the winter, while some occupants of less efficient dwellings were satisfied with the indoor temperature. Further investigation of the actual energy consumption in these dwellings is required to determine whether these responses are related to excessive energy use in dwellings with low energy efficiency or very low consumption in the more energy-efficient dwellings.

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?

Clothing

The most preferred clothing ensemble for both types of dwellings was the warm ensemble. When tenants felt warmer, they replaced the warm ensemble by lighter ensembles. The only instances when tenants reported wearing the outdoors warm ensemble were when they had just come in from outside and immediately filled in the comfort app/log book. They usually reported feeling rather warm or warm in these cases, probably because of the lower outdoor temperature.

The clo value corresponding to neutral thermal sensation was determined by plotting the clo value against the reported thermal sensation and applying regression analysis to the resulting graph. Although the spread of the data was large, especially in A/B dwellings, the clo value was found to decrease with increasing thermal sensation in both cases. This confirms that clothing is an adaptive behavioral feature exercised in order to feel more comfortable. According to the regression analysis, 15.7% of the variance in clo relates to the thermal sensation.

The data collected in this measurement campaign indicated that the tenants of both A/B and F dwellings seem to wear much the same type of clothing, which means that clothing does not seem to be the reason for the lower neutral temperatures found in the living rooms of F dwellings. The same trend was found for the other types of rooms (kitchen, bedroom 1 and 2).

Analysis of variance was used to determine if there are any significant differences for the clo value between A/B and F label dwellings. The Anova was performed for the clothing level that corresponded to the tenant's neutral votes of thermal sensation, and showed that the clo values in the living room for neutral thermal sensations between A/B and F rated dwellings are equal.

Metabolic activity

The metabolic activity most often reported in both A/B and F dwellings was ''sitting relaxed''. This was followed by "light desk work" in A/B labeled dwellings and ''walking'' in F dwellings. ''Lying/sleeping'' was the fourth metabolic activity level for both types of dwellings.

The metabolic activity of the tenants was calculated as a function of the reported thermal sensation, in much the same way as was done for the clo value above. Similar levels of metabolic activity were found in the living room in both types of dwellings.

Analysis of variance was used to determine if there are any significant differences between the metabolic activity value between A/B and F rated dwellings. The Anova was performed for the metabolic activity level for the living rooms that corresponded to the neutral votes of thermal sensation of the tenants for both A/B and F label dwellings. The result showed that the metabolic activity values in the living room for neutral thermal sensation between A/B and F label dwellings are equal.

4 Is there a relationship between type of clothing /metabolic activity and the thermal sensation?

The most preferred clothing ensemble for both types of dwellings is the warm ensemble (long sleeved sweat shirt). For both A/B and F label dwellings, when thermal sensation increases clothing decreases, which indicates that occupants might be using clothing as an adaptive feature towards the improvement of their thermal comfort. Furthermore, for both A/B and F label dwellings the clothing level that corresponds to the neutral thermal sensation, for the living room, was the same.

The activity levels, for both A/B and F label dwellings, were similar for neutral thermal sensation an increase when the reported thermal sensation increases.

5 Is there a relationship between type of clothing /metabolic activity and the indoor operative temperature?

Occupants in A/B label dwellings tend to wear warmer clothing as the operative temperature rises from 20 °C to 24 °C, while people in F dwellings wear lighter clothing. Clothing levels converge at a temperature of 24 °C. In both cases, however, changes are very slight. The rise in the clothing levels when temperature increases in the A/B label dwellings is counter intuitive and it might be related to the ventilation air speed (usually A/B label dwellings were equipped with mechanical ventilation), which might be creating topical discomfort to the occupants who in turn they compensate with increased clothing levels. The same conclusions apply for the relationship between activity levels and operative temperature.

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

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?

Despite the uncertainties in the parameters needed to calculate the PMV (air speed and operative temperature), which were determined indirectly on the basis of assumptions and simulations, the neutral temperature (T_o) in both A/B and F label dwellings is well predicted by the PMV model and closely matches the neutral temperatures obtained using the reported thermal sensation of tenants. However, when all dwellings are considered together, the neutral temperature is less well predicted by the PMV model, especially for the living room.

An analysis of variance was performed in order to explore if there are significant differences between the neutral temperatures for the living room between the label

A/B and F dwellings. The results showed that there are significant differences between the neutral temperatures of the living rooms of A/B and F label dwellings.

The neutral temperature for the living rooms of A/B label dwellings is about 3 °C higher than that for the living rooms of F label dwellings. There are various explanations for this difference. The lower neutral temperatures in F dwellings could indicate that air velocities are lower in these dwellings (the balanced and mechanical ventilation systems used in A/B dwellings are known to give higher air velocities). Furthermore, people in F dwellings may wear warmer clothes or have higher metabolic activity, or this difference could be attributed to different thermal expectations, age, and gender differences between the tenants of A/B and F label dwellings. The last-mentioned explanation seems unlikely, however, since the average age of the tenants of the A/B and F dwellings is 56 and 57 years respectively, and men and women were equally distributed between the two dwelling types.

2 To what extent does the PMV comfort index agree with the thermal sensation reported by the tenants?

In order to validate further the PMV index and its ability to predict tenants' real thermal sensation, all thermal sensation values collected during the campaign were compared with the calculated values of the PMV. The thermal sensation reported by tenants ranged from -3 (cold) to +2 (warm), while the PMV calculations showed thermal comfort levels ranging from -8 to +3, which suggests that people feel more comfortable than indicated by the predictions.

The prediction success of the PMV model never exceeded 30%. When the PMV fails to predict the thermal sensation correctly, it usually underestimates it especially at higher indoor air speeds. These findings are in agreement with other studies from various countries[4,5,6] and are similar for each type of room. However, the PMV method never claimed to give accurate predictions on a case-by-case level, but only at a statistical level. However, less than 1.7 % of the variations in the reported thermal sensation could be explained by the PMV. Therefore, the PMV cannot be considered as an accurate predictor of the actual thermal sensation and other parameters must play a role.

The PMV model's underestimation of thermal comfort in residential dwellings and tenant's better perception of thermal comfort around neutrality suggests that there is a certain level of psychological adaptation and expectation since each person's home is associated with comfort, relaxation and rest. In contrast, office buildings are associated with work and higher levels of stress, effort and fatigue.

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

This research question utilized the in-situ and real time measurement of quantitative and subjective data to provide insight in the adaptive model theory, and its success in the prediction of occupants' thermal comfort in the residential built environment.

1 How successfully does the adaptive model predict occupants' thermal sensations in the residential dwellings that participated in the monitoring study?

In the sample of residential dwellings that participated in the Ecommon measurement campaign, the adaptive model predicted that tenants would have thermal sensations at the cold end, while the tenants themselves recorded sensations at the warmer end such as 'a bit warm' or 'warm'. While many data points were inside the comfort band of the adaptive model, the thermal sensation scores corresponded to comfort levels other than 'neutral'. Furthermore, many tenants recorded that they felt 'neutral' when the indoor temperatures were below the lower limits of the adaptive model. The model might thus be both overestimating and underestimating tenants' adaptive capacity in relation to achieving thermal comfort. The tenants that participated in the Ecommon study had various options at their disposal to improve their thermal comfort (clothing, actions such as having a hot or cold drink, control over thermostats and windows) and probably used many (if not all) of these options. It may be that the non-neutral sensations reported are experienced as completely acceptable, belonging to a normal range of differing sensations and therefore, these non-neutral sensations would not require any further adaptations. It is equally possible that the neutral sensations reported could have been experienced as uncomfortable, necessitating some adaptation. Such phenomena have already been mentioned by De Dear [7], and in chapter 3 we considered the possibility of indiscrimination between the thermal sensations of 'a bit cool', 'neutral' and 'a bit warm', which can also be seen in the ASHRAE RP884 database [8].

2 To what extent do outdoor temperatures affect indoor temperature set points, clothing and metabolic activity?

For an outdoor temperature range between -3 °C and 16 °C, the indoor temperatures of A/B dwellings show a slight inclination while the ones from the F-label dwellings show a bigger inclination. However, the explanatory power of outdoor temperature on indoor temperature is very low, low R^2 values, meaning that the outdoor temperature is only for a marginal part responsible for the variance in indoor temperature. This in turn means that the indoor temperatures chosen by the occupants only marginally relate to the outdoor temperature.

During the non-sleeping hours in which tenants recorded their clothing levels (clo), the outdoor temperatures varied between 2.5 °C and 15 °C. Indoor temperature for A/B-labelled dwellings varied between 19 °C and 25.5 °C, while for F-labelled dwellings varied between 16 °C and 25.5 °C. The clothing level for both A/B and F-labelled dwellings was between 0.5 and a little over 0.6 clo. Therefore, regardless of the thermal quality of the dwelling and the indoor temperature, people had a consolidated clothing pattern, which did not change despite the 13 °C difference in outside temperature. This does not mean that the indoor clothing patterns do not relate to the outdoor temperature at seasonal level. However, when the adaptive model is used to assess the performance of houses, which generally can only be done using a shorter period of measurements, one can assume that clothing is not dependent on outdoor temperature, even if the temperature range is high. As in the case of clothing, outdoor temperatures appear to have no effect on the metabolic activity, which seems in line with common sense that, except in extreme situations, undertaking indoor activities could be driven of habits, obligations etc. rather than a response to outdoor temperature.

3 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?

Tenants turned their thermostat up more often while feeling 'a bit cool' than when they were feeling 'cool', which might be another evidence of the difficulty in discriminating between thermal sensations. Furthermore, they turned their thermostat up when feeling 'neutral' and even when feeling 'a bit warm', which offers additional evidence of the habitual use of the thermostat. Having a hot drink was another popular action, with tenants doing so while reporting all of the four thermal sensations mentioned above.

This could be an indication that tenants undertake specific actions/adaptations due to habits developed over the long term, regardless of their reported thermal sensation such as having a coffee in the morning to wake up or after lunch to avoid afternoon sleepiness. Chi^2 tests were performed to explore possible habitual connections between actions aimed to create thermal comfort and the various levels of thermal sensations. No correlations were found between the RTS and 'opening' or 'closing the window', 'take off clothing', 'turn the thermostat down' or 'having a hot shower' for both A/B and F label dwellings, which is a good indication that these actions are habitual and therefore not related to thermal comfort.

The only action that correlates to RTS in A/B label dwellings is 'having a cold drink' and in F label dwellings 'put on clothes' and 'thermostat up'. This suggests that in A/B dwellings the conditions during the heating season are so good (e.g. operative temperature, air velocities) that people do not feel the need to undertake any additional action. In F buildings, which generally have a poorer thermal envelope, these actions are needed to increase comfort. It should be noted that 'Opening the window', which could significantly affect the energy consumption of a dwelling, was not related to the reported thermal sensation level for either the A/B or F-labelled dwellings. Thus, people probably open the window out of habit to ventilate the room, regardless of their thermal sensation.

4 What is the impact of clothing level and metabolic activity on tenants' thermal sensations?

Concerning clothing levels, no correlations were found between the RTS and wearing a 'very light', 'normal', and 'warm' combination of clothes. Only 'rather warm' clothing (long-sleeved sweatshirt) was related to the RTS and the majority of the cases were recorded for 'neutral' and 'a bit cool' thermal sensations. This means that there were significantly more people wearing a long-sleeved shirt in the categories of 'neutral' and 'a bit cool' than in other categories. For metabolic activity, only jogging was unrelated to the RTS. 'Lying sleeping/ relaxed', 'sitting relaxed' and 'light desk work' were all found to be significantly related to the RTS. The only clothing or metabolic activity correlated to RTS in A/B label dwellings are wearing a 'rather warm' clothing (long-sleeved sweatshirt), 'sitting relaxed' and doing 'light deskwork' and in F label dwellings wearing 'light clothing' (T-shirt), and 'walking'.

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?

This last research question demonstrates a methodology for predicting occupancy behavior related to indoor thermal comfort and energy consumption in the residential built environment. pattern recognition algorithm (GSP), 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 three hours in the morning and three hours 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.

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:

- 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?

Using large sets of data, from a sensor rich environment in residential dwellings, into a pattern recognition model such as the GSP algorithm could lead to the prediction of occupancy behavior patterns. Grouping all dwellings together, regardless of the energy label revealed that 59% of dwellings in the morning hours between 7-9 a.m. have been increasing their temperature from 20 °C< T< 22 °C to T> 22°C. 56% of dwellings were finding temperatures between 20 °C< T< 22 °C to be a bit cool and even for temperatures above 22 °C they were having a warm shower leading to the suspicion that a warm shower is a routine action not related to thermal comfort. For the evening hours, between 5-7 p.m. 65% of the dwellings' tenants were finding temperatures higher than 22 °C to be neutral and half of them was increasing the temperature from 20 °C < T< 22 °C to T>22 °C.

For the A/B label dwellings, the analysis showed that 80% of them feel neutral for temperatures above 22 °C. For the F label dwellings, 64% found T > 22 °C to be neutral and increased the temperature from 20 °C < T< 22 °C to T>22 °C. This suggests that tenants of lower labeled dwellings do not compromise their comfort for increased energy consumption compared to their counterparts of A/B label dwellings. This agrees with some of the findings of the initial questionnaire given to the tenants. In the question 'do you find it difficult to pay you monthly energy bills' all tenants replied 'no' despite the fact that the household incomes ranged between 700 to 4.5 thousand euros.

The sequential patterns analysis of occupancy were categorized as energy consuming, non-energy consuming, thermal sensation related, and surprising. The common notion in building simulations, reflected in the premade models of occupancy available in simulation software, was that during the night the heating is switched off and is switched on back again in the morning hours when people wake up. The hourly temperature profiles of the dwellings though suggest otherwise. The profiles were very stable and most of the time above 20 °C for every hour of the day. If the "energy consuming" patterns are due to habitual reasons then the GSP could reveal these patterns and feed them back to the tenants leading to potential energy savings, as long as of course these patterns do not compromise their comfort levels.

2 How does the use of actual behavioral patterns affect the simulated energy use? The GSP pattern recognition could be proven beneficial in the improvement of the building simulation process. Subjective parameters, to be used in simulations, that are very difficult to capture and transform into hourly profiles, can be fed to the GSP algorithm, via information technology applications for mobile phones or tablets, and can be processed into hourly profiles. These customized profiles can afterwards be used to predict more accurately the energy consumption of a specific dwelling. If common patterns are found between large groups of dwellings then profiles that are more generic can be created for larger groups of dwellings based on their energy label, heating system or other categories.

§ 6.3 Limitations in data collection and propositions for further research

§ 6.3.1 Energy Performance and comfort in residential buildings: Sensitivity for building parameters and occupancy.

Building simulation is a very complex task and its results may vary significantly from reality due to specific modelling assumptions and input assumptions that are made during each simulation. Based on the findings of this chapter, it is very important to know (or be able to measure) the exact U-values of walls, assuming the determination of the U-values and g values for windows is not a problem. This problem was also pointed out by Majcen (2013). Most of the time it is very difficult to find information on the building characteristics of older dwellings, therefore, a new method has to be developed for the fast and reliable in situ determination of the U-values for walls, floors, roofs or other building surfaces.

Furthermore, the thermostat settings and ventilation have a very high impact in energy consumption, however, they cannot be determined precisely on beforehand. Thus, energy consumption should be shown as bandwidth, particularly for design purposes. Moreover, simulations for energy labelling should take place post construction and delivery of a dwelling. The average heating set-point temperature of each specific dwelling should be used, for crude yearly energy consumption calculations performed by non-dynamic software, which should be determined by a measuring campaign with sensors across all classes of building stock, during occupancy. For more complex and dynamic simulations hourly profiles obtained from the yearly measurements should be used.

Another important issue that has to be studied is the effect of air speed on the PMV. Actual air speed profiles are very difficult to obtain because it is a very difficult task technically and economically since air speed may vary significantly in different places of a room. A CFD model of each building could be a good alternative. Hourly air speed profiles for typical ventilation configurations have to be obtained which will later be loaded to a whole building simulation software.

Finally the effects of curtains and window blinds on the heating and PMV, should be studied in modes other than on/off that are compatible with real occupancy patterns. Curtains and solar blinds on windows affect radiant temperature and consequently the operative temperature of a dwelling.

§ 6.3.2 In-situ and real time measurements of thermal comfort and its determinants in thirty residential dwellings in the Netherlands

An important point of discussion is related to the 7-point scale used for the PMV. This scale was developed in climate chamber experiments where subjects were exposed to a variety of climatic conditions and it was validated by regression analysis between the calculated PMV values and the subjects' reported thermal sensations. However, there is no guarantee that a thermal comfort level of -3 reported by a Dutch subject corresponds to -3 on the PMV scale. Greater robustness could be achieved by collecting large scale data sets for a wide variety of subjects and areas in the Netherlands and using these data to define the PMV scale for the Netherlands together with the thermal sensation scale for Dutch subjects. Ideally, further development in sensor technology should make miniaturized sensor systems, developed for the residential built environment, more economically viable. Such sensor systems, along with IT based application for capturing the related subjective data, would capture all the necessary data related to thermal comfort, energy consumption, and occupancy behavior in an individual dwelling, analyze them and recreate all existing thermal comfort models tailor made for the occupants of each dwelling.

Furthermore, the possible effect of psychological adaptation of the tenants have hardly been researched. Thermal adaptation can cause people to perceive, and react to, sensory information differently on the basis of past experience and expectations. Personal comfort set points are far from thermostatic, and expectations may be more relaxed as shown by habituation in psychophysics where repeated exposure to a constant stimulus leads to a diminishing evoked response [7]. A way must be found in order to incorporate such adaptations and, since the only possibility to measure such parameters is during occupancy, these adaptations could be researched with the use of big data obtained by sensors systems in each dwelling.

§ 6.3.3 In-situ real time measurements of thermal comfort and comparison with the adaptive comfort theory in Dutch residential dwellings.

A general limitation of the Ecommon measuring campaign was its short time span. This limitation does not allow to refute or validate the adaptive model, as described by de Dear, which was aimed at modelling seasonal and regional differences. However, extending the study to more dwellings and for a longer period, our measurement method, by which the reported thermal sensation is measured many times a day and coupled to physical data, will allow the collection of more accurate data on actual comfort.

The expectation aspect of the adaptive model relative to outdoor temperature lacks a solid foundation, a finding supported by several other studies [9, 10]. Expectations should also be explored with respect to the ideal indoor conditions and the thermal comfort level tenants have consolidated in their minds. Furthermore, local behavioural, social and psychological aspects should be explored to create a robust expectation factor for the residential dwellings, which can subsequently be validated by field experiments similar to the Ecommon study. However, one should keep in mind that the technical systems installed in residential dwellings may induce self-fulfilling prophecies: if the dwellings are equipped with constant temperature systems, the occupants will take this for granted and no adaptability to outdoor temperature will be observed, while such adaptability may exist and might be demonstrated by studies of dwellings that do have this adaptation possibility. The fact that in our sample the indoor temperatures in the A/B-labelled dwellings are higher than in the F-labelled dwellings and that there were not more people feeling non-neutral in the F dwellings, indicates this adaptation possibility.

Finally, rethinking of the theoretical background of the adaptive model is required if it is to be applied to residential buildings. Despite the fact that they account for a very large share of energy consumption in the EU, residential buildings have been treated up to now as if they were similar to office buildings when it comes to thermal comfort models. The equations used are developed based on office buildings, while it is clear that the use of space, the activities undertaken, clothing worn, and actions aimed to improve thermal comfort differ in these two types of buildings. Future research must aim to develop and validate new equations that take the specific qualities of residential buildings and their inhabitants into account.

§ 6.3.4 Pattern recognition related to energy consumption and thermal comfort from in-situ real time measurements in Dutch residential dwellings.

Just like in the case of whole building simulation, the most important factor for pattern recognition tasks is the quality of data. Furthermore, for pattern recognition applications the volume of data is similarly important. The more data are fed into the algorithm, the more its precision will improve. In addition, a challenging task would be how the findings of such patter recognition could be used in home management systems. Some people might be interested in reducing their energy consumption while others might interested in maximizing their comfort, or some might be interesting in finding a balance between the two. Such results could be used in an attempt to alter tenants' behavior by introducing a teaser function in order to save energy, or they could just be used for tenants to help them find the appropriate levels of indoor parameters to maximize their comfort. Additionally most often occurring patterns could be used in simulation models in order to increase their accuracy or to make sensitivity analysis on building use.

§ 6.4 General Conclusion

The existing simulation software, in the way they are being used at the moment, are not sufficient enough to accurately calculate the energy consumption of the residential built environment. Occupancy behavior is responsible for a great part of the residential buildings' energy consumption. At this moment, occupancy behavior is incorporated in the simulation software in a rather simplistic way, which does not allow the accurate calculation of occupancy behavior's impact in energy consumption. However, advances in sensor and wireless communication technology could allow the installation of home sensor systems that would gather, in real time and in a non-intrusive way, atmospheric data as well as data related to occupancy behavior. These data could be incorporated in existing or new simulation software and increase their accuracy of prediction.

The discrepancy between theoretical and actual energy consumption in residential buildings is a very important obstacle towards a more sustainable built environment. It is very difficult to reduce the energy consumption in the building sector when we cannot calculate and predict it successfully. Despite the fact that building simulation software have made huge steps forward, the problem still persists. Building simulation software have transformed from static to dynamic, their algorithms have been refined and new ones have been added to cover more components and aspects of the built environment. Furthermore, new user friendly interfaces have been developed making the software more user friendly and bringing whole building simulation calculations to the mainstream of energy engineering. However, these simulations are still complex, prone to numerous assumptions, and the users generally lack proper input data. Some of these data are very important for the calculations such as the U values of old buildings and occupancy related data, the latter being available only during the occupancy phase.

In addition, another problem are the comfort models which have attracted criticism from the scientific community but still are incorporated in national policies and used by the construction industry. Such comfort models are trying to describe a complex combination between physical and psychological aspects of humans in indoor environments. As already mentioned extensively in this thesis, the PMV model has been developed in climate chambers with steady state conditions with a certain number of subjects. It was originally developed for office buildings but it was used extensively by architects, engineers and developers for the residential sector as well. Furthermore, despite the fact that it was developed in specific climatic chambers, it has been used all over the world. No one knows if the 7 point comfort scale, developed from Fanger, means the same for a person in the Netherlands and a person in Indonesia.

The adaptive model has been developed based on specific data on non-conditioned spaces in areas with warm climate. However, scientists made certain modifications and tried to adapt the model to other weather conditions, such as the climate of the Netherlands and Belgium although their modifications were tested on experimental data from heated spaces. This model, despite its many uncertainties was incorporated to the national directives for energy in the built environment.

Given all the theoretical and scientific uncertainties and assumptions maybe it is time for the scientific community to stop investing most of its effort and money in the development or the further refinement of the existing calculating tools and theoretical models for the prediction of energy consumption in the built environment.

On the planet there is a multitude of people, climates, behaviors, housing qualities, expectations, behavioral routines, economic abilities, psychological reactions and many more parameters related to energy consumption in the built environment. Instead of focusing in the improvement of a few models, that would satisfactory explain the energy consumption in the built environment in every place and for all people in the world, the focus should shift into a more tailor made approach that would target every single person individually. Such a paradigm would be impossible a couple of decades earlier.

However, the extremely fast development of information technology and computational power, in combination with the rapid expansion of the internet, opened a window of new opportunities towards a more sustainable built environment. A focused advancement should take place towards the miniaturization and economic viability of sensor technology, which will allow every household to afford installing complex IT systems in their homes (just like it happened with the electricity infrastructure in houses a hundred years ago). At the same time, advancements in pattern recognition and big data management would allow the processing of the big data, gathered from each dwelling. Every available comfort model could be calculated, adjusted, and customized to every individual dwelling according to the specific twists and needs of each household.

The following figure explains briefly the outline of such an attempt towards the individualization of energy consumption, indoor environment optimization, and comfort calculation. The sensors could be providing big data, during the occupancy phase, to a central or even local database. There the data would be processed and used as training data sets in order to adjust or construct a model specific to each individual dwelling. These models could then be used to propose individual energy saving measures.

Such a system could be modular in terms of hardware and software. When research in this field would discover a new parameter that could add value to the calculations of the comfort behavior of the dwellings then it should be easily incorporated to the whole system in a plug a play manner (for example new sensors should be able to be easily added to the existing system, just like plugging in a new mouse in a laptop). Furthermore, new more advanced comfort models might be set up by scientists. Then these new models could be incorporated as well into the software of the system.

Next to individual solutions big data from home energy management systems could be gathered in order to identify the most energy efficient solutions without compromising the comfort of the tenants. Consequently, good solutions in both terms of energy conservation and uncompromised indoor comfort could be chosen and the indoor environment could be adjusted real time by a control device that would be installed in the dwelling. This control device (we could imagine it as something similar to nowadays thermostat boxes) would be the mean of interaction between the tenants and the complex system of sensors, databases, occupancy patterns, and building characteristics of a dwelling.

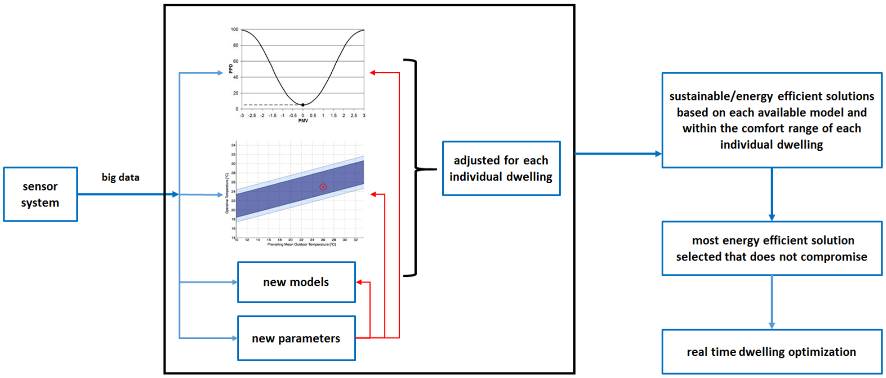

FIGURE 6.1 Schematic for the final conclusion of this thesis

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Appendix A Questionnaire occupants were asked to fill in during the initial installation of the sensors in their homes (in Dutch)

Unieke code woning:…………………………

ALGEMENE INFORMATIE

Deze vragenlijst is onderdeel van het onderzoek Energie en COMfort MONitoring (Ecommon). Dit onderzoek wordt uitgevoerd door de Technische Universiteit Delft.

In deze vragenlijst wordt gevraagd naar de samenstelling van uw huishouden, het gebruik van verwarming en ventilatiesystemen in uw huis, en er zijn vragen over comfort en gezondheid.

Het kost ongeveer 20 minuten om deze vragenlijst in te vullen. Wij vragen u deze lijst in te vullen tijdens de installaties van de sensoren in uw woning.

Wanneer u de vragenlijst heeft ingevuld geeft u die terug aan de installateur van VOLT. Hij schrijft dan bovenaan de unieke code van uw woning.

De gegevens worden anoniem en strikt vertrouwelijk behandeld volgens de Wet bescherming persoonsgegevens.

Alvast bedankt!

GEGEVENS HUISHOUDEN

1 Woont u in een sociale huurwoning? *(omcirkel wat van toepassing is)*

- Ja
- Nee
- Weet ik niet

2 Hoeveel kamers heeft uw woning in totaal? *(Badkamer en afgesloten keuken moeten als kamer meegeteld worden. De gang en hal hoeven niet meegeteld te worden.)*

_ _ _ _ _ kamers

3 Uit hoeveel personen bestaat uw huishouden? *(Alleen personen meetellen die in deze woning wonen, uzelf graag meetellen!)*

_ _ _ _ _ personen

4 Wat is de leeftijd van deze personen? Begin met uzelf en ga door met de rest van uw huishouden.

Uzelf, persoon 1	_ _ _ _ _	Persoon 5	_ _ _ _ _
Persoon 2	_ _ _ _ _	Persoon 6	_ _ _ _ _
Persoon 3	_ _ _ _ _	Persoon 7	_ _ _ _ _
Persoon 4	_ _ _ _ _	Persoon 8	_ _ _ _ _

5 Kunt u per dag aangeven hoeveel mensen er normaal gesproken thuis zijn op de volgende dagdelen?

	ochtend	middag	avond	nacht
Maandag	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _
Dinsdag	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _
Woensdag	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _
Donderdag	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _
Vrijdag	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _
Zaterdag	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _
Zondag	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _	_ _ _ _ _

6 Hoe energiezuinig is uw woning? *(omcirkel wat van toepassing is)*

- Heel zuinig
- Zuinig
- Gemiddeld zuinig
- Niet zo zuinig
- Helemaal niet zuinig
- Weet ik niet

7 Weet u welk energielabel uw huis heeft? *(omcirkel wat van toepassing is)*

- Ja, namelijk energielabel _ _ _ _ _
- Nee

GEGEVENS VERWARMEN EN VENTILEREN

8 Welke toestellen heeft u in uw woning *(omcirkel wat van toepassing is, u kunt meerdere opties kiezen)*

- Combiketel of ketel
- Geiser
- Gaskachel
- Elektrische boiler (bv een close-in boiler)
- Zonneboiler
- PV-cellen
- Weet ik niet
- Anders, namelijk _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

9 Hoe regelt u de temperatuur in huis? *(omcirkel wat van toepassing is)*

Handmatige thermostaat		
Geen thermostaat		
Weet ik niet		

10 We willen graag weten hoe u uw woning verwarmd in de winter. Denk aan een winterdag die niet heel warm of heel koud is. Hoeveel kamers verwarmt u in de winter en op welke temperatuur verwarmt u de kamers?

	Aantal kamers	Temperatuur (in graden)
Overdag of 's avonds wanneer niemand thuis is	----	----
Overdag wanneer er wel iemand thuis is	----	----
's avonds wanneer er wel iemand thuis is	----	----
's nachts	----	----

11 Verwarmt u in de winter wel eens de gang of de hal bij de voordeur? Zo ja, hoe vaak? *(omcirkel wat van toepassing is)*

- Ja, vaak
- Ja, soms
- Nee

12 In sommige woningen zijn er ventilatie-installaties waarmee de lucht kan worden ververst. Dit kan mechanische ventilatie of balansventilatie zijn. Bij mechanische ventilatie ziet u in uw woning alleen maar ventielen (afbeelding 1). As uw woning balansventilatie heeft dan is er vaak ook een grote installatie in uw stookhok of op zolder (afbeelding 2).

Afbeelding 1 (een ventiel)

Afbeelding 2 (Installatie voor balansventilatie)

Heeft u in uw woning zo een ventilatiesysteem? *(omcirkel wat van toepassing is)*

- Ja, mechanische ventilatie
- Ja, balansventilatie
- Ja, maar ik weet niet of dit mechanische of balansventilatie is
- Nee -> ga naar vraag 15
- Weet ik niet -> ga naar vraag 15

13 Kunt u deze zelf instellen? *(omcirkel wat van toepassing is)*

- Ja
- Nee -> ga na vraag 15
- Weet ik niet -> ga naar vraag 15

14 Op welke stand heeft u het ventilatiesysteem staan? ____

15 Hoe lang ventileert u **in de winter** per dag normaal uw huis door ramen en roosters te openen of buitendeuren open te zetten? Kunt u dit per ruimte aangeven met een kruis?

	niet	Minder dan 1 uur	1-4 uur	5-8 uur	9-12 uur	13-24 uur	Niet van toepasssing
Woonkamer	_____	_____	_____	_____	_____	_____	_____
Keuken	_____	_____	_____	_____	_____	_____	_____
Badkamer	_____	_____	_____	_____	_____	_____	_____
Slaapkamer(s)	_____	_____	_____	_____	_____	_____	_____

16 Ventileert u in het weekend meer of minder dan doordeweeks? *(omcirkel wat van toepassing is)*

- In het weekend meer dan doordeweeks
- In het weekend even vaak als doordeweeks
- In het weekend minder dan doordeweeks

17 Wilt u hieronder aangeven welke van de volgende apparaten u gebruikt? Wij willen graag het aantal weten.
Als in uw huishouden 3 telvisies gebruikt worden, dan mag u 3 invullen bij televisie.

	Aantal		Aantal
Televisie	_ _ _ _ _	Vaatwasser	_ _ _ _ _
Computer, laptop, tablet	_ _ _ _ _	Wasmachine	_ _ _ _ _
Draadloos internet	_ _ _ _ _	Droger	_ _ _ _ _
Draadloze huistelefoon	_ _ _ _ _	Voordeurverlichting of tuinverlichting	_ _ _ _ _
Koffiezetapparaat/waterkoker	_ _ _ _ _	Zonnebank, jacuzzi of huissauna	_ _ _ _ _
Elektrische grill of oven	_ _ _ _ _	Waterbed	_ _ _ _ _
Cooker in de keuken	_ _ _ _ _	Aquarium of terrarium	_ _ _ _ _
Magnetron	_ _ _ _ _	Airco unit of ventilator (plafond/staand)	_ _ _ _ _
Inductie of elektrische kookplaat	_ _ _ _ _	Terras- of balkonverwarmer	_ _ _ _ _
Gasfornuis/oven	_ _ _ _ _	Extra elektrische radiatoren	_ _ _ _ _
Vriezer	_ _ _ _ _	Afzuigkap	_ _ _ _ _
Koelkast	_ _ _ _ _	Close-in boiler (extra boilertje in de keuken)	_ _ _ _ _
Koel-vriescombinatie (koelkast en vriezer in 1)	_ _ _ _ _		_ _ _ _ _

De volgende vragen gaan over het gebruik van douche en bad.

18 Hoe vaak wordt er in uw huishouden gebruik gemaakt van een douche op een gemiddelde DAG?
Als er 4 mensen 1 keer douchen op een dag, dan vult u hier 4 in. Douchen er 2 mensen 3 keer op een dag, dan vult u hier 6 in. Is er minder dan 1 douche per dag vult u 0 in.

_ _ _ _ _ aantal douches per dag

19 Hoeveel minuten doucht men gemiddeld per keer?

_ _ _ _ _ minuten

20 Als u een bad heeft, wat is normaal gesproken het totaal aantal baden per WEEK? *Is er minder dan 1 bad per week vult u 0 in.*

_ _ _ _ _ aantal baden per week
Er is geen bad

VRAGEN OVER UW ENERGIEGEBRUIK

21 Hoe gaat u met uw energiegebruik om? *(omcirkel wat van toepassing is)*

- Zuinig/energiebewust
- Gemiddeld
- Niet zuinig/energiebewust

22 Bestaat meer dan de helft van uw verlichting uit spaarlampen, LED lampen of tl-buizen? *(omcirkel wat van toepassing is)*

- Ja
- Nee
- Weet ik niet

23 Welke energiebesparende maatregelen worden in uw huishouden genomen? *(omcirkel wat van toepassing is, meerdere antwoorden mogelijk)*

- Gebruik spaardouchekop
- Thermostaat niet hoger zetten dan nodig is
- Niet ventileren wanneer de verwarming aan staat
- Lichten uit in kamers waar u niet bent
- Gebruik apparaten A++
- Gebruik standby-killer *(stekkerdoos waarmee u alle apparaten in 1 keer uit kunt zetten)*
- Geen enkele

24 Hoe vaak komen de volgende zaken in uw huishouden voor? Kunt u dit aangeven met een kruis?

	vaak	soms	(bijna) nooit	Niet van toepassing
Adapters/opladers in stopcontact laten zonder dat er een apparaat op aangesloten is	-----	-----	-----	-----
Lichten aanlaten in ruimten waar voor langere tijd niemand aanwezig is	-----	-----	-----	-----
Apparaten op standby-stand laten, zoals de tv	-----	-----	-----	-----

25 In het algemeen vindt u het thuis in de winter...? *(omcirkel wat van toepassing is)*

- Te koud
- Goede temperatuur
- Te warm
- Weet ik niet

26 In het algemeen vindt u het thuis in de winter…? *(omcirkel wat van toepassing is)*

- Te vochtig
- Goede vochtigheid
- Te droog
- Weet ik niet

27 Heeft u of een ander persoon in uw huishouden regelmatig in de winter last van tocht binnen? *(omcirkel wat van toepassing is)*

- Ja
- Nee

28 In het algemeen vindt u het thuis in de zomer…? *(omcirkel wat van toepassing is)*

- Te koud
- Goede temperatuur
- Te warm
- Weet ik niet

29 Wat zou u het liefst willen veranderen aan uw woning, om het prettig te hebben in de winter? *(maximaal 3 keuzen mogelijk, omcirkel wat van toepassing is)*

- Woning warmer
- Woning kouder
- Lucht in woning vochtiger
- Lucht in woning droger
- Minder tocht
- Sneller warm water uit de kraan
- Meer mogelijkheid tot ventilatie
- Niets
- Anders, namelijk: _______________________________________

30 Weet u wat (ongeveer) uw energierekening per maand is?

_____ euro per maand

Weet ik niet, of geen antwoord

31 Is het voor u gemakkelijk of moeilijk om de maandelijkse energierekening te betalen? *(omcirkel wat van toepassing is)*

– Heel gemakkelijk
– Redelijk gemakkelijk
– Een beetje moeilijk
– Heel moeilijk

32 Wat is de hoogst voltooide opleiding in uw huishouden? *(omcirkel wat van toepassing is)*

– Geen opleiding gevolgd, of enkele jaren lagere school/basisschool gevolgd
– Lagere school/basisschool/speciaal onderwijs
– VSO, VBO/LBO (huishoud- ambacht- technische school, interne bedrijfsopleiding), MBO-kort
– Leerlingwezen, ULO, BBL/BOL 1-2
– MAVO, MULO, VMBO
– MBO-lang, interne opleiding op MBO-niveau, BBL/BOL 3-4
– HAVO, VWO, HBS, MMS
– HBO, interne opleiding op HBO-niveau
– WO, universiteit, kandidaatsexamen
– Opleiding in het buitenland
– Anders, namelijk ____

33 Wat is het netto inkomen per maand waarover uw huishouden beschikt? *(Dit is exclusief inkomen van kinderen jonger dan 18 jaar, vakantiegeld en kinderbijslag)*

__________ euro per maand

34 In deze vragenlijst zijn verschillende onderwerpen aan bod gekomen. Wellicht zijn er onderwerpen die niet in deze vragenlijst aan de orde zijn geweest, maar waarover u wel graag iets kwijt zou willen. Ook suggesties voor verbetering zijn welkom.

Hartelijk dank voor het invullen van deze vragenlijst!

Appendix B Installation checklist used by the installation technicians while installing the sensors in the dwellings (in Dutch)

E-COMMON
Energie & Comfort Monitor

INSPECTIELIJST EN CHECKLIST VOOR DE INSTALLATEUR

1 Adres huis: ………………………………………………………………………….

2 Is het adres ingevuld op de vragenlijst: Ja / Nee

3 Is het adres ingevuld op de inventarisatielijst: Ja / Nee

4 Voor het installeren van de Youless:

METERSTANDEN	Bij installatie	Bij ophalen
Elektriciteit A	_ _ _ _ _	_ _ _ _ _
Elektriciteit B	_ _ _ _ _	_ _ _ _ _
Gas	_ _ _ _ _	_ _ _ _ _
Warmte	_ _ _ _ _	_ _ _ _ _
Overigen	_ _ _ _ _	_ _ _ _ _

5 Ventilatie:

Is er een afzuigkap in de keuken?	Ja / Nee	
Is er een andere mechanische ventilatiesysteem aanwezig? *(Te herkennen aan ventielen meestal in keuken, badkamer en WC)*	Ja / Nee	
Zo ja, is het balansventilatie (dan graag merk en type): *(Bij balansventilatie is ook een warmtewisselaar aanwezig zie afbeelding hiernaast)*		

6 Vóór het installeren van de Eltako bij de ketel , Warmtepomp of ventilatiesystem:
Checken wat de thermostaat/ventilatie instellingen zijn van de bewoner:

Temperatuur? Tijdschema?

Prioriteit: ketel of warmtepomp

- *Alleen ketel aanwezig: Eltako plaatsen bij ketel*
- *Ketel en mechanische ventilatie: Eltako plaatsen bij ketel (Hoeveel eltakos hebben wij? Als wij er 2 per woning hebben kunnen wij beiden doen)*
- *Warmtepomp aanwezig: Eltako plaatsen bij warmtepomp*
- *Warmtepomp en mechanische ventilatie: Eltako plaatsen bij warmtepomp. (Als wij er 2 per woning hebben kunnen wij beiden doen)*

7 Thermostaat: handmatig / programmeerbaar / geen

8 Na het installeren van de Eltako:
Thermostaat/ventilatie instellingen checken en zo nodig herstellen :

9 Als een ketel aanwezig is:
Merk en type ketel, zo compleet mogelijk (meestal zit het ergens onderaan op een sticker): …………………………………………………………………………………….

10 Als een warmtepomp aanwezig is:
Merk en type ketel, zo compleet mogelijk: ……………………………………………

Wordt de warmtepomp ook gebruikt voor warm tapwater? Ja / Nee / Weet niet

11 Als er gaskachels zijn:
In hoeveel kamers:……………………………………………………………………………

Is de gaskachel gekoppeld aan centrale verwarming? Ja / Nee

12 Warm tapwater:
Welke toestellen zijn er voor warm tapwater *(meerdere kruizen mogelijk)*:

- Combiketel
- (keuken) Geiser
- Elektrische close-in boiler
- Warmtepompboiler
- Anders: ……………………………………………

13 Beglazing; is er:

- Overwegend dubbel glas
- Overwegend enkel glas

14 Andere opmerkingen gedurende de installatie: