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.

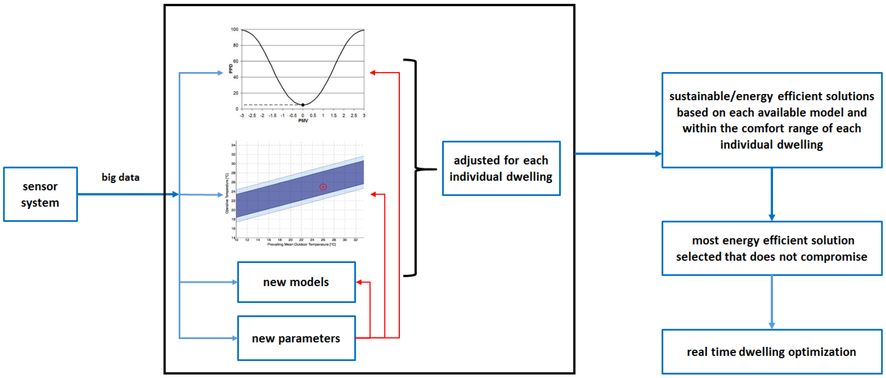

FIGURE 6.1 Schematic for the final conclusion of this thesis

References

REF. 6.01 Van der Linden, A. C., et al. “Adaptive temperature limits: A new guideline in The Netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate.” Energy and buildings 38.1 (2006): 8-17.

REF. 6.02 Peeters, Leen, et al. “Thermal comfort in residential buildings: Comfort values and scales for building energy simulation.” *Applied Energy* 86.5 (2009): 772-780.

REF. 6.03 Majcen D., Itard L., Visscher H. 2015, Statistical model of the heating prediction gap in Dutch dwell-ings: Relative importance of building, household and behavioral characteristics, Energy and Buildings 105 (2015), 43-59.

REF. 6.04 Becker, R. and Paciuk, M., 2009. Thermal comfort in residential buildings–failure to predict by standard model. Building and Environment, 44(5), pp.948-960.

REF. 6.05 Khan, Muhammad Hammad, and William Pao. “Thermal Comfort Analysis of PMV Model Prediction in Air Conditioned and Naturally Ventilated Buildings.”*Energy Procedia* 75 (2015): 1373-1379.

REF. 6.06 Beizaee, Arash, and Steven K. Firth. “A comparison of calculated and subjective thermal comfort sensation in home and office environment.” (2011).

REF. 6.07 De Dear, Richard. “Revisiting an old hypothesis of human thermal perception: alliesthesia.” *Building Research & Information* 39.2 (2011): 108-117.

REF. 6.08 http://sydney.edu.au/architecture/staff/homepage/richard_de_dear/ashrae_rp-884.shtml

REF. 6.09 Nicol, J. Fergus, and Michael A. Humphreys. “Adaptive thermal comfort and sustainable thermal standards for buildings.” Energy and buildings 34.6 (2002): 563-572.

REF. 6.10 Halawa, E., and J. Van Hoof. “The adaptive approach to thermal comfort: A critical overview.” Energy and Buildings 51 (2012): 101-110.