Understanding thermal comfort and heating energy use in Dutch dwellings: Analysis of smart meter data, indoor climate and comfort in 78 Dutch dwellings

Anastasia Petropoulou - 5147352
MSc Thesis

December 2021

TU Delft

Delft University of Technology
Faculty of Civil Engineering & Geosciences

Understanding thermal comfort and heating energy use in Dutch dwellings: Analysis of smart meter data, indoor climate and comfort in 78 Dutch dwellings

By

Anastasia Petropoulou

in partial fulfilment of the requirements for the degree of

Master of Science
in Civil Engineering
Building Engineering: Building Technology and Physics

Student number:	5147352	
Thesis committee:	Dr. Laure Itard	TU Delft, Chair
	Dr. Arjen Meijer	TU Delft, Daily Supervisor
	Ir. Andrea Thaddeus	TU Delft, Daily Supervisor
	Ir. Hoessein Alkisaei	TU Delft, Supervisor

6 December 2021

Summary

According to the European Commission, buildings are responsible for approximately 40% of the EU energy consumption and 36% of the CO_2 emissions, resulting in the largest energy consumer in Europe. Especially, the reduction of energy consumption for heating of residential dwellings has gained more and more interest in the last decades. Although some reduction has been achieved by implementing passive or active strategies and improving the thermal performance of new or renovated dwellings, the decrease is found to be lower than predicted by the energy performance models. One possible reason is that the existing thermal comfort models, the PMV and the adaptive thermal comfort model, are not appropriate for all different types of buildings and climates, resulting in inaccurate predictions of thermal comfort and leading to amounts of energy use different than the actual ones. In addition, the occupants' behaviour, which is determined by their thermal comfort preferences might play a significant role on the energy use which needs to be explored. Therefore, the main topic of the current thesis is to explore the relationship that different parameters such as dwelling and installation characteristics, indoor and outdoor climate parameters, household and physiological characteristics as well as occupants' behaviour have with thermal comfort and energy use.

A measurement campaign took place within the context of the OPSCHALER project and data related to thermal comfort perception, indoor climate and energy consumption was collected for 96 dwellings in the Netherlands during periods ranging from two to twelve months over a one-year period (2017-2018). The gathered data included both quantitative and subjective data. The quantitative data included the indoor climate data (air temperature, relative humidity, CO_2, presence), the gas use and the electricity use collected through smart meters and sensors. The subjective data related to comfort was gathered by a comfort mobile application where users recorded their thermal sensation and other comfort related parameters (thermal preference, clothing, metabolic activities, actions), while questionnaires and inspections did also take place. This data was analysed using different types of graphical representation (bar charts, pie charts, stacked bar plots, scatterplots) as well as statistical tests such as chi-square tests, regression analysis, Kruskal-Wallis and correlation tests. Due to limited or unavailable data only 78 dwellings were included in the analysis, while the reliability and generalisation of the results entails some uncertainty due to the number of dwellings and data points available.

All in all, it was found that the thermal sensation is correlated with the four comfort related factors (thermal preference, clothing, metabolic activity, action), the indoor air temperature as well as the energy labels and the ventilation types, while only age was resulted in not being associated with thermal sensation. Indoor air temperature was found to be related with the energy label of the dwellings, but not with their ventilation type. In addition, the results indicated that the heating energy use is related with the outdoor air temperature as well as with the indoor-outdoor air temperature difference, but not with the indoor air temperature. Energy labels and ventilation types were found to be related with the heating energy use, while thermal sensation, actions and income did not show any correlation with it.

Based on the findings it is concluded that the adaptive thermal comfort model is more accurate and closer to the reality of a residential environment in comparison with the steady-state PMV model, where no adaptations take place. However, it is highly recommended that instead of improving the existing thermal comfort models, personalised comfort models could be developed for each single person separately by gathering data using sensors. This would help to trace all different parameters that influence the thermal comfort and the energy use as well and lead to more accurate prediction and lower actual energy use.

Acknowledgements

The current thesis marks the end of an era throughout which the contribution of professors, family and friends was definitive.

First of all, I thank my professors for the opportunity I had to dive more into the field of thermal comfort, indoor climate and energy use by using real data and, also, to make my first steps in data analysis as well as to get familiar with lots of statistics. I would like to thank my Chair, Laure Itard, not only for always being willing to help, your valuable feedback, advice and guidance but also for your smile, enthusiasm and kind words in every single meeting we had. I would like to thank my daily supervisor, Arjen Meijer, for being such a good listener, for sharing your knowledge and your challenging comments and suggestions, which always helped me to find the right path and continue with my research. Moreover, I would like to give a special thanks to Andrea Thaddeus who was always eager to help, open to listen to each difficulty or doubt I had, and sharing your ideas, knowledge and suggestions with me. I would also like to thank Hoessein Alkisaei for your critical and straight to the point questions and remarks, which always made me think more in-depth about my research.

Secondly, I would also like to thank my family. I thank my parents, Kostas and Fay, for always being there for me and, especially, during the difficult times of Coronavirus your support both practical and emotional was valuable. Many thanks to my brother, Christos, not only for boosting me and giving me the strength to continue, but also for your advice and help whenever I asked for it.

Lastly, many thanks to my friends who were all very supportive throughout this whole procedure. Thank you for always believing in me, motivating and encouraging me, making me laugh and forget my stress. Thank you to all my TU Delft friends for the wonderful experience!

Anastasia Petropoulou
Thessaloniki, Greece, December 2021

Contents

List of Figures

List of Tables

1 Introduction

1.1 Research context

According to the European Commission, buildings are responsible for approximately 40% of the EU energy consumption and 36% of the CO2 emissions, resulting in the largest energy consumer in Europe. 63% out of this 40% is coupled with the residential building energy use [1]. Therefore, the reduction of energy consumption in the building sector has gained more and more interest in the last decades.

New technologies and methods have been developed including both passive and active strategies that have been applied and proven beneficial in terms of reducing the energy consumption [2]-[6]. However, differences can be observed in the energy consumption of dwellings with similar characteristics. It has been shown that the energy consumption of similar dwellings may differ up to 3 times [7],[8]. At the same time, several studies have concluded that there is a difference between the actual and the predicted energy consumption, which is the so-called "energy performance gap", with the difference reaching up to a factor of 2 [9]-[11].

These discrepancies are related to the inaccurate estimation of occupancy behaviour and the building characteristics as well as the rebound effects, while many believe that the first one is the most influential since people are the ones that control the heating and the hot domestic water use [12]-[14]. Specifically, "Technology alone does not guarantee low energy use in buildings", and human interactions with the building play as a significant role as the technology itself in achieving lower energy consumption of buildings [15]. However, current simulation software is simplified and do not take occupant's energy related behaviour largely into account [16]. Therefore, since it has been proven that there is a strong relation between the actual energy consumption of residential buildings and the household characteristics, habits and occupant's behaviour, further research needs to be carried out in order to explore these factors [7],[17],[18]. Bridging this gap will help towards the goal of building energy efficiency [19].

An important aspect to keep in mind while designing buildings with lower energy consumption is not to compromise the indoor thermal comfort. Since the 70's, two thermal comfort models have been developed. The first one is the PMV (predicted Mean Vote) or heat balance model and the other is the adaptive comfort model [20][21]. Since, the PMV model was developed for the HVAC industry by P.O. Fanger, it is more suitable and predicts better the thermal comfort in public buildings and offices, which are equipped with mechanical ventilation instead of natural that most dwellings have [20]. In addition, changes in people's activities, clothing or actions for adapting into their thermal environment are not taken into account in the PMV method, which just assumes that these are static. For this reason, the adaptive comfort model was introduced considering the occupant's adaptions which can be divided into physiological, behavioural and psychological [22]. Behavioural adaptations are considered to be the most influential, in which activities, clothing and actions like opening/closing the windows, setting the thermostat up/down, taking a warm/cold shower have a great impact on the thermal comfort and therefore, the residential energy use as well [23]. Therefore, the adaptive comfort model accounts for all adaptive behaviour, by simply taking into account a broad range of acceptable temperatures, which depends on the season and climate.

Looking into the interactions that different parameters have with the occupant's thermal perception and the actual energy use of the dwelling, will help in predicting occupant's thermal comfort as well as energy use better.

In the Netherlands, not a lot of research has been done in the field of thermal comfort in residential buildings. One of the most related recent studies was carried out by Ioannou et al. in which the thermal comfort and energy related occupancy behaviour in Dutch dwellings was investigated by performing in-situ and real time measurements of subjective and quantitative data.

More detailed, in Ioannou et al. research the Ecommon monitoring campaign took place, for which 32 social housing dwellings were chosen and monitored for a 6-month period during the heating season (October till April). Quantitative data (air temperature, relative humidity, CO_2 level and presence of people) was measured wirelessly in each room (bedrooms, living room, kitchen) per 5 minutes. Moreover, qualitative data related to thermal comfort (thermal sensation, metabolic activity, clothing, actions during the last half hour) was collected for a 2-week period with the use of a wireless device (comfort dial) and a paper logbook. In addition, surveys and inspections did take place in the dwellings. The analysis of all this data led to useful results some of which are described in Chapter 2 (2.7).

Moreover, a follow-up similar monitoring campaign, the Opschaler, was carried out in which 96 dwellings were monitored. Apart from the larger sample in this campaign, the duration of it varied between 3 to 12 months. In addition, gas and electricity use were included in the measurements. The monitoring campaign set-up will be described in more detail in Chapter 4.

1.2 Main focus and objective

Based on the follow-up monitoring campaign, the current research could be characterised as a validation study of the research by Ioannou et al. as well as an extension of it due to the larger sample of dwellings and the longer period of measurements. In addition to that, as already mentioned, in the current collected data, gas and electricity use are also included. Therefore, it will be possible to link the actual energy consumption to the reported thermal sensation coupled to the climate parameters.

The main objective of the thesis is to explore the interactions between different parameters, which could help and go a step further into explaining the factors that influence resident's thermal comfort and as a result the actual energy used by them. More specifically, as shown in Figure 1.1, different parameters such as dwelling and installation characteristics and outdoor climatic parameters influence the indoor climate, which together with the household and physiological characteristics affect the occupant's thermal sensation (TS). Then, the occupant's thermal preference (TP) can be considered as a control set point.

- If TP is OK, then no action is taken.
- If TP is not OK, then action is taken. The action taken may be person related influencing either the metabolic rate or the clothing type or maybe both of them, but it can also be energy related leading to changes in the heating/cooling energy used and therefore, affecting the indoor climate as well.

In Figure 1.1, the factors with the star sign are the ones that were not measured, while the bold type factors are the ones that are studied in the current thesis. In addition, the numbers of the research questions that are described in the next section have been included in the diagram to show the relationships that each question will explore.

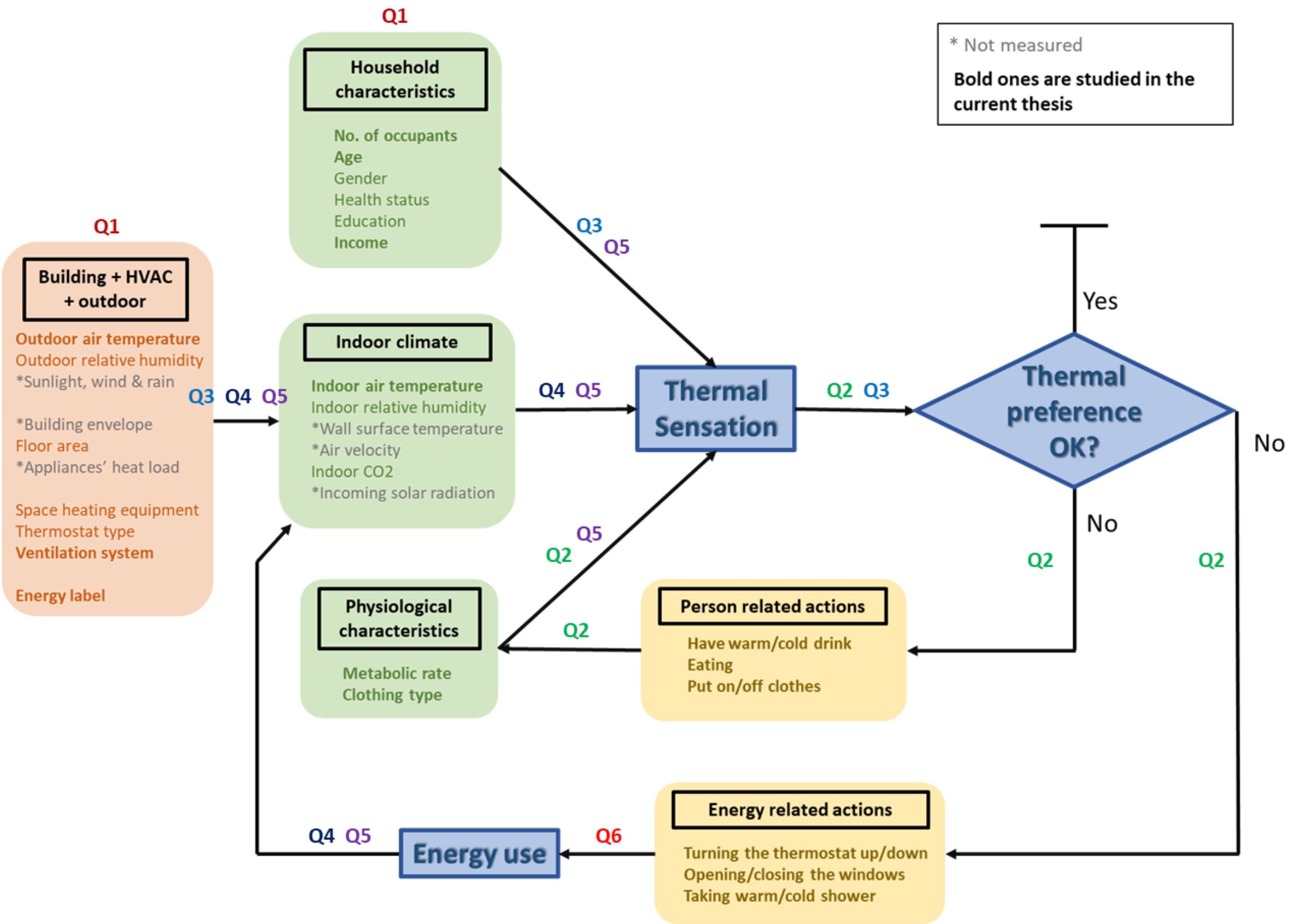


Figure 1.1: *Conceptual model of the interactions between all parameters. (Source: own)*

This exploration will possibly lead to a better prediction of human thermal comfort and therefore to the development of better prediction models of the heating energy use in dwellings. In addition, such an analysis can be useful for householders regarding their energy behaviour.

1.3 Research questions and methodology

In this section, the main research question along with the sub-questions that will help in answering it will be presented. Also, the methodology that will be followed in order to answer the research questions will be explained.

The main research question is:

> *"Which internal, external, individual and contextual parameters influence the occupant's comfort perception and how is the total heating energy affected?*

The sub-questions are as follows:

1. *What are the installation characteristics, household characteristics, tenant's behaviour and comfort perception of the studied dwellings and what can be concluded by that?*
2. *What are the reported thermal sensations and how do thermal preferences, clothing types, metabolic activities, actions reported per dwelling relate to them?*
3. *How does the thermal sensation and thermal preference vary between individuals and for different energy labels and ventilation system?*
4. *What is the relation between indoor air temperature and comfort perception, energy label, and ventilation system?*
5. *What is the relationship between energy use and indoor air temperature taking into account comfort perception, energy label, ventilation system as well as household characteristics?*
6. *Do actions like opening/closing the windows, setting the thermostat up/down, taking warm/cold shower influence the energy use significantly?*

The main goal of the research is to find out the interactions between the different parameters shown in the conceptual diagram that will give a better understanding on how thermal comfort and its parameters affect the energy use.

As shown in Figure 1.2, a measurement campaign took place within the context of the Opschaler project and data was collected for 96 dwellings in the Netherlands during a one-year period (2017-2018).

- The quantitative data which is the indoor climate data (air temperature, relative humidity, CO2, presence), the gas use and the electricity use were collected through smart meter and sensors.

- The subjective data related to comfort was gathered by the comfort mobile application, while the data related to household characteristics, heating and ventilation patterns as well as general thermal perception by filling in questionnaires. In addition, inspections took place in order to gather data related to the dwelling and installation characteristics.

To answer the research questions, graphical and statistical analysis take place using Python programming language and the SPSS Statistics software. The 1st step is to clean the data by detecting and excluding any missing, zero or strange values. Then the 2nd step, in order to get useful results, is the data analysis and more specifically graphical and statistical analysis. Methods such as chi-square tests, regression analysis, Kruskal-Wallis test and correlation test are included. Finally, the 3rd step from which conclusions are made is the interpretation of the results.

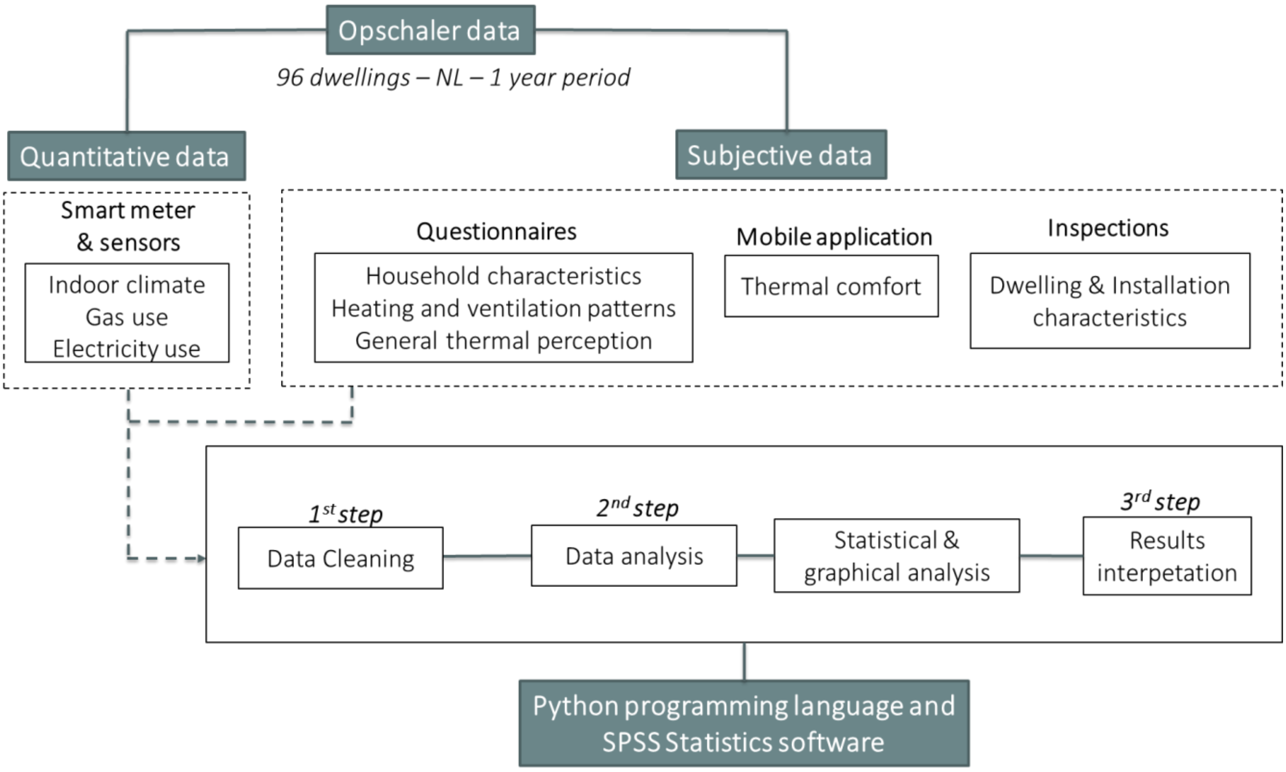


Figure 1.2: *Methodological approach.*

As mentioned already statistical analysis will take place and more specifically statistical hypothesis testing. First of all, some null hypotheses have been formulated as shown in Table 1.1, each one related to one of the research questions of the thesis. In addition, each time the appropriate statistical test was chosen based on the literature and the tests used will be explained later explicitly. By doing the tests, the null hypotheses will either be rejected or accepted and therefore, will help to answer the research questions and give more insights in the relationships between the different variables. It is worth mentioning that some of the hypotheses' result might be obvious in real life, but it is still useful to prove it based on the data gathered.

Table 1.1: *Null hypothesis and statistical test per research question.*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q2	**H1**	The thermal sensation is not related with the thermal preference.	Thermal sensation	Thermal preference	Chi-square test
	H2	The thermal sensation is not related with the clothing type.	Thermal sensation	Clothing type	Chi-square test
	H3	The thermal sensation is not related with the metabolic activity.	Thermal sensation	Metabolic activity	Chi-square test
	H4	The thermal sensation is not related with the actions.	Thermal sensation	Actions	Chi-square test
Q3	**H5**	The thermal sensation is not related with the energy labels.	Thermal sensation	Energy labels	Chi-square test
	H6	The thermal preference is not related with the energy labels.	Thermal preference	Energy labels	Chi-square test
	H7	The thermal sensation is not related with the type of ventilation.	Thermal sensation	Ventilation type	Chi-square test
	H8	The thermal preference is not related with the type of ventilation.	Thermal preference	Ventilation type	Chi-square test
	H9	The thermal sensation is not related with the age.	Thermal sensation	Age	Ordinal Logistic regression
	H10	The thermal preference is not related with the age.	Thermal preference	Age	Ordinal Logistic regression
Q4	**H11**	The thermal sensation is not related with the indoor air temperatures.	Thermal sensation	Indoor air temperature	Multinomial Logistic regression
	H12	The thermal preference is not related with the indoor air temperatures.	Thermal preference	Indoor air temperature	Multinomial Logistic regression
	H13	The indoor air temperature is not related with the energy labels.	Indoor air temperature	Energy labels	Kruskal-Wallis
	H14	The indoor air temperature is not related with the type of ventilation.	Indoor air temperature	Ventilation type	Kruskal-Wallis
Q5	**H15**	The energy use is not related with the indoor-outdoor air temperature difference.	Energy use	Indoor-outdoor air temperature difference	Spearman's correlation
	H16	The energy use is not related with the thermal sensation.	Energy use	Thermal sensation	Kruskal-Wallis
	H17	The energy use is not related with the energy labels.	Energy use	Energy labels	Kruskal-Wallis
	H18	The energy use is not related with the type of ventilation.	Energy use	Ventilation type	Kruskal-Wallis
	H19	The energy use is not related with the income.	Energy use	Income	Spearman's correlation
Q6	**H20**	The energy use is not related with the actions.	Energy use	Actions	Kruskal-Wallis

1.4 Outline of the research

The report is divided as shown in Figure 1.3, where different sub-questions are answered in different chapters in order to get sufficient insight to answer the main research question.

Part I – Literature Review

Part I consists of a literature study on research that has been done on the field of thermal comfort, indoor climate and energy use. The goal of this section is to collect sufficient information about the results of similar studies and different methods used to get them.

- ❖ Chapter 2: Literature Review

Part II – Monitoring campaign and basic analysis of the data

Part II explains the methodology of the research including the link between literature and current research as well as the methods that will be followed to answer the research questions. Afterwards, it describes how the monitoring campaign took place, what and how data was collected. And an initial graphical analysis of the available data is then developed.

- ❖ Chapter 3: Methodology
- ❖ Chapter 4: Monitoring Campaign
- ❖ Chapter 5: Basic Graphical Analysis of the Data

1. *What are the installation characteristics, household characteristics, tenant's behaviour and general comfort perception of the studied dwellings and what can be concluded by that?*

Part III – Detailed analysis and interactions between variables

Part III contains the core of the research, focusing on the interactions between thermal comfort, indoor-outdoor climate and energy use.

- ❖ Chapter 6: Real time comfort perception

2. *What are the reported thermal sensations and how do thermal preferences, clothing types, metabolic activities, actions reported per dwelling relate to them?*
3. *How does the thermal sensation and thermal preference vary between individuals and for different energy labels and ventilation system?*

- ❖ Chapter 7: Comfort Perception and Indoor Climate Parameters

4. *What is the relation between indoor air temperature and comfort perception, energy label and ventilation system?*

- ❖ Chapter 8: Comfort Perception, Climate Parameters and Energy Use

5. *What is the relationship between energy use and air temperature taking into account comfort perception, energy label, ventilation system as well as household characteristics?*
6. *Do actions like opening/closing the windows, setting the thermostat up/down, taking warm/cold shower influence the energy use significantly?*

Part IV – Research outcome

Part IV summarizes the results of the analysis.

- ❖ Chapter 9: Results and Discussion
- ❖ Chapter 10: Conclusions and Recommendations

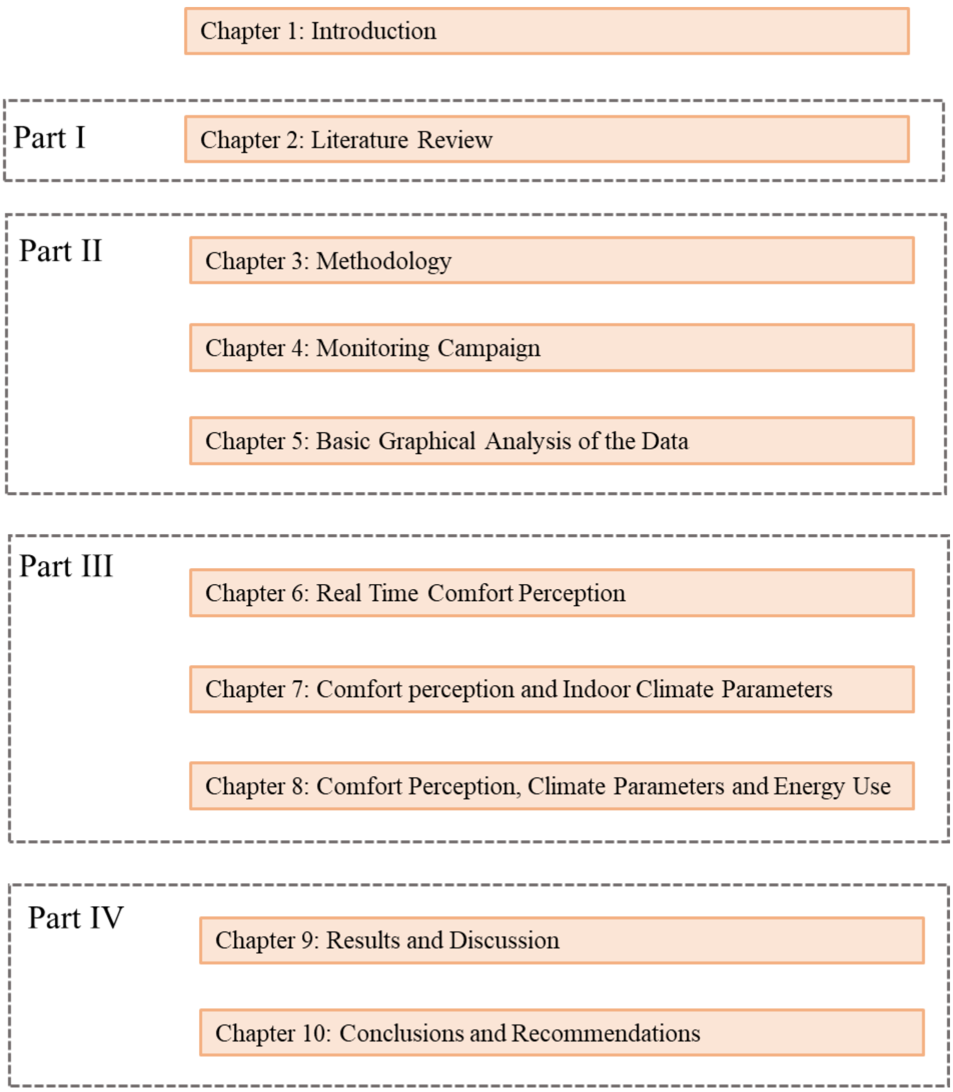


Figure 1.3: *Thesis outline.*

All in all, the sub-questions that have been formulated will help to find out step by step the parameters that influence the thermal comfort and as a result the energy use as well. Therefore, the parameters that influence directly and indirectly the thermal sensation, the indoor air temperature and the energy use will be explored.

1. *What are the installation characteristics, household characteristics, tenant's behaviour and general comfort perception of the studied dwellings and what can be concluded by that?*

The 1st research question is more related with the analysis of the data itself and is based on the surveys. This will give a better idea about the characteristics of the sample and will help to distinguish the dwellings in groups of same installation characteristics for example. In addition, a general idea of the occupants' behaviour and comfort perception independent of the time will be analysed.

2. *What are the reported thermal sensations and how do thermal preferences, clothing types, metabolic activities, actions reported per dwelling relate to them?*

The 2nd research question explores the relation between the more direct parameters that influence the thermal sensation, where a loop is created, as shown in Figure 1.1.

3. *How does the thermal sensation and thermal preference vary between individuals and for different energy labels and ventilation system?*

In the 3rd research question, direct and indirect parameters that affect the thermal sensation and the preference are studied.

4. *What is the relation between indoor air temperature and comfort perception, energy label, and ventilation system?*

In the 4th research question, the relation of the indoor air temperature with the thermal sensation as well as the influence of some direct parameters on the indoor air temperature are examined.

5. *What is the relationship between energy use and air temperature taking into account comfort perception, energy label, ventilation system as well as household characteristics?*

The 5th research question takes into account the energy use in relation with the air temperature and how this is influenced by direct and indirect parameters that were explored in the previous questions as well.

6. *Do actions like opening/closing the windows, setting the thermostat up/down, taking warm/cold shower influence the energy use significantly?*

The 6th research question elaborates on the influence that energy related actions might have on the energy use.

Therefore, the combination of the answers to all the sub-questions will help to answer the main research question about the parameters that influence the occupant's comfort perception and how then the total heating energy is affected.

2 Literature Review

2.1 Thermal comfort in general

In the past years, a lot of research is being done in the field of thermal comfort focusing more on commercial and office buildings than on residential ones. The most widely used thermal comfort models for assessing thermal sensations are Fanger's Predictive Mean Vote or the PMV model [24] and the adaptive thermal comfort model [22].

According to Fanger, thermal comfort is used to describe that "the sensation that is experienced by a person is a function of the physiological strain that has been imposed on him by the environment" [24]. Another definition based on ASHRAE is that comfort is "a state of mind that expresses satisfaction with the thermal environment where it is located" [25]. Thermal comfort is mostly influenced by environmental and human factors.

According to Orosa (2010) there is a considerable number of studies where it was reported that the PMV could not predict the actual mean vote (AMV) accurately [26]. At the same time, Peeters (2009) identified that the currently used thermal comfort models are not able to make accurate predictions on residential buildings, suggesting the division of the dwelling into 3 different thermal zones and thus, different equations [27].

At this point it is worth mentioning that indoor comfort in residential buildings also includes acoustic, visual and respiratory comfort. However, the focus of this thesis is on various factors that affect thermal comfort and as a result the energy consumption in residential dwellings.

2.2 Conceptual terminologies

In this section, some conceptual terminologies related to thermal comfort, that will be frequently mentioned, will be explained.

2.2.1 Thermal sensation

Thermal sensation vote (TSV) refers to the subjective sensation that is experienced and expressed by an individual and is evaluated using a Likert scale, which is a specific procedure to rate agreement and disagreement [28]. In thermal comfort, the thermal sensation vote scale, termed as ''ASHRAE scale'', refers to a 7-point scale from being hot as +3, warm as +2, slightly warm as +1, neutral as 0, slightly cool as -1, cool as -2 and cold as -3. This scale has been used by Fanger while developing the PMV model [24]. In this study the actual thermal sensation vote was reported for which the same 7-point scale was used.

2.2.2 Thermal preference

Thermal preference is another subjective evaluation of thermal comfort, introduced by McIntyre (1978). It is a scale used to express the thermal conditions that people would prefer to experience in contrast to the ones they are in. According to McIntyre it only includes 3 votes expressing "want warmer", "no change", "want cooler". The same scale is used in this study as well.

2.3 Predicted Mean Vote (PMV) model

During 60's Fanger developed a method for predicting the comfort that a group of people experience when being exposed in specific environmental conditions. After carrying out experimental studies in climate chambers in which the indoor climate could be totally under control, human body heat balance equations were used to develop the comfort equation, which could predict the conditions that people would feel thermally neutral [20]. The comfort equation is based on the fact that the heat produced in the body must be equal to the heat loss from the body:

M - W = H + EC + Cres + Eres (1)

where M is the metabolic rate, W is the effective mechanical power, H is the dry heat loss from the body, EC is the evaporative heat exchange at the skin, Cres is the respiratory convective heat exchange and Eres is the respiratory evaporative heat exchange [29].

Then, for practical reasons, Fanger expanded his comfort equation into the current PMV model by combining data from different studies and incorporating the ASHRAE thermal sensation scale. The PMV predicts the mean thermal sensation for a group of people and shows the deviation from feeling neutral [30]. As mentioned before, the "ASHRAE scale" from cold (-3) to hot (+3) is used [31]. Zero is considered to be the ideal value, revealing thermal neutrality. Values between -0.5 and +0.5 are deemed to be in the range that an occupant would report when he/she feels comfortable in his/her environment [24]. The PMV model takes into account 6 main factors which influence the thermal comfort [28]. These are divided into 4 environmental factors and 2 human factors as described below accordingly:

- Air temperature
- Relative humidity
- Mean radiant temperature
- Air speed
- Clothing insulation
- Metabolic rate

In addition, since it was developed for an HVAC industry, the PMV model is more appropriate for mechanically ventilated buildings, not allowing for accurate results in naturally ventilated buildings [28].

2.4 Predicted Percentage Dissatisfied (PPD)

Due to the fact that people are not alike and there will be differences in the thermal sensations of a large group of people, the Predicted Percentage Dissatisfied (PPD) index was introduced. This is an indicator closely related to the PMV as it predicts the percentage of people being dissatisfied with the thermal conditions they are in, feeling either too warm or too cold and wanting to change it in order to feel thermally comfortable [32]. Both PMV and PPD can be used to predict people's thermal sensation in mechanically ventilated indoor spaces [33]. Experimental studies in which participants reported their thermal sensation took place and an empirical relationship between PMV and PPD was derived as follow [34]:

$$PPD = 100\text{-}95 \times \exp(-0.03353 \times PMV^4 - 0.219 \times PMV^2) \quad (2)$$

Equation (2) shows that even when feeling neutral, which means PMV = 0, there is a 5% of people who may still not be satisfied. Therefore, the main goal while designing would be to explore the range of thermal comfort. This means to find out the range of thermal sensations in which the percentage of dissatisfied people would be acceptable. Consequently, this would affect the energy use positively, since a wider range of thermal conditions would result in lower energy use for heating/cooling than a narrower one [35].

2.5 Adaptive thermal comfort model

The application of the PMV model is limited due to the fact that it considers a static thermal environment in combination with air-conditioned space. In order to encounter the problems of the PMV model, the adaptive model was created and was also included in the two international standards: the ASHRAE Standard 55 for North America [36] and the European EN 15251 [37]. The Netherlands is a European country and thus the adaptive model is in its regulations.

Several field studies [22],[38],[39] indicated that people tend to constantly adapt to their environment by taking certain actions in order to feel thermally comfortable. These human adaptations towards thermal comfort can be divided into three categories: physiological, behavioural and psychological [22]. Among them, the behavioural adaptations are the ones playing the most important role in allowing people to adapt to their thermal environment retaining thermal comfort, such as changing the activity or clothing levels as well as opening/closing the windows, turning on/off the thermostat, having hot/cold drink, etc [40]. Regarding the psychological adaptations, they are related to the occupant's expectations; for example, people expect and feel comfortable in lower temperatures in winter, while higher temperatures in summer depending on the climate [41]. When it comes to the physiological adaptive behaviour, this is associated with the acclimatization and the fact that after a long time exposed in certain conditions, people adjust, get used to them and perceive them as comfortable [41].

Therefore, the adaptive thermal comfort model is an alternative and suitable model for naturally ventilated buildings and as a result appropriate for most dwellings. In this model, the comfort temperature is described as a function of the outdoor temperature but taking into account occupants' possible adaptations, while the comfort temperature can range from 17^oC to 30^oC [38][39].

Field studies have shown that the adaptive models have positive impact on the energy use. Accepting higher or lower indoor temperatures in summer or winter conditions would result in less energy use due to cooling or heating systems accordingly.

2.6 Thermal comfort related studies in residential buildings in different climates

At this point, it has to be mentioned that the current thesis focuses on residential dwellings. The latter are divided into several thermal zones requiring different thermal conditions. Moreover, people's activities cannot be easily predicted, while at the same time there are various ways through which occupants can adapt to their thermal environment. Therefore, such indoor conditions differ greatly with the ones in the climate chamber used to develop the PMV model.

Various field studies have taken place throughout the years in the field of thermal comfort and energy use in the built environment. Each study includes various parameters, uses different methods, differs in the duration and the period as well as the climate and the type of building that the measurements are carried out [42][48]. In this section, the focus will be on studies related to the PMV compared to the TSV, the neutral temperatures and the thermal preference in different climates and specifically for residential buildings.

Several literature and scientific papers were searched and reviewed especially through Google Scholar, Science Direct and Scopus. The selection of the papers to be included here was done based on the relevance with the topic of the current research, which focuses on the thermal comfort perception. Thus, only field research that was done in residential buildings was chosen and with climate as similar as possible to the Netherlands, so that the results can be comparable. Apart from this, a lot of research found was carried out in other types of buildings, such as office, educational, public buildings as well as in other climates (for example tropical) or only during the summer period and which were excluded from this literature review for relevance reasons. Moreover, as recent as possible published papers were chosen in order to end up with an updated overview of what has been concluded regarding thermal comfort.

Oseland (1994) carried out a field study in the UK in order to compare the predicted and reported thermal sensation in homes during winter and summer [48]. A survey using the ASHRAE scale as well as physical measurements took place in order to allow the PMV calculation. The total number of participants was 515 in winter and 293 in summer. The results showed that the neutral temperature was 5^oC lower than the one calculated from PMV in winter, while 3^oC lower in summer. Therefore, he concluded that the PMV model overpredicts the required use of heating in terms of thermal comfort in UK homes. In addition, he found that the occupants preferred to be “slightly warm” in winter and “neutral” in summer [48].

Humphreys and Nicol (2002) stated that PMV can differ from thermal sensation mean vote (TSV) due to measurement error, human differences and equation error [49]. Moreover, Orosa (2010) concluded that the PMV model is appropriate for predicting the neutral temperature with an error margin of 1.4°C in comparison with the neutral temperature calculated based on the AMV (actual thermal sensation mean vote) [26].

Xu et al. (2018) carried out a field study related to thermal comfort and the adaptive behaviour of the occupants in traditional dwellings in Nanjing, China, both in summer and winter [28]. They found out that occupants of traditional dwellings show more tolerance to extreme climate conditions than the ones living in modern dwellings; their neutral temperature was lower in winter (15.8°C) and higher in summer (28°C) compared to the ASHRAE standard and that of modern dwellers. Thus, Xu et al. concluded that occupants’ long thermal experience led to lower thermal sensitivity and as a result to a wider range of comfort temperatures [50].

Furthermore, Beizaee and Firth (2011) investigated the accuracy of the PMV model in naturally ventilated houses and offices in the UK [51]. The results, in agreement with Oseland (1994), showed that the PMV model in general underestimates the TSV in both types of buildings, predicting higher neutral temperatures.

Humphreys and Hancock (2007) in their study explored if people like to feel neutral [44]. In their survey they did not only ask for the thermal sensation but also for the thermal preference. Their findings indicated that people’s desired thermal sensation differed between them, ranging from “slightly cool” to “hot” and that the most common thermal desire was “neutral”, followed by “slightly warm” [44].

Another study by Valodaria (2014) analysed the PMV with two different values of metabolic rate (1.0 and 1.7 met) for sedentary occupants in the UK homes [52]. Based on a survey with 60 participants, he found that the difference between PMV and TSV was lower with the metabolic rate of 1.0 met compared to the metabolic of 1.7 met.

Another study was conducted by Beker and Paciuk (2009) in Haifa, Israel, for 189 dwellings in winter and 205 dwellings in summer [53]. In this one, the percentage of dissatisfied people was plotted against the TSV for both winter and summer samples and compared with the standard PMV-PPD line. The graphs indicated that in winter the PMV-PPD line predicts lower percentage of dissatisfaction at TSV = -1, while much higher percentage at TSV>1. On the other hand, in summer the PMV-PPD line predicts much lower percentage of dissatisfied people at TSV = +1 and greatly lower percentage at TSV < -1 [53].

To conclude, several studies have shown that the PMV predicts higher neutral temperatures, that the thermal preference might be different than neutral as well as that the PMV-PPD line differs from the actual percentage of dissatisfied people. Moreover, people tend to adapt to their environment due to long experience into it and therefore, a wider range of comfort temperatures is introduced.

2.7 Thermal comfort related studies in residential buildings in the Netherlands

However, specifically for the Netherlands not a lot of research related to thermal comfort and indoor climate has been done, let alone in residential buildings. A description and the results of the most related studies are presented in this section [27][54]-[56].

A. Ioannou & L. Itard in their research studied the parameters that influence both comfort and actual energy consumption in residential buildings [54]. For this purpose, they analysed data taken by in-situ real time measurements in 30 dwellings in the Netherlands. The data included both quantitative and subjective parameters with the first related to the indoor climate conditions (air temperature, humidity, CO2, presence) during a 6-month period and the latter related to the occupant's thermal sensations, activities, actions and clothing for two weeks. Furthermore, questionnaires were filled in by the occupants regarding the household characteristics, their heating and ventilation behaviour.

Based on this data, several conclusions were made. They deduced that the neutral temperatures calculated by the *PMV* model are in accordance with the ones derived by the reported *thermal sensations*. This result contradicts with the results from the abovementioned studies where the neutral temperature was often lower than the one predicted. In addition, it was shown that people reported feeling comfortable even though the PMV method was not predicting so. In other words, they concluded that the PMV method underestimates the occupant's thermal comfort by predicting lower comfort level, due to undefined psychological adaptation expectations. Moreover, it was found that although people's clothing and metabolic activities were the same, the neutral temperatures were higher for higher energy rating houses than for lower ones.

Regarding the *reported actions* during the last half hour before filling in the comfort diary, the authors found that people in lower energy rating houses tended to increase the indoor temperature in comparison with the higher rating dwellings. Furthermore, it was concluded that having a hot drink was quite popular, but this was more related to the tenants' habits rather than to improving their thermal comfort.

When it comes to *clothing*, the most usual clothing type identified between March and early April was the warm ensemble with a clo value of 0.91. Other than that, it was proven that clothing is an adaptation type towards comfort, since the clo value was getting lower when the thermal sensation was increasing.

The most popular *activities* during the last half hour before filling in the comfort diary reported in a descending sequence for both A/B and F labelled dwellings were "sitting relaxed", light desk work", "walking" and "lying/sleeping". Thus, the results showed that similar metabolic activities were taking place in the living room while feeling neutral in both types of dwellings.

In a follow-up research A. Ioannou et al. compared the results calculated by the *adaptive comfort model* with the ones obtained by the real time measurements data [55]. Their analysis indicated that although the indoor temperatures fluctuate within the limits of the adaptive comfort model, the reported thermal sensations were often different than neutral and vice versa. In general, it was concluded that the adaptive comfort model could both overestimate and underestimate the occupant's thermal comfort.

In addition, Peeters et al. developed the adaptive thermal comfort model for residential dwellings used in the Netherlands [27]. Acceptable temperature ranges and comfort scales were conducted based on a previous study by Van der Linden et al.

In their study, they separated the residential dwelling into 3 thermal zones based on the conditions, level of activity and clothing type: bathroom, bedroom and others including kitchen, living room and office.

Morgan and de Dear mention that clothing and comfort temperature are influenced not only from today's weather but also the weather of yesterday as well as that of the last few days [27]. The adaptive temperature limits were calculated for the Dutch official purposes, where according to Van der Linden et al., $T_{e,ref}$ is given by the following formula:

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

$T_{e,ref}$: the reference external temperature (in °C),
T_{today}: the arithmetic average of today's maximum and minimum external temperature (°C),
$T_{today-1}$: the arithmetic average of yesterday's maximum and minimum external temperature (°C),
$T_{today-2}$: the arithmetic average of maximum and minimum external temperature of 2 days ago (°C) and
$T_{today-3}$: the arithmetic average of maximum and minimum external temperature of 3 days ago (°C).

Peeters et al. set up equations for calculating the neutral temperatures in different rooms in Belgium, which is close to the Netherlands, as follows:

$T_n = 20.4 + 0.06 * T_{e,ref}$ for $T_{e,ref} < 12.5°C$ (4)
$T_n = 16.63 + 0.36 * T_{e,ref}$ for $T_{e,ref} \geq 12.5°C$ (5)

According to the commonly used standards, the upper and lower temperature limits are defined symmetrically around the neutral temperature:
$T_n \pm \alpha$, where α is a constant (°C) (6)

The constant α is not related with the season and therefore, the comfort temperature band width is also constant. In order to take into account both enhanced sensitivity to cold versus heat and the seasonal independence, the following equations were suggested by Peeters et al.:

$T_{upper} = T_n + w\alpha$ (7)
$T_{lower} = \max (T_n – w (1-\alpha)$ (8)

with T_{upper} is the upper limit of comfort band (°C), T_{lower} is the lower limit of comfort band (°C), w is the width of comfort band (°C), and a is a constant (≤1). In addition, it was concluded that the bandwidth was 5oC for 90% acceptability, while 7oC for 80% acceptability. The study showed that the desired thermal sensation is an average 0.2 above neutral which results in a 70-30% split for the temperature band around neutral and leading to an α equal to 0.7.

2.8 Conclusion and aim of the research

Although both PMV and adaptive models are largely used in building simulation software in order to evaluate the indoor thermal comfort, it is still doubtful whether they are valid and applicable for all cases, different types of buildings and climates.

All the above-mentioned inaccuracies resulting from the thermal comfort models, lead to discrepancies in the prediction of the buildings' energy consumption as well. In order to address this issue and to be able to design energy-efficient buildings, more suitable thermal comfort models based on the climate, the type of building, the needs and preferences of people as well as the interactions between all these are needed.

Thus, to better understand the determinants of thermal comfort and their relation to energy, different factors that may influence occupants' thermal comfort need to be identified such as households' characteristics, habits and behaviour. All these factors are also associated with the energy consumption of the residential buildings and their exploration will further help with the goal of designing energy efficient buildings.

3 Methodology

In this chapter, the methodology followed in the current research in order to achieve the goal of it and answer the main research question will be described. Thus, the following will be explained in detail:

- The conceptual diagram (Figure 1.1)
- How the research questions and hypotheses are linked to the conceptual diagram and comfort theories
- The aggregation levels of the data
- The statistical hypothesis testing theory

3.1 Conceptual diagram

In this section, the logic behind the conceptual diagram will be explained based on the literature.

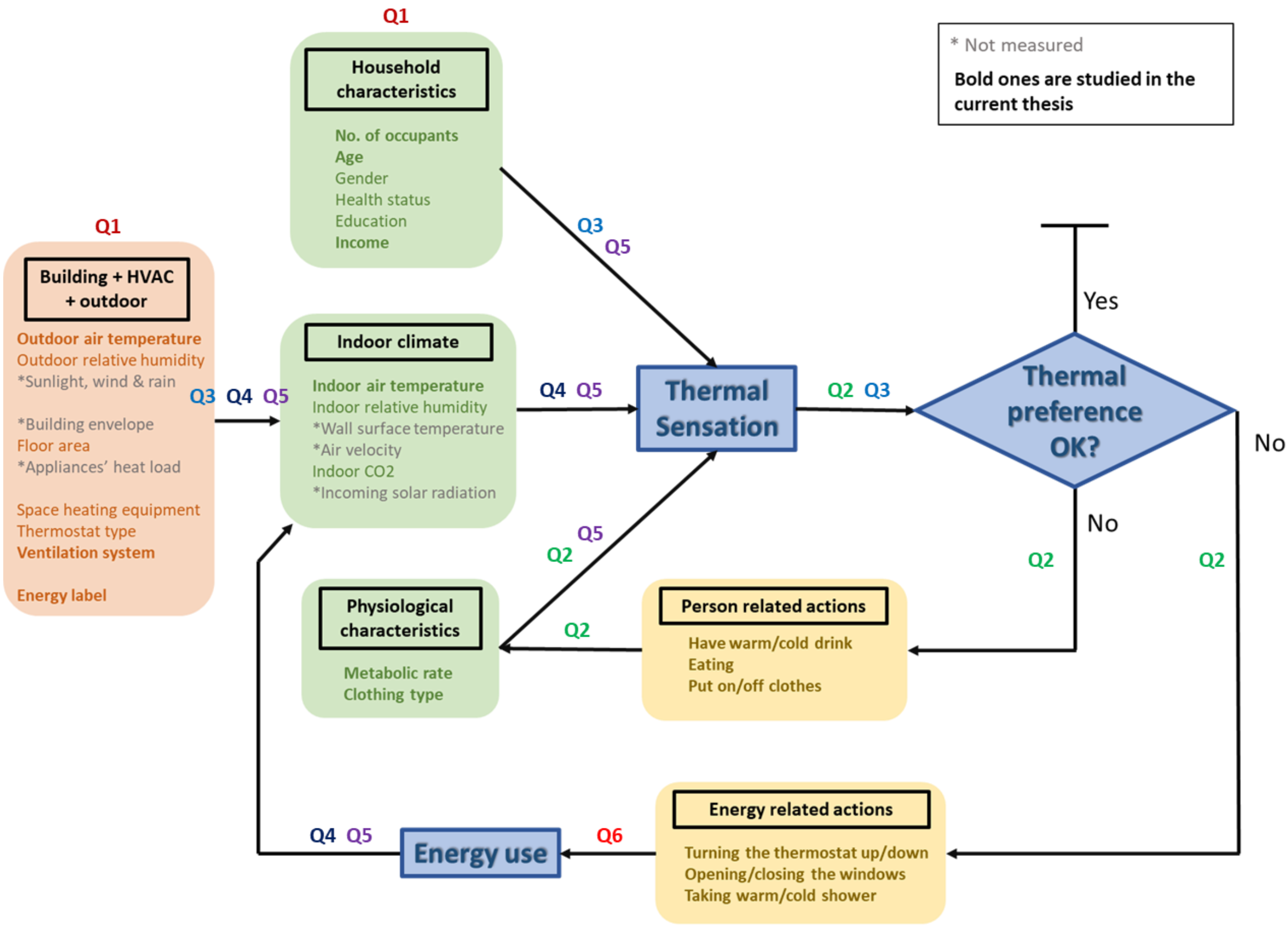


Figure 3.1: *Conceptual model of the interactions between all parameters. (Source: own)*

According to Guerra Santin et al. building and installation characteristics such as the building envelope construction (insulation thickness, type of materials), the floor area, the heat loads emitted by the appliances as well as thermostat, ventilation and space heating systems determine a large part of the energy use in a dwelling (about 42% of the variation in the energy use for space heating) [57]. But how do all these characteristics influence the energy use? For example, the lesser the thickness of the insulation, the higher the heating losses and therefore, the indoor air temperature is getting lower resulting in higher demand of energy used to keep the temperature at the desired level and people in their thermal comfort zone.

In addition, according to Delzendeh et al., climatic parameters such as outdoor temperature, relative humidity, sunlight, wind and rain are critical parameters influencing the indoor climatic conditions and therefore, affecting the occupants' interaction with the building systems in order to reach their desired thermal conditions [58].

Therefore, all these parameters, including building and installation characteristics as well as outdoor climatic conditions, were put together in the first block of the conceptual diagram that directly influences the indoor climatic conditions and as a result the energy use.

Other than that, Martinaitis et al. in their study concluded that social and personal parameters play an important role on the occupants' thermal comfort and thus, their energy related behaviour. Such social and personal parameters included gender, age, income, number of occupants, user's awareness on energy savings [57]. These parameters are represented by the household characteristics block which, as shown in the conceptual diagram, influences the occupants' thermal comfort.

Cabanac described a term called "alliesthesia", which means that "a given external stimulus can be perceived either as pleasant or unpleasant depending upon signals coming from inside the body" [57]. In case that any change in the conditions of the living environment makes people feel uncomfortable, then people try to find a way to make themselves feel comfortable again. However, not all people react the same to such changes and this happens due to physical, physiological and psychological as well as economic and regulatory differences among people. For that reason, the conceptual diagram shows two different blocks, one with thermal sensation and the other with thermal preference, which can both differ among individuals.

According to Bluyssen, in order to improve the overall comfort in the living environment including air quality, acoustics, visual or lighting quality as well as thermal comfort, the occupants tend to adjust the building systems and components and thus, they can affect the indoor environment just by being present and active in the building.

According to Hong, D'Oca actions, such as changing clothing type, turning the thermostat up/down, opening/closing the windows, as well as inactions, such as moving to a different room or bearing some discomfort, were found to be ways of the occupants' adaptation and behaviour while not feeling comfortable [57]. The abovementioned actions and inactions can both influence the occupants' thermal comfort and the amount of energy consumed as well. Moreover, apart from the energy related behaviour of the occupants, the metabolic activity of them such as relaxing, walking, running can produce a certain amount of heat which can have a higher or lower impact on the energy use due to the increase of the internal heat gains. In addition, the type of clothing, metabolic rate and actions of the occupants vary among different building types such as office, educational or residential buildings influencing the degree of interaction of the occupants with the building and, all in all, the energy consumption.

To conclude, the occupants' thermal comfort and behaviour is a dynamic phenomenon that is influenced by various internal, external, individual and contextual factors that are shown in the conceptual model. The relationships among them need to be explored and understood so that the design of energy efficient buildings with a balance between energy consumption and comfortable indoor environment is improved.

3.2 Research questions and hypotheses linked to the conceptual diagram and comfort theories

This section introduces how the research questions along with their hypotheses are linked to the conceptual diagram and the comfort theories as well. This will help to understand the structure of the current research and its goal.

1. *What are the installation characteristics, household characteristics, tenant's behaviour and general comfort perception of the studied dwellings and what can be concluded by that?*

The 1st research question is mostly about introducing the data and some characteristics of the gathered sample based on the survey carried out. Installation characteristics, household characteristics, tenant's behaviour (linked to actions) and general comfort perception (linked to thermal sensation and preference) are parameters included in the conceptual diagram and which influence or show occupants' thermal comfort.

2. *What are the reported thermal sensations and how do thermal preferences, clothing types, metabolic activities, actions reported per dwelling relate to them?*

Research Question No.	Hypothesis No.	Null Hypothesis
Q2	H1	The thermal sensation is not related with the thermal preference.
	H2	The thermal sensation is not related with the clothing type.
	H3	The thermal sensation is not related with the metabolic activity.
	H4	The thermal sensation is not related with the actions.

The 2nd research question includes all thermal comfort related parameters and their relationship with the thermal sensation. Among these parameters, the PMV model takes into account the clothing insulation and the metabolic rate, but since it is a steady-state model, it does not take into account any adaptations. On the other hand, the adaptive model considers all types of adaptations and therefore, changes in the clothing and the activity or any actions taken are considered. Therefore, the relation between these variables and the thermal sensation as well as whether people tend to adapt to their thermal environment or not are explored in the current thesis. In addition, the relation between thermal sensation and thermal preference is quite useful in order to create the thermal comfort graph (so-called PMV-PPD graph). A lot of research has shown that people might prefer or feel comfortable with thermal sensations different than neutral, which will also be studied based on the current sample.

3. *How does the thermal sensation and thermal preference vary between individuals and for different energy labels and ventilation system?*

Research Question No.	Hypothesis No.	Null Hypothesis
Q3	**H5**	The thermal sensation is not related with the energy labels.
	H6	The thermal preference is not related with the energy labels.
	H7	The thermal sensation is not related with the type of ventilation.
	H8	The thermal preference is not related with the type of ventilation.
	H9	The thermal sensation is not related with the age.
	H10	The thermal preference is not related with the age.

In the 3rd research question, direct and indirect parameters that affect the thermal sensation and the preference are studied.

The building type apart from determining certain type of clothing, metabolic activities and actions, it also determines occupants' specific needs and expectations. Therefore, hypotheses H5 and H6 aim to explore not only how the energy label of the house influences the occupants' thermal sensation/preference but, also, if occupants have higher or lower expectations based on their awareness about their dwelling energy label.

In theory, there are different types of ventilation that lead to different amounts of heat losses and as a result, energy use. At this point, the influence of these heat losses per ventilation type on the thermal comfort of the occupants will be explored.

As mentioned in the previous section, some studies have shown that occupants' thermal comfort is influenced by social and personal factors such as gender, age, income, number of occupants, user's awareness on energy savings, leading to certain personal or energy related actions. As shown in the hypotheses, only the relation between age and thermal sensation/ preference is explored in this study.

4. *What is the relation between indoor air temperature and comfort perception, energy label, and ventilation system?*

Research Question No.	Hypothesis No.	Null Hypothesis
Q4	H11	The thermal sensation is not related with the indoor air temperatures.
	H12	The thermal preference is not related with the indoor air temperatures.
	H13	The indoor air temperature is not related with the energy labels.
	H14	The indoor air temperature is not related with the type of ventilation.

In the 4th research question the indoor air temperature is taken into account as well, studying its relationship with thermal comfort, energy labels and ventilation type. Since indoor air temperature is one of the 4 environmental factors of the PMV model, it is interesting to explore its effect on thermal comfort. Another parameter taken into account is the energy labels of the dwellings, which are highly linked to the thickness of the insulation layer as well as the general thermal resistance and airtightness of the building envelope, leading to lower or higher transmission heat losses and infiltration losses and therefore, affecting the indoor air temperature and the energy use as well. Moreover, the different amounts of heat losses per ventilation type might lead to differences in the indoor air temperature and thus, the association between them is studied.

5. *What is the relationship between energy use and air temperature taking into account comfort perception, energy label, ventilation system as well as household characteristics?*

Research Question No.	Hypothesis No.	Null Hypothesis
Q5	H15	The energy use is not related with the indoor-outdoor air temperature difference.
	H16	The energy use is not related with the thermal sensation.
	H17	The energy use is not related with the energy labels.
	H18	The energy use is not related with the type of ventilation.
	H19	The energy use is not related with the income.

In the 5th research question energy use is also taken into consideration and its relationship with all previous mentioned parameters is explored, since at the end all different parameters have a higher or lower impact on the energy use either directly or indirectly. First of all, the relation between air temperature and energy use is explored. Both indoor air temperature, as a parameter of the PMV model, and outdoor air temperature, as a parameter of the adaptive thermal comfort model are taken into account. In addition, the difference between indoor and outdoor air temperature is studied as another representative and combined measure of the two models.

Then, how the different thermal sensations might lead the occupants to actions that have an effect on the energy use is investigated. In addition, the study of the relationship between energy labels or type of ventilation and energy use will help to validate the theory between them, according to which differences occur in the energy use among the several categories of energy labels and ventilation types.

The last hypothesis has to do with the relation between energy use and income of the occupants. Chen and Wang (2013) concluded that occupants' economic situation affects the quality and size of their dwelling, which then influences the energy use. In addition, Park and Kim in their study, found out that more than half of the questionnaire respondents reported energy costs as the reason for reducing the use of mechanical fans and therefore, accepting some discomfort. So, there might be a connection between these two parameters, which will be explored.

6. *Do actions like opening/closing the windows, setting the thermostat up/down, taking warm/cold shower influence the energy use significantly?*

Research Question No.	Hypothesis No.	Null Hypothesis
Q6	H20	The energy use is not related with the actions.

Finally, the 6th question focuses on the actions taken by the occupants and how these affect the energy use. In the PMV model, actions are not taken into account since no adaptations are considered in contrast with the adaptive model in which they are. All in all, it is useful to know if these actions towards making themselves more comfortable affect the energy use.

To conclude, by answering all these sub-questions a good overview of the various relations between the variables will be given and that will help to answer the main research question regarding the parameters influencing thermal comfort and the overall impact on the heating energy use.

3.3 Aggregation levels of the data

In this section the aggregation levels of the data will be explained for better understanding the nature of the data.

First of all, in total 96 dwellings were included in the measurements. The gathered data can be divided into two categories, the quantitative data and the subjective data.

The quantitative data, as shown in Figure 3.2, includes:

- Indoor climate data, which was measured in 96 dwellings, every 5 minutes, in 4 different rooms (Living room, Kitchen, Bedroom 1, Bedroom 2)
- Gas use data, which was measured in 92 dwellings and every 1 hour
- Electricity use data, which was measured in 40 dwellings every 1-10 minutes

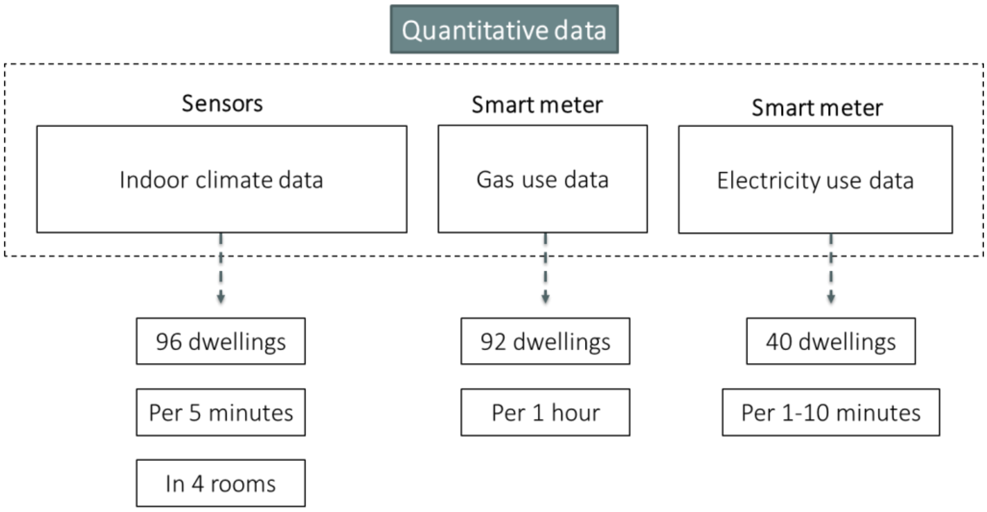


Figure 3.2: *Aggregation levels of the quantitative data. (Source: own)*

The subjective data, as shown in Figure 3.3, includes:

- Questionnaires related to the household characteristics, heating and ventilation patterns as well as occupants' general thermal perception that took place in 87 dwellings
- The mobile application related to thermal comfort which was available for 94 dwellings and was filled in by 1 or 2 members of the house, randomly in time (ideally 3 times per day) with the respondent located in 6 different rooms in the dwelling during the last half an hour (Living room, Kitchen, Bathroom, Bedroom, Outside, Other)
- Inspections related to the dwelling and installation characteristics that took place in 88 dwellings

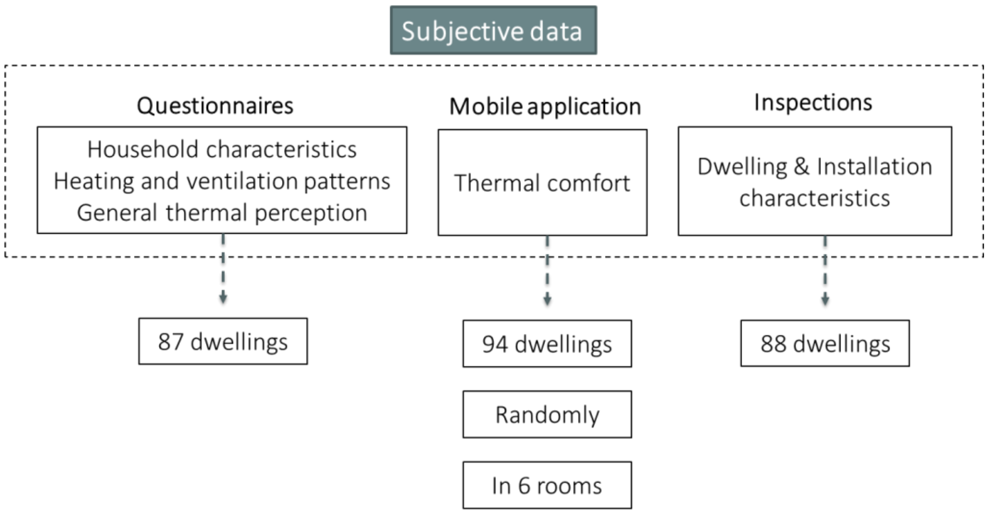


Figure 3.3: *Aggregation levels of the subjective data. (Source: own)*

3.4 Statistical hypothesis testing

At this point, after having mentioned all research questions and null hypotheses made, it is important to mention the statistics that are going to play a significant role in exploring the relations between different variables and thus, answering the research questions.

This section includes information about hypothesis testing, how to choose the appropriate statistical test and a more detailed description of the tests that are going to be used in this research.

First of all, research hypotheses are formulated about which the truth might be known or not and for which the null and alternative hypotheses are also stated. The null hypothesis is usually a hypothesis of no statistical difference or relationship between groups, while the alternative is the opposite statement and thus, only one of them can be true.

In order to run a valid statistical test, the sample size has to be large enough approaching the right distribution of the population being studied. The appropriate statistical test to be chosen depends on the following:

- Whether certain assumptions are satisfied,
- the number and type of the variables involved.

The common assumptions that need to be met in various statistical tests are:

1. Independence of observations: no relation between the observations included in the test.
2. Homogeneity of variance: the variance of each group is similar among all groups.
3. Normality of data: the data is normally distributed (only for quantitative data).

If assumptions 2 and 3 are not met, then non-parametric statistical test can be carried out, allowing for no assumptions about the data distribution.

The type of the variables as well as the number of them involved is definitive for the statistical test to be chosen. The variables can be divided into independent (predictor), dependent (outcome), quantitative (continuous and discrete) and categorical (nominal, ordinal, binary) variables.

Statistical tests can be parametric or non-parametric tests. The first category includes regression (cause-and-effect relationship), comparison (differences among group means) and correlation (two variables relationship) tests. The non-parametric tests are carried out when some of the common assumptions are not satisfied.

Therefore, in order to choose the appropriate statistical test, the following flowcharts can be used.

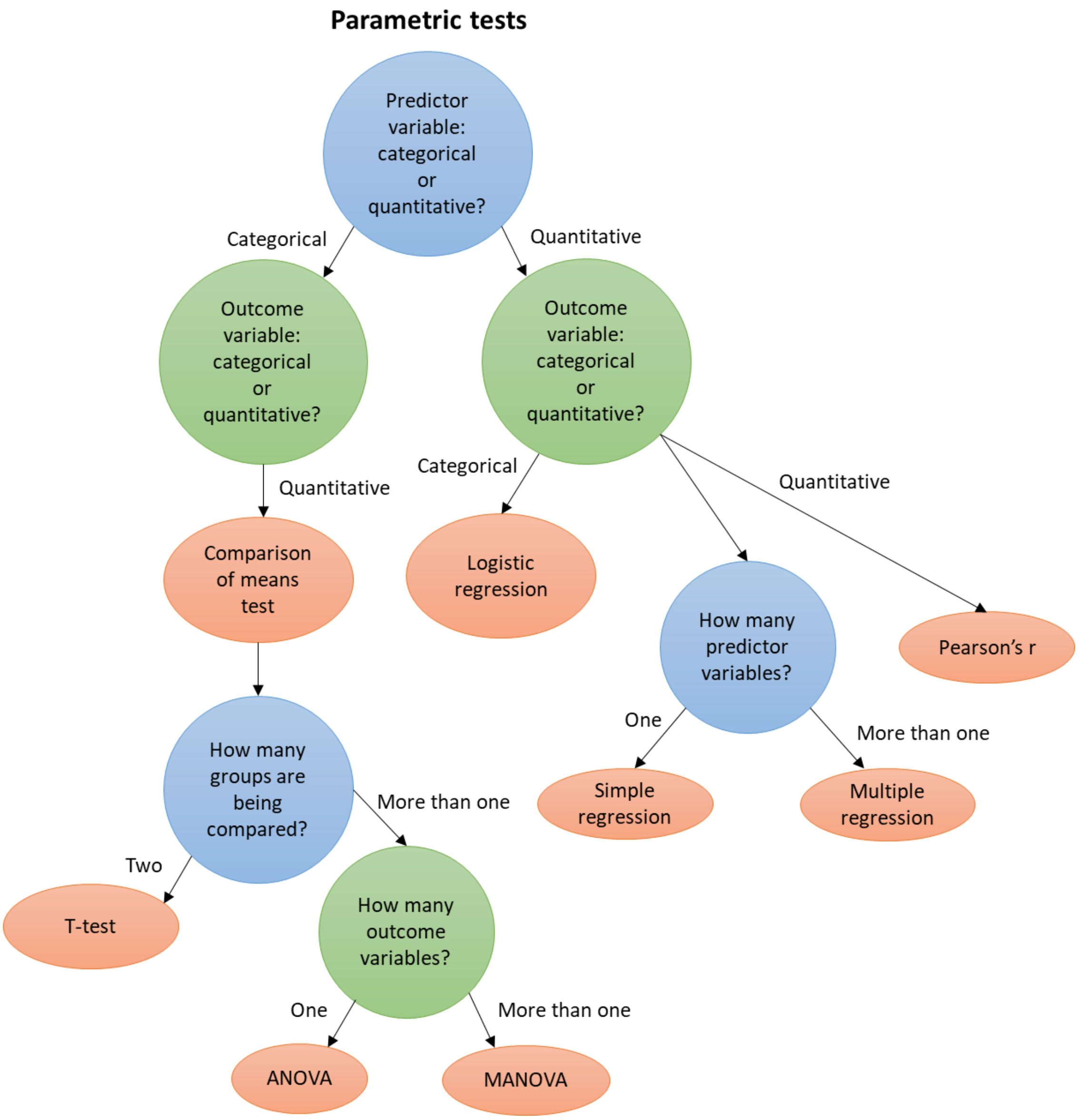
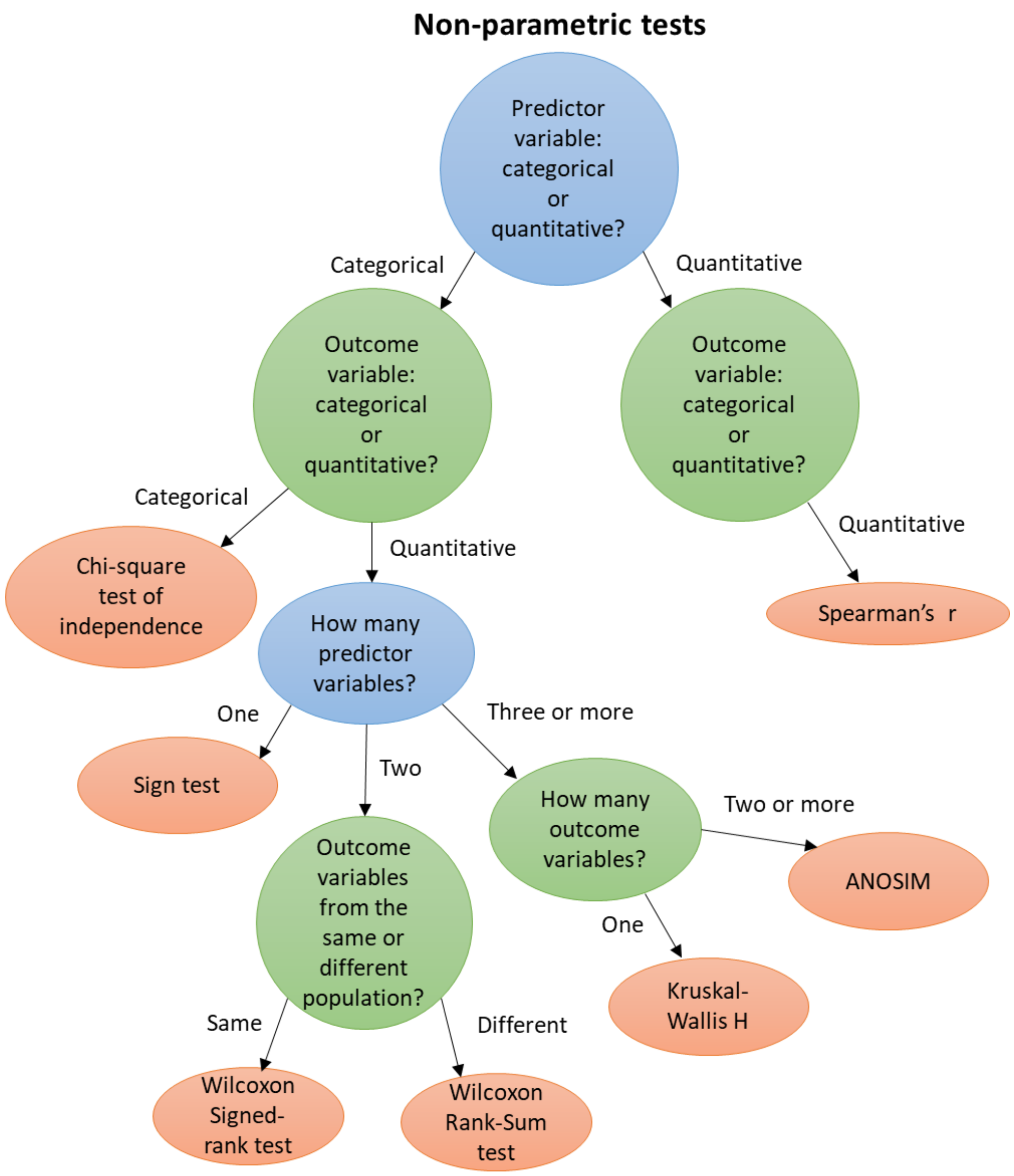


Figure 3.4: *Flowchart for choosing among parametric tests. (Source: own)*



Non-parametric test	Use in place of...
Spearman's r	Pearson's r
Chi-square test of independence	Pearson's r
Sign test	One-sample t-test
Kruskal-Wallis H	ANOVA
ANOSIM	MANOVA
Wilcoxon Rank-Sum test	Independen t t-test
Wilcoxon Signed-rank test	Paired t-test

Figure 3.5: *Flowchart for choosing among non-parametric tests. (Source: own)*

According to these, the appropriate statistical test for each hypothesis test was chosen and is described below in detail.

3.4.1 Chi-square test of independence

There are two main kinds of chi-square tests, the goodness-of-fit test and the test of independence. In this case, the chi-square test of independence was chosen, which determines whether there is a relationship between categorical variables.

This test is based on the contingency table of the categorical variables in order to analyse the data. In the contingency table (known as cross-tabulation, crosstab or two-way table) one variable is represented by the rows and the other by the columns. Each cell shows the frequency for each specific pair of categories.

To be able to carry out the test, the following requirements must be met:

1. Two categorical variables.
2. Two or more categories (groups) for each variable.
3. Independence of observations.
    - There is no relationship between the subjects in each group.
    - The categorical variables are not "paired" in any way (e.g., pre-test/post-test observations).
4. Relatively large sample size.
    - Expected frequencies for each cell are at least 1.
    - Expected frequencies should be at least 5 for the majority (80%) of the cells.

The test statistic for the chi-square test of independence is represented by the X^2 and is calculated based on the following formula:

$$\chi^2 = \sum_{i=1}^{R}\sum_{j=1}^{C}\frac{(o_{ij}-e_{ij})^2}{e_{ij}} \quad (9)$$

o_{ij} is the observed cell count in the i^{th} row and j^{th} column of the table
e_{ij} is the expected cell count in the i^{th} row and j^{th} column of the table, computed as

$$e_{ij} = \frac{row\ i\ total \times column\ j\ total}{grand\ total} \quad (10)$$

The quantity (o_{ij} - e_{ij}) is sometimes referred to as the residual of cell (i, j), denoted r_{ij}.

Then the test statistic can be interpreted in two ways:

- Within the context of the χ^2 distribution table based on the degrees of freedom df = (R -1) × (C -1) and the chosen confidence level. If the calculated X^2 value > critical X^2 value, then the result is significant, and the null hypothesis is rejected.
- In terms of the calculated p-value and a chosen significance level alpha (α). If the calculated p-value > alpha, then the result is significant, and the null hypothesis is rejected.

The significance level alpha is the probability of rejecting the null hypothesis when it is true. The most common values used are 0.05 and 0.01. For example, a significance level of 0.05 indicates a 5% risk of concluding that a difference exists when there is no actual difference.

In order to understand the nature of the test better with simple words, the following example is given:

If there is no relationship between thermal sensation and clothing, then wearing a specific clothing type will not influence tenant's reported thermal sensation. If the variables are related, then wearing a specific clothing type will help to predict tenant's thermal sensation.

3.4.2 Chi-square post hoc test

According to Sharpe, when a chi-square test is carried out for larger than a 2 x 2 contingency table, resulting in higher than one degree of freedom, then the source of a statistically significant result is unknown. He suggests that there are at least four available ways to research further a statistically significant chi-square test which are calculating residuals, comparing cells, ransacking and partitioning. The first one is mentioned as the easiest one and which is appropriate for the chi-square test of independence. A residual analysis will make it possible to identify the specific cells which contribute the most to the significant result of the chi-square test.

A residual is the difference between the observed and expected values for a cell. The larger the residual, the greater the contribution of the cell to the magnitude of the resulting chi-square obtained value.

The raw residuals are the ones derived by subtracting the expected from the observed values.

There is also, the standardized or Pearson residual which is calculated by dividing the raw residual by the square root of the expected value as an estimate of the raw residual's standard deviation:

$$Std\ Residual = \frac{O-E}{\sqrt{E}} \quad (11)$$

The sum of all squared standardized residuals is the chi-square obtained value. There is also what Agresti (2013) calls a standardized residual, but SPSS calls an adjusted standardized residual which is calculated based on the following formula:

$$Adj\ Residual = \frac{O-E}{\sqrt{E*\left(1-\frac{RowMarginal}{n}\right)*\left(1-\frac{ColumnMarginal}{n}\right)}} \quad (12)$$

The O and E represent the observed values and expected values accordingly. The RowMarginal refers to the row marginal for the cell. The ColumnMarginal refers to the column marginal for the cell. The n refers to the total number of cases across all cells.

According to Agresti (2007) "a [n adjusted] standardized residual having absolute value that exceeds about 2 when there are few cells or about 3 when there are many cells indicates lack of fit of Ho in that cell", and thus, this cell contributes to a significant chi-square test result.

MacDonald and Gardner (2000) suggest a Bonferroni adjustment to the z critical of 1.96 (from which the +/- 2 criteria is derived) if the number of cells in the contingency table is large. In the case of a large contingency table, the possibility of observing an infrequent event is higher and therefore, it is more likely to wrongly reject the null hypothesis (Type I error). The type I error occurs when the null hypothesis is rejected although it is true and this happens in the case that the result is proven significant but due to pure chance. The Bonferroni correction reduces this possibility by testing all possible cell combinations at a significance level α/m, calculated by dividing the desired overall alpha level (α) by the total number of tests (m). So, for example, in a 3 x 5 contingency table there are 15 cells and thus, the significance level is equal to 0.05 (chosen alpha) divided by 15 (0.05/15 = 0.003) and which returns a critical z value of +/- 2.96 (or approximately +/- 3). An adjusted residual that is higher than 2.96 shows that the number of cases in that cell is significantly more than would be expected if the null hypothesis was true and vice versa when it is lower than -2.96.

3.4.3 Simple linear regression

Regression analysis is a statistical tool used for predicting the relationship between a dependent variable and one or more independent variables by fitting a line to the observed data. The most common type of regression analysis is the linear regression in which the dependent variable is quantitative. The outcome variable Y is predicted from the equation of a straight line:

$$Y_i = b_0 + b_1X_{1i} + \varepsilon_i \quad (13)$$

in which b_0 is the Y intercept, b_1 is the gradient of the straight line, X_1 is the value of the predictor variable and ε is a residual term.

In the case that there are more than one independent variables, multiple linear regression can be used. In this case, a similar equation is derived where each predictor has its own coefficient.

$$Y_i = b_0 + b_1X_{1i} + b_2X_{2i} + \ldots + b_nX_{ni} + \varepsilon_i \quad (14)$$

in which b_n is the regression coefficient of the corresponding variable X_n.

All common assumptions mentioned at the beginning of the chapter need to be satisfied. One additional assumption is needed for linear regression: the relationship between the independent and dependent variable is linear, which means that the line fitting all data points is a straight line.

3.4.4 Logistic regression

Logistic regression is, similar to all regression analyses, a predictive analysis and is described by a curved line instead of a straight one. *Simple logistic regression* is used to describe and explain the relation between a dependent binary variable and one or more nominal, ordinal, interval or ratio-level independent variables. In logistic regression, instead of predicting the value of a variable Y from a predictor variable X_1, the probability of Y occurring given known values of X_1. The logistic regression equation from which the probability of Y is predicted is given by:

$$P(Y) = \frac{1}{1+e^{-(b0+b1X1i)}} \quad (15)$$

If the dependent variable is nominal with more than two levels, then *multinomial logistic regression* needs to take place, which is used to explain the relationship between one nominal dependent variable and one or more independent variables. Thus, in this case, the probability of Y is given by:

$$P(Y) = \frac{1}{1+e^{-(b0+b1X1i+b2X2i+\cdots+bnXni)}} \quad (16)$$

In addition, if the dependent variable is ordinal with more than two levels then *ordinal logistic regression* is used, which is similar to multinomial, but with ordinal dependent variable instead. By carrying out an ordinal regression the independent variables that have a statistically significant effect on the dependent variable will be determined.

To be able to carry out a logistic regression, the following requirements must be met:

1. The dependent variable is measured on an ordinal level.
2. One or more of the independent variables are either continuous, categorical or ordinal.
3. No Multi-collinearity, which means that none of the independent variables are highly correlated with each other.
4. Proportional Odds, which means the relationship between each pair of outcome groups is the same. In other words, the coefficients that describe the relationship between the lowest versus all higher categories of the response variable are the same as those that describe the relationship between the next lowest category and all higher categories.

3.4.5 ANOVA and Kruskal-Wallis test

The one-way analysis of variance (ANOVA) is used to determine whether there are any statistically significant differences between the means of two or more independent groups.

In order to be able to run the ANOVA test all common assumptions mentioned at the beginning of the chapter need to be satisfied in combination with the following:

1. The dependent variable has to be continuous.
2. The independent variable needs to consist of two or more categorical independent groups.
3. No significant outliers.

However, the ANOVA test can only show if there is a statistically significant difference between at least two groups but not exactly between which ones this occurs. Therefore, it is important for the analysis to determine which of the groups differ and this can take place with a post hoc test like the one described in section 2.2.2 for the Chi-square post hoc test.

Furthermore, if in any case one of the common assumptions is not satisfied, then a non-parametric test and more specifically Kruskal-Wallis test can take the place of the ANOVA.

The Kruskal-Wallis test is a rank-based non-parametric test that is used to determine if there are statistically significant differences between two or more groups of an independent variable on a continuous or ordinal dependent variable. For this test the following requirements need to be met:

1. The dependent variable has to be either ordinal or continuous.
2. The independent variable needs to consist of two or more categorical independent groups.
3. Independence of the observations.

In addition, as described before a post hoc test can take place after the Kruskal-Wallis test in order to find out between which groups exactly the statistically significant difference occurs.

3.4.6 Spearman's Rank-Order Correlation test

Correlation (ρ) of two variables implies that there is a statistical relationship between them. The correlation between two variables can be interpreted as follows:

- Positive correlation ($\rho = 1$): both variables move in the same direction
- Neutral correlation ($\rho = 0$): the variables are unrelated
- Negative correlation ($\rho = -1$): variables change in opposite directions

The Spearman's rank-order correlation is a non-parametric test used in place of Pearson product-moment correlation and it measures the strength and direction of association between two variables.

The assumptions of Spearman's correlation are that the two variables are ordinal, interval or ratio and there is a monotonic relationship between them.

4 Monitoring Campaign

In this chapter, the realization of the Opschaler monitoring campaign will be described. This includes a description of the data acquisition sets used as well as a description of the surveys and inspections that took place. The campaign was realized before the start of this master thesis, however a good description of it is necessary in order to understand how such real time measurements of both quantitative and qualitative data on comfort and occupant behaviour as well as other parameters can be performed in residential dwellings. Most part of this chapter comes from the Monicair report [61] and Tasos Ioannou PhD thesis [56].

4.1 Opschaler monitoring campaign set up

The sample used in the Opschaler monitoring campaign was not restricted to social housing as it was done in the previous Ecommon monitoring campaign. The main criterion for people to participate in it was that they had a smart meter at home. As soon as enough were registered, further registration would be stopped. In addition, participants would receive a gift voucher of 20 euros and if desired an analysis of the energy data and tailor-made advice about energy-saving options.

Ninety-six dwellings were selected in total, which had energy labels from A to G. The method for calculating the energy label of the dwellings is described in the Dutch building code ISSO 82.3. On the EPC, buildings are divided into energy label categories, ranging from "A++" (the most efficient) to "G". The categories are determined by calculating the energy index, which depends on the overall energy performance, based on the construction of the building envelope as well as the building services systems used to provide space heating, cooling, hot tap hater, ventilation and lighting [42].

For the first batch of dwellings the equipment was installed between March and April 2017, while for the second batch around the end of June 2017. The measurements period differed per home lasting from 3 weeks to 1 year. The equipment was installed by two TU Delft students and took approximately 2.5 hours. The sensors were placed on the walls or cabinets, in close consultation with the residents. The data from the sensors were sent to a central database by using a minicomputer, which could only be used for this purpose.

4.2 Data acquisition and equipment

The sensors and equipment used as well as their locations are shown in Table 4.1 and are described in more detail in this section.

Table 4.1: *Sensor and equipment used along with their locations. (Source: Tasos Ioannou PhD thesis)*

Sensor / Equipment for:	Location
Temperature, humidity and CO2 concentration	Living room, bedrooms, kitchen
Presence (heat sensor)	Living room, bedrooms, kitchen
Humidity	Bathroom
Gas and electricity consumption	Meter box
Pump capacity of the boiler/heat pump	At the boiler/heat pump
Minicomputer	Meter cupboard or living room
Comfort experience	App on mobile phone, tablet or computer

4.2.1 Honeywell equipment used to collect indoor climate data

The system used to collect temperature (T), relative humidity (RH), CO2 level and presence data was a custom-built combination of sensors developed by Honeywell. The temperature, humidity and CO2 sensors were all mounted in a single box that was installed in up to four habitable rooms (living room, bedrooms, kitchen) in each house participating in the measuring campaign. The type, model and accuracy of the sensors are shown in Table 4.2. The T, CO2 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 4.1 gives an impression of the arrangement of the sensors.

Table 4.2: *Types, models and accuracy of sensors used during the Opschaler measurement campaign. (Source: Tasos Ioannou PhD thesis)*

SENSOR TYPE	MODEL	ACCURACY
CO2	GE Telaire	400-1250 ppm: 3% of reading 1250-2000 ppm: 5% of reading
Relative Humidity	Honeywell HiH5031	+/- 3%
Temperature	KT Thermistor	1% per oC
Movement	Honeywell IR8M	11x12 m (range at 2.3 m mounting height)

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 ^{o}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.

Figure 4.1: *T, CO2, RH box (left) and movement sensor (right) as used during the Opschaler measurement campaign. (Source: Monicair report)*

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 oC and 55 oC. 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.

4.2.2 Electricity consumption of appliances: Eltako

Parallel to the Honeywell sensors, another type of wireless sensor was installed in each of the dwellings of the Opschaler measurement campaign. This sensor was developed by Eltako Electronics for measuring electricity consumption of specific installations. Although in principle the device could measure electricity consumption of every appliance (television, coffee machine, toaster etc.) its large size makes it more suitable for measuring the consumption of larger home installations such as a balance ventilation system or a boiler. In this case the sensor was used for measuring the electricity consumption of the pump of the combined heat and hot water boiler, see Figure 4.2. The idea was that by combining data on gas consumption and data on the pump, it would make it possible to differentiate between space heating and tap water heating. In houses with a balance ventilation system, the Eltako was also used to measure the electricity use of the ventilators and in houses with heat pumps it was used to measure the specific electricity use of the heat pump.

Figure 4.2: *Eltako Electricity meter used for measuring in real time the combi-boiler's pump energy consumption. (Source: Monicair report)*

4.2.3 Gas and electricity consumption: Cloudia

Apart from the atmospheric data (T, RH and CO2), presence, and electricity of the combi-boiler's pump, ventilation and heat pump, the total electricity consumption of each dwelling was monitored in real time with the Cloudia system. The Cloudia energy meter can be attached on the electricity meter (Figure 4.3) and its sensor can count the number of pulses that the meter is emitting. Its technology allows it to work with analog, dial gauges, as well as newer digital meters. A specific number of meter pulses per time interval (minute, quarter, hour etc.) is related to a specific number of kWh. The Cloudia sensor counts the amount of pulses, translates them into kWh of electricity consumption and then stores the data online. The Cloudia energy meter plugs into a home network using the supplied network so that the tenants, with the use of a smart phone, computer or tablet can view the current or historical energy usage. These possibilities, however, were masked during the measurement campaign, in order not to influence the behaviour of the occupants.

Figure 4.3: *Electricity smart meter sensor mounted on a new digital meter (left) and an old gas meter (right). ((Source: Monicair report)*

4.2.4 Subjective data: ComfortApp, Surveys and Inspections

The Opschaler measurement campaign collected subjective as well as quantitative data. Data on perceived comfort levels were collected with the aid of a mobile app developed by Delft University of Technology's Department of Industrial Design. By downloading the mobile app on their smart phone, tablet or computer, tenants were able to fill in various subjective data as indicated in Figure 4.4, such as:

- The room they are occupying when filling in the log (kitchen, living room, bedroom etc.)
- Perceived comfort level on a 7-point scale, from -3 (very cold) via 0 (neutral) to +3 (hot) as well as preferred comfort level, from -1 (cooler) to +1 (warmer).
- Activity level: lying /sleeping, relaxed sitting, doing light deskwork, walking, jogging, running. These activities can then be related to the metabolic rate.
- Actions taken during the past half hour related to comfort and energy consumption, such as opening or closing the windows, drinking a cold or hot drink, eating, taking clothes off or putting them on, raising or lowering the thermostat setting and having a hot or cold shower.
- Clothing combination worn: a choice of six combinations from very light (sleeveless T-shirt) to very warm clothing (jacket and hood) is available.

Figure 4.4: *Subjective data filled in the ComfortApp. (Source: own app screenshots)*

The occupants of the houses were asked to fill in the app a few times per day (preferably in the morning, midday and evening).

The data from the comfort app were directly sent to the database. In that way thermal sensation data (comfort app), subjective data related to the PMV (clothing and metabolic activity), and quantitative data related to the PMV (temperature and humidity) were obtained all universally time stamped.

4.3 Data storage and management

4.3.1 Honeywell

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. In the data log panel, we can see the string of data recorded every 5 minutes, in the first column there is a detailed timestamp that includes date and time. The second column shows the code of the sensor kit which refers to a room and then the next columns are the actual data (CO2, Temperature, Relative Humidity, Relative Humidity of the Bathroom, and presence. The column with the indication 255 denotes an error which in our case was just that this column was not in use. The interface was also providing the possibility to download in csv format the total amount of data recorded or data from specific days.

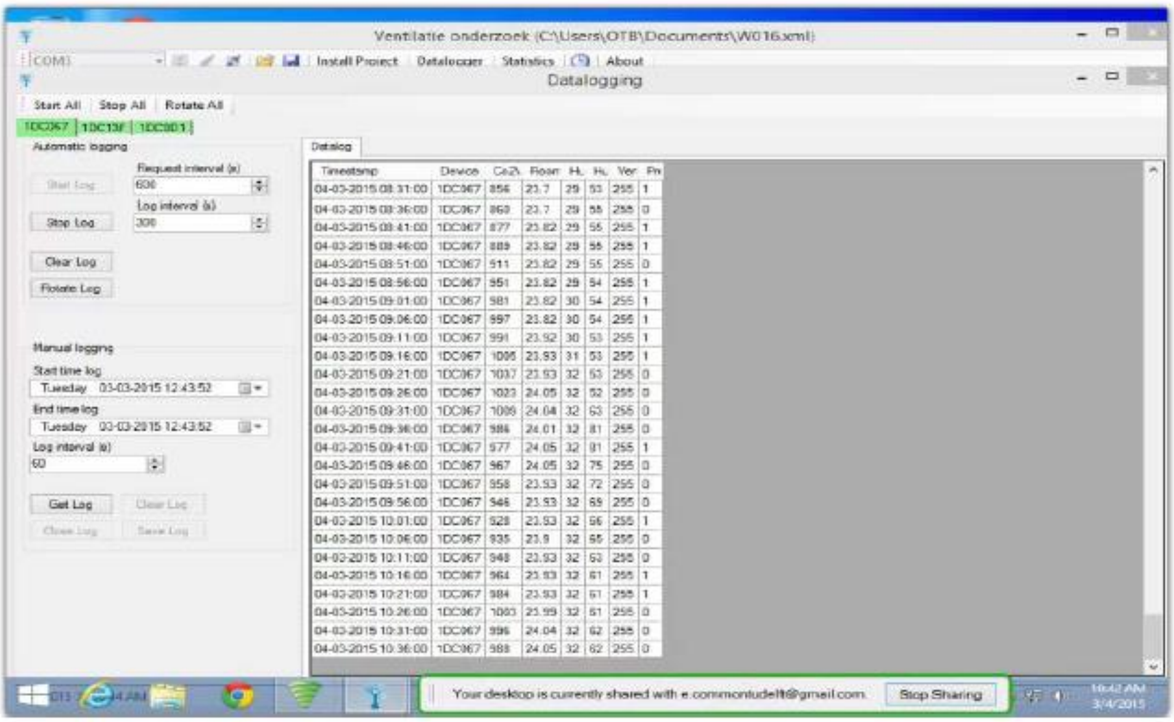


Figure 4.5: *Honeywell interface for managing the sensor data. (Source: Monicair report)*

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 CO2 sensors) also acted as a wireless transmitter for the adjacent sensor box, so that one mini-PC could collect data from neighbouring 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.

4.3.2 Eltako

The Eltako sensor had also its own software, developed by Eltako Electronics which can be downloaded for free from the company site (Figure 4.6).

Figure 4.6: *Eltako interface and consumption display in real time. (Source: Monicair report)*

Via this interface each sensor can be monitored and data can be requested for any day of the campaign and as a whole. The measurement frequency was 1 minute and the display was taking place real time. Though, data could be requested and downloaded in different intervals (5 or ten minutes, sub-hourly or hourly). Transmission was taking place wirelessly and the storage was local. From the mini pc the data were being transferred to the TU database and each week a virtual copy of the local storage drive was saved in the Opschaler Google drive.

4.4 Occupant survey and inspection list

Occupants were asked to fill in a questionnaire during installation of the sensors in their home. The questions asked fall 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 Opschaler.

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, 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).

5 Basic Graphical Analysis of the Data

In this chapter a basic description of the sample and the most related for the current research data gathered by the surveys and the inspections will be illustrated in tables and graphs in order to better understand the analysis in the following chapters. The rest of the graphical analysis of the data will be included in the Appendices.

In the data shown in this section, there are some dwellings with missing information. It is also important to mention here that there is some uncertainty in the inspections' data due to the fact that it was gathered by students and not professionals.

The first research question: "What are the installation characteristics, household characteristics, tenant's behaviour and general comfort perception of the studied dwellings and what can be concluded by that?" is answered in this chapter. First, a global description of the data will be given. The rest of the chapter will be formed as follows:

- Installation characteristics including heating equipment and ventilation system
- Household characteristics including number of people per dwelling and age of the occupants
- Tenants' behaviour including the heating behaviour
- General comfort perception including tenants' comfort perception about the temperature, humidity, draft and possible changes in the apartment to improve it.

As already mentioned, there is more data related to the chapters above shown in the Appendices.

5.1 Global description of the data

The total number of the dwellings that were included in the measurements was 96. However, it was decided to take into account in the research only dwellings for which there are data points filled in the ComfortApp. Therefore, the first step was to clean the ComfortApp data by excluding the first two data points of each dwelling, since these took place while students were explaining to the tenants how to use the app, and as a result the number of dwellings with filled in data points dropped from 96 to 83.

First of all, in Tables 5.1 and 5.2 an overview of the total of 83 dwellings left after cleaning the data is shown along with information related to the energy label, the heating system, the type of installation for hot tap water, the type of ventilation and finally the type of data gathered per dwelling based on the devices placed in them as well as the number of times each house filled in the ComfortApp.

***Table 5.1:** Overview of the dwellings' characteristics in the Opschaler monitoring campaign. (Source: own)*

	Energy Label	**Space Heating**	**Hot tap water**			**Ventilation**			**Measurement devices placed**			**ComfortApp data points**
House no.			*Gasboiler*	*Electrical boiler*	*Heatpump boiler*	*Natural*	*Mechanical*	*Balanced*	*Honeywell*	*Eltako*	*Cloudia*	
P01S01W0373	A	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	19
P01S01W0378	C	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	226
P01S01W0998	-	Heat pump	Yes	No	No	No	No	Yes	Yes	No	Yes	3
P01S01W1347	B	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	98
P01S01W2471	F	HR 107 Boiler	Yes	No	No	Yes	No	No	No	Yes	No	19
P01S01W2581	B	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	Yes	Yes	10
P01S01W2743	A	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	32
P01S01W3155	C	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	2
P01S01W3497	D	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	223
P01S01W3955	D	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	454
P01S01W4002	B	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	3
P01S01W4091	F	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	31
P01S01W4313	-	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	9
P01S01W4489	-	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	75
P01S01W4553	G	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	Yes	Yes	9
P01S01W4569	C	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	85
P01S01W4579	-	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	15
P01S01W4589	B	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	79
P01S01W4979	C	HR 107 Boiler	Yes	No	No	No	No	Yes	Yes	No	Yes	111
P01S01W5040	C	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	8
P01S01W5292	C	HR 107 Boiler	Yes	Yes	No	No	Yes	No	Yes	No	Yes	127
P01S01W5339	A	HR 107 Boiler	Yes	Yes	No	No	Yes	No	Yes	No	Yes	65
P01S01W5476	A	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	14
P01S01W5564	C	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	29
P01S01W5588	C	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	1
P01S01W5855	D	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	190
P01S01W6240	B	HR 107 Boiler	Yes	Yes	No	No	Yes	No	Yes	No	Yes	21
P01S01W6271	B	HR 107 Boiler	Yes	No	No	No	No	Yes	Yes	No	Yes	7
P01S01W6289	A	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	5
P01S01W6549	B	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	4
P01S01W6595	C	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	14
P01S01W6835	C	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	29
P01S01W6959	C	VR Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	66
P01S01W7025	C	HR 107 Boiler	Yes	No	No	No	Yes	No	No	No	Yes	23
P01S01W7548	B	HR 107 Boiler	Yes	No	No	No	No	Yes	Yes	No	Yes	119
P01S01W7980	C	VR Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	13
P01S01W8171	B	HR 107 Boiler	Yes	No	No	No	No	Yes	Yes	No	Yes	1
P01S01W8239	C	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	145
P01S01W8655	B	HR 107 Boiler	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	76
P01S01W8669	D	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	8
P01S01W8828	B	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	38
P01S01W9431	B	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	52
P01S01W9617	A	HR 107 Boiler	Yes	No	No	No	No	No	Yes	No	Yes	7

Table 5.2: *Overview of the dwellings' characteristics in the Opschaler monitoring campaign (continues). (Source: own)*

	Energy Label	**Space Heating**	**Hot tap water**			**Ventilation**			**Measurement devices placed**			**ComfortApp data points**
House no.			*Gasboiler*	*Electrical boiler*	*Heatpump boiler*	*Natural*	*Mechanical*	*Balanced*	*Honeywell*	*Eltako*	*Cloudia*	
P01S02W0167	E	VR Boiler	Yes	No	No	Yes	No	No	Yes	Yes	Yes	239
P01S02W0225	A	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	Yes	Yes	336
P01S02W0248	A	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	Yes	Yes	10
P01S02W0264	C	HR Boiler	Yes	Yes	No	Yes	Yes	No	Yes	No	Yes	17
P01S02W0599	C	-	-	-	-	Yes	No	No	Yes	No	Yes	4
P01S02W1050	D	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	252
P01S02W1967	G	-	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	146
P01S02W3195	B	HR 107 Boiler	Yes	No	No	No	Yes	No	Yes	Yes	Yes	101
P01S02W3780	A	HR 107 Boiler	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes	107
P01S02W3976	-	-	-	-	-				Yes	Yes	Yes	2
P01S02W4042	A	HR 107 Boiler	Yes	No	No	No	No	Yes	Yes	Yes	Yes	78
P01S02W4644	A	HR 107 Boiler	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes	64
P01S02W4827	B	-	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	118
P01S02W4850	-	-	-	-	-	-	-	-	Yes	Yes	No	306
P01S02W4953	-	HR 107 Boiler	-	-	-	Yes	No	No	Yes	Yes	Yes	28
P01S02W5065	B	HR 100 Boiler	Yes	No	No	No	Yes	No	Yes	No	Yes	6
P01S02W5363	-	HR 107 Boiler	-	-	-	Yes	No	No	Yes	Yes	Yes	29
P01S02W5463	C	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	Yes	No	67
P01S02W5881	-	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	Yes	Yes	20
P01S02W5973	-	HR 100 Boiler	Yes	No	Yes	No	Yes	No	Yes	Yes	Yes	11
P01S02W6119	A	HR 100 Boiler	Yes	No	No	No	Yes	No	Yes	Yes	Yes	7
P01S02W6402	G	VR Boiler	Yes	No	No	Yes	No	No	Yes	Yes	Yes	735
P01S02W6658	B	HR 107 Boiler	Yes	No	No	-	-	-	Yes	Yes	Yes	249
P01S02W6848	E	HR 100 Boiler	Yes	No	No	Yes	No	No	Yes	No	Yes	32
P01S02W7251	A	HR 107 Boiler	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	21
P01S02W7591	F	-	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	19
P01S02W8515	E	HR 107 Boiler	No	Yes	No	Yes	No	No	Yes	Yes	Yes	807
P01S02W8517	B	-	Yes	No	No	No	Yes	Yes	Yes	No	Yes	154
P01S02W8598	E	HR 100 Boiler	Yes	No	No	Yes	No	No	Yes	Yes	Yes	64
P01S02W9048	A	HR 107 Boiler	Yes	No	No	Yes	Yes	No	Yes	No	Yes	98
P01S02W9239	A	HR 107 Boiler	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	193
P01S02W9260	C	HR 107 Boiler	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	129
P01S02W9332	D	HR 107 Boiler	Yes	No	No	Yes	No	No	Yes	Yes	Yes	5
P01S02W0596	-	-	-	-	-	-	-	-	Yes	Yes	No	342
P01S01W1341	-	-	-	-	-	-	-	-	Yes	No	Yes	250
P01S01W7042	-	-	-	-	-	-	-	-	Yes	No	Yes	65
P01S02W0393	-	-	-	-	-	-	-	-	Yes	Yes	Yes	36
P01S02W5388	-	-	-	-	-	-	-	-	Yes	Yes	Yes	22
P01S01W1554	-	-	-	-	-	-	-	-	Yes	No	Yes	19
P01S01W7525	-	-	-	-	-	-	-	-	Yes	No	No	1

The histograms in Figure 5.1 show the number of dwellings where Honeywell, Eltako and Cloudia smart meter sensors were placed. Almost all dwellings were equipped with Honeywell and Cloudia sensors, while Eltako sensors were installed in less than half of them.

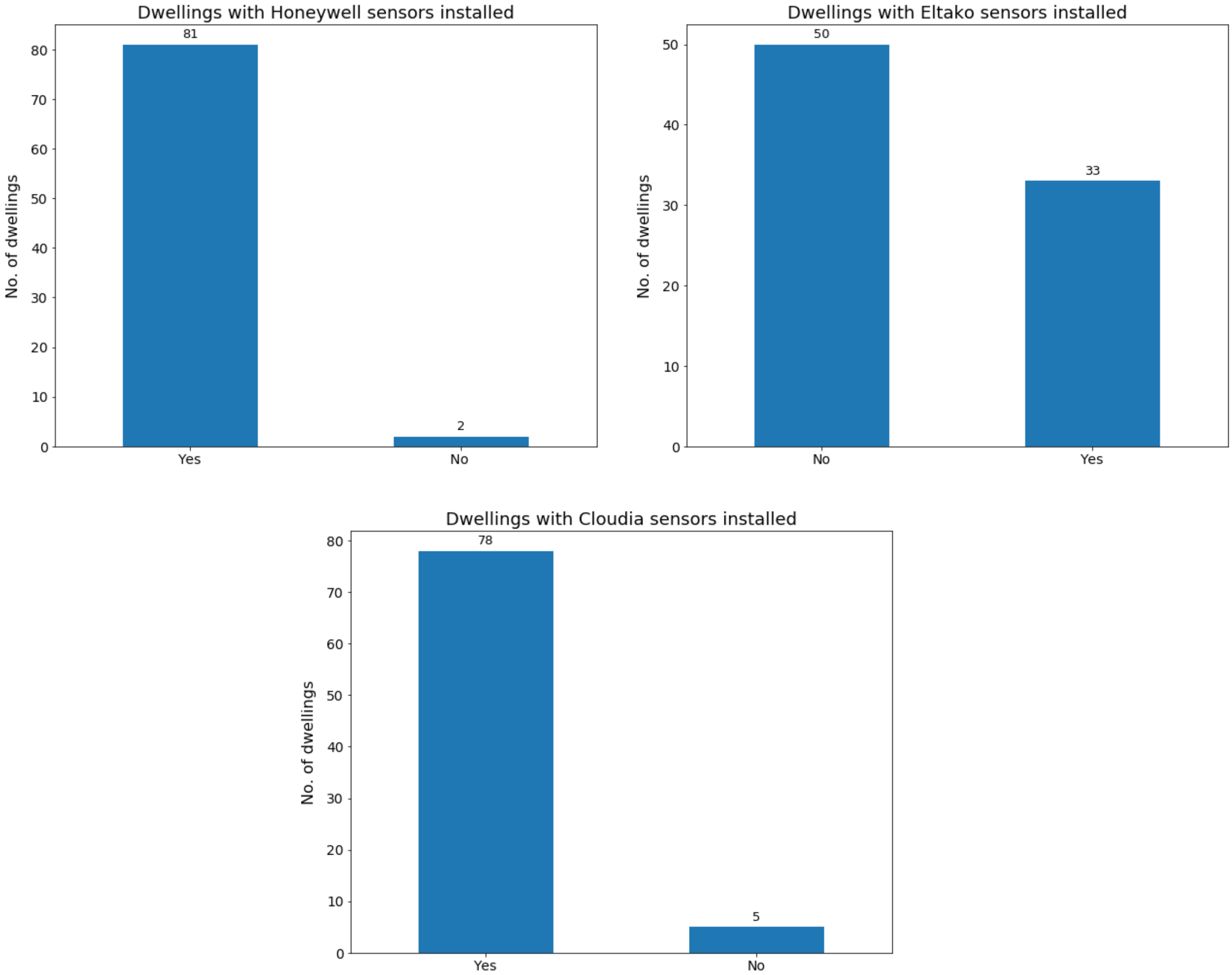


Figure 5.1: *No. of dwellings with Honeywell, Eltako and Cloudia sensors with the actual number shown above the bars. (Source: own)*

5.2 Installation characteristics

In this section data related to the installations characteristics of the dwellings (heating equipment and ventilation system) based on the inspections are shown.

5.2.1 Heating equipment

As illustrated in Figure 5.2, most of the dwellings were using combined space heating and hot tap water (HTW) gas boilers, with some of them also having a HTW electrical boiler, while only one dwelling had heat pumps. Therefore, there is no point of studying if there are any differences related to thermal comfort, indoor climate and energy use between dwellings with different type of space heating.

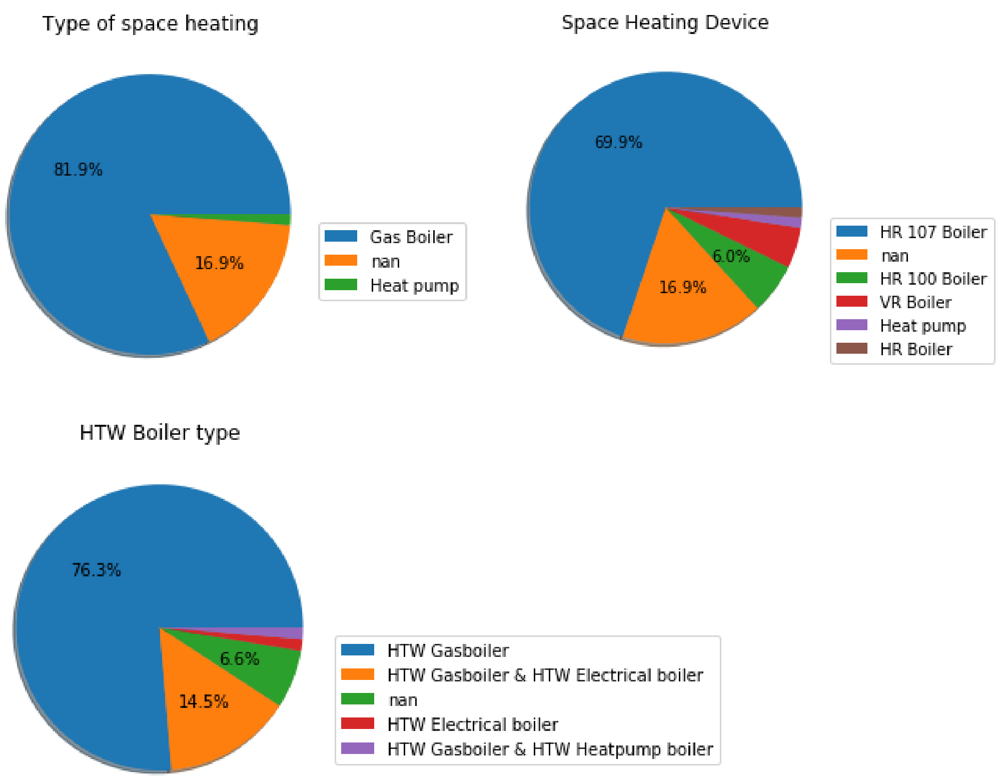


Figure 5.2: *Types of space heating and HTW equipment with the actual percentage per type shown in the pie. (Source: own)*

5.2.2 Ventilation system

Regarding the ventilation type of the dwellings, as indicated in Figure 5.3, about 31 of them had only natural supply and exhaust, 34 of them had natural supply and mechanical exhaust, while only 7 had balanced ventilation system. In Figure 5.4, the ventilation type per energy label for all dwellings is shown. Natural ventilation systems can be found in all energy label categories. Mechanical exhaust systems are found mostly in energy labels A, B, C and D, while all balanced ventilation systems are found in energy labels A, B and C.

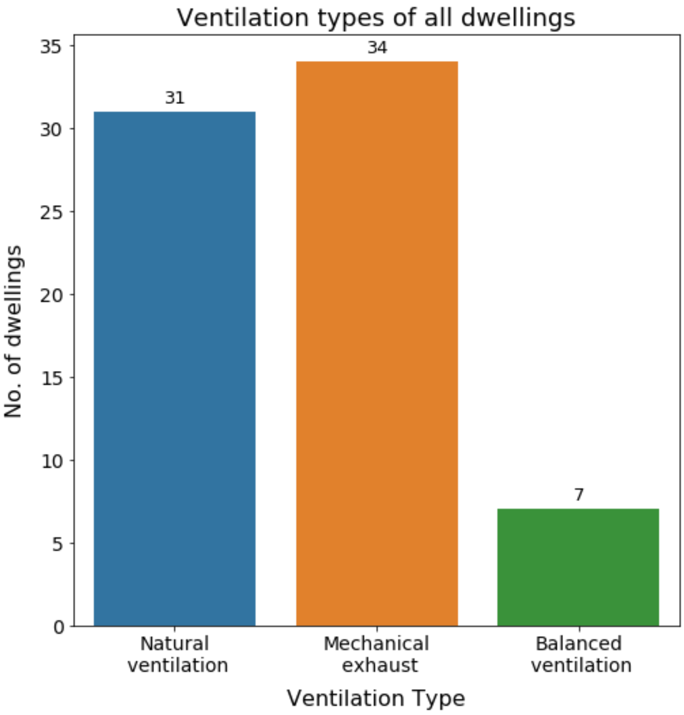


Figure 5.4: *Ventilation type of all dwellings with the actual number of dwellings per type shown above the bars. (Source: own)*

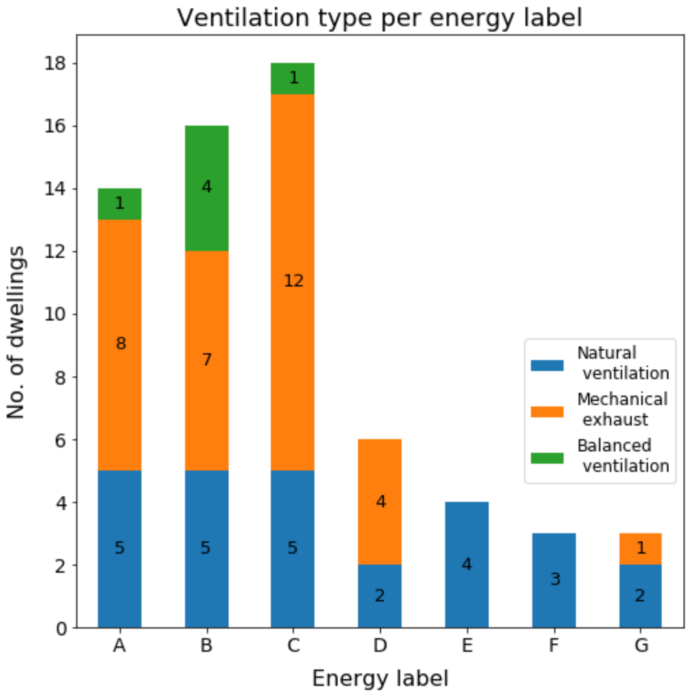


Figure 5.3: *Ventilation type per energy label of all dwellings with the actual number of dwellings per type shown in the bars. (Source: own)*

5.3 Household Characteristics

In this section some of the household characteristics based on the survey are described; information that might be interesting to take into account when analysing the energy consumption and conclude if any of these characteristics might influence it.

5.3.1 Number of people per dwelling

Most dwellings were occupied by 2 people, while there were a few of them with 3, 4 or even 5 people living together, as shown in the histogram in Figure 5.5.

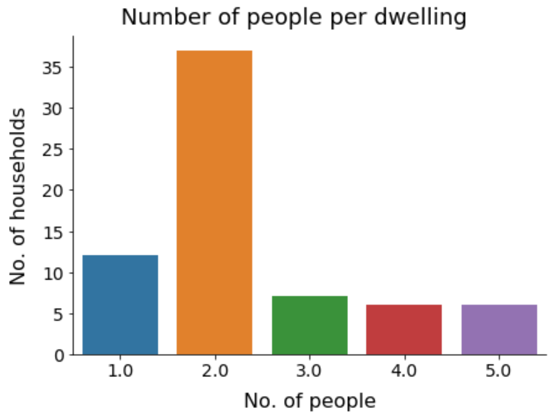


Figure 5.5: *Histogram of the number of people per dwelling. (Source: own)*

5.3.2 Age of the members of the household

The age of people living in the studied dwellings is presented in Figure 5.6. It can be observed that the age of person 1 (respondent) and 2 was mostly concentrated between 28 and 83 years old. While the age of person 3, 4 and 5 was between 3 and 23. This is reasonable, since the respondent was usually one of the senior members of the household, then person 2 was either the husband or the wife of the respondent and people 3, 4 and 5 were usually the children.

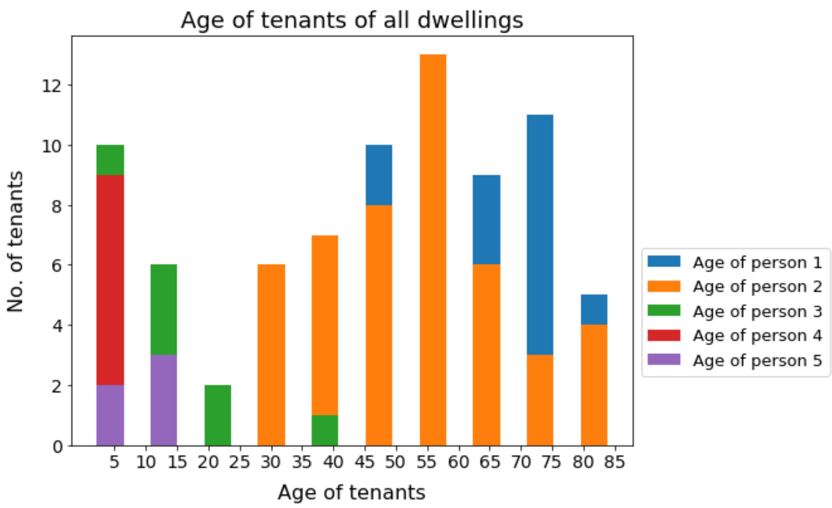


Figure 5.6: *Age of tenants of all dwellings. (Source: own)*

5.4 Tenants' behaviour

The survey included questions related to the tenants' habits and behaviour, from which only the heating behaviour is presented here with the rest included in the Appendix.

5.4.1 Heating behaviour

At the same time the indoor temperature of the dwellings in terms of thermostat settings was reported by the tenants again for both cases of no one and someone being at home as well. Figure 5.7a shows that when nobody is home, the indoor temperature of most dwellings ranges from 14°C to 22°C. However, when people are present at home during the day (Figure 5.7b) the indoor temperature of the majority of the dwellings is 20°C to 21°C and quite the same happens during the evening (Figure 5.7c). In addition, some extreme values like 16°C or 26°C can be observed. During night, as shown in Figure 5.7d, most dwellings' reported temperature ranges from 15°C to 20°C, while the rest have lower temperatures reaching up to 0°C which could be the case of turning the thermostat off.

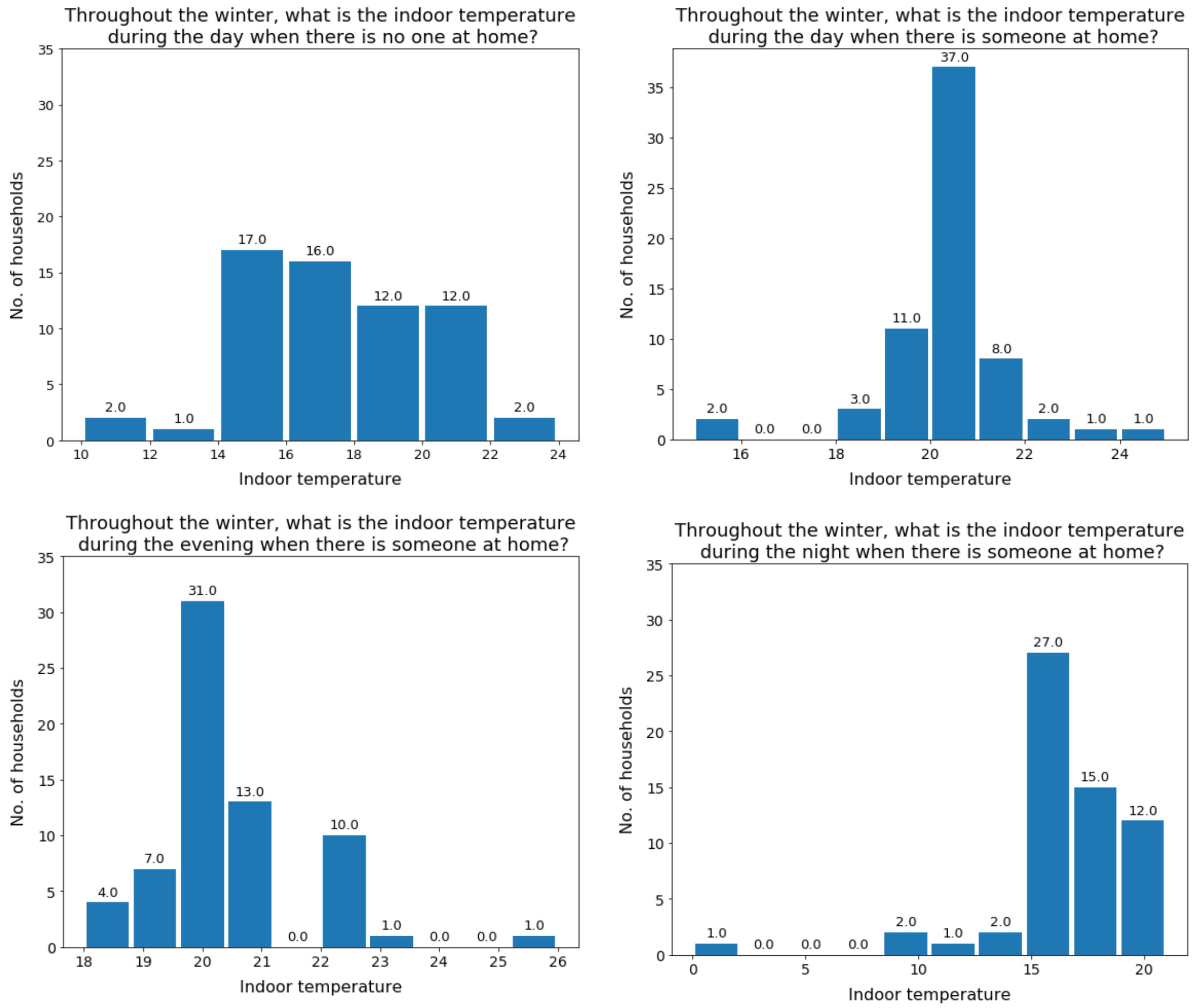


Figure 5.7: *Indoor temperature when nobody is at home (a). Indoor temperature when there is someone at home during the day (b), during the evening (c) and at night (d) with the actual number of households shown above the bars. (Source: own)*

5.5 General Comfort Perception

The survey included also questions related the occupants' general comfort perception in their dwelling taking into account temperature, humidity and draft, as described in the following subsections.

5.5.1 Comfort perception

The survey, also, included questions related to the comfort perception of the tenants. More specifically, tenants reported their perception of the temperature of the dwelling during winter and summer, the humidity and draft during the winter as well as what changes they would like to do in their apartment.

5.5.1.1 Temperature perception in relation to the energy labels

In Figure 5.8 the tenants' perception of the temperature in their apartment during winter and summer is presented in total and per dwelling's energy label, while the bold numbers above each bar show the total number of houses taken into account per energy label. For winter, it can be observed that the majority of the respondents reported feeling good with the temperature, while only a few of them reported feeling too cold and which are classified in energy labels B and C.

In Majcen 2015 as well as Ioannou 2018, that similar analysis took place, the results showed that the lower the energy rating of the house, the more the answers for feeling too cold. This is probably related to the thickness of the insulation and the airtightness of the house. However, in this study it looks like higher energy rating houses complain more about the temperature in winter. However, since the sample size of lower energy rating houses is small, no clear relationship between comfort perception and energy label can be drawn.

In addition, during summer, the answers for feeling too warm seem to be more or less the same for different energy labels except for energy label G, and in agreement with Ioannou about one fourth of the people experience higher temperatures than preferred.

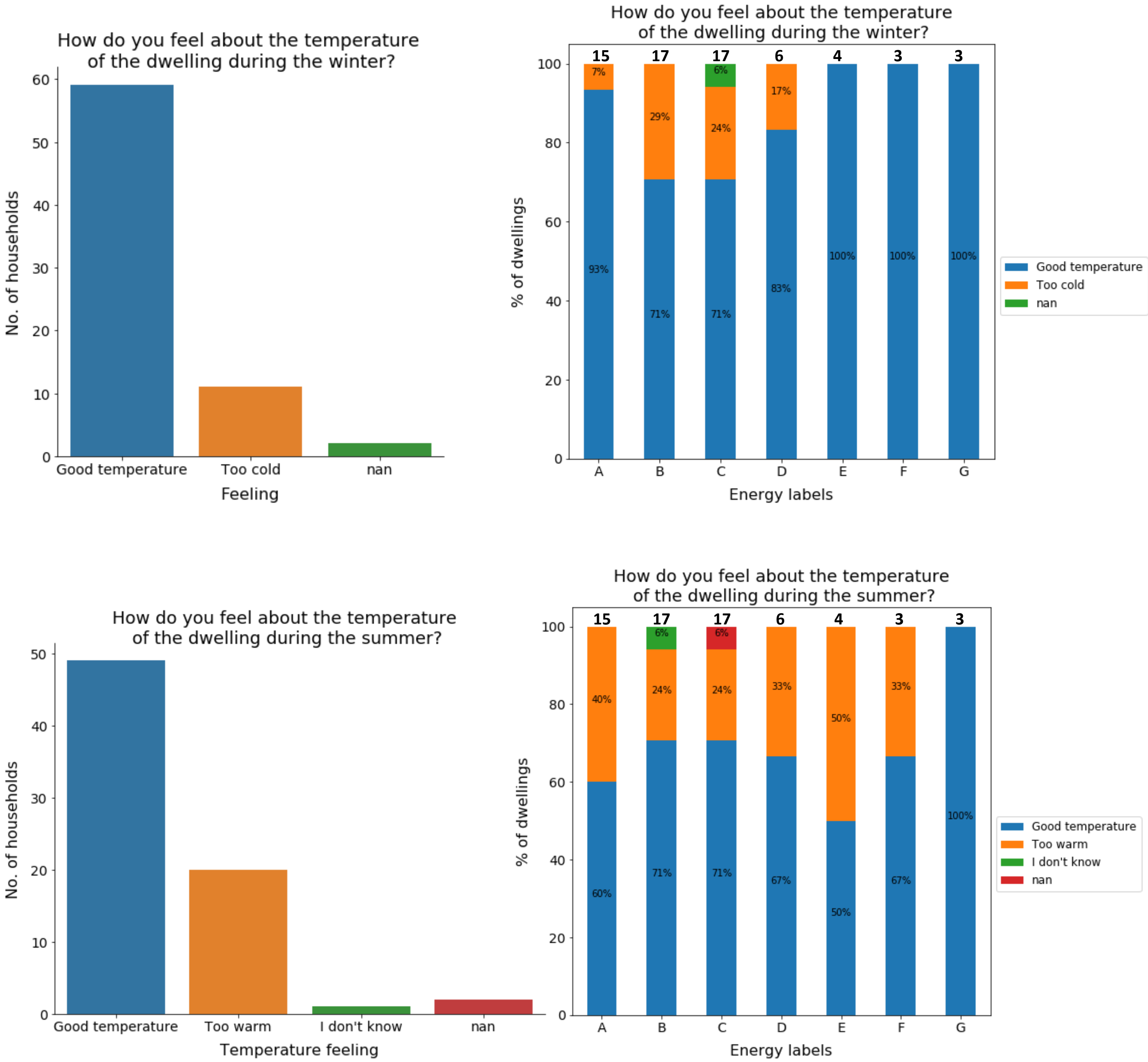


Figure 5.8: *Temperature perception of the tenants in winter and summer in total and per energy label with the actual percentage and number of dwellings shown in and above the bars accordingly. (Source: own)*

5.5.1.2 Humidity and draft in relation to the energy labels

The answers regarding the perception of the humidity and the draft during the winter are shown in total and per energy label in Figures 5.9 and 5.10. The majority of the dwellings answered that the humidity was good, while a few of them and especially in higher energy labels reported that it was too dry or too moist. At the same time when tenants were asked if they have any complaints about draft about one fourth answered yes, while it can be observed that the percentage of positive answers increases when moving to lower energy rating houses.

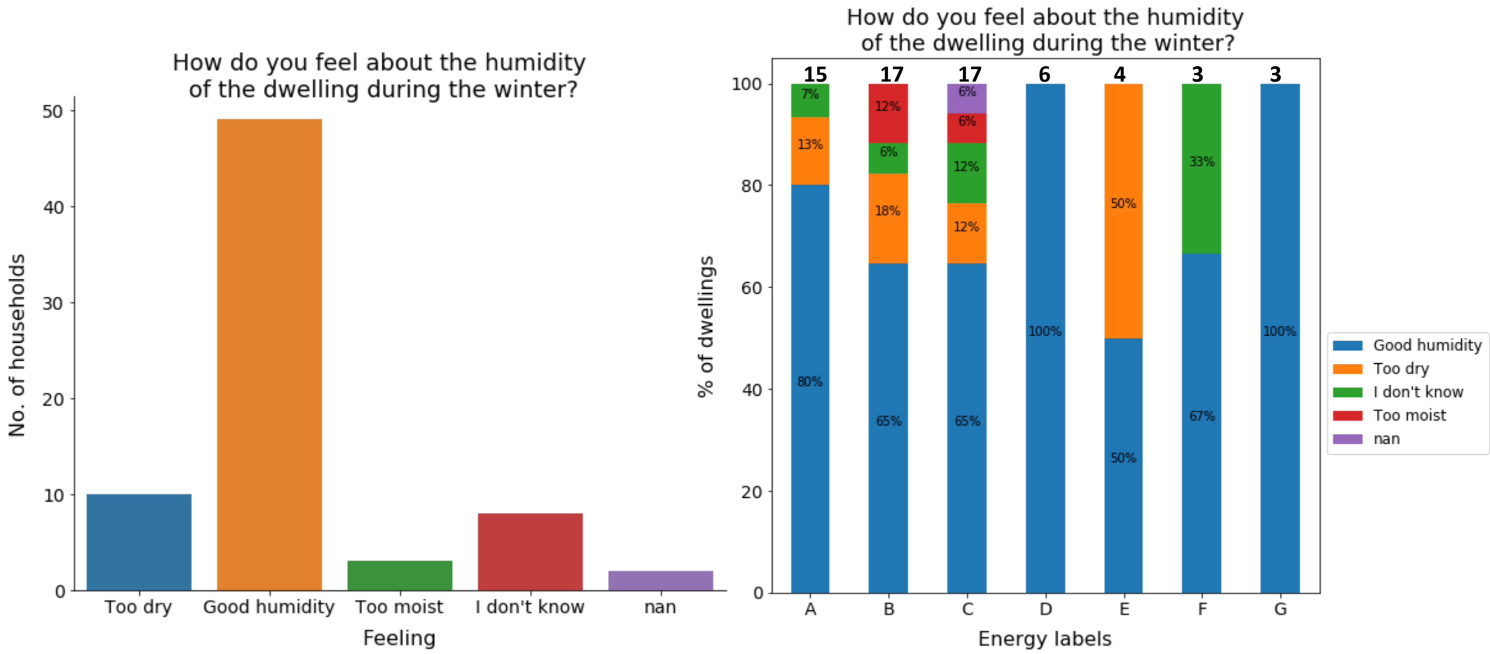


Figure 5.9: *Humidity perception of the tenants in winter in total and per energy label with the actual percentage and number of dwellings shown in and above the bars accordingly. (Source: own)*

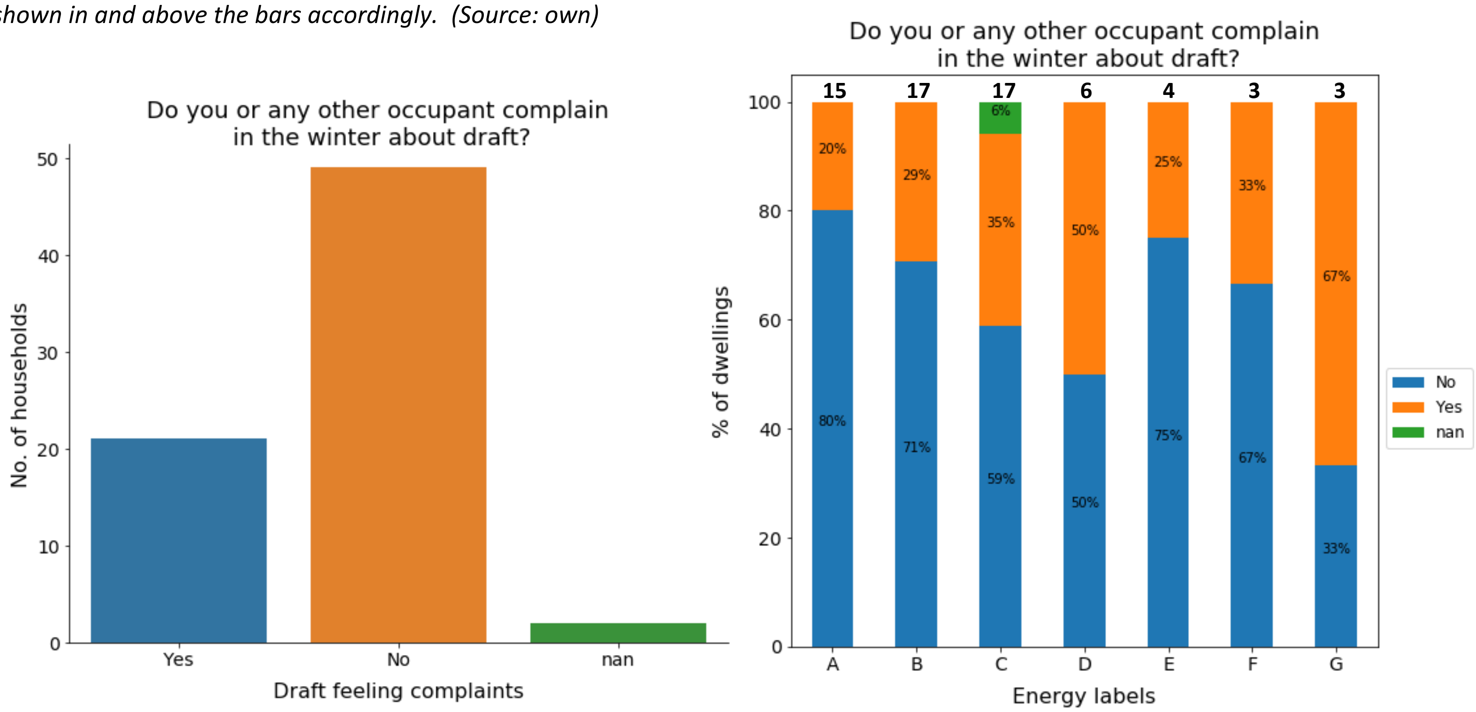


Figure 5.10: *Draft perception of the tenants in winter in total and per energy label with the actual percentage and number of dwellings shown in and above the bars accordingly. (Source: own)*

5.5.1.3 Changes in the apartment

In the question ''what would you most like to change in your house to make it more comfortable in winter'' most dwellings (22) answered nothing, while the next three most common answers were about quicker hot tap water, warmer dwelling and less draft. Regarding the energy labels, even higher energy label dwellings would like to change the above mentioned in their apartments.

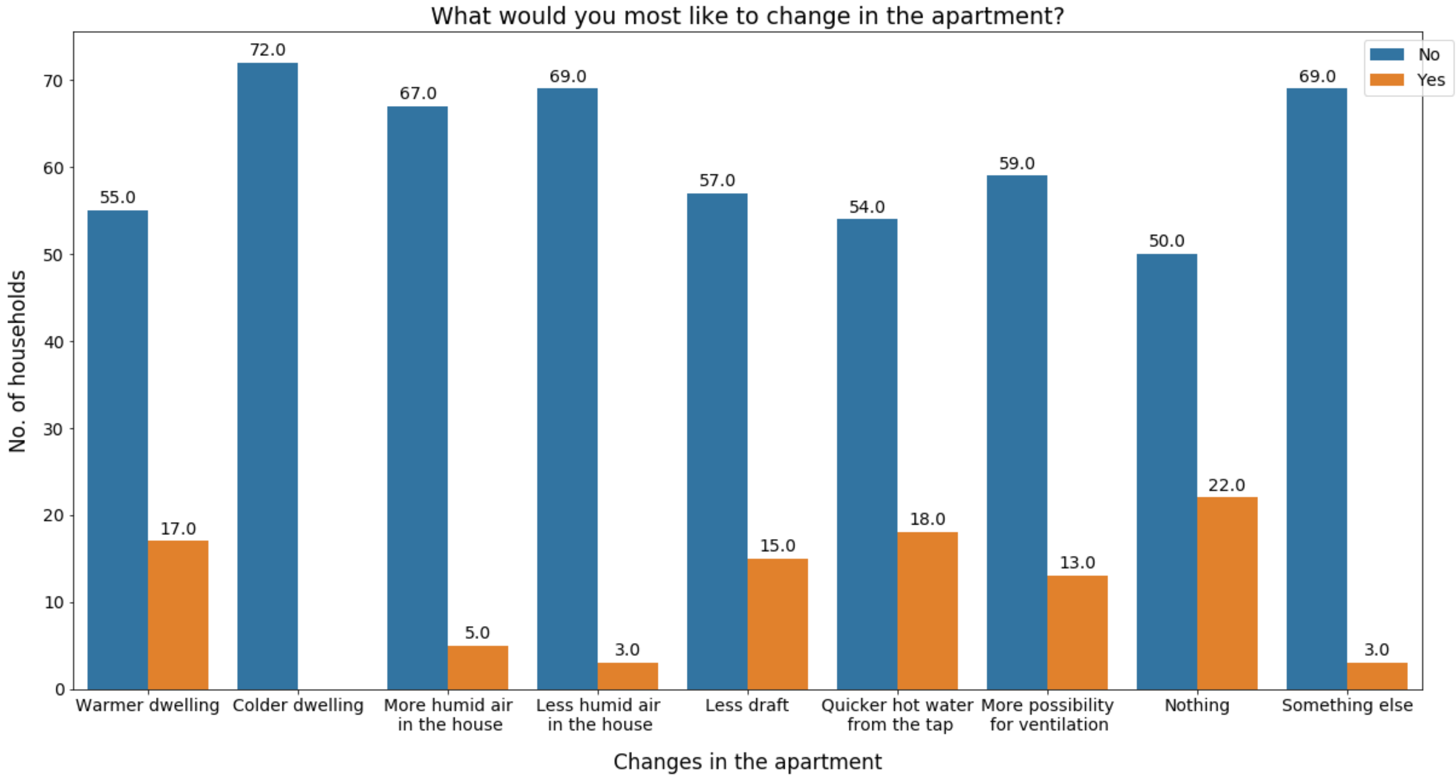


Figure 5.11: *Answers to the question: "What would you most like to change in your apartment?" with the actual number of dwellings shown above the bars. (Source: own)*

5.6 Conclusions

All in all, the following conclusions can be made:

- No point of dividing the dwellings into groups of different type of space heating and their effect on thermal comfort, indoor climate and energy use since all of them use gas boilers apart from one which uses heat pump.
- For the analysis, it would be interesting to divide the dwellings into groups of different type of ventilation (natural ventilation, mechanical exhaust and balanced ventilation) and study their effect on thermal comfort, indoor climate and energy use.
- Most dwellings were occupied by 2 people, while the age of the occupants filling in the Comfort app varied between 30 and 85. Age could be further explored in order to

test if there are any discrepancies in the thermal sensation and preference between different ages.

- Regarding the heating behaviour, the analysis of the thermostat settings during the day, evening, night with people present or absent, gives a good indication about the indoor air temperature and a comparison or validation based on the smart meter measurements can be done.
- As for the general comfort perception, this gives a good insight about the comfort of the occupants based on temperature, humidity and draft, taking also into account the energy label of the dwellings. The results from this analysis can be compared or validated with the real time comfort perception reported in the Comfort app.

6 Real Time Comfort Perception

In this chapter all real time comfort perception data will be analysed. The analysis will help to answer the second and third research questions:

> 2. *What are the reported thermal sensations and how do thermal preferences, clothing types, metabolic activities, actions reported per dwelling relate to them?*
> 3. *How does the thermal sensation and thermal preference vary between individuals and for different energy labels and ventilation system?*

It is important to distinguish here between the 2nd research question which explores the relation among real time data variables and the 3rd one which explores the relation between real time data variables and constant parameters such as energy label, ventilation type and age which do not vary with time.

How all the above-mentioned parameters influence each other is shown in the conceptual diagram (Figure 6.1), where a loop is created between the various factors.

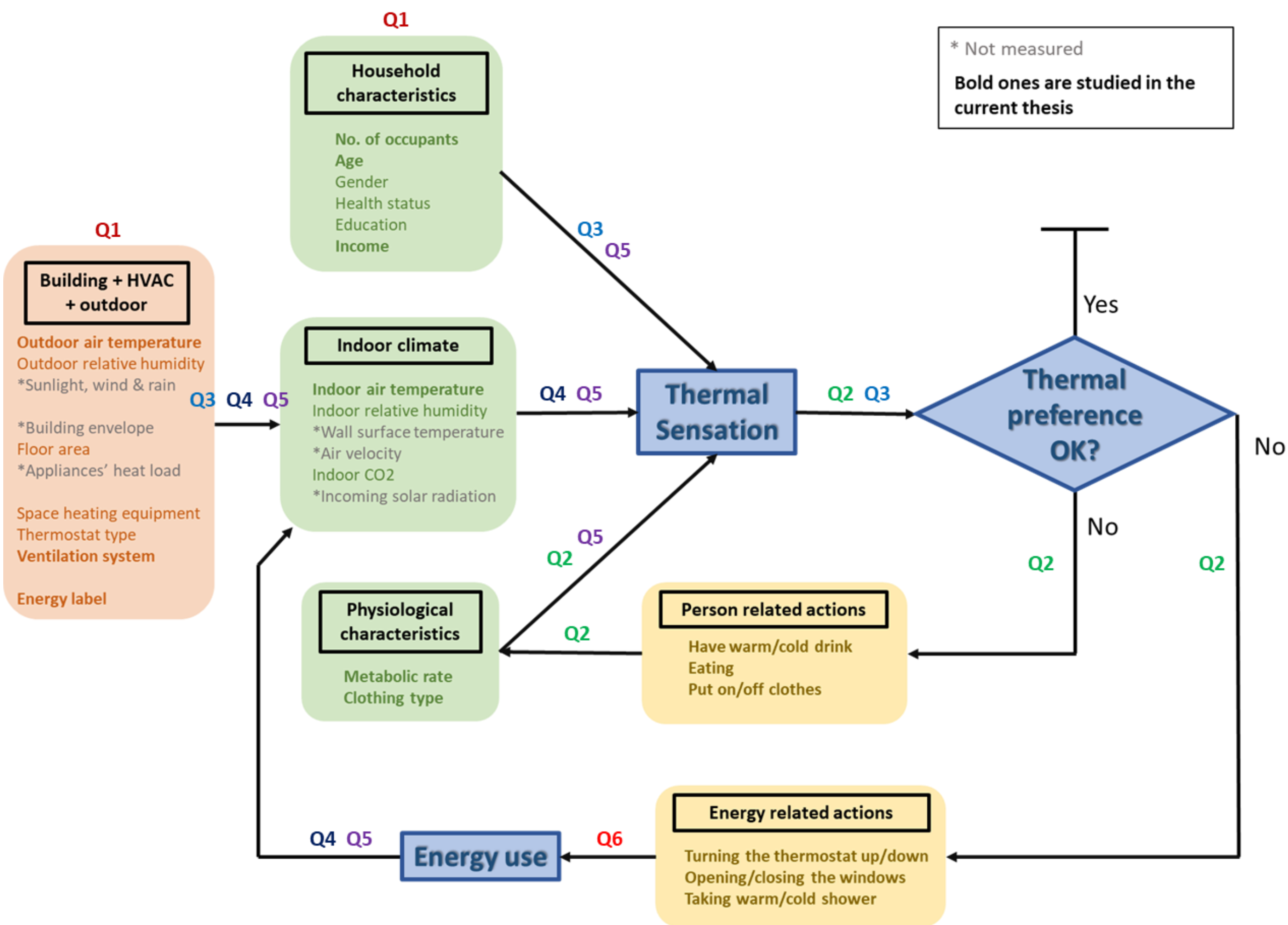


***Figure 6.1:** Conceptual model of the interactions between all parameters. (Source: own)*

Therefore, the first 10 hypotheses, shown in Table 6.1, that are linked to these questions will be tested.

Table 6.1: *First ten null hypotheses and statistical tests for the 2nd and 3rd research questions. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q2	**H1**	The thermal sensation is not related with the thermal preference.	Thermal sensation	Thermal preference	Chi-square test
	H2	The thermal sensation is not related with the clothing type.	Thermal sensation	Clothing type	Chi-square test
	H3	The thermal sensation is not related with the metabolic activity.	Thermal sensation	Metabolic activity	Chi-square test
	H4	The thermal sensation is not related with the actions.	Thermal sensation	Actions	Chi-square test
Q3	**H5**	The thermal sensation is not related with the energy labels.	Thermal sensation	Energy labels	Chi-square test
	H6	The thermal preference is not related with the energy labels.	Thermal preference	Energy labels	Chi-square test
	H7	The thermal sensation is not related with the type of ventilation.	Thermal sensation	Ventilation type	Chi-square test
	H8	The thermal preference is not related with the type of ventilation.	Thermal preference	Ventilation type	Chi-square test
	H9	The thermal sensation is not related with the age.	Thermal sensation	Age	Ordinal Logistic regression
	H10	The thermal preference is not related with the age.	Thermal preference	Age	Ordinal Logistic regression

Before starting with the analysis, a description of the real time comfort perception data will first take place. The rest of the chapter is organised based on the hypotheses, taking them one by one, showing graphs and doing the statistical tests.

As already mentioned in section 5.1, after cleaning the data, the total number of the studied dwellings is 83. The total number of data points that were reported by these 83 dwellings is 7754. In Figure 6.2, the total number of data points per dwelling will be shown. It can be seen that a few dwellings have many more data points than the other, reaching maximum around 800 data points, while the rest has about 100 data points and less.

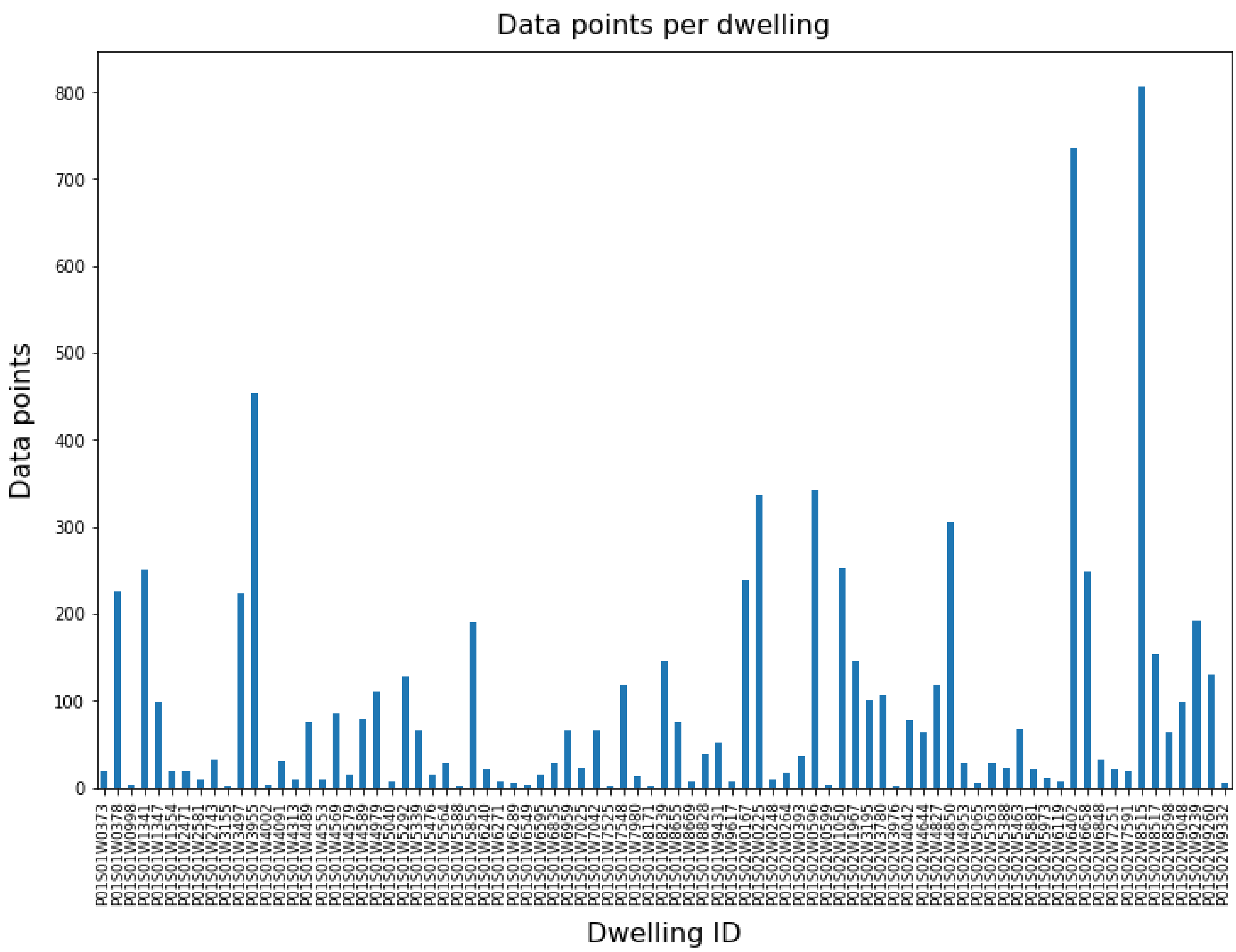


Figure 6.2: *Total number of data points per dwelling for the whole period of measurements. (Source: own)*

In order to make more concrete conclusions, the data was divided into two seasons, winter and summer, and all graphs are presented for both seasons. The separation was done by considering the period from October to March as winter and from April till September as summer. In Figure 6.3, the number of data points separately for winter and summer and per month is shown. It can be observed that there are more data points during the summer months than in the winter months. Also, the number of data points in March is the highest of all, probably because this was the starting month for the first batch of the dwellings and thus, people were filling in the Comfortapp more frequently.

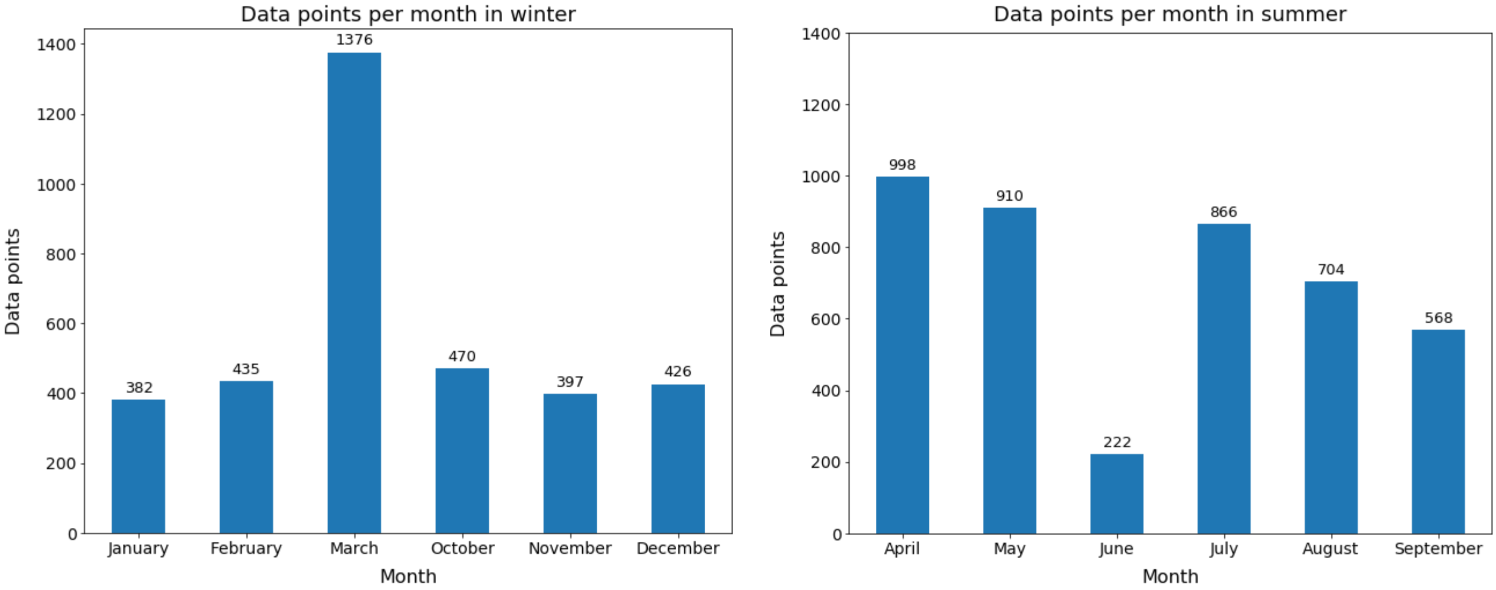


Figure 6.3: *Number of data points per month separately for winter and summer with the actual number of data points shown above the bars. (Source: own)*

6.1 Thermal sensation

It is essential to mention that from this point onwards, the analysis helps to answer the 2nd research question. More specifically here, the first part of it, which is related to the reported thermal sensations is analysed.

*2. What are the **reported thermal sensations** and how do thermal preferences, clothing types, metabolic activities, actions reported per dwelling relate to them?*

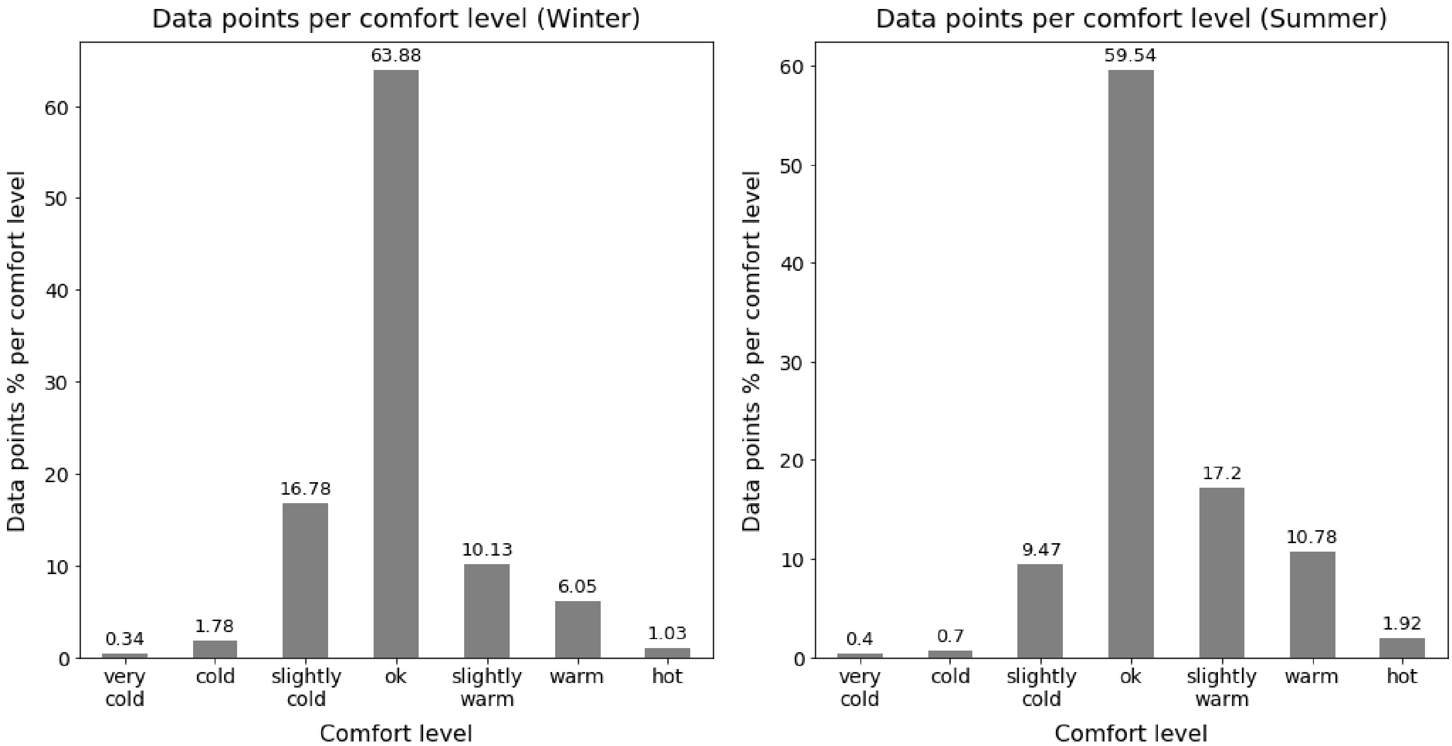


Figure 6.4: *Percentage of data points per comfort level in winter and summer with the actual percentage shown above the bars. (Source: own)*

In Figure 6.4 the percentage of data points per comfort level is shown for both winter and summer. From these it can be observed that the majority of data points, about 64% and 60% for winter and summer, accordingly, were about feeling ok. In addition, only 0.3% to about 2% of the data points were related to feeling very cold, cold or hot. Furthermore, the mean thermal sensation was found to be 0.04 ≈ 0 in the heating period and 0.32 in the cooling period. It makes sense that there are more people feeling slightly cold in winter than in summer, while more people feeling slightly warm or warm in summer.

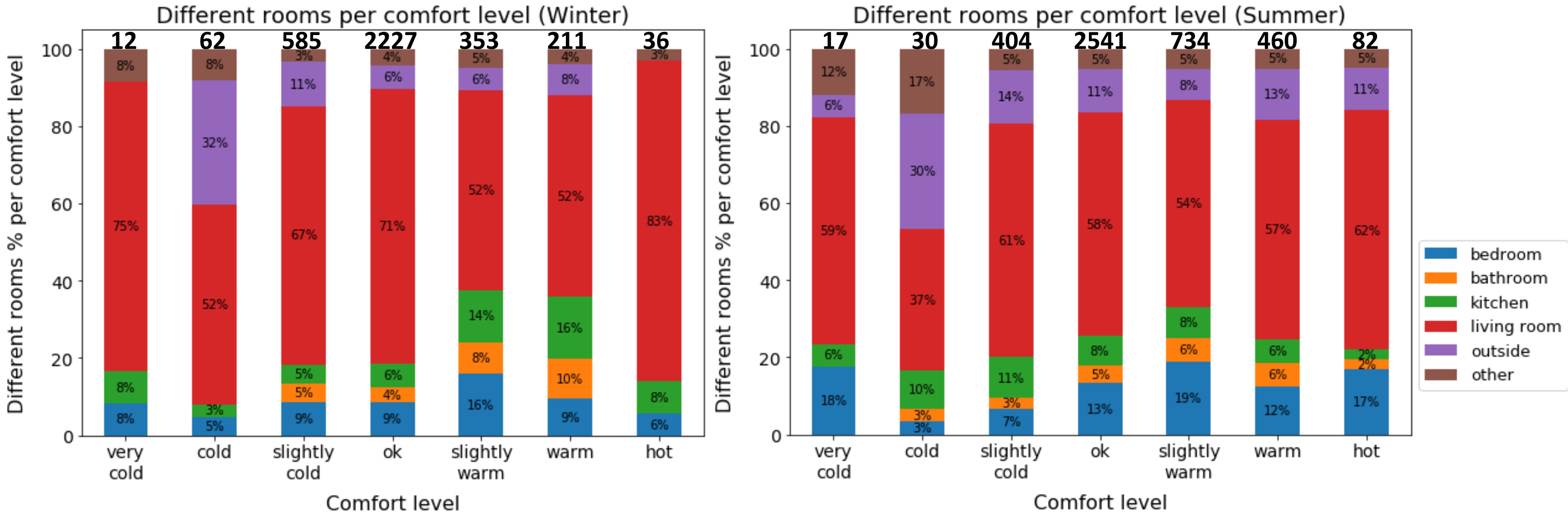


Figure 6.5: *Percentage of different rooms per comfort level in winter and summer with the actual number of data points shown above the bars. (Source: own)*

In Figure 6.5 the room in which people were located during the last half hour for each thermal sensation for both seasons is presented. All different rooms are color-coded, while the numbers on top of each bar represent the number of times each thermal sensation was reported (Total n=3486 for winter and n=4268 for summer).

It can be seen that in all thermal sensations apart from cold, about half of the people or more were in the living room and the rest in one of the other locations (bedroom, outside, kitchen, bathroom and other). When feeling cold, approximately 30% of the data reported being outside during the last half hour, which is reasonable if the outdoor temperature was low, and people just came in the house and filled in the comfort app immediately without having the time to get warmer. For winter this is reasonable, but for summer not. But since winter and summer months are divided as described before based on the theory, it is possible that there are some cold days even during summer months.

6.2 Reported thermal preference and thermal sensation

In this section, the part of the 2nd research question that refers to the relation between thermal sensations and thermal preferences is studied.

> *2. What are the **reported thermal sensations** and how do **thermal preferences**, clothing types, metabolic activities, actions reported per dwelling relate to them?*

6.2.1 Reported thermal preference and thermal sensation stacked bar graphs

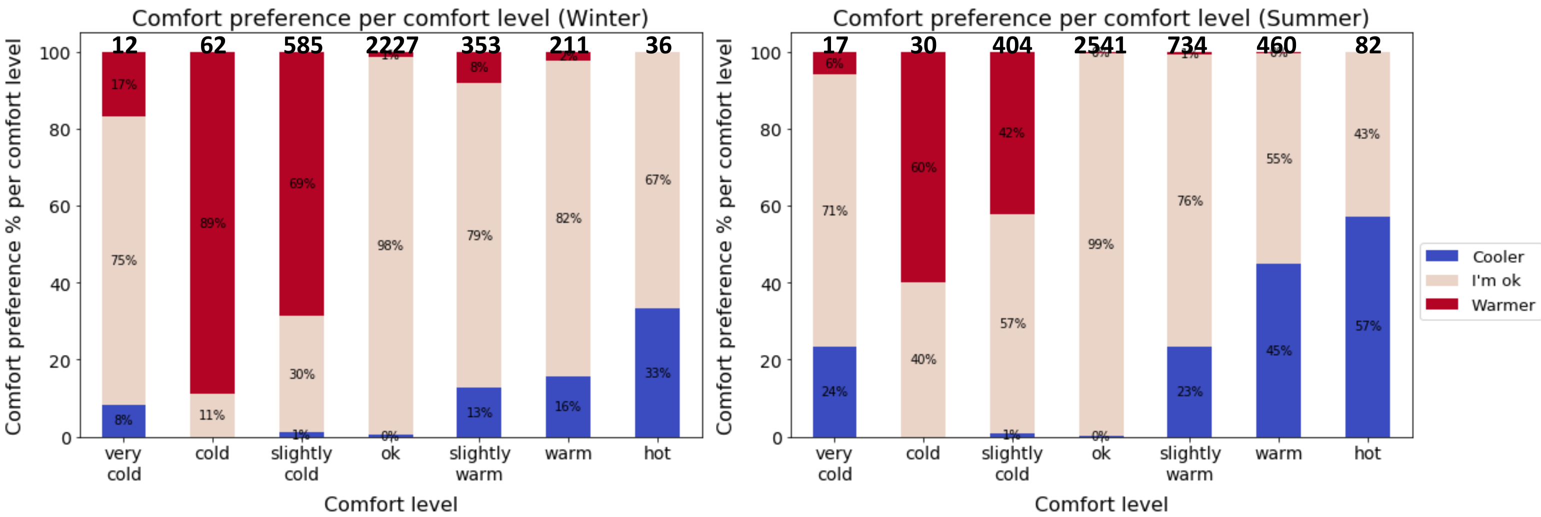


Figure 6.6: *Percentage of comfort preference per comfort level in winter and summer with the actual number of data points shown above the bars. (Source: own)*

As mentioned in the literature part, various studies have concluded that it is important to not only ask about how people feel (thermal sensation vote or TSV) but also about how they would prefer to feel (thermal preference). Both subjective evaluations can give more insights about the thermal sensation in which people feel comfortable, which in many cases could be different than neutral (TSV = 0).

In Figure 6.6 the thermal preference of the tenants for each reported thermal sensation during winter and summer is illustrated. The thermal preference is color-coded with blue for feeling cooler, beige for no change and red for feeling warmer.

In winter, most people feeling “cold” or “slightly cold” wanted to feel warmer, while just a few of those feeling “slightly warm” to “hot” wanted to feel cooler. In summer, it seems that about half of those who were feeling different than neutral wanted to change their thermal conditions. The cold feeling in both cases has not enough data points in order to make concrete conclusions.

6.2.2 Thermal comfort graphs

At this point it would be useful to create the thermal comfort graph in order to compare the PMV-PPD standard line with the one derived by the actual thermal sensation and percentage of dissatisfied people.

To do that, the contingency tables (Figure 6.7) were created first, which show the number of people who would prefer to feel warmer, cooler or the same based on how they actually feel.

Winter

Feel	Very cold (-3)	Cold (-2)	Slightly cold (-1)	Ok (0)	Slightly warm (1)	Warm (2)	Hot (3)	*Row Total*
Rather								
-1 – Cooler	1	0	6	10	45	33	12	***107***
0 – I'm ok	9	7	177	2188	280	173	24	***2858***
1 – Warmer	2	55	402	29	28	5	0	***5421***
Column Total	***12***	***62***	***585***	***2227***	***353***	***211***	***36***	***3486***

Summer

Feel	Very cold (-3)	Cold (-2)	Slightly cold (-1)	Ok (0)	Slightly warm (1)	Warm (2)	Hot (3)	*Row Total*
Rather								
-1 – Cooler	4	0	4	7	171	206	47	***439***
0 – I'm ok	12	12	229	2525	558	253	35	***3624***
1 – Warmer	1	18	171	9	5	1	0	***205***
Column Total	***17***	***30***	***404***	***2541***	***734***	***460***	***82***	***4268***

Figure 6.7: *Contingency table of thermal preference per thermal sensation in winter and summer. (Source: own)*

The PPD (Predicted Percentage of Dissatisfied) was calculated by summing up the number of people preferring to feel warmer (0) or cooler (2) per column and then dividing it by the Column Total. Then, the graph in Figure 6.8 was derived showing actual percentage of dissatisfied people per reported thermal sensation for winter, summer and the whole year.

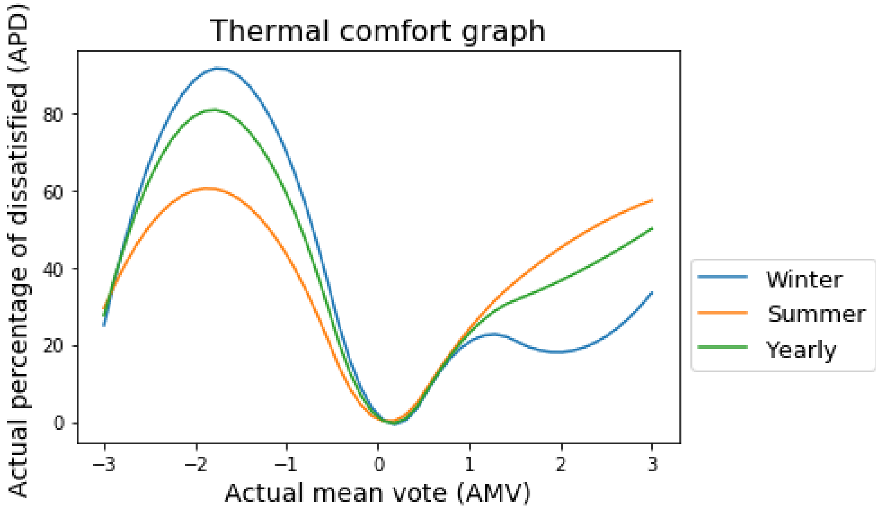


Figure 6.8: *Thermal comfort graph (AMV-APD) for winter, summer and yearly. (Source: own)*

In order to compare the actual percentage of dissatisfied with the predicted one, the standard PMV-PPD line was created based on the following formula:

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.219 \times PMV^2)$$

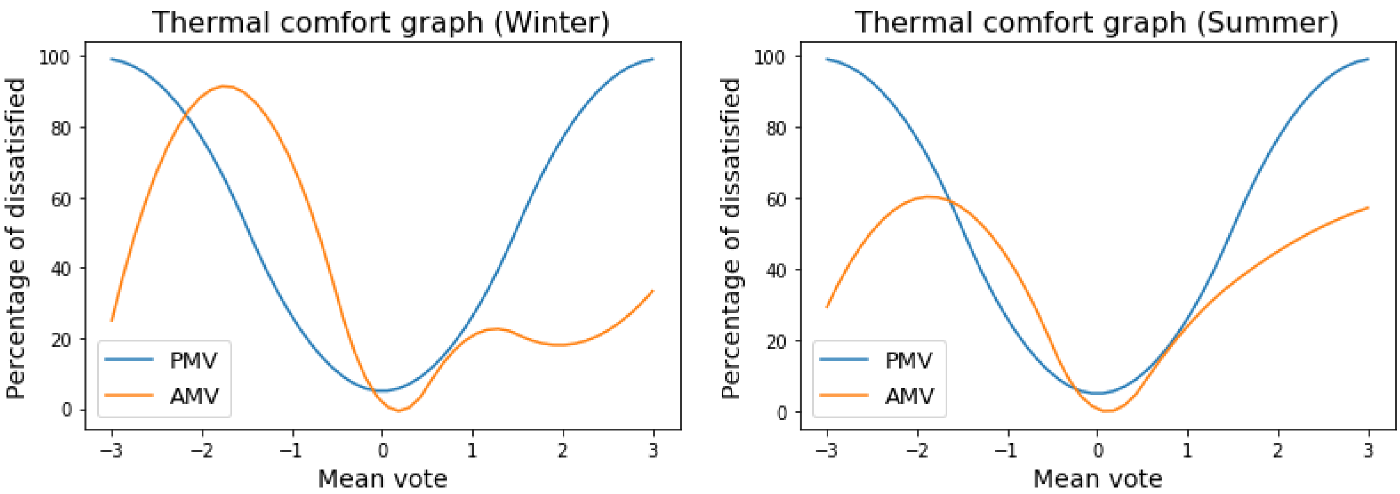


Figure 6.9: *Thermal comfort graphs comparing actual and predicted percentage of dissatisfied people in winter and summer. (Source: own)*

Comparing the line based on the actual data with the standard PMV-PPD line, it can be concluded that both in winter and summer the PMV-PPD line predicts lower percentage of dissatisfaction at TSV = -1, while much higher percentage at TSV > +1 and TSV = -3. Therefore, there is quite a difference between the actual and predicted percentage of dissatisfied, leading to doubts about the comfort thermal sensation and the range of comfort temperatures as well.

Due to the fact that there are only a few data points in the very cold (-3) and hot (+3) thermal sensation and that it is also hard and quite subjective to distinguish between all different levels of thermal sensation, the same graphs were created by merging the “very cold” with the “cold” column as well as the “hot” with the “warm”. These will be shown in the Appendix. By doing so, the two lines come closer, and the deviations are not as large as before, but some of them still exist. Thus, in winter, the PMV-PPD line predicts lower percentage of dissatisfaction at TSV = -1, while higher percentage at TSV=2, while in summer the PMV-PPD line predicts a bit higher percentage of dissatisfied people at TSV = +2 and TSV = -2 and lower percentage at TSV= -1.

6.2.3 Statistical relation between thermal sensation and thermal preference

In order to be able to carry out this and all following chi-square tests (in terms of enough data points per cell), the same merging of the “very cold” with the “cold” column and the “hot” with the “warm” that was described before is held.

At this point the first hypothesis (H1), as shown in Table 6.2, will be tested with the chi-square test and furthermore, with a post-hoc test. The procedure for both tests was described in section 3.4.

Table 6.2: *1st null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q2	**H1**	The thermal sensation is not related with the thermal preference.	Thermal sensation	Thermal preference	Chi-square test

By doing so, it will help to find out if there is a relationship between thermal sensation and thermal preference. More explicitly:

- If there is no relationship between thermal sensation and thermal preference, then having a specific thermal preference does not have any influence on the tenant's reported thermal sensation.
- If the variables are associated, then having a specific thermal preference will help to predict tenant's thermal sensation.

The tests are carried out for both winter and summer in SPSS and the results are shown in Tables 6.3-6.6. In Tables 6.3 and 6.5, the crosstabulation of the thermal sensation and thermal preference is shown and includes apart from the frequencies (counts), the expected counts and the adjusted residuals. In Tables 6.4 and 6.6, the results from the Chi-2 test are presented including the X^2 value, the degrees of freedom (df) and the p-value (asymptomatic significance).

Regarding the Chi-2 test, all requirements are satisfied and by choosing a significance level of 0.05, it is concluded that:

- For winter, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.
- For summer, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.

Therefore, the null hypothesis "The thermal sensation is not related with the thermal preference." is rejected and it is concluded that the thermal sensation is associated with the thermal preference.

Looking now again at Tables 6.3 and 6.5 on the adjusted residuals (post-hoc test), it can be observed that there are some of them highlighted with yellow. Both Tables have 15 cells (3 x 5 tables) and thus, the significance alpha level (by applying the Bonferroni adjustment) equals to 0.05/15 = 0.003, which results in a critical z-value of +/-2.96. All in all, the cells which have an absolute value higher than 2.96 have more or less observed counts than expected and are characterised as significant. The significant difference occurs when the expected counts differ a lot compared to the observed ones. The higher the adjusted value the higher the significant difference.

Thus, in this case, most of the cells are significant with the higher adjusted residuals values being more than others. For example, in winter there is a highly significant relationship between feeling “slightly cold” and preferring “no change” or being “warmer” as well as between feeling “ok” and preferring “no change” or being “warmer”. In summer, there is a highly significant relationship between feeling “ok” and preferring “no change” or being “cooler” as well as between feeling “warm” and preferring “no change” or being “cooler”.

Table 6.3: *Crosstabulation table for thermal sensation and preference including the expected counts and the adjusted residuals in winter with the highlighted cells to be the significant ones. (Created in SPSS)*

WINTER - Feel * Rather Crosstabulation

Threshold value for the residual = 2.96			Thermal preference (Rather)			
			Cooler	*I'm ok*	*Warmer*	Total
Thermal sensation (Feel)	*Cold*	Count	1	16	57	74
		Expected Countgnt	2.3	60.7	11.1	74.0
		Adjusted Residual	-.9	-13.7	15.1	
	Slightly cold	Count	6	177	402	585
		Expected Count	18.0	479.6	87.4	585.0
		Adjusted Residual	-3.1	-35.7	40.0	
	Ok	Count	10	2188	29	2227
		Expected Count	68.4	1825.8	332.8	2227.0
		Adjusted Residual	-11.9	33.2	-30.0	
	Slightly warm	Count	45	280	28	353
		Expected Count	10.8	289.4	52.8	353.0
		Adjusted Residual	11.1	-1.4	-3.9	
	Warm	Count	45	197	5	247
		Expected Count	7.6	202.5	36.9	247.0
		Adjusted Residual	14.3	-.9	-5.9	
Total		Count	107	2858	521	3486
		Expected Count	107.0	2858.0	521.0	3486.0

Table 6.4: *Chi-square test results for thermal sensation and preference in winter. (Created in SPSS)*

WINTER - Chi-Square Tests

	X^2 Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	2286.219[a]	8	.000
Likelihood Ratio	1818.717	8	.000
Linear-by-Linear Association	1038.409	1	.000
N of Valid Cases	3486		

a. 1 cells (6.7%) have expected count less than 5. The minimum expected count is 2.27.

Table 6.5: *Crosstabulation table for thermal sensation and preference including the expected counts and the adjusted residuals in summer with the highlighted cells to be the significant ones. (Created in SPSS)*

SUMMER- Feel * Rather Crosstabulation

			Thermal preference (Rather)			
Threshold value for the residual = 2.96			*Cooler*	*I'm ok*	*Warmer*	**Total**
Thermal sensation (Feel)	*Cold*	Count	4	24	19	47
		Expected Count	4.8	39.9	2.3	47.0
		Adjusted Residual	-.4	-6.5	11.5	
	Slightly cold	Count	4	229	171	404
		Expected Count	41.6	343.0	19.4	404.0
		Adjusted Residual	-6.5	-16.7	37.1	
	Ok	Count	7	2525	9	2541
		Expected Count	261.4	2157.6	122.0	2541.0
		Adjusted Residual	-26.1	32.0	-16.5	
	Slightly warm	Count	171	558	5	734
		Expected Count	75.5	623.2	35.3	734.0
		Adjusted Residual	12.8	-7.4	-5.7	
	Warm	Count	253	288	1	542
		Expected Count	55.7	460.2	26.0	542.0
		Adjusted Residual	29.9	-22.1	-5.4	
Total		Count	439	3624	205	4268
		Expected Count	439.0	3624.0	205.0	4268.0

Table 6.6: *Chi-square test results for thermal sensation and preference in summer. (Created in SPSS)*

SUMMER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	2741.655[a]	8	.000
Likelihood Ratio	1917.437	8	.000
Linear-by-Linear Association	1383.386	1	.000
N of Valid Cases	4268		

a. 2 cells (13.3%) have expected count less than 5. The minimum expected count is 2.26.

6.3 Clothing and reported thermal sensation

In this section, the part of the 2nd research question that refers to the relation between thermal sensations and clothing types is studied.

2. *What are the **reported thermal sensations** and how do thermal preferences, **clothing types**, metabolic activities, actions reported per dwelling relate to them?*

6.3.1 Clothing and reported thermal sensation stacked bar graphs

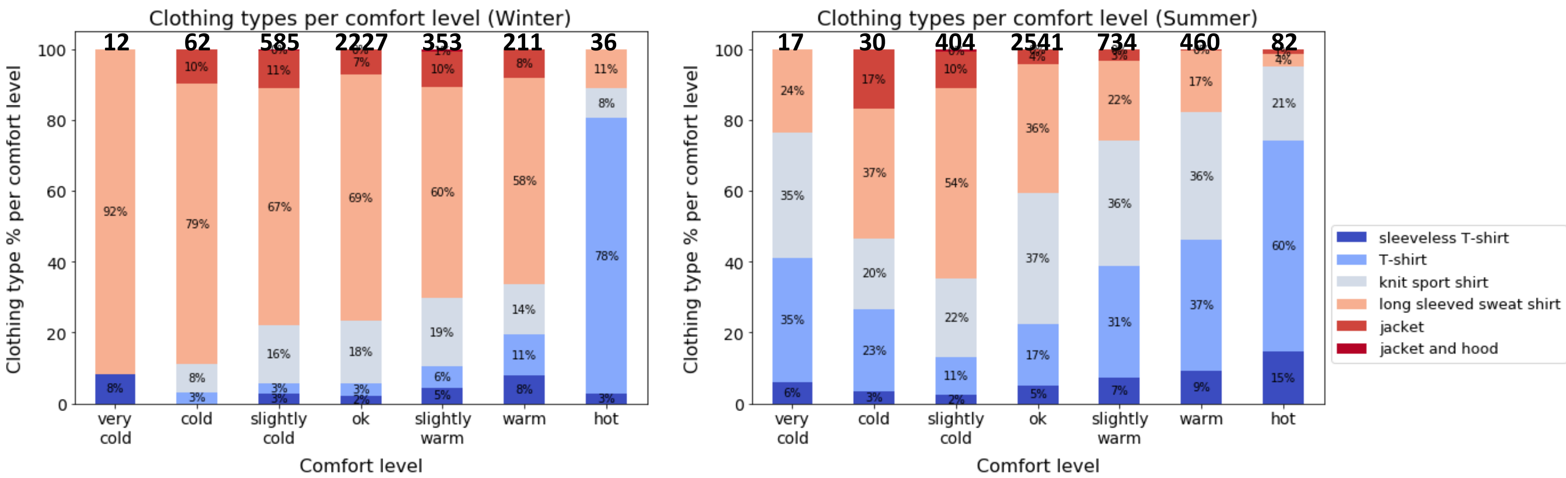


Figure 6.10: *Percentage of clothing type per comfort level in winter and summer with the actual number of data points shown above the bars. (Source: own)*

Figure 6.10 shows the clothing types worn by the tenants for each reported thermal sensation during winter and summer. The different types of clothing are represented with different colours from blue to red for lighter to heavier clothes accordingly.

The stacked graphs show that the most usual clothing type in winter is the long-sleeved sweatshirt, while in summer lighter clothes are worn as well. For winter, the clo value slightly drops with increasing thermal sensation, while for summer, the pattern is a bit different with the clo value to increase from very cold to slightly cold, while greatly decrease from ok till hot. Therefore, the clothing type is one of the tenants' adaptive behaviours in order to make themselves feel comfortable.

6.3.2 Statistical relation between thermal sensation and clothing

In order to carry out the chi-2 test for thermal sensation and clothing, apart from the merging in the thermal sensation categories, some of the clothing categories were merged as well and these were the "sleeveless T-shirt" with the "T-shirt" and the "jacket and hood" with the "jacket".

At this point the second hypothesis (H2), as shown in Table 6.7, will be tested with the chi-square test and furthermore, with a post-hoc test. The procedure for both tests was described in section 3.4.

Table 6.7: *2nd null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q2	**H2**	The thermal sensation is not related with the clothing type.	Thermal sensation	Clothing type	Chi-square test

This will help to find out if there is a relationship between thermal sensation and clothing. More explicitly:

- If there is no relationship between thermal sensation and clothing, then wearing a specific clothing type does not have any influence on the tenant’s reported thermal sensation.
- If the variables are related, then wearing a specific clothing type will help to predict tenant’s thermal sensation.

Regarding the Chi-2 test, all requirements are satisfied and by choosing a significance level of 0.05, it is concluded that:

- For winter, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.
- For summer, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.

Therefore, the null hypothesis “The thermal sensation is not related with the clothing type.” is rejected. Thereby showing that the thermal sensation is influenced by the type of clothing the person was wearing at the time of reporting the thermal sensation.

Tables 6.8 and 6.10 include also the adjusted residuals (post-hoc test), some of which are highlighted with yellow. Both Tables have 20 cells (4 x 5 tables) and thus, the significance alpha level (by applying the Bonferroni adjustment) equals to 0.05/20 = 0.0025, which results in a critical z-value of +/-3.02. All in all, the cells which have an absolute value higher than 3.02 have more or less observed counts than expected and are characterised as significant.

For winter, it seems that the “ok” and “warm” thermal sensations in combination with the “T-shirt” and “long-sleeved sweatshirt” clothing types create the significant difference leading to the null hypothesis rejection. For summer there are more significant cells with the four highly significant relationships appearing when feeling “warm” and wearing “T-shirt” or “long-sleeved sweatshirt”, when feeling “ok” and wearing “T-shirt” as well as when feeling “slightly cold” and wearing “long-sleeved sweatshirt”.

The tests are carried out for both winter and summer in SPSS and the results are shown in Tables 6.8-6.11.

Table 6.8: *Crosstabulation table for thermal sensation and clothing type including the expected counts and the adjusted residuals in winter with the highlighted cells to be the significant ones. (Created in SPSS)*

WINTER- Feel * Clothing Crosstabulation

Threshold value for the residual = 3.02

			Clothing				
			T-shirt	*Knit-sport shirt*	*Long-sleeved sweatshirt*	*Jacket*	**Total**
Feel	*Cold*	Count	3	5	60	6	74
		Expected Count	5.7	12.7	49.5	6.1	74.0
		Adjusted Residual	-1.2	-2.4	2.6	.0	
	Slightly cold	Count	34	96	390	65	585
		Expected Count	45.1	100.7	391.2	48.0	585.0
		Adjusted Residual	-1.9	-.6	-.1	2.8	
	Ok	Count	125	398	1543	161	2227
		Expected Count	171.8	383.3	1489.1	182.7	2227.0
		Adjusted Residual	-6.2	1.4	4.0	-2.8	
	Slightly warm	Count	37	68	211	37	353
		Expected Count	27.2	60.8	236.0	29.0	353.0
		Adjusted Residual	2.1	1.1	-3.0	1.6	
	Warm	Count	70	33	127	17	247
		Expected Count	19.1	42.5	165.2	20.3	247.0
		Adjusted Residual	12.6	-1.7	-5.4	-.8	
Total		Count	269	600	2331	286	3486
		Expected Count	269.0	600.0	2331.0	286.0	3486.0

Table 6.9: *Chi-square test results for thermal sensation and clothing type in winter. (Created in SPSS)*

WINTER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	191.947[a]	12	.000
Likelihood Ratio	139.196	12	.000
Linear-by-Linear Association	70.301	1	.000
N of Valid Cases	3486		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 5.71.

Table 6.10: *Crosstabulation table for thermal sensation and clothing type including the expected counts and the adjusted residuals in summer with the highlighted cells to be the significant ones. (Created in SPSS)*

SUMMER - Feel * Clothing Crosstabulation

			Clothing				
Threshold value for the residual = 3.02			*T-shirt*	*Knit-sport shirt*	*Long-sleeved sweatshirt*	*Jacket*	**Total**
Feel	*Cold*	Count	15	12	15	5	47
		Expected Count	13.1	16.4	15.5	2.0	47.0
		Adjusted Residual	.6	-1.4	-.2	2.2	
	Slightly cold	Count	53	89	218	44	404
		Expected Count	113.0	141.0	133.1	16.8	404.0
		Adjusted Residual	-7.0	-5.7	9.4	7.1	
	Ok	Count	568	945	925	103	2541
		Expected Count	710.9	887.1	837.1	106.0	2541.0
		Adjusted Residual	-9.9	3.8	5.8	-.5	
	Slightly warm	Count	284	262	165	23	734
		Expected Count	205.3	256.2	241.8	30.6	734.0
		Adjusted Residual	7.1	.5	-6.6	-1.5	
	Warm	Count	274	182	83	3	542
		Expected Count	151.6	189.2	178.6	22.6	542.0
		Adjusted Residual	12.5	-.7	-9.3	-4.5	
Total		Count	1194	1490	1406	178	4268
		Expected Count	1194.0	1490.0	1406.0	178.0	4268.0

Table 6.11: *Chi-square test results for thermal sensation and clothing type in summer. (Created in SPSS)*

SUMMER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	420.704[a]	12	.000
Likelihood Ratio	413.213	12	.000
Linear-by-Linear Association	339.709	1	.000
N of Valid Cases	4268		

a. 1 cells (5.0%) have expected count less than 5. The minimum expected count is 1.96.

6.4 Metabolic activity and reported thermal sensation

In this section, the part of the 2nd research question that refers to the relation between thermal sensations and metabolic activities is studied.

> 2. *What are the **reported thermal sensations** and how do thermal preferences, clothing types, **metabolic activities**, actions reported per dwelling relate to them?*

6.4.1 Metabolic activity and reported thermal sensation stacked bar graphs

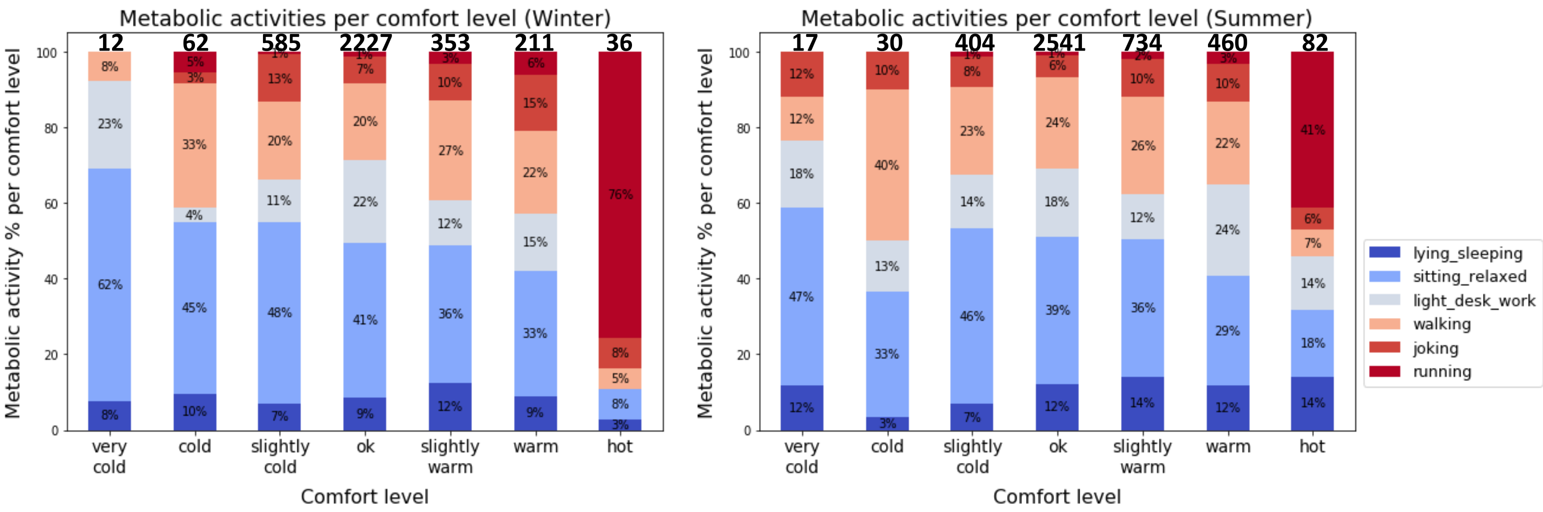


Figure 6.11: *Percentage of metabolic activity per comfort level in winter and summer with the actual number of data points shown above the bars. (Source: own)*

Figure 6.11 shows the metabolic activities done by the tenants for each reported thermal sensation during winter and summer. The different activities are represented with different colours moving from blue to red for higher metabolic activity.

The stacked graphs show that the most usual activity is sitting relaxed, followed by walking and light desk work both in winter and summer. In addition, it can be observed that there is a slight increase in the metabolic rate with increasing thermal sensation, better shown in winter. All in all, the relationship between metabolic activity and thermal sensation is not very clear.

6.4.2 Statistical relation between thermal sensation and metabolic activity

In this section, the third hypothesis (H3), as shown in Table 6.12, will be tested with the chi-square test and furthermore, with a post-hoc test. The procedure for both tests was described in section 3.4.

Table 6.12: *3rd null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q2	**H3**	The thermal sensation is not related with the metabolic activity.	Thermal sensation	Metabolic activity	Chi-square test

This will help to find out if there is a relationship between thermal sensation and metabolic activity. More explicitly:

- If there is no relationship between thermal sensation and metabolic activity, then reporting a specific metabolic activity does not have any influence on the tenant's reported thermal sensation.
- If the variables are related, then reporting a specific metabolic activity will help to predict tenant's thermal sensation.

Regarding the Chi-2 test, all requirements are satisfied and by choosing a significance level of 0.05, it is concluded that:

- For winter, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.
- For summer, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.

Therefore, the null hypothesis "The thermal sensation is not related with the metabolic activity." is rejected. Thereby showing that the thermal sensation is influenced by the type of metabolic activity the person was doing at the time of reporting the thermal sensation.

Tables 6.13 and 6.15 include also the adjusted residuals (post-hoc test), some of which are highlighted with yellow. Both Tables have 30 cells (6 x 5 tables) and thus, the significance alpha level (by applying the Bonferroni adjustment) equals to 0.05/30 = 0.00167, which results in a critical z-value of +/-3.14. All in all, the cells which have an absolute value higher than 3.14 have more or less observed counts than expected and are characterised as significant.

In winter there is a highly significant relationship between feeling "ok", "slightly warm" or "warm" and "walking" as well as between feeling "ok" or "warm" and doing "light desk work". In summer, there is a highly significant relationship between feeling "slightly cold" and doing "light desk work" or "joking" as well as between feeling "ok" and doing "light desk work" or "running".

The tests are carried out for both winter and summer in SPSS and the results are shown in Tables 6.13-6.16.

Table 6.13: *Crosstabulation table for thermal sensation and metabolic activity including the expected counts and the adjusted residuals in winter with the highlighted cells to be the significant ones. (Created in SPSS)*

WINTER- Feel * Activity Crosstabulation

			Activity						
Threshold value for the residual = 3.14			Lying sleeping	Sitting relaxed	Light desk work	Walking	Joking	Running	**Total**
Feel	*Cold*	Count	5	32	20	8	4	5	74
		Expected Count	6.1	29.7	13.1	15.4	7.9	1.8	74.0
		Adjusted Residual	-.5	.6	2.1	-2.1	-1.5	2.4	
	Slightly cold	Count	46	239	97	94	83	26	585
		Expected Count	48.3	234.6	103.7	121.5	62.6	14.3	585.0
		Adjusted Residual	-.4	.4	-.8	-3.1	3.0	3.4	
	Ok	Count	174	843	349	570	244	47	2227
		Expected Count	184.0	893.1	394.8	462.5	238.3	54.3	2227.0
		Adjusted Residual	-1.3	-3.6	-4.2	9.3	.7	-1.7	
	Slightly warm	Count	33	155	102	33	29	1	353
		Expected Count	29.2	141.6	62.6	73.3	37.8	8.6	353.0
		Adjusted Residual	.8	1.5	5.8	-5.6	-1.6	-2.8	
	Warm	Count	30	129	50	19	13	6	247
		Expected Count	20.4	99.1	43.8	51.3	26.4	6.0	247.0
		Adjusted Residual	2.3	4.0	1.1	-5.3	-2.9	.0	
Total		Count	288	1398	618	724	373	85	3486
		Expected Count	288.0	1398.0	618.0	724.0	373.0	85.0	3486.0

Table 6.14: *Chi-square test results for thermal sensation and metabolic activity in winter. (Created in SPSS)*

WINTER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	172.189[a]	20	.000
Likelihood Ratio	180.393	20	.000
Linear-by-Linear Association	36.086	1	.000
N of Valid Cases	3486		

a. 1 cells (3.3%) have expected count less than 5. The minimum expected count is 1.80.

Table 6.15: *Crosstabulation table for thermal sensation and metabolic activity including the expected counts and the adjusted residuals in summer with the highlighted cells to be the significant ones. (Created in SPSS)*

SUMMER- Feel * Activity Crosstabulation

Threshold value for the residual = 3.14			Activity						Total
			Lying sleeping	Sitting relaxed	Light desk work	Walking	Joking	Running	
Feel	Cold	Count	8	9	3	19	4	4	47
		Expected Count	5.5	18.3	7.9	11.4	2.9	1.0	47.0
		Adjusted Residual	1.1	-2.8	-1.9	2.6	.7	3.0	
	Slightly cold	Count	55	162	40	96	46	5	404
		Expected Count	47.4	157.7	67.8	97.9	24.5	8.7	404.0
		Adjusted Residual	1.2	.5	-3.9	-.2	4.7	-1.3	
	Ok	Count	288	981	464	581	155	72	2541
		Expected Count	298.3	991.9	426.3	615.6	154.2	54.8	2541.0
		Adjusted Residual	-1.0	-.7	3.1	-2.5	.1	3.7	
	Slightly warm	Count	82	313	120	181	30	8	734
		Expected Count	86.2	286.5	123.1	177.8	44.5	15.8	734.0
		Adjusted Residual	-.5	2.2	-.3	.3	-2.5	-2.2	
	Warm	Count	68	201	89	157	24	3	542
		Expected Count	63.6	211.6	90.9	131.3	32.9	11.7	542.0
		Adjusted Residual	.6	-1.0	-.2	2.8	-1.7	-2.7	
Total		Count	501	1666	716	1034	259	92	4268
		Expected Count	501.0	1666.0	716.0	1034.0	259.0	92.0	4268.0

Table 6.16: *Chi-square test results for thermal sensation and metabolic activity in summer. (Created in SPSS)*

SUMMER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	93.747[a]	20	.000
Likelihood Ratio	92.858	20	.000
Linear-by-Linear Association	5.338	1	.021
N of Valid Cases	4268		

a. 2 cells (6.7%) have expected count less than 5. The minimum expected count is 1.01.

6.5 Action during the last half hour and reported thermal sensation

In this section, the last part of the 2nd research question that refers to the relation between thermal sensations and metabolic activities is examined.

> 2. *What are **the reported thermal sensations** and how do thermal preferences, clothing types, metabolic activities, **actions** reported per dwelling relate to them?*

6.5.1 Actions and reported thermal sensation stacked bar graphs

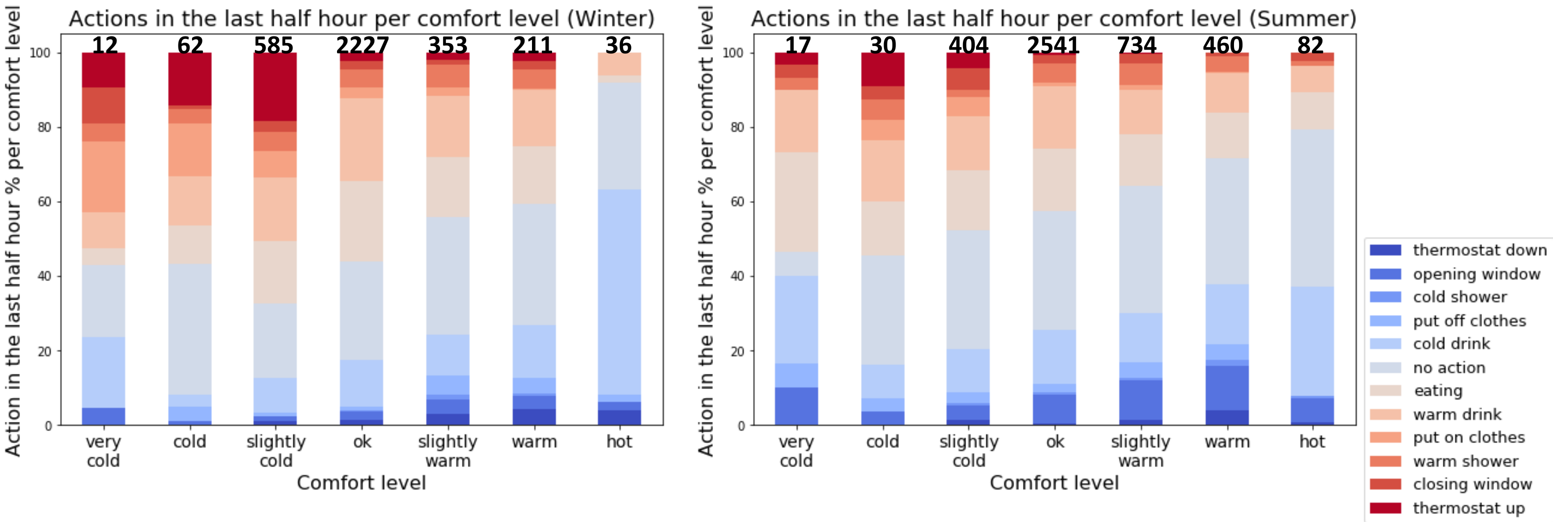


Figure 6.12: *Percentage of actions per comfort level in winter and summer with the actual number of data points shown above the bars. (Source: own)*

Figure 6.12 illustrates the actions taken during the last half hour by the tenants for each reported thermal sensation during winter and summer. The different actions are color-coded with the blue colour shading representing actions that make people feel cooler, while the orange-red colour shading representing actions that make them feel warmer. The gradient of the colours does not indicate any ordinal relation between the different actions since they are just nominal values. So, for example, it does not mean that turning the thermostat up makes people feel warmer than having a warm drink. Important to note that the "no action" is coloured with the lightest blue.

In general, it can be said that there is an increase in the blue-colour actions when moving from cold to hot, which reveals that people try to adapt in their thermal conditions. More specifically, there seems to be an adaptation by having a cold drink, putting clothes off and turning the thermostat down while feeling warmer as well as an adaptation by having a warm drink, putting clothes on and turning the thermostat up when feeling cooler. In addition, the "opening window" action as expected takes place much more during the summer period. The highest percentage in most bars is related to "no action".

6.5.2 Statistical relation between thermal sensation and actions

In this section, the fourth hypothesis (H4), as shown in Table 6.2, will be tested with the chi-square test and furthermore, with a post-hoc test. The procedure for both tests was described in section 3.4.

Table 6.17: *4th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q2	**H4**	The thermal sensation is not related with the action.	Thermal sensation	Action	Chi-square test

This will help to find out if there is a relationship between thermal sensation and metabolic activity. More explicitly:

- If there is no relationship between thermal sensation and action taken during the last half hour, then reporting a specific action does not have any influence on the tenant's reported thermal sensation.
- If the variables are related, then reporting a specific action will help to predict tenant's thermal sensation.

Regarding the Chi-2 test, all requirements are satisfied and by choosing a significance level of 0.05, it is concluded that:

- For winter, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.
- For summer, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.

Therefore, the null hypothesis "The thermal sensation is not related with the action." is rejected. Thereby showing that the thermal sensation is influenced by the action the person was doing half an hour before the time of reporting the thermal sensation.

Tables 6.18 and 6.20 include also the adjusted residuals (post-hoc test), some of which are highlighted with yellow. Both Tables have 60 cells (12 x 5 tables) and thus, the significance alpha level (by applying the Bonferroni adjustment) equals to 0.05/60 = 0.00083, which results in a critical z-value of +/-3.34. All in all, the cells which have an absolute value higher than 3.34 have more or less observed counts than expected and are characterised as significant. For both winter and summer, it was observed that moving from cold to warm, different actions showing some kind of adaptation seem to be significant.

The highest the adjusted residual, the more significant the difference and thus, these will be noted. In winter there is a highly significant relationship between feeling "slightly cold" or "ok" and "turning the thermostat up" as well as between feeling "ok" or "slightly warm" and "putting off clothes". In summer, there is a highly significant relationship between feeling "slightly cold" and "closing the window" or "putting on clothes" or "turning the thermostat up" as well as between feeling "ok" or "warm" and "turning the thermostat down".

The tests are carried out for both winter and summer in SPSS and the results are shown in Tables 6.18-6.21.

Table 6.18: *Crosstabulation table for thermal sensation and action including the expected counts and the adjusted residuals in winter with the highlighted cells to be the significant ones. (Created in SPSS)*

WINTER - Feel * Action Crosstabulation

Threshold value for the residual = 3.34			Action: closing window	cold drink	cold shower	eating	no action	opening window	put off clothes	put on clothes	thermostat down	thermostat up	warm drink	warm shower	Total
Feel	Cold	Count	3	7	0	14	45	2	6	19	0	18	18	6	138
		Expected Count	3.0	16.6	.5	26.2	36.8	3.0	2.9	5.0	2.4	8.0	26.2	7.5	138.0
		Adjusted Residual	.0	-2.5	-.7	-2.7	1.6	-.6	1.9	6.5	-1.6	3.7	-1.8	-.6	
	Slightly cold	Count	38	128	0	225	269	20	21	89	15	245	216	74	1340
		Expected Count	29.5	160.8	5.1	254.8	357.1	29.5	27.7	48.1	23.1	77.6	254.0	72.8	1340.0
		Adjusted Residual	1.8	-3.1	-2.5	-2.3	-6.1	-2.0	-1.4	6.7	-1.9	21.9	-3.0	.2	
	Ok	Count	88	502	12	841	1114	89	41	111	61	96	849	221	4025
		Expected Count	88.7	482.9	15.2	765.3	1072.6	88.7	83.2	144.6	69.2	233.2	762.8	218.7	4025.0
		Adjusted Residual	-.1	1.5	-1.3	4.9	2.4	.1	-7.5	-4.5	-1.6	-14.8	5.5	.3	
	Slightly warm	Count	7	69	11	109	196	22	51	17	20	15	105	42	664
		Expected Count	14.6	79.7	2.5	126.2	176.9	14.6	13.7	23.8	11.4	38.5	125.8	36.1	664.0
		Adjusted Residual	-2.1	-1.3	5.7	-1.8	1.8	2.1	10.7	-1.5	2.7	-4.1	-2.2	1.1	
	Warm	Count	10	89	2	71	142	13	18	2	18	10	68	17	460
		Expected Count	10.1	55.2	1.7	87.5	122.6	10.1	9.5	16.5	7.9	26.7	87.2	25.0	460.0
		Adjusted Residual	.0	5.0	.2	-2.0	2.1	.9	2.9	-3.8	3.7	-3.4	-2.4	-1.7	
Total			146	795	25	1260	1766	146	137	238	114	384	1256	360	6627
		Expected Count	146.0	795.0	25.0	1260.0	1766.0	146.0	137.0	238.0	114.0	384.0	1256.0	360.0	6627.0

Table 6.19: *Crosstabulation table for thermal sensation and action including the expected counts and the adjusted residuals in summer with the highlighted cells to be the significant ones. (Created in SPSS)*

SUMMER - Feel * Action Crosstabulation

Threshold value for the residual = 3.34			Action: closing window	cold drink	cold shower	eating	no action	opening window	put off clothes	put on clothes	thermostat down	thermostat up	warm drink	warm shower	Total
Feel	Cold	Count	3	12	0	16	18	5	4	3	0	6	14	4	85
		Expected Count	2.4	12.6	.9	13.7	27.1	6.9	2.5	1.3	.9	.8	11.8	4.0	85.0
		Adjusted Residual	.4	-.2	-.9	.7	-2.1	-.8	.9	1.5	-1.0	5.7	.7	.0	
	Slightly cold	Count	47	86	4	131	239	29	22	35	12	32	106	13	756
		Expected Count	21.6	111.7	7.7	121.8	240.6	61.4	22.6	11.7	8.1	7.5	105.3	36.0	756.0
		Adjusted Residual	5.8	-2.8	-1.4	1.0	-.1	-4.5	-.1	7.2	1.4	9.4	.1	-4.1	
	Ok	Count	130	739	51	834	1515	376	123	68	26	31	747	246	4886
		Expected Count	139.9	722.0	49.6	787.1	1555.2	396.9	145.8	75.3	52.6	48.4	680.8	232.5	4886.0
		Adjusted Residual	-1.3	1.1	.3	2.9	-1.9	-1.7	-3.0	-1.3	-5.8	-4.0	4.3	1.4	
	Slightly warm	Count	40	198	11	214	492	147	61	17	19	11	175	89	1474
		Expected Count	42.2	217.8	15.0	237.5	469.2	119.7	44.0	22.7	15.9	14.6	205.4	70.1	1474.0
		Adjusted Residual	-.4	-1.6	-1.1	-1.8	1.4	2.9	2.9	-1.3	.9	-1.0	-2.5	2.5	
	Warm	Count	14	173	17	122	338	107	34	3	31	1	97	37	974
		Expected Count	27.9	143.9	9.9	156.9	310.0	79.1	29.1	15.0	10.5	9.7	135.7	46.3	974.0
		Adjusted Residual	-2.8	2.8	2.4	-3.2	2.1	3.5	1.0	-3.3	6.8	-3.0	-3.8	-1.5	
Total			234	1208	83	1317	2602	664	244	126	88	81	1139	389	8175
		Expected Count	234.0	1208.0	83.0	1317.0	2602.0	664.0	244.0	126.0	88.0	81.0	1139.0	389.0	8175.0

Table 6.20: *Chi-square test results for thermal sensation and action in winter. (Created in SPSS)*

WINTER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	902.970[a]	44	.000
Likelihood Ratio	738.191	44	.000
N of Valid Cases	6627		

a. 8 cells (13.3%) have expected count less than 5. The minimum expected count is .52.

Table 6.21: *Chi-square test results for thermal sensation and action in summer. (Created in SPSS)*

SUMMER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	417.859[a]	44	.000
Likelihood Ratio	350.499	44	.000
N of Valid Cases	8175		

a. 7 cells (11.7%) have expected count less than 5. The minimum expected count is .84.

6.6 Energy labels and reported thermal sensation

It is essential to mention that from this point onwards, the analysis helps to answer the 3rd research question. More specifically here, the relation between thermal sensation and energy labels is studied.

> 3. *How does the **thermal sensation** and thermal preference vary between individuals and for different **energy labels** and ventilation system?*

6.6.1 Energy labels and reported thermal sensation stacked bar graphs

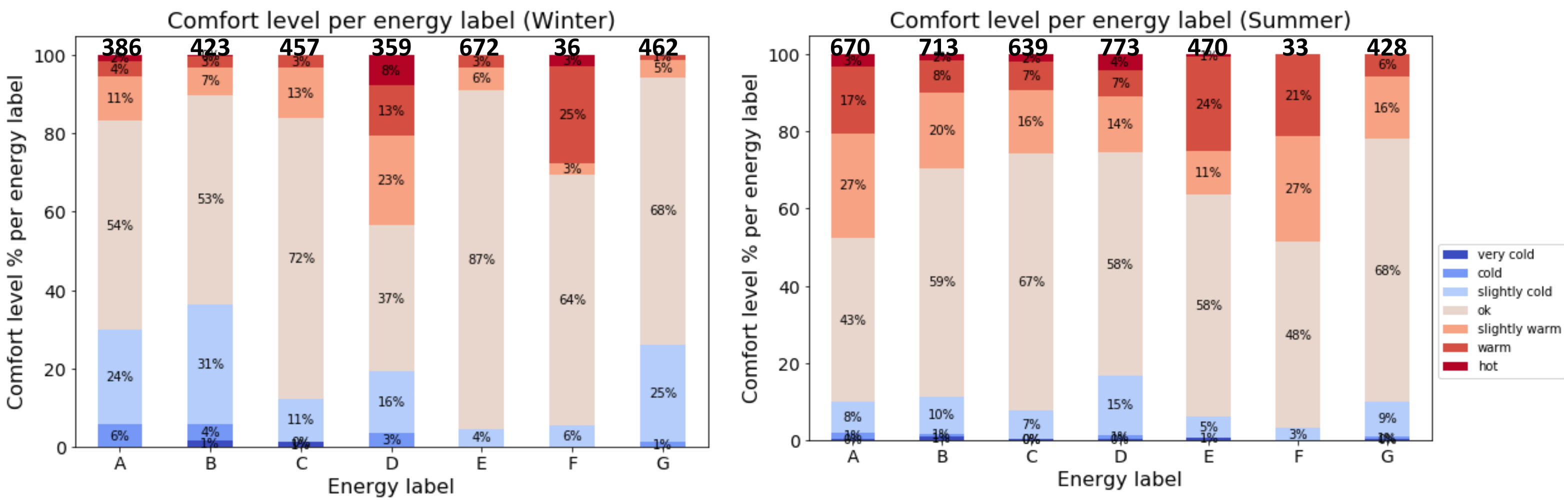


Figure 6.13: *Percentage of comfort level per energy label in winter and summer with the actual number of data points shown above the bars. (Source: own).*

Before starting with the analysis of the thermal sensation per energy label, it is vital to refer to the energy label role itself. As already mentioned in chapter 4, the dwellings' energy labels are dependent on the energy index calculation, which is based on the overall energy performance. The total energy efficiency is based on the building envelope construction as well as the various installation systems. For the building envelope construction, insulation thickness plays an extremely important role allowing more or less transmission heat losses or gains. However, insulation and total resistance of the envelope is hard to be inspected and therefore, the energy label can be used as a measure of the insulation quality of the building. So, for investigating the relation between insulation thickness and thermal sensation, energy label is used instead.

Figure 6.13 shows the reported thermal sensation (comfort level) per energy label of the dwellings in winter and summer. The different thermal sensations are color-coded with the blue colour shading for feeling cooler, the beige for feeling neutral and the red colour shading for feeling warmer.

In general, it can be observed that in winter in most energy labels, the highest percentage feels neutral, while feeling slightly cold is following in energy labels A and B. In energy labels

D and F, apart from feeling neutral, a lot of data points reported were about feeling slightly warm to hot. In summer, it seems that there is a slight decrease in the percentage of people feeling “slightly warm” to “hot” when going from the energy labels A to D. It is worth mentioning that from D to F, the percentage goes up again reaching the same percentage as in the energy label A.

6.6.2 Statistical relation between thermal sensation and energy labels

At this point the fifth hypothesis (H5), as shown in Table 6.22, will be tested with the chi-square test and furthermore, with a post-hoc test. The procedure for both tests was described in section 3.4.

Table 6.22: *5th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q3	**H5**	The thermal sensation is not related with the energy labels.	Thermal sensation	Energy label	Chi-square test

This will help to find out if there is a relationship between thermal sensation and energy label. More explicitly:

- If there is no relationship between thermal sensation and energy label, then reporting a specific energy label does not have any influence on the tenant’s reported thermal sensation.
- If the variables are associated, then reporting a specific energy label will help to predict tenant’s thermal sensation.

Regarding the Chi-2 test, all requirements are satisfied and by choosing a significance level of 0.05, it is concluded that:

- For winter, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.
- For summer, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.

Therefore, the null hypothesis “The thermal sensation is not related with the energy labels.” is rejected and it is concluded that the thermal sensation is associated with the energy labels.

Tables 6.23 and 6.25 include also the adjusted residuals (post-hoc test), some of which are highlighted with yellow. Both Tables have 35 cells (7 x 5 tables) and thus, the significance alpha level (by applying the Bonferroni adjustment) equals to 0.05/35 = 0.00142, which results in a critical z-value of +/-3.20. All in all, the cells which have an absolute value higher than 3.20 have more or less observed counts than expected and are characterised as significant.

In winter, there is a highly significant relationship between most of the thermal sensations and energy labels apart from A and F. In summer, there is a highly significant relationship mostly between thermal sensations ranging from “ok” to “warm” and almost all energy labels.

The tests are carried out for both winter and summer in SPSS and the results are shown in Tables 6.23-6.26.

Table 6.23: *Crosstabulation table for thermal sensation and energy labels including the expected counts and the adjusted residuals in winter with the highlighted cells to be the significant ones. (Created in SPSS)*

WINTER- Feel * Energy_label Crosstabulation

Threshold value for the residual = 3.20			Energy_label							
			A	*B*	*C*	*D*	*E*	*F*	*G*	**Total**
Feel	*Cold*	Count	30	54	14	19	0	0	15	132
		Expected Count	19.8	17.4	25.3	15.6	21.1	1.3	31.5	132.0
		Adjusted Residual	2.5	9.5	-2.5	.9	-5.1	-1.1	-3.4	
	Slightly cold	Count	179	264	111	114	32	3	336	1039
		Expected Count	155.9	137.2	198.8	123.2	166.0	9.9	248.0	1039.0
		Adjusted Residual	2.3	13.1	-7.8	-1.0	-12.8	-2.5	7.2	
	Ok	Count	413	278	687	229	607	26	752	2992
		Expected Count	449.0	395.2	572.5	354.6	478.1	28.4	714.1	2992.0
		Adjusted Residual	-2.9	-10.1	8.5	-11.3	10.2	-.7	2.6	
	Slightly warm	Count	86	43	110	113	118	1	61	532
		Expected Count	79.8	70.3	101.8	63.1	85.0	5.1	127.0	532.0
		Adjusted Residual	.8	-3.7	1.0	7.1	4.1	-1.9	-7.1	
	Warm	Count	34	14	24	111	33	17	16	249
		Expected Count	37.4	32.9	47.6	29.5	39.8	2.4	59.4	249.0
		Adjusted Residual	-.6	-3.6	-3.9	16.4	-1.2	9.8	-6.6	
Total		Count		653	946	586	790	47	1180	4944
		Expected Count		653.0	946.0	586.0	790.0	47.0	1180.0	4944.0

Table 6.24: *Chi-square test results for thermal sensation and energy label in winter. (Created in SPSS)*

WINTER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	1037.721[a]	24	.000
Likelihood Ratio	951.173	24	.000
N of Valid Cases	4944		

a. 2 cells (5.7%) have expected count less than 5. The minimum expected count is 1.25.

Table 6.25: *Crosstabulation table for thermal sensation and energy labels including the expected counts and the adjusted residuals in summer with the highlighted cells to be the significant ones. (Created in SPSS)*

SUMMER- Feel * Energy_label Crosstabulation

Threshold value for the residual = 3.20			Energy_label A	B	C	D	E	F	G	Total
Feel	Cold	Count	24	18	3	21	3	0	8	77
		Expected Count	14.2	12.6	17.7	15.4	5.5	.8	10.9	77.0
		Adjusted Residual	2.9	1.7	-4.0	1.6	-1.1	-.9	-.9	
	Slightly cold	Count	102	111	117	212	25	2	91	660
		Expected Count	121.3	107.8	151.8	132.1	46.8	7.1	93.1	660.0
		Adjusted Residual	-2.0	.4	-3.4	8.2	-3.5	-2.0	-.2	
	Ok	Count	531	683	1160	768	281	20	700	4143
		Expected Count	761.7	676.5	953.1	829.2	293.6	44.6	584.3	4143.0
		Adjusted Residual	-14.4	.4	11.9	-3.7	-1.2	-5.8	8.0	
	Slightly warm	Count	383	235	241	195	64	33	153	1304
		Expected Count	239.7	212.9	300.0	261.0	92.4	14.0	183.9	1304.0
		Adjusted Residual	11.3	1.8	-4.3	-5.1	-3.4	5.6	-2.7	
	Warm	Count	257	105	102	216	127	21	43	871
		Expected Count	160.1	142.2	200.4	174.3	61.7	9.4	122.8	871.0
		Adjusted Residual	9.1	-3.6	-8.5	3.8	9.2	4.1	-8.3	
Total		Count		1152	1623	1412	500	76	995	7055
		Expected Count		1152.0	1623.0	1412.0	500.0	76.0	995.0	7055.0

Table 6.26: *Chi-square test results for thermal sensation and energy label in summer. (Created in SPSS)*

SUMMER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	673.474[a]	24	.000
Likelihood Ratio	666.679	24	.000
N of Valid Cases	7055		

a. 1 cells (2.9%) have expected count less than 5. The minimum expected count is .83.[1]

[1] The expected cell value that is less than 1 can be interpreted as no difference between the specific thermal sensation and energy label (feeling cold and energy label F).

6.7 Energy labels and reported thermal preference

In this section, the part of the 3rd research question that refers to the relation between thermal preference and energy labels is examined.

> 3. *How does the thermal sensation and **thermal preference** vary between individuals and for different **energy labels** and ventilation system?*

6.7.1 Energy labels and reported thermal preference stacked bar graphs

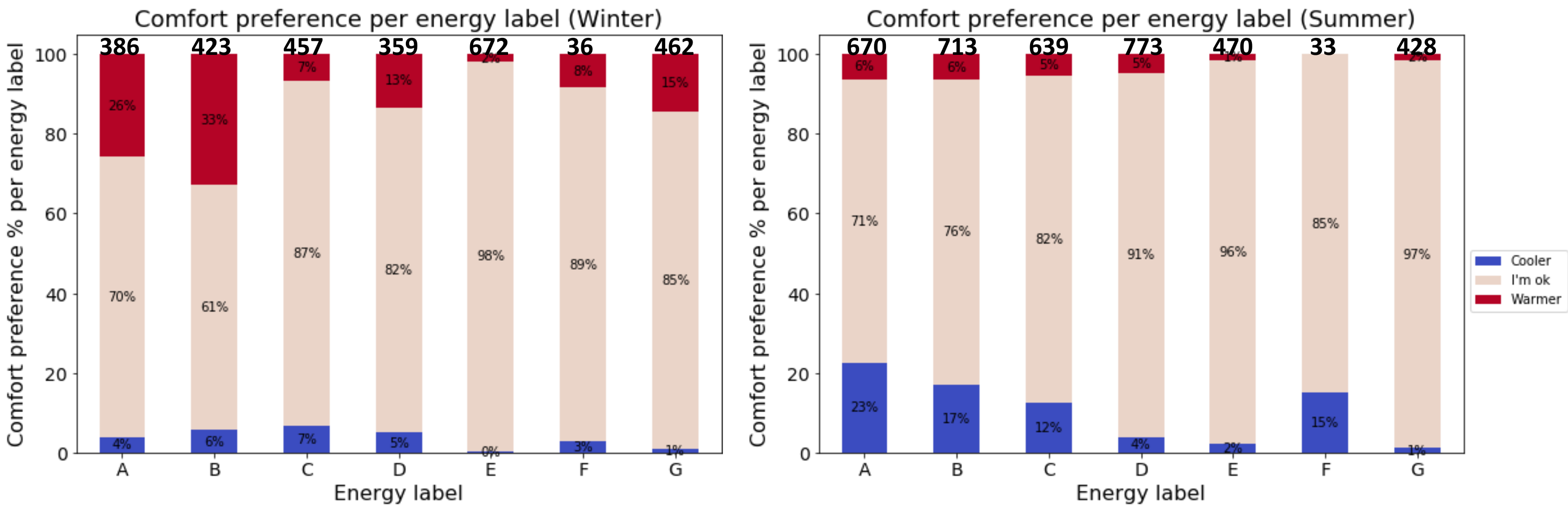


Figure 6.14: *Percentage of comfort preference per energy label in winter and summer with the actual number of data points shown above the bars. (Source: own)*

Figure 6.14 shows the reported thermal preference (comfort preference) per energy label of the dwellings in winter and summer. The thermal preference is color-coded with blue for feeling cooler, beige for no change and red for feeling warmer.

In winter it is worth mentioning that more respondents living in dwellings with higher energy labels preferred to feel warmer than in lower ones. Also, in summer more dwellings with higher energy rating preferred to feel cooler than in lower ones. This fact could be related with Ioannou conclusion that neutral temperatures were found to be higher in higher energy rating houses than in lower ones.

6.7.2 Statistical relation between thermal preference and energy labels

At this point the sixth hypothesis (H6), as shown in Table 6.27, will be tested with the chi-square test and furthermore, with a post-hoc test. The procedure for both tests was described in section 3.4.

Table 6.27: *6th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q3	**H6**	The thermal preference is not related with the energy labels.	Thermal preference	Energy label	Chi-square test

This will help to find out if there is a relationship between thermal preference and energy label. More explicitly:

- If there is no relationship between thermal preference and energy label, then reporting a specific energy label does not have any influence on the tenant's reported thermal preference.
- If the variables are associated, then reporting a specific energy label will help to predict tenant's thermal preference.

Regarding the Chi-2 test, all requirements are satisfied and by choosing a significance level of 0.05, it is concluded that:

- For winter, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.
- For summer, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.

Therefore, the null hypothesis "The thermal preference is not related with the energy labels." is rejected and it is concluded that the thermal preference is associated with the energy labels.

Tables 6.28 and 6.30 include also the adjusted residuals (post-hoc test), some of which are highlighted with yellow. Both Tables have 21 cells (7 x 3 tables) and thus, the significance alpha level (by applying the Bonferroni adjustment) equals to 0.05/21 = 0.00238, which results in a critical z-value of +/-3.05. All in all, the cells which have an absolute value higher than 3.05 have more or less observed counts than expected and are characterised as significant.

In winter, there is a highly significant relationship between feeling "ok" or preferring to feel "warmer" and the energy labels A, B, C and E as well as between preferring to feel "cooler" and the energy labels C, D, E and G. In summer, there is a highly significant relationship between feeling "ok" or preferring to feel "cooler" and the energy labels A, B, D, G and E as well as between preferring to feel "cooler" and the energy labels E and G.

The tests are carried out for both winter and summer in SPSS and the results are shown in Tables 6.28-6.31.

Table 6.28: *Crosstabulation table for thermal preference and energy labels including the expected counts and the adjusted residuals in with the highlighted cells to be the significant ones. (Created in SPSS)*

WINTER - Rather * Energy_label Crosstabulation

Threshold value for the residual = 3.05			Energy_label A	B	C	D	E	F	G	Total
Rather	*Cooler*	Count	26	31	67	37	2	4	9	176
		Expected Count	26.4	23.2	33.7	20.9	28.1	1.7	42.0	176.0
		Adjusted Residual	-.1	1.8	6.5	3.8	-5.5	1.8	-5.9	
	I'm ok	Count	543	331	821	455	770	38	949	3907
		Expected Count	586.4	516.0	747.6	463.1	624.3	37.1	932.5	3907.0
		Adjusted Residual	-4.2	-19.1	6.5	-.9	13.9	.3	1.4	
	Warmer	Count	173	291	58	94	18	5	222	861
		Expected Count	129.2	113.7	164.7	102.1	137.6	8.2	205.5	861.0
		Adjusted Residual	4.6	19.6	-10.2	-.9	-12.2	-1.2	1.5	
Total		Count	742	653	946	586	790	47	1180	4944
		Expected Count	742.0	653.0	946.0	586.0	790.0	47.0	1180.0	4944.0

Table 6.29: *Chi-square test results for thermal preference and energy label in winter. (Created in SPSS)*

WINTER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	680.209[a]	12	.000
Likelihood Ratio	706.128	12	.000
N of Valid Cases	4944		

a. 1 cells (4.8%) have expected count less than 5. The minimum expected count is 1.67.

Table 6.30: *Crosstabulation table for thermal preference and energy labels including the expected counts and the adjusted residuals in summer with the highlighted cells to be the significant ones. (Created in SPSS)*

SUMMER - Rather * Energy_label Crosstabulation

			Energy_label							
Threshold value for the residual = 3.05			*A*	*B*	*C*	*D*	*E*	*F*	*G*	**Total**
Rather	*Cooler*	Count	300	207	161	94	12	12	6	792
		Expected Count	145.6	129.3	182.2	158.5	56.1	8.5	111.7	792.0
		Adjusted Residual	15.0	7.9	-1.9	-6.1	-6.5	1.3	-11.5	
	I'm ok	Count	918	881	1372	1226	481	64	971	5913
		Expected Count	1087.1	965.5	1360.3	1183.4	419.1	63.7	833.9	5913.0
		Adjusted Residual	-14.1	-7.4	.9	3.4	7.8	.1	12.7	
	Warmer	Count	79	64	90	92	7	0	18	350
		Expected Count	64.3	57.2	80.5	70.0	24.8	3.8	49.4	350.0
		Adjusted Residual	2.1	1.0	1.2	3.0	-3.8	-2.0	-4.9	
Total			1297	1152	1623	1412	500	76	995	7055
		Expected Count	1297.0	1152.0	1623.0	1412.0	500.0	76.0	995.0	7055.0

Table 6.31: *Chi-square test results for thermal preference and energy label in summer. (Created in SPSS)*

SUMMER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	490.862[a]	12	.000
Likelihood Ratio	556.695	12	.000
N of Valid Cases	7055		

a. 1 cells (4.8%) have expected count less than 5. The minimum expected count is 3.77.

6.8 Ventilation system and reported thermal sensation

In this section, the part of the 3rd research question that refers to the relation between thermal sensation and ventilation system is examined.

> 3. *How does the **thermal sensation** and thermal preference vary between individuals and for different energy labels and **ventilation system**?*

6.8.1 Ventilation system and reported thermal sensation stacked bar graphs

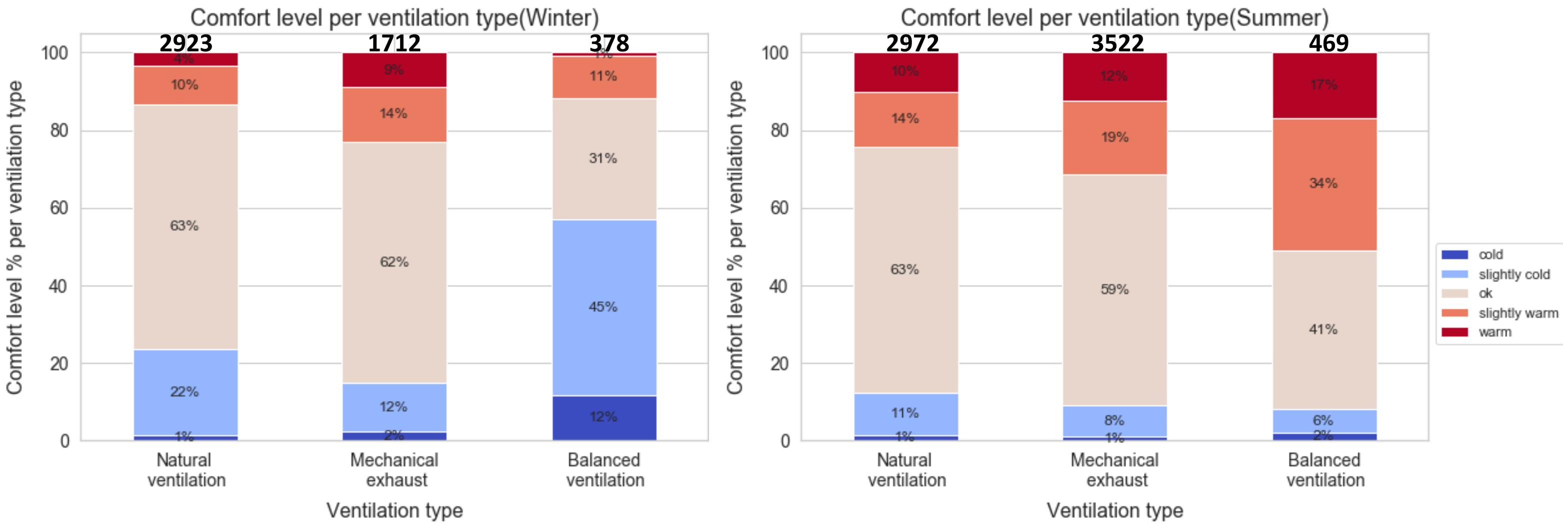


Figure 6.15: *Percentage of comfort level per ventilation type in winter and summer with the actual number of data points shown above the bars. (Source: own)*

Figure 6.15 shows the reported thermal sensation (comfort level) per ventilation type of the dwellings in winter and summer. The different thermal sensations are color-coded with the blue colour shading for feeling cooler, the beige for feeling neutral and the red colour shading for feeling warmer.

In general, it can be observed that in winter the highest percentage feels “neutral” when having natural ventilation or mechanical exhaust, while in the balanced ventilation cases almost half of the data points reported feeling “slightly cold” or “cold”. On the other hand, in summer it seems that there is a slight increase in the percentage of people feeling “warmer” going from the natural ventilation to the mechanical exhaust and then, the balanced ventilation. All in all, the largest deviations appear to be in the cases with the balanced ventilation, where also not that many data points are available.

6.8.2 Statistical relation between thermal sensation and ventilation type

At this point the seventh hypothesis (H7), as shown in Table 6.32, will be tested with the chi-square test and furthermore, with a post-hoc test. The procedure for both tests was described in section 3.4.

Table 6.32: *7th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q3	**H7**	The thermal sensation is not related with the type of ventilation.	Thermal preference	Ventilation type	Chi-square test

This will help to find out if there is a relationship between thermal sensation and energy label. More explicitly:

- If there is no relationship between thermal sensation and ventilation type, then reporting a specific ventilation type does not have any influence on the tenant's reported thermal sensation.
- If the variables are related, then reporting a specific ventilation type will help to predict tenant's thermal sensation.

Regarding the Chi-2 test, all requirements are satisfied and by choosing a significance level of 0.05, it is concluded that:

- For winter, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.
- For summer, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.

Therefore, the null hypothesis "The thermal sensation is not related with the type of ventilation." is rejected and it is concluded that the thermal sensation is influenced by the ventilation type.

Tables 6.33 and 6.35 include also the adjusted residuals (post-hoc test), some of which are highlighted with yellow. Both Tables have 15 cells (3 x 5 tables) and thus, the significance alpha level (by applying the Bonferroni adjustment) equals to 0.05/15 = 0.00333, which results in a critical z-value of +/-2.95. All in all, the cells which have an absolute value higher than 2.95 have more or less observed counts than expected and are characterised as significant.

In winter, it seems that there is a highly significant relationship between almost all thermal sensations and ventilation types. In summer, there is a highly significant relationship especially between feeling "ok", "slightly warm", "warm" and balanced or natural ventilation.

The tests are carried out for both winter and summer in SPSS and the results are shown in Tables 6.33-6.36.

Table 6.33: *Crosstabulation table for thermal sensation and ventilation types including the expected counts and the adjusted residuals in winter with the highlighted cells to be the significant ones. (Created in SPSS)*

WINTER - Feel * Ventilation_type Crosstabulation

Threshold value for the residual = 2.95			Ventilation_type			Total
			Balanced	*Mechanical*	*Natural*	
Feel	*Cold*	Count	44	38	41	123
		Expected Count	9.3	42.0	71.7	123.0
		Adjusted Residual	12.0	-.8	-5.7	
	Slightly cold	Count	171	214	649	1034
		Expected Count	78.0	353.1	602.9	1034.0
		Adjusted Residual	12.3	-10.2	3.3	
	Ok	Count	119	1066	1846	3031
		Expected Count	228.5	1035.1	1767.3	3031.0
		Adjusted Residual	-12.0	1.9	4.6	
	Slightly warm	Count	41	241	283	565
		Expected Count	42.6	193.0	329.4	565.0
		Adjusted Residual	-.3	4.5	-4.2	
	Warm	Count	3	153	104	260
		Expected Count	19.6	88.8	151.6	260.0
		Adjusted Residual	-4.0	8.6	-6.1	
Total			378	1712	2923	5013
		Expected Count	378.0	1712.0	2923.0	5013.0

Table 6.34: *Chi-square test results for thermal sensation and ventilation type in winter. (Created in SPSS)*

WINTER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	463.841[a]	8	.000
Likelihood Ratio	396.398	8	.000
N of Valid Cases	5013		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 9.27.

Table 6.35: *Crosstabulation table for thermal sensation and ventilation types including the expected counts and the adjusted residuals in summer with the highlighted cells to be the significant ones. (Created in SPSS)*

SUMMER - Feel * Ventilation_type Crosstabulation

Threshold value for the residual = 2.95			Ventilation_type: Balanced	Mechanical	Natural	Total
Feel	Cold	Count	9	31	37	77
		Expected Count	5.2	38.9	32.9	77.0
		Adjusted Residual	1.7	-1.8	1.0	
	Slightly cold	Count	29	292	329	650
		Expected Count	43.8	328.8	277.4	650.0
		Adjusted Residual	-2.4	-3.0	4.3	
	Ok	Count	192	2092	1882	4166
		Expected Count	280.6	2107.2	1778.2	4166.0
		Adjusted Residual	-8.6	-.7	5.1	
	Slightly warm	Count	159	668	426	1253
		Expected Count	84.4	633.8	534.8	1253.0
		Adjusted Residual	9.3	2.1	-6.9	
	Warm	Count	80	439	298	817
		Expected Count	55.0	413.3	348.7	817.0
		Adjusted Residual	3.7	1.9	-3.8	
Total			469	3522	2972	6963
		Expected Count	469.0	3522.0	2972.0	6963.0

Table 6.36: *Chi-square test results for thermal sensation and ventilation type in summer. (Created in SPSS)*

SUMMER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	168.029[a]	8	.000
Likelihood Ratio	158.181	8	.000
N of Valid Cases	6963		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 5.19.

6.9 Ventilation system and reported thermal preference

In this section, the part of the 3rd research question that refers to the relation between thermal preference and ventilation system is analysed.

> 3. *How does the thermal sensation and **thermal preference** vary between individuals and for different energy labels and **ventilation system**?*

6.9.1 Ventilation system and reported thermal preference stacked bar graphs

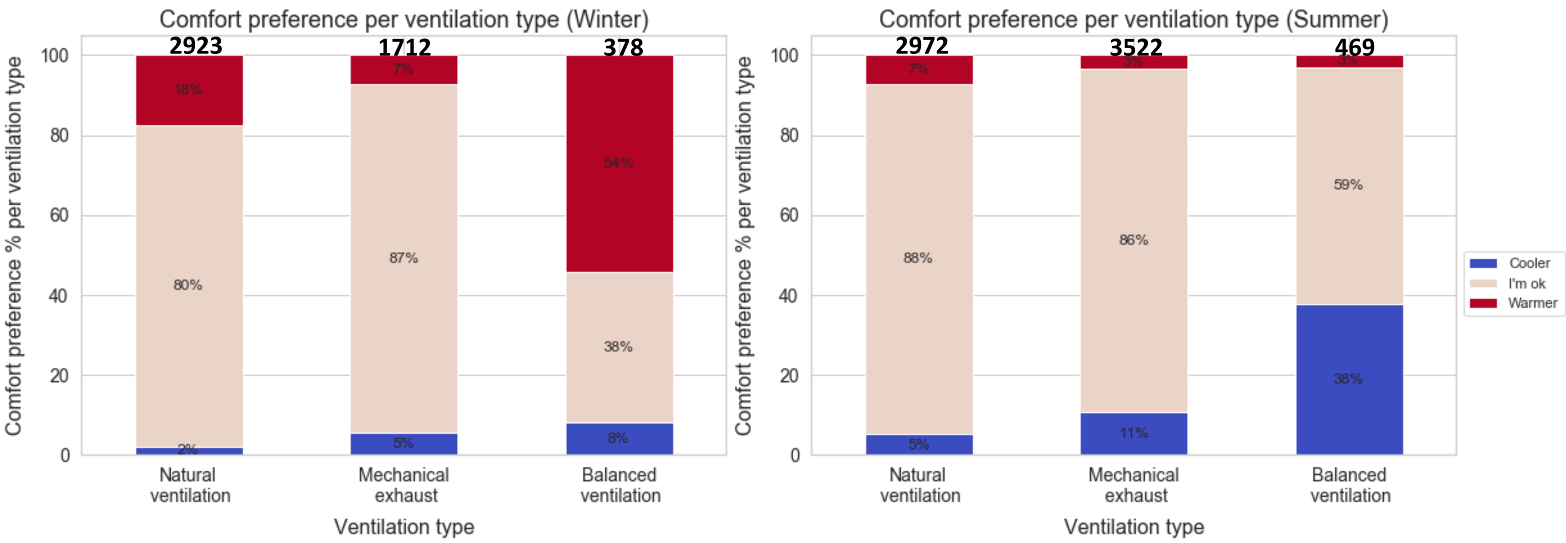


Figure 6.16: *Percentage of comfort level per ventilation type in winter and summer with the actual number of data points shown above the bars. (Source: own)*

Figure 6.16 shows the reported thermal preference (comfort preference) per ventilation type of the dwellings in winter and summer. The thermal preference is color-coded with blue for feeling cooler, beige for no change and red for feeling warmer.

In general, it can be observed that in winter the highest percentage feels "ok" when having natural ventilation or mechanical exhaust, while in the balanced ventilation cases almost half of the data points reported preferring to feel warmer. On the other hand, in summer it seems that there is a slight increase in the percentage of people preferring to feel "cooler" going from the natural ventilation to the mechanical exhaust and the balanced ventilation. The large percentages of people with balanced ventilation preferring to feel warmer in winter and cooler in summer can be explained by the fact that they reported feeling "slightly cold" to "cold" and "slightly warm" to "warm" in winter and summer correspondingly (see Figure 5.11).

6.9.2 Statistical relation between thermal preference and ventilation type

At this point the eighth hypothesis (H8), as shown in Table 6.37, will be tested with the chi-square test and furthermore, with a post-hoc test. The procedure for both tests was described in section 3.4.

Table 6.37: *8th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q3	**H8**	The thermal preference is not related with the type of ventilation.	Thermal preference	Ventilation type	Chi-square test

This will help to find out if there is a relationship between thermal preference and ventilation type. More explicitly:

- If there is no relationship between thermal preference and ventilation type, then reporting a specific ventilation type does not have any influence on the tenant's reported thermal preference.
- If the variables are related, then reporting a specific ventilation type will help to predict tenant's thermal preference.

Regarding the Chi-2 test, all requirements are satisfied and by choosing a significance level of 0.05, it is concluded that:

- For winter, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.
- For summer, the p-value = 0.0 < 0.05 and thus, the null hypothesis is rejected.

Therefore, the null hypothesis "The thermal preference is not related with the type of ventilation." is rejected and it is concluded that the thermal preference is influenced by the ventilation type.

Tables 6.38 and 6.40 include also the adjusted residuals (post-hoc test), some of which are highlighted with yellow. Both Tables have 9 cells (3 x 3 tables) and thus, the significance alpha level (by applying the Bonferroni adjustment) equals to 0.05/9 = 0.0055, which results in a critical z-value of +/-2.77. All in all, the cells which have an absolute value higher than 2.77 have more or less observed counts than expected and are characterised as significant.

In winter, there is a highly significant relationship between feeling "ok" or preferring to feel "warmer" and all different types of ventilation as well as between preferring to feel "cooler" and the natural ventilation type. In summer, a highly significant relationship can be observed for being "ok" or preferring to feel "cooler" and especially with balanced or natural ventilation.

The tests are carried out for both winter and summer in SPSS and the results are shown in Tables 6.38-6.41.

Table 6.38: *Crosstabulation table for thermal preference and ventilation types including the expected counts and the adjusted residuals in winter with the highlighted cells to be the significant ones. (Created in SPSS)*

WINTER - Rather * Ventilation_type Crosstabulation

Threshold value for the residual = 2.77			Ventilation_type			Total
			Balanced	*Mechanical*	*Natural*	
Rather	*Cooler*	Count	30	93	57	180
		Expected Count	13.6	61.5	105.0	180.0
		Adjusted Residual	4.7	5.0	-7.4	
	I'm ok	Count	143	1495	2352	3990
		Expected Count	300.9	1362.6	2326.5	3990.0
		Adjusted Residual	-21.0	9.8	1.8	
	Warmer	Count	205	124	514	843
		Expected Count	63.6	287.9	491.5	843.0
		Adjusted Residual	20.2	-13.1	1.7	
Total		Count	378	1712	2923	5013
		Expected Count	378.0	1712.0	2923.0	5013.0

Table 6.39: *Chi-square test results for thermal preference and ventilation type in winter. (Created in SPSS)*

WINTER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	562.955[a]	4	.000
Likelihood Ratio	487.857	4	.000
N of Valid Cases	5013		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 13.57.

Table 6.40: *Crosstabulation table for thermal preference and ventilation types including the expected counts and the adjusted residuals in summer with the highlighted cells to be the significant ones. (Created in SPSS)*

SUMMER - Rather * Ventilation_type Crosstabulation

Threshold value for the residual = 2.77			Ventilation_type *Balanced*	*Mechanical*	*Natural*	**Total**
Rather	*Cooler*	Count	176	377	149	702
		Expected Count	47.3	355.1	299.6	702.0
		Adjusted Residual	20.4	1.7	-12.1	
	I'm ok	Count	279	3022	2608	5909
		Expected Count	398.0	2988.9	2522.1	5909.0
		Adjusted Residual	-15.9	2.2	5.8	
	Warmer	Count	14	123	215	352
		Expected Count	23.7	178.0	150.2	352.0
		Adjusted Residual	-2.1	-6.0	7.2	
Total			469	3522	2972	6963
		Expected Count	469.0	3522.0	2972.0	6963.0

Table 6.41: *Chi-square test results for thermal preference and ventilation type in summer. (Created in SPSS)*

SUMMER - Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	515.251[a]	4	.000
Likelihood Ratio	391.015	4	.000
N of Valid Cases	6963		

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 23.71.

6.10 Age and reported thermal sensation

In this section, the part of the 3rd research question that refers to the relation between thermal sensation and age is analysed.

3. *How does the **thermal sensation** and thermal preference vary between **individuals** and for different energy labels and ventilation system?*

6.10.1 Age and reported thermal sensation scatter plots

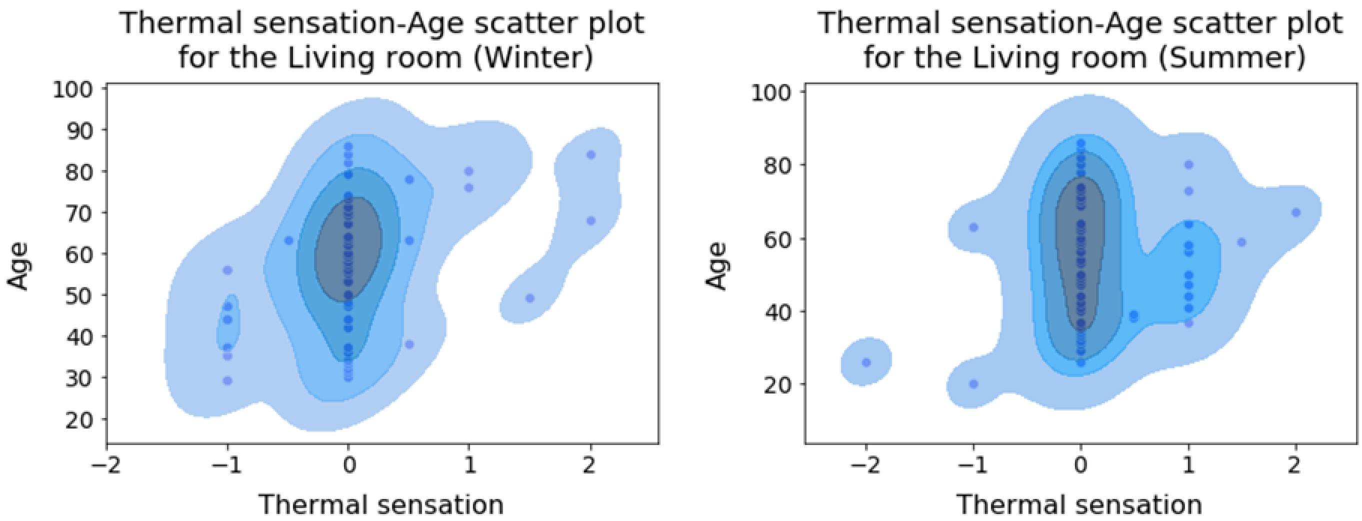


Figure 6.17: *Scatter plots of thermal sensation and age for the living room in winter and summer. (Source: own)*

It is still doubtful if the thermal sensation is influenced by the age of people. To create the scatter plots in Figure 6.17, the median reported thermal sensation per person was calculated for all dwellings, reaching up to 66 people with available data. Therefore, each point represents the thermal sensation per person's age. The kernel density estimate (KDE) contour plot was also used in order to show the distribution of the observations. Both the larger width and the darker shading areas imply higher density. By observing the scatterplots, no significant difference between different ages is visible. Both in winter and summer, most observations are 0 with some exceptions being from -1 to 2. However, only in winter a very slight increase of the thermal sensation along with the age can be observed.

6.10.2 Statistical relation between thermal sensation and age

In this section, the ninth hypothesis (H9), as shown in Table 6.42, will be tested by creating a predictive model through ordinal logistic regression, as this was described in section 3.4.

Table 6.42: *9th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q3	**H9**	The thermal sensation is not related with the age.	Thermal sensation	Age	Ordinal logistic regression

This will help to find out if there is a relationship between thermal sensation and age. In other words, if the independent variable is known (age), then the dependent variable (thermal sensation) can be predicted by the model.

The assumptions of the ordinal logistic regression are satisfied. The results shown in Table 6.43 indicate that age is a significant variable for predicting thermal sensation, since 0.002 < 0.05 (chosen significance level). The "Estimate" column represents the coefficients. Thus, the coefficients indicate that as the independent variable (age) increases, there is an increased probability of the dependent variable (thermal sensation) to be increased as well. In other words, for a one unit increase on age, there is a predicted increase of 0.067 in the log odds of a person reporting higher thermal sensation. So, for a one unit increase in age, the odds of feeling "warm" versus the combination of all other thermal sensation categories are 1.07 greater. Likewise, the odds of the combination of all other thermal sensation categories versus feeling "slightly cold" are 1.07 greater. All in all, the above indicate that a person of higher age is more likely to report higher thermal sensation. Therefore, the null hypothesis "The thermal sensation is not related with the age." is rejected for winter and thermal sensation is associated with age.

For summer, the results showed that age is not a significant predictor of thermal sensation and for that reason they are not presented. Thus, the null hypothesis is accepted, and thermal sensation is not associated with age.

Table 6.43: *Ordinal logistic regression results for thermal sensation (dependent) and age (independent) in winter. (Created in SPSS)*

Parameter Estimates

Link function: Logit.		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Threshold	[feel = -1.00]	1.410	1.108	1.621	1	.203	-.761	3.581
	[feel = -.50]	1.576	1.105	2.033	1	.154	-.591	3.743
	[feel = .00]	6.069	1.469	17.060	1	.000	3.189	8.949
	[feel = .50]	6.578	1.503	19.157	1	.000	3.632	9.523
	[feel = 1.00]	7.368	1.573	21.953	1	.000	4.286	10.450
	[feel = 1.50]	7.801	1.630	22.917	1	.000	4.607	10.995
Location	age	.067	.021	9.902	1	.002	.025	.109

6.11 Age and reported thermal preference

In this section, the last part of the 3rd research question that refers to the relation between thermal preference and age is analysed.

3. *How does the thermal sensation and **thermal preference** vary between **individuals** and for different energy labels and ventilation system?*

6.11.1 Age and reported thermal preference scatter plots

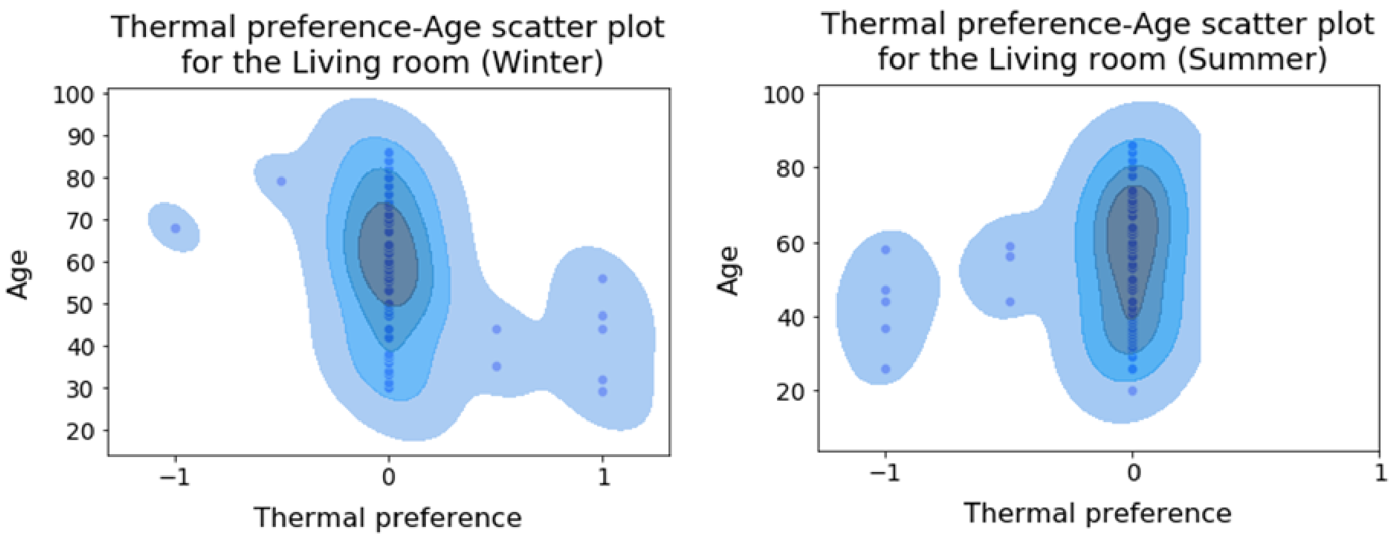


Figure 6.18: *Scatter plots of thermal preference and age for the living room in winter and summer with each point representing one person. (Source: own)*

To create the scatter plots in Figure 6.18, again the median reported thermal preference per person was calculated for all dwellings. Therefore, each point represents the thermal preference per person's age. The scatter plots show that almost all people did not want any change, while only a few up until the age of 60 would prefer to feel warmer in winter and cooler in summer.

6.11.2 Statistical relation between thermal preference and age

In this section, the tenth hypothesis (H10), as shown in Table 6.44, will be tested by creating a predictive model through ordinal logistic regression, as this was described in section 3.4.

Table 6.44: *10th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q3	**H10**	The thermal preference is not related with the age.	Thermal preference	Age	Ordinal logistic regression

This will help to find out if there is a relationship between thermal preference and age. In other words, if the independent variable is known (age), then the dependent variable (thermal preference) can be predicted by the model.

In this case, no ordinal logistic regression took place, since it would not make any sense due to the reported data of thermal preference per age. Therefore, the null hypothesis “The thermal preference is not related with the age.” is accepted and no significant relationship can be concluded between thermal preference and age.

6.12 Conclusions

In this chapter, the 2nd and 3rd research questions, as shown below, were explored.

> *2. What are the reported thermal sensations and how do thermal preferences, clothing types, metabolic activities, actions reported per dwelling relate to them?*
> *3. How does the thermal sensation and thermal preference vary between individuals and for different energy labels and ventilation system?*

Table 6.45 shows all null hypotheses that were tested in this chapter and which of them were rejected or accepted as well.

Table 6.45: *First ten hypotheses rejected or accepted. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Winter	Summer
Q2	H1	The thermal sensation is not related with the thermal preference.	Rejected	Rejected
	H2	The thermal sensation is not related with the clothing type.	Rejected	Rejected
	H3	The thermal sensation is not related with the metabolic activity.	Rejected	Rejected
	H4	The thermal sensation is not related with the actions.	Rejected	Rejected
Q3	H5	The thermal sensation is not related with the energy labels.	Rejected	Rejected
	H6	The thermal preference is not related with the energy labels.	Rejected	Rejected
	H7	The thermal sensation is not related with the type of ventilation.	Rejected	Rejected
	H8	The thermal preference is not related with the type of ventilation.	Rejected	Rejected
	H9	The thermal sensation is not related with the age.	Rejected	Accepted
	H10	The thermal preference is not related with the age.	Accepted	Accepted

Regarding the 2nd research question, it was concluded that thermal sensation is closely related with the thermal preference and influenced by all thermal comfort related parameters, such as clothing, metabolic activities and actions.

In more than half of the data points, the thermal sensation reported was “ok”, while some reported “slightly cold”, “slightly warm” and “warm”. When comparing thermal sensation with thermal preference, a relation between the two was found. The thermal comfort graphs show better that in winter the highest percentage of people (about 80%) is dissatisfied when feeling “slightly cold” or “cold”, while much lower percentage (about 20%) is dissatisfied when feeling “slightly warm” or “warm”. Moreover, in summer it can be concluded that the percentage of dissatisfied people is on average 40% for thermal sensations different than “ok”.

Regarding the clothing type, it was proven to be one of the tenants’ adaptive behaviours in order to make themselves feel comfortable. This means that when people do not feel comfortable, they put clothes on or off in order to feel warmer or cooler accordingly and thus, more comfortable in their thermal environment.

Furthermore, it was concluded that the metabolic activities affect the occupants' thermal sensation. The higher the metabolic rate of the activity, the warmer they feel and vice versa.

Last but not least, actions taken during the last half hour were found to influence the thermal sensation and some of them can be considered more like an adaptation type towards comfort. More specifically, having a cold drink, putting clothes off and turning the thermostat down are among the adaptive actions for feeling cooler, while having a warm drink, putting clothes on and turning the thermostat up accordingly for feeling warmer.

To conclude, taking all the above conclusions into account, the adaptive model seems to be more suitable and closer to the reality since it calculates the comfort temperatures taking into account all possible adaptations made by the occupants.

Regarding the 3rd research question, it was concluded that thermal sensation and preference are associated with the energy labels and the ventilation type. Between age and thermal sensation/preference a slight association was found only in winter.

The analysis showed that the energy labels play a significant role in the occupants' thermal sensation and preference. More complaints about feeling "slightly cold" and "slightly warm" and preferring to feel warmer and cooler in winter and summer correspondingly were observed in the higher energy labels of A and B. In general, higher energy label dwellings are supposed to offer better indoor thermal conditions and comfort to the occupants. However, for winter, the result could be explained by the fact that people in higher energy label dwellings have higher expectations than people in lower ones regarding their thermal comfort. On the other hand, for summer, it makes sense that higher percentage reported feeling warmer in higher energy label dwellings, because even though their dwellings are better insulated and airtight and block the heat from entering, possible solar gains are also hard to get through.

Regarding the ventilation type of the dwellings, the results indicated that the thermal sensation and preference are influenced by it. About 6 of the studied dwellings were equipped with balanced ventilation and had energy labels A, B and C. It is worth mentioning that half of the reported data points with balanced ventilation were about feeling "slightly cold" or "cold" in winter and "slightly warm" or "warm" in summer, while preferred to feel warmer and cooler accordingly. In general, it is known that balanced ventilation systems reduce drafts and heat losses and offer an improved indoor environment. Thus, the observation made for the balanced ventilation might have to do again with the higher expectations or perception of comfort when living in a high energy label dwelling with balanced ventilation. Another reason could be the low number of dwellings and as a result, data points reported in this sample. All in all, comparing naturally and mechanically ventilated dwellings, it can be concluded that regarding thermal preference the first lead to more complaints than the latter in winter, while the opposite happens in summer.

Although some previous research has shown a relation between thermal comfort and age, in the current research with a sample of 66 people, no significant relationship was found.

7 Comfort perception and Indoor Climate Parameters

In this chapter the relationship between the indoor air temperature and the real time comfort perception data as well as the energy labels and the ventilation types will be explored. The analysis will help to answer the fourth research question:

> 4. *What is the relation between indoor air temperature and comfort perception, energy label and ventilation system?*

It is important to mention here that this question explores the relation among real time data variables (indoor air temperature and comfort perception) as well as the relation between real time data variables (indoor air temperature) and constant parameters such as energy label and ventilation type which do not vary with time.

How all the above-mentioned parameters influence each other is shown in the conceptual diagram (Figure 7.1), where the energy labels and the ventilation system influence the indoor air temperature and then, the temperature affects the thermal sensation.

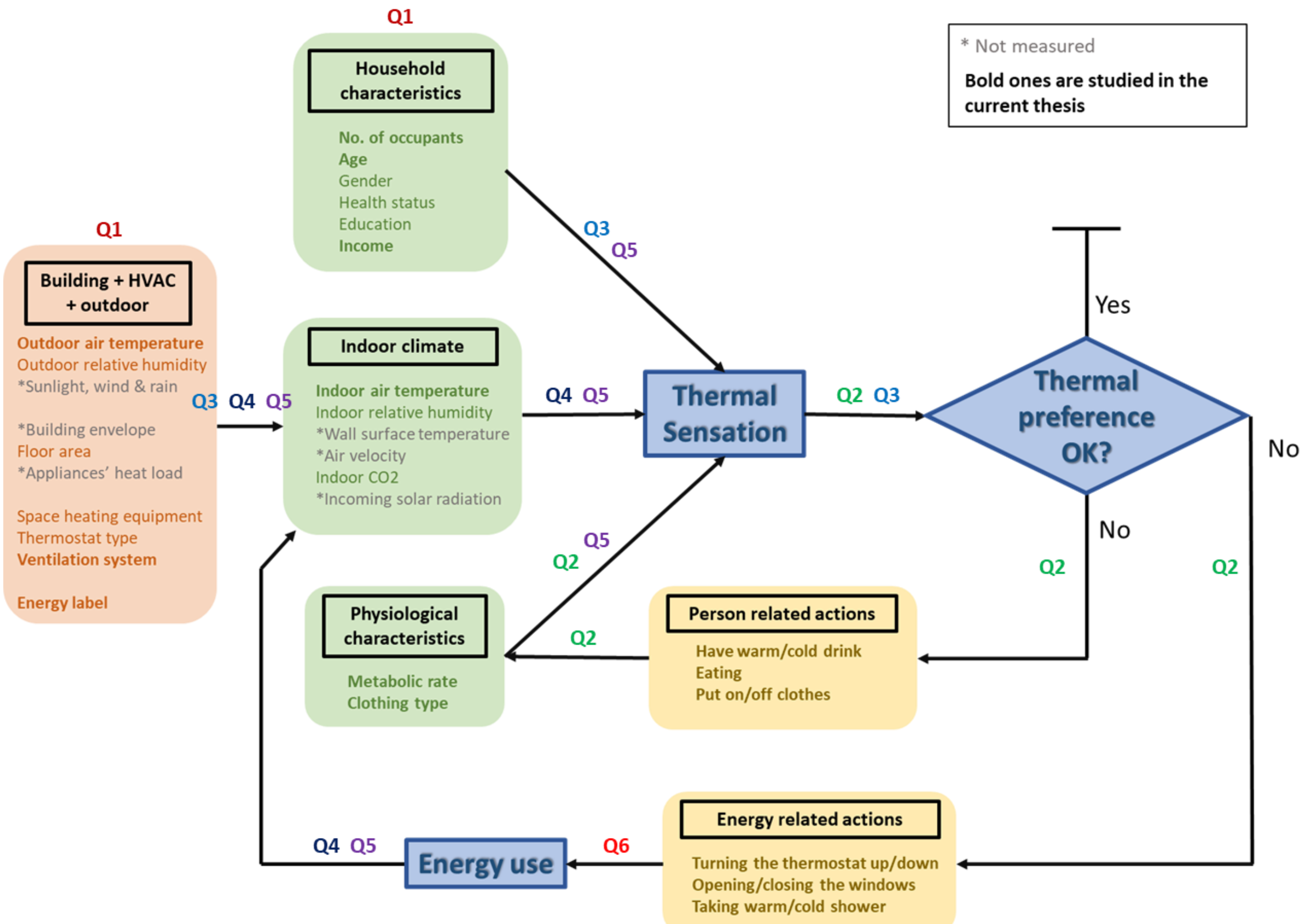


Figure 7.1: *Conceptual model of the interactions between all parameters. (Source: own)*

Therefore, the next 4 hypotheses (H11-H14), shown in Table 7.1, that are linked to the 4thresearch question will be tested.

Table 7.1: *H11-H14 null hypotheses and statistical tests for the 4th research question. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q4	**H11**	The thermal sensation is not related with the indoor air temperatures.	Thermal sensation	Indoor air temperature	Multinomial Logistic regression
	H12	The thermal preference is not related with the indoor air temperatures.	Thermal preference	Indoor air temperature	Multinomial Logistic regression
	H13	The indoor air temperature is not related with the energy labels.	Indoor air temperature	Energy labels	Kruskal-Wallis
	H14	The indoor air temperature is not related with the type of ventilation.	Indoor air temperature	Ventilation type	Kruskal-Wallis

Before starting with the analysis, a description of the indoor air temperature and real time comfort perception data will first take place. The rest of the chapter is organised based on the hypotheses, taking them one by one, showing graphs and doing the statistical tests.

<u>Indoor air temperature</u>

As already mentioned in section 3.3, temperature was measured in 96 dwellings for different duration and periods. More specifically, it was measured in 4 different rooms (Living room, Kitchen, Bedroom 1, Bedroom 2) and every 5 minutes.

<u>Thermal sensation/preference</u>

On the other hand, the comfort app was eventually filled in by 83 dwellings in total. In some cases, it was filled in more often, like for example 3 times per day every day, while in others once per day and not even every day. Therefore, the data points vary in time. Also, one of the questions included was “In the past half an hour I was in the...”, with the possible answers including 6 different options (bedroom, bathroom, kitchen, living room, outside, other).

7.1 Indoor air temperature and thermal sensation/preference

At this point the analysis that will help to answer the 4th research question starts. More specifically, the first part of it, which relates the indoor air temperature with the comfort perception is explored.

> 4. *What is the relation between* ***indoor air temperature and comfort perception****, energy label and ventilation system?*

It is essential to explain first how the thermal sensation and thermal preference will be coupled with the indoor air temperature measured in different rooms. To do so, the following assumptions will be made.

Regarding the temperature:

- Living room and kitchen are considered as a continuous space without walls or walls separating them and therefore, the mean temperature will be calculated.
- Bedrooms 1 and 2 are considered to have similar temperatures and therefore, the mean temperature will be calculated.

Regarding the thermal sensation/preference:

- The thermal sensation/preference with reported answer in the living room, kitchen, outside and other will be coupled with the mean temperature of the living room and the kitchen.
- The thermal sensation/preference with reported answer in the bedroom will be coupled with the mean temperature of bedrooms 1 and 2.
- The thermal sensation/preference with reported answer in the bathroom cannot be coupled with the temperature as no measurements took place in there.

The percentage of comfort data points per room can be seen in Figure 5.2 with the living room having been reported in the majority of them. For that reason, the analysis will be focused on the living room together with the kitchen.

The thermal sensation was coupled with the temperature that was measured half an hour ago, because according to physics, some time is needed until the thermal sensation changes as the temperature also changes.

7.1.1 Indoor air temperature and thermal sensation/preference scatter plots

As a starting point for the analysis 3 dwellings which had the most comfort data points were chosen:

- P01S02W8515 (807 data points) - Energy label E
- P01S02W6402 (735 data points) - Energy label G
- P01S01W3955 (454 data points)- Energy Label D

In this part, where the temperature does also take place, the separation of the data points in winter and summer is not needed, since the temperature itself shows the different seasons. Thus, the following scatter plots represent the whole year and indicate the thermal sensation and preference versus the temperature.

In the following scatter plots different patterns can be observed. In Figure 7.2, it seems that the temperature ranges from 18.5°C till 28°C with most data points shown in feeling either "ok" or "warm", while none of them wanted any change in their thermal sensation. In Figure 7.3, the temperature fluctuates from about 18°C to 30°C with the thermal sensation rising gradually as the temperature increases. At the same time, again most of the data points reported show that no change is desired, while some of them would like to feel warmer and only a few prefer cooler. In Figure 7.4, the temperature range is between 21°C and 27°C, proving the higher energy label of this dwelling comparing to the other two, which could probably be due to better (thicker) insulation layer, better glazing system (for example double-glazing). In addition, the scatter plot shows that even with the same temperatures people might have a different thermal sensation from "slightly cold" to "hot". However, again most of the data points reported show that no change is desired, with just a few preferring to feel cooler.

In addition, it is worth mentioning that not only the temperature, but also clothing, activities, actions as well as number of people present play a role in people's thermal sensation and these are the factors that might lead to the various thermal sensations reported for the same temperature. Moreover, the question about whether people feel comfortable when feeling "neutral" pops up, since no matter what the thermal sensation was, people did not want any change.

- **P01S02W8515 (807 data points) - Energy label E**

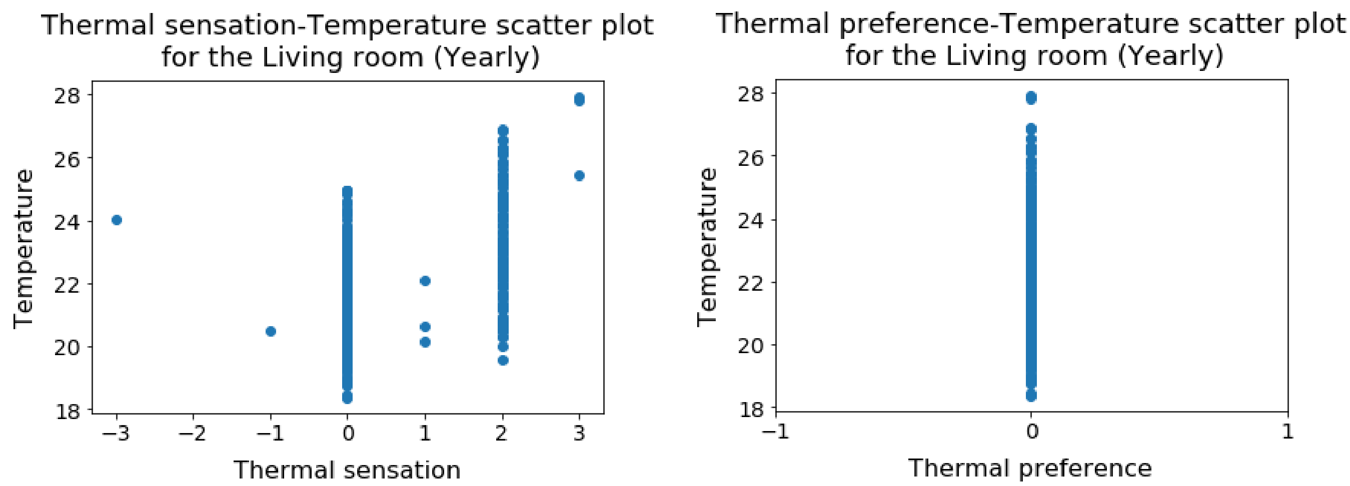


Figure 7.2: *Scatter plots of thermal sensation and preference versus temperature during the whole year for the dwelling P01S02W8515. (Source: own)*

- **P01S02W6402 (735 data points) - Energy label G**

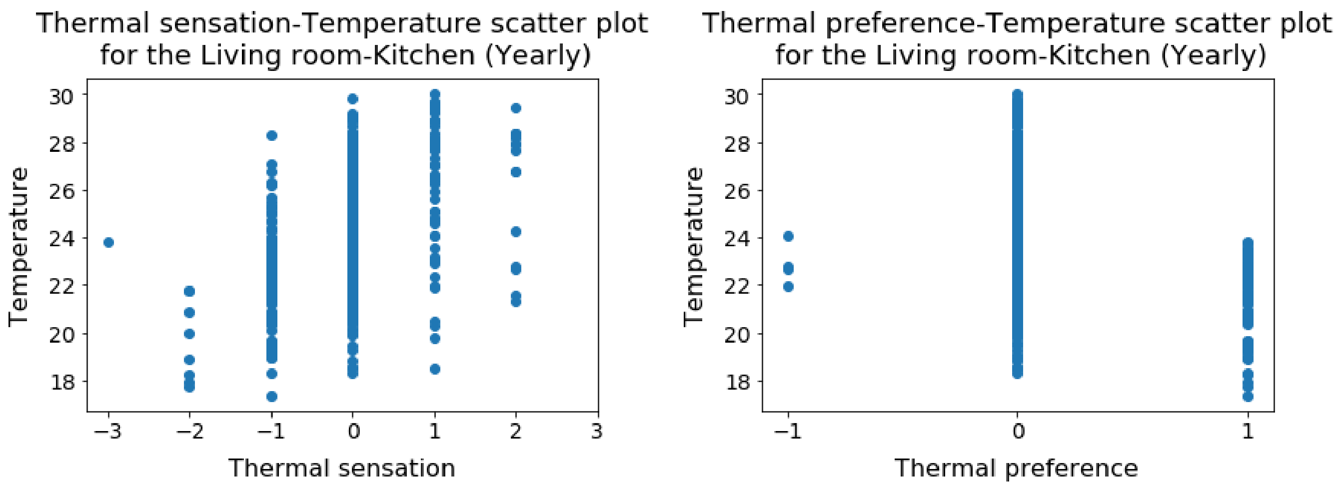


Figure 7.3: *Scatter plots of thermal sensation and preference versus temperature during the whole year for the dwelling P01S02W6402. (Source: own)*

- **P01S01W3955 (454 data points)- Energy Label D**

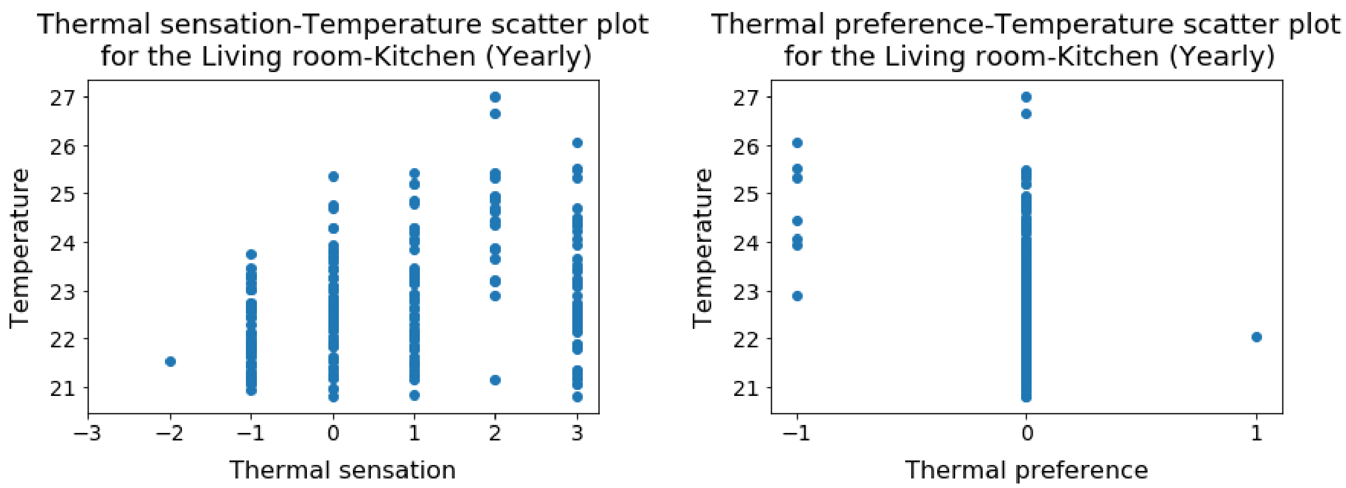


Figure 7.4: *Scatter plots of thermal sensation and preference versus temperature during the whole year for the dwelling P01S01W3955. (Source: own)*

Moreover, in order to be able to make generalised conclusions, it is better to include all dwellings in the analysis. For that purpose, each data point, where the thermal sensation and preference were reported, was coupled with the temperature that was measured half an hour ago for each dwelling, taking into account only the data points reported in the living room or kitchen.

For the total of the dwellings, it seems that the temperature ranges from 15°C to 30°C with different thermal sensations and preferences having been reported. The kernel density estimate (KDE) contour plot was used in order to show the distribution of the observations. Both the larger width and the darker shading areas imply higher density.

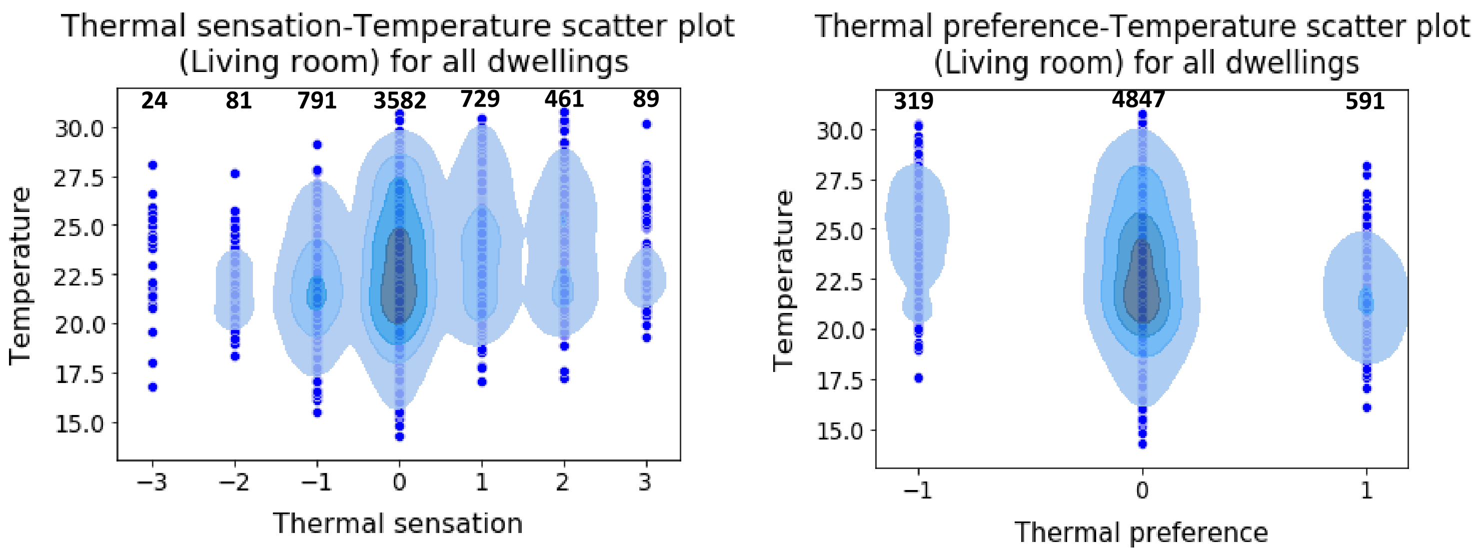


Figure 7.5: *Scatter plots of thermal sensation and preference versus temperature during the whole year for all dwellings. (Source: own)*

7.1.2 Statistical relation between thermal sensation/preference and indoor air temperature

At this point the eleventh and twelfth hypotheses (H11, H12), as shown in Table 7.2, will be tested with a multinomial logistic regression, as this was described in section 3.4.

Table 7.2: *11th and 12th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q4	**H11**	The thermal sensation is not related with the indoor air temperatures.	Thermal sensation	Indoor air temperature	Multinomial Logistic regression
	H12	The thermal preference is not related with the indoor air temperatures.	Thermal preference	Indoor air temperature	Multinomial Logistic regression

By doing so, it will help to find out if there is a relationship between thermal sensation/preference and indoor air temperature. More explicitly:

- If there is no relationship between thermal sensation/preference and indoor air temperature, then given a specific indoor air temperature does not imply anything about tenant's reported thermal sensation/preference.
- If the variables are associated, then given a specific indoor air temperature will help to predict tenant's thermal sensation/preference. For example, the higher the temperature, the higher the thermal sensation or the higher the thermal preference (warmer), the lower the temperature.

In order to get more insight regarding the relationship between thermal sensation/preference and temperature, an ordinal logistic regression will take place. However, due to the fact that one of the assumptions and specifically the proportional odds one is not satisfied, an alternative test needs to be found. According to Adeleke and Adepoju, multinomial logistic regression was found to be an important alternative to the ordinal regression technique when proportional odds assumption failed. Multinomial logistic regression is similar to the ordinal logistic regression but disregarding the order of the dependent variable.

In Table 7.3, all different thermal sensations are compared to the reference category of feeling "ok". It can be observed that temperature is significant for thermal sensations between "cold" and "hot" (yellow coloured). The interpretation of the results is as follows with the reference category being "ok":

- As the temperature increased by 1 unit, the probability of people feeling "cold" compared to "ok" was less by 0.854 times.
- As the temperature increased by 1 unit, the probability of people feeling "slightly cold" compared to "ok" was less by 0.850 times.
- As the temperature increased by 1 unit, the probability of people feeling "slightly warm" compared to "ok" was more by 1.164 times.
- As the temperature increased by 1 unit, the probability of people feeling "warm" compared to "ok" was more by 1.167 times.
- As the temperature increased by 1 unit, the probability of people feeling "hot" compared to "ok" was more by 1.159 times.

Table 7.3: *Multinomial logistic regression results for temperature and thermal sensation during the whole year for all dwellings. (Created in SPSS)*

Parameter Estimates

Feel[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	95% Confidence Interval for Exp(B) Lower Bound	95% Confidence Interval for Exp(B) Upper Bound
Very cold	Intercept	-6.245	1.961	10.148	1	.001			
	Temperature	.054	.084	.410	1	.522	1.056	.895	1.245
Cold	Intercept	-.262	1.107	.056	1	.813			
	Temperature	-.158	.050	9.898	1	.002	.854	.774	.942
Slighlty cold	Intercept	2.119	.392	29.206	1	.000			
	Temperature	-.162	.018	84.461	1	.000	.850	.821	.880
Slighlty warm	Intercept	-5.122	.393	169.567	1	.000			
	Temperature	.152	.017	83.449	1	.000	1.164	1.127	1.203
Warm	Intercept	-5.640	.477	139.751	1	.000			
	Temperature	.154	.020	58.959	1	.000	1.167	1.122	1.214
Hot	Intercept	-7.131	1.026	48.268	1	.000			
	Temperature	.148	.043	11.747	1	.001	1.159	1.065	1.262

Same procedure was followed also for temperature and thermal preference. In this case, “no change” was the reference category.

- As the temperature increased by 1 unit, the probability of people preferring to feel “warmer” compared to “no change” was less by 0.787 times.
- As the temperature increased by 1 unit, the probability of people preferring to feel “cooler” compared to “no change” was more by 1.333 times.

Table 7.4: *Multinomial logistic regression results for temperature and thermal preference during the whole year for all dwellings. (Created in SPSS)*

Parameter Estimates

								95% Confidence Interval for Exp(B)	
Rather[a]		B	Std. Error	Wald	df	Sig.	Exp(B)	Lower Bound	Upper Bound
Warmer	Intercept	3.235	.445	52.781	1	.000			
	Temperature	-.240	.020	139.220	1	.000	.787	.756	.819
Cooler	Intercept	-9.548	.582	268.919	1	.000			
	Temperature	.287	.024	147.721	1	.000	1.333	1.272	1.396

a. The reference category is: No change.

Therefore, both null hypotheses “The thermal sensation/preference is not related with the indoor air temperature.” are rejected and it is concluded that the thermal sensation/preference is related with the indoor air temperature.

7.2 Indoor air temperature and energy labels

In this section, the part of the 4th research question that refers to the relation between indoor air temperature and energy labels is examined.

> *4. What is the relation between **indoor air temperature** and comfort perception**, energy label** and ventilation system?*

7.2.1 Indoor air temperature and energy labels scatter plot

To create the scatter plot in Figure 7.6, the mean temperature of the living room per dwelling separately for winter and summer was calculated. It can be observed that there is a variance of different mean temperatures even in the same energy labels. In winter the temperatures are in general lower than in summer.

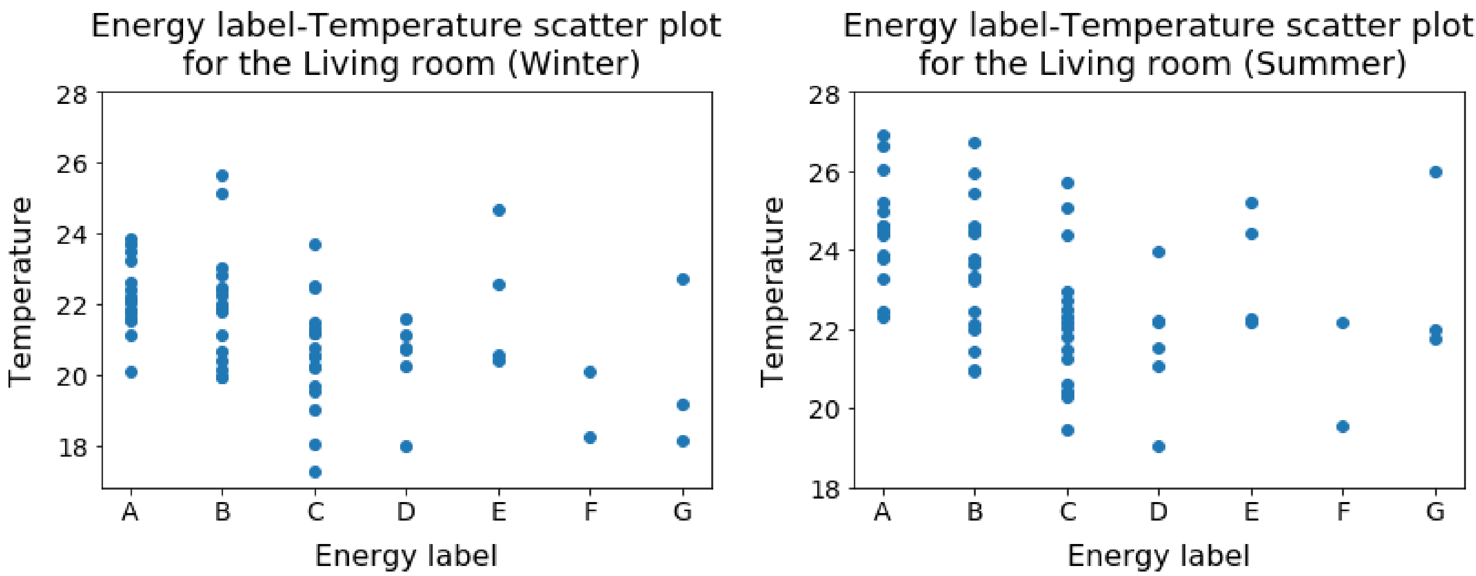


Figure 7.6: *Scatter plot of energy label versus temperature for winter and summer for all dwellings.*

7.2.2 Statistical relation between indoor air temperature and energy labels

At this point the thirteenth hypothesis (H13), as shown in Table 7.5, will be tested with a Kruskal Wallis test, as this was described in section 3.4.

Table 7.5: *13th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q4	**H13**	The indoor air temperature is not related with the energy labels.	Indoor air temperature	Energy labels	Kruskal Wallis test

By doing so, it will help to find out if there is a relationship between indoor air temperature and energy labels. Do the mean temperatures differ between dwellings with different energy labels?

At first, the statistical test chosen for this case was the ANOVA, which is a parametric test, and the common assumptions have to be satisfied. However, due to the fact one of the assumptions, and specifically the one related to the normal distribution of the dependent variable (temperature), was not fulfilled, an alternative needed to be found. Thus, a non-parametric test was chosen in place of the ANOVA, called the Kruskal-Wallis test. This test helps to find out whether there is a statistically significant difference in temperature between the different energy labels, but in order to find exactly where the differences lie, a post-hoc test is also needed. The post-hoc test is similar to what was done after the chi-square test as well.

As shown in Table 7.6, since 0.011 < 0.050 (chosen significance level) and 0.003 < 0.050, the null hypothesis is rejected and therefore, the temperature is dependent on the energy label of the dwellings both in winter and summer.

Table 7.6: *Kruskal-Wallis test for temperature and energy labels for winter and summer for all dwellings. (Created in SPSS)*

Hypothesis Test Summary-WINTER

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Temperature is the same across categories of Energy Labels.	Independent-Samples Kruskal-Wallis Test	.011	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .050.

Hypothesis Test Summary-SUMMER

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Temperature is the same across categories of Energy Labels.	Independent-Samples Kruskal-Wallis Test	.003	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .050.

In Figure 7.7, the boxplots are displayed, showing the variation of the temperature along all dwellings per energy label for winter and summer.

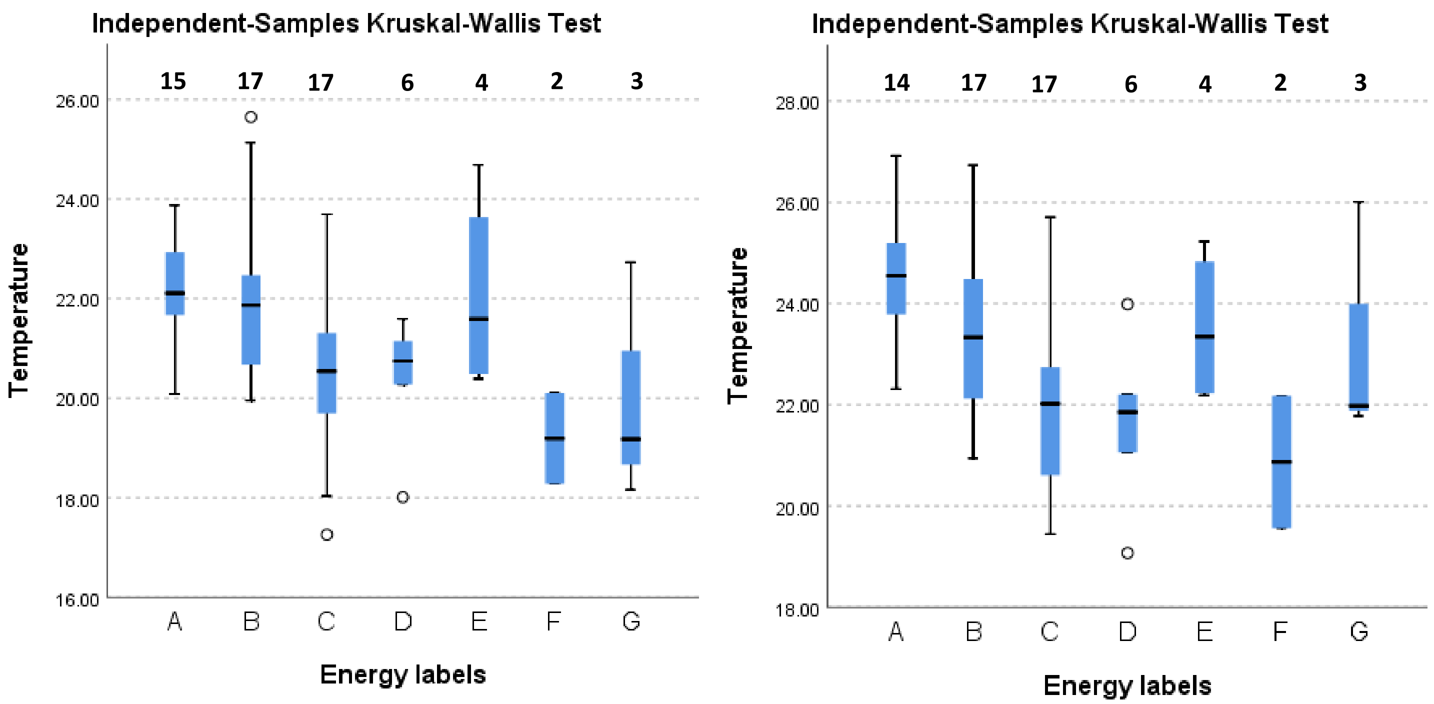


Figure 7.7: *Boxplots of temperature per energy labels for winter(left) and summer(right) for all dwellings with the number of dwellings per label shown above the bars. (Created in SPSS)*

The post-hoc test results are presented in Tables 7.7 and 7.8, where all possible paired combinations have taken place in order to understand exactly in which energy labels the temperature differs significantly.

Looking at Tables 7.7 and 7.8 and comparing the significance with the chosen significance level of 0.05, it is concluded that some of the pairs are characterised as statistically different. For winter these are energy labels A with C, D, F and B with C, F, while for summer these are again energy labels A with C, D, F and B with C.

Table 7.7: *Post-hoc test after Kruskal-Wallis test pairing all different energy labels with each other for winter. (Created in SPSS)*

Pairwise Comparisons of Energy labels in WINTER

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
F-G	-12.667	16.997	-.745	.456	1.000
F-D	13.167	15.202	.866	.386	1.000
F-C	15.176	13.919	1.090	.276	1.000
F-B	29.000	13.919	2.084	.037	.781
F-E	29.500	16.125	1.830	.067	1.000
F-A	34.533	14.016	2.464	.014	.289
G-D	.500	13.166	.038	.970	1.000
G-C	2.510	11.660	.215	.830	1.000
G-B	16.333	11.660	1.401	.161	1.000
G-E	16.833	14.220	1.184	.237	1.000
G-A	21.867	11.776	1.857	.063	1.000
D-C	2.010	8.841	.227	.820	1.000
D-B	15.833	8.841	1.791	.073	1.000
D-E	-16.333	12.019	-1.359	.174	1.000
D-A	21.367	8.994	2.376	.018	.368
C-B	13.824	6.386	2.165	.030	.639
C-E	-14.324	10.347	-1.384	.166	1.000
C-A	19.357	6.596	2.935	.003	.070
B-E	-.500	10.347	-.048	.961	1.000
B-A	5.533	6.596	.839	.402	1.000
E-A	5.033	10.477	.480	.631	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.

Asymptotic significances (2-sided tests) are displayed. The significance level is .05.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Table 7.8: *Post-hoc test after Kruskal-Wallis test pairing all different energy labels with each other for summer. (Created in SPSS)*

Pairwise Comparisons of Energy labels in SUMMER

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
F-D	5.833	14.967	.390	.697	1.000
F-C	9.471	13.703	.691	.489	1.000
F-G	-17.333	16.733	-1.036	.300	1.000
F-B	22.294	13.703	1.627	.104	1.000
F-E	24.500	15.875	1.543	.123	1.000
F-A	33.714	13.856	2.433	.015	.419
D-C	3.637	8.704	.418	.676	1.000
D-G	-11.500	12.961	-.887	.375	1.000
D-B	16.461	8.704	1.891	.059	1.000
D-E	-18.667	11.832	-1.578	.115	1.000
D-A	27.881	8.944	3.117	.002	.051
C-G	-7.863	11.479	-.685	.493	1.000
C-B	12.824	6.287	2.040	.041	1.000
C-E	-15.029	10.186	-1.475	.140	1.000
C-A	24.244	6.615	3.665	.000	.007
G-B	4.961	11.479	.432	.666	1.000
G-E	7.167	14.000	.512	.609	1.000
G-A	16.381	11.662	1.405	.160	1.000
B-E	-2.206	10.186	-.217	.829	1.000
B-A	11.420	6.615	1.726	.084	1.000
E-A	9.214	10.392	.887	.375	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .05.
a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

7.3 Indoor air temperature and ventilation type

In this section, the last part of the 4th research question that refers to the relation between indoor air temperature and ventilation system is studied.

> 4. *What is the relation between **indoor air temperature** and comfort perception, energy label and **ventilation system**?*

7.3.1 Indoor air temperature and ventilation type scatter plot

To create the scatter plot in Figure 7.8, same procedure as described in the previous section was followed. The mean temperature of the living room per dwelling separately for winter and summer was calculated but now the temperature is compared per type of ventilation. It seems that temperature varies a lot among dwellings with the same ventilation system.

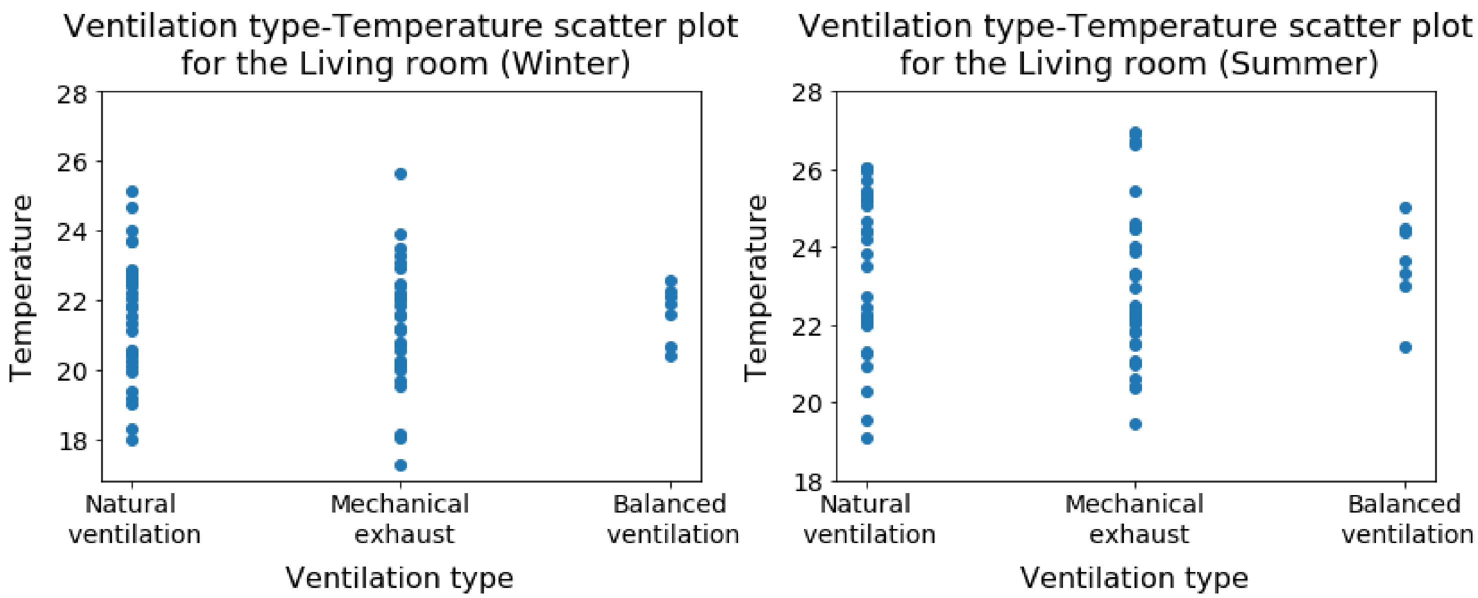


Figure 7.8: *Scatter plot of ventilation type versus temperature for winter and summer for all dwellings. (Source: own)*

7.3.2 Statistical relation between indoor air temperature and ventilation type

At this point the fourteenth hypothesis (H14), as shown in Table 7.9, will be tested with a Kruskal Wallis test, as this was described in section 3.4.

Table 7.9: *14th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q4	**H14**	The indoor air temperature is not related with the ventilation type.	Indoor air temperature	Ventilation type	Kruskal Wallis test

By doing so, it will help to find out if there is a relation between indoor air temperature and ventilation type. Do the mean temperatures differ between dwellings with different ventilation type?

Again here, due to the non-normality of the data, Kruskal-Wallis test was chosen. This test will help to find out whether there is a statistically significant difference in temperature between the different ventilation types.

As shown in Table 7.10, since 0.559 > 0.050 (chosen significance level) and 0.454 > 0.050, the null hypothesis is retained and therefore, the temperature is not related with the ventilation type of the dwellings for both winter and summer.

Table 7.10: *Kruskal-Wallis test for temperature and ventilation type during the whole year for all dwellings. (Created in SPSS)*

Hypothesis Test Summary-WINTER

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Temperature is the same across categories of Ventilation Type.	Independent-Samples Kruskal-Wallis Test	.559	Retain the null hypothesis.

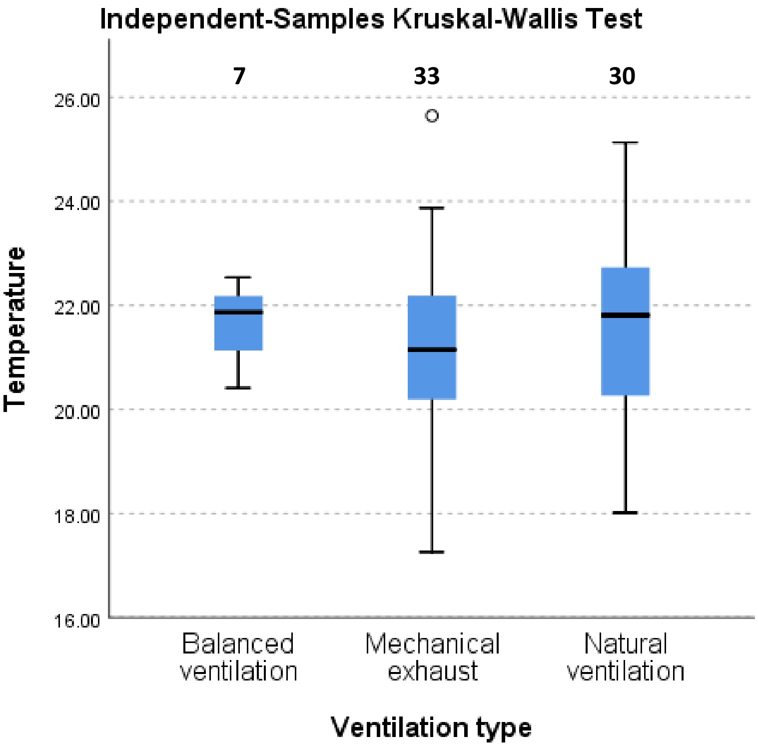
Asymptotic significances are displayed. The significance level is .050.

Hypothesis Test Summary-SUMMER

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Temperature is the same across categories of Ventilation Type.	Independent-Samples Kruskal-Wallis Test	.454	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .050.

In Figure 7.9, the boxplots are displayed, showing that the mean temperature along all different types of ventilation for winter is between 21ºC and 22ºC, while for summer between 22ºC and 23.5ºC.



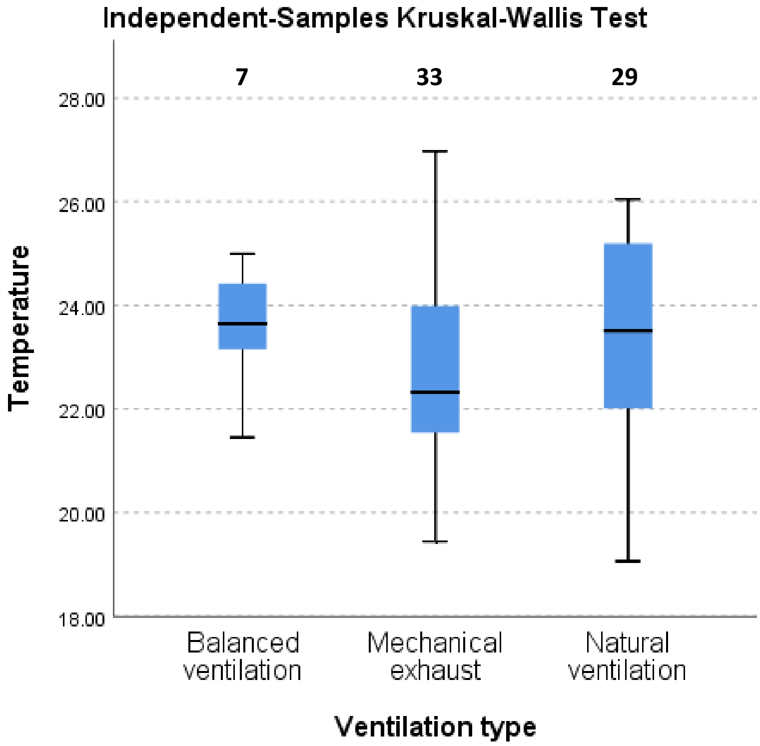


Figure 7.9: *Boxplots of temperature per ventilation type for winter(left) and summer (right) for all dwellings with the number of dwellings per ventilation type shown above the bars. (Created in SPSS)*

7.4 Overall correlation test

In this section, a Spearman's correlation test will be run taking into account the ordinal or continuous variables that were found to influence the thermal sensation, thermal preference and indoor air temperature. By doing that, the variables that have higher correlation among them will be distinguished.

Table 7.11 shows the results of the Spearman's correlation test where thermal sensation, thermal preference, metabolic activity, clothing, indoor air temperature and energy labels were taken into account. Correlation coefficients (ρ) higher than 0.1 were highlighted with yellow colour shading, getting darker when the correlation get stronger.

All in all, the following variables are higher correlated with thermal sensation in a descending order:

- Thermal preference
- Clothing
- Indoor air temperature

In addition, thermal preference shows almost the same correlation with both clothing and indoor air temperature.

The following conclusions about the correlations indicated in Table 7.11 were made, including some additional relationships that were not explored before.

- Thermal sensation and thermal preference have the strongest relation among all other parameters, showing a moderate correlation (ρ= -0.571) where the minus sign implies a negative relationship between them, which means that the higher the thermal sensation, the lower the thermal preference and vice versa.
- The second strongest relationship was identified between indoor air temperature and clothing, which was not explored before. A negative relationship between them is indicated since ρ = -0.445, which means that the higher the indoor air temperature, the lighter the clothing and vice versa.
- The next higher correlation was found between energy label and clothing, which was also not explored before. A positive relationship between them is indicated since ρ = 0.280, which means that the lower the energy label, the heavier the clothing and vice versa.
- Other low correlations indicated are between thermal sensation/preference and clothing as well as thermal sensation/preference and indoor air temperature. Thermal sensation has a negative correlation with clothing, illustrating that the higher the thermal sensation the lighter the clothing and vice versa for the thermal preference. While thermal sensation has a positive correlation with indoor air temperature, which means that the higher the indoor air temperature, the higher the thermal sensation and vice versa for the thermal preference.
- Finally, an extremely low and negative correlation was revealed between indoor air temperature and energy labels, which means that the lower the energy label the lower the indoor air temperature.

Table 7.11: *Spearman's correlation test among different variables.*

Correlations

			Thermal sensation	Thermal preference	Metabolic activity	Clothing	Indoor air temperature	Energy label
Spearman's rho	Thermal sensation	Correlation Coefficient	1.000	-.571**	.088**	-.249**	.209**	-.033*
		Sig. (2-tailed)	.	.000	.000	.000	.000	.022
		N	5757	5757	5757	5757	5757	4807
	Thermal preference	Correlation Coefficient	-.571**	1.000	-.067**	.225**	-.234**	.027
		Sig. (2-tailed)	.000	.	.000	.000	.000	.058
		N	5757	5757	5757	5757	5757	4807
	Metabolic activity	Correlation Coefficient	.088**	-.067**	1.000	-.024	-.023	-.063**
		Sig. (2-tailed)	.000	.000	.	.074	.085	.000
		N	5757	5757	5757	5757	5757	4807
	Clothing	Correlation Coefficient	-.249**	.225**	-.024	1.000	-.445**	.280**
		Sig. (2-tailed)	.000	.000	.074	.	.000	.000
		N	5757	5757	5757	5757	5757	4807
	Indoor air temperature	Correlation Coefficient	.209**	-.234**	-.023	-.445**	1.000	-.122**
		Sig. (2-tailed)	.000	.000	.085	.000	.	.000
		N	5757	5757	5757	5757	5757	4807
	Energy label	Correlation Coefficient	-.033*	.027	-.063**	.280**	-.122**	1.000
		Sig. (2-tailed)	.022	.058	.000	.000	.000	.
		N	4807	4807	4807	4807	4807	4807

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

7.5 Conclusions

In this chapter, the 4th research question, as shown below, was studied.

> *4. What is the relation between indoor air temperature and comfort perception, energy label and ventilation system?*

Table 7.12 shows all null hypotheses that were tested in this chapter and which of them were rejected or accepted as well.

Table 7.12: *Hypotheses H11-H14 rejected or accepted. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Winter	Summer
Q4	H11	The thermal sensation is not related with the indoor air temperatures.	Rejected	Rejected
	H12	The thermal preference is not related with the indoor air temperatures.	Rejected	Rejected
	H13	The indoor air temperature is not related with the energy labels.	Rejected	Rejected
	H14	The indoor air temperature is not related with the type of ventilation.	Accepted	Accepted

Regarding the 4th research question, it was concluded that thermal sensation and preference are influenced by the indoor air temperature. Moreover, indoor air temperature was found to be affected by the energy label of the dwelling, but not by its ventilation type.

From the analysis, it was concluded that indoor air temperature influences the thermal sensation and preference. This means that, as the indoor air temperature increases the probability of people feeling warmer increases, while the probability of people feeling cooler decreases. Furthermore, as the indoor air temperature increases, the probability of people preferring to feel warmer is lower, while the probability of people preferring to feel cooler is higher. All these conclusions are deducted considering as a reference category feeling “ok” for thermal sensation and preferring “no change” for thermal preference. Therefore, it could be said that indoor air temperature is a variable that is reasonably taken into account in the calculation of the PMV.

Apart from these, the impact that the energy labels of the dwellings have on their indoor air temperature was studied in this chapter. As already mentioned, energy labels are calculated based on the overall performance of the dwellings, which is, thus, highly dependent on the thermal resistance of the building envelope. The higher the thermal resistance of the building envelope, the lower the heat losses and as a result, the easier it is to heat and maintain a higher and constant indoor air temperature. The results showed that energy labels are significantly associated with the indoor air temperature. In other words, it was illustrated that the higher energy labels such as A and B had higher mean indoor air temperature and differed significantly with some of the lower energy labels.

Additionally, the relationship between the indoor air temperature and the ventilation type of the dwellings was explored. The results indicated that there are no significant differences of the indoor air temperature between different ventilation types. Hence, it can be concluded that the type of ventilation does not affect the mean indoor air temperature of the dwellings, but it is highly possible that different amounts of energy are used in each case, which will be explored in chapter 8.

8 Energy Use, Climate and Comfort Parameters

In this last chapter of the analysis, the relationship between the energy use and temperature, comfort parameters and others will be explored. This exploration will help to answer the fifth and sixth research questions:

> 5. *What is the relationship between energy use and air temperature taking into account comfort perception, energy label, ventilation system as well as household characteristics?*
> 6. *To what extent do actions like opening/closing the windows, setting the thermostat up/down, taking warm/cold shower influence the energy use?*

It is important to mention here that both real time data variables and constant parameters are involved in the relations that are explored.

How all the above-mentioned parameters influence each other is shown in the conceptual diagram (Figure 8.1), where the outdoor temperature together with other parameters influence the indoor air temperature, which then affects the thermal sensation and actions of the occupants resulting in the amount of energy used.

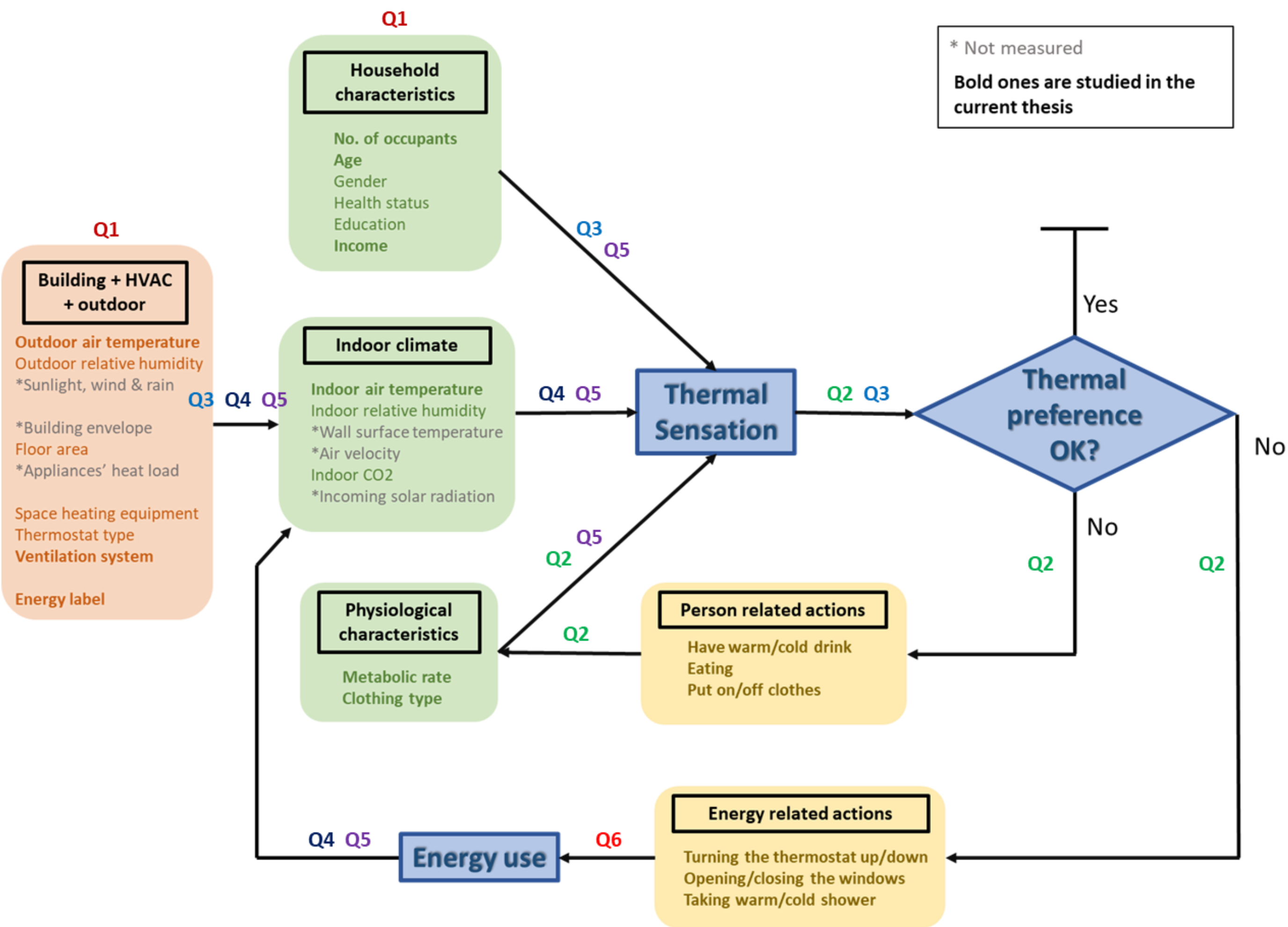


Figure 8.1: *Conceptual model of the interactions between all parameters. (Source: own)*

Therefore, the last 6 hypotheses, shown in Table 8.1, that are linked to these questions will be tested.

Table 8.1: *H15-H20 null hypotheses and statistical tests for the 5th and 6th research questions. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q5	**H15**	The energy use is not related with the air temperature.	Energy use	Air temperature	Simple regression
	H16	The energy use is not related with the thermal sensation.	Energy use	Thermal sensation	Kruskal-Wallis
	H17	The energy use is not related with the energy labels.	Energy use	Energy labels	Kruskal-Wallis
	H18	The energy use is not related with the type of ventilation.	Energy use	Ventilation type	Kruskal-Wallis
	H19	The energy use is not related with the income.	Energy use	Income	Simple regression
Q6	**H20**	The energy use is not related with the actions.	Energy use	Actions	Kruskal-Wallis

Before starting with the analysis, a description of the data related to the energy use, indoor and outdoor temperature as well as thermal sensation will be given. The rest of the chapter is organised by testing the hypotheses one by one, after presenting the related graphs.

The whole analysis of this chapter was decided to be carried out on a daily basis and focus on the heating season, which is highly related to the energy consumption.

<u>Gas meter data</u>

As already mentioned in section 3.3, the gas meter use was measured every 1 hour in 92 dwellings for different duration and periods. Since the gas meter use data column represented the cumulative one and in order to calculate the daily gas meter use per dwelling, the min and max values per day per dwelling were identified and the difference between the two gave the daily gas meter use. After applying that, the total number of dwellings decreased to 84. Finally, after keeping only the dwellings that had gas use measurements during the winter months (from October until March), the number of dwellings reduced to 76. It is important to note that for this particular research the gas data was not decomposed into gas used for space heating and domestic hot water (DHW) for simplification reasons.

<u>Indoor air temperature</u>

Regarding the indoor air temperature, the data of the same 76 dwellings was kept for the analysis and in order to be coupled with the daily gas use, the daily mean indoor air temperature of the living room per dwelling was calculated.

<u>Outdoor air temperature</u>

The daily mean outdoor air temperature was requested by the KNMI meteorological data. Based on the location area, each dwelling is assigned to a 4-digit postal code. According to this postal code, the closest KNMI station per dwelling was found and then, the daily mean outdoor air temperature was acquired and coupled with the gas use and indoor air temperature data.

Thermal sensation

In addition, the comfort app was filled in by 83 dwellings in total, 67 of which did during the heating season. However, in 54 of them gas meter measurements took place during this period. To couple the thermal sensation data points with the daily gas use, the daily median thermal sensation per dwelling was calculated.

8.1 Energy use and air temperature

It is essential to mention that from this point onwards, the analysis helps to answer the 5th research question. More specifically here, the first part of it, which is related to the energy use and the indoor-outdoor air temperature, is analysed.

*5. What is the relationship between **energy use and air temperature** taking into account comfort perception, energy label, ventilation system as well as household characteristics?*

8.1.1 Indoor/outdoor air temperature and energy use scatter plot

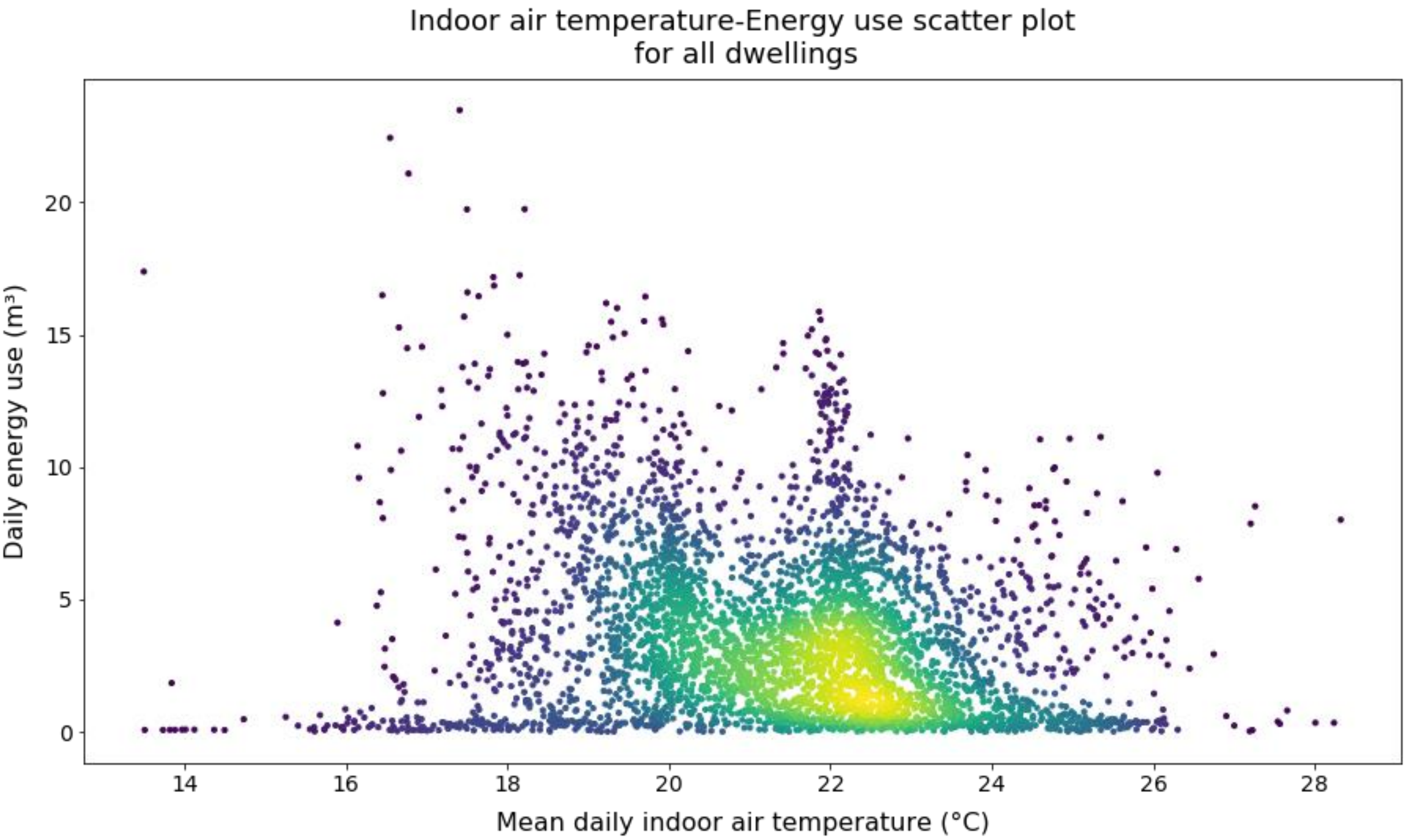


Figure 8.2: *Scatterplot of mean daily indoor air temperature and daily energy use in winter. (Source: own)*

The scatterplot in Figure 8.2 shows the mean daily indoor air temperature in relation with the daily energy use. The kernel density estimation (KDE), which is a non-parametric way to estimate the probability density function of a random variable, is used in this scatterplot. Thus, the yellow colour represents the highest probability, while the purple the lowest one. This means, that there is a higher probability for the mean daily indoor air temperature to range from 21°C to 23°C and the daily energy use between 0 and 5m^3.

By observing the scatter plot, two peaks with most of the data points gathered there can be identified for 20ºC and 22ºC with the daily energy use varying a lot. In addition, there is a lot of spread data going from 14ºC to 28ºC with nearly zero daily energy use. For the lower temperatures this could happen in case occupants are absent and the thermostat is off, resulting in no energy use. On the other hand, for the higher temperatures it could be that the outdoor air temperature is high enough, resulting in no need of turning the thermostat on and also, due to solar radiation the indoor air temperature increases a lot. All in all, no clear correlation between the two variables can be identified.

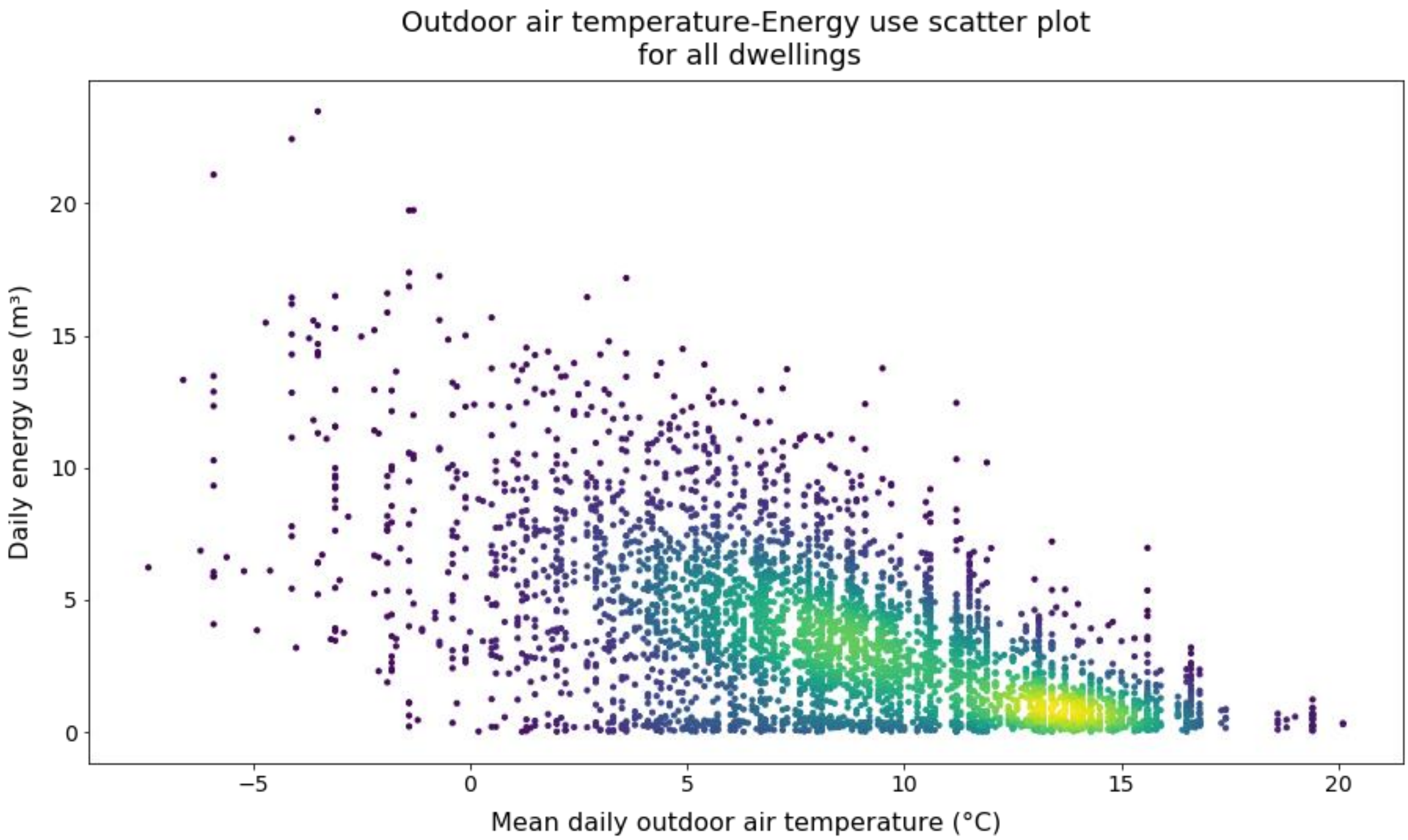


Figure 8.3: *Scatterplot of mean daily outdoor air temperature and daily energy use in winter. (Source: own)*

The scatterplot in Figure 8.3 shows the mean daily outdoor air temperature in relation with the daily energy use. The kernel density estimation (KDE), that there is a higher probability for the mean daily outdoor air temperature to range from 12.5ºC to 15ºC and the daily energy use between 0 and 2.5m^3.

In this scatterplot, a linear relationship between the two variables can be observed. As expected, the lower the mean daily outdoor air temperature, the higher the daily energy use in order to keep the indoor climate conditions stable and comfortable for the occupants.

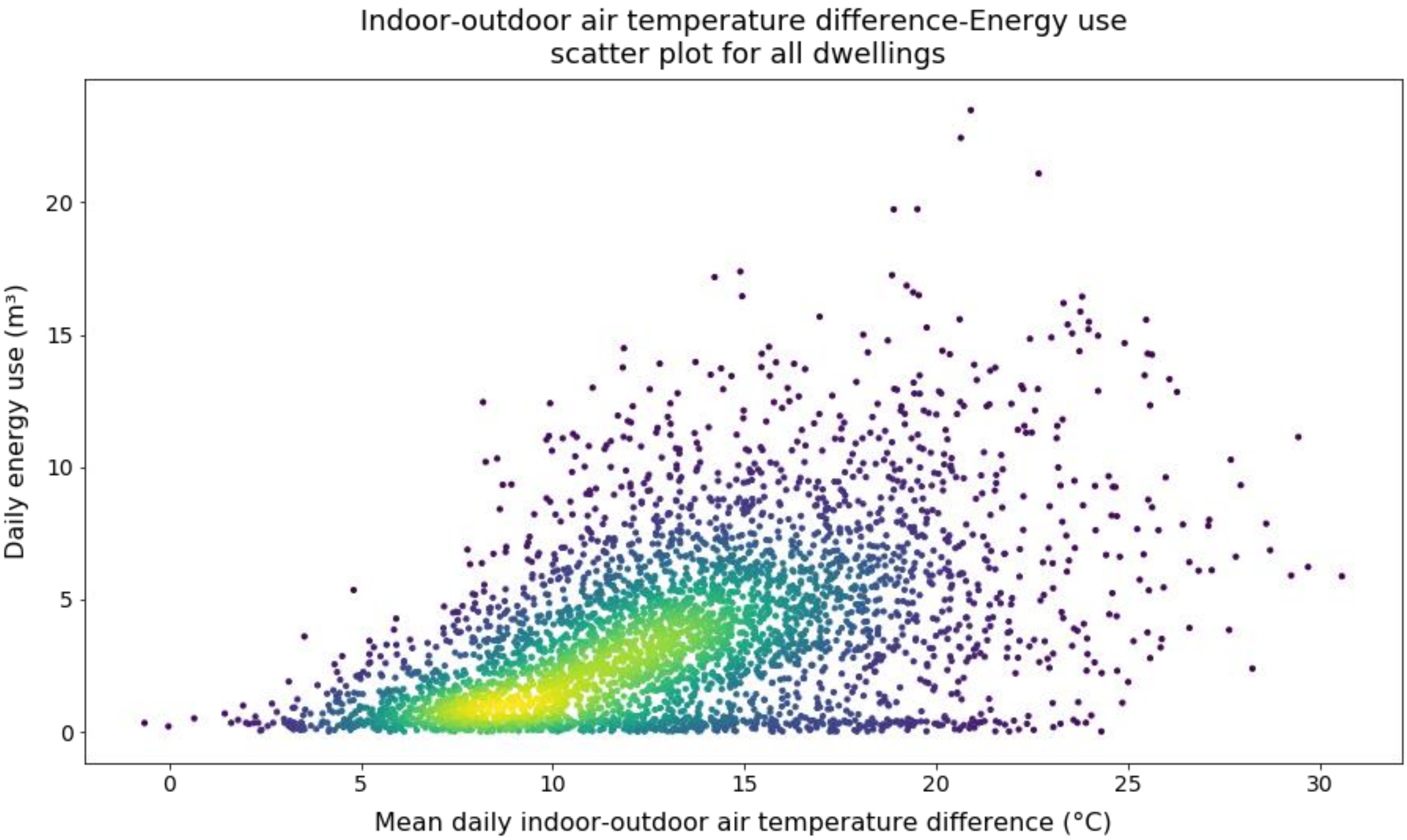


Figure 8.4: *Scatterplot of mean daily indoor-outdoor air temperature difference and daily energy use in winter. (Source: own)*

Moreover, in order to get a better understanding about how the outdoor air temperature influences the indoor air temperature and as a result the energy use, the difference between indoor and outdoor air temperature was calculated and then related to the gas use, as shown in Figure 8.4.

In this scatterplot, again a linear relationship between the two variables can be observed. It is concluded that the higher the air temperature difference, the more the gas use.

8.1.2 Statistical relation between energy use and indoor-outdoor air temperature difference

For this and the following analysis the difference between indoor and outdoor air temperature was decided to be taken into account as the most representative and better to compare variable.

Following the above scatterplots, in this section, the fifteenth hypothesis (H15), as shown in Table 8.2, will be tested by exploring the correlation between the energy use and the indoor-outdoor air temperature difference as this was described in section 3.4.

Table 8.2: *15th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q5	H15	The energy use is not related with the indoor-outdoor air temperature difference.	Energy use	Indoor-outdoor air temperature difference	Spearman's correlation test

The results shown in Table 8.3 indicate that there is a significant relationship between the gas use and the indoor-outdoor air temperature difference. Spearman's correlation coefficient is equal to almost 0.5 which indicates a moderate correlation between them.

Table 8.3: *Spearman's rho correlation table of daily gas use and indoor-outdoor air temperature difference. (Created in SPSS)*

Correlations

			Daily gas use	Indoor-outdoor air temperature difference
Spearman's rho	Daily gas use	Correlation Coefficient	1.000	.495**
		Sig. (2-tailed)	.	.000
		N	3895	3895
	Indoor-outdoor air temperature difference	Correlation Coefficient	.495**	1.000
		Sig. (2-tailed)	.000	.
		N	3895	3895

**. Correlation is significant at the 0.01 level (2-tailed).

8.2 Energy use and thermal sensation

In this section, the part of the 5th research question that refers to the relation between energy use, temperature difference and thermal sensation is studied.

*5. What is the relationship between **energy use and air temperature** taking into account **comfort perception**, energy label, ventilation system as well as household characteristics?*

8.2.1 Indoor-outdoor air temperature difference, energy use and thermal sensation scatter plot

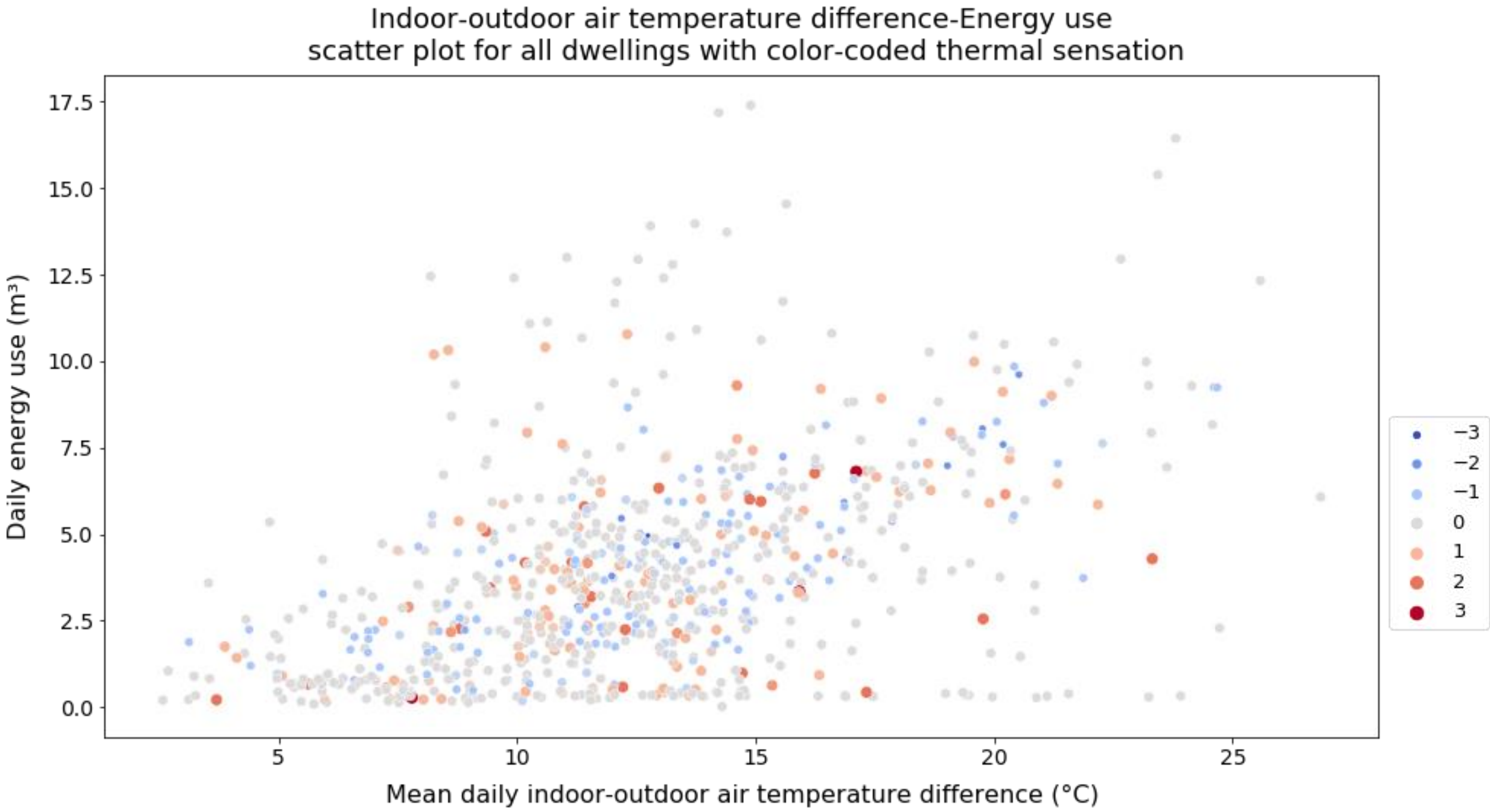


***Figure 8.5:** Scatterplot of mean daily indoor-outdoor air temperature difference and daily energy use with color-coded thermal sensation for all dwellings with 779 data points in total. (Source: own)*

The scatterplot in Figure 8.5 shows the mean daily indoor-outdoor air temperature difference on the x-axis and the daily gas use on the y-axis with the median daily reported thermal sensation represented by different colours. By looking into the graph, no relationship between the different variables can be concluded since all different thermal sensations are spread along various air temperature differences and amount of energy use.

8.2.2 Statistical relation between energy use and thermal sensation

In this section, the sixteenth hypothesis (H16), as shown in Table 8.4, will be tested by carrying out a Kruskal-Wallis test, as this was described in section 3.4.

Table 8.4: *16th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q5	**H16**	The energy use is not related with the thermal sensation.	Energy use	Thermal sensation	Kruskal-Wallis

This will help to find out if there is a relationship between energy use and thermal sensation. For example, if when the occupants feel cold, the energy use is lower and the opposite.

As shown in Table 8.5, since 0.161 > 0.050 (chosen significance level), the null hypothesis is retained and therefore, as expected by just looking at the scatterplot the energy use is not related with the reported thermal sensations.

Table 8.5: *Kruskal-Wallis test for daily energy use and thermal sensation categories for winter for all dwellings. (Created in SPSS)*

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Daily energy use is the same across categories of Thermal sensations.	Independent-Samples Kruskal-Wallis Test	.161	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .050.

8.3 Energy use and energy labels

In this section, the part of the 5th research question that refers to the relation between energy use, temperature difference and energy labels is studied.

> *5. What is the relationship between* ***energy use and air temperature*** *taking into account comfort perception,* ***energy label****, ventilation system as well as household characteristics?*

8.3.1 Indoor-outdoor air temperature difference, energy use and energy labels scatter plot

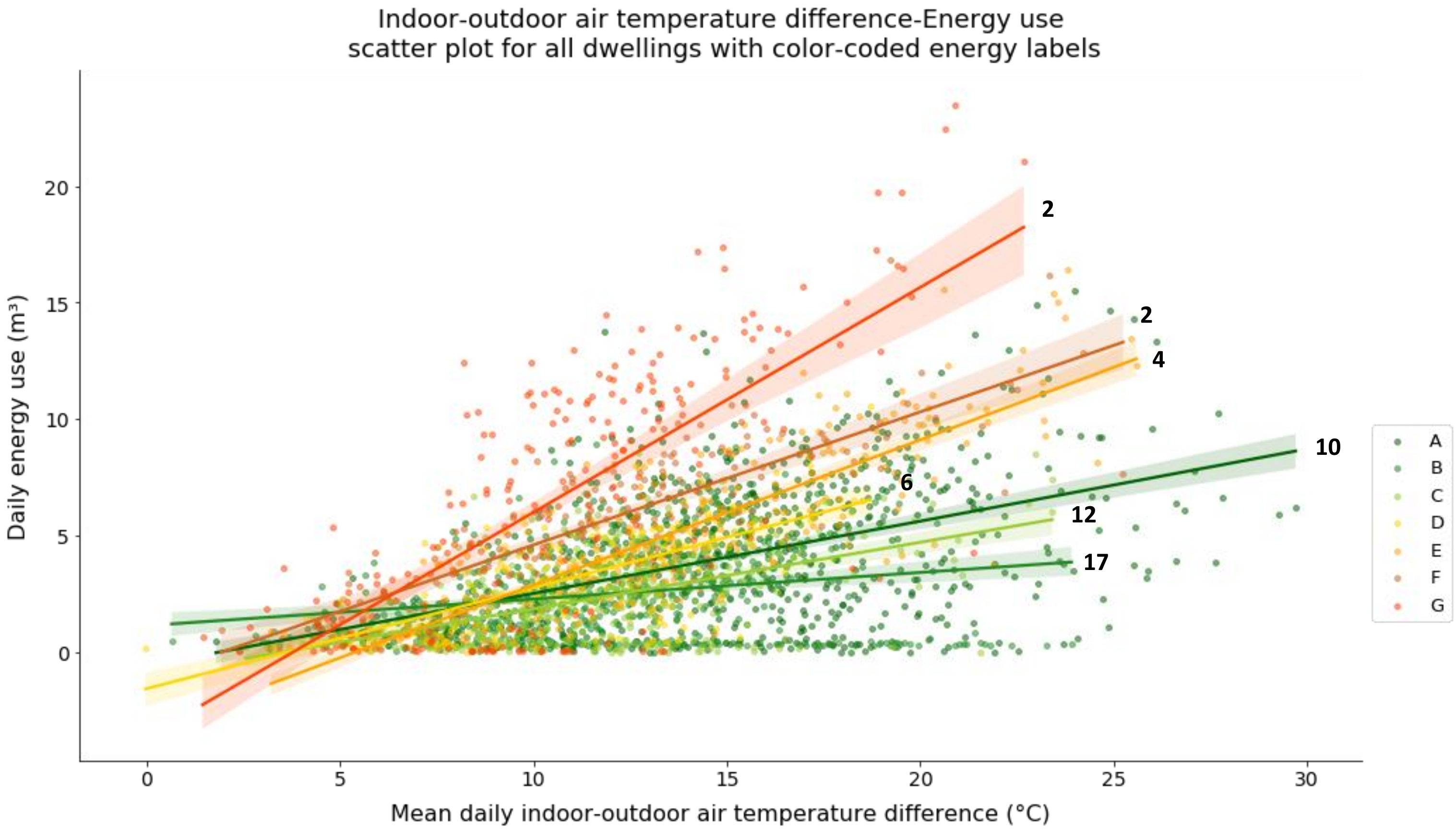


Figure 8.6: *Scatterplot of mean daily indoor-outdoor air temperature difference and daily energy use with color-coded energy labels for all dwellings with the actual number of dwellings per energy label shown next to the regression lines. (Source: own)*

Table 8.6: *Table showing the number of dwellings and data points per energy label taken into account in Figure 8.6. (Source: own)*

ENERGY LABEL	NO. OF DWELLINGS	NO. OF DATA POINTS
A	10	811
B	17	556
C	12	434
D	6	180
E	4	267
F	2	160
G	2	225

Figure 8.6 indicates the scatterplot with the mean daily indoor-outdoor air temperature difference and the daily gas use on the x and y axes correspondingly, while also the energy labels are illustrated with different colours. At the same time, the regression line per energy label is shown, where the translucent band around them represents the size of the confidence interval, which largely depends on the sample size and the variability of the data. Therefore, the smaller the sample size or the higher the variability, the wider the confidence interval with a larger margin of error. In this case, it can be concluded that going from higher to lower energy rating dwellings, the gas use is higher for the same indoor-outdoor air temperature difference. This conclusion is a validation of the reason that dwellings are divided into different energy labels categories. However, it is worth mentioning that based on this sample, energy labels B and C seem to consume less gas than energy label A for maintaining the same indoor-outdoor air temperature difference.

8.3.2 Statistical relation between energy use and energy labels

In this section, the seventeenth hypothesis (H17), as shown in Table 8.7, will be tested by carrying out a Kruskal-Wallis test, as this was described in section 3.4.

Table 8.7: *17th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q5	**H17**	The energy use is not related with the energy labels.	Energy use	Energy labels	Kruskal-Wallis

This will help to find out if there is a relationship between energy use and energy labels. These two variables are not directly linked in the conceptual diagram, but since the energy label categorization is based on the overall energy performance, a relationship between them exists.

As shown in Table 8.8, since 0.000 < 0.050 (chosen significance level), the null hypothesis is rejected and therefore, the energy use is related to the energy label.

Table 8.8: *Kruskal-Wallis test for daily energy use and energy labels for winter for all dwellings. (Created in SPSS)*

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Daily energy use is the same across categories of Energy labels.	Independent-Samples Kruskal-Wallis Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .050.

In Figure 8.7, the boxplots are displayed, showing the variation of the daily energy use along all dwellings per energy label.

The post-hoc test results are presented in Table 8.9, where all possible paired combinations have taken place in order to understand exactly in which energy labels the energy use differs significantly.

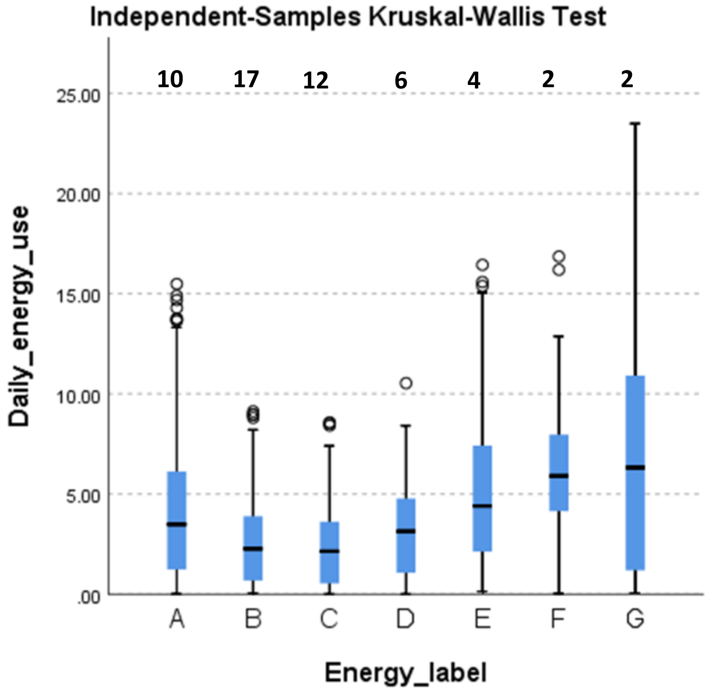


Figure 8.7: *Boxplot of energy use per energy label for winter for all dwellings. (Created in SPSS)*

Looking at Table 8.9 and comparing the significance with the chosen significance level of 0.05, it is concluded that all pairs of energy labels are characterised as statistically different except for the pairs B-C and E-G.

Table 8.9: *Post-hoc test after Kruskal-Wallis test pairing all different energy labels with each other for winter. (Created in SPSS)*

Pairwise Comparisons of Energy_label

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
C-B	78.947	49.674	1.589	.112	1.000
C-D	-260.048	68.754	-3.782	.000	.004
C-A	402.847	45.628	8.829	.000	.000
C-E	-629.599	60.319	-10.438	.000	.000
C-G	-682.698	63.709	-10.716	.000	.000
C-F	-907.003	71.727	-12.645	.000	.000
B-D	-181.100	66.506	-2.723	.006	.181
B-A	323.900	42.164	7.682	.000	.000
B-E	-550.652	57.743	-9.536	.000	.000
B-G	-603.750	61.276	-9.853	.000	.000
B-F	-828.056	69.575	-11.902	.000	.000
D-A	142.799	63.541	2.247	.025	.689
D-E	-369.551	74.793	-4.941	.000	.000
D-G	-422.650	77.553	-5.450	.000	.000
D-F	-646.956	84.263	-7.678	.000	.000
A-E	-226.752	54.302	-4.176	.000	.001
A-G	-279.851	58.045	-4.821	.000	.000
A-F	-504.156	66.747	-7.553	.000	.000
E-G	-53.099	70.183	-.757	.449	1.000
E-F	-277.404	77.534	-3.578	.000	.010
G-F	224.306	80.200	2.797	.005	.145

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.

Asymptotic significances (2-sided tests) are displayed. The significance level is .05.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

8.4 Energy use and ventilation type

In this section, the part of the 5th research question that refers to the relation between energy use, temperature difference and ventilation type is studied.

> *5. What is the relationship between **energy use and air temperature** taking into account comfort perception, energy label, **ventilation system** as well as household characteristics?*

8.4.1 Indoor-outdoor air temperature difference, energy use and ventilation type scatter plot

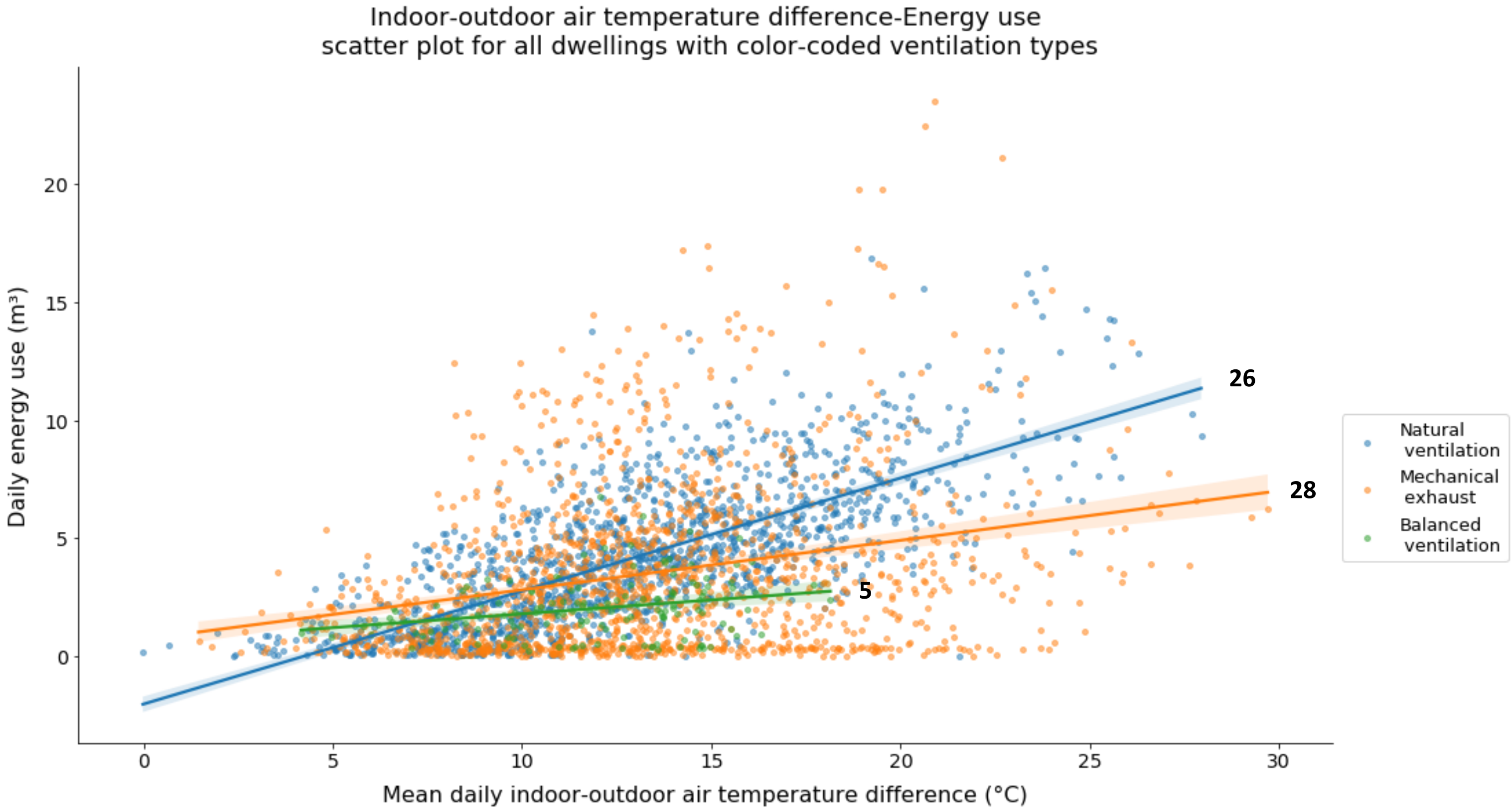


Figure 8.8: *Scatterplot of mean daily indoor-outdoor air temperature difference and daily energy use with color-coded types of ventilation for all dwellings with the actual number of dwellings per ventilation type shown next to the regression lines. (Source: own)*

Table 8.10: *Table showing the number of dwellings and data points per ventilation type taken into account in Figure 8.8. (Source: own)*

VENTILATION TYPE	NO. OF DWELLINGS	NO. OF DATA POINTS
NATURAL VENTILATION	26	1432
MECHANICAL EXHAUST	28	1383
BALANCED VENTILATION	5	146

Figure 8.8 shows the same scatterplot as presented before, but this time with the ventilation type instead of the energy labels. It can be concluded that going from natural ventilation to mechanical exhaust and then balanced ventilation, the gas use is higher for the same indoor-outdoor air temperature difference. This can be explained by the fact that natural ventilation results in larger ventilation losses in comparison with the other two types of ventilation, while the balanced system is considered to be the best among them.

8.4.2 Statistical relation between energy use and ventilation types

In this section, the eighteenth hypothesis (H18), as shown in Table 8.11, will be tested by carrying out a Kruskal-Wallis test, as this was described in section 3.4.

Table 8.11: *18th null hypothesis and statistical test. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Dependent Variable	Independent Variable	Statistical test
Q5	**H18**	The energy use is not related with the type of ventilation.	Energy use	Ventilation type	Kruskal-Wallis

This will help to find out if there is a relationship between energy use and ventilation types. These two variables are not directly linked in the conceptual diagram, but the type of ventilation affects the indoor air temperature, which then influences the energy use.

As shown in Table 8.12, since 0.000 < 0.050 (chosen significance level), the null hypothesis is rejected and therefore, the energy use is related to the ventilation type.

Table 8.12: *Kruskal-Wallis test for daily energy use and ventilation types for winter for all dwellings. (Created in SPSS)*

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Daily energy use is the same across categories of Ventilation types.	Independent-Samples Kruskal-Wallis Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .050.

In Figure 8.9, the boxplots are displayed, showing the variation of the daily energy use along all dwellings per ventilation type.

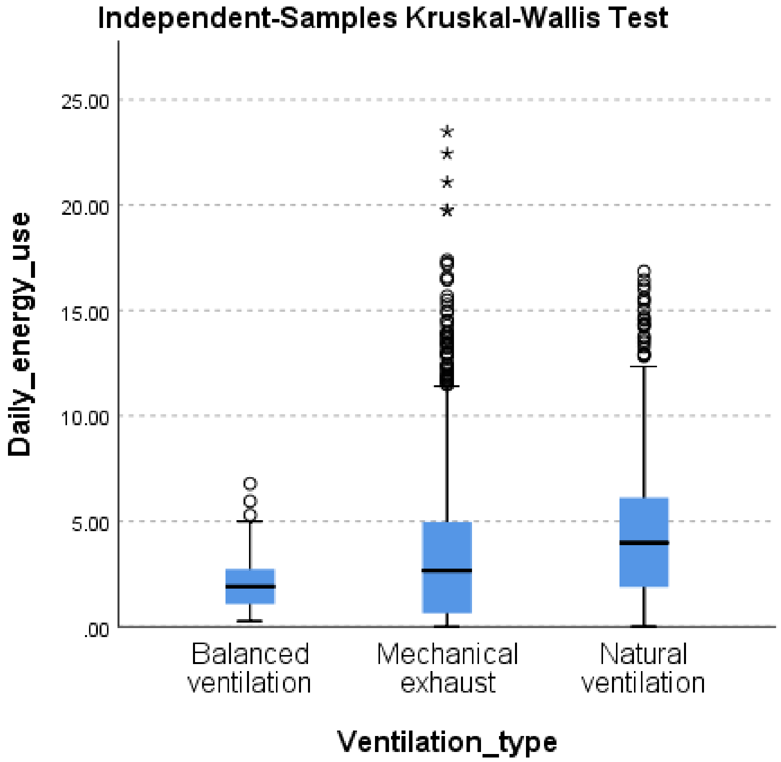


Figure 8.9: *Boxplot of energy use per ventilation type for winter for all dwellings. (Created in SPSS)*

The post-hoc test results are presented in Table 8.13, where all possible paired combinations have taken place in order to understand exactly in which ventilation type the energy use differs significantly.

Looking at Table 8.13 and comparing the significance with the chosen significance level of 0.05, it is concluded that all pairs of ventilation types are characterised as statistically different.

Table 8.13: *Post-hoc test after Kruskal-Wallis test pairing all different ventilation types with each other for winter. (Created in SPSS)*

Pairwise Comparisons of Ventilation_type

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Balanced ventilation-Mechanical exhaust	-327.558	77.911	-4.204	.000	.000
Balanced ventilation-Natural ventilation	-663.882	77.462	-8.570	.000	.000
Mechanical exhaust-Natural ventilation	-336.324	33.008	-10.189	.000	.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .05.
a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

8.5 Energy use and income

In this section, the last part of the 5th research question that refers to the relation between energy use and household characteristics explores if the monthly income influences the mean monthly energy use.

> *5. What is the relationship between **energy use** and air temperature taking into account comfort perception, energy label, ventilation system as well as **household characteristics**?*

8.5.1 Energy use and income scatter plot

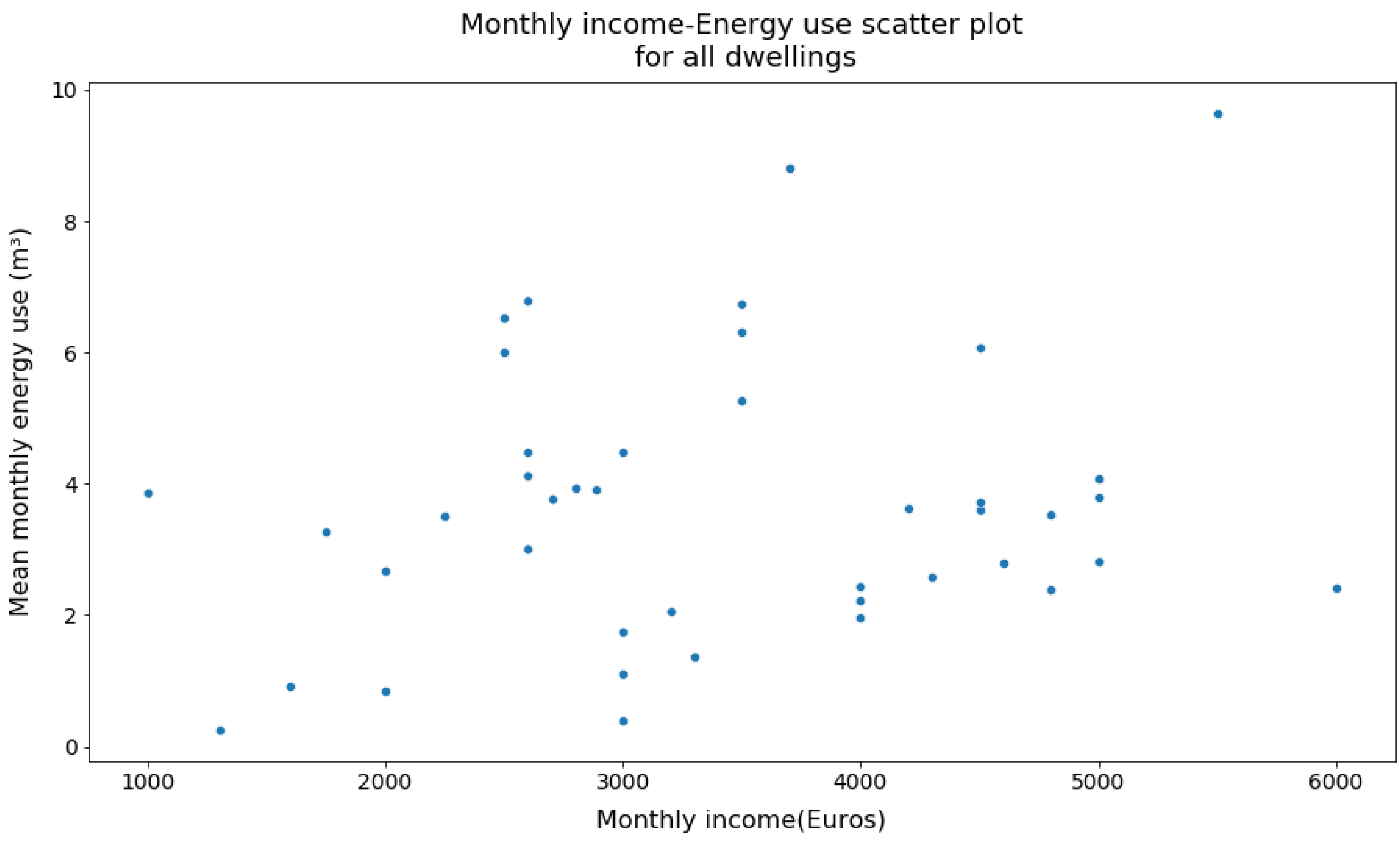


Figure 8.10: *Scatterplot of monthly income and mean monthly energy use for all dwellings. (Source: own)*

In contrast with all previous sections of this chapter, here in order to relate the monthly income with the energy use, the mean monthly energy use was calculated per dwelling and coupled with the monthly income recorded per household. The scatterplot in Figure 8.10 does not indicate any significant relationship between monthly income and mean monthly energy use. It can be observed that there are dwellings with low monthly income and energy use as well, but also others that have lower income but much higher energy use.

8.6 Energy use and actions

In this section, the 6th research question that refers to the influence of the actions on the energy use is analysed.

6. Do actions like opening/closing the windows, setting the thermostat up/down, taking warm/cold shower influence the energy use significantly?

8.6.1 Indoor-outdoor air temperature difference, energy use and actions scatter plot

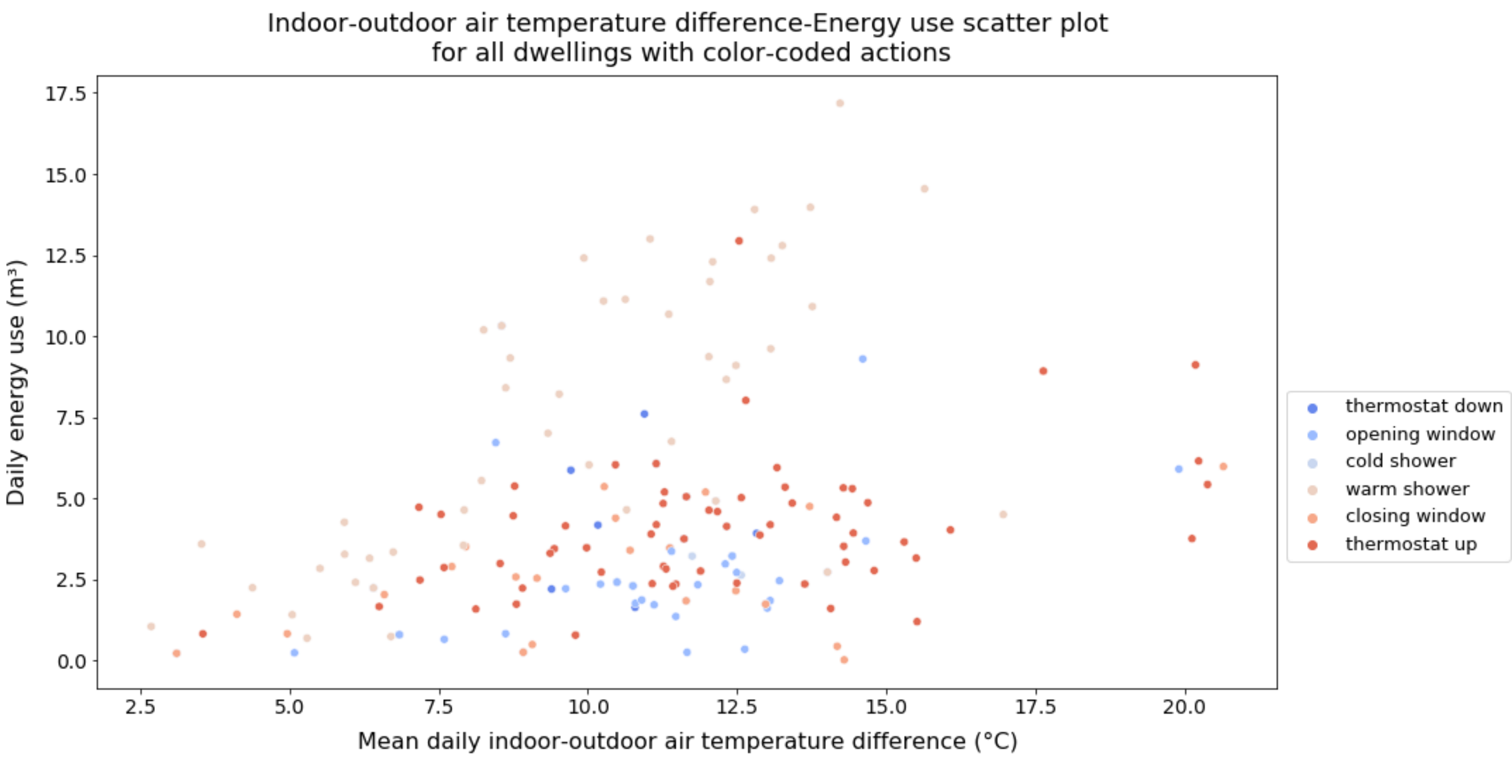


Figure 8.11: *Scatterplot of mean daily indoor-outdoor air temperature difference and daily energy use with color-coded energy-related actions for all dwellings. (Source: own)*

Figure 8.11 shows the same scatterplot, including now only the energy related actions of the occupants. These are opening/closing the window, turning the thermostat up/down, taking a warm/cold shower. However, the sample here is quite small with only 28 dwellings and 204 data points where the above-mentioned actions were reported by them. Thus, the small sample size might mislead the results or do not give a good indication about the relationship between the two variables. From the scatterplot, it can be observed that there is no clear relation between the 3 variables, apart from the fact that taking a warm shower increases the energy use by a lot. But this is reasonable since the gas use data used here includes gas consumption for both space heating and hot tap water. Other than that, all actions take place whatever the air temperature difference is and without large deviations on the energy use. To conclude, only warm shower creates a significant difference among the other actions.

8.7 Conclusions

In this chapter, the 5th and 6th research questions, as shown below, were investigated.

> 5. *What is the relationship between energy use and air temperature taking into account comfort perception, energy label, ventilation system as well as household characteristics?*
> 6. *To what extent do actions like opening/closing the windows, setting the thermostat up/down, taking warm/cold shower influence the energy use?*

Table 8.14 shows all null hypotheses that were tested in this chapter and which of them were rejected or accepted as well. The following hypotheses refer to the gas use and for that reason it is interesting to only study the heating period.

Table 8.14: *Hypotheses H15-H20 rejected or accepted. (Source: own)*

Research Question No.	Hypothesis No.	Null Hypothesis	Winter
Q5	H15	The energy use is not related with the indoor-outdoor air temperature difference.	Rejected
	H16	The energy use is not related with the thermal sensation.	Accepted
	H17	The energy use is not related with the energy labels.	Rejected
	H18	The energy use is not related with the type of ventilation.	Rejected
	H19	The energy use is not related with the income.	Accepted
Q6	H20	The energy use is not related with the actions.	Accepted

Regarding the 5th research question, it was concluded that the heating energy use is influenced by the indoor-outdoor air temperature difference, the energy labels as well as the ventilation type, but not by the occupants' thermal sensation and income.

First of all, it was found out that among indoor and outdoor air temperature, outdoor is the one that is higher correlated with gas use, meaning that it influences it more. In other words, the lower the outdoor air temperature, the higher the gas consumption is. No clear pattern could be recognised between indoor air temperature and gas use. In order to take both indoor and outdoor air temperature into consideration though, the difference between them was calculated and it was concluded that there is a linear relationship with gas use. More specifically, the higher the temperature difference, the more the energy use needed. This can be explained by referring to the transmission and ventilation heat losses, where according to their equation the higher the temperature difference, the higher the losses and therefore, the more energy is needed to heat the dwelling.

Moreover, the relation between energy use and reported thermal sensation was studied, but no significant relationship between them was found.

Then, the energy use was also researched in relation with the energy labels as well as the ventilation types. It was proven that both energy labels and ventilation types play a significant role in the dwellings' gas use. More specifically, it is reasonable that a dwelling with lower energy rating needs higher amount of daily energy than one with higher energy rating for the same mean daily air temperature difference. Similar for the ventilation type, it was proven that naturally ventilated dwellings need more daily gas than mechanically ventilated dwellings and the latter more than balanced ventilated dwellings for the same mean daily air temperature difference.

The last part of the 5th research question explored if there is any relation between the mean monthly energy use and the households' monthly income. However, in contrast with other research no significant relationship was found based on this data. A point of discussion here is the fact that it is not known if the monthly income reported from the occupants is the household's total income or only the member's filling in the survey.

As for the 6th and last research question, the relation between energy use and the actions taken by the tenants in order to feel more comfortable was investigated. The analysis did not indicate any significant difference on the impact that different actions have on the energy use. It is worth mentioning that the action of taking a warm shower seems to increase the energy use a lot. But this reasonably happens, because the gas use data includes both energy for space heating and hot tap water.

9 Results and Discussion

In this chapter assumptions and simplifications that were done and could influence the results will be mentioned and discussed.

General

- The quality and reliability of the Opschaler data plays an important role on the results, the interpretation and generalisation of them.

  Regarding the comfort app data, it is difficult and quite subjective to distinguish between all different thermal sensations and assess them. In addition, how each individual perceives the different levels of thermal sensation might differ. Regarding the surveys, there might be cases that the data is not that reliable or is missing, because, for example, the survey respondent did not care much about answering or did not want to share personal information such as income or other. Inspections also took place, but there is some uncertainty about it since the data was collected by students and not professionals.

  The smart meters and sensors used for the temperature data, gas use data and electricity use data are considered to be quite accurate on their measurements. However, they are still machines and inevitably sometimes things may go wrong, leading to gaps in the data.

  In addition, the number of dwellings participating in the monitoring campaign might be considered as a good sample size for analysis, but from a statistical point of view the data might be limited. Therefore, it is important to analyse here what the difference would be in case of a larger sample size.

  The size of the sample determines the amount of information available and as a result the precision or confidence level of the sample estimates. An estimate does always have a level of uncertainty, which is related with the variability of the data as well as the sample size. Thus, the more variable the population, the greater the uncertainty of the estimate and the larger the sample size, the more the available information and the lower the uncertainty.

  Figure 9.1 shows the difference in the confidence interval of an estimate for two different sample sizes. For example, in case of asking 100 dwellings and if 60 of them have a mechanical exhaust, it is estimated that the proportion in the NL is 60/100 = 60% with a 95% confidence interval ranging from 50.4% to 69.6% and a margin error of ±9.6%. On the other hand, in case of asking 900 more dwellings and if 600 out of 1000 dwellings have a mechanical exhaust, it is estimated that the proportion in the NL is again 60% but now with a considerably reduced 95% confidence interval ranging from 56.96% to 63.04% and a margin error of ±3.03%.

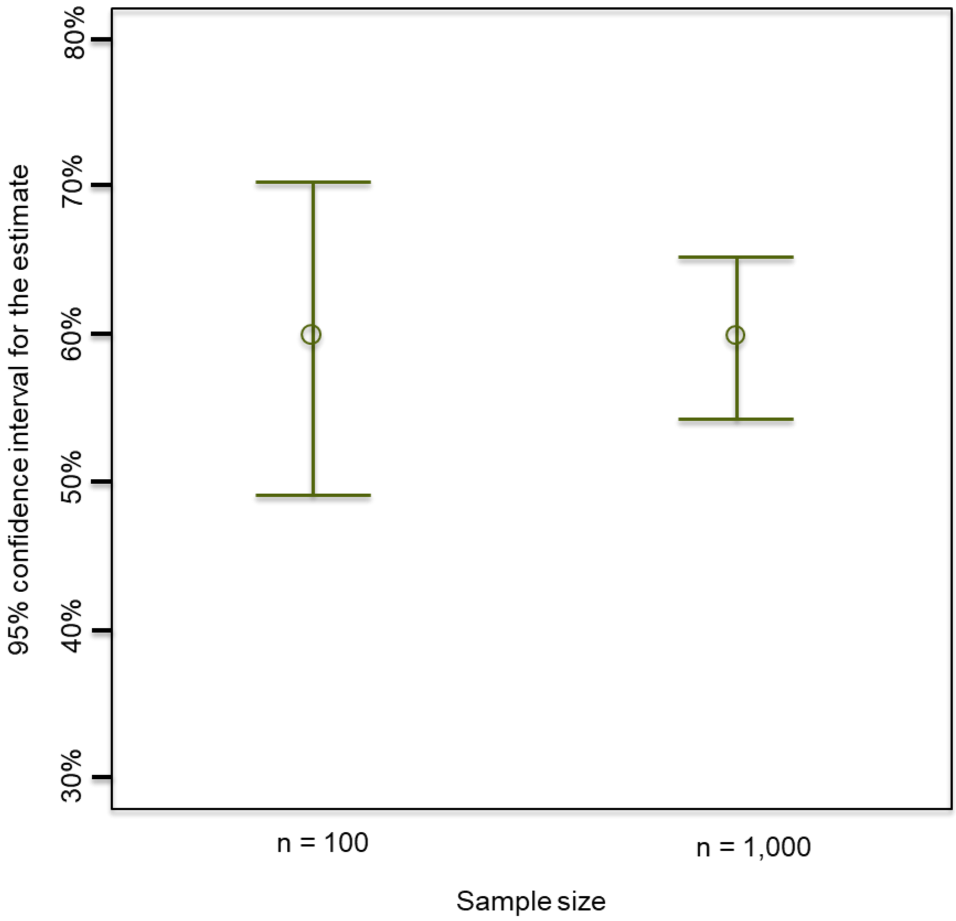


Figure 9.1: *Example with difference in the confidence interval of an estimate for two different sample sizes. (Source: own)*

Therefore, as the sample size increases, the confidence of the estimate increases, while the uncertainty decreases, and the precision is greater. All in all, in case of a larger sample, the results would become more robust and precise with less uncertainty.

An example based on the current data sample regarding the energy labels in relation with the indoor-outdoor air temperature difference plotted against the energy use will be given. It was proven that the energy label A dwellings need more energy than energy label B and C dwellings for the same indoor-outdoor air temperature difference. But this result contradicts with the theory of the energy labels and therefore, it is assumed that a larger sample size with almost the same number of dwellings in all energy labels would give more precise and robust results.

- There is some uncertainty regarding the separation of the data into winter and summer, since it is done in a conventional way. The separation was done based on the theory considering October till March as winter months and April till September as summer months, but this is not always a guarantee. Lower temperatures might also be present during some summer days.

Comfort app data

- The analysis of the Comfort app data was done without taking into account the room of the dwelling or the time of the day of the reported thermal sensation. It was concluded that most data points were reported by the tenants while being in the living room and were quite uniformly distributed throughout the day with most data points in the evening. Ignoring the room but keeping in mind that most data points were reported in the living room, the conclusions made are most focused on the living room. However, there is a risk of misleading the results for the living room by keeping data from other rooms in the analysis. To continue with, the analysis was done without separating the data points that were reported into morning, afternoon, evening, night and therefore, no explicit conclusion could be made regarding the time of the reported thermal sensation.
- The thermal comfort graphs, created based on the total of data points, were compared with the standard PMV-PPD graph and conclusions were made. However, the number of data points might not be enough from a statistical point of view in order to make generalised conclusions. Moreover, due to limited data points in some categories, some of them were merged together in order to be able to run statistical tests. It is assumed that by merging them, the final result would not differ or being distorted.
- For analysing the metabolic activities and actions, due to the fact that more than one may have been reported by the tenants at the same timestamp, these were split into more data points keeping one of the metabolic activities and actions per data point while the rest of the reported data (timestamp, thermal sensation) were kept the same. This simplification was done in order to make it easier to analyse the data. Another way of doing that would be to consider the combination of the multiple reported metabolic activities or actions as a separate category. However, when trying this option, so many different combinations and hence, categories were created that it was not possible to analyse it.

Indoor air temperature

- For simplification for the analysis of the indoor air temperature it was assumed that living room and kitchen as well as bedrooms 1 and 2 had about the same temperatures and therefore the mean of the two rooms accordingly was calculated. This assumption is applicable for some dwellings, but it might not be for all of them and therefore, further research would be needed for more accurate results.
- The analysis was done by taking into account the Comfort app data points reported while being in the living room, kitchen, outside or other during the last half hour and coupling them with the mean indoor air temperature of the living room and kitchen.
- In addition, the thermal sensation was coupled with the indoor air temperature that was measured half an hour ago, because according to physics, some time is needed until the thermal sensation changes as the temperature also changes. The half an hour period was also chosen in order to be in accordance with the metabolic activities and

actions taken half an hour ago. However, it is uncertain if half an hour is the best-chosen duration for coupling thermal sensation and indoor air temperature.

- Another point of discussion is how the results would differ if the data was divided into morning, afternoon, evening and night, but also if instead of taking the temperature at a certain point of time, a period of time was chosen. For example, coupling the thermal sensation reported in the morning with the mean of the indoor air temperature measured during the same morning.
- The relation between indoor air temperature and thermal sensation was explored. However, a better measure for assessing thermal comfort is the operative temperature which is derived from air temperature, mean radiant temperature and air speed. In this case, due to the fact that mean radiant temperature and air speed were not measured, operative temperature could not be easily calculated and indoor air temperature was used instead.

Energy use

- Regarding the energy use analysis, it is critical to mention that the gas use measurements included gas use for both space heating and hot tap water, while for simplification reasons no separation took place afterwards. However, such simplification does not mislead the results of this study, since no in detail research regarding space heating and hot tap water influenced by different parameters takes place.
- It is worth mentioning here that the high thermal mass structures use more energy than low thermal mass structures. Both occupancy and thermal mass can influence the overall energy use, but they are not taken into account in this study.
- The gas use was chosen to be analysed in a daily basis, considered as an appropriate period of time to be coupled with temperature, but also weekly or monthly could be chosen as well.
- The daily gas use was coupled with the mean daily temperature of the living room since this room is considered to be the main heated room throughout the day. However, due to the fact that daily data was used, more details like which time of the day the indoor air temperature or the gas use were the highest cannot be explored.
- The mean daily indoor air temperature might be influenced a lot by lower temperatures during night that occupants might turn the thermostat off or set it at a lower temperature and thus, influencing the relation with gas use.
- The calculated mean monthly energy use might not be representative for all dwellings, since some of them might have available data for two winter months and other for all winter months. Additionally, regarding the monthly income, there is some uncertainty about the reported income. Was it the total income of their household or only the respondent's personal one? In order to get a valid relation between gas use and income, the total income per household is needed.

Outdoor temperature

- For the mean daily outdoor temperature only the closest KNMI station per dwelling was chosen. However, it would be more representative to take the mean temperature of at least the 2 or 3 closest KNMI stations, but this was a time-consuming procedure that did not take place in this study.

10 Conclusions and Recommendations

10.1 Introduction

The broader aim of the current thesis was to explore the relation between different parameters and identify the factors that affect the occupants' thermal comfort and thus, the actual energy used by them. The different parameters included dwelling and installation characteristics, outdoor and indoor climatic parameters, household and physiological characteristics as well as occupants' person or energy related actions. Such exploration would give some indications about whether PMV or adaptive thermal comfort models are appropriate to be used in the prediction of thermal comfort used in the prediction models of the heating energy use in dwellings. The existing thermal comfort models were developed either for mechanically ventilated buildings based on the steady-state conditions of the climate chambers or for naturally ventilated buildings based on statistical data from mostly warm climates. Therefore, the abovementioned models are not considered appropriate for naturally ventilated buildings in a cold climate like in the Netherlands, although they are largely used. Therefore, the current study is a step towards exploring the parameters that influence the indoor thermal comfort and energy use and should be taken more into account in such a climate. A first step towards this direction was done by Ioannou et al. by using a limited data with both subjective and quantitative data gathered by the Ecommon measurement campaign. Finally, the extended data gathered by the Opschaler monitoring campaign was used in this study as an additional step for validating and discovering the parameters that influence thermal comfort and energy use.

10.2 Main research question

The main research question of the current thesis was:

> *"Which internal, external, individual and contextual parameters influence the occupant's comfort perception and how is the total heating energy affected?*

In order to answer the main research question, 6 sub-questions were explored and answered in Chapters 5,6,7 and 8. By combining the answers to the sub-questions, the main research question can be answered as well.

Table 10.1 shows the relation between the main studied variables and the factors that were found to be related with or not.

All following conclusions are based on the Opschaler data, which after all needed procedures ended up with a sample size of maximum 78 dwellings and therefore, it is not certain if such a sample can allow for generalised conclusions. The results can give an indication about parameters that influence thermal comfort and as a result energy use, but further research is also needed with more extended data in order to validate these results as well.

The parameters that were found to be correlated with the thermal sensation are the four comfort related factors (thermal preference, clothing, metabolic activity, action), the energy labels, the ventilation types and the indoor air temperature. From the studied parameters, only age was resulted in not being associated with thermal sensation.

At this point, it is important to mention that thermal sensation and thermal preference do have a cause-and-effect relationship[2] and therefore, it can be concluded that the variables that influence the first, do influence the second as well. Therefore, the parameters that have an influence on thermal sensation, do also have on thermal preference as well.

Indoor air temperature is not part of the main research question but, since it was found to be a parameter that influences thermal sensation, some factors that might be related with it were explored and will be mentioned as well. Indoor air temperature was found to be related with the energy label of the dwellings, but not with their ventilation type.

Finally, the relation of the heating energy use and various parameters was studied. The results indicated that the heating energy use is related with the outdoor air temperature as well as with the indoor-outdoor air temperature difference, but not with the indoor air temperature. Furthermore, energy label and ventilation type were found to be related with the heating energy use, while thermal sensation, actions and income did not show any correlation with it.

Table 10.1: *Table showing the related and unrelated variables based on the current research. (Source: own)*

Variable	Is related with…	Less or not related with…
Thermal sensation	Thermal preference	
	Clothing	
	Metabolic activity	
	Actions	
	Indoor air temperature	
	Energy labels	Age
	Ventilation type	
Indoor air temperature	Energy labels	Ventilation type
Energy use	Outdoor air temperature	Indoor air temperature
	Indoor-outdoor air temperature difference	Thermal sensation
		Actions
	Energy labels	Income
	Ventilation type	

[2] Events that occur at the same time and place. One event appears before the other, with the second being unlikely to occur if the first has not occurred.

The results of the current thesis will be mentioned here along with other researchers' findings and especially Tasos Ioannou thesis.

First of all, thermal sensation is negatively correlated with thermal preference, which means that in general while thermal sensation increases, occupants prefer to feel cooler and while thermal sensation decreases, occupants prefer to feel warmer. The highest percentage (80%) of dissatisfied people, meaning people that would prefer a different thermal sensation, was observed while feeling "cold" during winter. In addition, it was found that occupants can withstand thermal sensations like "slightly warm" or "warm" in higher percentage.

Ioannou concluded that the PMV cannot accurately predict the actual thermal sensation and thus, other parameters should be taken into account as well. The PMV was mostly underestimating the thermal comfort, meaning that the tenants were feeling more comfortable than predicted by the model. Such a result is related with the occupants' psychological adaptation and expectation regarding thermal comfort, while that is different in an office building environment. In the current thesis, the PMV could not be calculated, but the PMV-PPD line was compared with the actual percentage of dissatisfied people per thermal sensation instead. From that it was concluded that the standard PMV-PPD line can both underestimate and overestimate the actual percentage of dissatisfied people, but this cannot be considered as a generalised conclusion since it is based on a limited number of data points.

The second parameter that influences the thermal sensation is the clothing type, resulting in a negative correlation between them. Similar to Ioannou conclusions, clothing type was proven to be an adaptation type towards thermal comfort, meaning that when people started feeling "slightly cold" or "cold" and preferred to feel "warmer", they were putting more clothes on. Similarly, in case people started feeling "slightly warm" or "warm" and preferred to feel "cooler", they were putting clothes off in order to feel more comfortable.

Moreover, indoor air temperature was found to be the third higher correlated parameter with thermal sensation. Their positive correlation indicates that as the indoor air temperature increases, it is more probable that occupants' thermal sensation also increases, making them feel warmer, while as the indoor air temperature decreases, it is more probable that occupants' thermal sensation decreases, resulting in feeling cooler.

The next parameter that affects occupants' thermal sensation but was found to have a lower correlation with it is the metabolic activity. As Ioannou also found in his thesis, their positive correlation implies that as the metabolic activity increases, which means that people instead of just sitting, they walk or do jogging at home, their thermal sensation also increases. However, it does not seem to be an adaptive behaviour in order to feel more comfortable, but more like daily habits that take place.

Another parameter is the actions that were taken half an hour before occupants reported their thermal sensation. It was concluded that some actions were taken by the occupants in order to adapt themselves in the thermal environment. Actions such as having a warm drink, putting clothes on and turning the thermostat up were taken for feeling warmer, while actions such as having a cold drink, putting clothes off and turning the thermostat down were taken for feeling cooler accordingly.

To continue with, energy labels were found to have an impact not only on thermal sensation, but also on indoor air temperature and energy use as well. The energy labels are calculated based on the overall energy performance of the dwelling, which can be said that is highly dependent on the thermal resistance of the building envelope. Hence, the higher the thermal resistance, the lower the transmission heat losses and the easier it is to heat and maintain the indoor air temperature at a constant and satisfying level. This can explain the association between indoor air temperature and energy labels, according to which, the higher energy label dwellings such as A and B have higher indoor air temperature than lower ones.

Ioannou and Majcen et al. findings showed that the percentage of occupants who reported their dwelling as being “too cold” increased when moving from A label to F label dwellings, which is reasonable due to the insulation thickness and airtightness of the dwellings. However, Ioannou also described that some occupants from higher energy label dwellings reported feeling “cold”, while some occupants from lower energy label dwellings were satisfied with the indoor air temperature. But that result needed further investigation regarding the actual amount of energy that was used in each case. In agreement with that, in the current thesis, occupants of higher energy rating dwellings were found to have more complaints regarding feeling “slightly cold” or “cold” in comparison with lower ones. Such a result can be explained by the fact that probably people in higher energy label dwellings have higher expectations when being aware of their well-insulated and airtight dwelling. However, as expected in summer, there were again more complaints about feeling “slightly warm” or “warm” by those living in higher energy label dwellings, due to the fact that the better the insulation, the harder it is for solar heat gains to get through resulting in overheated dwellings. Moreover, the daily heating energy use was found to be lower in higher energy rating dwellings comparing with lower ones for the same mean daily indoor-outdoor air temperature difference, which is reasonable based on the fact that the first have higher envelope’s thermal resistance.

Additionally, ventilation type was found to influence the occupants’ thermal sensation as well as the dwellings’ energy use. In theory, going from natural ventilation to mechanical exhaust and balanced ventilation, the ventilation heat losses and possible drafts are reduced. More complaints regarding thermal comfort were reported from occupants with balanced ventilated dwellings, which might be a misleading result due to low number of dwellings in that category. Another possible explanation could be again that people of higher energy label dwellings that are equipped with balanced ventilation have higher expectations regarding their thermal comfort. Comparing the other two ventilation types, natural ventilation leads to more complaints than mechanical exhaust during winter, while the opposite happens in summer. Regarding the relation between ventilation types and energy use, the theory was confirmed by the results which indicated that naturally ventilated dwellings need more daily gas than mechanically ventilated dwellings and the latter more than balanced ventilated dwellings for the same mean daily air temperature difference.

Last but not least, the heating energy use demonstrated a negative correlation with the outdoor air temperature. This means that the lower the outdoor air temperature, the higher the heating energy use. In addition to that, the relation with the indoor-outdoor air temperature difference was also explored and a positive correlation was identified. Thus, the higher the temperature difference, the more the heating energy needed to maintain a comfortable indoor environment. This is reasonable, because according to theory, the higher the temperature difference, the higher the transmission and ventilation heat losses and hence, the more energy is used.

To conclude, there are many parameters that influence the occupants' thermal comfort in a residential dwelling. The adaptive thermal comfort model seems to be more accurate and closer to the reality of such an environment in comparison with the steady-state PMV model, where no adaptations take place. Therefore, all the above-mentioned parameters that play a role on the occupants' thermal comfort should be taken into account in the developed models for predicting comfort, with the adaptive model being more promising for residential buildings. Regarding energy use and the parameters that influence it, it was proven that these are mostly building characteristics, installation characteristics as well as outdoor climatic conditions. In contrast with what researchers are trying to prove about the influence of the occupants' perception, characteristics and behaviour on the energy use, the current research did not show any relation, but that reliability of that result is uncertain due to the low number of data points.

10.3 Further research

The Opschaler gathered data and the current research offer a lot of possibilities for further research either by looking more in depth what was studied here or by taking into account more variables that were measured during the monitoring campaign but were not included in the current thesis.

Possible further research:

- While analysing the Comfort app data, take into account the respondent's room location, the duration of being in that room as well as the time of the day that the reported thermal sensation took place. This would give an indication about whether these variables play a role in the occupants' thermal sensation. For example, it might be that most people reported feeling "cold" at night or in the morning because of turning the thermostat off and the dwelling has not heated up yet.
- Mean radiant temperature and air velocity were not measured during the monitoring campaign, but they could be taken into account either by measuring them or by assuming them based on the literature. Then, by running simulations in the EnergyPlus software, the PMV could be calculated and be compared with the actual thermal sensation that people reported. In addition, the operative temperature could also be calculated and be used in place of the indoor air temperature as a measure for better assessing thermal comfort.

- Other indoor climate parameters that were measured could also be taken into account in the analysis and maybe help into explaining the occupants' reported thermal sensations as well as indoor air temperature and energy use. Such parameters are the CO_2 concentration in the room, the relative humidity in the room as well as the relative humidity in the bathroom.
- In addition, data related to the presence of people, based on the PIR sensors, could also be useful to create some kind of profiles and test the influence that people have on the energy use while being present or absent. The answers given to the questionnaire regarding the daily presence of occupants at home could be useful for analysing them further, creating occupancy profiles and combining them with measured data in order to end up with valuable conclusions.

10.4 Recommendations

The use of building simulation software for the analysis of new or refurbished buildings is a common practice among engineers, designers, developers and public authorities. Such software have highly been extended and improved throughout the years to reflect as much as possible the situation of real buildings. However, some of the many parameters taken into account in a building simulation are more important than others with regard to thermal comfort and energy consumption. Therefore, enhancing the quality and accuracy of the prediction models and software is highly linked with the better understanding of the impact that each parameter has on thermal comfort and energy use, which is the main topic of the current research.

First of all, regarding the existing thermal comfort models, the PMV and the adaptive model, it is not certain that they are appropriate for residential dwellings in the climate of the Netherlands. Especially the thermal sensation vote based on the 7-point scale is considered as quite a subjective evaluation which might differ per person and per climate. In addition, the possible impact of psychological thermal adaptation can make people perceive and adapt to situations differently due to their previous experiences and expectations. In order to take into account these adaptations and data related to thermal comfort, energy consumption and occupancy behaviour, sensor systems along with IT based application for gathering the subjective data could be used. Such information could be gathered for each dwelling separately and therefore, be analysed and used for the creation of personalised thermal comfort models for the occupants of each dwelling. By doing so, the goal of reducing the energy consumption in the building sector becomes more feasible, since more accurate predictions will take place, lowering the discrepancy between predicted and actual energy consumption in residential buildings.

Other than the simulation software, while designing in practice engineers should pay more attention in some parameters than in others in order to end up with a well-designed thermally comfortable and energy efficient dwelling. The results, as expected, showed that the energy label and the ventilation type of the dwelling do influence thermal comfort and energy use.

The energy label, determined by the energy index, is highly dependent on the construction of the building envelope as well as the building services. Therefore, the thermal resistance and the construction materials of the envelope are among the most influential parameters taking place. In other words, the thermal resistance of the insulation layer and the glazing do play a significant role in the total thermal resistance of the building envelope and much of attention should be given there. Given the fact that building properties, such as thermal resistance or ventilation flow rates, are cumbersome to measure in real life, data from smart meters could help towards this direction as well.

Differences in thermal comfort, indoor air temperature and energy use were even observed among dwellings with the same energy labels. From that, it can be concluded that it is not only the thermal resistance of the envelope and the building services that affect the abovementioned variables, but also the outdoor climate, the occupants' characteristics and behaviour in the dwelling regarding the temperature settings, clothing, metabolic activities and actions.

All in all, all over the world, there are different people, climates, behaviours, dwelling characteristics, expectations, economic situations, psychological adaptations and many other parameters that affect the thermal comfort as well as the energy consumption in the building sector, but the extent at which each one of them does, needs to be further investigated with larger datasets. Thus, instead of adjusting the current models for each climate and for all people in the world, the use of smart meter and sensors data along with artificial intelligence, machine learning and data analysis techniques could help towards creating personalised models for each single person individually. As a result, given that personalised models, the highest possible reduction of energy consumption will be achieved per household. In addition, the occupants' behaviour that leads to the lower energy consumption will be observed and therefore, guidelines will be given to the occupants in order to behave in a way that their dwelling will be more energy efficient.

11 References

[1] Balaras, C.A., Gaglia, A.G., Georgopoulou, E., Mirasgedis, S., Sarafidis, Y. and Lalas, D.P., 2007. European residential buildings and empirical assessment of the Hellenic building stock, energy consumption, emissions and potential energy savings. *Building and environment*, *42*(3), pp.1298-1314.

[2] Paolini, R., Zani, A., MeshkinKiya, M., Castaldo, V.L., Pisello, A.L., Antretter, F., Poli, T. and Cotana, F., 2017. The hygrothermal performance of residential buildings at urban and rural sites: Sensible and latent energy loads and indoor environmental conditions. *Energy and Buildings*, *152*, pp.792-803.

[3] Rosso, F., Pisello, A.L., Cotana, F. and Ferrero, M., 2014. Integrated thermal-energy analysis of innovative translucent white marble for building envelope application. *Sustainability*, *6*(8), pp.5439-5462.

[4] de Gracia, A., Navarro, L., Coma, J., Serrano, S., Romaní, J., Pérez, G. and Cabeza, L.F., 2018. Experimental set-up for testing active and passive systems for energy savings in buildings–lessons learnt. *Renewable and Sustainable Energy Reviews*, *82*, pp.1014-1026.

[5] Sadineni, S.B., Madala, S. and Boehm, R.F., 2011. Passive building energy savings: A review of building envelope components. *Renewable and sustainable energy reviews*, *15*(8), pp.3617-3631.

[6] Pisello, A.L., Piselli, C. and Cotana, F., 2015. Influence of human behavior on cool roof effect for summer cooling. *Building and Environment*, *88*, pp.116-128.

[7] Santín, O.G., 2010. *Actual energy consumption in dwellings: The effect of energy performance regulations and occupant behaviour* (Vol. 33). Ios Press.

[8] Lutzenhiser, L., 1992. A question of control: alternative patterns of room air-conditioner use. *Energy and Buildings*, *18*(3-4), pp.193-200.

[9] Jeeninga, H., Uyterlinde, M. and Uitzinger, J., 2001. Energy Use of Energy Efficient Residences, Report. *ECN and IVAM, Pelten*.

[10] De Wilde, P., 2014. The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in construction*, *41*, pp.40-49.

[11] Rinaldi, A., Schweiker, M. and Iannone, F., 2018. On uses of energy in buildings: Extracting influencing factors of occupant behaviour by means of a questionnaire survey. *Energy and Buildings*, *168*, pp.298-308.

[12] Janda, K.B., 2011. Buildings don't use energy: people do. *Architectural science review*, *54*(1), pp.15-22.

[13] Aydin, E., Brounen, D. and Kok, N., 2013. *The Rebound Effect in Residential Heating*. Working Paper.

[14] Gram-Hanssen, K., 2013. Efficient technologies or user behaviour, which is the more important when reducing households' energy consumption?. *Energy Efficiency*, *6*(3), pp.447-457.

[15] D'Oca, S., Hong, T. and Langevin, J., 2018. The human dimensions of energy use in buildings: A review. *Renewable and Sustainable Energy Reviews*, *81*, pp.731-742.

[16] Boomsma, C., Jones, R.V., Pahl, S. and Fuertes, A., 2019. Do psychological factors relate to energy saving behaviours in inefficient and damp homes? A study among English social housing residents. *Energy Research & Social Science*, *47*, pp.146-155.

[17] Poortinga, W., Steg, L. and Vlek, C., 2004. Values, environmental concern, and environmental behavior: A study into household energy use. *Environment and behavior*, *36*(1), pp.70-93.

[18] Gram-Hanssen, K., Kofod, C. and Petersen, K.N., 2004. Different everyday lives: different patterns of electricity use. In *Proceedings of the 2004 American Council for an Energy Efficient Economy* (pp. 1-13).

[19] Pigliautile, I., Casaccia, S., Morresi, N., Arnesano, M., Pisello, A.L. and Revel, G.M., 2020. Assessing occupants' personal attributes in relation to human perception of environmental comfort: Measurement procedure and data analysis. *Building and Environment*, *177*, p.106901.

[20] Fanger, P.O., 1970. Thermal comfort. Analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering.*

[21] Roaf, S., Nicol, F., Humphreys, M., Tuohy, P. and Boerstra, A., 2010. Twentieth century standards for thermal comfort: promoting high energy buildings. *Architectural Science Review*, *53*(1), pp.65-77.

[22] De Dear, R. and Brager, G.S., 1998. Developing an adaptive model of thermal comfort and preference.

[23] Ioannou, A. and Itard, L.C., 2015. Energy performance and comfort in residential buildings: Sensitivity for building parameters and occupancy. *Energy and Buildings*, *92*, pp.216-233.

[24] Fanger, P. (1973). Assessment of man's thermal comfort in practice. *Occupational And Environmental Medicine*, *30*(4), 313-324. https://doi.org/10.1136/oem.30.4.313

[25] Nicol, F., Humphreys, M., & Roaf, S. (2012). *Adaptive thermal comfort: principles and practice*. Routledge.

[26] Orosa, J., & Oliveira, A. (2011). A new thermal comfort approach comparing adaptive and PMV models. *Renewable Energy*, *36*(3), 951-956. https://doi.org/10.1016/j.renene.2010.09.013

[27] Peeters, L., Dear, R., Hensen, J., & D'haeseleer, W. (2009). Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy*, *86*(5), 772-780. https://doi.org/10.1016/j.apenergy.2008.07.011

[28] Likert, R. (1932). A technique for the measurement of attitudes. *Archives of psychology*.

[29] Shukor, S. A. A., Kohlhof, K., & Jamal, Z. A. Z. (2007, May). Development of a PMV-based thermal comfort modelling. In *18th IASTED International Conference on Modelling and Simulation* (pp. 670-675).

[30] Ekici, C. (2013, June). A review of thermal comfort and method of using Fanger's PMV equation. In *5th International Symposium on Measurement, Analysis and Modelling of Human Functions, ISHF* (pp. 61-64).

[31] Chen, K., Jiao, Y., & Lee, E. S. (2006). Fuzzy adaptive networks in thermal comfort. *Applied Mathematics Letters*, *19*(5), 420-426.

[32] Markov, D. (2002). Practical evaluation of the thermal comfort parameters. *Annual International Course: Ventilation and Indoor climate, Avangard, Sofia*, 158-170.

[33] Rocca, M. (2017, June). Health and well-being in indoor work environments: a review of literature. In *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)* (pp. 1-6). IEEE.

Yang, L., Yan, H., & Lam, J. C. (2014). Thermal comfort and building energy consumption implications–a review. *Applied energy*, *115*, 164-173.

[34] Arens, E., Humphreys, M. A., de Dear, R., & Zhang, H. (2010). Are 'class A'temperature requirements realistic or desirable?. *Building and Environment*, *45*(1), 4-10.

[35] Standard, A. S. H. R. A. E. (2013). Standard 55-2013: Thermal Environmental Conditions for Human Occupancy. *ASHRAE, Atlanta, GA*, *30329*.

[36] CEN, E. (2007). 15251, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. *European Committee for Standardization, Brussels, Belgium*.

[37] Nicol, J. F., & Humphreys, M. (1998). Understanding the adaptive approach to thermal comfort. *ASHRAE transactions*, *104*, 991-1004.

[38] Humphreys, M. (1975). *Field Studies of Thermal Comfort Compared and Applied*.

[39] Butera, F. M. (1998). —Principles of thermal comfort. *Renewable and Sustainable Energy Reviews*, *2*(1-2), 39-66.

[40] Brager, G. S., & De Dear, R. J. (1998). Thermal adaptation in the built environment: a literature review. *Energy and buildings*, *27*(1), 83-96.

[41] Dhaka, S., Mathur, J., Brager, G. and Honnekeri, A., 2015. Assessment of thermal environmental conditions and quantification of thermal adaptation in naturally ventilated buildings in composite climate of India. *Building and Environment*, *86*, pp.17-28.

[42] Kumar, S., Singh, M.K., Loftness, V., Mathur, J. and Mathur, S., 2016. Thermal comfort assessment and characteristics of occupant's behaviour in naturally ventilated buildings in composite climate of India. *Energy for Sustainable Development*, *33*, pp.108-121.

[43] Shahzad, S., Brennan, J., Theodossopoulos, D., Calautit, J.K. and Hughes, B.R., 2018. Does a neutral thermal sensation determine thermal comfort?. *Building Services Engineering Research and Technology*, *39*(2), pp.183-195.

[44] Humphreys, M.A. and Hancock, M., 2007. Do people like to feel 'neutral'?: Exploring the variation of the desired thermal sensation on the ASHRAE scale. *Energy and buildings*, *39*(7), pp.867-874.

[45] Wang, L. and Zheng, D., 2020. Integrated analysis of energy, indoor environment, and occupant satisfaction in green buildings using real-time monitoring data and on-site investigation. *Building and Environment*, *182*, p.107014.

[46] van den Brom, P., Meijer, A. and Visscher, H., 2018. Performance gaps in energy consumption: household groups and building characteristics. *Building Research & Information*, *46*(1), pp.54-70.

[47] Day, J.K., McIlvennie, C., Brackley, C., Tarantini, M., Piselli, C., Hahn, J., O'Brien, W., Rajus, V.S., De Simone, M., Kjærgaard, M.B. and Pritoni, M., 2020. A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort. *Building and Environment*, *178*, p.106920.

[48] Oseland, N. A. (1994). A comparison of the predicted and reported thermal sensation vote in homes during winter and summer. *Energy and Buildings*, *21*(1), 45-54.

[49] Humphreys, M. A., & Nicol, J. F. (2002). The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and buildings*, *34*(6), 667-684.

[50] Xu, C., Li, S., Zhang, X., & Shao, S. (2018). Thermal comfort and thermal adaptive behaviours in traditional dwellings: A case study in Nanjing, China. *Building and Environment*, *142*, 153-170.

[51] Beizaee, A., & Firth, S. (2011). A comparison of calculated and subjective thermal comfort sensation in home and office environment.

[52] Vadodaria, K., Loveday, D. L., & Haines, V. (2014). Measured winter and spring-time indoor temperatures in UK homes over the period 1969–2010: a review and synthesis. *Energy Policy*, *64*, 252-262.

[53] Becker, R., & Paciuk, M. (2009). Thermal comfort in residential buildings–failure to predict by standard model. *Building and Environment*, *44*(5), 948-960.

[54] Ioannou, A. and Itard, L., 2017. In-situ and real time measurements of thermal comfort and its determinants in thirty residential dwellings in the Netherlands. Energy and Buildings, 139, pp.487-505.

[55] Ioannou, A., Itard, L. and Agarwal, T., 2018. In-situ real time measurements of thermal comfort and comparison with the adaptive comfort theory in Dutch residential dwellings. Energy and Buildings, 170, pp.229-241.

[56] Ioannou, A., 2018. Thermal comfort and energy related occupancy behavior in Dutch residential dwellings. A+ BE| Architecture and the Built Environment, (27), pp.242-242.

[57] Santin, O. G., Itard, L., & Visscher, H. (2009). The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. Energy and buildings, 41(11), 1223-1232.

[58] Delzendeh, E., Wu, S., Lee, A., & Zhou, Y. (2017). The impact of occupants' behaviours on building energy analysis: A research review. Renewable and sustainable energy reviews, 80, 1061-1071.

[59] Samsuddin, S. (2020). *Investigation and development of a thermal comfort model for UK homes during heating season* (Doctoral dissertation, Loughborough University).

[60] Enescu, D. (2017). A review of thermal comfort models and indicators for indoor environments. *Renewable and Sustainable Energy Reviews*, *79*, 1353-1379.

[61] Itard, L., Ioannou, T., Meijer, A., & Rasooli, A. (2016). Development of improved models for the accurate pre-diction of energy consumption in dwellings. Monicair report, 111.

[62] García, J. A. O. (2010). *A review of general and local thermal comfort models for controlling indoor ambiences* (pp. 978-953). ISBN.

[63] Bluyssen, P. M. (2009). *The indoor environment handbook: how to make buildings healthy and comfortable*. Routledge.

[64] De Dear, R. J., & Brager, G. S. (2002). Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and buildings*, *34*(6), 549-561.

[65] Song, Y., Mao, F., & Liu, Q. (2019). Human Comfort in Indoor Environment: A Review on Assessment Criteria, Data Collection and Data Analysis Methods. *IEEE Access*, *7*, 119774-119786.

[66] C2h.gr. 2021. Energy Performance Certificates. [online] Available at: <https://www.c2h.gr/en/energy-performance-certificate> [Accessed 31 October 2021].

[67] Scribbr. 2021. Statistical tests: which one should you use?. [online] Available at: <https://www.scribbr.com/statistics/statistical-tests/> [Accessed 31 October 2021].

[68] Scribbr. 2021. An introduction to simple linear regression. [online] Available at: <https://www.scribbr.com/statistics/simple-linear-regression/> [Accessed 31 October 2021].

[69] SearchBusinessAnalytics. 2021. What is logistic regression? - Definition from WhatIs.com. [online] Available at: <https://searchbusinessanalytics.techtarget.com/definition/logistic-regression> [Accessed 31 October 2021].

[70] Ibm.com. 2021. *Interpreting adjusted residuals in Crosstabs cell statistics*. [online] Available at: <https://www.ibm.com/support/pages/interpreting-adjusted-residuals-crosstabs-cell-statistics> [Accessed 16 July 2021].

[71] Brownlee, J., 2021. How to Calculate Correlation Between Variables in Python. [online] Machine Learning Mastery. Available at: <https://machinelearningmastery.com/how-to-use-correlation-to-understand-the-relationship-between-variables/> [Accessed 31 October 2021].

[72] Statistics.laerd.com. 2021. Spearman's Rank-Order Correlation - A guide to when to use it, what it does and what the assumptions are.. [online] Available at: <https://statistics.laerd.com/statistical-guides/spearmans-rank-order-correlation-statistical-guide.php> [Accessed 31 October 2021].

12 APPENDIX

12.1 Installation characteristics

12.1.1 Type of thermostat

In Figure 12.1 the type of thermostat of all dwellings is presented. More than half of the dwellings, about 60.5%, had a programmable thermostat, almost 30% had a manual one, while a few of them had both options (manual/ programmable) available.

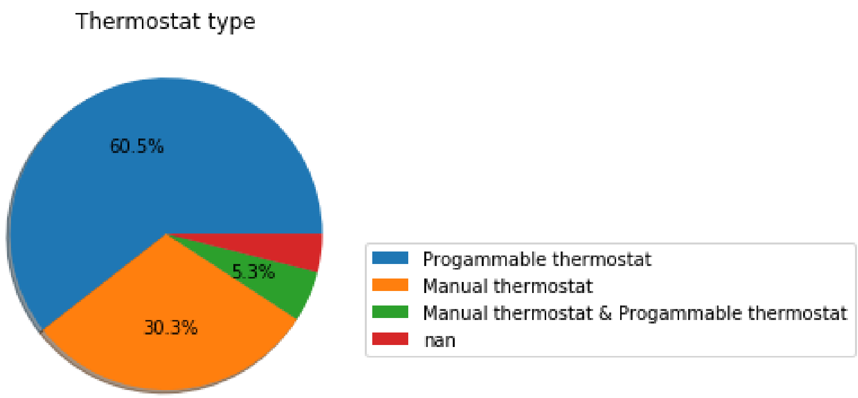


Figure 12.1: *Thermostat type.*

12.2 Household characteristics

12.2.1 Education level of the respondents

Regarding the education level of the tenants, it can be concluded there was a wide range of levels as indicated in the pie chart in Figure 12.2 with the two highest percentages being the WO (higher academic education) and the HBO (higher professional education).

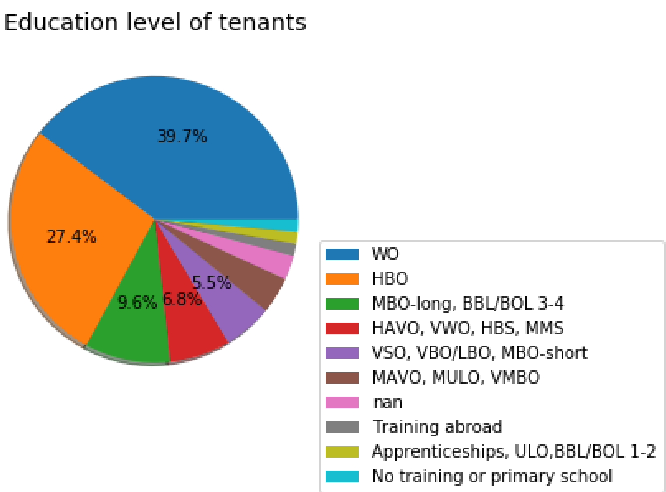


Figure 12.2: *Education level of the tenants.*

12.2.2 Income and ability to pay the energy bill

Figure 12.3 shows the reported net monthly income per household. Most households' monthly income ranges from 2500 to 4600 Euros, while there were some with higher and other with lower income.

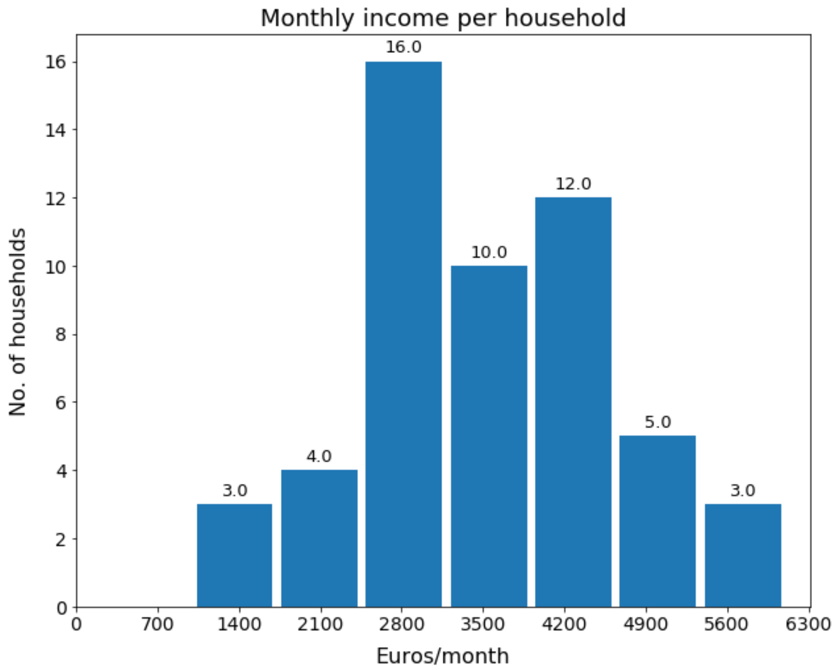


Figure 12.3: *Reported net monthly income per household.*

While Figure 12.4shows the monthly energy bill per household which for the majority of the dwellings was ranging between 80 and 150 Euros.

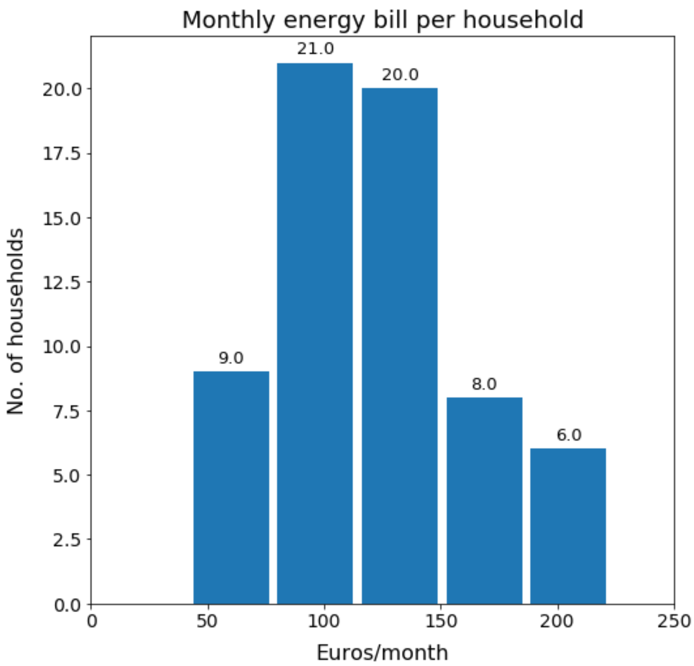


Figure 12.4: *Monthly energy bill per household.*

Tenants were asked to answer a question about their difficulty in paying their energy bill, as illustrated in Figure 12.5. The majority of the tenants found it easy or fairly easy to pay their monthly energy bill, while only 4 dwellings (with energy labels A, B and F) reported it as a bit difficult.

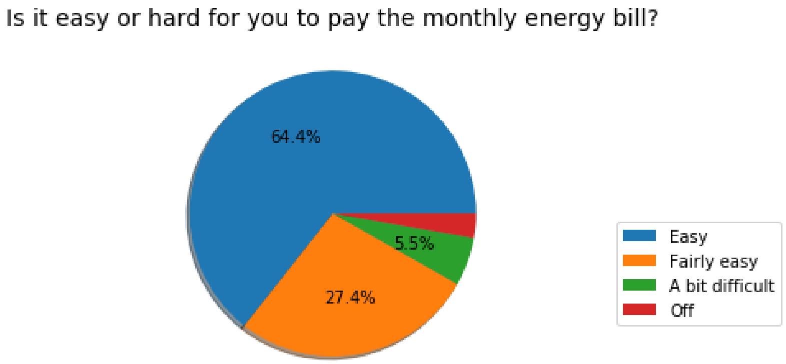


Figure 12.5: *Distribution of the answers to the question 'Is it easy or hard for you to pay the monthly energy bill?''*

In the scatterplot in Figure 12.6, the relation between the monthly income and the monthly energy bill is presented with the different colours representing the difficulty in paying the energy bill. Here only 2 households appear to find it a bit difficult to pay their energy bill (the other 2 are not shown due to missing info about their monthly income), which also seem to have somewhat low income and high energy bill compared to others as well. All in all, no clear relationship between income, energy bill and difficulty to pay was found.

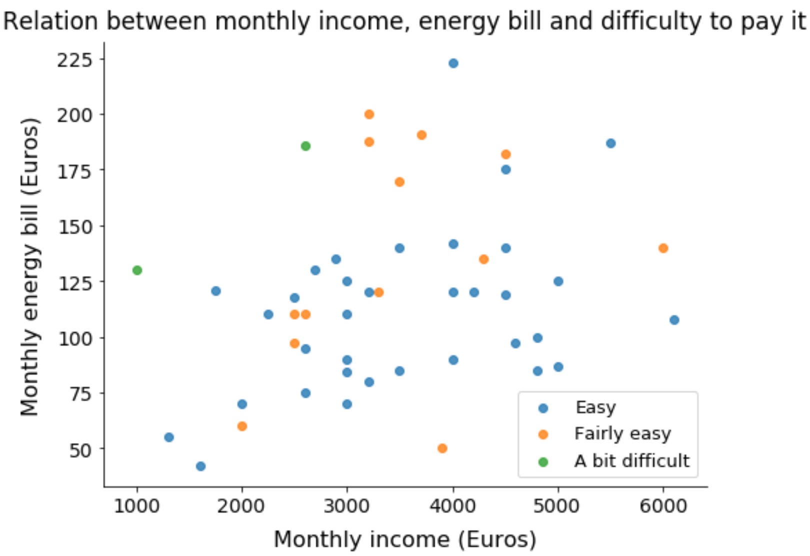


Figure 12.6: *Scatterplot showing the relation between monthly income, monthly energy bill and tenants' difficulty to pay it.*

12.3 Behaviour and General Comfort Perception

The survey included questions related to the tenants' habits and behaviour as well as their general comfort perception in their dwelling, as described in the following subsections.

12.3.1 Number of people present at home

In the survey, the number of people usually present at home was reported by the tenants for every day of the week and for morning, midday, evening and night. In this subsection, Figures 12.7-12.13 show the percentage of dwellings with certain number of people present for all different days and time. More explicitly, the different colours represent the number of people present at home, while the percentages are referred to the percentage of dwellings.

In Table 12.1 the number as well as the percentage of dwellings where a certain total number of people living there is shown.

Table 12.1: *Number and percentage of dwellings for certain number of people living.*

No. of people	*No. of dwellings*	*% of dwellings*
1.0	12	17.7 %
2.0	37	54.4 %
3.0	7	10.3 %
4.0	6	8.8 %
5.0	6	8.8 %

As observed in the graphs, during the weekdays, there is an average of 18% of the dwellings where during morning nobody was present at home, while an average of 22% of the dwellings where during midday nobody was present as well. On the other hand, during evening and night, it seems that almost all members of each dwelling were home.

Regarding the weekends, as expected almost all members were present throughout the whole day, while in just a few of them nobody was home.

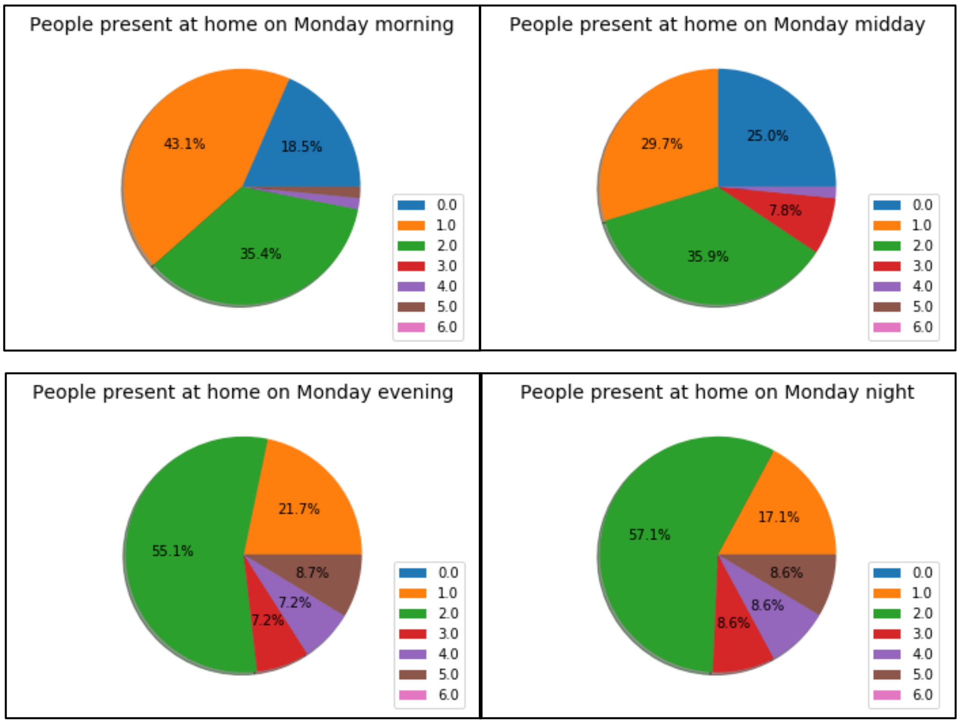


Figure 12.7: *Percentage of dwellings where certain number of people was present for Monday morning, midday, evening and night.*

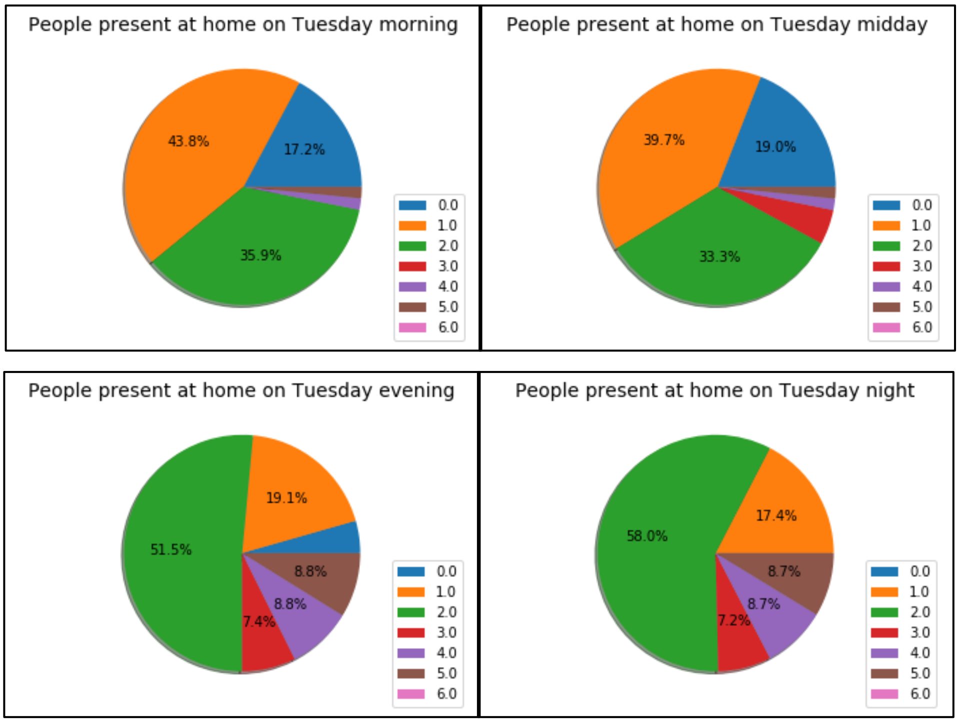


Figure 12.8: *Percentage of dwellings where certain number of people was present for Tuesday morning, midday, evening and night.*

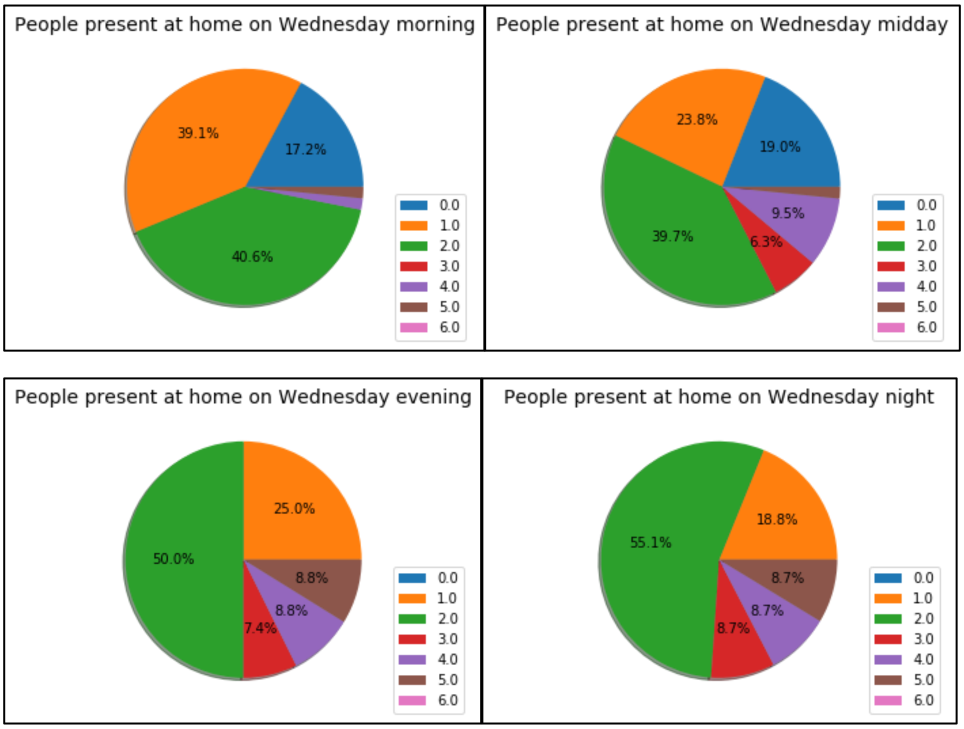


Figure 12.9: *Percentage of dwellings where certain number of people was present for Wednesday morning, midday, evening and night.*

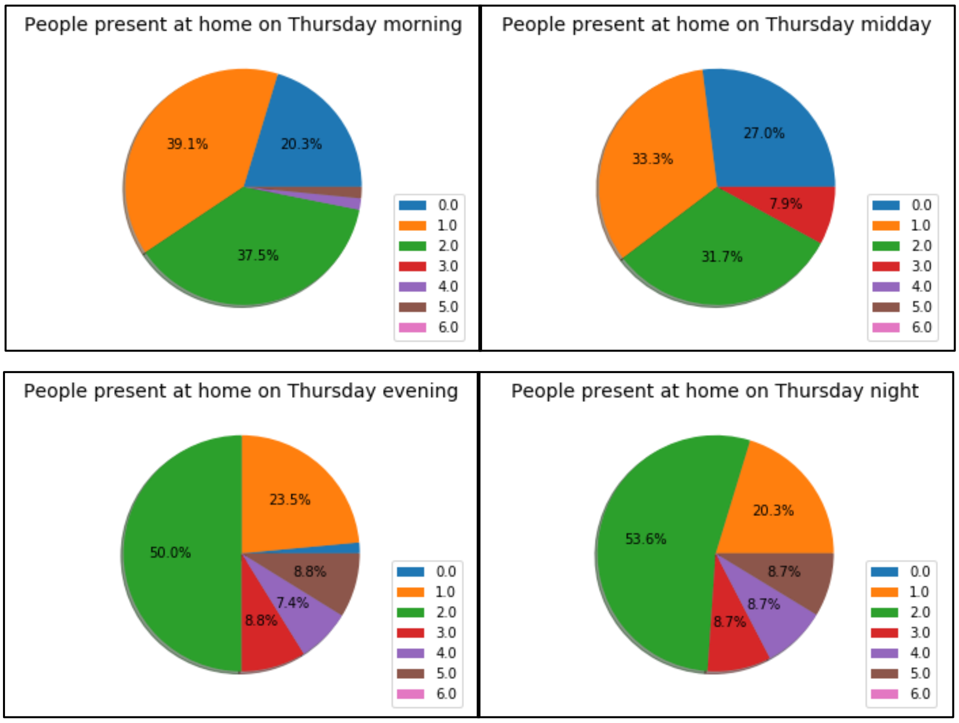


Figure 12.10: *Percentage of dwellings where certain number of people was present for Thursday morning, midday, evening and night.*

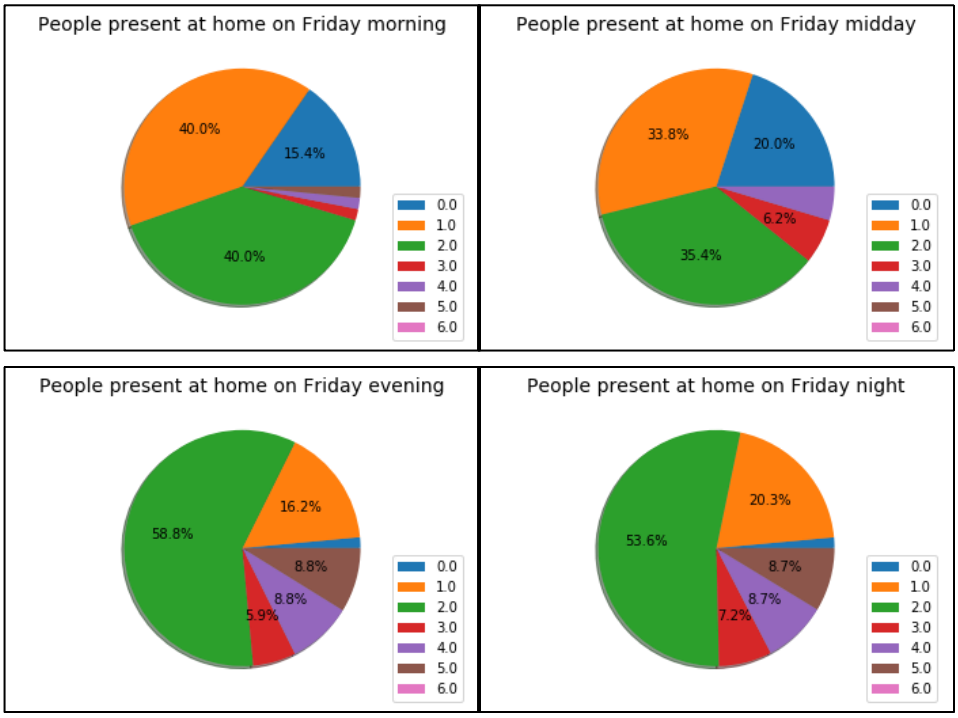


Figure 12.11: *Percentage of dwellings where certain number of people was present for Friday morning, midday, evening and night.*

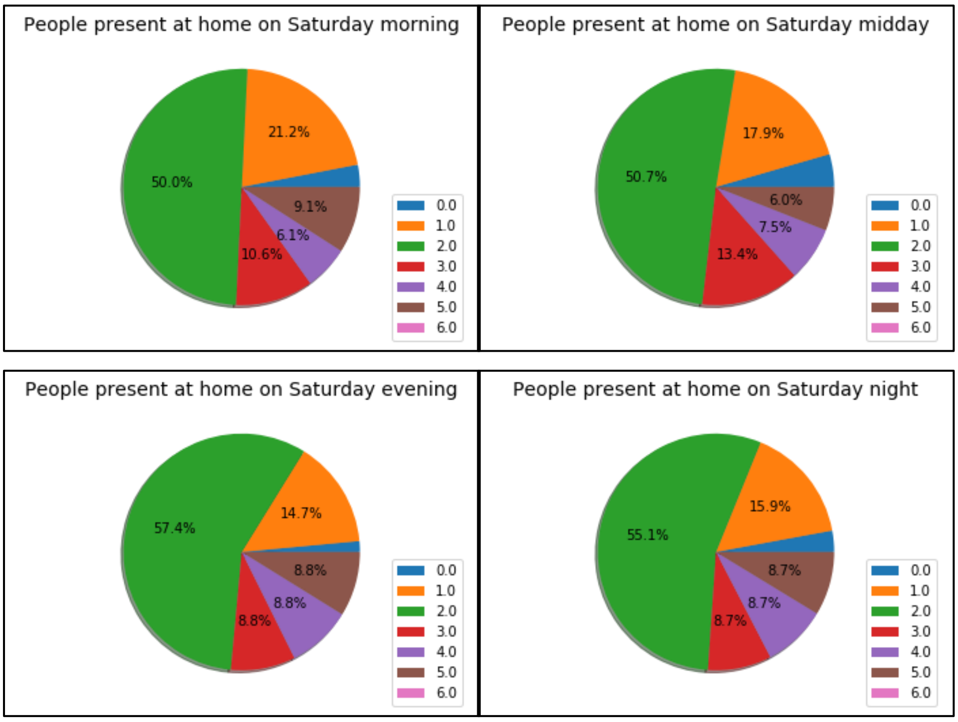


Figure 12.12: *Percentage of dwellings where certain number of people was present for Saturday morning, midday, evening and night.*

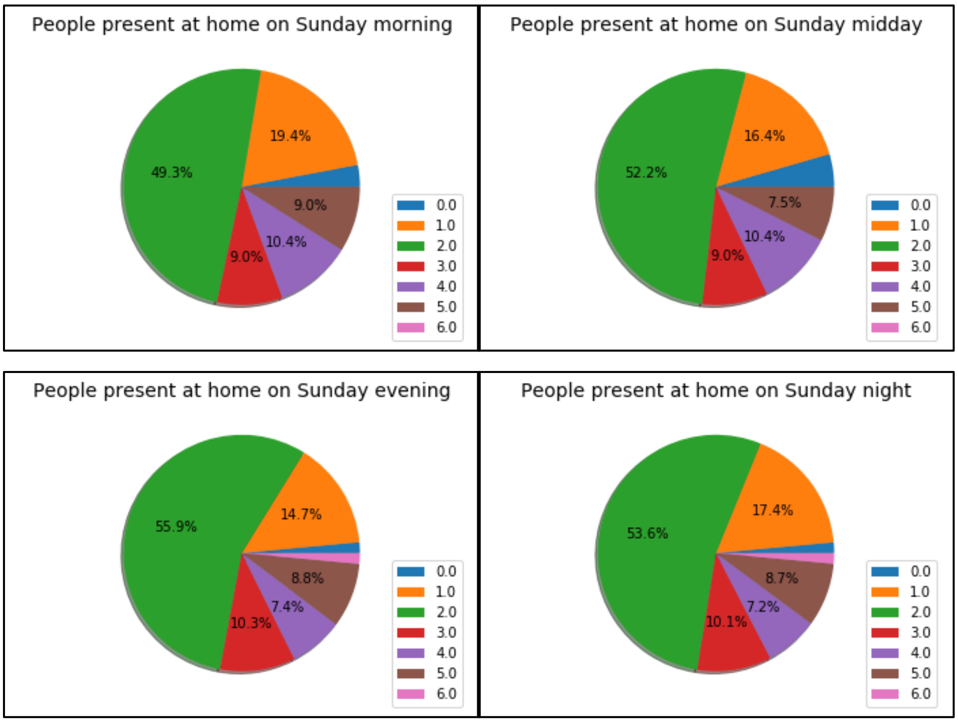


Figure 12.13: *Percentage of dwellings where certain number of people was present for Sunday morning, midday, evening and night.*

12.3.2 Heating behaviour

In this subsection, questions regarding the heating behaviour of the tenants were answered.

In Figure 12.14 the total number of rooms per dwelling is shown, according to which most dwellings have 6 rooms, while some have less and other have more.

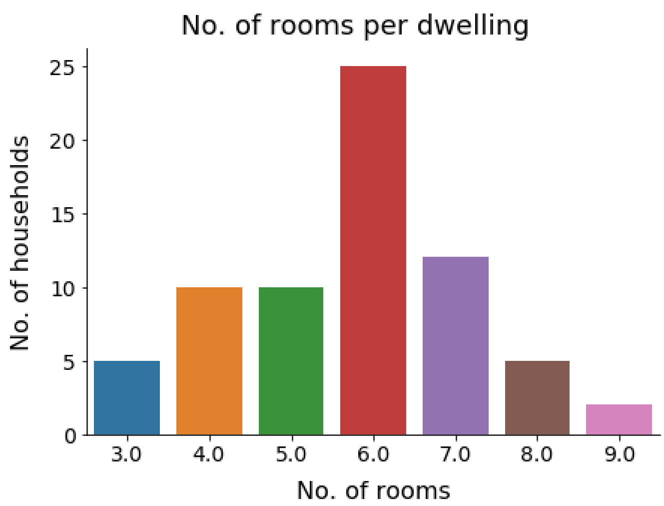


Figure 12.14: *No. of rooms per dwelling. (n=69 dwellings)*

In the survey, tenants were asked if they change the thermostat settings when they get home as well as if they heat the hallway during winter and how often.

Figure 12.15 shows that almost 60% of the dwellings change the thermostat sometimes, 23% often, while about 14% never do that. Figure 12.16 indicates that about 60% of the dwellings heats the hallway often or sometimes, while about 35% of them does not heat it at all.

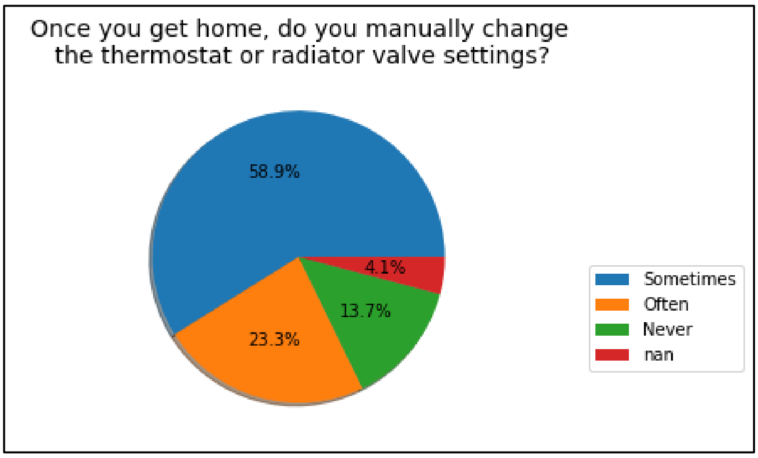


Figure 12.16: *Distribution of answers to the question: "Once you get home, do you manually change the thermostat or radiator valve settings?".*

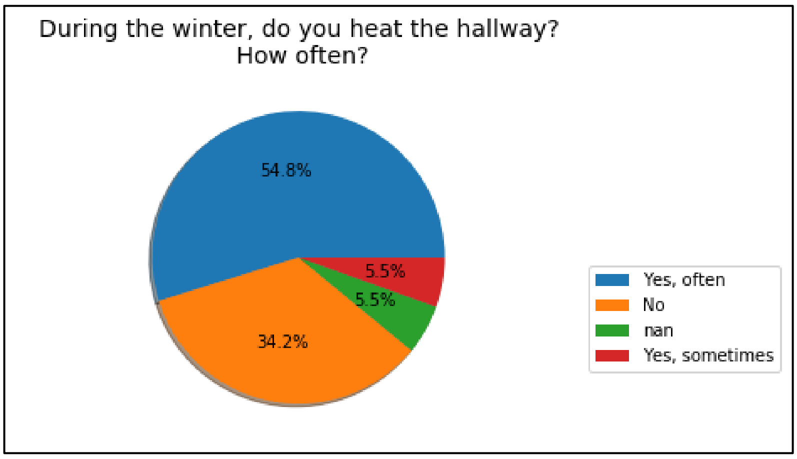


Figure 12.15: *Distribution of answers to the question: "During the winter, do you heat the hallway? How often?".*

In Figures 12.17 and 12.18, the number of rooms that were heated when nobody was at home and when someone was, respectively, is presented. It can be concluded that when there was nobody at home, about 15 out of 67 dwellings would not heat any of the rooms at all, while the rest would heat from 1 to 7 rooms. On the other hand, when there was someone home, during the day and evening most dwellings would heat 1 to 4 rooms, while at night about 14 of them would not heat the house at all.

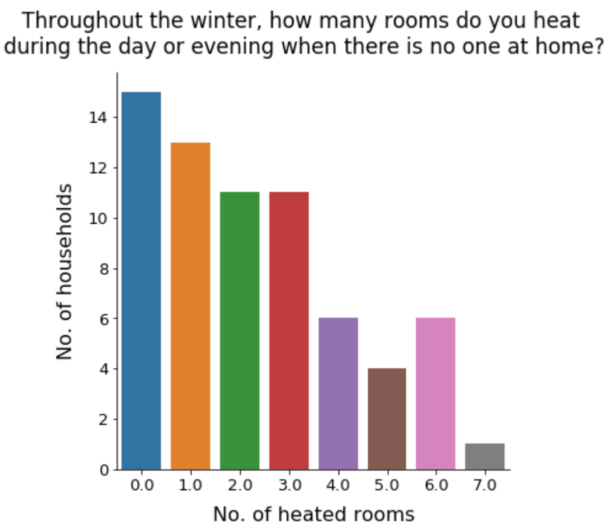


Figure 12.17: *No. of heated rooms when there is no one at home. (n= 67 dwellings)*

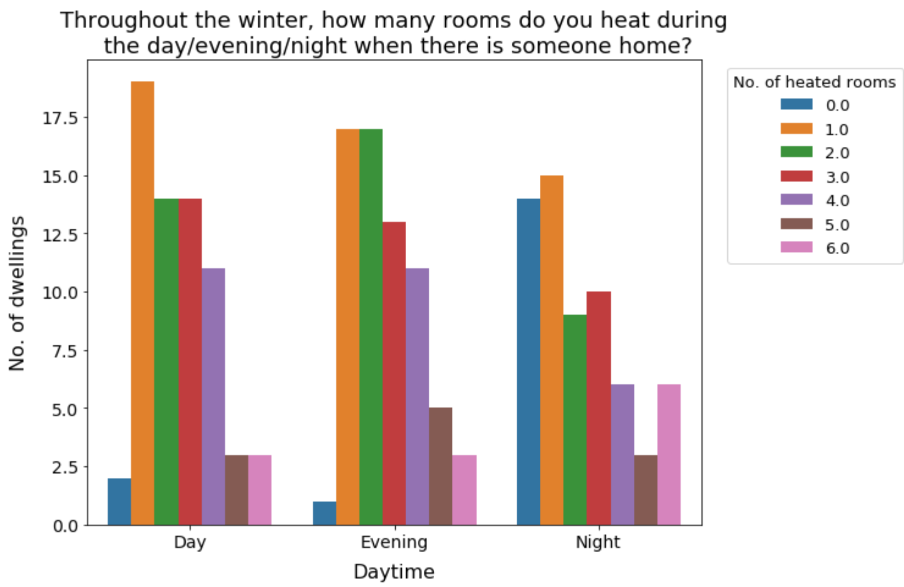


Figure 12.18: *No. of heated rooms when there is someone home. (n= 67 dwellings)*

12.3.3 Ventilation behaviour

In this subsection, the reported ventilation patterns (windows, doors, grilles) per room type and per ventilation system are described.

In Figure 12.19, for the living room and the kitchen of the naturally ventilated dwellings, the most usual answer (37%) was less than 1 hour, with 1-4 hours, 13-24 hours and, surprisingly, not ventilating at all following with the same percentages. For bedrooms almost half of the dwellings answered 13-24 hours, while for the bathroom half of the dwellings reported less than 4 hours and about 30% of them 9-24 hours.

For the dwellings with natural supply and mechanical exhaust, as shown in Figure 12.20, for the living room, the kitchen and the bedrooms the higher percentage (33%, 40% and 60% respectively) answered for 13-24 hours. For the bathroom, most dwellings reported either 1-4 hours or “not applicable”, which means that there are no windows or grilles in it.

For the balanced ventilation dwellings, as shown in Figure 12.21, it is important to mention that the majority of dwellings reported no ventilation at all in all types of rooms, relying on the mechanical ventilation.

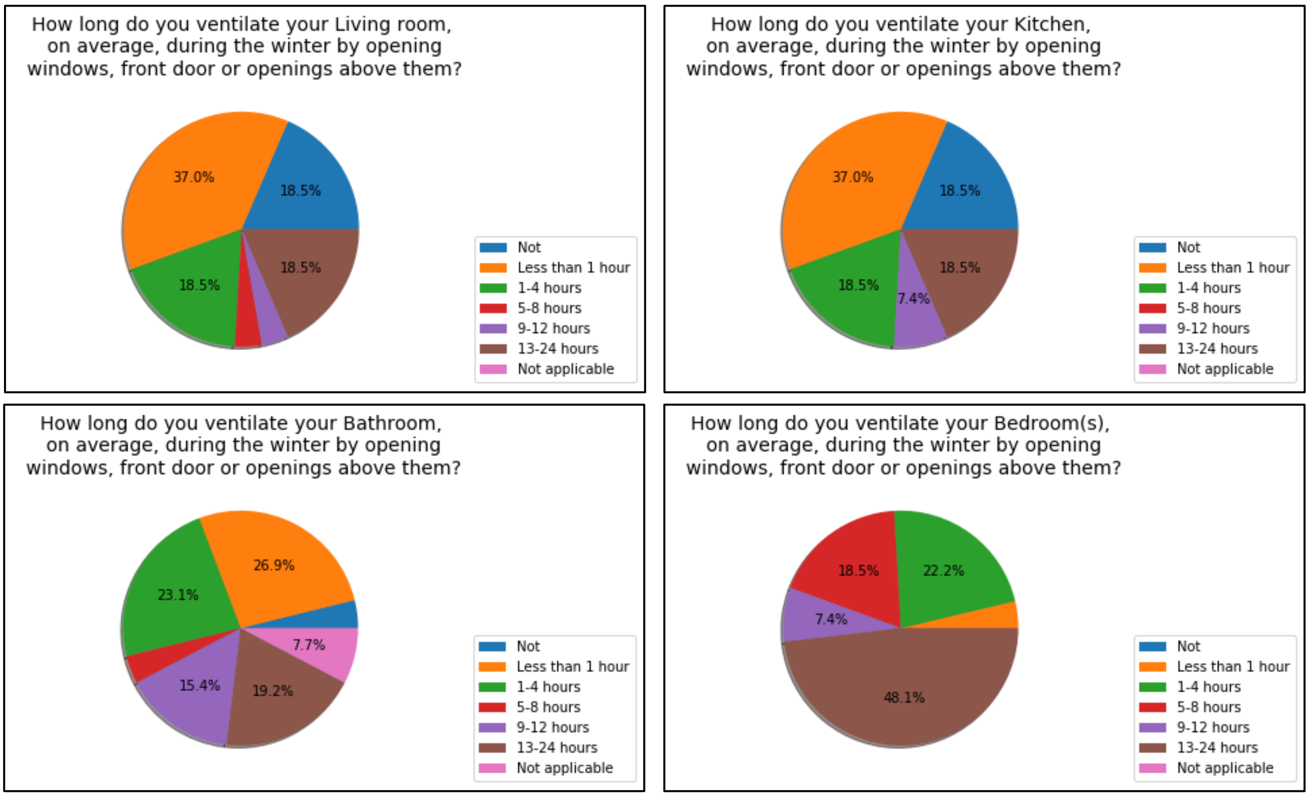


Figure 12.19: *Ventilation patterns for living room, kitchen, bathroom and bedrooms based on the survey-Dwellings with natural ventilation (n = 29 dwellings)*

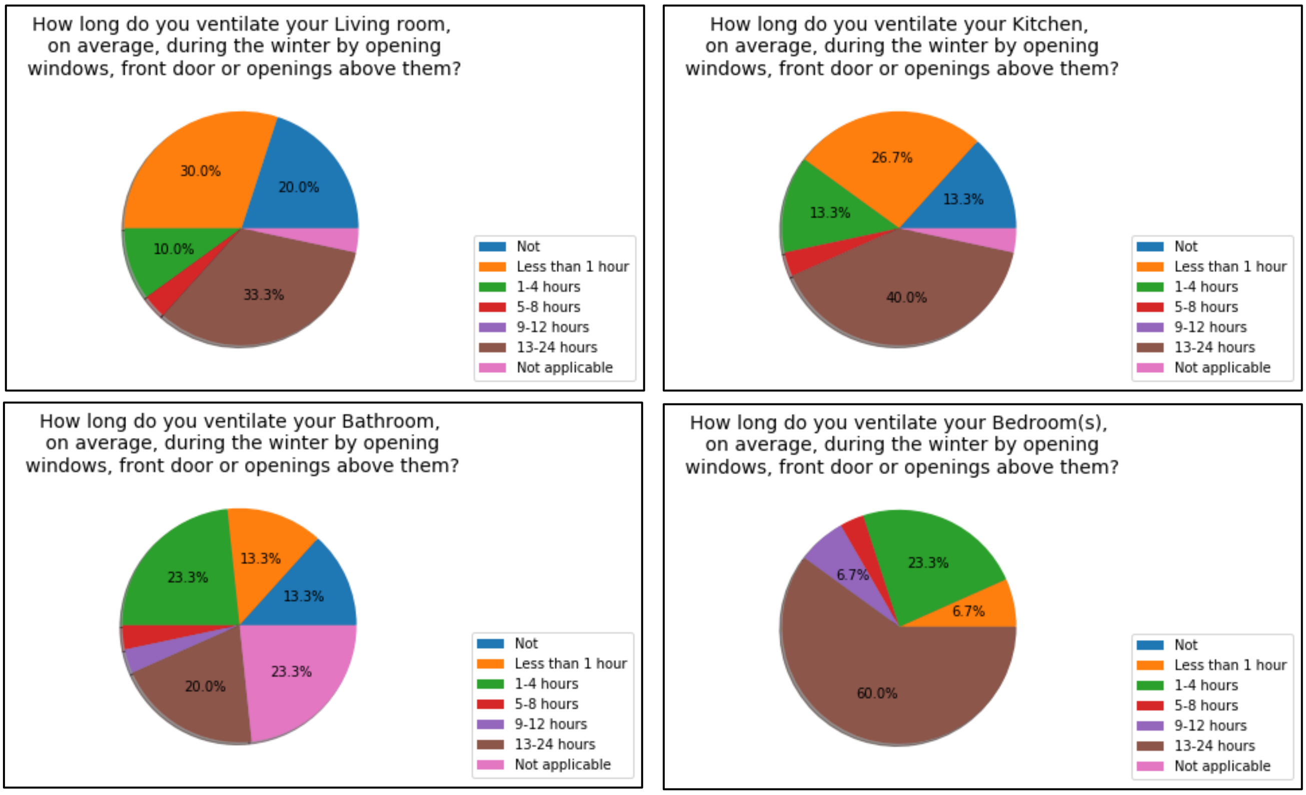


Figure 12.21: *Ventilation patterns for living room, kitchen, bathroom and bedrooms based on the survey-Dwellings with natural supply and mechanical exhaust (n = 32 dwellings)*

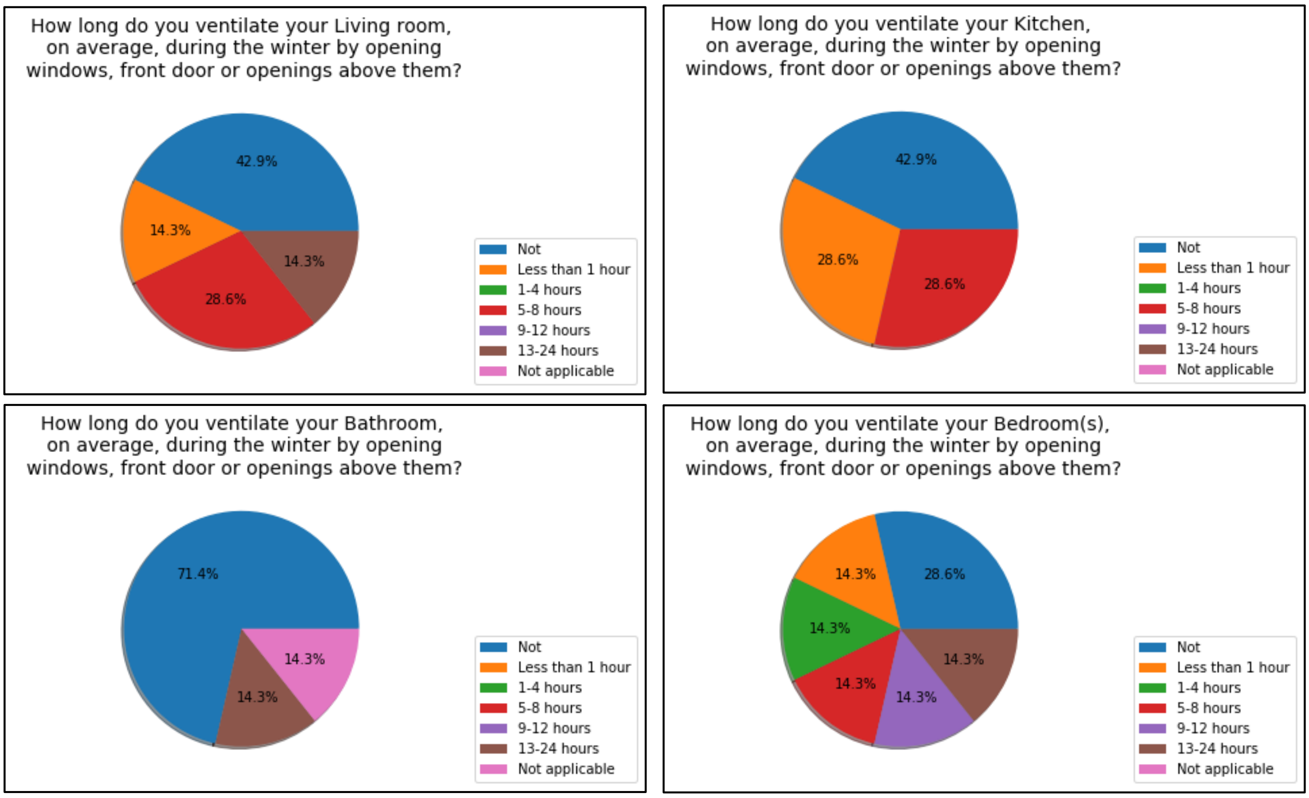


Figure 12.20: *Ventilation patterns for living room, kitchen, bathroom and bedrooms based on the survey-Dwellings with balanced ventilation (n = 7 dwellings)*

Furthermore, the distribution of the answers to the question "Do you ventilate more in the weekend than during the week?" is shown in Figure 12.22. According to that, the majority of the dwellings ventilate on the weekends as often as they do on the weekdays, while about 1/5 of them reported for more ventilation on the weekends.

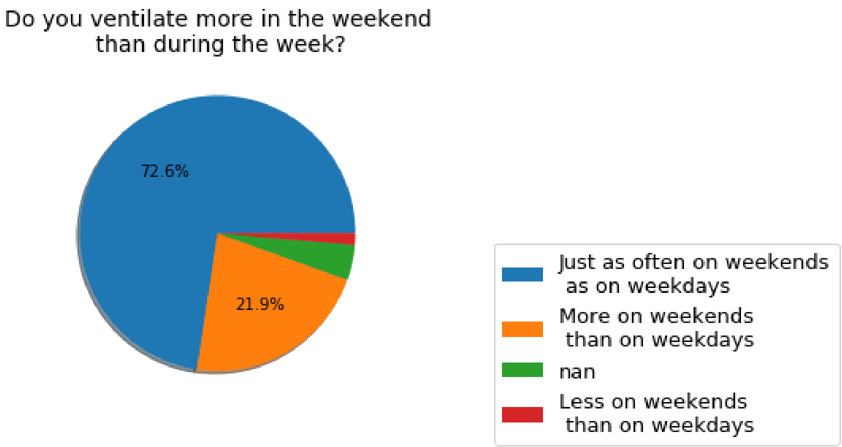


Figure 12.22: *Distribution of the answers to the question "Do you ventilate more in the weekend than during the week?"*

12.3.4 Showering and bathing behaviour

In Figure 12.23, the showering and bathing habits of the tenants are shown, based on the survey results. The majority of the answers were 2 showers per day, followed by 1, 0 and 3. Most of the showers last for less than 5 minutes, followed by 10 and 15 minutes. Finally, bathing is not a common practice in the monitored sample, since most dwellings had no bath. 3 tenants answered that they have 1 bath per week, while there was one tenant having 7 baths per week.

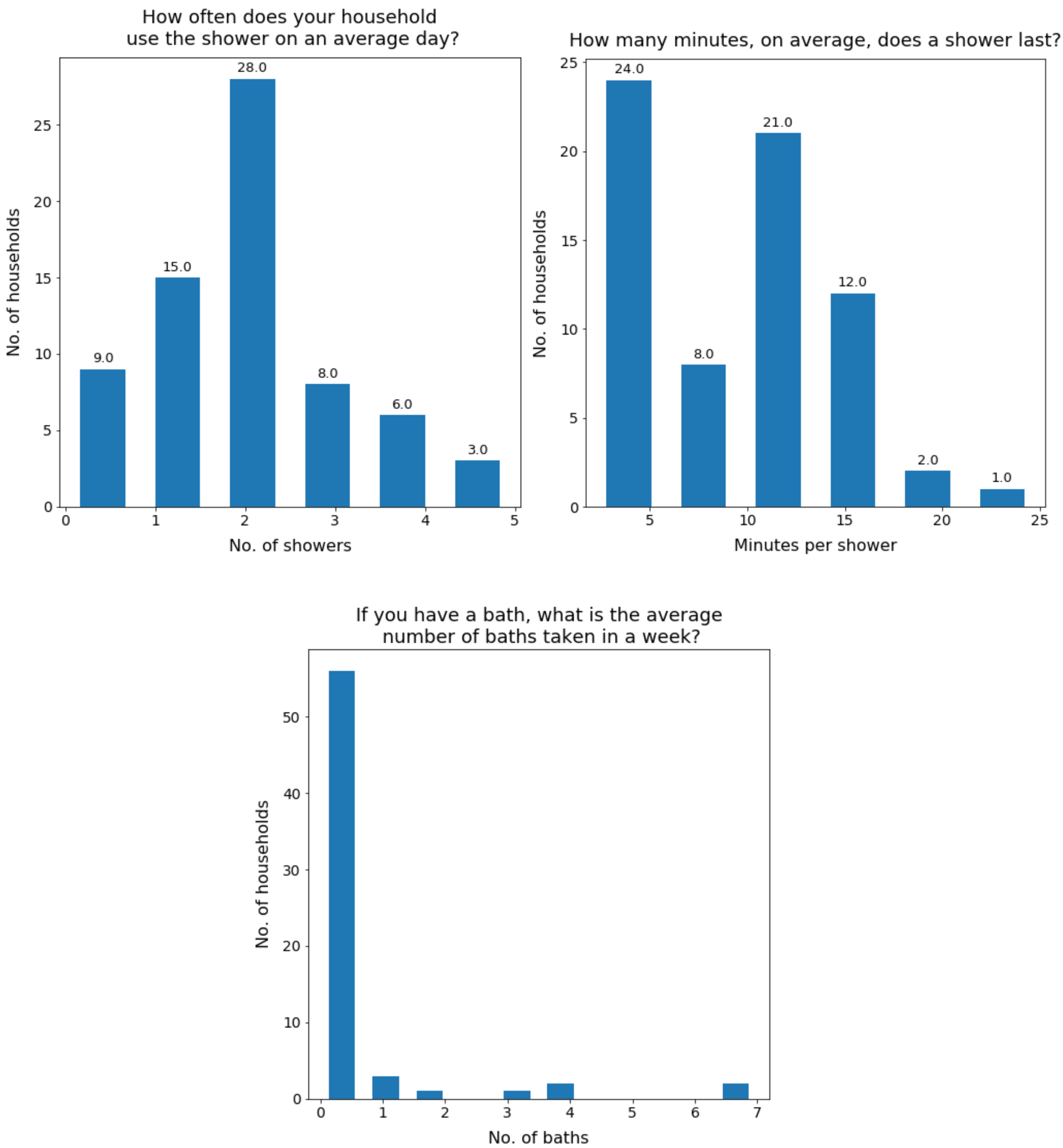


Figure 12.23: *Showering and bathing habits based on the survey.*

12.3.5 Energy related actions

Tenants were also asked about possible energy measures that they take. Thus, in Figure 12.24, it is shown that the most common measures taken are switching off the lights when not in the room as well as not setting the thermostat higher than necessary which is in accordance with the answers given about the thermostat settings. Measures like no ventilation while heating is on, use of A++ appliances and water saving shower head are following. Such measures are taken by all different energy label dwellings.

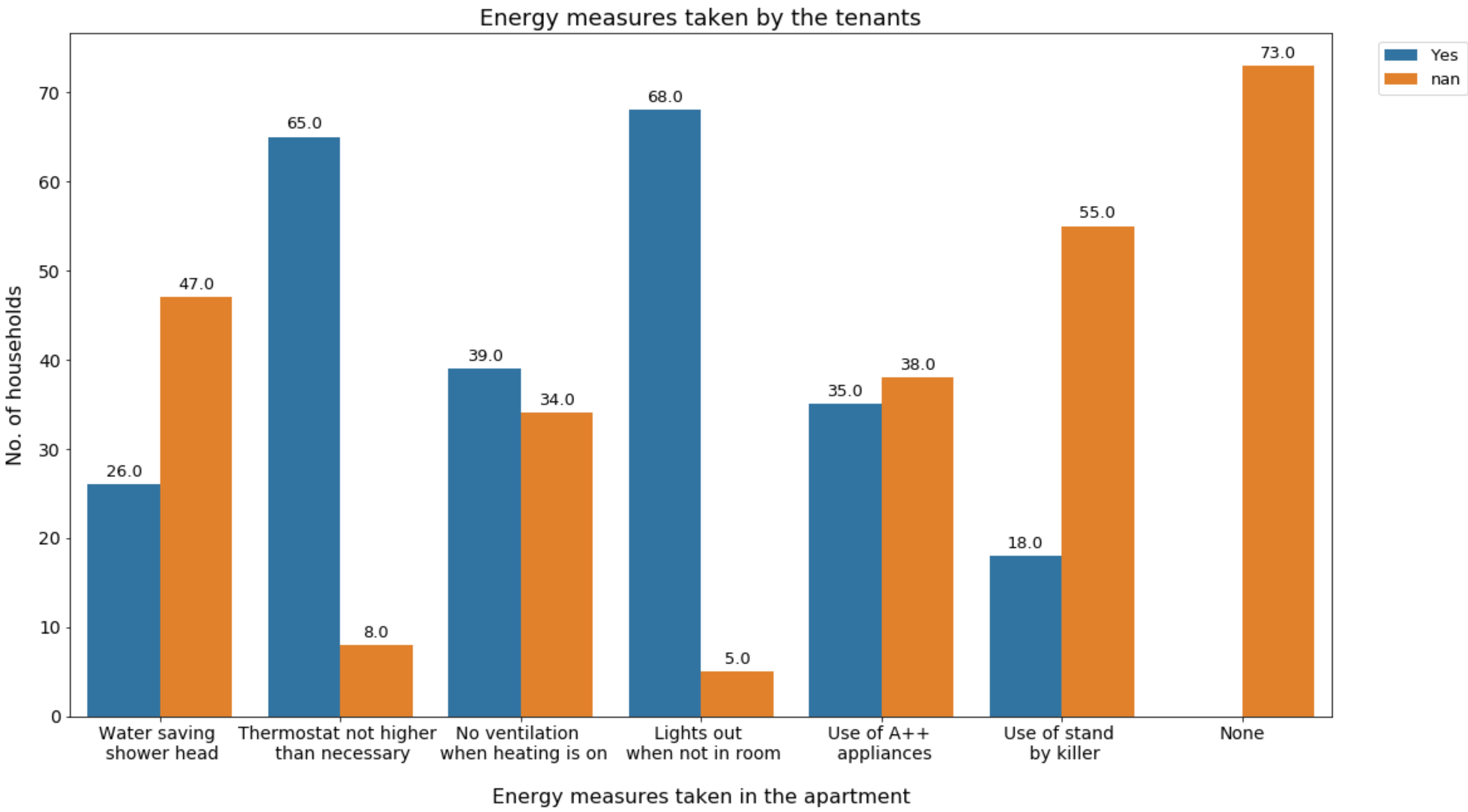


Figure 12.24: *Energy measures taken by the tenants.*

Moreover, tenants were asked about various energy wasting actions taking place in their apartment as well. Figure 12.25 indicates that 31 dwellings (almost) never leave adapters/chargers in a wall outlet without a device connected, while 24 of them do that often. Almost all dwellings answered that they do not leave the lights on in rooms where nobody is present for a long time. Finally, regarding the energy wasting action of leaving devices on standby, most dwellings (36) answered doing that often.

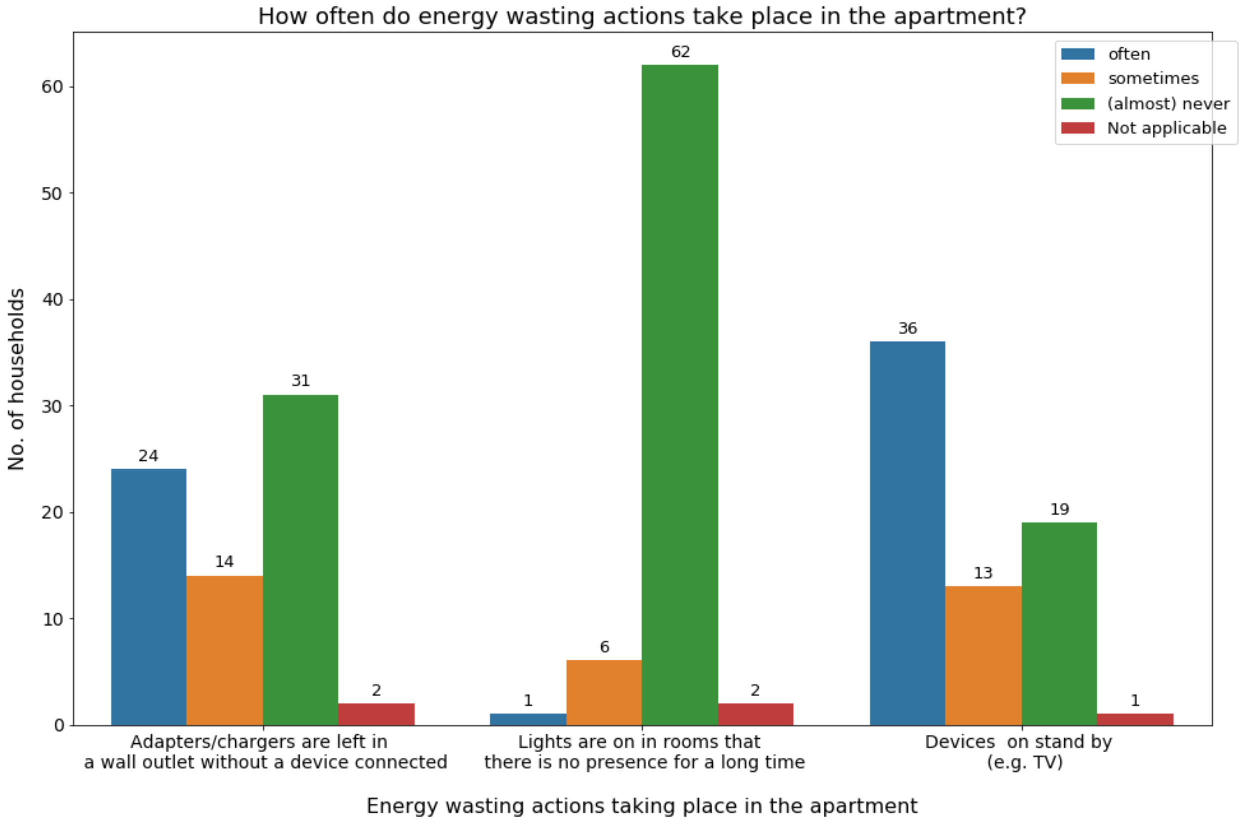
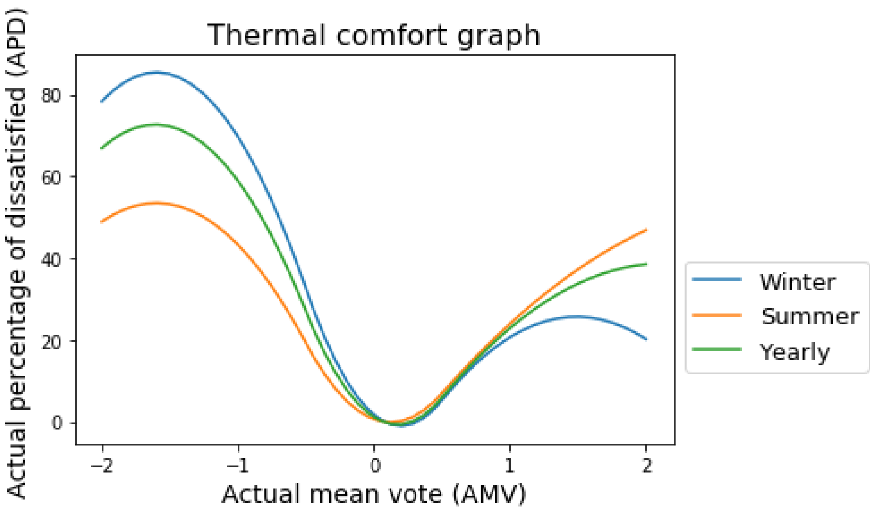
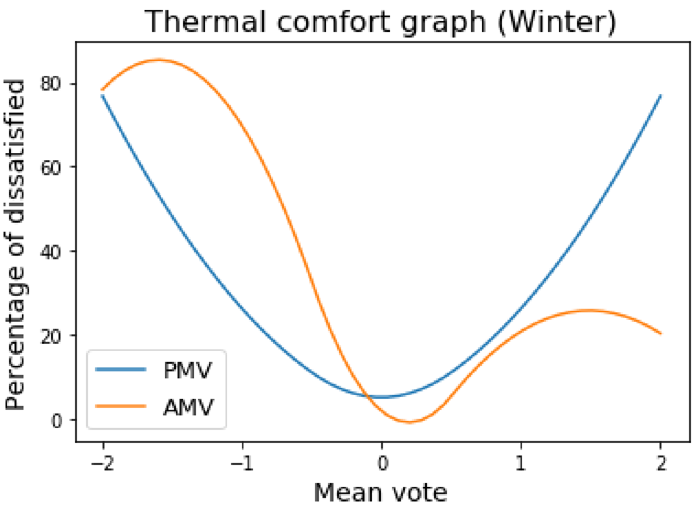


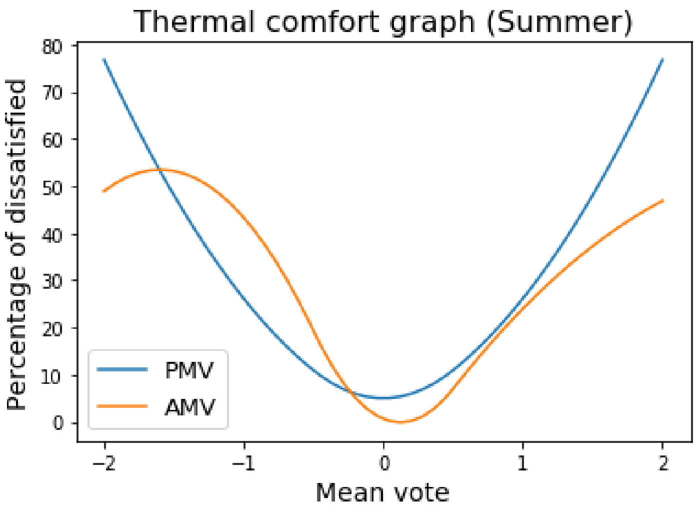
Figure 12.25: *Energy wasting actions taking place in the apartment.*

12.4 Thermal comfort graphs

Here the thermal comfort graphs after merging the "very cold" with the "cold" and the "hot" with the "warm" thermal sensation are illustrated.




Thermal comfort graph (Winter)
Percentage of dissatisfied
Mean vote
PMV
AMV
0
20
40
60
80
−2
−1
0
1
2


Thermal comfort graph (Summer)
Percentage of dissatisfied
Mean vote
PMV
AMV
0
10
20
30
40
50
60
70
80
−2
−1
0
1
2