MASTER

Differences in energy consumption explained by thermoregulatory behaviour and comfort of the occupant

Visser, L.

Award date:
2017

Technische Universiteit
Eindhoven
University of Technology

Authors:
ing. L. (Loes) Visser | 0920484

Supervisors:
dr. ir. H.L. Schellen
ir. E.M.M. Willems
dr. ir. B.R.M. Kingma
dr. ir. A.W.M. van Schijndel

DIFFERENCES IN ENERGY CONSUMPTION EXPLAINED BY THERMOREGULATORY BEHAVIOUR AND COMFORT OF THE OCCUPANT

MASTER THESIS

Department of Building Physics and Services

March 2017, Eindhoven

Title page

General information

Document:	Master thesis
Title:	Differences in energy consumption explained by thermoregulatory behaviour and comfort of the occupant

Student

Surname:	Visser
First name:	Loes
E-mail:	lvisser7815@gmail.com
Student number:	0920484
Graduation period:	February 2016 – March 2017

Study program

University:	University of Technology Eindhoven
Master track:	Architecture Building and Planning
Specialization:	Building Physics and Services
Unit:	Building Physics

Supervisory committee

First faculty supervisor:	dr. ir. H.L. Schellen	
Second faculty supervisor:	dr. ir. A.W.M. van Schijndel	
First external supervisor:	dr. ir. B.R.M. Kingma	(Maastricht University)
Second external supervisor:	ir. E.M.M. Willems	(Huygen Ingenieurs & Adviseurs BV)

Preface

I am Loes Visser and I enrolled for the Master track Building Physics and Services at the Eindhoven University of Technology in February 2015. Previous to this Master program, I finished my HBO Bachelors at Avans Tilburg, University of Applied Sciences, and the pre-Master at Eindhoven University of Technology. My motivation for choosing this particular Master was that I am very passionate about research, experiments and user behaviour in combination with energy use. During my graduation period at Avans University of Applied Sciences I started to work with Maastricht University to assess occupant behaviour and thermal comfort. After obtaining my Bachelors degree I was eager to learn more about thermoregulatory behavior and comfort and started the Master Building Physics and Services at the TU/e. My previous Master projects were all in line with the main topic of my graduation thesis of my bachelor. This Master thesis is the conclusion of this passion of the last three years. In addition, I hope that the results of this study will be implemented in future designs of dwellings and installations. Therefore, I will be working at Huygen Engineers and Consultants B.V. after my graduation in the position of Junior Researcher to continue doing applied research in the field of occupant behaviour, energy efficiency, thermal comfort and health in buildings.

Finally, I would like to thank my supervisors: ir. Eric Willems, dr. Boris Kingma, dr. Jos van Schijndel and dr. Henk Schellen for their support and of course dr. Lisje Schellen for introducing me to this field of research.

Maastricht, March 22, 2017

Loes Visser

Summary

Multiple studies have demonstrated that there can be, up to a factor 5, deviation in heating demand between similar dwellings. These differences in energy demand are mostly due to differences in occupant behaviour. Since every person has different preferences for their thermal comfort, this leads to difficulties in energy demand predictions. This study investigates how people due to their physiology and thermoregulatory behaviour tend to have different set-point temperature preferences that may have a substantial influence on the energy demand of a dwelling. In addition, real-life measurements are used to calculate the energy demand. This made it possible the assess differences in heating demand, utilization of the dwelling and user behaviour.

During this study, which was carried out three weeks over a period of three months, two female subjects of approximately the same age, height and weight participated in the study. Both subjects were closely monitored to measure their micro climate (wireless-sensor as brioche), skin temperatures (wireless-sensors at 5 sites), their thermoregulatory behavior, activity level, clothing worn, and thermal comfort and sensation (ASHRAE 7-point scale) were self-reported through questionnaires. The most comfortable (optimal) daily indoor temperature was calculated for each subject individually by adopting a biophysical model. This model took into account the differences in clothing and their activity level. In addition, a dwelling with an advanced monitoring system (sensors for e.g. temperatures per zone, ventilation flows, CO^2, electricity consumptions of installations and electicity consumption for domestic use) was monitored for two winter seasons. Where the dwelling was occupied by different tenants during both winters.

Furthermore, in this study a code-only energy demand model was developed. This energy model can be used to connect directly to databases, to access measurement data and information of the dwelling such as dimensions. In addition, this model can be ran indepently on a server, without manual manipulation from a user. Inverse modelling is used to increase the accuracy of this model and to determine the building parameters in practice. Because studies show that these parameters might differ from design values and might have a great influence on the energy demand of a dwelling. Finally, principal component analysis is used to determine the slope of energy demand lines and to find patterns of utilization and user behaviour.

The measured data showed quite significant differences in the subjects perception of the surrounding thermal environment, where subject 1 was more comfortable with lower temperatures than subject 2. In addition, differences up to 7K in indoor temperature preferences for the two subjects were found. By means of the calculated energy demand lines, it could be derived that if the test subjects would act on their calculated optimal temperature instead of the agreed set-point temperature, the energy demand could differ a factor 2. In addition differences in utilization of the dwelling were observed between the different tenants. Furthermore, inverse modelling made it possible to assess the effiency of the dwelling; there are probably major thermal bridges in the building façade. Finally, principal

component analysis showed differences in utilization of the dwelling and differences in user behaviour; the internal heat load had a greater influence on the total heating demand during the first winter compared to the second winter. This was probably due to the higher electricity consumption for domestic use.

The presented study showed that people perceive the surrounding thermal environment differently. Consequently, this can lead to occupants choosing different indoor temperature set-points due to differences in thermoregulatory behaviour and thermal comfort. Several studies also showed differences among subpopulations in thermal comfort vote (e.g. males versus females, lean versus obese, young versus elderly). These studies imply there is even a greater difference in indoor temperature preferences between subpopulations than is found in this study.

Contents

1 Introduction

1.1 Introduction

This Master thesis is part of a Dutch interdisciplinary project; TRECO, which stands for ‘Towards Real Energy performance and Control by predicting user behaviour’. As the title suggests, the main aim of the project is to predict real energy performance and energy consumption, including occupant behaviour. One of the reasons why TRECO was initiated was the strong deviation in energy use between almost similar dwellings. Multiple studies have adressed and demonstrated this issue, the study by Steen et al. reports a difference in energy consumption of factor 5 between similar dwellings (Steen et al., 2010; Borg, 2015). Because of the significant differences in energy use between almost similar dwellings, it is hard to predict the reduction in energy use after renovation. In addition studies show that these differences might be strongly dependent on user behaviour. In the Netherlands, housing associations increase the monthly rent after renovation to finance the renovation costs. When actual monthly energy savings are not as predicted, this results in higher monthly costs after the renovation for the occupants.

Building related energy use is often calculated with simulation programs, these specific calculations are focussed on energy use of buildings based on fixed user behaviour conditions and a reference climate year. They are therefore lacking information about real-life performances. This leads to an inevitable gap between measured and calculated energy use of dwellings. Some studies (Tohoku University, 2013) indicate that the three major causes of this gap are:

1. Human factor – responsible for 80% of performance gap
2. Climate factor – responsible for 15% of performance gap
3. Building intrinsic factor – responsible for 5% of performance gap

This shows the human factor is an important influencing factor and should be taken into account. This human factor consists mainly of routine and thermoregulatory behaviour. Routine is a series of operations which are often carried out without thinking. In addition, examples of thermoregulatory behaviour are: moving from one environment to another, changing clothes and adjusting the thermostat. These actions are done to avoid thermal discomfort and to seek thermal comfort in the environment (Jacquot, Schellen, Kingma, van Baak, & van Marken Lichtenbelt, 2013). Especially adjusting the indoor temperature can have a substantial influence on the energy use of a dwelling (Brohus, Heiselberg, Simonsen, & Sørensen, 2010). Therefore, real-life measurements should be taken into account while calculating the energy use of a dwelling. These measurements can be an alternative for the assumed heating set-points, ventilation flow rates and installation performances. The overall goal of this Master thesis is to clarify variation in energy use between similar dwellings by means of differences in thermoregulatory behaviour of the occupants resulting from differences in comfort levels and physiology. This might gain insight in why there are such strong deviations in energy use between similar dwellings.

Therefore, the hypothesis that will be investigated in this study is that differences in energy use might be linked to the differences in thermoregulatory behaviour and comfort. It is expected that the influence of the comfort vote of occupants can directly be related to their energy use. Figure 1 shows a schematic overview of the resulting differences in energy demand resulting from the differences in comfort vote, which is for the main part related to indoor temperature. The slope and position of the energy demand line depends on different aspects of a dwelling and its utilization. In addition, the indoor temperature that corresponds with optimal comfort might vary between different occupants. This might result in differences in energy use, as can be derived from Figure 1, where ΔT is the indoor temperature minus the outdoor temperature.

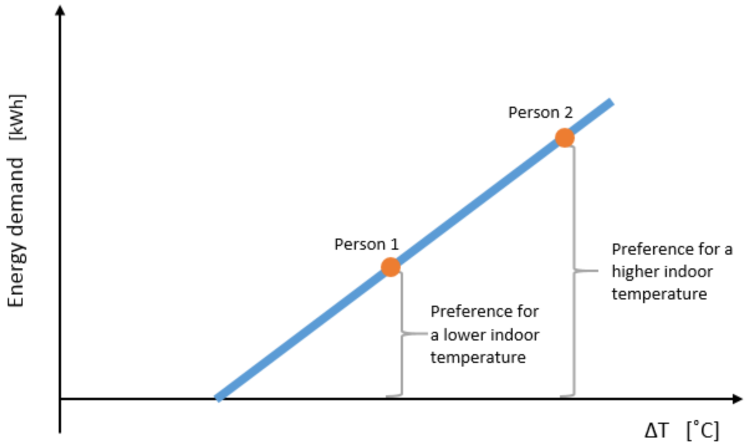


Figure 1 Energy demand as a result of differences in comfort vote.

1.2 Objectives

The research and scientific objectives of this Master thesis are directly related to the issue described in *section 1.1 Introduction*. The primary research question is:

Is it possible to explain differences in energy consumption due to differences in thermoregulatory behaviour and comfort of the occupant?

Secondary research questions are:

1) *Is it possible to explain differences in comfort and thermoregulatory behaviour between occupants?*
2) *What thermoregulatory behavior do the test subject show?*
3) *Is it possible to define optimal indoor temperatures at an individual level?*

4) *Is it possible to explain differences in energy consumption due to differences in utilization of the dwelling?*
5) *Is it possible to predict energy consumption per day for a perticulair dwelling with its utilization pattern?*

1.3 Outline

In order to answer the primary research question and to test the hypothesis, this thesis consists of two different approaches; the first approach is related to the the built environment aspects and the latter to the physiological aspects. These two approaches are first introduced and discussed individually in the chapters: literature review, methodology and the results. Afterwards the results will be discussed together in order to answer the primary research question in *Chapter 7 Conclusion*.

Secondary research question 1 and 2 are partly answered in *Chapter 2 Background study on thermal comfort and thermoregulatory behaviour*, this chapter serves as an input for the experimental program which is explained in *Chapter 4 Experimental program* and gives insight in the methodology of the data analysis. Results *section 5.1.1 Differences in comfort and thermoregulatory behaviour* is used to answer the first secondary research question. Results *section 5.1.2 Thermoregulatory behaviour of the test subject* provides an answer to secondary research question 2. Secondary research question 3 is answered in section 5.1.3 Optimal indoor temperatures.

Furthermore, secondary research question 4 and 5 are to a certain extent answered in *Chapter 3 Methodology to calculate energy consumption* and will give an insight in how the data should be analysed in the results. *Chapter 3 Methodology to calculate energy consumption* shows the method that can be used for the analysis of building performance and occupant behaviour in a general way. In addition, results *section 5.2 Energy demand* will than be used to answer secondary research question 4 and 5.

Finally, the results and answers from all five secondary research questions will be combined and the primary research question will be answered and discussed in *Chapter 7 Conclusion*.

2 Background study on thermal comfort and thermoregulatory behaviour

As stated in the introduction, adjusting the thermostat, which is an example of thermoregulatory behaviour, might have a substantial influence on the energy use of a dwelling (Brohus et al., 2010). Occupants exhibit thermoregulatory behaviour to avoid discomfort and to seek thermal comfort in the environment (Jacquot, Schellen, Kingma, van Baak, & van Marken Lichtenbelt, 2013). Fanger (1973) already concluded that there are a number of aspects that contribute to thermal comfort, such as air temperature, mean radiant temperature, relative air velocity, vapor pressure in ambient air, the activity level and the clothing. Fanger's predicted mean vote model (PMV) is based on the predicted mean vote of the general population. Several studies show a good agreement between the PMV and the actual mean vote, this is particularly found for uniform and steady-state environments (Brager & de Dear, 2000; Nicol & Humphreys, 2002). Other studies found differences between the PMV and the actual mean vote due to differences in subpopulations (e.g. males versus females, lean versus obese, elderly and young) (Karjalainen, 2011). The model used in this study, the thermoneutral zone model (TNZ), includes these physiological differences between occupants and is therefore a more individual approach to investigate comfort (B. R. M. Kingma et al., 2014). This individual approach may be more suitable to reach the goal of clarifying variation in heating demand between similar dwellings by means of differences in thermoregulatory behaviour of occupants.

2.1 The thermoneutral zone model (TNZ)

First it is neccesary to explain the thermoneutral zone model (TNZ). From a biological point of view the body wants to use as little energy as possible to ensure its core temperature (B. Kingma & Lichtenbelt, 2016), which is shown in Figure 2. The body defends a core temperature around 37 degrees Celsius. The range of ambient temperatures at which temperature regulation is achieved only by control of sensible (dry) heat loss, i.e. without regulatory changes in metabolic heat production or evaporative heat loss is called the thermoneutral zone, the comfort zone is the centre of this zone (B. R. M. Kingma et al., 2014). When the operative temperature increases or decreases the body has to work harder to maintain its core temperature by regulating blood flow, this leads to dilatation or contraction of blood vessels to increase or decrease the heat loss of the body. When the core temperature can not be maintained only by dry heat loss, the temperature is regulated by sweating or (non-)shivering thermogenesis. This can be observed in Figure 2, more energy is needed to maintain the core temperature when the operative temperature is low, which results in (non-)shivering thermogenesis. When the exposed temperature is higher than the TNZ, the body uses more energy as well, which results in sweating to cool down the body.

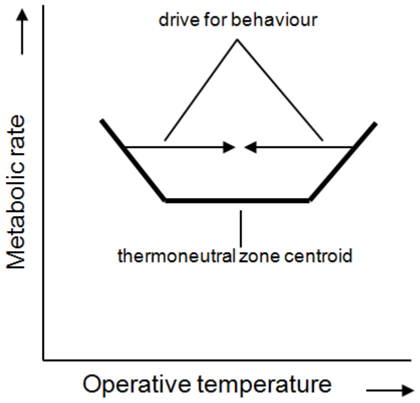


Figure 2 Increasing metabolism when the body has to regulate its heat loss (Kingma, 2016)

Therefore, the TNZ depends on different physical aspects of the person, e.g. gender, body area, body fat and activity level. In addition, the air velocity, relative humidity and the clothing degree are important as well for the calculation of the TNZ. Consequently, this means that the TNZ varies per person and per moment. By taking into account the physiological differences of occupants it is possible to calculate the skin temperature and thus the optimal indoor environment for individuals, see *Appendix I*. The calculation of the skin temprature can be compared with the calculation of the surface temperature of a wall. The human body has a stable core temperature, the skin temperature can then be determined by knowing the person's body fat percentage and its metabolic rate (produced body heat). Clothing also creates a certain thermal insulation, combined with the relative humidity and the air velocity of the environment, the optimal operative temperature can be determined for that person with these defined specifics, see Figure 3 (B. Kingma & Lichtenbelt, 2016).

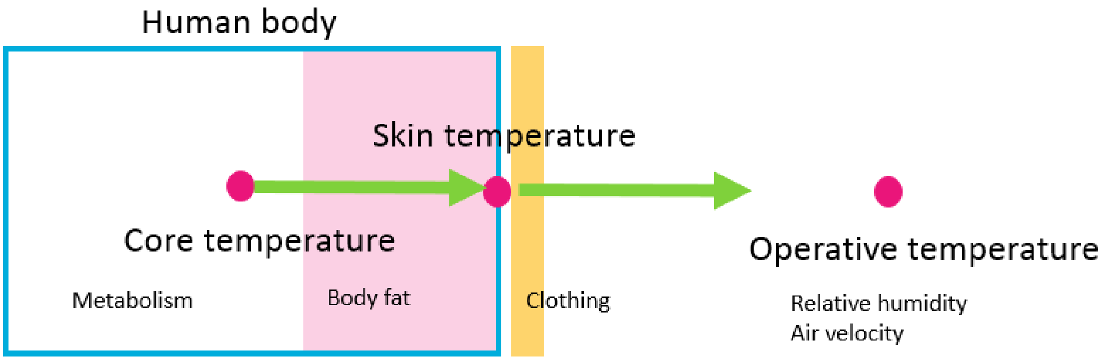


Figure 3 Schematic overview of the calculation of the skin temperature and the optimal operative temperature

The influence of all these parameters can be derived from these calculations; this makes it possible to calculate the TNZ as a relation of the skin temperature and the operative temperature, see Figure 4 and *Appendix I*.

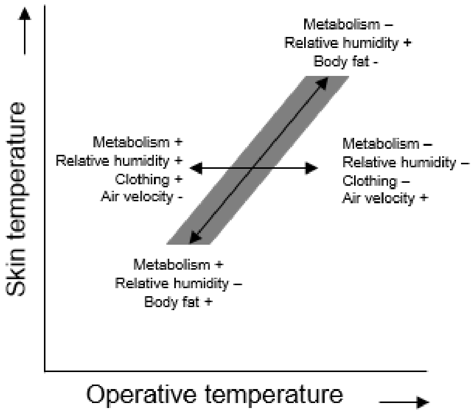


Figure 4 The thermoneutral zone as a result of the relation between skin temperature and operative temperature (Kingma, 2016)

As seen in Figure 4, the grey zone indicates the thermoneutral zone. The position of this zone in the graph depends on the characteristics of the person and its environment, for example: body fat, metabolism, the clo-value, relative humidity and air velocity. Outside of this zone, the body will need to regulate its temperature more extensively through sweating and (non-) shivering thermogenesis, which can be experienced as uncomfortable.

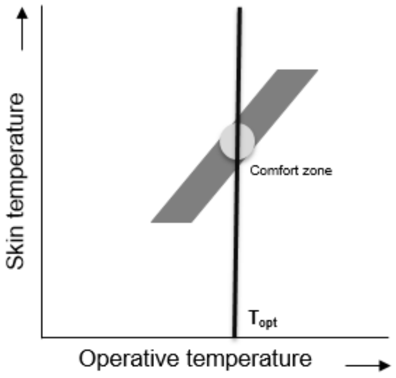


Figure 5 Optimal indoor temperature per individual

The comfort zone is the center of the thermoneutral zone, the corresponding operative temperature is described as most comfortable (optimal) indoor temperature for that person at that moment, see Figure 5. Because parameters such as relative humidity, air velocity, activity level and clothing can vary over time, this will lead to a different comfort zone and thus a different optimal indoor temperature.

2.2 Preliminary research and its findings

During the preliminary research of this study (Visser, 2016), which was carried out three weeks over a period of three months, two female subjects of approximately the same age, height and weight participated in the study to get insight in their preferred thermal environment and related thermoregulatory behaviour. The methods and results of the preliminary research can be used as an example for the thesis study, this is further discussed in *Chapter 4 Experimental program*. During this preliminary research the following parameters were monitored: activity level, clothing worn, micro climate, skin temperatures, and thermal comfort and sensation. Micro climate near the body to assess exposed conditions and skin temperature at five positions on the body were measured with wireless sensors. They wore an Actiwatch® to measure their activity level, and every two hours the subjects filled in a questionnaire regarding their thermal comfort and sensation vote (7-point scale), clothing, activities, and thermoregulatory behaviour.

During the preliminary research the sensation and comfort vote were handled separately. For both test subjects no significant correlations were found between skin temperatures and comfort or sensation vote (respectively $R^2 = 0.0087$, $p = 0.1947$ and $R^2 = 0.0007$, $p = 0.7212$).

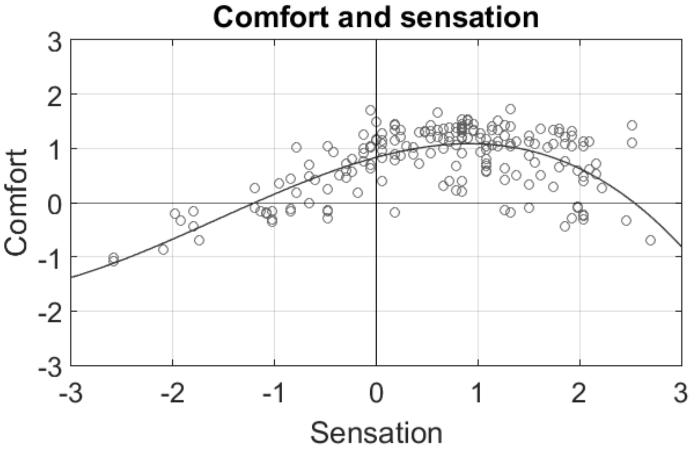


Figure 6 Comfort vote against sensation vote

In the PMV-model of Fanger, sensation and comfort are identified as one and the same. Figure 6 shows the comfort vote against the sensation vote. A significant correlation was found ($R^2 = 0.5000$, $p = 0.0279$). As can be derived through the trend line, this test subject was most comfortable at the top of the trendline, which represents a sensation vote of 1, ‘slightly warm’.

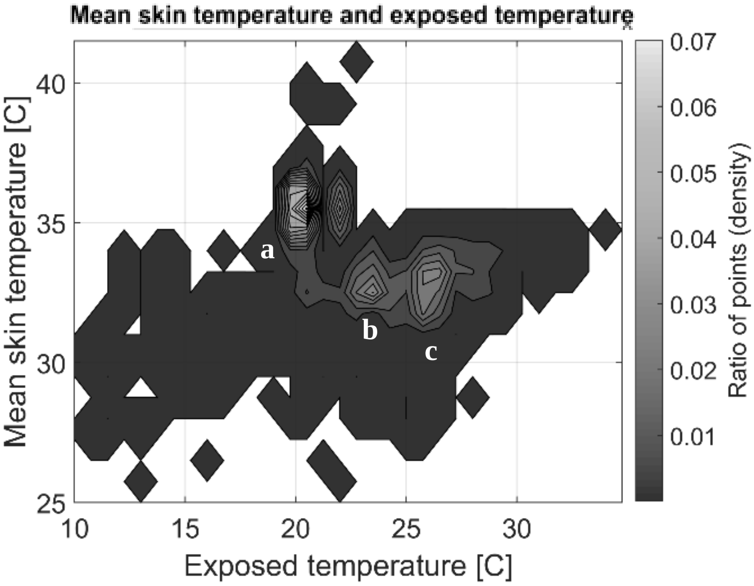


Figure 7 Contourplot of the exposed- and skin temperatures with three centers (a, b, c)

Both participants showed a unique pattern when looked at the relationship between exposed- and skin temperatures. The results of one test subject is shown in Figure 7. Three areas could been distinguished in the measuring data: one sleeping area and two living areas. All three areas were associated with maximum comfort. These three centers represent the thermal environment of this test subject in real life. Combinations of parameters filled in in the questionnaires showed that centre a. corresponds with measurements during the night. Center b. corresponds with standing activities in an indoor environment with regular winter clothing (e.g. jeans and sweater, clo-value ±0.8). Center c. corresponds with sitting/resting activities and lower clo-values (<0.6).

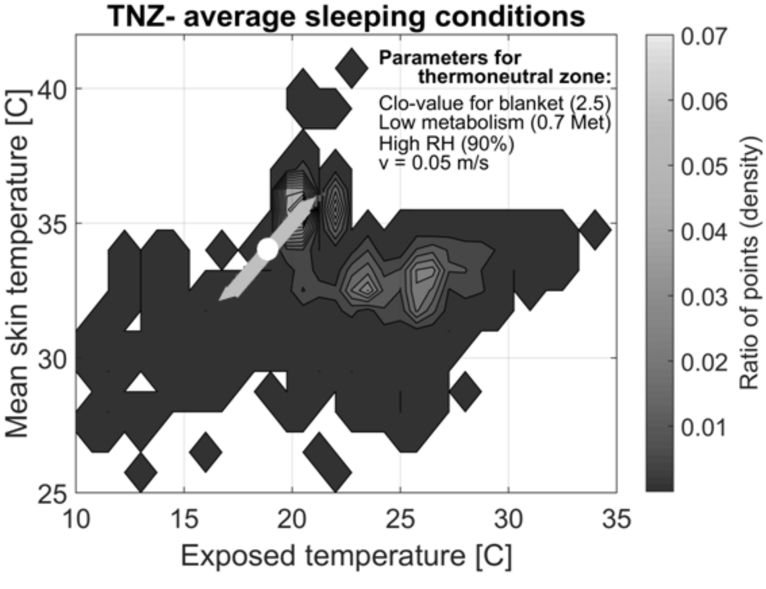


Figure 8 Contourplot of measurements including the calculated TNZ for this test subject with parameters that should represent the micro climate in bed

Figure 8 shows the thermoneutral zone with the characteristics for this test subject with parameters that should represents the micro climate in bed, e.g. a low air velocity, a high relative humidity, a low metabolism and a high clo-value for the blanket. As can be seen in the figure, this calculated TNZ corresponds with the measured data. During the night blood vessels relax and are therefore opened, which corresponds with higher heat losses. Therefore, the measurements of the test subject would be positioned in the higher end of the calculated thermoneutral zone, which is in line with Figure 8.

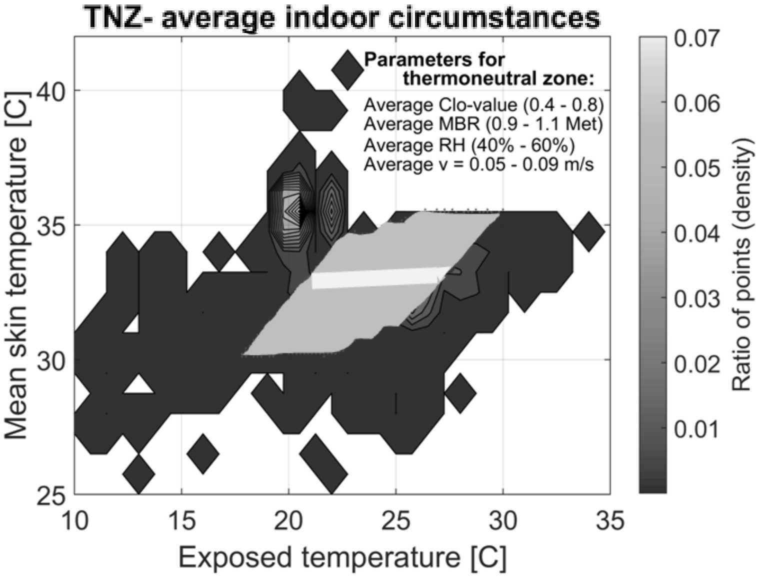


Figure 9 Contourplot of measurements including a range of calculated TNZ's for this test subject with parameters that should represent the indoor environment

Figure 9 shows a range of calculated thermoneutral zones with the characteristics for this test subject with parameters that should represent deviations for a normal indoor climate during the day. A range of TNZ's was calculated because the relative humidity, air velocity and metabolism can change every hour. As can be seen in the figure, the calculated thermoneutral zones correspond with the measured data. In conclusion, the subjects acted on their thermal comfort and sensation vote by changing their clothing or their activity level.

2.3 Conclusion background study

The first two secondary research questions can to a certain extend be answered with this background study and preliminary research;

- *Is it possible to explain differences in comfort and thermoregulatory behaviour between occupants?*
- *Is it possible to define optimal indoor temperatures on a individual level?*

The thermoneutral zone model can be used to explain differences in comfort and thermoregulatory behaviour between occupants. To use the thermoneutral zone model, the skin- and exposed temperature of the occupants need to be measured. These combinations of temperatures can then be used to predict the comfort level and the expectation that the occupant exhibites thermoregulatory behaviour. In addition, using the same experimental program makes it possible to assess the thermal environment of the test subject and their thermoregulatory behaviour.

When the thermoneutral zone model is used, the optimal indoor temperature per test subject can be calculated as well (*Appendix I*). The comfort zone is the center of the thermoneutral zone, the corresponding operative temperature is the most comfortable (optimal) indoor temperature for that person at that moment.

In conclusion, the thermoneutral zone model can be used to answer the two secondary research questions and can be used to answer the primary research question. To calculate TNZ’s for the test subjects, the experimental program of the preliminary research can be used. This experimental program is therefore explained in *Chapter 4 Experimental program*.

3 Methodology to calculate energy consumption

The goal of this study is to explain differences in energy use due to differences in thermoregulatory behaviour of occupants in similar dwellings. The hypothesis that is investigated is that a difference in comfortable indoor temperature between occupants might be the reason for variation in energy demand between similar dwellings. Therefore, real-life measurements should be taken into account during the calculation of the energy use of a dwelling in order to include the actual differences in setpoint temperatures. These measurements can be an alternative for the assumed temperature set-points, ventilation flows and installation performances.

As explained earlier, this study is part of a Dutch interdisciplinary project TRECO. One of the goals of TRECO is to integrate an energy prediction model into the TRECO monitoring system. This set a restriction and defined a boundary condition for the energy model where it was not possible to use a model requiring commercial software or a license. This defined the boundary condition for choosing the energy prediction model. Therefore, the development of the model was based on equation (1). In addition, this model is developed because it is adjustable, and it is possible to investigate differences in utilization of the dwelling. Furthermore, real measurements can be used in the calculation of $Q_{predicted}$ [kWh] (e.g. in- and outdoor temperatures, ventilation flow, wind speed and energy use of appliances and installations).

$$Q_{predicted} = Q_{out} - Q_{in} \qquad [\mathrm{kWh_{th}}] \qquad (1)$$

In equation (1), $Q_{predicted}$ is the total predicted heating demand for a dwelling in kWh_{th}. Q_{out} [kWh_{th}] stands for the heat flows going out of the dwelling, e.g. ventilation, infiltration and transmission. Q_{in} [kWh] stands for the incoming heat flows by internal heat gain and solar radiation. In addition, for the calculation of $Q_{predicted}$, information of general parameters of the dwelling are necessary, such as thermal resistance of closed parts, thermal transmittance of transparent parts, air tightness of the dwelling and g-values of glass. These parameters might have a great influence on the calculated energy use and the actual values of these parameters might differ from the expected values in practise. These deviations might also have a great influence on the energy demand (Rasooli, Itard, & Infante, 2016) but remain constant during these monitoring experiments. This shows a need to use inverse modelling to determine the building parameters in practice.

3.1 Inverse modelling

Inverse modelling is the opposite of traditional modelling. In traditional modelling, the model is known and the result is unknown. With inverse modelling the goal is to find the parameters that minimize the error between the modelling result and the measurements, this error can be calculated with equation (2). For the purpose of the thesis, this means finding parameters that minimize the difference between $Q_{predicted}$ and the measured energy use for space heating ($Q_{measured}$). The minimization of the error between the modelling result and the measurements is calculated by using equation (3).

$$SS_{res} = \sum_i (y_i - f(x_i)^2 = \sum_i \varepsilon_i^2 \tag{2}$$

$$\hat{\theta}_N = argmin_\theta \frac{1}{N} \sum_{k=1}^{N} \varepsilon^2\,(t,\theta) \tag{3}$$

In equation (2), y_i is the i^{th} value of the variable to be predicted, x_i is the i^{th} value of the explanatory variable, and $f(x_i)$ is the predicted value of y_i. ε_i is the error term. In equation (3), $\hat{\theta}_N$ stands for the resulting parameters based on measurement data with N samples. $\varepsilon^2(t,\theta)$ is the simulation error relying on the time and parameter values (Kramer, Schijndel, & Schellen, 2013). The real energy use for space heating needs to be measured to validate $Q_{predicted}$ and this should result in an accuracy of more than 70%, which corresponds with $R^2 > 0.7$ this can be calculated with equation (4) and (5).

$$SS_{tot} = \sum_i (y_i - \bar{y})^2 \tag{4}$$

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \tag{5}$$

In equation (4), y_i is the i^{th} value of the variable to be predicted $\bar{y}$, and is the mean of variable to be predicted. So the difference of the dependent variable and its mean. The TRECO energy demand model is further described in *Appendix II*. When the calculation method is accurate enough the different sub parts (e.g. $Q_{internal}$, Q_{sun}, $Q_{transmission}$, $Q_{ventilation}$, and $Q_{infiltration}$) might show differences in utilization of the dwelling. Figure 10 gives an overview of the calculation of $Q_{predicted}$.

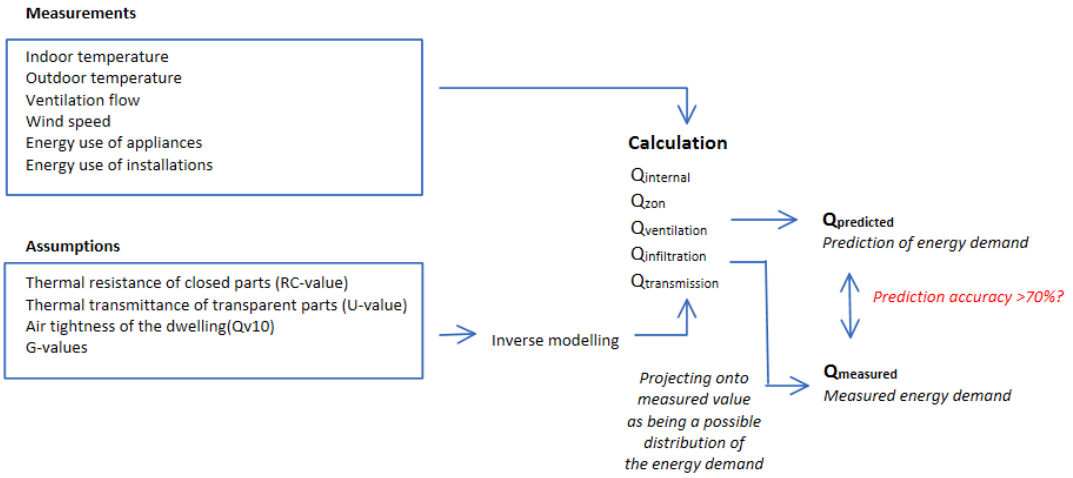


Figure 10 Method to calculate $Q_{predicted}$

From previous research it is known that there is a strong linear correlation between the energy demand and the difference between in- and outdoor temperature (ΔT). This means that the energy demand will always increase when the difference between the in- and outdoor temperature increases (a higher ΔT). Figure 11 shows this principle. The slope and the place of the line in the graph depends on different aspects and the utilization of the dwelling, such as the number of occupants, the ventilation rate, the internal heat load, the efficiency of the energy production and the amount of insulation.

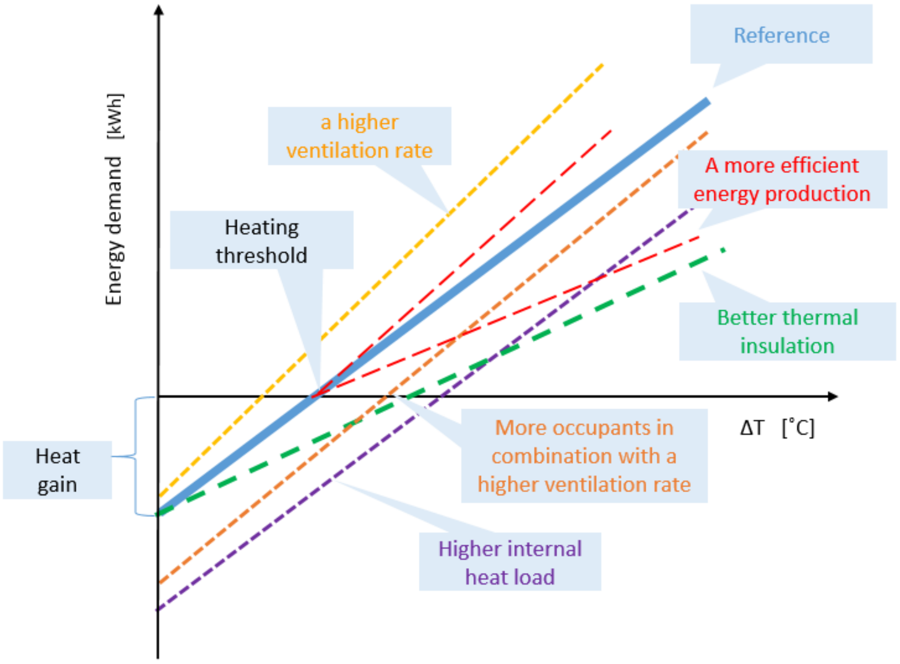


Figure 11 Energy demand against the difference in in- and outdoor temperatures

To understand which line corresponds with which calculated $Q_{predicted}$, it is necessary to analyse which variables within the calculations are most important in the prediction of which line corresponds with each calculated $Q_{predicted}$. In other words, when for example the $Q_{predicted}$ of a certain day is calculated with its specific utilization (with an average ventilation rate, in- and outdoor temperature, wind speed, sunlight etc.) the slope of the line through this point is not known, so it is not known what the energy demand would be when the indoor temperature set-point would be different, see Figure 12.

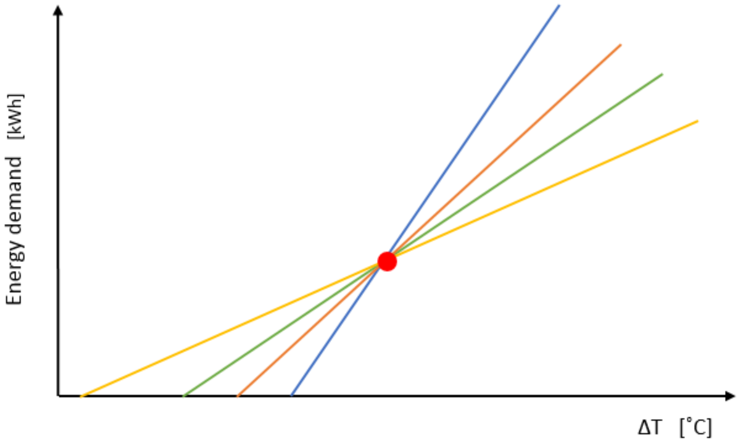


Figure 12 Possible energy demand lines

3.2 Principal component analysis (PCA)

To understand which line corresponds with each calculated $Q_{predicted}$, it is necessary to analyse which variables within the calculations are most important in the prediction of which line corresponds with each calculated $Q_{predicted}$. This can be done with a principal component analysis (PCA). In addition, PCA can be used to find certain patterns of user behaviour, for example with PCA it is possible to identify a variable that is most influenced by an occupant and to define which variables have the biggest impact on the heating demand calculation.

Principal component analysis (PCA) is a technique used to emphasize variation and bring out strong patterns in a dataset. It is often used to make data easy to explore and to visualize. It is a statistical procedure that uses an orthogonal transformation (rotation) to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible.

As an example of PCA (Starmer, 2015); when two variables are correlated, the data points are evenly divided over a diagonal line. Whereby the maximum variance is found in the direction of this diagonal line. The data is also evenly divided at the upper and lower side of this line, this is the direction of the second largest variance, see Figure 13.

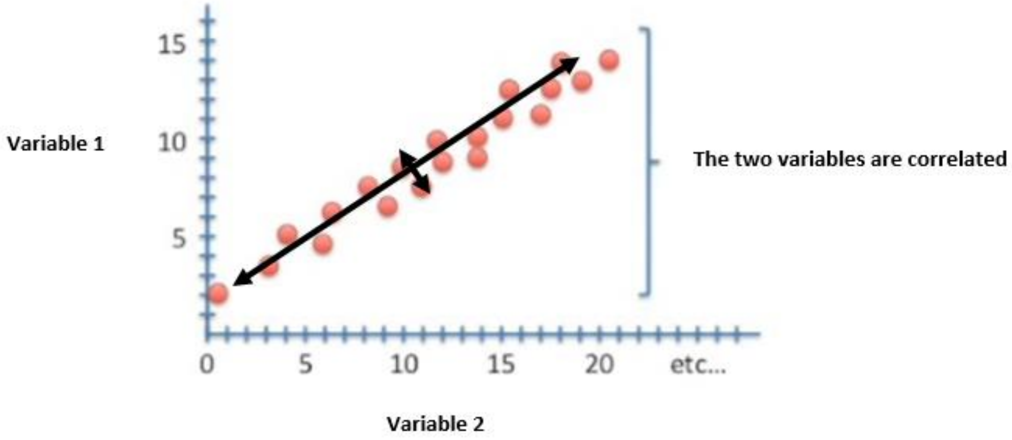


Figure 13 Explanation of principal component analysis

When this graph is rotated (see Figure 14), the two arrows make a new x- and y-axis. As can be seen, the data varies a lot from left to right and a little up and down. All variance can be described as a variance from left to right or up and down. There is no need to describe the diagonal correlation anymore. The two new axis that describe the variance in the different directions are the principal components (PC’s) (Starmer, 2015).

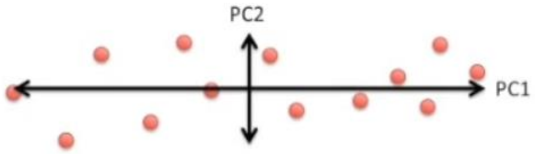


Figure 14 Principal components (PC's)

When a third variable would be introduced, there would be a third principal component as well. PC1 would then show again the direction of the most variance, PC2 the second most variance and PC3 the third most variance. The length and direction of a principal component is mainly determined by the data points at the end and beginning of the arrows. The first and last data points have a greater influence on PC1 then the data points in the middle of the arrow. This influence can be translated to scores, higher scores when the data point has a great influence and lower scores when the data point has less influence on a PC. This can be repeated for all data points and all PC's. At the end of this analysis it is possible to see which PC's explain how much percent of the variance in the data. And which variables have the most influence on that variance and in which direction (Starmer, 2015).

This method can be used to show which variables have the most influence in the different directions. With this analysis it might be possible to form different energy demand lines based on different utilization patterns. In addition, this analysis might show which variables have the greatest influence on the prediction of the heating demand. In other words, it can tell which variable is the most important in order to predict the heating demand as accurately as possible (reducing the gap between measured and predicted heating demand). Furthermore, when PCA will be used for different occupants of the same dwelling, it might be possible to see differences in utilization of the dwelling.

3.3 Conclusions of the methods

The third and fourth secondary research questions can partly be answered after this chapter;

- *Is it possible to explain differences in energy consumption due to differences in utilization of the dwelling?*
- *Is it possible to predict energy consumption per day for a perticulair dwelling with its utilization pattern?*

It is possible to explain differences in energy consumption due to differences in utilization of the dwelling. This has been possible in an advanced stage for a couple of years through different calculation software. Although, because of the boundary conditions of this study it is not possible to use such a program. Therefore, the model that is developed in this study is based on equation (1). The hypothesis that is investigated in this study is that a difference in comfortable indoor temperature might be the reason for variation in energy demand between similar dwellings. Therefore, real-life measurements should be taken into account during the calculation of the energy use of a dwelling in order to include the actual differences in setpoint temperatures. This is possible with the TRECO energy demand model. Wherein real measurements (e.g. in- and outdoor temperatures, ventilation flow, wind speed and energy use of appliances and installations) can be used in the calculation of $Q_{predicted}$ [kWh]. *Section 3.1 Inverse modelling* discussed inverse modelling to increase the accuracy of this calculation model.

To predict energy consumption per day for a particular dwelling with its utilization pattern it is not only necessary to know the $Q_{predicted}$, but also the increase in energy demand when the difference between the in- and outdoor temperature changes. From previous research it is known that there is a strong linear correlation between the energy demand and the difference between in- and outdoor temperature (ΔT). This means that the energy demand will always increase when the difference between the in- and outdoor temperature increases (a higher ΔT). The slope and the place of the line in the graph depends on different aspects and the utilization of the dwelling, as was seen in Figure 11. To understand which line corresponds with which calculated $Q_{predicted}$, it is necessary to analyse which variables within the calculations are most important in the prediction of which line corresponds with each calculated $Q_{predicted}$. In other words, when for example the $Q_{predicted}$ of a certain day is calculated with its specific utilization (with an average ventilation rate, in- and outdoor temperature, wind speed, sunlight etc.) the slope of the line through this point is not known, so it is not known what the energy demand would be when the indoor temperature set-point would be different. *Section 3.2 Principal component analysis (PCA)* discussed that principal component analysis could be used to predict the slope of the energy demand line for each calculated $Q_{predicted}$. In addition, this method might show which variables have the greatest influence on the prediction of the heating demand. In other words, which variable is most important to measure and predict for a better prediction of the total heating demand. Furthermore, when PCA will be used for different occupants of the same dwelling, it might be possible to see differences in utilization of the dwelling.

To use this calculation model during the experiments, it is necessary to choose a dwelling with an advanced monitoring system. This allows measurements of in- and outdoor temperatures, ventilation flow, wind speed and energy use of appliances and installations.

4 Experimental program

The data has been collected during two periods. The first data collection period was on behalf of the preliminary study (Visser, 2016), and the second data collection period was initiated on behalf of this Master thesis. During the preliminary study (Visser, 2016), which was discussed in *section 2.2 Preliminary research*, two females were measured who were living in a dwelling in Heerlen. They were measured for three weeks over a time span of three months to get insight in their preferred thermal environment and related thermoregulatory behaviour. For the current study, two other subjects - in a later stage of the project - were also measured with a similar approach, in the same dwelling.

The expectation was that differences in energy use and utilization of the dwelling were to be observed between the two previous tenants and the current tenants. The goal of these measurements was to link the differences in energy use to the differences in thermoregulatory behaviour.

The dwelling in Heerlen which is used as a pilot for the TRECO project, was previously used in a different TKI-project to monitor the performance of this dwelling. This pilot-dwelling is therefore equipped with an advanced monitoring system with multiple sensors per zone for the measurements of;

- the in- and outdoor temperatures,
- the set-point temperatures,
- the CO_2 concentrations,
- the ventilation flows,
- the temperatures of the ventilation flows,
- the heat flow of the central heating,
- the heat flow used for hot water,
- the total electrical power use,
- the electricity used for the heat pump,
- the electricity used for the boilers,
- the electricity used for the ventilation.

Furthermore, data from the weather station in Maastricht is being collected in the same database.

In addition to these physical measurements it was necessary to conduct physiological measurements to identify the user and to relate individual biological characteristics to their thermal comfort and their thermal behaviour. Information regarding thermal comfort, thermal sensation, clothing and activities were collected by means of an online questionnaire.

4.1 Dwelling

In Heerlen a single-family house was renovated to a near zero energy building in 2014 (see Figure 15 and *Appendix III*), which is equipped with multiple sensors to measure temperatures (JAGA device [± 0.5ºC]), ventilation (JAGA device [± 1%]), CO_2 concentration (JAGA device [± 50 ppm]) and energy use (de Slimme Meter (Slimme Meter, 2016)). All devices have a sample rate of once per ten minutes. In addition, data from the weather station in Maastricht is collected in the same database. Because the same data will be collected during this study as during the preliminary study, both datasets will be used in *Chapter 5 Results*.

Figure 15 Pilot dwelling in Heerlen

4.2 Test subjects

The same experimental program is used as during the preliminary research discussed in *section 2.2 Preliminary research*. This makes it possible to use those data sets for this study as well. Therefore all test subjects will be discussed in this section.

There were four test subjects divided over two periods willing to participate in this study. The first two test subjects were female and approximately of the same age, height and weight, see Table 2. They were measured for three weeks over a time span of three months during the winter of 2015-2016, see Table 1. The second two test subjects were respectively female and male, their age, height and weight are also shown in Table 2. They were measured for four weeks over a time span of three months during the winter of 2016-2017, see Table 1. With the parameters in Table 2, the body metabolic rate (BMR) was calculated with the Harrison-Benedict equation (Harris & Benedict, 1918) and the total body surface is calculated with the Dubois method (Dubois & Dubois, 1916). The female test subjects were using a birth control pill or IUD and were not measured during their menstruation period to exclude hormonal effects on thermoregulation (Baker, Mitchell, & Driver, 2001) (Baker, et al., 2001).

Table 1 Measuring weeks

	October 2015				**November 2015**					**December 2015**			
Date	**5**	**12**	**19**	**26**	**2**	**9**	**16**	**23**	**30**	**7**	**14**	**21**	**28**
Measurements													
Test subject 1		🟦				🟦				🟦			
Test subject 2			🟦			🟦				🟦			

	November 2016				**December 2016**				**January 2017**			
Date	**7**	**14**	**21**	**28**	**5**	**12**	**19**	**26**	**2**	**9**	**16**	**23**
Measurements												
Test subject 3				🟦			🟦			🟦	🟦	
Test subject 4				🟦			🟦			🟦	🟦	

Table 2 General information about the test subjects

	Test subject 1	***Test subject 2***	***Test subject 3***	***Test subject 4***
Sex	Female	Female	Female	Male
Age	22	20	19	21
Height	169 cm	172.5 cm	167 cm	181 cm
Weight	60.9 kg	66.9 kg	98.8 kg	82.0 kg
BMI	21.4	22.4	35.4	25
Health	Crohn’s disease	Healthy	Healthy	Healthy
Birth control	IUD	Birth control pill	Birth control pill	-

Before the measurements started the subjects filled in a general questionnaire (*Appendix IV*) to obtain background information on their health, see Table 2. The week previous to the first measurements, the test subjects were instructed on the use of the equipment and questionnaires, which are explained in *section 4.3 Measurements*. The test subjects were measured and monitored in their own home and were encouraged to behave as they normally would. Each day a timeslot was reserved to have contact and to provide feedback. In addition, the week schedule per test subject was discussed and written down, see *Appendix V*.

4.3 Measurements

4.3.1 Skin temperature sensors

The test subjects wore wireless sensors to measure skin temperature, exposed temperature and relative humidity. Skin temperatures were measured with wireless iButton dataloggers (iButton®) (DS1923, Maxim, USA) at the 4 point ISO-defined skin sites (left hand, right shin, neck, right shoulder blade), in ten minute intervals. An extra iButton was placed at the under arm, since studies show that this temperature might be related to thermal comfort as well (Wang, Zhang, Arens, & Huizenga, 2006). The mean skin temperature was calculated using these five measured skin temperatures. The measurement devices were constantly worn; just after taking a shower the band aids were replaced. The locations of the iButtons are shown in Figure 16.

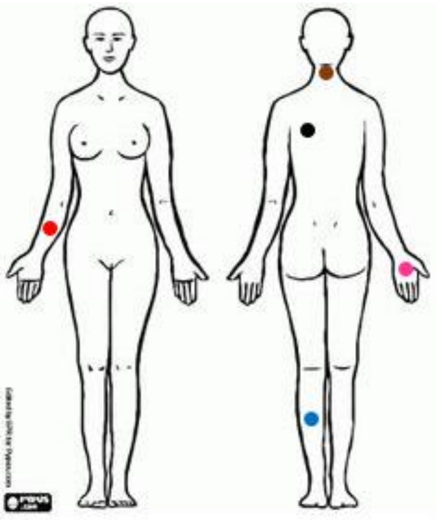


Figure 16 The iButtons were placed at the 4 point ISO-defined skin sites (right hand, left calf, neck, left shoulder blade) plus one additional skin sites the left under arm.

4.3.2 Exposed temperature

Air temperature and relative humidity close to the test subject were also measured using iButton® dataloggers (DS1923, Maxim, USA) in ten minute intervals. An iButton was placed with a brioche at the outer layer of the clothing.

4.3.3 Questionnaire

The test subjects were provided with an app that was used to fill in questionnaires with respect to thermal sensation and comfort, activities, thermoregulatory behaviour and clothing worn. Thermal comfort and sensation are self-reported using visual analogue scales (VAS). A comfort scale and a standard 7-point thermal sensation scale were used (see

Appendix VI). Questionnaires were filled in every two hours and took about 2 minutes to fill in each time. They would start filling in the questionnaires when they woke up or came home. In addition, they were asked to fill in the questionnaire as often as possible.

4.3.3.1 Clo-value

Table 16 in *Appendix VII* shows the clothing choices in the questionnaire and the corresponding Clo-value (McCullough, Jones, & Huck, 1985) used. The test subjects could choose one garment per category. With;

$$Clo_{total} = Clo_{footwear} + Clo_{lower\ body} + Clo_{upper\ body\ 1} + Clo_{upper\ body\ 2} + Clo_{upper\ body\ 3}$$

4.3.3.2 Activity level

Furthermore, the test subjects were asked to fill in their current and previous activity in the questionnaire. The test subjects could choose between seven activities, see Table 3.

Table 3 Activity categories

Number of activity	**Activity**
1	Lying (sleeping/resting)
2	Lying (active)
3	Sitting (resting/reading/eating)
4	Sitting (office work)
5	Standing (light physical effort)
6	Standing (medium physical effort)
7	Standing (heavy physical effort)

5 Results

5.1 Physiology

As discussed in *section 4.2 Test subjects,* the same experimental program was used as during the preliminary research discussed in *section 2.2 Preliminary research*. Therefore, it was possible to use the same datasets. In this study test subject 1 and 2 are both female and were measured during the winter season of 2015-2016 for three weeks over a period of three months. Test subjects 3 and 4 are respectively female and male and were measured during the winter season of 2016-2017 for four weeks over a period of three months. They were measured one week longer then intended because of the low responses in the online questionnaire. Over the complete duration of the experiments test subject 1 and 2 filled in the online questionnaire approximately 200 times. Test subject 1 had to remove the wireless sensors occasionally, because of hospital visits and the flu. Test subject 2 never removed the wireless sensors for more than 30 minutes, the datasets from subject 2 presented the most complete datasets and the datasets from subject 2 was used also during the preliminary study. Test subject 3 and 4 filled in the online questionnaire approximately 30 times. In addition, they wore the wireless sensors only in the evening hours because of work during the day. Furthermore, they frequently forgot to wear the wireless sensors at the outer side of the clothing. These data sets are therefore incomplete, and cannot be used for the extensive analysis in this study. For this reason and to not repeat the same results as the preliminary study, the results from test subject 1 were used in this chapter, and where needed the results from the other test subjects. The complete results from the other three test subjects are included in *Appendix IIX* and the attached USB.

5.1.1 Differences in comfort and thermoregulatory behaviour

From the results of the preliminary study of this research (*section 2.2 Preliminary research*) it is known that the relationship between skin- (weighted average) and operational temperature can be used to determine comfort zones and thermoregulatory behaviour. Figure 17 shows the mean skin temperature against the exposed temperature from test subject 1 during the three measuring weeks. The wireless sensors logged data every 10 minutes, so Figure 17 shows approximately 2000 measuring points. At first sight no relations can be found, but the density of the measuring points is interesting. This is why a contour plot was made of the same data, see Figure 18.

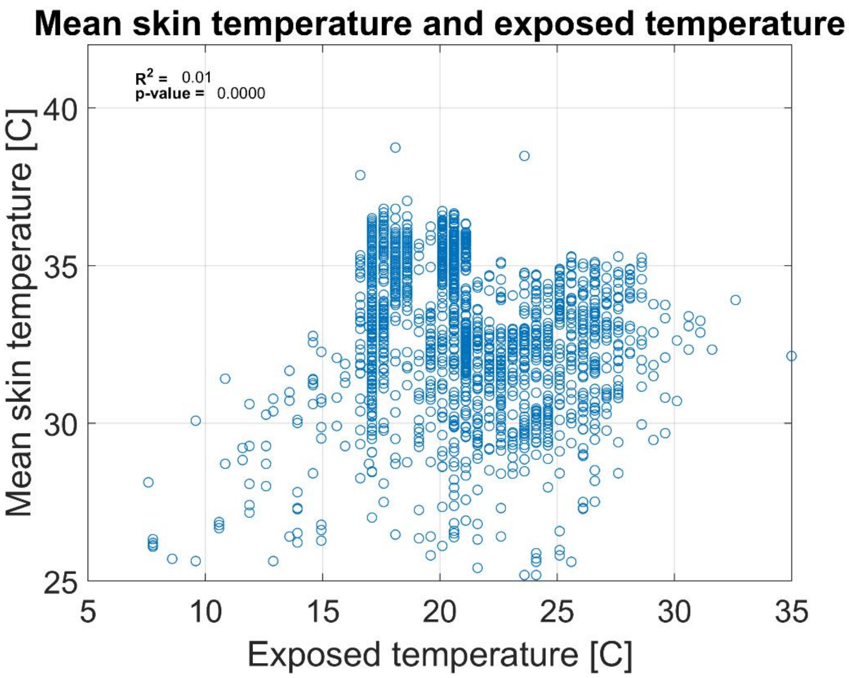


Figure 17 Mean skin temperature and exposed temperature of test subject 1

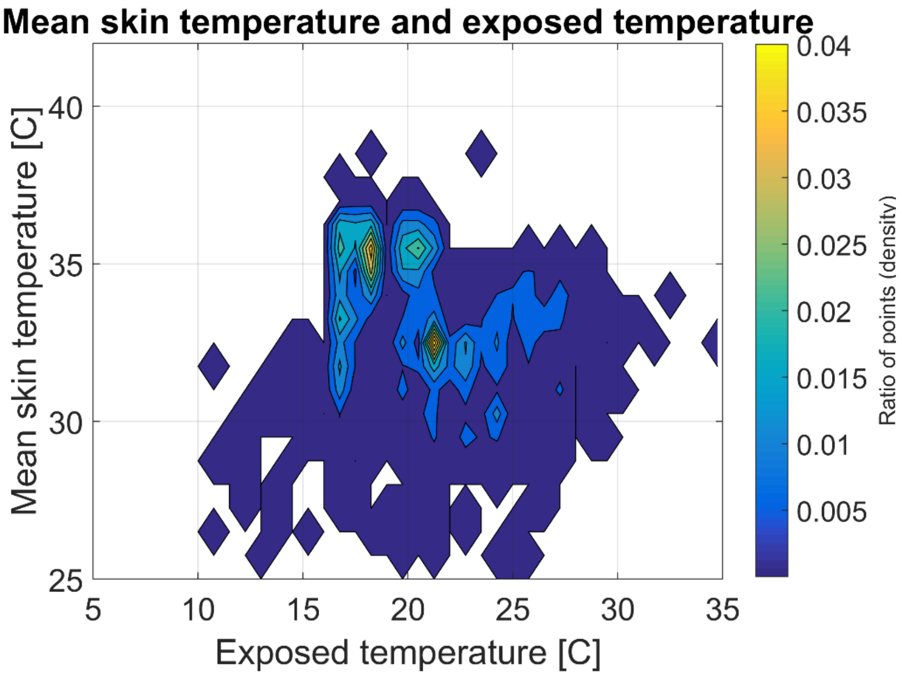


Figure 18 Contour plot of mean skin temperature and exposed temperature data of test subject 1

The colours in the contour plot show the density of the measuring points. A matrix was made using MATLAB, where MATLAB counted how much measuring points where within that one cell. Yellow colour indicates that 4% of all the measuring points are within that cell and purple means that less than 0.5% of all the measuring points are within that cell.

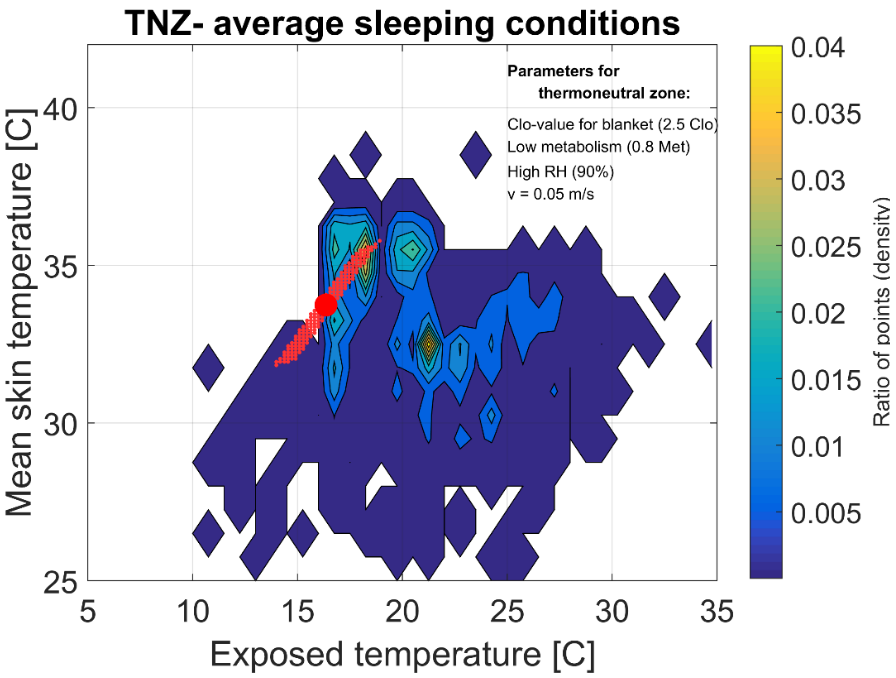


Figure 19 Contour plot of mean skin temperature and exposed temperature data including the thermoneutral zone (red) during the night of test subject 1

Figure 19 shows the same contour plot, including the calculated thermoneutral zone for test subject 1 during the night (red). For the blanket a Clo-value of 2.5 was used. The assumption was made that during the night, the relative humidity under the blanket is high and the metabolism and air velocity is low.

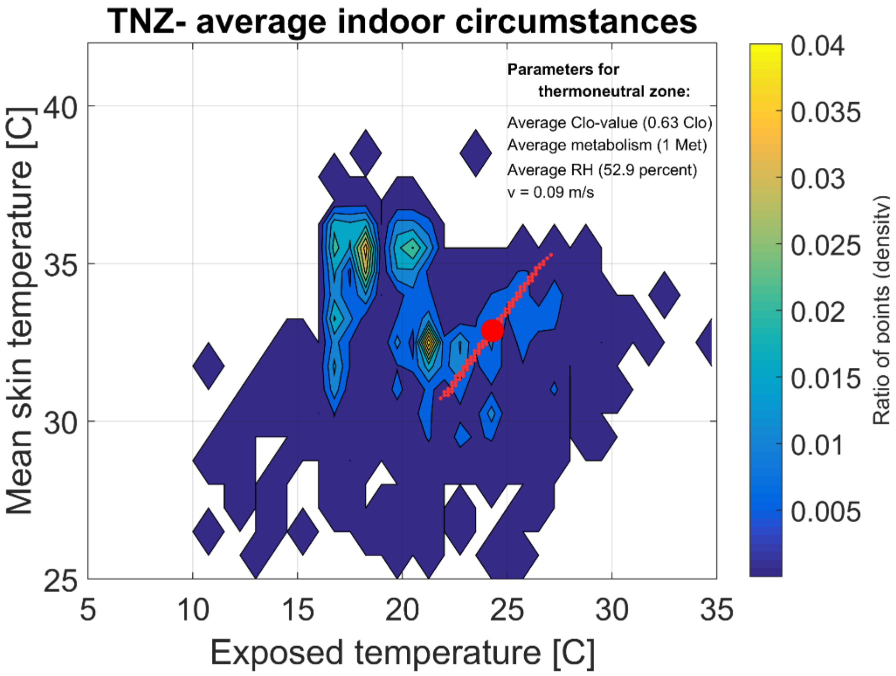


Figure 20 Contour plot of mean skin temperature and exposed temperature data including the thermoneutral zone (red) of test subject 1

Figure 20 shows the same contour plot, only including the calculated thermoneutral zone (red) for test subject 1 with the average Clo-value and average relative humidity of the data set, an average metabolic rate (Harris & Benedict, 1918) and an average air velocity (ISSO, 2008). The activity level, the Clo-value, the relative humidity and air velocity can vary. Figure 21 indicates the area wherein the thermoneutral zone (red) could vary in indoor circumstances during the day.

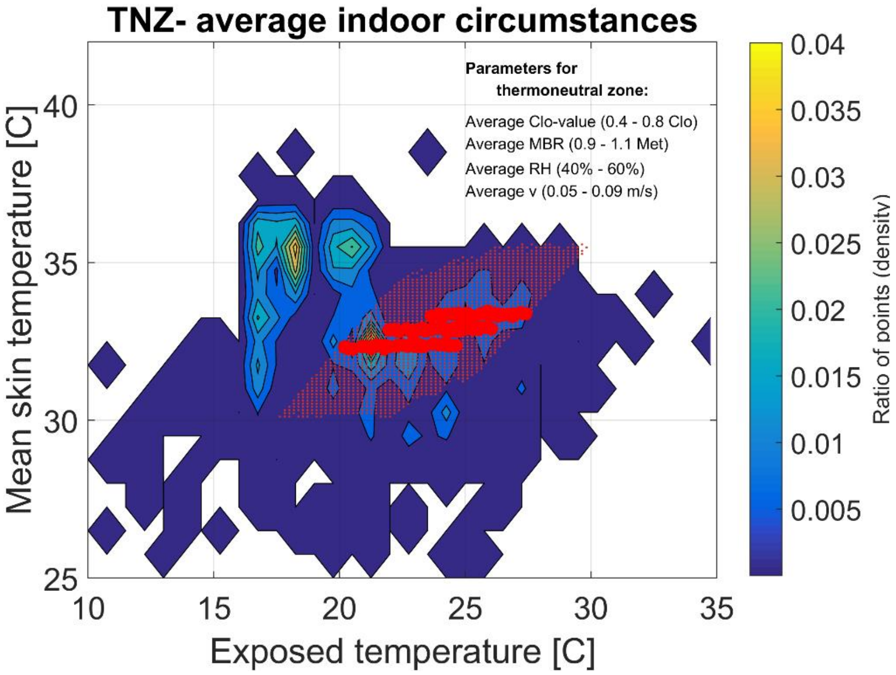


Figure 21 Contour plot of mean skin temperature and exposed temperature data including the dispersion of thermoneutral zones (red) of test subject 1

In addition, Figure 21 raises questions about the differences between the peaks in measuring points in the contour plots. Figure 22 through Figure 27 give more insight in those differences. These contour plots differ from the previous graphs. The test subjects filled in the questionnaire every two hours. The test subjects filled in what they were wearing, what activities they did at that moment and in the past hour, if they felt warm or cold and if this was comfortable or uncomfortable. In these three weeks they filled in the questionnaire approximately 200 times. For every entry the mean skin temperature and exposed temperature with the same time-stamp was matched with MATLAB. So the overlays in Figure 22 to Figure 27 are based on only these 200 measuring points.

Figure 22 shows the same outlines of the contour plot (density of the measuring points), which were shown in the previous graphs, to give an indication of the position in the graphs. The entries of the questionnaires are shown as an overlay (black and grey squares). The calculation of the TNZ is not included anymore. The colours in the overlay show the density of the questionnaire entries. A matrix was made using MATLAB, where after MATLAB counted how much measuring points where within that one cell. Black means that 5% of all the questionnaire entries are within that cell and light grey means that less than 1% of all the questionnaire entries are within that cell.

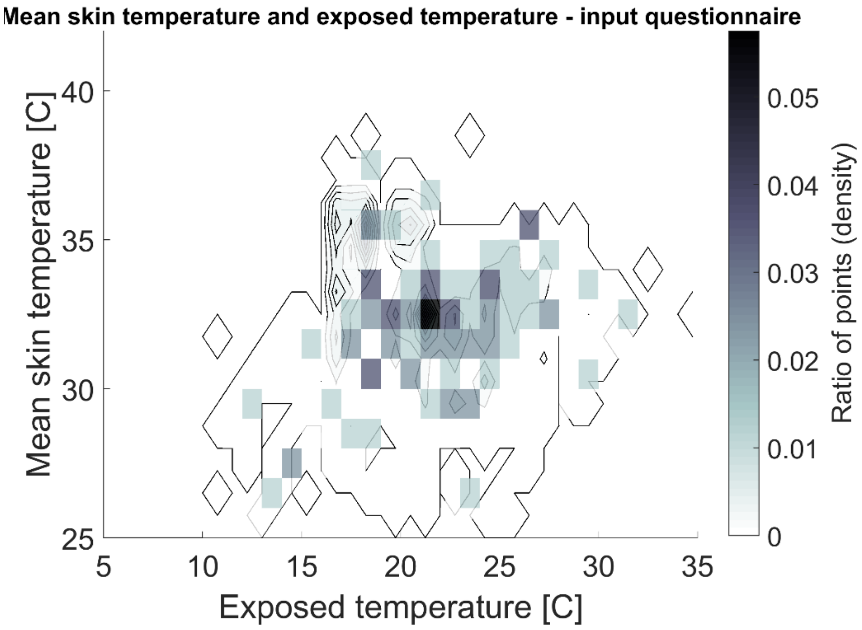


Figure 22 Contour plot of the questionnaire entries of test subject 1

The colours in Figure 23 show the sensation of the environment at each entry point. The sensation vote was filled in by the test subject over three measuring weeks by means of a standard 7-point thermal sensation scale, were -3 is very cold, -2 cold, -1 cool, 0 is neutral, 1 slightly warm, 2 warm and 3 is hot. The colours in this graph correspond with this scale; red colours correspond with hot, yellow corresponds with neutral and blue corresponds with cold.

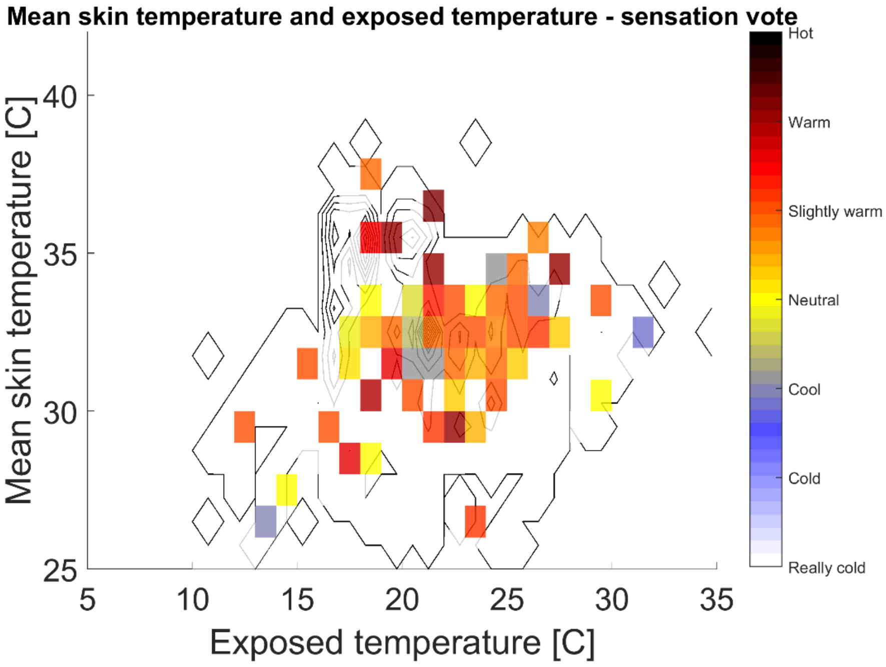


Figure 23 Contour plot of the sensation votes of test subject 1

The colours in Figure 24 show the comfort level at each entry point. The comfort vote was filled in by the test subject over three measuring weeks by means of a standard 7-point thermal comfort scale, were -3 is very uncomfortable, -2 uncomfortable, -1 just uncomfortable, 0 is neutral, 1 slightly comfortable, 2 comfortable and 3 is very comfortable. The colours in this graph correspond with this scale; red colours are comfortable, yellow is neutral and blue is uncomfortable.

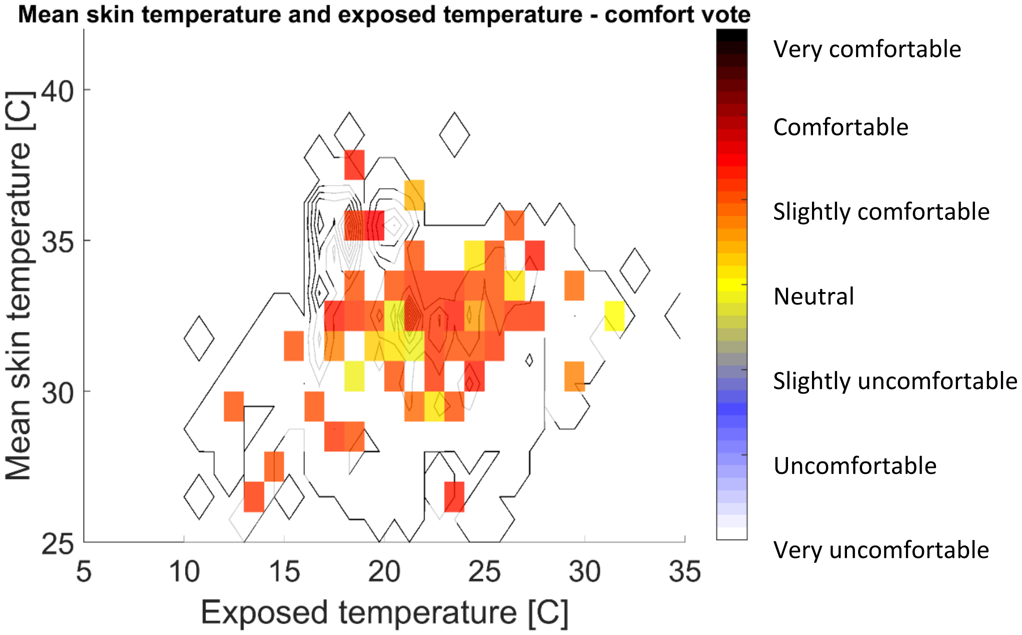


Figure 24 Contour plot of the comfort zones of test subject 1

Figure 25 shows the previous activity of test subject 1. The previous activity was used because the test subject would have to fill in her activity on her phone. When she would come home after school, she would probably be sitting or standing while filling in the questionnaire. Although her previous activity was cycling.

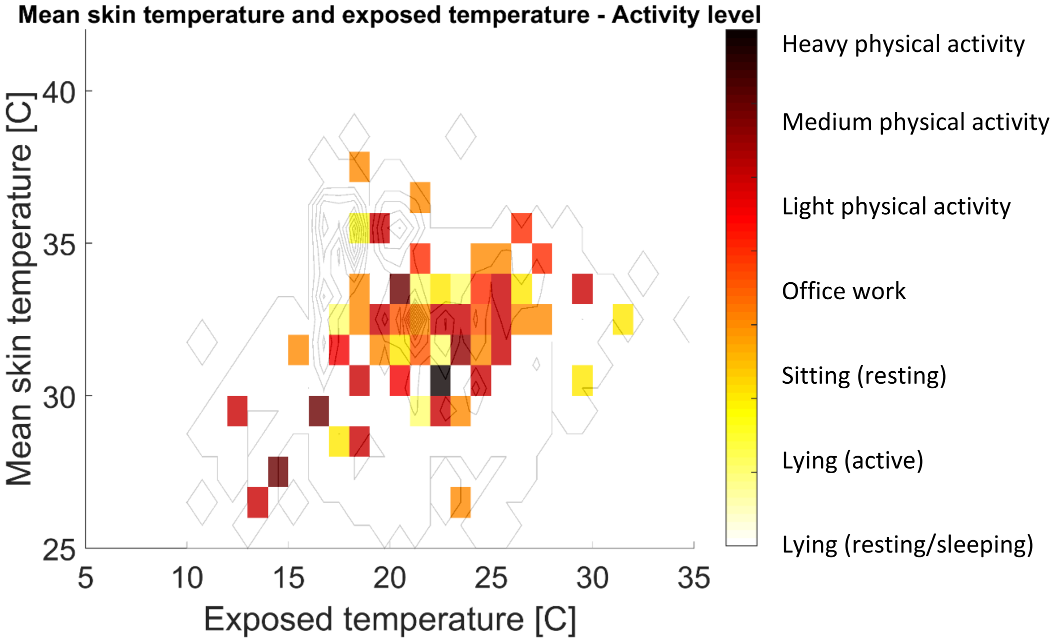


Figure 25 Contour plot of the activity level of test subject 1

Figure 26 shows the Clo-values of test subject 1. The colours show the clothing degree. Where 0.3 is underwear only, a Clo-value between 0.5 and 0.8 is regular clothing and a Clo-value higher than 0.8 corresponds with thick clothing, for example a thick sweater or a coat.

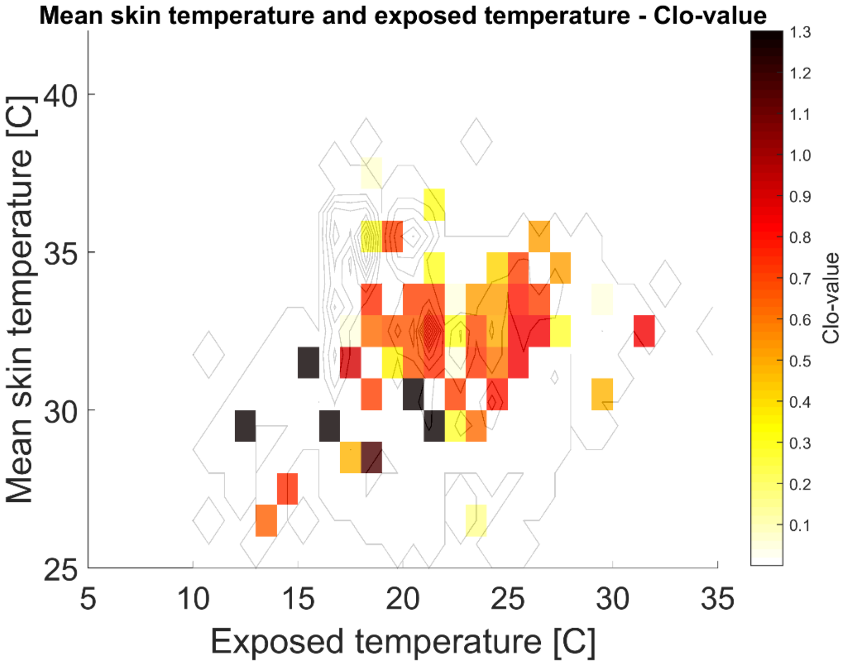


Figure 26 Contour plot of clothing worn by test subject 1

Figure 27 shows a combination of the previous graphs. All nine subplots show the outline of the contour plot with the density of the measuring points. The overlay in each subplot shows the comfort vote at each point in the graph with boundary conditions for Clo-values and activity levels. Here the red colours are once more comfortable, yellow is neutral and blue is uncomfortable.

The first row of graphs show the comfort votes when the Clo-values are low (less than 0.5). The second row of graphs show the comfort votes when the Clo-values are within the range of 0.5 and 0.8. The last row of graphs show the comfort votes when the Clo-values are high (higher than 0.8). In addition, the first column of graphs show the comfort votes when her activity level is low, thus lying and resting or sleeping. The second column of graphs show the comfort votes when her activity level is intermediate, thus sitting and resting or doing homework. The last column of graphs show the comfort votes when her activity level is high, thus doing household chores, cycling to school or running.

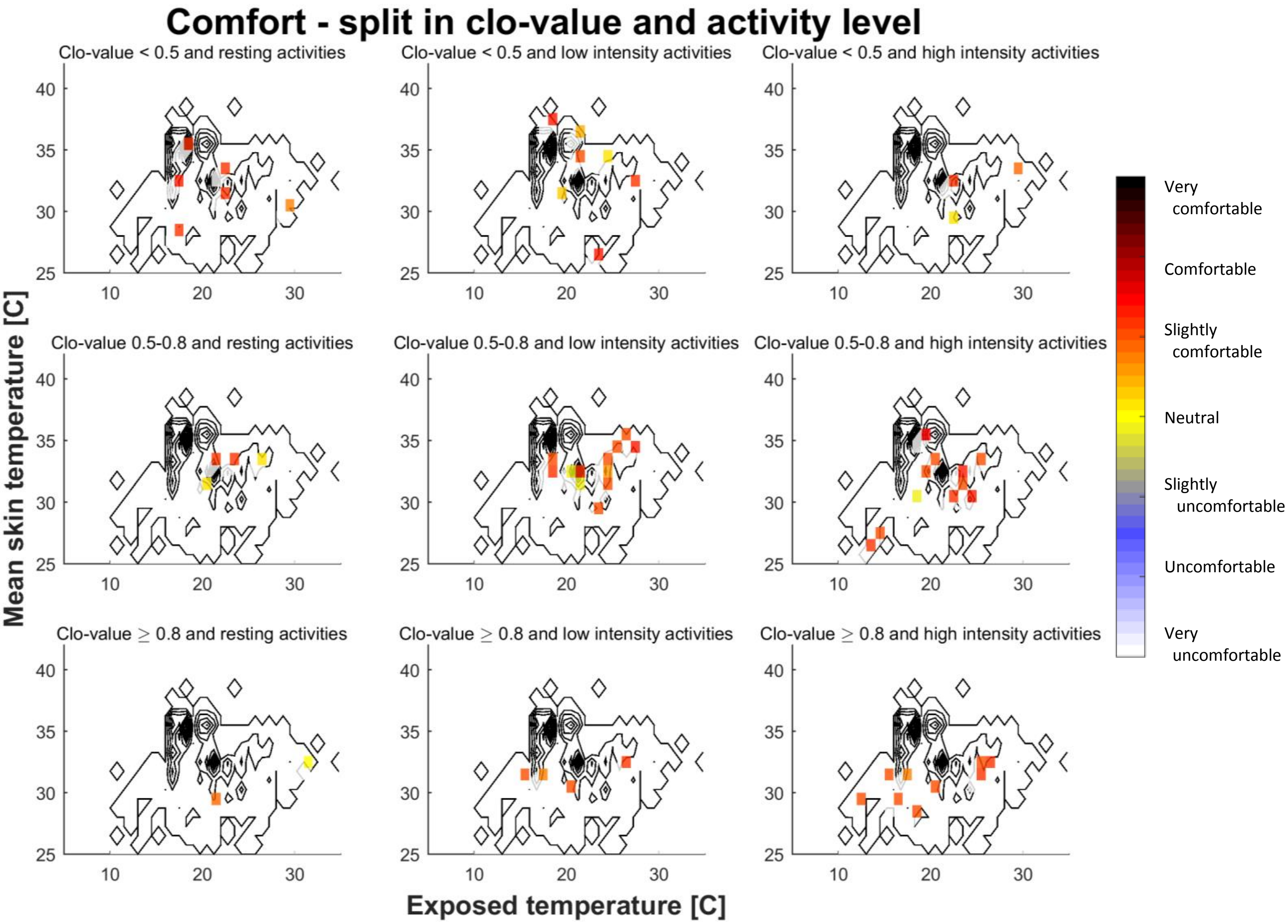


Figure 27 Contour plots of the comfort vote of test subject 1, with boundary conditions for Clo-values and activity levels

5.1.2 Thermoregulatory behaviour of the test subject

In addition to the previous results, Figure 28 shows the comfort and sensation vote filled in by test subject 1 over three measuring weeks. In this graph once more a standard 7-point thermal sensation scale was used, were -3 is very cold or very uncomfortable, -2 cold or uncomfortable, -1 cool or slightly uncomfortable, 0 is neutral, 1 slightly warm or slightly comfortable, 2 warm or comfortable and 3 is hot or very comfortable.

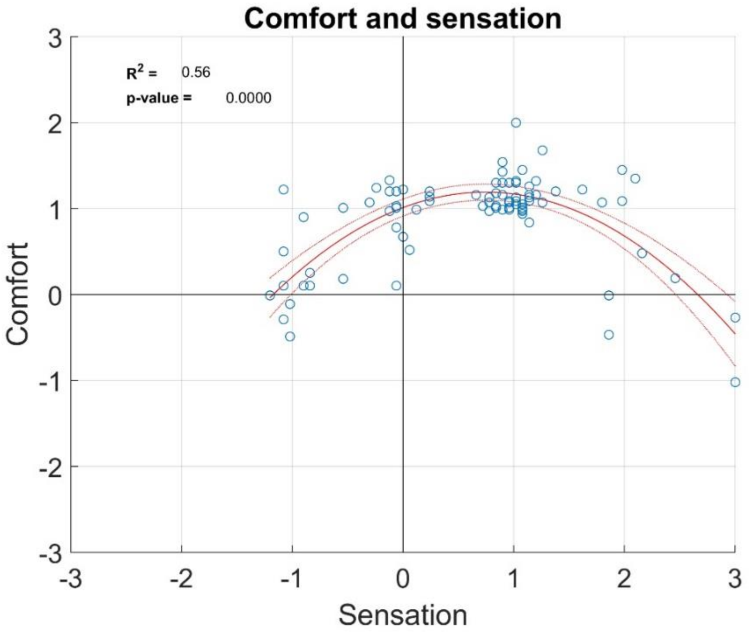


Figure 28 Comfort and sensation vote of test subject 1

Finally, the thermoneutral zone can be calculated for each measuring point individually. The calculation of the thermoneutral zone can only be done as a steady state condition. Therefore it is not possible to calculate the thermoneutral zone for the measuring points where the test subjects have a higher activity level. It is physically not possible to maintain this activity level for a longer period of time, therefore it is not possible to calculate a steady state condition for higher activity levels. So the thermoneutral zones are only calculated for the individual measuring points where the metabolic equivalent is below 1.2 (MET < 1.2). This means that for this analysis there are 58 measuring points left for test subject 1. For this section only one day, December 13th 2015, will be presented and discussed. The other graphs can be found in the short movies on the added USB-stick.

In addition, there are two unknown variables for the calculation of the thermoneutral zone; the metabolic rate and the air velocity, these variables are not measured. Although, the test subjects entered their activity level in the online questionnaire. The metabolic rates used per activity entry can be found in Table 4 (Ainsworth et al., 1995). The air velocity is partly dependent on the metabolic rate. No references could be found for air velocities corresponding with activities of metabolic rates. From practice it is known that the air velocity in dwellings is normally found between 0.05-0.1 m/s (ISSO, 2008). The air velocity around the body increases when the body moves faster. In addition, the air velocity underneath a blanket is near zero so around 0.05 m/s.

Table 4 Metabolic rates and air velocity used per activity entry

Activity entry questionnaire	**Used metabolic rate (Ainsworth et al., 1995)**	**Used air velocity**
Lying (sleeping/resting)	0.9 Met	0.05 m/s
Lying (active)	0.9 Met	0.06 m/s
Sitting (resting/reading/eating)	1.0 Met	0.07 m/s
Sitting (office work)	1.1 Met	0.09 m/s
Standing (light physical effort)	Not included in analysis	Not included in analysis
Standing (medium physical effort)	Not included in analysis	Not included in analysis
Standing (heavy physical effort)	Not included in analysis	Not included in analysis

Figure 86 in *Appendix V* shows the week schedule of test subject 1. A short summary of December 13th 2015 can be found in Table 5.

Table 5 Schedule of Sunday December 13th 2015 of test subject 1

Time	**Action**
10:45:00	Getting out of bed
12:30:00	Going to the grocery store
13:30:00	Back home
18:15:00	Going for a run
18:55:00	Back home
20:25:00	Taking a shower
22:45:00	Going to sleep

Figure 29 shows the first measuring point of December 13th 2015 of test subject 1, at 10:37 hour. She is probably still in bed, according to her schedule. As can be derived from the graph, the wireless sensors measured a relative humidity of 56%, an exposed temperature of 17.6˚C and a weighted average skin temperature of 35.2˚C. According to her entries in the questionnaire, she has a Clo-value of 0.48 and the corresponding metabolic rate and air velocity are respectively 0.9 Met and 0.05 m/s (Table 4). She entered a sensation vote of 1.8 and a comfort vote of 1.07, so she feels warm and this is just comfortable.

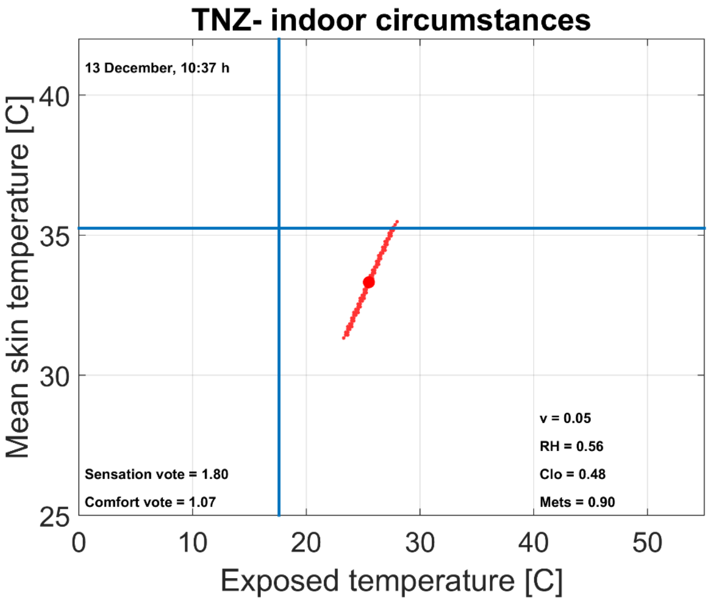


Figure 29 Thermoneutral zone (in red) and comfort zone (red dot) calculated for measuring point 13th December 10.37h for test subject 1, including the measured weighted mean skin temperature (blue horizontal line) and measured exposed temperature (blue vertical line)

The body can only regulate its temperature in the surrounding environment by regulating its heat loss by dilatation and contraction of blood vessels, which increases or decreases the skin temperature. Therefore, a higher skin temperature suggests that the test subject feels warm and a lower skin temperature suggests that the test subject feels cold. In Figure 29 the skin temperature of test subject 1 is within the higher end of the calculated thermoneutral zone. This corresponds with her sensation and corresponding comfort vote. The exposed temperature is lower than the TNZ. This indicates that the person is not in heat balance: more heat is lost and consequently she would probably start feeling colder if she does not change her environment, her clothing or her activity level.

A quarter of an hour later she is probably out of bed, according to her schedule. Figure 30 shows this measuring point. Her environment, clothing and activity level are not changed after the last measuring point. Although, her sensation and comfort vote did change. She feels slightly cool, although close to neutral and this is just comfortable. Her weighted average skin temperature has decreased to 33.5˚C. The exposed temperature is still lower than the thermoneutral zone. This indicates that the person is not in heat balance: more heat is lost and consequently she would probably start feeling colder if she does not change her environment, her clothing or her activity level.

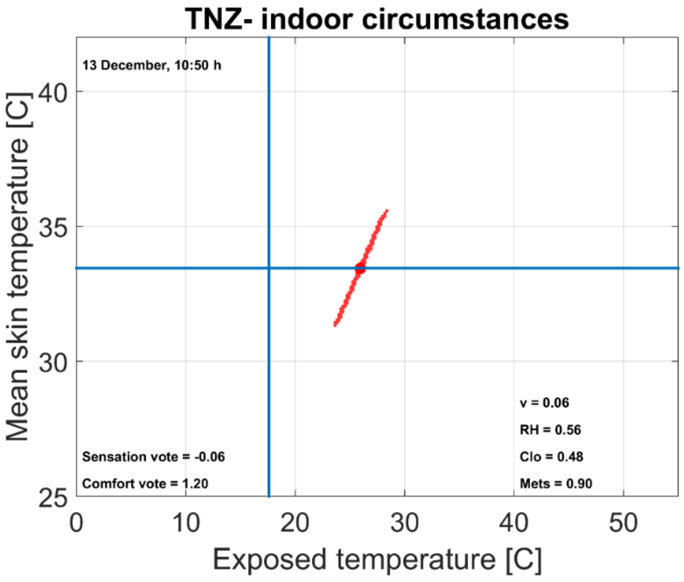


Figure 30 Thermoneutral zone (in red) and comfort zone (red dot) calculated for measuring point 13th December 10.50h for test subject 1, including the measured weighted mean skin temperature (blue horizontal line) and measured exposed temperature (blue vertical line)

Figure 31 shows that after she probably dressed herself, her Clo-value increased, she moved to another room in the house and her activity level increased. In addition, her exposed temperature increased to 24.6˚C, which is at the higher end of her calculated thermoneutral zone. Her weighted average skin temperature decreased further to 31.8˚C, which is at the lower side of her calculated thermoneutral zone. Her sensation vote increased to 0.96 which corresponds with slightly warm and this is just comfortable (comfort vote = 1.09). Because of the higher exposed temperature she would probably increase feeling warmer if she does not change her environment, her clothing or her activity level.

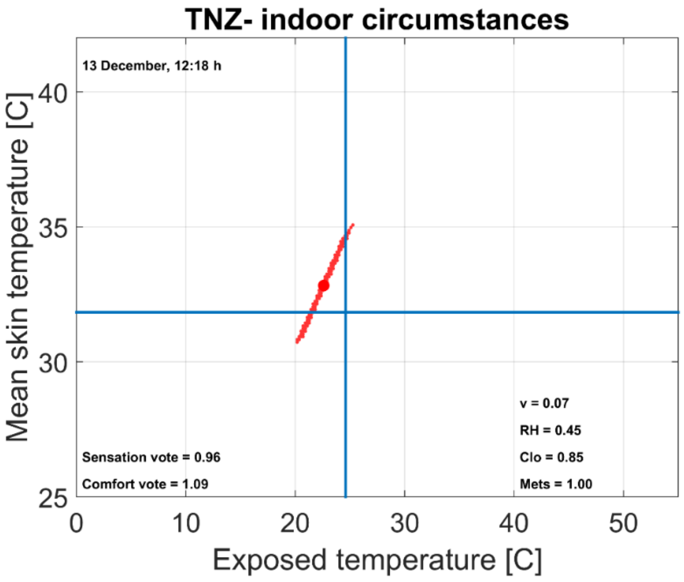


Figure 31 Thermoneutral zone (in red) and comfort zone (red dot) calculated for measuring point 13th December 12.18h for test subject 1, including the measured weighted mean skin temperature (blue horizontal line) and measured exposed temperature (blue vertical line)

Figure 32 shows the fourth measuring point of the day. Between the third and fourth measuring point, the test subject went to the grocery store. Her clo-value stayed the same since the last measuring point. Her activity level increased. In addition, her skin temperature increased to 32.3˚C and her exposed temperature increased to 30.6˚C. Her skin temperature is within the thermoneutral zone and the exposed temperature is higher than the calculated thermoneutral zone. She feels cool (sensation vote = -1.2) which is neither comfortable nor uncomfortable (comfort vote = -0.01).

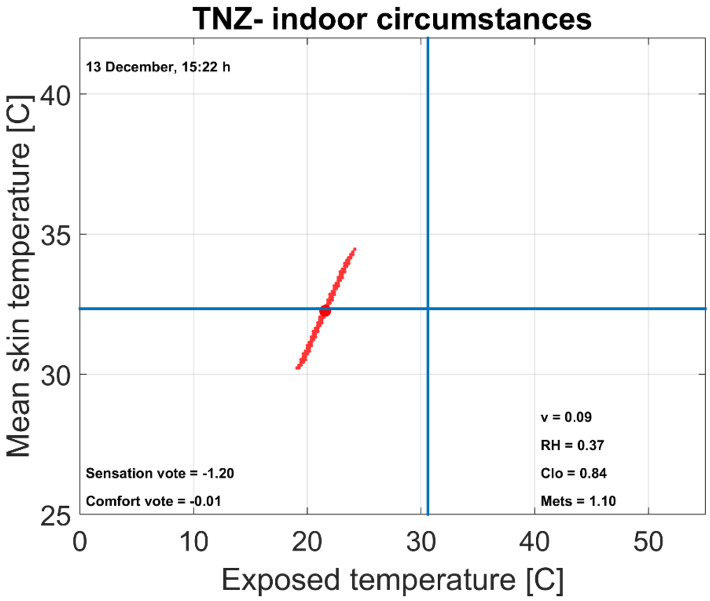


Figure 32 Thermoneutral zone (in red) and comfort zone (red dot) calculated for measuring point 13th December 15.22h for test subject 1, including the measured weighted mean skin temperature (blue horizontal line) and measured exposed temperature (blue vertical line)

Figure 33 shows the fifth measuring point of the day. Her clo-value stayed approximately the same since the last measuring point. Her activity level decreased. In addition, her skin temperature stayed the same (32.3˚C) and her exposed temperature decreased to 26.1˚C. Her skin temperature is within the thermoneutral zone and the exposed temperature is higher than the calculated thermoneutral zone. She feels slightly warm (sensation vote = 1.14) which is slightly comfortable (comfort vote = 1.16). The person is not in heat balance because of the higher exposed temperature: more heat is retained and consequently she would probably increase feeling warmer if she does not change her environment, her clothing or her activity level.

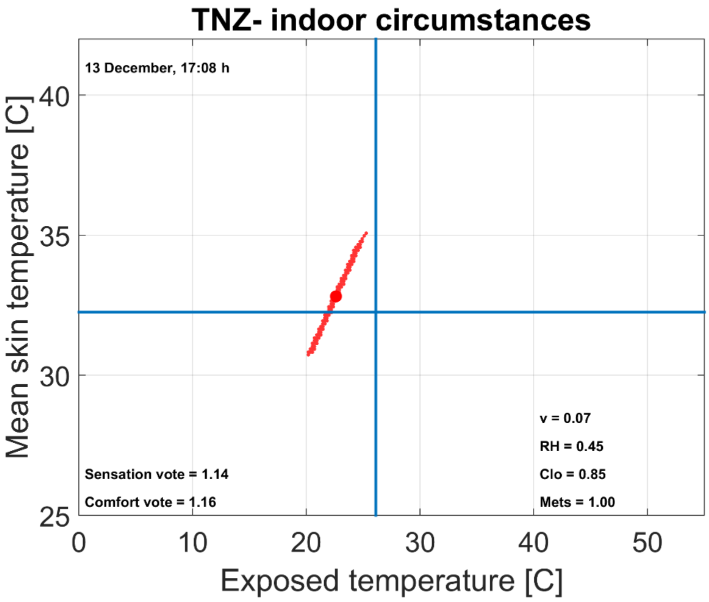


Figure 33 Thermoneutral zone (in red) and comfort zone (red dot) calculated for measuring point 13th December 17.08h for test subject 1, including the measured weighted mean skin temperature (blue horizontal line) and measured exposed temperature (blue vertical line)

Figure 34 shows the sixth measuring point of the day. Her clo-value and activity level stayed the same since the last measuring point. In addition, her skin temperature decreased to 30.8˚C and her exposed temperature decreased to 21.1˚C. Her skin temperature and measured exposed temperature are on the edge of her thermoneutral zone. She feels cool (sensation vote = -0.84) which is around neutral (comfort vote = 0.25). The combination of her skin temperature and the measured exposed temperature suggest that she is not completely in heat balance, more heat is lost. She would probably start feeling colder if she does not change her environment, her clothing or her activity level.

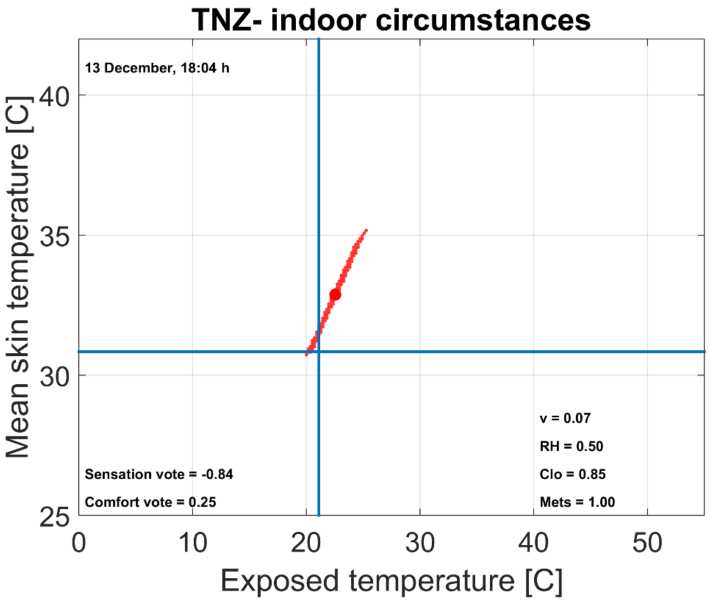


Figure 34 Thermoneutral zone (in red) and comfort zone (red dot) calculated for measuring point 13th December 18.04h for test subject 1, including the measured weighted mean skin temperature (blue horizontal line) and measured exposed temperature (blue vertical line)

Figure 35 shows the seventh measuring point of the day. Between the sixth and seventh measuring point, test subject 1 went for a run. At the seventh measuring point she is probably still in her running clothes, because her clo-value decreased to 0.33. Her activity level increased. In addition, her skin temperature increased to 31.8˚C and her exposed temperature increased to 23.6˚C. Her skin temperature and measured exposed temperature are within her thermoneutral zone, although on the lower side of the zone. She feels cool (sensation vote = -0.9) which feels slightly comfortable (comfort vote = 0.9). The position of the thermoneutral zone compared to the exposed temperature indicates that she would probably increase feeling colder if she does not change her environment, her clothing or her activity level.

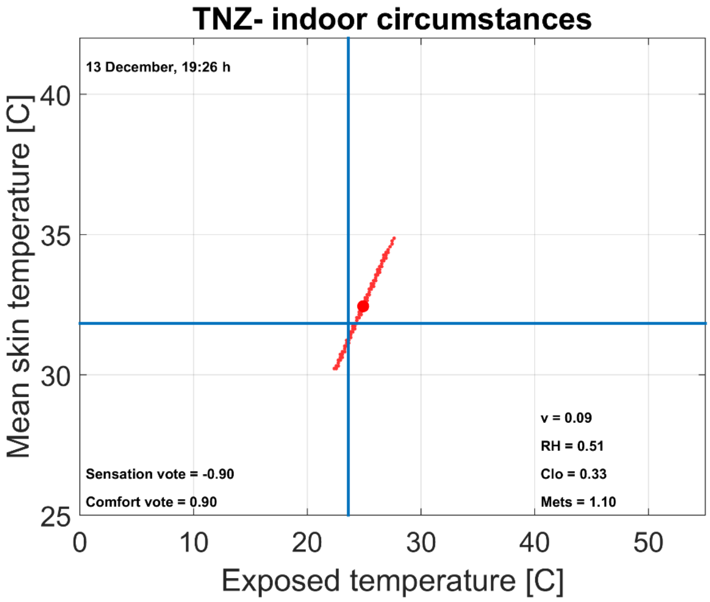


Figure 35 Thermoneutral zone (in red) and comfort zone (red dot) calculated for measuring point 13th December 19.26h for test subject 1, including the measured weighted mean skin temperature (blue horizontal line) and measured exposed temperature (blue vertical line)

5.1.3 Optimal indoor temperatures

As discussed in *section 2.1 The thermoneutral zone model (TNZ)* and as can be seen in Figure 5, the comfort zone is the center of the thermoneutral zone, the corresponding operative temperature is the most comfortable (optimal) indoor temperature for that person at that moment (T_{opt}). Because parameters such as relative humidity, air velocity, activity level and clothing can vary over time this will lead to a different comfort zone and thus a different optimal indoor temperature. The thermoneutral zone is calculated for the 57 questionnaire entries of test subject 1. For all these moments a T_{opt} is calculated (see *Appendix I*). As discussed in the previous section, this calculation is a steady state calculation, and the human body adapts to the exposed temperature with a slight delay over time. However, the average T_{opt} per test subject can give an insight in the differences in prefered indoor temperatures.

There was only one week that both test subject 1 and 2 were measured together. They were measured together for a second week, but some of the data was lost because of malfunction of equipment. For each test subject the T_{opt} per questionnaire entry was calculated for one week. Per day the average optimal temperature (T_{opt}) was calculated, see Table 6. Figure 36 through Figure 42 show histograms per day and per test subject of all the calculated optimal temperatures.

Table 6 Average calculated T_{opt} per day

Date	Test subject 1	Test subject 2
10-nov-2016	19.42 ˚C	25.48 ˚C
11-nov-2016	19.45 ˚C	28.16 ˚C
12-nov-2016	20.20 ˚C	24.73 ˚C
13-nov-2016	20.20 ˚C	24.04 ˚C
14-nov-2016	20.73 ˚C	24.28 ˚C
15-nov-2016	24.61 ˚C	25.69 ˚C
16-nov-2016	18.99 ˚C	25.84 ˚C

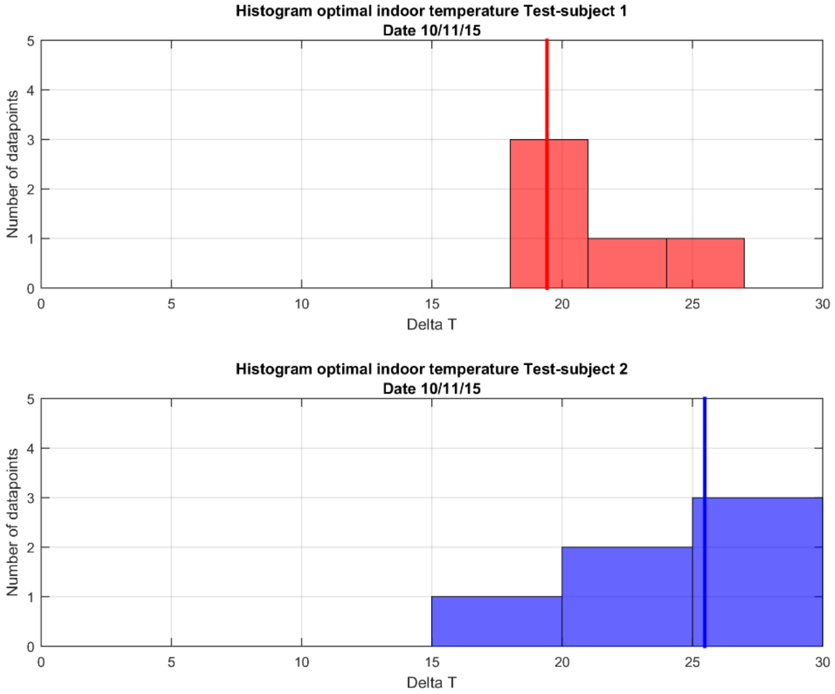


Figure 36 Histograms for test subjects 1 and 2 of all the calculated T_{opt}'s – 10th november 2016

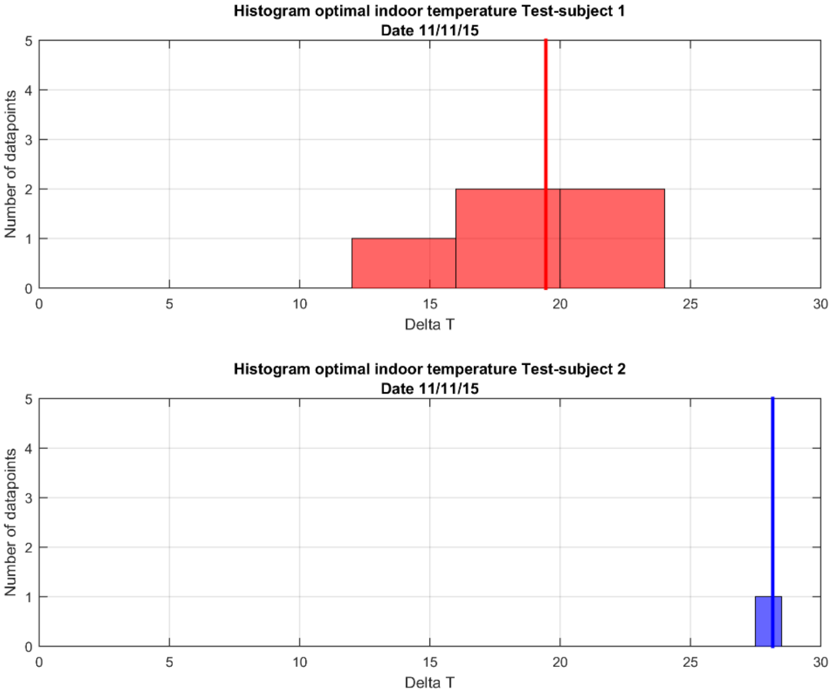


Figure 37 Histograms for test subjects 1 and 2 of all the calculated T_{opt}'s – 11th november 2016

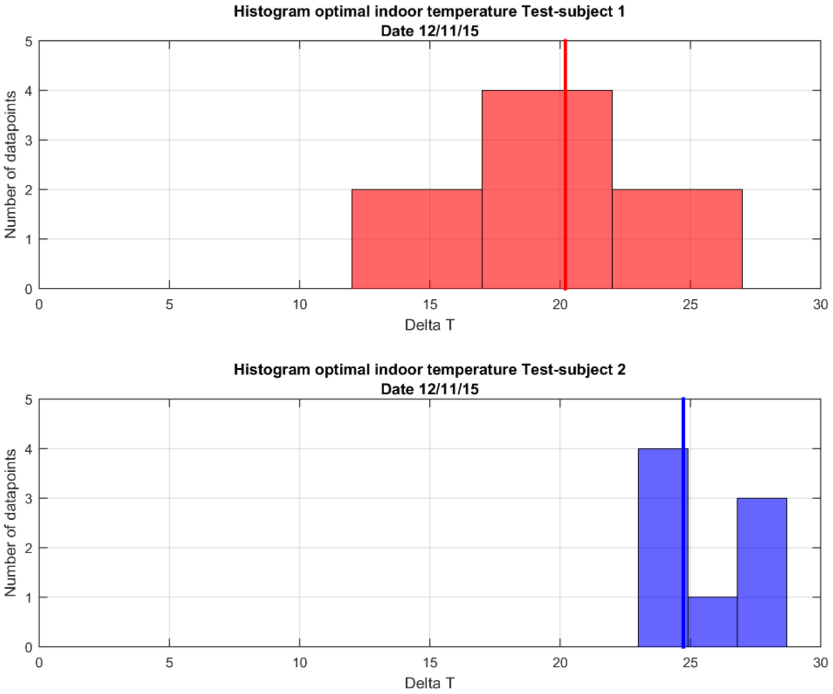


Figure 38 Histograms for test subjects 1 and 2 of all the calculated T_{opt}'s – 12th november 2016

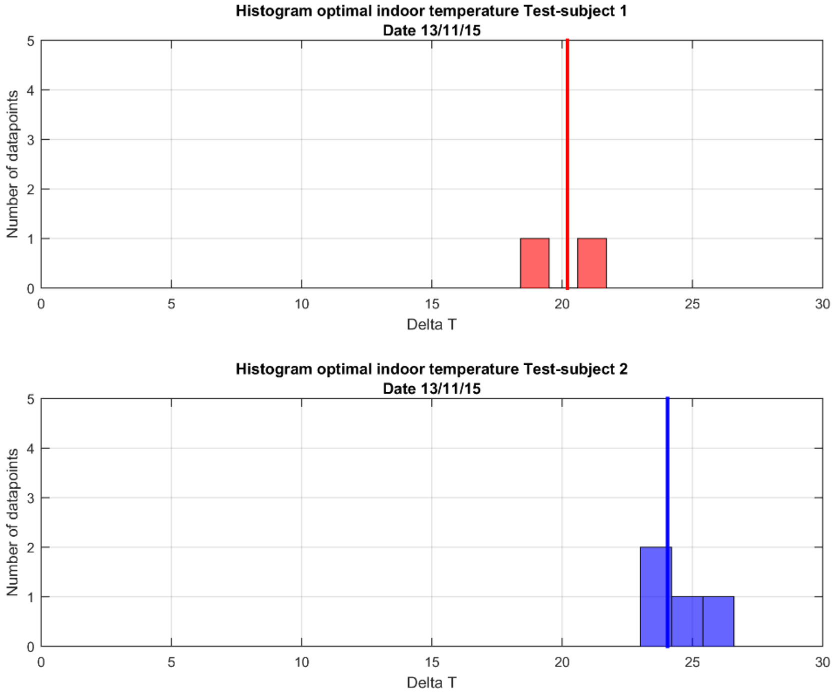


Figure 39 Histograms for test subjects 1 and 2 of all the calculated T_{opt}'s – 13th november 2016

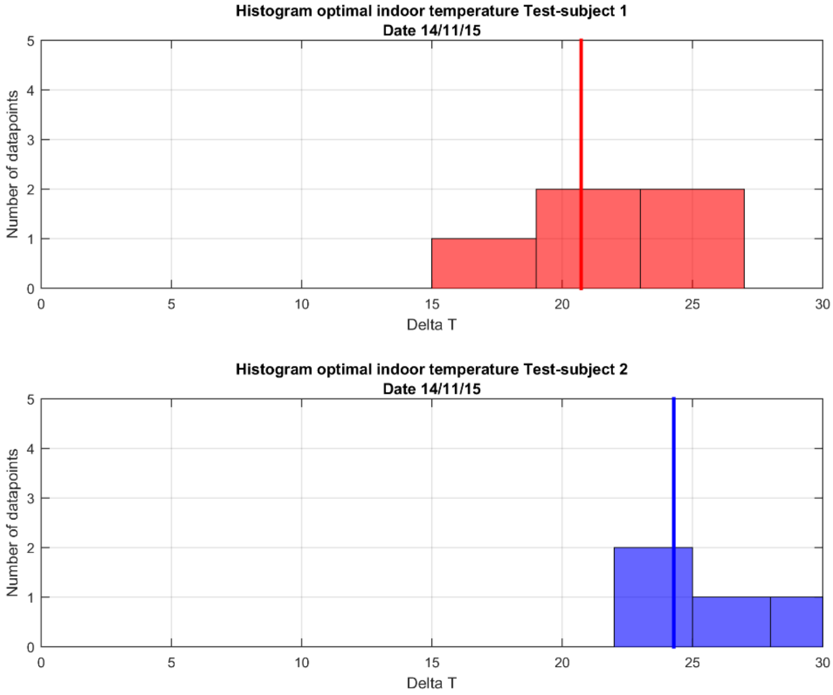


Figure 40 Histograms for test subjects 1 and 2 of all the calculated T_{opt}'s – 14th november 2016

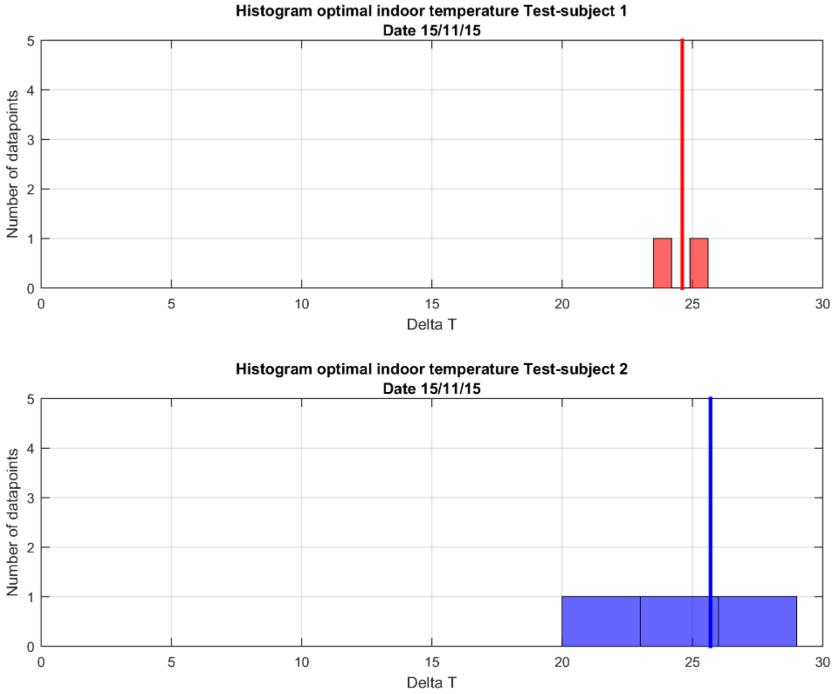


Figure 41 Histograms for test subjects 1 and 2 of all the calculated T_{opt}'s – 15th november 2016

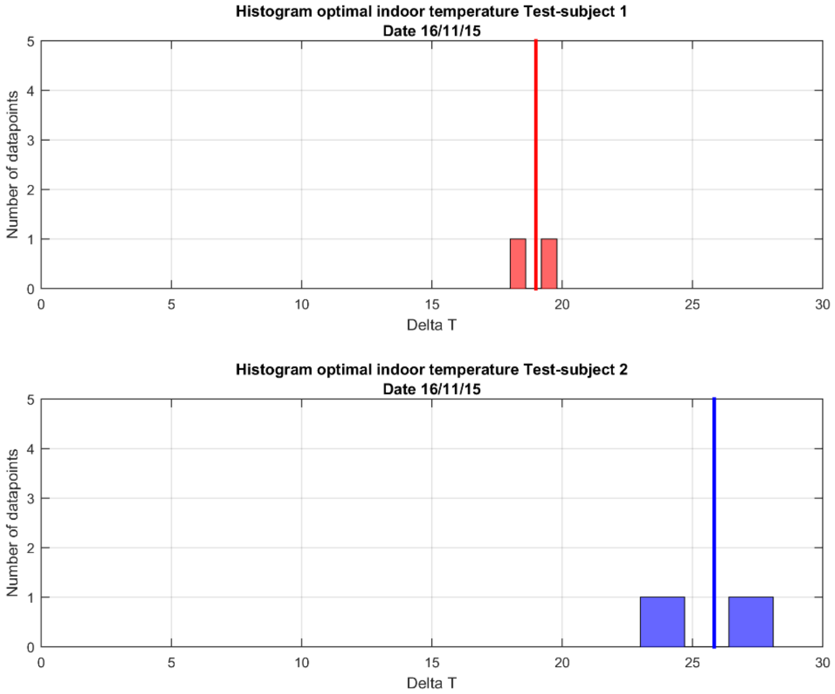


Figure 42 Histograms for test subjects 1 and 2 of all the calculated T_{opt}'s – 16th november 2016

5.2 Energy demand

As discussed in *section 4.1 Dwelling*, the same dwelling was used as during the preliminary research and similar data was collected. This made it possible to use this data set for this study as well. During the winter of 2015-2016 two female students were living in the dwelling in Heerlen. For this study the collected data of the period October 2015 through March 2016 is used. This was the first winter season that the dwelling was being monitored. Since the summer of 2016 there are two new tenants living in this dwelling. This is a young couple who both work during the day. For this study the collected data of the period October 2016 through February 2017 is used of 2016-2017. It is important to note that the model as discussed in *Chapter 3 Methodology to calculate energy consumption*, was only applied during the colder months of the year, i.e. October through February/March, because of the major differences between the months when heating is turned on and the period when it is switched off (i.e. colder and warmer seasons in the Netherlands/Heerlen). Therefore, this model needs to be revised when applied to warmer months, such as the summer period in the Netherlands. The model is now restricted to application where solar radiation is limited and thermal mass can be neglected.

5.2.1 Data sets

It is first needed to get an impression of the data. Figure 43 and Figure 44 show the measured energy demand for heating ($Q_{measured}$) [kWh_{th}/per day] for both periods as function of the difference between out- and indoor temperature (ΔT) [˚C]. As can be derived from the graphs, as mentioned in *Chapter 3 Methodology to calculate energy consumption*, there appears a linear correlation between $Q_{measured}$ and ΔT in both cases (2015-2016: $R^2 = 0.68$, 2016-2017: $R^2 = 0.79$).

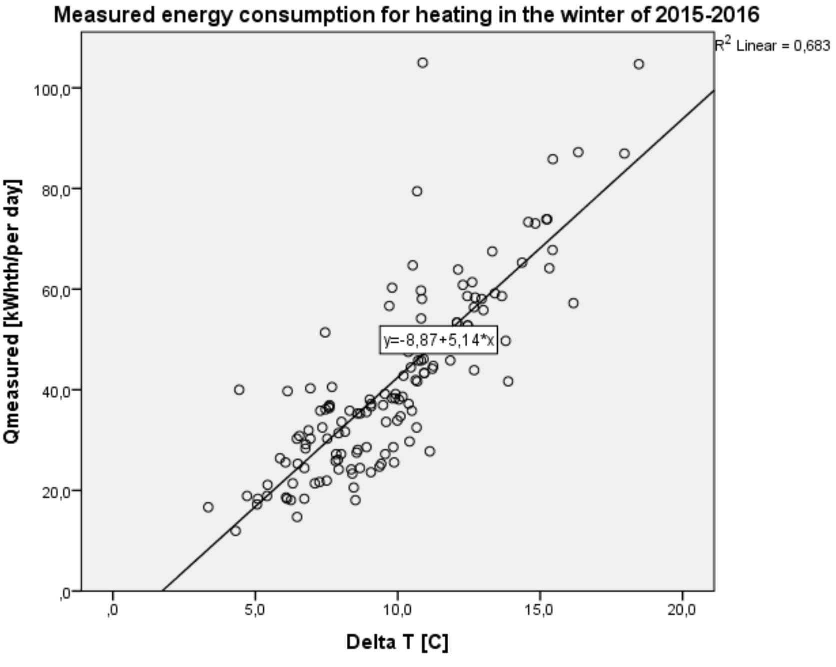


Figure 43 Measured energy consumption for heating in the winter of 2015-2016 [kWh_{th}/per day]

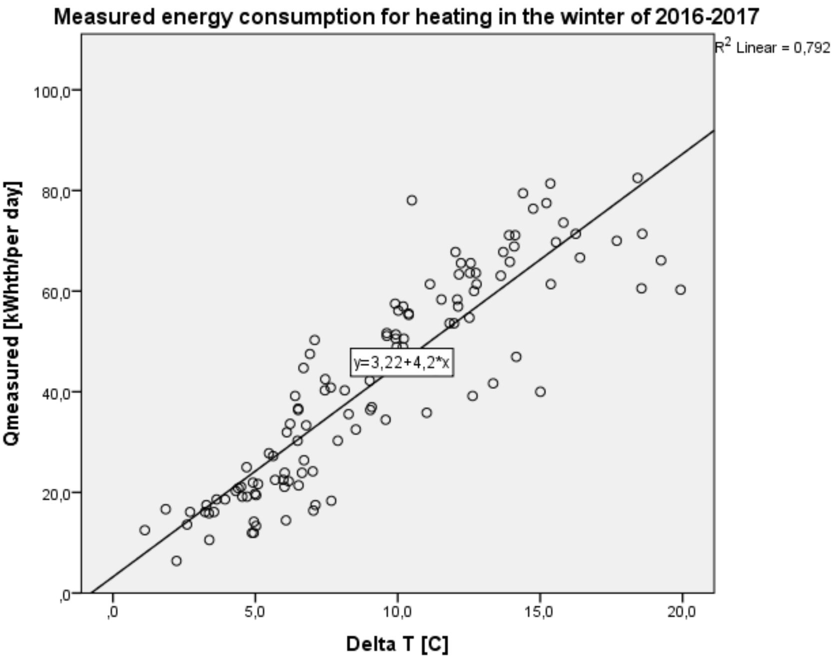


Figure 44 Measured energy consumption for heating in the winter of 2016-2017 [kWh$_{th}$/per day]

As can be derived from Figure 43 and Figure 44, the performance of the dwelling in the winter of 2016-2017 seems to be more energy efficient than during the winter of 2015-2016 (Oct 2015- Jan 2016: 5.14 kWh$_{th}$/K per day, Oct 2016- Jan 2017: 4.2 kWh$_{th}$/K per day). Figure 45 and Figure 46 show the difference in energy consumption between both winter seasons over time.

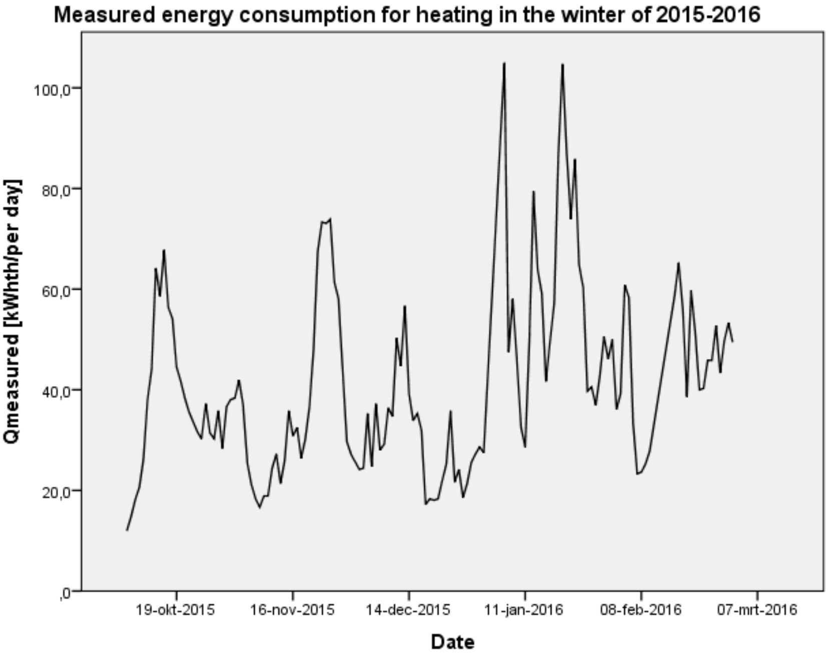


Figure 45 Measured energy consumption for heating over time in the winter of 2015-2016

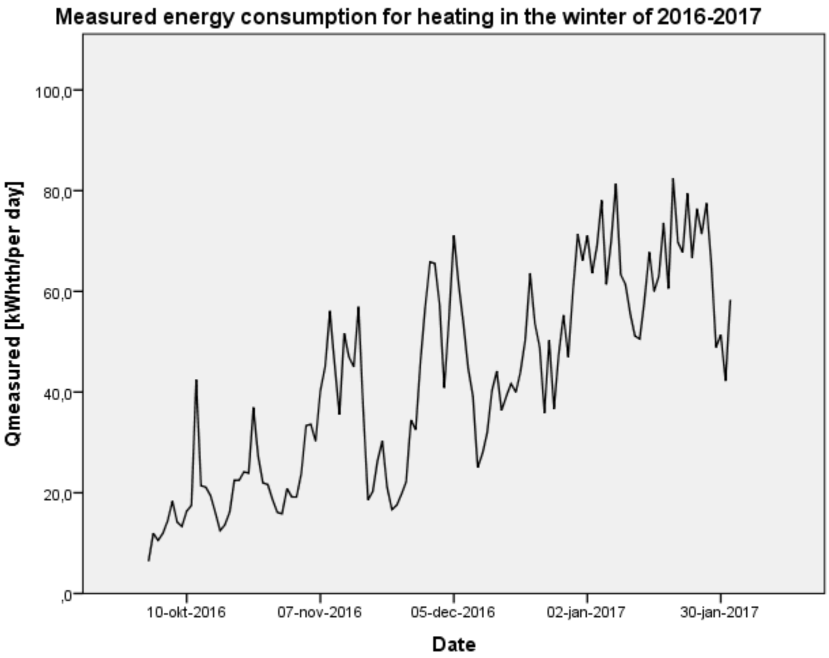


Figure 46 Measured energy consumption for heating over time in the winter of 2016-2017

Figure 47 and Figure 48 show the measured in- and outdoor temperature over time for both data sets. As can be derived from the four graphs, the winter of 2016-2017 started relative mild, although February was on average colder than the winter season of 2015-2016.

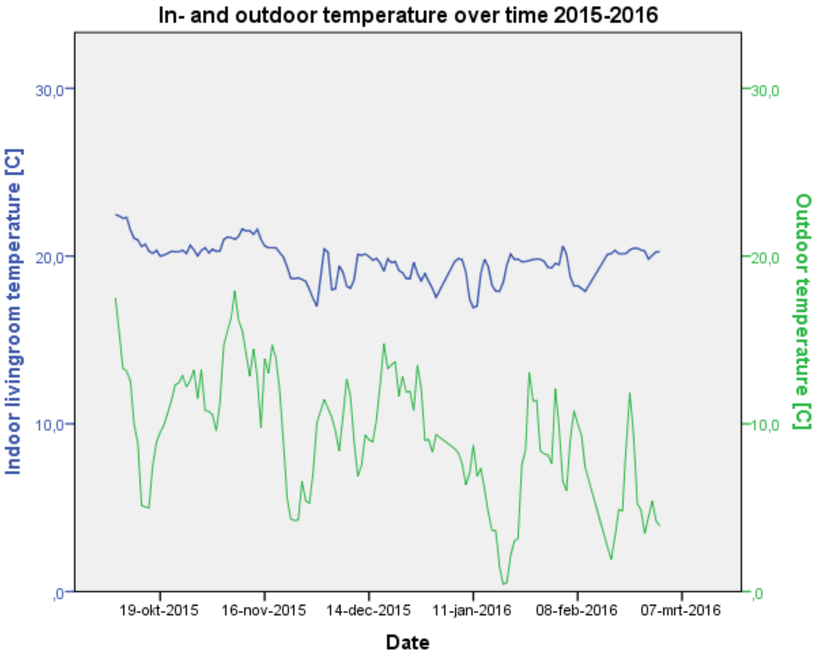


Figure 47 Measured in- and outdoor temperature over time in the winter of 2015-2016

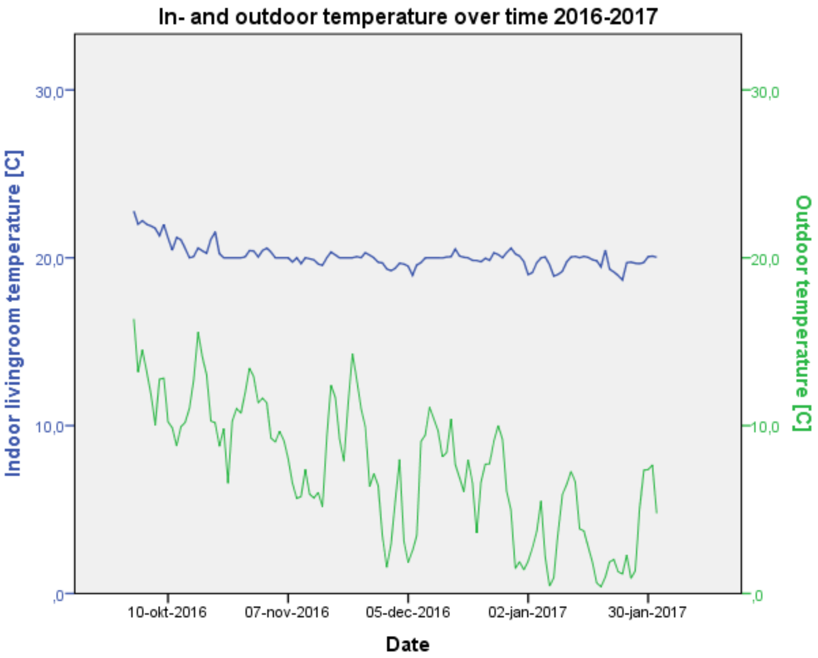


Figure 48 Measured in- and outdoor temperature over time in the winter of 2016-2017

Table 7 and Table 8 describe the measuring data in more detail. As can be derived from the tables and from Figure 47 and Figure 48, the indoor temperature during the winter of 2016-2017 was on average slightly higher than during the winter of 2015-2016, although it was more constant. The winter of 2016-2017 was on average colder (Oct 2015- Jan 2016: 1278 degree days, Oct 2016- Jan 2017: 1715 degree days). However, the measured energy demand for heating did not vary a lot between both winters. So the occupants during the winter of 2016-2017 were more efficient. The tables of the degree days of 2015 until 2017 can be found in *Appendix IX*.

Table 7 Description of the measured data for the winter of 2015-2016

	Mean	**Standard deviation**	**Minimum**	**Maximum**
Indoor temperature	19.8˚C	± 1.1 ˚C	16.9 ˚C	22.5 ˚C
Outdoor temperature	9.1 ˚C	± 3.8 ˚C	0.4 ˚C	17.9 ˚C
ΔT	9.8 ˚C	± 2.9 ˚C	3.3 ˚C	18.5 ˚C
$Q_{measured}$	41.4 kWh_{th}	± 18.0 kWh_{th}	11.9 kWh_{th}	105.0 kWh_{th}

Table 8 Description of the measured data for the winter of 2016-2017

	Mean	**Standard deviation**	**Minimum**	**Maximum**
Indoor temperature	20.1˚C	± 0.7 ˚C	18.7 ˚C	22.8 ˚C
Outdoor temperature	7.4 ˚C	± 4.0 ˚C	0.4 ˚C	16.4 ˚C
ΔT	9.2 ˚C	± 4.3 ˚C	1.1 ˚C	19.9 ˚C
$Q_{measured}$	42.1 kWh_{th}	± 20.3 kWh_{th}	6.4 kWh_{th}	82.5 kWh_{th}

5.2.2 Inverse modelling

As mentioned in *Chapter 3 Methodology to calculate energy consumption*, the model that was formulated in this study was based on equation (1). Wherein real measurements (e.g. in- and outdoor temperatures, ventilation flow, wind speed and energy use of appliances and installations) were used in the calculation of $Q_{predicted}$ [kWh]. This TRECO energy demand model is described in *Appendix II*.

In addition, for the calculation of $Q_{predicted}$, information of general parameters of the dwelling were collected, such as thermal resistance of closed parts, thermal transmittance of transparent parts, air tightness of the dwelling and g-values of glass. These parameters might have a great influence on the calculated energy use and the actual values of these parameters might differ from the expected values. These deviations might have a great influence on the energy demand (Rasooli et al., 2016). This shows a need to use inverse modelling to determine the building parameters in practice. The goal of inverse modelling was to find the parameters that minimize the error between the modelling result and the measurements. For the purpose of the thesis, this means finding parameters that minimize the difference between $Q_{predicted}$ and the measured energy use for space heating ($Q_{measured}$). *Appendix II* describes that the variables 'a, b, c, d, e, f' used in the prediction model, were the parameters that were predicted during the inverse modelling stage.

The data sets discussed in *section 5.2.1 Data sets*, were used to validate the prediction model. The energy demand of the dwelling was predicted with its parameters and compared with the real energy demand. For this calculation, the building characteristics of the dwelling were applied, see *Appendix III*. Figure 49 and Figure 50 show a first calculation and the real energy demand on a daily average. For this first calculation the factors 'a, b, c, d, e, f' were set to 1.

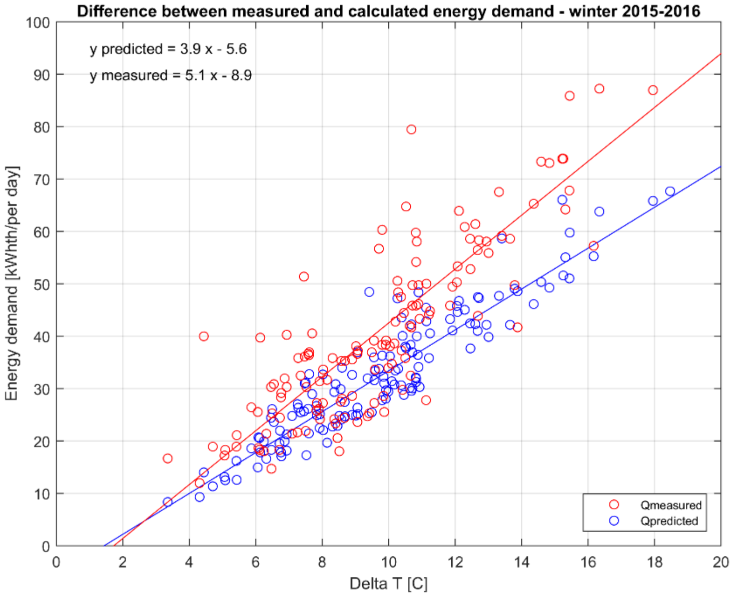


Figure 49 First calculation and the measured energy demand on a daily average before inverse modelling – winter 2015-2016

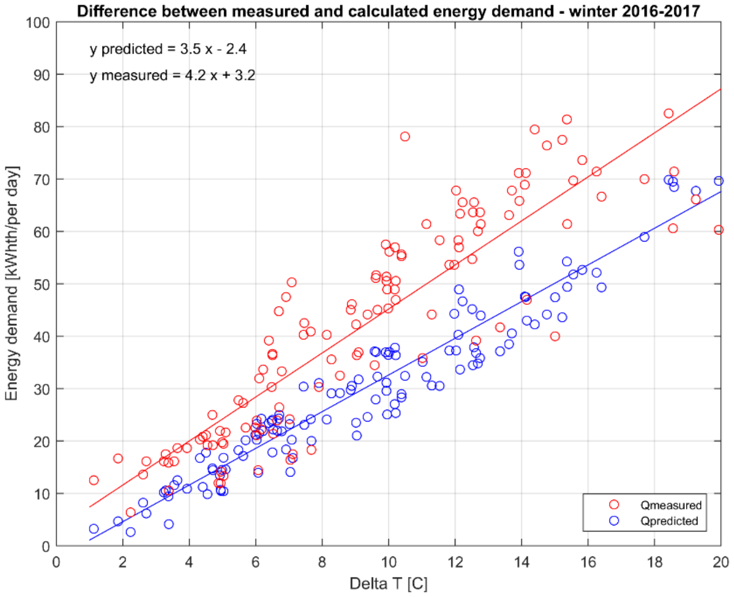


Figure 50 First calculation and the measured energy demand on a daily average before inverse modelling – winter 2016-2017

Figure 51 and Figure 52 show the difference between the calculated and measured energy demand on a daily average over time.

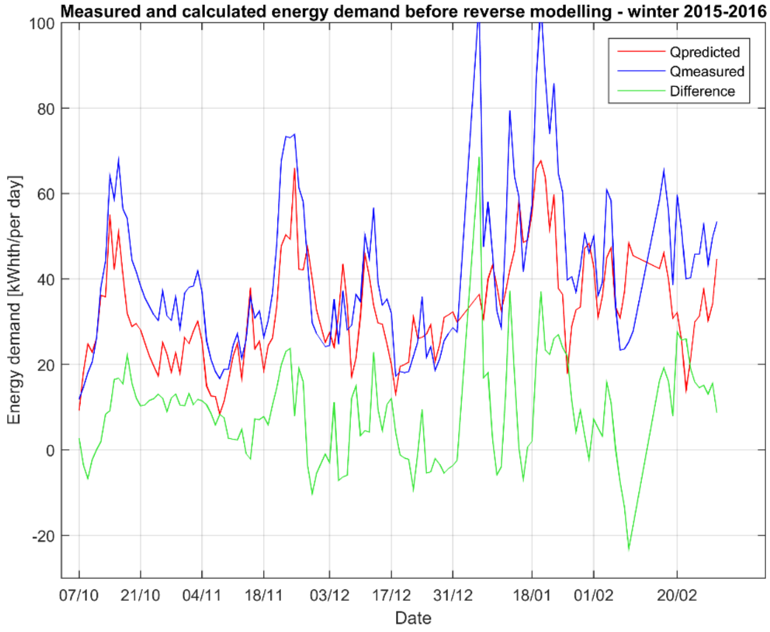


Figure 51 Measured and predicted energy consumption for heating over time in the winter of 2015-2016

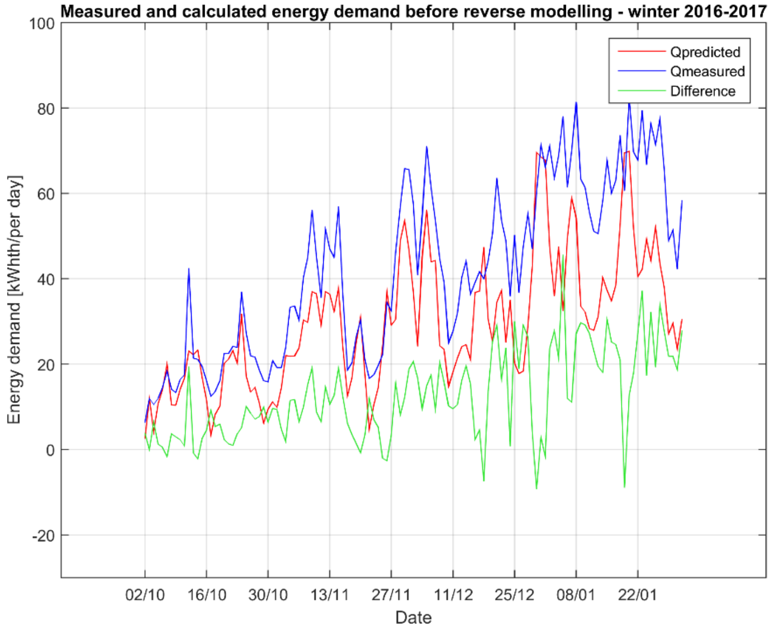


Figure 52 Measured and predicted energy consumption for heating over time in the winter of 2016-2017

As discussed in *section 3.1 Inverse modelling*, the aim of the inverse modelling stage was to increase the accuracy of the model to more than 70% ($R^2 > 0.7$). When the calculation method is accurate enough the different sub parts (e.g. $Q_{internal}$, Q_{sun}, $Q_{transmission}$, $Q_{ventilation}$, and $Q_{infiltration}$) might show differences in utilization of the dwelling. As can be seen in Figure 49 to Figure 52, the calculation was not accurate enough in this initial stage (2015-2016: SS_{res} = 28078 and R^2 = 0.41, 2016-2017: SS_{res}= 32935 and R^2 = 0.40). For the data set of 2015-2016, the error of 15% of the predictions was less than 10%; the error of 39% of the predictions was less than 25%. For the data set of 2016-2017, the error of 15% of the predictions was less than 10%; de error of 33% of the predictions was less than 25%. After this calculation, inverse modelling was used to optimize the model and to determine building parameters in practice.

As mentioned above, the variables ‘a, b, c, d, e, f’ used in the energy model of *Appendix II* were the parameters that were predicted during the inverse modelling stage. For the inverse modelling stage boundary conditions for these parameters needed to be imposed. The upper boundary conditions for the parameters ‘b, c, d, e’ are set to 1. Because ‘b, c, and d’ indicate factors for not intended thermal bridges, those will always have a negative effect on the thermal resistance of a material. The upper boundary condition for parameter ‘a’ is set to 1.2. Parameter ‘a’ indicates a factor for not intended thermal bridges for the windows, this will always have a negative effect on the thermal transmittance. The parameter ‘f’ indicates a factor that stands for the changes which were made after the infiltration (qv_{50}) measurement, thus this factor is less than 1 as well. The lower limits were set slightly higher than zero, namely 0.1, since the applied building system was an experiment and it is not exactly known what the thermal resistances of the building elements are. The limits of parameter ‘e’ were broadly chosen, namely 0.1

till 5. This was because it is uncertain what the deviation between transformation tables and the real ventilation flow is. The results of the inverse modelling stage are shown in Table 9.

Table 9 Results of the inverse modelling stage

Parameter	Value
a	0.1
b	0.1
c	0.4876
d	1.0
e	0.1
f	0.3347

Figure 53 to Figure 56 show the results of the model after the inverse modelling stage for both data sets. Although the unrealistically low outcomes, the accuracy for both data sets was increased (2015-2016: SS_{res} = 1428 and R^2 = 0.67, 2016-2017: SS_{res} = 726 and R^2 = 0.86), although both R^2 indicate that there is still a parameter missing in the model or a variable is incorrectly predicted possibly by incorrect assumptions (wind speed near the façade, effective internal heat gain or solar radiation). Only 67% and 86% of the data could be explained with the prediction model. The other 33% and 14% had another explanation. However, the accuracy was increased greatly. For the data set of 2015-2016, the error of 31% of the predictions was less than 10%; the error of 71% of the predictions was less than 25%. For the data set of 2016-2017, the error of 40% of the predictions was less than 10%; the error of 86% of the predictions was less than 25%. Inaccuracies of sensors or the efficiency of the heating system can give more residual errors as well, consequently this will influence the accuracy of the model too.

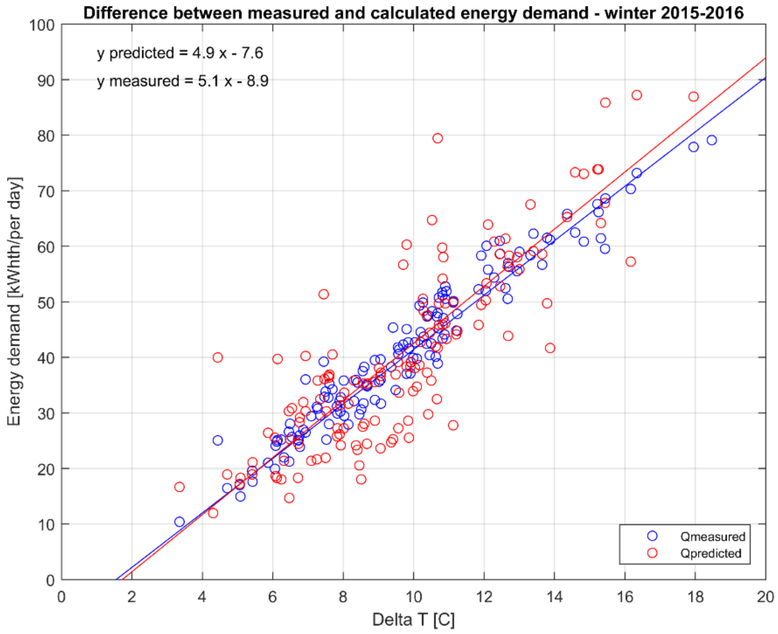


Figure 53 The measured and predicted energy demand on a daily average after inverse modelling – winter 2015-2016

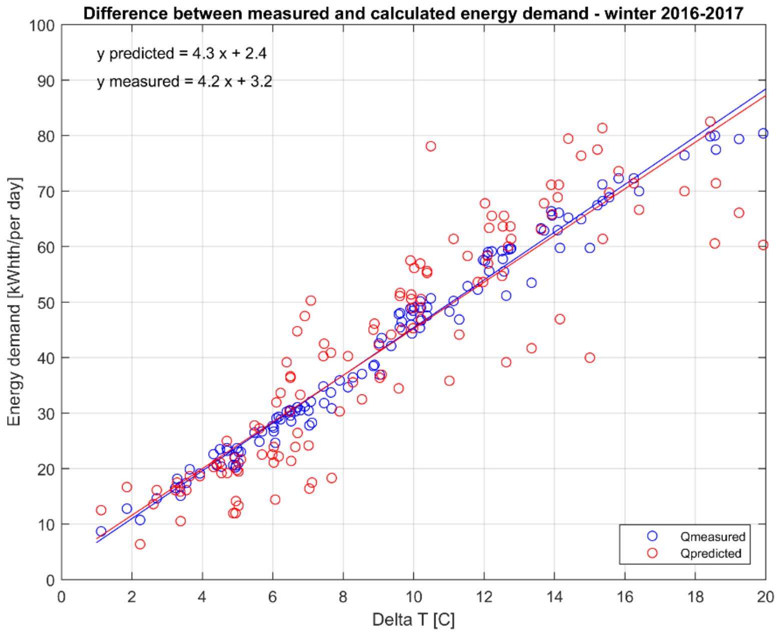


Figure 54 The measured and predicted energy demand on a daily average after inverse modelling – winter 2016-2017

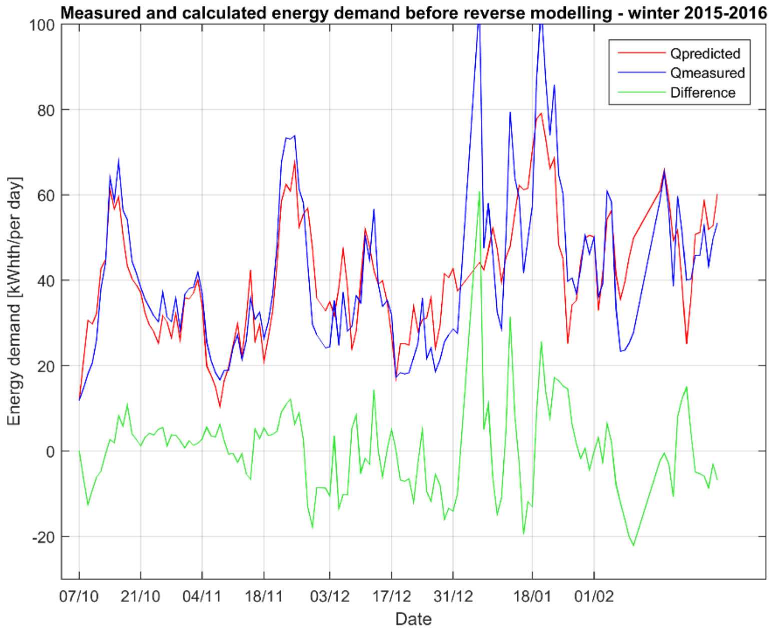


Figure 55 Measured and predicted energy consumption for heating over time in the winter of 2015-2016

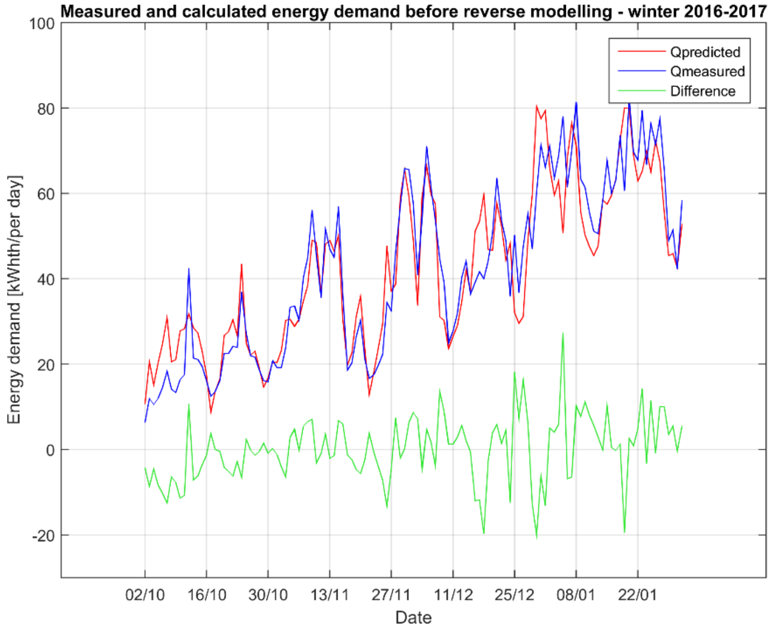


Figure 56 Measured and predicted energy consumption for heating over time in the winter of 2016-2017

5.2.3 Principal component analysis (PCA)

As discussed in *Chapter 3 Methodology to calculate energy consumption*, Figure 11, Figure 53 and Figure 54, the slope and the place of the trend line in the graph of energy demand against ΔT depends on different aspects and the utilization of the dwelling. For example the number of occupants, the ventilation rate, and the internal heat load, the efficiency of the energy production, and the amount of insulation. As can be derived from Figure 53 and Figure 54, there is a difference in utilization of the dwelling between the tenants. The results of the energy demand calculation can possibly be used to explain these differences. For a single calculation of $Q_{predicted}$ of a certain day with its specific utilization (with an average ventilation rate, in- and outdoor temperature, wind speed, sunlight etc.) the slope of the line through this point is not known, so it is not known what the energy demand would be when the indoor temperature set-point would be different. To understand which line corresponds with which calculated $Q_{predicted}$, it is necessary to analyse which variables within the calculations are most important in the prediction of which line corresponds with each calculated $Q_{predicted}$. This can be done with a principal component analysis (PCA). At the end of this analysis it is possible to see which principal components (PC's) explain how much percent of the variance in the data. And which variables have the most influence on that variance and in which direction. This method can be used to show which variables have the most influence in the different directions. With this analysis it might be possible to form different energy demand lines based on different utilization patterns. In addition, this analysis might show which variables have the greatest influence on the prediction of the heating demand. In other words, which variable is most important to measure and predict for a better prediction of the total heating demand. Furthermore, PCA can be used to identify a variable which is most influenced by an occupant and to define which variables have the biggest impact on the heating demand calculation.

Figure 57 and Figure 58 show a first overview of the influence of different measured variables on the measured energy demand of both data sets. To make these graphs, the different calculated variables (e.g. $Q_{internal}$, Q_{sun}, $Q_{transmission}$, $Q_{ventilation}$, and $Q_{infiltration}$) were projected onto $Q_{measured}$ showing a possible distribution of the energy demand.

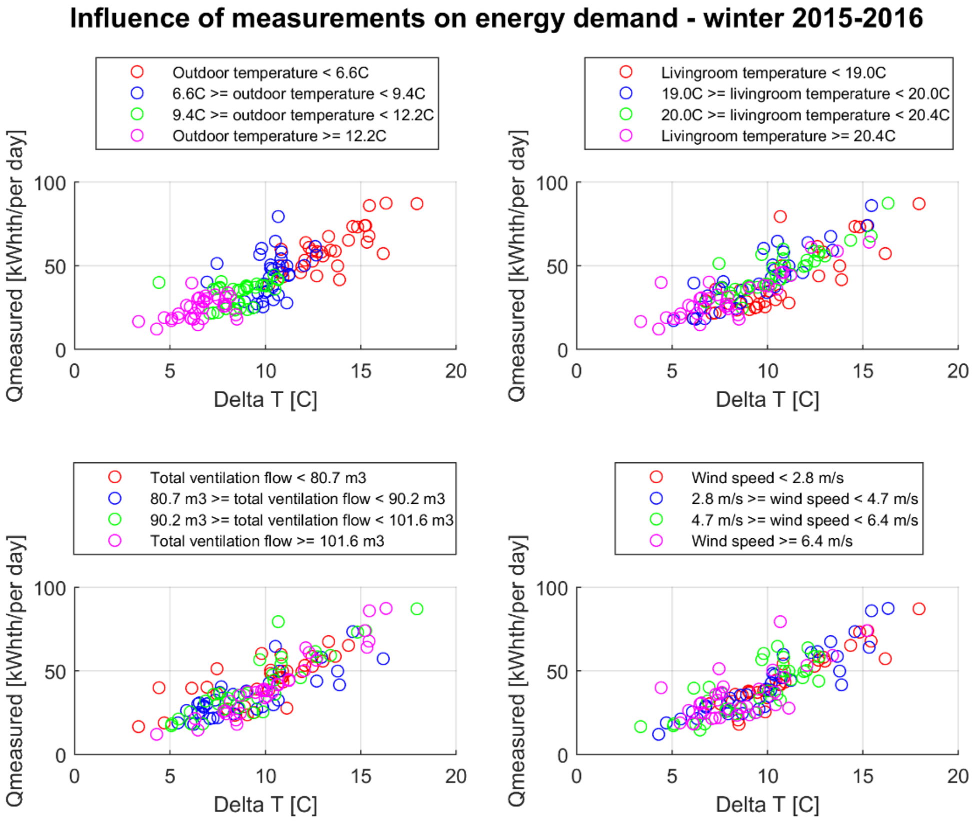


Figure 57 The influence of measured variables on the measured energy demand – winter 2015-2016

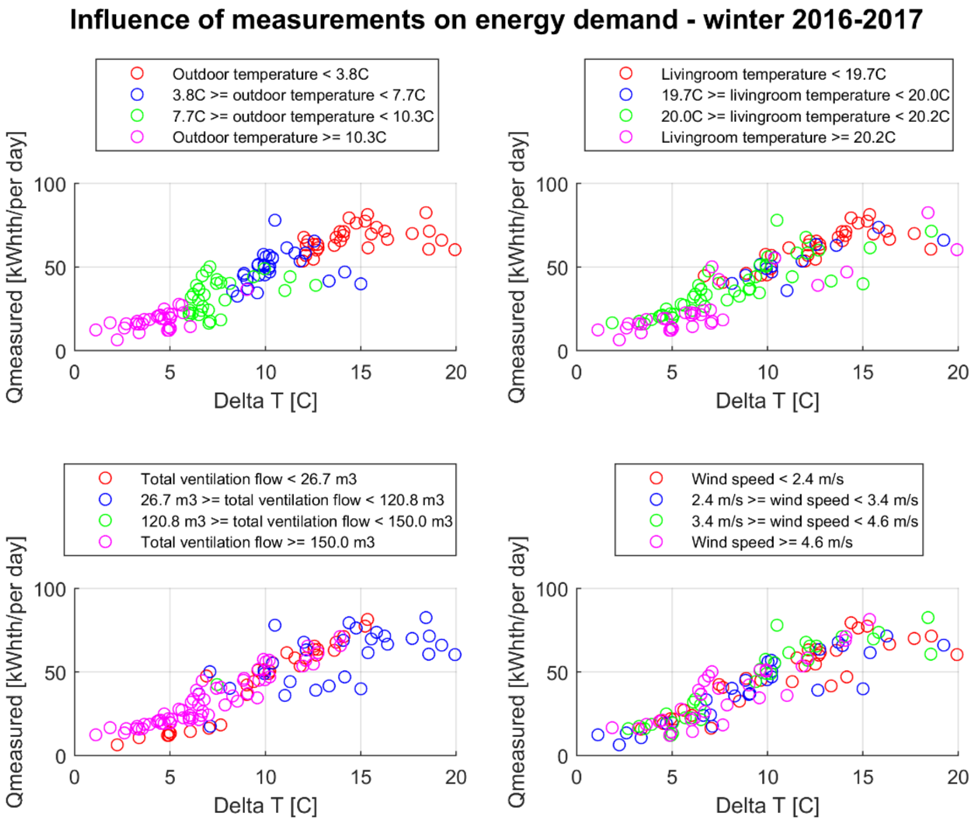


Figure 58 The influence of measured variables on the measured energy demand – winter 2016-2017

Finally, the principal component analysis was carried out for both data sets. Figure 59 and Figure 60 show which principal components explain how much of the variance in the data.

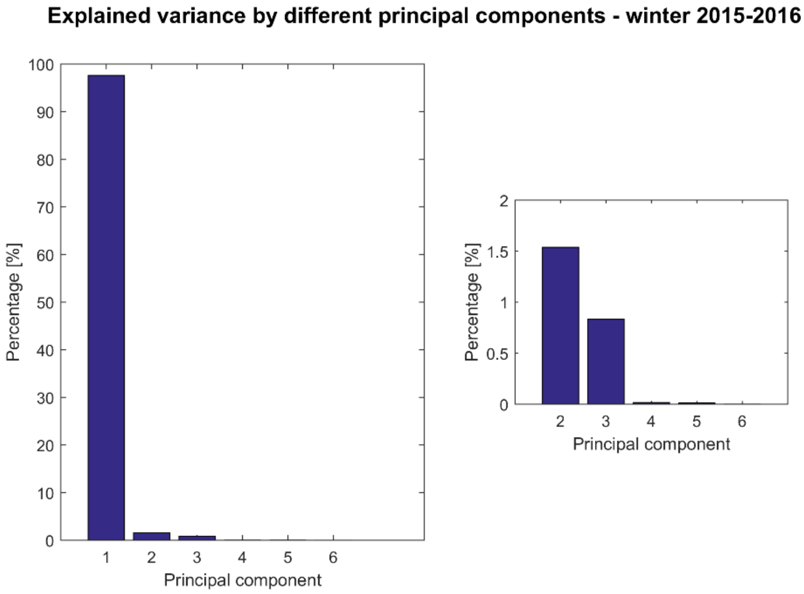


Figure 59 Explanation of the variance by the different principal components – winter 2015-2016

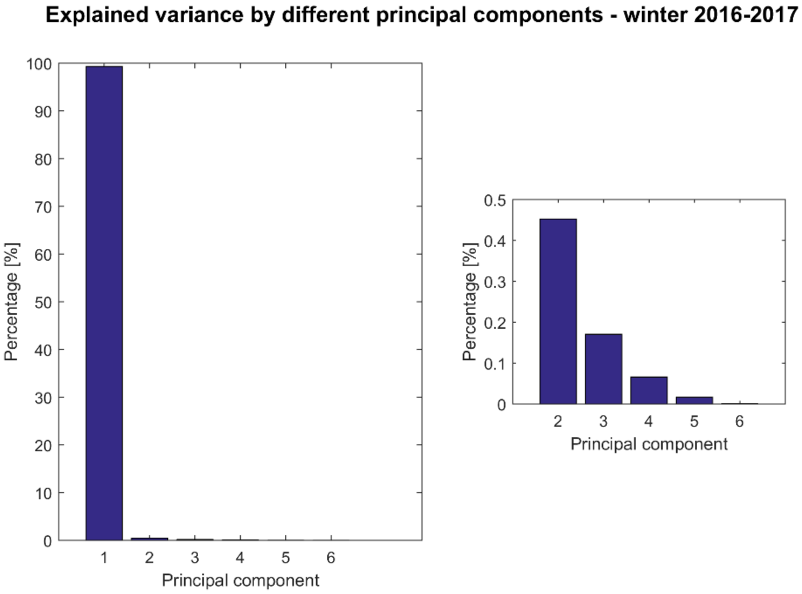


Figure 60 Explanation of the variance by the different principal components – winter 2016-2017

As was described in *section 3.2 Principal component analysis (PCA)*, PC1 would explain the most variance of the data. Figure 61 and Figure 62 show that $Q_{TRwalls}$ (transmission of the walls) has the most influence on PC1 (2015-2016: PC1 = 97.6%, PC2 = 1.5%, PC3 = 0.8%, 2016-2017: PC1 = 99.3%, PC2 = 0.5%, PC3 = 0.2%). This variable is only dependent on the measured ΔT, this principal component is probably in line with the trend lines of Figure 53 and Figure 54, because ΔT is the leading parameter. Therefore, to understand which slope of a line corresponds with each calculated $Q_{predicted}$, it is necessary to look at PC2. As can be derived from Figure 61 and Figure 62, $Q_{infiltration}$ has the most influence on PC2. More than 80% of the variance in PC2 of both data sets can be explained by a difference in $Q_{infiltration.}$ In addition, the only difference between both outcomes is the influence of Q_{int} on PC2 for the winter of 2015-2016, see Figure 61 and Figure 62. The electricity demand for domestic use was in the winter of 2015-2016 higher and the average wind speed and average ΔT were lower compared to the winter of 2016-2017 (2015-2016: electricity demand for domestic use = 1174 kWh, wind speed = 3.59 [± 2.3], ΔT = 9.8 [± 2.9], 2016-2017: electricity demand for domestic use = 880 kWh, wind speed = 4.87 [± 1.45], ΔT = 9.2 [± 4.3]).

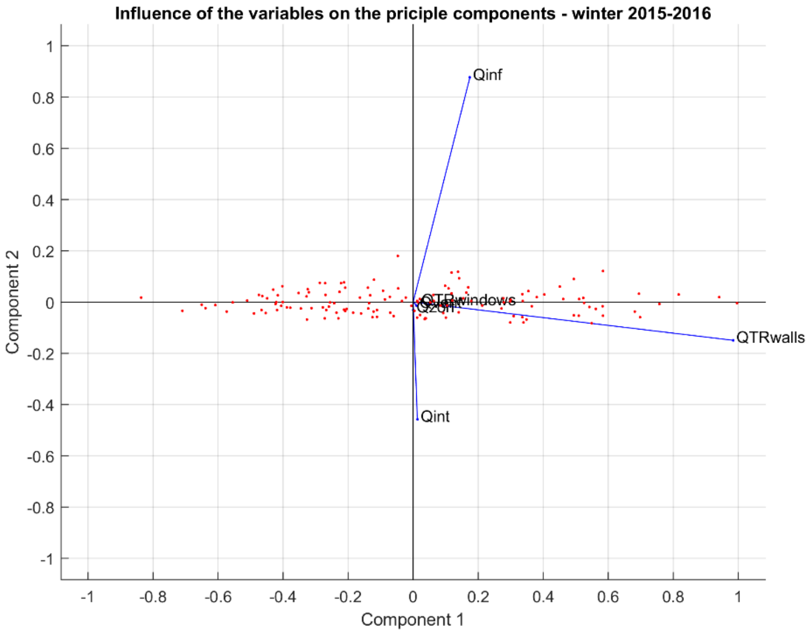


Figure 61 Influence of variables on the principal component 1 and 2 – winter 2015-2016

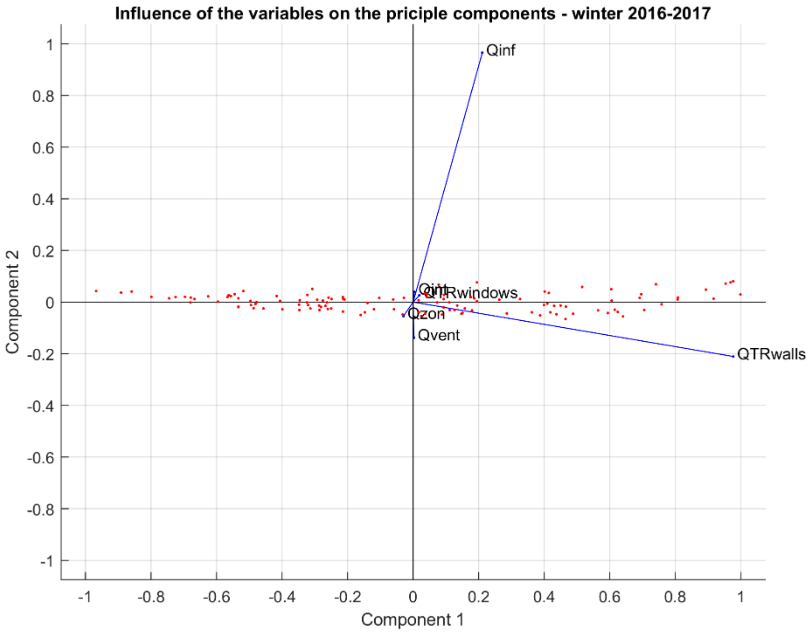


Figure 62 Influence of variables on the principal component 1 and 2 – winter 2016-2017

6 Discussion

6.1 Is it possible to explain differences in comfort and thermoregulatory behaviour between occupants?

From the results of the preliminary study of this research (*section 2.2 Preliminary research and its findings*) it is known that the relationship between skin- (weighted average) and exposed temperature was very useful for determining comfort zones and thermoregulatory behaviour. In *section 5.1.1 Differences in comfort and thermoregulatory behaviour*, the results of test subject 1 are shown.

Figure 17 shows the mean skin temperature against the exposed temperature for test subject 1 during the three measuring weeks. At first sight no relations were found, but the density of the measuring points were interesting. By means of the contour plot in Figure 18, which shows the density of the measuring points, areas in the graph can be distinguished. These areas correspond with the thermal environments where the test subject is most frequently exposed to. Figure 19 shows the same contour plot, including the calculated thermoneutral zone (red) for test subject 1 during the night. The thermoneutral zone of test subject 1 with these parameters corresponds with the measured data. During the night blood vessels relax and are therefore dilated, which corresponds with higher heat losses. Therefore, the measurements of the test subject would be positioned in the higher end of the calculated thermoneutral zone, which is in line with Figure 19.

Figure 20 shows the same contour plot, only including the calculated thermoneutral zone (red) for test subject 1 with the average Clo-value and average relative humidity of the data set, an average metabolic rate (Harris & Benedict, 1918) and an average air velocity (ISSO, 2008) for the dwelling where the test subject lives. The thermoneutral zone corresponds quite accurate with the measured data during the day. The activity level, Clo-value, relative humidity and air velocity varies through the day, this is why the average thermoneutral zone does not correspond entirely with the measured data. However, Figure 21 shows the area wherein the thermoneutral zone (red) could vary in indoor circumstances during the day. As can be seen, these thermoneutral zones correspond quite accurate with the measured data.

Figure 22 shows the outlines of the contour plot, with the answers of the questionnaires as an overlay. The colours in the overlay show the density of the questionnaire entries. As can be seen in the graph, the questionnaire is more frequently used in the same areas in graph as where there are more measuring points of skin temperatures and exposed temperatures. This can easily be explained, there is a greater chance that the test subject fills in the questionnaire in the areas where she is more frequently exposed to. In addition, there is a greater chance of comfort per combination of skin- and exposed temperature if she uses the questionnaire more frequently by a certain combination of skin- and exposed temperatures than when filled only for a few situations. And the chance of an outlier is getting greater if she uses the questionnaire less frequently by a certain combination of skin- and exposed temperatures.

This can be seen in Figure 23 through Figure 26, when there are less questionnaire entries at a certain combination of skin- and exposed temperatures, there is a greater possibility that that combination of skin- and exposed temperature will show a cold or hot sensation, instead of neutral, cool or warm.

In addition it can be derived from Figure 24 that the test subject exhibits maximum comfort at the thermal environments where the test subject is most frequently exposed to. As already seen in Figure 23 and Figure 24, Figure 28 shows that comfort and sensation are not experienced as one and the same. Where the model of Fanger (Fanger, 1973) concludes that most people are comfortable when they feel neutral, this is not the case for test subject 1. As can be seen through the trend line in Figure 28, test subject 1 is most comfortable when she feels slightly warm.

Figure 63 shows once again the contour plot with the density of the measuring points. In this graph multiple areas can be distinguished and these correspond with the thermal environments where the test subject is most frequently exposed to. In conclusion, area a. corresponds with the measurements during the night. Area c. and d. correspond with measurements during the day. The measurements in area b. are not yet specified.

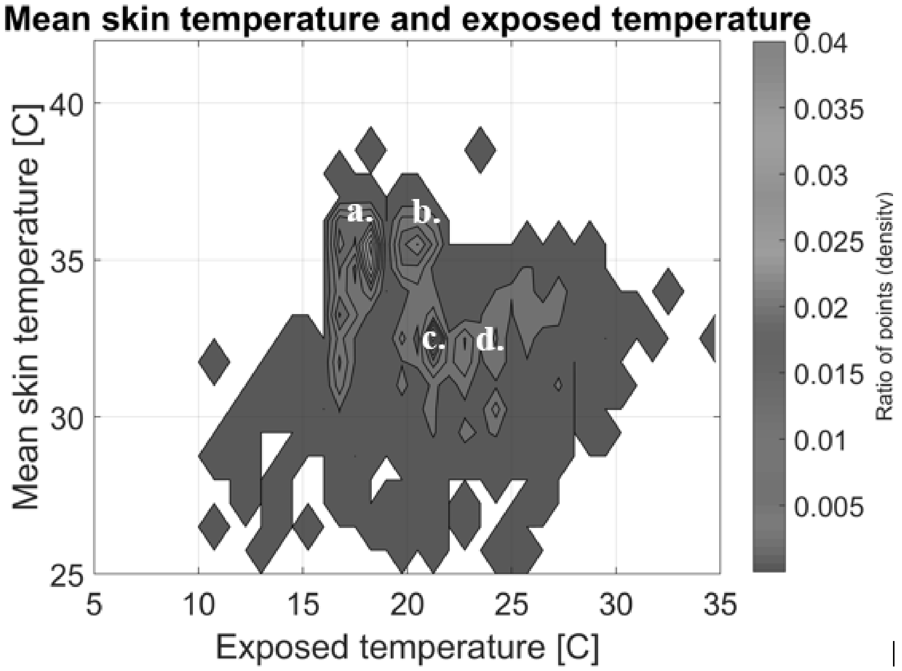


Figure 63 Contourplot of the exposed- and skin temperatures with four centers (a, b, c, d)

It was hypothesized that there would only be two major areas with a higher density of measuring points, namely during the night (around area a.) and during the day (around area c. and d.). However, no published research study was found where such a hypothesis was tested and could therefore serve as a reference. Both test subjects 1 and 2 show at least three areas with a higher density of measuring points, at least one during the night and two during the day. Figure 25 through Figure 27 and Figure 64 can give an insight in the differences between these areas. Further research is necessary to investigate if more test subjects would show three or more major areas with a higher density of measuring points, instead of the expected two areas.

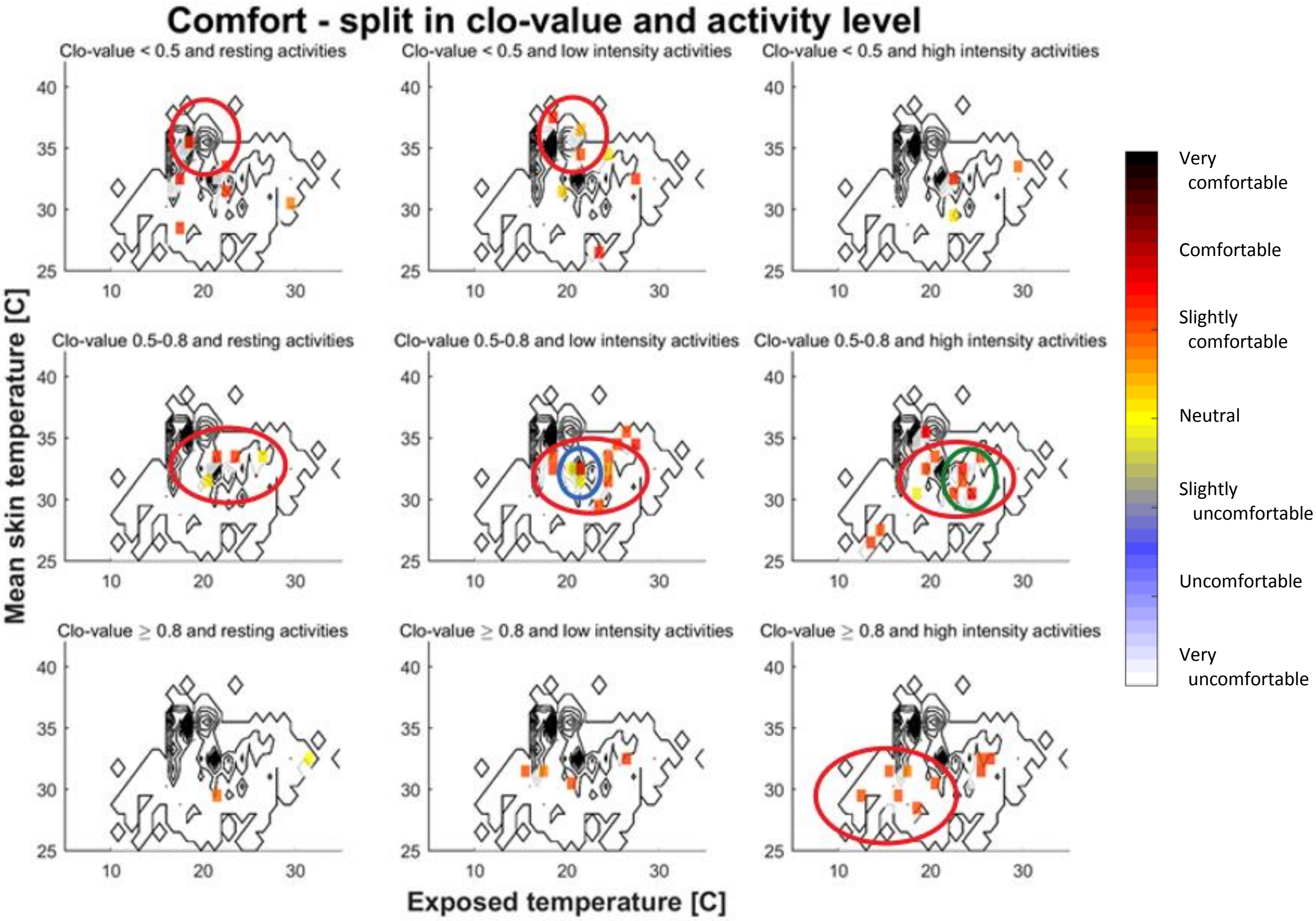


Figure 64 Contour plots of the comfort vote of test subject 1, with boundary conditions for Clo-values and activity levels

Figure 64 shows a recap of Figure 27. As can be derived from Figure 27 and Figure 64, area b. probably corresponds with low Clo-values and low intensity activities. Because there are only questionnaire entries in this place in the graph (area b.) when she filled in that she wore clothing with a clo-value of less than 0.5. This could for example be in bed after waking up, that is probably why this area is close to area a. Area c. and d. probably correspond with normal Clo-values for indoor circumstances (Clo-values between 0.5-0.8). Because there are more measuring points in area c. and d. when the test subject answered that she was wearing clothing with a clo-value between 0.5 and 0.8. The difference between both areas can be related to the activity level of test subject 1. Area c. probably corresponds with lower activity levels and area d. corresponds probably with higher activity levels. Because there are more measuring points in area c. when the test subject answered that she was undertaking low intensity activities and wearing clothing with a clo-value between 0.5 and 0.8 (blue circle). In addition, there are more measuring points in area d. when the test subject answered that she was undertaking high intensity activities and wearing clothing with a clo-value between 0.5 and 0.8 (green circle). The area at the lower left side of the graph corresponds with higher activity levels and higher Clo-values, in consolidation with the lower exposed temperatures these measurements are probably measured outside.

When these findings are being compared with the conclusions from test subject 2 from the preliminary study, differences in comfort and thermoregulatory behaviour can be found. Figure 65 shows the contour plots of test subject 1 (upper graph) and 2 (lower graph). As can be derived from both graphs, the measurement zones of test subject 1 are moved to the left of the graph compared to the measurements of test subject 2. In conclusion, test subject 1 is probably comfortable at lower temperatures than test subject 2.

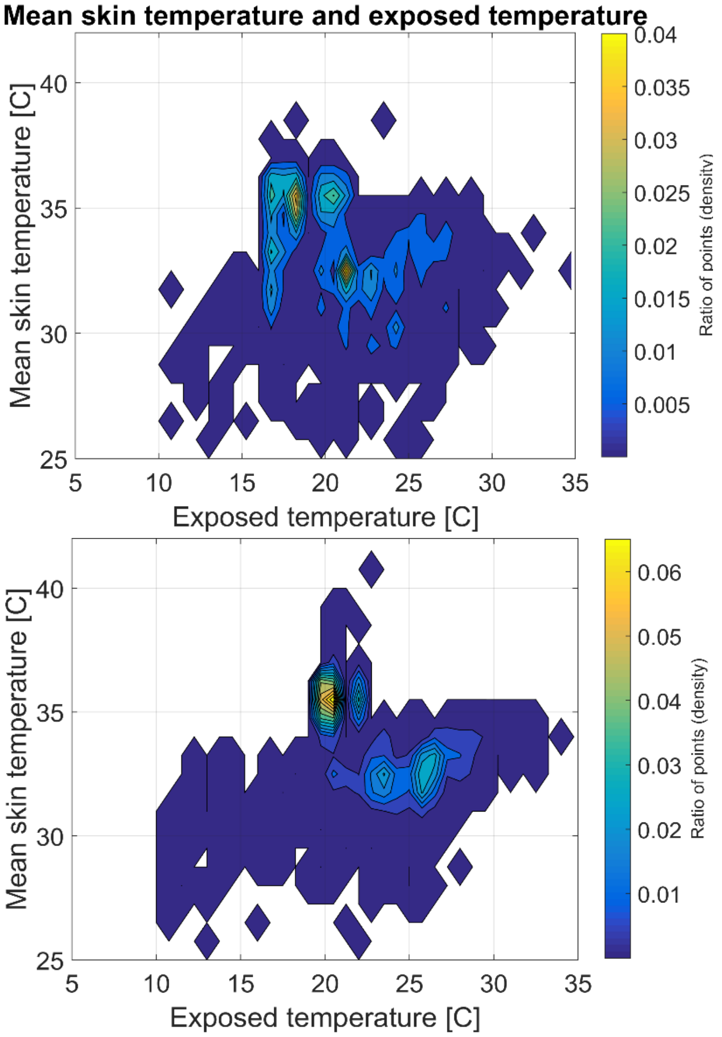


Figure 65 Contourplot of the exposed- and skin temperatures for test subject 1 (upper graph) and test subject 2 (lower graph)

6.2 What thermoregulatory behavior do the test subjects show?

Figure 29 through Figure 35 show the measurements of one day of test subject 1. These graphs show how the physiology of the test subject cooperates with the behaviour of the person. When the operative temperature increases or decreases the body has to work harder to maintain its core temperature by regulating blood flow by dilating or contracting blood vessels to increase or decrease the heat loss of the body. When regulating through dry heat loss is not sufficient enough, the temperature will be regulated by sweating or (non-)shivering thermogenesis. When the exposed temperature of the body increases or decreases the body will adapt to this change in exposed temperature to retain its core temperature. Therefore, a higher skin temperature suggests that the test subject feels warm and a lower skin temperature suggests that the test subject feels cold. Because of this mechanism of dilatation and contraction of blood vessels, the body will adapt with a slight time delay and has therefore the ability to build up a small buffer to overcome the sudden changes in exposed temperature. This phenomenon can be observed in Figure 29 through Figure 35 as well.

For example Figure 29 and Figure 30 show two measurements which were taken in a time span of 15 minutes. In Figure 29 the skin temperature of test subject 1 is within the higher end of the calculated thermoneutral zone. This corresponds with her sensation and comfort vote. The exposed temperature is lower than her thermoneutral zone, the person is not in heat balance, more heat is lost, so after a while she would probably start feeling cold in case she does not change the environment, her clothing or her activity level. After 15 minutes nothing changed (environment, clothing or activity level), hence, her sensation and comfort vote changed. She started to feel slightly cool, although close to neutral and this is just comfortable. Her weighed average skin temperature has decreased to 33.5˚C. Her body responded to the relative cold exposed temperature; blood vessels are contracted, which resulted in a lower skin temperature. In addition, her sensation and comfort vote changed negatively although she still feels neutral. The body is still adapting to the colder exposed temperature, the person is still not in heat balance, more heat is lost. Most likely, she would start feeling colder if she would not change her environment, her clothing or her activity level.

Figure 32 shows another phenomenon. Test subject 1 went to the grocery store between 12.30h and 13.30h, Figure 32 shows the first measurement after this action at 15.22h (after 112 minutes). The last measurement before her visit to the grocery store was at 12.18h. Her clo-value stayed the same between those measuring points. Her activity level increased. In addition, her skin temperature increased to 32.3˚C and her exposed temperature increased to 30.6˚C. Her skin temperature at 15.22h is within the thermoneutral zone and the exposed temperature is higher than the calculated thermoneutral zone. Although these parameters might suggest that she would feel warm, she feels cool (sensation vote = -1.2) which is neither comfortable nor uncomfortable (comfort vote = -0.01). A similar kind of phenomenon was found in a recent study of Schweiker et al. (Schweiker, Kingma, & Wagner, 2017). In this study a rather low mean actual sensation vote (ASV) after 105 minutes of entering the office was measured, this was neither predicted by the thermoneutral zone model, by the PMV model nor to be expected looking at the course of physical conditions (Schweiker et al., 2017). One similar measurement was found for test subject 2. Further research is necessary to investigate this phenomenon. There are little consecutive measuring points where no changes to clothing or activity level are done within two hours after entering the dwelling. This could be the reason why there were only two measurement points found where this phenomenon is observed.

In addition, the thermostat was not used often and changes in activity level were mostly changes because of routine, e.g. cycling to school, walking to the grocery store, watching television in the evening. Most of the changes in Clo-value are probably changes because of routine as well, e.g. putting on pyjamas when going to bed, putting clothes on after taking a shower. Although, some changes were because of the exposed temperature, e.g. getting a blanket or putting on a sweater. It might be possible that the dwelling is very comfortable, whereby no changes to the set-point temperatures were necessary. However, from Figure 29 through Figure 35 it can be derived that the skin temperature of test subject 1 adapts to the exposed temperature and her comfort and sensation votes, even without changes to the thermostat, clothing or activity level. Further research is necessary to evaluate the influence of a less comfortable dwelling (less constant indoor temperature and easy adjustment of the thermostat) on the thermoregulatory behaviour of occupants.

6.3 Is it possible to define optimal indoor temperatures on an individual level?

As discussed in section 2.1 The thermoneutral zone model (TNZ) and as can be seen in Figure 5, the comfort zone is the center of the thermoneutral zone where the corresponding operative temperature is the most comfortable (optimal) indoor temperature for that person at that moment (T_{opt}). Because parameters such as relative humidity, air velocity, activity level and clothing can vary over time this will lead to a different comfort zone and thus a different optimal indoor temperature. However, the average T_{opt} per test subject can give an insight in the differences in prefered indoor temperatures, this can be seen for subject 1 and 2 from Figure 65.

The thermoneutral zone is calculated for the 57 questionnaire entries of test subject 1. For all these entries a optimal temperature (T_{opt}) is calculated. Figure 36 to Figure 42 show histograms per day and per test subject for all the calculated optimal temperatures. Differences in optimal indoor temperatures can be distinguished the two test subjects. These calculations lead to the same conclusions as concluded from Figure 65; test subject 1 is more comfortable at lower temperatures compared to test subject 2.

As discussed in the previous section, the calculation of the TNZ presents a steady state calculation, and the human body adapts to the exposed temperature with a slight delay over time. This delay depends on the physiology of a person (e.g. gender, weight, height, amount of body fat and metabolism) and his or her clothing. A person with little body fat is more sensitive to variations in ambient temperatures, because of the lack of thermal resistance. Consequently, a person with more body fat is less sensitive to deviations in ambient temperatures. Furthermore, a taller person has a higher body surface, so will easier be cold. However, it is not always possible to change the temperature set-points for example in office buildings or when multiple people are living in the same dwelling, with all different comfort levels. As an addition to changing set-point temperatures, people can reduce their sensitivity for variations in temperatures by changing the worn clothing. More clothing, a higher clo-value, will result in a shift of the TNZ to a lower ambiant temperature. Less clothing will result in the oposite.

As an example, Figure 66 shows the calculated thermoneutral zone for a fictional woman of the age of 25, with an avarage female height and weight, with a clo-value of 0.5. Within the range of ambient temperatures of the TNZ, the body temperature regulation is achieved only by control of sensible (dry) heat loss, i.e. without regulatory changes in metabolic heat production or evaporative heat loss (± 23 ˚C – 28 ˚C). For different ambient temperatures other then the TNZ, the person might change the thermostat set-point to achieve an acceptable thermal comfort level which will result in higher energy demands (for heating or cooling).

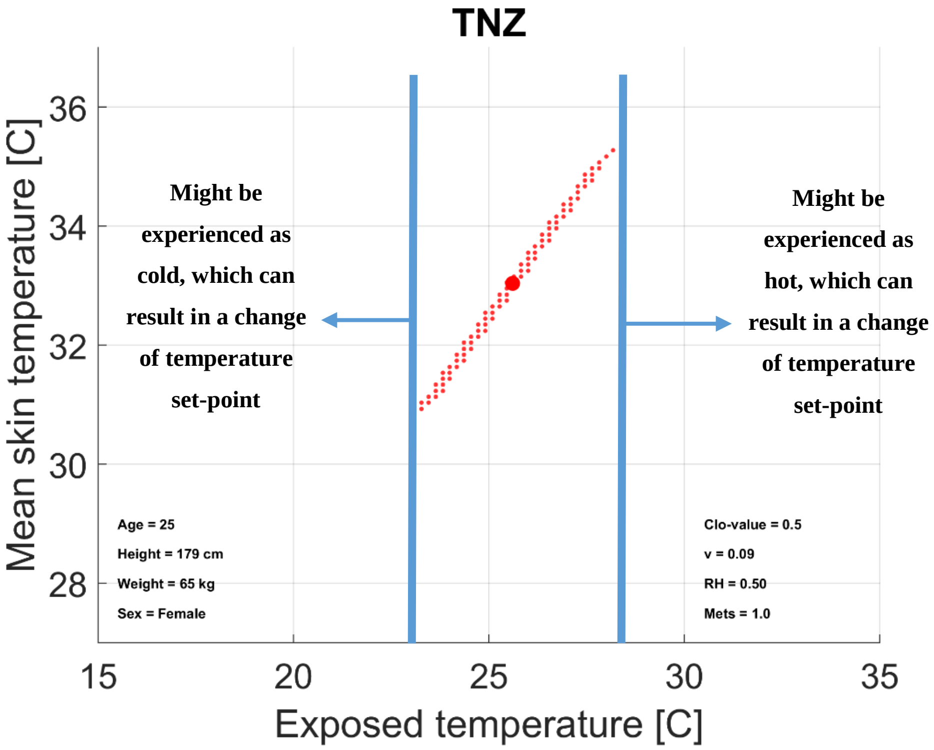


Figure 66 Example of the range of comfortable ambient temperatures

In addition, clothing is a variable that shifts the calculated TNZ to lower or higher ambient temperatures. This is therefore frequently used to adapt to uncomfortable thermal environments. Figure 67 shows the calculated thermoneutral zones for an fictional woman of the age of 25, with an avarage height and weight, with different clo-values. As can be derived from this graph, the range of ambient temperatures where in a person can adapt by changing her clothing is broad (± 19 ˚C – 28 ˚C). However, a clothing degree of less than 0.5 clo or more than 0.8 clo, is not common during daily indoor activities. This leaves a smaller range of ambient temperatures wherein the person can adapt to her thermal environment to maintain her thermal comfort (± 22 ˚C – 28 ˚C).

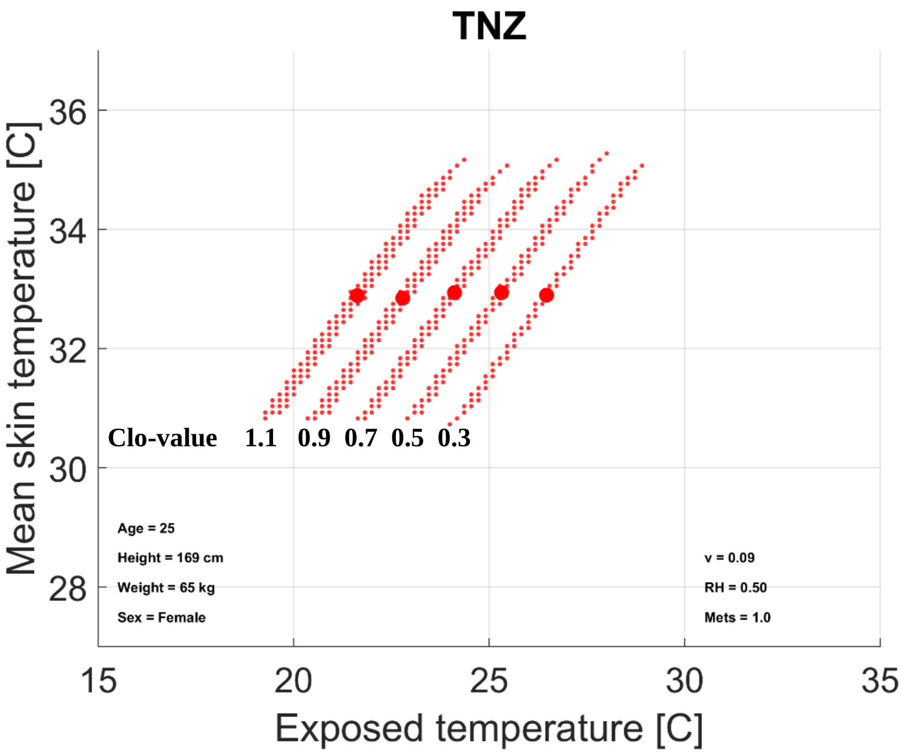


Figure 67 example of the range of comfortable ambient temperatures at different clo-values

In addition, the TNZ depends on different physical aspects of the person, e.g. gender, body area, body fat and age. Similar graphs as Figure 67 can be made for different type of people, *Appendix X* shows multiple graphs with examples of men and women, young and elderly, lean and obese and differences in height. When the ranges of ambient temperatures are being compared for all these different calculations, the resulting ambient temperatures where most people would feel comfortable with a clo-value between 0.5 and 0.7, during low intensity activities (1 Met) and an air velocity of 0.09 m/s and a relative humidity of 50 %, would be ± 23 ˚C – 26 ˚C. Although, every person has a different comfort level with a different bandwidth of acceptable ambient temperatures. Depending on differences in gender, age, length and weight the body of a person will adapt quick or slow to variations of the environment. Installations should therefore enable quick or slow changes in temperatures. This argues for individual systems in offices and fast installations in dwellings. Further research is necessary to investigate the influence of different types of installations on differences in subpopulations.

6.4 Is it possible to explain differences in energy consumption due to differences in utilization of the dwelling?

As discussed in *section 4.1 Dwelling*, the same dwelling was used as during the preliminary research and similar data was collected. This made it possible to use this data set for this study as well. During the winter of 2015-2016 two female students were living in the dwelling in Heerlen. For this study the collected data of the period October 2015 through March 2016 is used. This was the first winter season that the dwelling was being monitored. Since the summer of 2016 there are two new tenants living in this dwelling. This is a young couple who both work during the day. For this study the collected data of the period October 2016 through February 2017 was used.

As can be derived from Figure 43 and Figure 44, there is a linear correlation between $Q_{measured}$ and ΔT in both data sets. The indoor temperature during the winter of 2016-2017 was on average slightly higher than during the winter of 2015-2016, although it was more constant. The winter of 2016-2017 was on average colder (Oct 2015- Jan 2016: 1278 degree days, Oct 2016- Jan 2017: 1715 degree days). However, the measured energy demand for heating does not vary a lot between both winters. Figure 68 shows the difference in energy demand between both data sets. As can be derived, the occupants during the winter of 2016-2017 were slightly more efficient (Oct 2015- Jan 2016: 5.14 kWh_{th}/K per day, Oct 2016- Jan 2017: 4.2 kWh_{th}/K per day). The tables of the degree days of 2015 until 2017 can be found in *Appendix IX*.

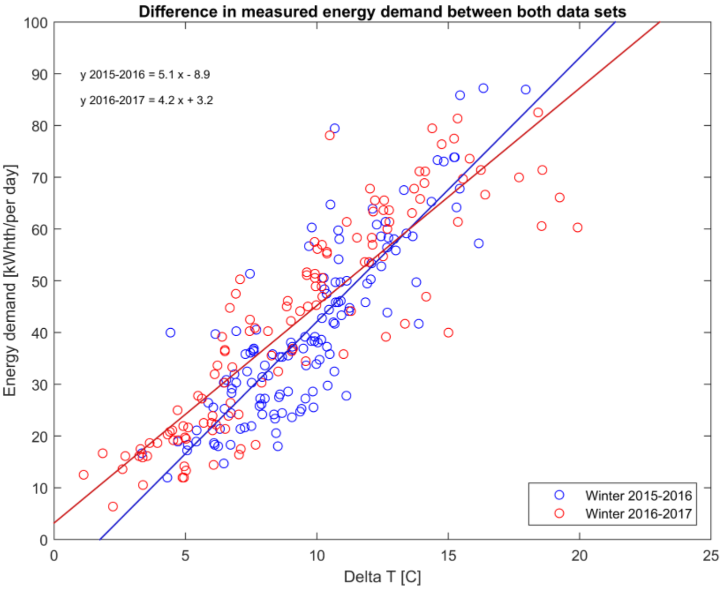


Figure 68 Measured energy demand of the winter of 2015-2016 and the winter of 2016-2017

As discussed in section 3.1 Inverse modelling, the aim of the inverse modelling stage was to increase the accuracy of the TRECO energy demand model to more than 70% ($R^2 > 0.7$). When the calculation method is accurate enough the different sub parts (e.g. $Q_{internal}$, Q_{sun}, $Q_{transmission}$, $Q_{ventilation}$, and $Q_{infiltration}$) might show the differences in utilization of the dwelling. As can be seen in Figure 49 through Figure 52, the calculation was not accurate enough in this initial stage (2015-2016: SS_{res} = 28078 and $R^2 = 0.41$, 2016-2017: SS_{res} = 32935 and $R^2 = 0.40$). After this calculation, inverse modelling was used to optimize the model. The goal of inverse modelling was to find the parameters that minimize the error between the modelling result and the measurements. For the purpose of the thesis, this means finding parameters that minimize the difference between $Q_{predicted}$ and the measured energy use for space heating ($Q_{measured}$). *Appendix II* describes that variables 'a, b, c, d, e, f' used in the prediction model, were the parameters that were predicted during the inverse modelling stage.

Figure 53 through Figure 56 show the results of the model after the inverse modelling stage for both data sets. Although the unrealistically low results of the inverse modelling stage, The accuracy for both data sets was increased (2015-2016: SS_{res} = 1428 and R^2 = 0.67, 2016-2017: SS_{res} = 726 and R^2 = 0.86), although both R^2 indicate that there is still a parameter missing in the model or a variable is incorrectly predicted possibly by incorrect assumptions (wind speed near the façade, effective internal heat gain or solar radiation). Only 67% and 86% of the data could be explained with the prediction model. The other 33% and 14% had another explanation. The routine of the tenants in the winter of 2016-2017 was probably more constant, and therefore better to predict. This resulted in a higher accuracy. However, inaccuracies of sensors or the efficiency of the heating system can give more residual errors as well, consequently this will influence the accuracy of the model too. Missing variables in the energy model might be presence of occupants and/or opening of windows and doors. Especially the presence of the occupants might be a great influence on the energy demand. As can be derived from Figure 55 and Figure 56, the predictions of the energy model during the holidays in December were of poorer quality than the prediction in October and November. These are especially the periods were the presence of the occupants differs from their normal routine. Further research is necessary to assess the influence of the presence of occupants and/or opening of windows and doors on the predictions of the energy model.

Finally, $Q_{predicted}$ showed less variance compared to $Q_{measured}$. There is probably a variable missing or underestimated which has an influence on this variation in the opposite direction of ΔT. This might be the presence of the occupants, efficiency of the heating system or one of the already included variables might be underestimated. Further research is necessary to assess the influence of the presence of the occupants and the efficiency of the heating system on the accuracy of the predictions.

The results of the inverse modelling stage are shown in Table 9. What stands out of these results is that the values for the parameters are very low. This could mean that there is something wrong with the building or the energy model. The renovation of the monitored dwelling was part of a different TKI-project. This renovation was a pilot for a new renovation principle, and therefore an experiment. From the high infiltration rates, it was already known that the dwelling was leak. But the results from the energy model suggests that the joints between different insulation materials are poor as well, which might have resulted in major thermal bridges.

To further explain, the measured heating demand for the winter of 2016-2017 was 5122.5 kWh_{th} (1715 degree days). An average year has 2817 degree days (Warmtepomp-weetjes.nl, 2017), this would correspond with 8423 kWh_{th}/ per year or 101 kWh_{th}/m^2 per year. According to the EPC calculations of the building, the dwelling should use 37.4 kWh_{th}/m^2 for heating after renovation, see *Appendix III*. The measured heat demand is more than double in comparison with the EPC.

The consultants made a calculation for the transmission losses of the dwelling as well, see *Appendix III*. These calculations present worst case scenarios where no heat recovery is considered and without including internal heat loads or sun irradiance. The result of this calculation is that the dwelling should use 3.5 kW to maintain a 20˚C indoor temperature with a -10˚C outdoor temperature. As can be seen in Figure 44, during the winter of 2016-2017 the dwelling used 4.2 kWhth/K per day, this equals 5.25 kW. This is 1.75 kW more than calculated. From these calculations it can be derived that the thermal transmittance of the building envelop is different than expected.

It was already assumed that the thermal resistance of the envelope might differ from the expected/design values. Therefore the ranges of the parameters for inverse modelling were chosen broadly. However, the outcomes for these parameters are unrealistically low/high, see Table 10.

Table 10 Results of inverse modelling stage (2015-2016: $R^2 = 0.67$, 2016-2017: $R^2 = 0.86$)

Parameter	Value	Translation to the model
a	0.1	U-value$_{windows}$ = 0.16 W/m²K
b	0.1	RC$_{walls}$ = 0.55 m²K/W
c	0.4876	RC$_{floor}$ = 1.7 m²K/W
d	1.0	RC$_{roof}$ = 6.5 m²K/W
e	0.1	
f	0.3347	c = 38.38 (m^3/h)/Pa

When the ranges are limited in order to satisfy more realistic lower boundary conditions such as 0.8, the inverse modelling fits the new outcomes to these smaller limits, see Table 11. Here five of the six parameters are set to the boundary conditions (a, b, c, d, f). This does not solve the problem or give better outcome of the model. The accuracy of the model is lower with these smaller boundary conditions and the certainty of the building parameters is as low as for the current results. From previous research it was already known that the building parameters might have a great influence on the calculated energy use and the actual values of these parameters might differ from the expected values in practice (Rasooli et al., 2016). When the building is less experimental, inverse modelling can be used to determine these building parameters in practice, which would increase the accuracy of the prediction model.

Table 11 Results of inverse modelling stage with smaller boundary conditions (2015-2016: $R^2 = 0.61$, 2016-2017: $R^2 = 0.71$)

Parameter	Value	Translation to the model
a	1.2	U-value$_{windows}$ = 1.92 W/m²K
b	0.8	RC$_{walls}$ = 4.4 m²K/W
c	0.8	RC$_{floor}$ = 2.8 m²K/W
d	0.8	RC$_{roof}$ = 5.2 m²K/W
e	1.4497	
f	1.0	c = 114.6 (m^3/h)/Pa

It is therefore recommended to not use this experimental dwelling for further calculations. The certainty of the building parameters is too low. However it is possible to make some assumptions about the cause of these great deviations between the EPC calculations and the measurements. The dwelling is renovated with an experimental renovation system; all installations are installed in the façades or in the 'engine' on the roof. At the position of the installations in the facades, a thinner insulation material is placed with a lower thermal conductivity. It is possible that the insulation layer is perforated at multiple places due to suspending installations, which results in thermal bridges. In addition, the insulation layer between the 'engine' on the roof and the attic is not completely closed because of equipment that needs to be accessible from the attic, this is a major thermal bridge as well.

Because of the uncertainties of the building parameters it was not possible to validate the energy model properly. It is only possible to validate as good as the certainty of the measurements. Infra-red pictures can be used to assess the influence of thermal bridges on the thermal resistance of the façade. In addition, because of the great influence of the thermal resistance of the walls, roof and floor, it is recommended to first validate the model with another energy model such as TRNSYS, VABI or EnergyPlus. These energy models can generate variables such as temperatures, infiltration and ventilations flows, which can be used as input variables for the TRECO energy demand model. With these input variables the model can be validated and improved. Where after, other residential buildings can be used to validate the model further.

In addition, validation of the model with another energy model such as TRNSYS, VABI or EnergyPlus is necessary to assess underestimated values and missing variables in the TRECO energy demand model. The experimental nature of the used dwelling might not give unambiguously results. The methods presented in *Chapter 3 Methodology to calculate energy consumption* and used in *section 5.2 Energy demand* can be used for further research concerning energy demand and occupant behaviour predictions. The energy model described in *Appendix II* can be used as a starting point for more and better energy demand predictions. One of the main advantages of this model is that it can be used as a code only model. Input variables can automatically be retrieved from a database. Not only measurement data, but information about the dwelling can be used from a database, e.g. dimensions, surfaces, parameters of building parts. Further research is necessary to assess the possibility to connect the model to BIM databases.

Overall, the energy model can be used to predict energy demand for specific dwellings with its specific utilization. It is therefore possible to investigate differences in utilization between similar dwellings, which result from differences in set-points, and as can be derived from Figure 53 and Figure 54, there is a difference in utilization of the dwelling between the tenants of 2015-2016 and 2016-2017.

6.5 Is it possible to predict energy consumption per day for a perticulair dwelling with its utilization pattern?

As discussed in *Chapter 3 Methodology to calculate energy consumption*, the slope and the place of the trend line in the graph of energy demand against ΔT depends on different aspects and the utilization of the dwelling. For example the number of occupants, the ventilation rate, and the internal heat load, the efficiency of the energy production, and the amount of insulation. As can be derived from Figure 53 and Figure 54, there is a difference in utilization of the dwelling between the tenants. The results of the energy demand calculation, and most important the method used in *Chapter 3 Methodology to calculate energy consumption*, can be used to explain these differences. For a single calculation of $Q_{predicted}$ of a certain day with its specific utilization (with an average ventilation rate, in- and outdoor temperature, wind speed, sunlight etc.) the slope of the line through this point is not known, so it is not known what the energy demand would be when the indoor temperature set-point would be different. To understand which line corresponds with which calculated $Q_{predicted}$, it is necessary to analyse which variables within the calculations are most important in the prediction. Principal component analysis (PCA) is used to analyse which variables are most important in this prediction. With this analysis it is possible to form different energy demand lines based on different utilization patterns. Figure 57 and Figure 58 show a first overview of the influence of different measured variables on the measured energy demand of both data sets. It is easy to see that the outdoor temperature has a great influence on the energy demand, the higher the outdoor temperature, the lower the energy demand.

Figure 59 and Figure 60 show which principal components explain how much of the variance of the data. As can be derived, $Q_{TRwalls}$ (transmission of the walls) has the most influence on PC1 (2015-2016: PC1 = 97.6%, PC2 = 1.5%, PC3 = 0.8%, 2016-2017: PC1 = 99.3%, PC2 = 0.5%, PC3 = 0.2%). This variable is only dependent on the measured ΔT, this principal component is probably in line with the trend lines of Figure 53 and Figure 54, because ΔT is the leading parameter. Therefore, to understand which slope of a line corresponds with each calculated $Q_{predicted}$, it is necessary to look at PC2. Even though this principal component has little influence on the data as a whole. As can be derived from Figure 61 and Figure 62, $Q_{infiltration}$ has the most influence on PC2. More than 80% of the variance in PC2 of both data sets can be explained by a difference in $Q_{infiltration}$. As expected, $Q_{internal}$ has a negative influence on the variance in PC2. The higher the internal heat load, the lower the energy demand. Although, the influence of $Q_{infiltration}$ has a considerably bigger influence on PC2, so $Q_{internal}$ will not be used as a variable to determine the slope of the energy demand lines.

Because $Q_{infiltration}$ has the greatest influence on PC2, this variable will be used to determine the slope of the energy demand lines. PC1 is in line with ΔT and is therefore already been taken into account to determine the slope of the energy demand line. To determine the equation for the different energy demand lines, it is necessary to divide $Q_{infiltration}$ into four groups. For this the inter quartile ranges are used. Figure 69 shows the different lines that are the result of these four groups. The two lower clusters and the two higher clusters show a similar line, these are then combined.

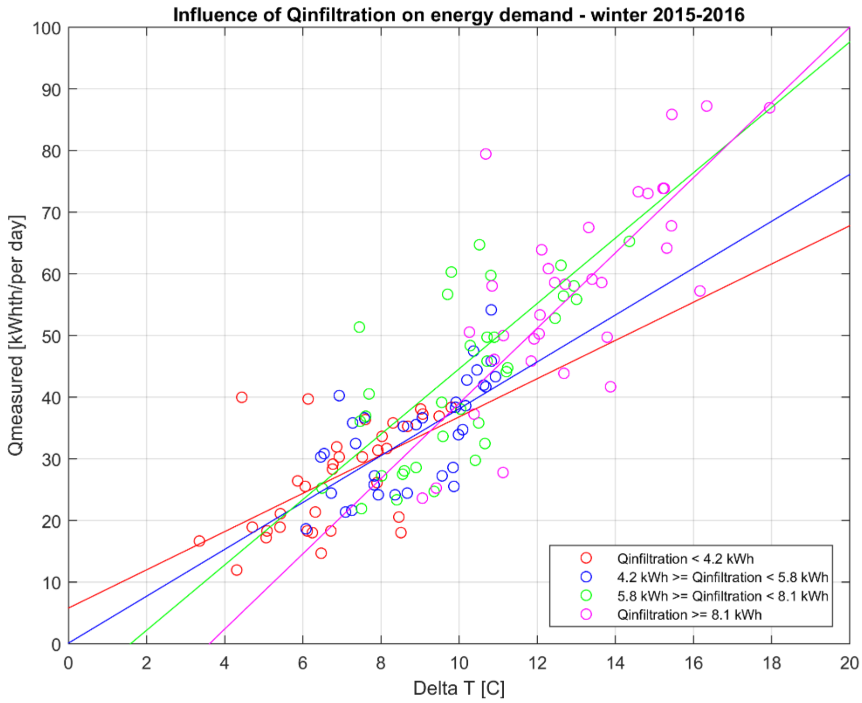


Figure 69 Energy demand lines based on differences in Q_{inf} – winter 2015-2016

As previous mentioned and shown in Figure 11, it was not expected that $Q_{infiltration}$ had a great influence on the slope of the energy demand lines and thus PC2. Because of the high infiltrations rates of the dwelling it is not implausible that $Q_{infiltration}$ has the greatest influence on the slope of the energy demand lines.

Because of the validation problems, because of the experimental dwelling, explained in *section 6.4 Is it possible to explain differences in energy consumption due to differences in utilization of the dwelling?*, the results from the PCA are influenced as well. Because PCA was applied after the inverse modelling stage. However, the results from the PCA are not implausible. And PCA can be used as a tool to find differences in utilization and user behaviour between different dwellings and different occupants.

For example Figure 61 and Figure 62 are almost similar, except for the influence of the internal heat load (Q_{int}) on PC2. This suggests that $Q_{infiltration}$ is smaller or $Q_{internal}$ is greater compared to results of winter of 2016-2017. The outdoor temperature and the wind speed, the depending variables of Q_{inf}, were higher or similar compared the winter of 2016-2017. However, the electricity demand for domestic use was in the winter of 2015-2016 higher compared to the winter of 2016-2017. This is an example of how PCA might show differences in utilization of a dwelling and differences in occupant behaviour. PCA shows which variables have the greatest influence on the measured data. More research is needed to investigate if all dwellings show the same main influencers or if this might vary between different occupants, which is hypothesized in this study.

6.6 Is it possible to explain differences in energy consumption due to differences in thermoregulatory behaviour and comfort of the occupant?

After answering and discussing the secondary research questions it is possible the answer the primary research question:

Is it possible to explain differences in energy consumption due to differences in thermoregulatory behaviour and comfort of the occupant?

Figure 70 through Figure 76 show the the difference in energy demand due to differences in comfort between the two female occupants for one week in the winter of 2016-2017. Each graph shows the result of one day where both test subject 1 and 2 were measured. On the right, similar graphs are shown as Figure 36 through Figure 42. For each test subject the optimal temperature (T_{opt}) per questionnaire entry was calculated, see Table 12. Per day the average optimal temperature (T_{opt}) was calculated and substracted by the outdoor temperature of that day, to exclude the influence of the weather. On the right the histograms per day and per test subject of all the calculated optimal temperatures (substracted by the outdoor temperature) are shown.

Table 12 Overview of the calculated optimal temperatures, in- and outdoor temperatures, the calculated and measured heating demand and the amount of infiltration for the week of 10 till 16 November 2015

Date	T_{opt} test subject 1	T_{opt} test subject 2	Indoor temperature	Outdoor temperature	$Q_{measured}$ [kWhth/per day]	$Q_{predicted}$ [kWhth/per day]	$Q_{infiltration}$ [kWhth/per day]
10-nov-2015	19.42 ˚C	25.48 ˚C	21.5 ˚C	14.2 ˚C	24.4	23.8	3.3
11-nov-2015	19.45 ˚C	28.16 ˚C	21.5 ˚C	12.8 ˚C	27.2	28.7	4.6
12-nov-2015	20.20 ˚C	24.73 ˚C	21.3 ˚C	14.5 ˚C	21.4	22.5	4.9
13-nov-2015	20.20 ˚C	24.04 ˚C	21.6 ˚C	12.8 ˚C	25.8	30.5	2.7
14-nov-2015	20.73 ˚C	24.28 ˚C	21.0 ˚C	9.8 ˚C	35.8	42.6	4.9
15-nov-2015	24.61 ˚C	25.69 ˚C	20.6 ˚C	13.9 ˚C	30.8	23.5	7.8
16-nov-2015	18.99 ˚C	25.84 ˚C	20.5 ˚C	13.0 ˚C	32.5	27.3	5.2

On the left again the average calculated T_{opt} are shown for test subject 1 and 2 (red and blue line). The grey line corresponds with the average indoor livingroom temperature of that day, subtracted by the corresponding outdoor temperature. The dark blue or green line is the energy demand line corresponding with the $Q_{measured}$ of that day. The slope of this line depends on the degree of infiltration on that day, see Table 12. The energy demand line is dark blue when the infiltration rate is low and the line is green when the infiltration rate is high. For high infiltration rates this line corresponds with equation (6), when the infiltration rates are low this line corresponds with equation (7). $Q_{predicted}$ and $Q_{measured}$ are shown as respectivitly a blue and a black dot. The energy demand line is a trendline calculated with multiple measuring values, this is why the blue and black dot might differ from this line.

$$y_{Q_{inf\_high}} = 5.4\,x - 11 \tag{6}$$

$$y_{Q_{inf\_low}} = 3.5\,x + 3.2 \tag{7}$$

In other words, the red line corresponds with the average optimal indoor temperature for test subject 1 of that day and the blue line corresponds with the average optimal temperature for test subject 2 of that day. The grey line indicates the real indoor temperature of that day. It is not sure if the test subject would act on their optimal indoor temperature if they would life alone, but it could be that test subject 1 would set a lower indoor temperature as a set-point compared to the setpoint that she agreed on with test subject 2. This applies vice versa, it is not sure if the test subject would act on her optimal indoor temperature if she would life alone, but it could be that test subject 2 would set a higher indoor temperature as a set-point compared to the setpoint that she agreed on with test subject 1. Except for the 15th of November, test subject 1 would always prefer on average a lower indoor temperature compared to test subject 2. The agreed indoor temperature set-point is except for the 15th of November, always in the middle of the average optimal indoor temperatures of both test subjects.

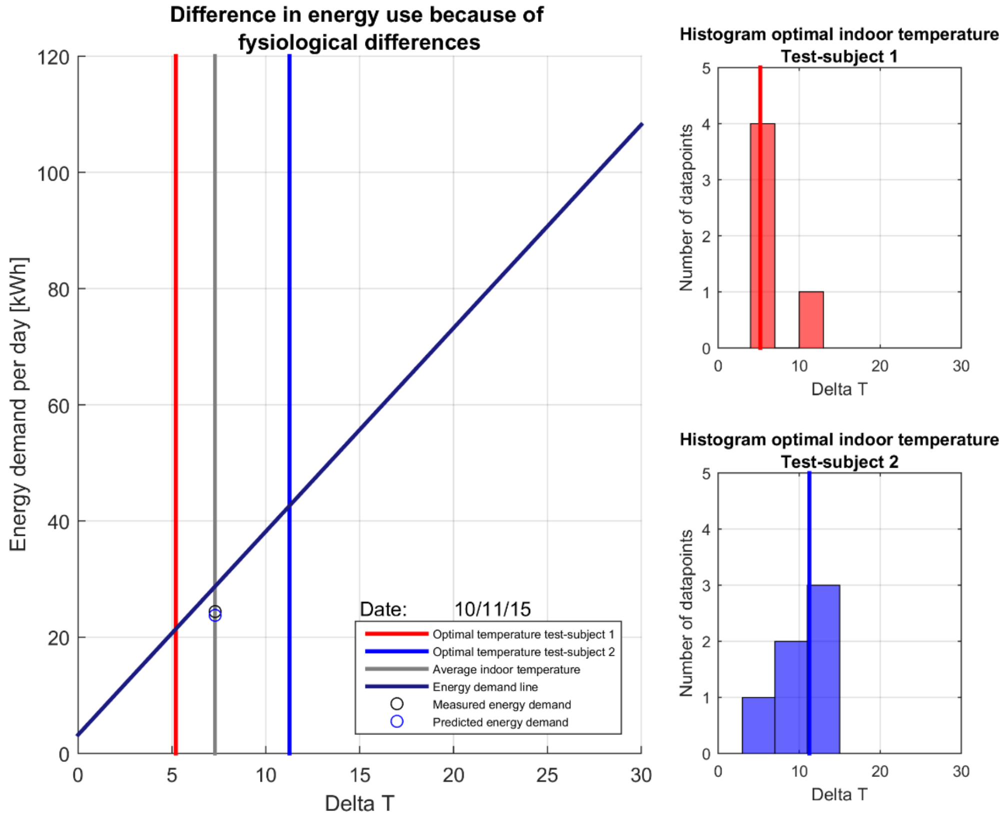


Figure 70 Differences in energy use because of physiological differences – 10th of November 2015. Including the calculated average ΔT_{opt} for test subject 1 (red) and 2 (blue), the measured ΔT of the living room (grey), the energy demand line depending on the amount of infiltration (dark blue) and the measured (black dot) and calculated (blue dot) energy demand

By means of the energy demand line it can be derived what approximatly would be the difference in energy use per day when the test subjects would act on their optimal indoor temperature instead of the agreed set-point temperature. As can be seen, this can differ a factor 2 between the average optimal indoor temperature of test subject 1 and test subject 2, see Table 13.

Table 13 Overview of the calculated ΔT_{opt}'s and the corresponding expected heating demand

	Test subject 1		Test subject 2		Indoor temperature (set-point)	
Date	**ΔT_{opt}**	**$Q_{expected}$ [kWh_{th}/per day]**	**ΔT_{opt}**	**$Q_{expected}$ [kWh_{th} /per day]**	**ΔT**	**$Q_{expected}$ [kWh_{th} /per day]**
10-nov-15	5.22 ˚C	21.47	11.28 ˚C	42.68	7.30 ˚C	28.75
11-nov-15	6.65 ˚C	26.48	15.36 ˚C	56.96	8.70 ˚C	33.65
12-nov-15	5.70 ˚C	23.15	10.23 ˚C	39.01	6.80 ˚C	27.00
13-nov-15	7.40 ˚C	29.10	11.24 ˚C	42.54	8.80 ˚C	34.00
14-nov-15	10.93 ˚C	41.46	14.48 ˚C	53.88	11.20 ˚C	42.40
15-nov-15	10.71 ˚C	46.83	11.79 ˚C	52.67	6.70 ˚C	25.18
16-nov-15	5.99 ˚C	24.17	12.84 ˚C	48.14	7.50 ˚C	29.45

Both test subjects are female and approximately the same age, height and weight. Several studies suggest that there might be great differences in comfort between men and women, lean and obese and young and elderly. When these results already show that between two almost similar females the energy demand might vary up to a factor 2, the differences between subpopulations might be even greater. This is discussed in *section 6.3 Is it possible to define optimal indoor temperatures on an individual level?* and *Appendix X* as well. In these sections differences up to 5 ˚C in optimal temperature (T_{opt}) where calculated by only physiological differences (e.g. gender, age, length, weight), without differences in clothing, activity level or enviromental parameters. People all dress and behave/adapt differently, otherwise their average calculated optimal temperatures (T_{opt}) would be similar. As can be derived from Table 13, this was also proven for the two test subjects, where the female subjects did not differ greatly in age, weight or height. This might explain why for the same type of dwellings the highest measured energy consumption is a factor 5 greater than the lowest measured energy consumption (Borg, 2015)(Steen et al., 2010).

Further research is necessary to investigate if the test subjects would act on their optimal temperature or if they would leave the indoor temperature set-point as is. In addition, further research is necessary to measure more occupants. The results of test subject 3 and 4 can be found in *Appendix VII*. Their were not enough measuring points to calculate a proper optimal temperature (T_{opt}) per day per test subject for test subject 3 and 4. These results might have shown differences between men and women.

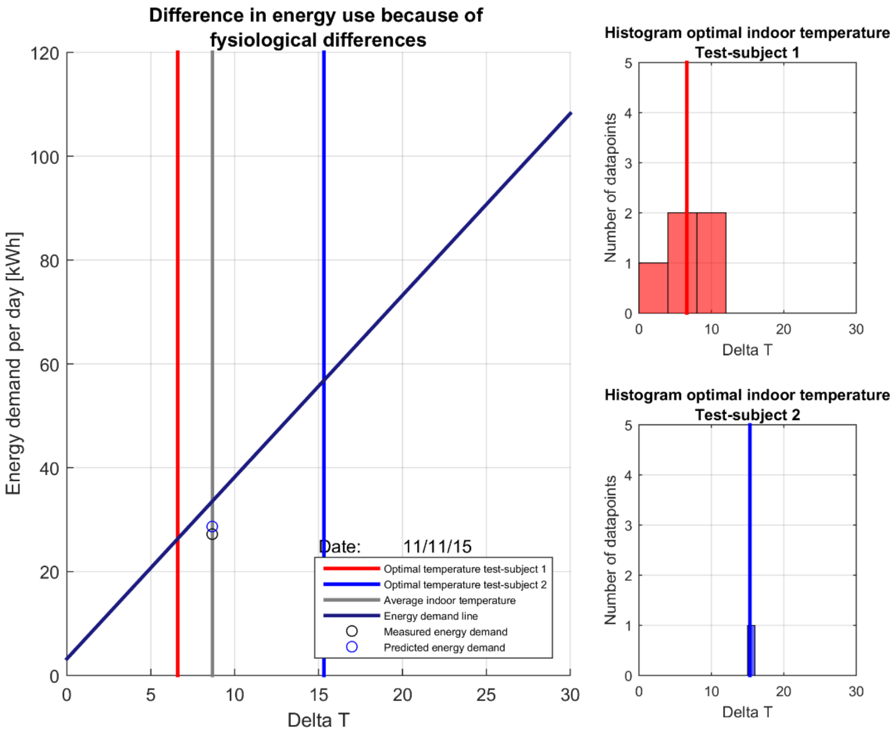


Figure 71 Differences in energy use because of physiological differences – 11th of November 2015. Including the calculated average ΔT$_{opt}$ for test subject 1 (red) and 2 (blue), the measured ΔT of the living room (grey), the energy demand line depending on the amount of infiltration (dark blue) and the measured (black dot) and calculated (blue dot) energy demand

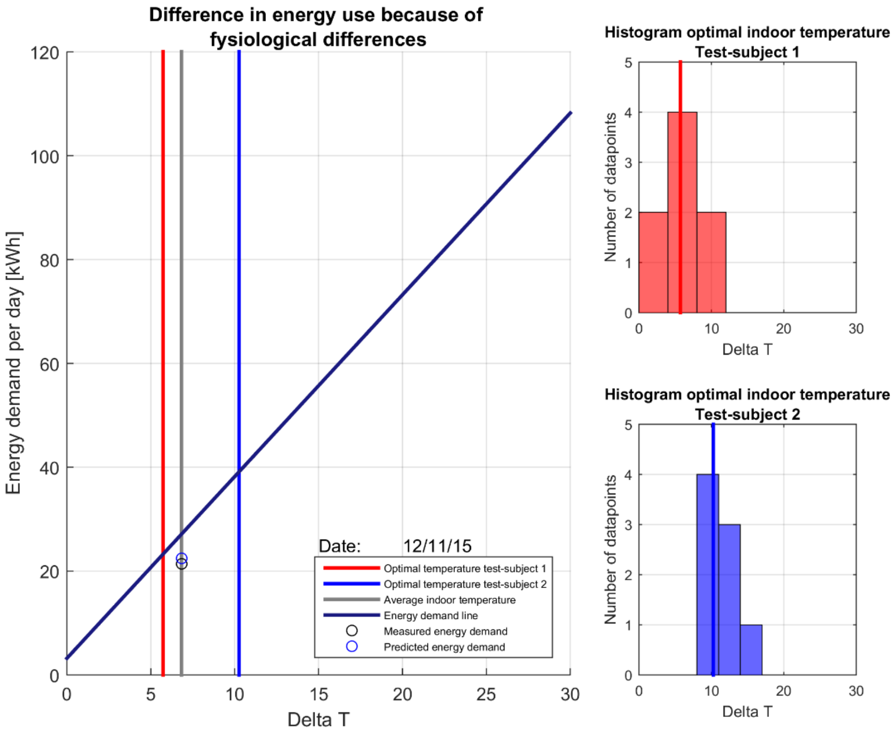


Figure 72 Differences in energy use because of physiological differences – 12th of November 2015. Including the calculated average ΔT$_{opt}$ for test subject 1 (red) and 2 (blue), the measured ΔT of the living room (grey), the energy demand line depending on the amount of infiltration (dark blue) and the measured (black dot) and calculated (blue dot) energy demand

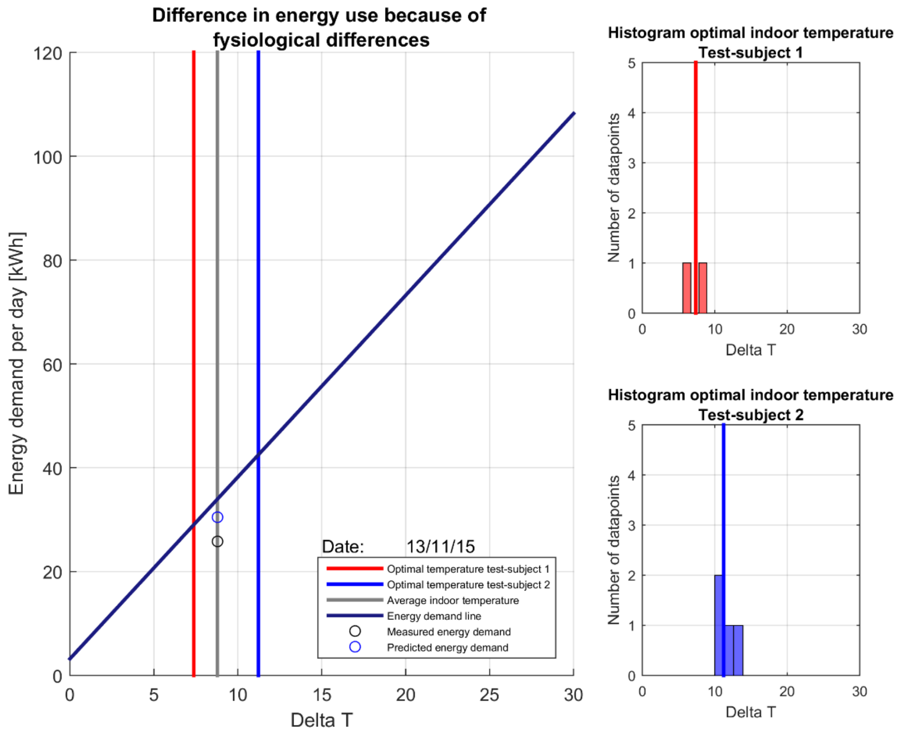


Figure 73 Differences in energy use because of physiological differences – 13th of November 2015. Including the calculated average ΔT_{opt} for test subject 1 (red) and 2 (blue), the measured ΔT of the living room (grey), the energy demand line depending on the amount of infiltration (dark blue) and the measured (black dot) and calculated (blue dot) energy demand

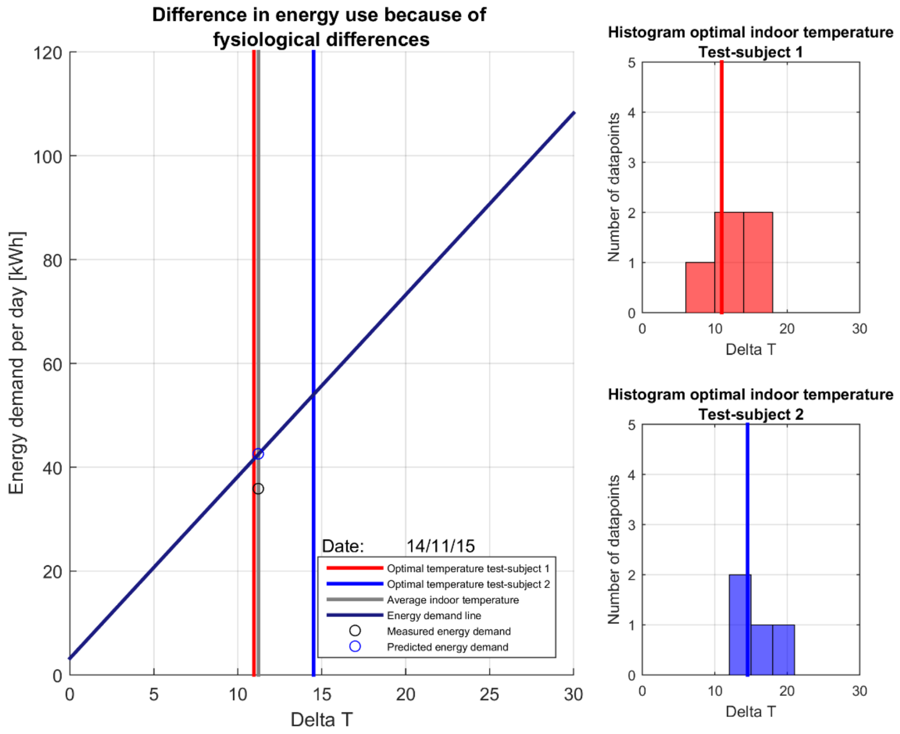


Figure 74 Differences in energy use because of physiological differences – 14th of November 2015. Including the calculated average ΔT_{opt} for test subject 1 (red) and 2 (blue), the measured ΔT of the living room (grey), the energy demand line depending on the amount of infiltration (dark blue) and the measured (black dot) and calculated (blue dot) energy demand

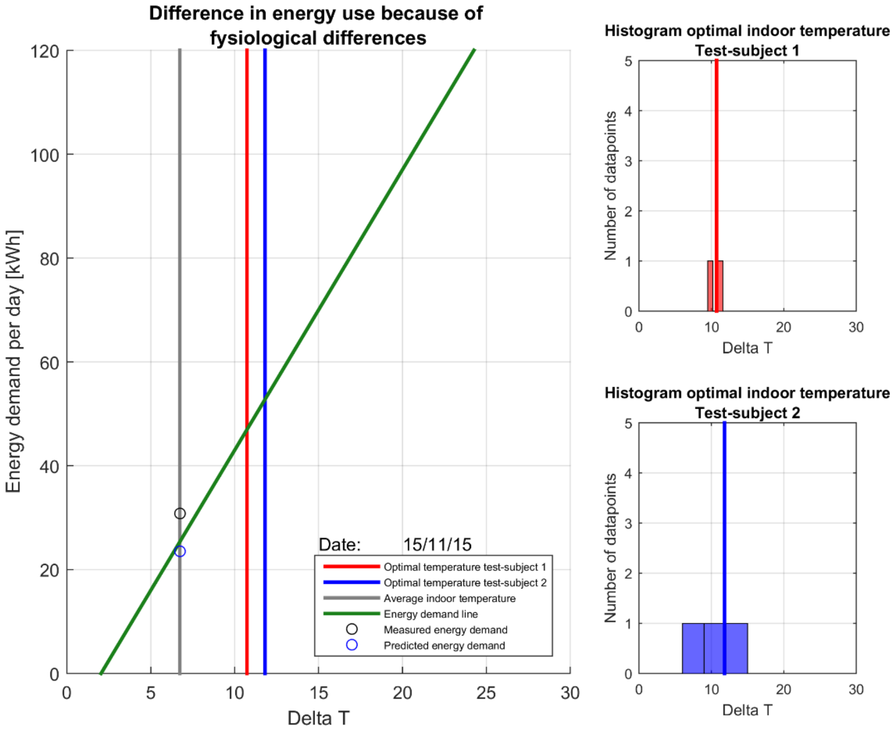


Figure 75 Differences in energy use because of physiological differences – 15th of November 2015. Including the calculated average ΔT_{opt} for test subject 1 (red) and 2 (blue), the measured ΔT of the living room (grey), the energy demand line depending on the amount of infiltration (green) and the measured (black dot) and calculated (blue dot) energy demand

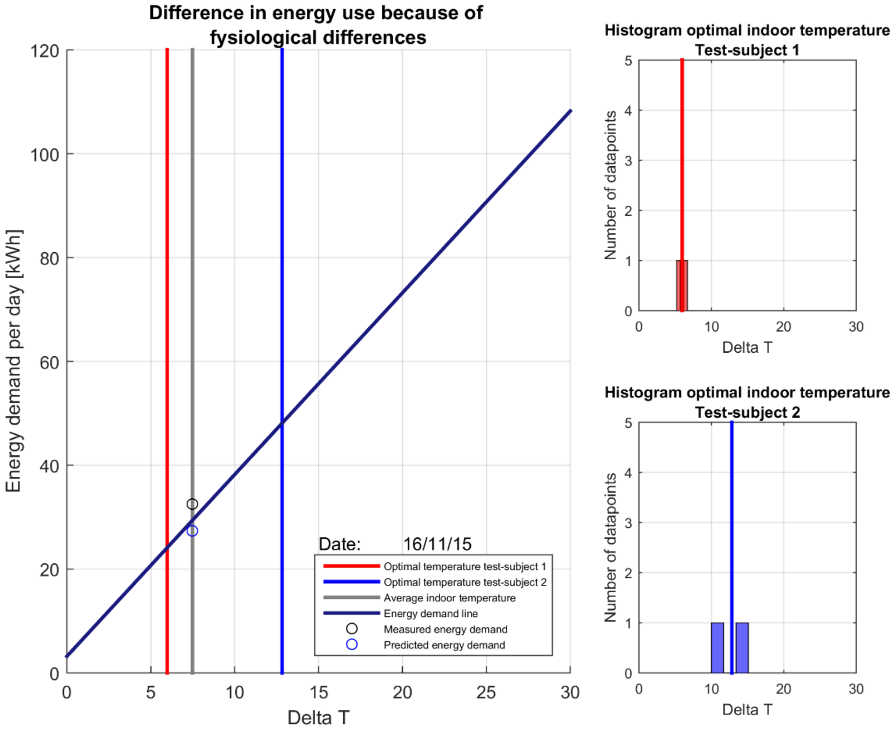


Figure 76 Differences in energy use because of physiological differences – 16th of November 2015. Including the calculated average ΔT_{opt} for test subject 1 (red) and 2 (blue), the measured ΔT of the living room (grey), the energy demand line depending on the amount of infiltration (dark blue) and the measured (black dot) and calculated (blue dot) energy demand

Finally, for answering the primary research question and thus the assessment of differences in energy use because of physiological differences, it might have been better to use a validated energy model such as TRNSYS, VABI or EnergyPlus. However, the boundary conditions set for this study made it not possible to use a licensed model. In addition, this model did not only allow for an actual calculation of energy demand based on real time measurements but it also allowed studies of user behavior and user's individual impact on dwelling's utilization and therefore dwelling's energy consumption. The TRECO energy demand model makes it possible identify and analyze these differences in energy demand in more detail. Finally, as can be derived from the results of the measurements, the energy demand of the dwelling is strongly liniear correlated with ΔT. And the developed energy model made it possible to predict the energy demand with an accuracy of > 70%. In addition, this simplistic energy model used in this study, has several great advantages compared to more advanced models such as TRNSYS, VABI or EnergyPlus;

- with this model it is possible to directly use data (measurements or information about the dwelling such as dimensions) from databases instead of files.
- One of the well-known type of databases are the BIM databases. At this moment it is time consuming and hard to connect BIM databases to energy models such as TRNSYs or EnergyPlus. Mainly because of bugs in the data export from BIM to an IFC-file and the import in the model. The TRECO energy demand model might be suitable to connect to the BIM database directly without exporting data to a file. Further research is necessary to assess the possibilities to connect the model to BIM databases.
- Finally, the model can automatically be run on a server, without any manual manipulation from a user. The calculated energy demand can automatically be written back to the database, which than can be used for further analysis.

Because of the uncertainties of the building parameters it was not possible to validate the energy model properly. Because of the great influence of the thermal resistance of the walls, roof and floor, it is recommended to first validate the model with another energy model such as TRNSYS, VABI or EnergyPlus. These energy models can generate variables such as temperatures, infiltration and ventilations flows, which can be used as input variables for the TRECO energy demand model. With these input variables the model can be validated and improved. Where after, more residential buildings can be used in order to validate the model. Finally, this model needs to be revised when applied to warmer months, such as the summer period in the Netherlands. The model is now restricted to application where solar radiation is limited and thermal mass can be neglected.

7 Conclusion

The overall goal of this Master thesis was to clarify variation in energy use between similar dwellings by means of differences in thermoregulatory behaviour of the occupant what results from differences in comfort levels and physiology. The hypothesis that was investigated in this study was that differences in energy use might be linked to the differences in thermoregulatory behaviour and comfort. It was expected that the influence of the comfort vote of occupants could be directly found in their energy use. The research and scientific objectives were directly related to this research goal. The primary research question was:

Is it possible to explain differences in energy consumption due to differences in thermoregulatory behaviour and comfort of the occupant?

Secondary research questions were:

- *Is it possible to explain differences in comfort and thermoregulatory behaviour between occupants?*
- *What thermoregulatory behavior do the test subjects show?*
- *Is it possible to define optimal indoor temperatures at an individual level?*
- *Is it possible to explain differences in energy consumption due to differences in utilization of the dwelling?*
- *Is it possible to predict energy consumption per day for a perticulair dwelling with its utilization pattern?*

These questions will be answered in the following sections by means of the results of the previous chapters.

7.1 Is it possible to explain differences in comfort and thermoregulatory behaviour between occupants?

Yes, it is possible to explain differences in comfort and thermoregulatory behaviour between occupants. All test subjects show a unique pattern in their thermal environment. Where in all cases at least three areas could be distinguished in the measuring data, one sleeping area and two living areas. Even though, it was hypothesized that there would only be two major areas, namely during the night and during the day. However, no published research study was found where such a hypothesis was tested and could therefore serve as a reference. In addition, all three areas are associated with maximum comfort. The difference between the two living areas could be explained by differences in clothing worn and differences in activity levels.

In addition, where the model of Fanger (Fanger, 1973) concludes that most people are most comfortable when they feel neutral, this is not the case for the test subjects in this study. In this study the test subjects are most comfortable when they feels slightly warm.

Furthermore, the thermoneutral zone (TNZ) model can be used to explain differences in comfort and thermoregulatory behaviour between occupants. The combination of skin- and exposed temperatures can be used to predict the comfort level and the expectation that the occupant exhibits thermoregulatory behaviour. The TNZ depends on different physical aspects of the person, e.g. gender, body area, body fat and activity level. In addition, the air velocity, relative humidity and the clothing degree are important as well for the calculation of the TNZ. Consequently this means that the TNZ varies per person and per moment. In this study the TNZ is calculated for the different test subjects and for different conditions, for example conditions during the night or average conditions during daily indoor activities. These calculations correspond quite accurate with the measured data.

Finally, when the findings of test subject 1 and 2 are being compared, differences in comfort and thermoregulatory behaviour where found. The measurement zones, the sleeping area and the two living areas, of test subject 1 are moved to lower exposed temperatures compared to the measurements of test subject 2. In conclusion, test subject 1 is probably comfortable at lower temperatures than test subject 2.

7.2 What thermoregulatory behavior do the test subjects show?

The test subjects did not show much thermoregulatory behaviour. The thermostat was not used often and changes in activity level were probably mostly changes because of routine, e.g. cycling to school, walking to the grocery store, watching television in the evening. Most of the changes in Clo-value were probably changes out of routine as well, e.g. putting on pyjamas when going to bed, putting clothes on after taking a shower. Although, some changes were because of the exposed temperature, e.g. getting a blanket or putting on a sweater. It might be possible that the dwelling is very comfortable, whereby no changes to the set-point temperatures were necessary.

However, the skin temperature of the test subjects adapted to the exposed temperature and their comfort and sensation votes, even without changes to the thermostat, clothing or activity level. This is probably because the body has to work harder to maintain its core temperature by regulating blood flow by dilating or contracting blood vessels when the operative temperature increases or decreases, to increase or decrease the heat loss of the body. When regulating through dry heat loss is not sufficient enough, the temperature will be regulated by sweating or (non-)shivering thermogenesis. When the exposed temperature of the body increases or decreases the body will adapt to this change in exposed temperature to retain its core temperature. Therefore, a higher skin temperature suggests that the test subject feels warm and a lower skin temperature suggests that the test subject feels cold. Because of this mechanism of dilating and contracting blood vessels, the body will adapt with a slight time delay and has therefore the ability to build up a small buffer to overcome the sudden changes in exposed temperature. This was observed in this study as well. Skin temperatures, comfort votes and sensation votes changed when the exposed temperature was higher or lower than the calculated TNZ.

7.3 Is it possible to define optimal indoor temperatures on an individual level?

Yes it is possible to calculate optimal indoor temperatures on an individual level. The comfort zone is the centre of the thermoneutral zone, the corresponding operative temperature is the most comfortable (optimal) indoor temperature for that person at that moment (T_{opt}). However, the TNZ depends on different physical aspects of the person, clothing degree, air velocity and relative humidity. This means that the TNZ varies per person and per moment. Because parameters such as relative humidity, air velocity, activity level and clothing can vary over time this will lead to a different comfort zone and thus a different optimal indoor temperature.

In this study, the TNZ and the corresponding optimal temperature (T_{opt}) is calculated for all the measuring point individually. When the average calculated optimal temperatures of the different test subjects are being compared, differences in optimal indoor temperatures can be distinguished. From these calculations the same conclusion can be drawn; test subject 1 is more comfortable at lower temperatures compared to test subject 2.

Finally, the human body adapts to the exposed temperature with a slight delay over time. This delay is dependent of the physiology of a person (e.g. gender, weight, height, amount of body fat and metabolism) and his or her clothing. A person with little body fat is more sensitive for variations in ambient temperatures, because of the lack of thermal resistance. Consequently, a person with more body fat is less sensitive for variations in ambient temperatures. Furthermore, a taller person has a greater body surface, so will easier be cold. And in conclusion, for different ambient temperatures other than of the TNZ, the person might change the thermostat set-point to achieve an acceptable thermal comfort level which will result in higher energy demands (for heating or cooling).

However, it is not always possible to change the set-point temperatures. For example in office buildings or when more people are living in the same dwelling, with all different comfort levels. As an addition to changing set-point temperatures, people can reduce their sensitivity for variations in temperatures by changing the clothing they wear. Clothing is a variable that can shift the calculated TNZ to lower or higher ambient temperatures. Clothing is therefore frequently used to adapt to uncomfortable thermal environments. However, a clothing degree of less than 0.5 clo or more than 0.8 clo, is not common during daily indoor activities. This leaves a smaller range of ambient temperatures wherein the person can adapt to her thermal environment to maintain her thermal comfort.

In conclusion, every person has a different comfort level with a different bandwidth of acceptable ambient temperatures. Depending on differences in gender, age, length and weight. The body of a person will adapt quick or slow to variations of the environment. Installations should therefore enable quick or slow changes in temperatures. This argues for individual systems in offices and fast installations in dwellings.

7.4 Is it possible to explain differences in energy consumption due to differences in utilization of the dwelling?

It is possible to explain differences in energy consumption due to differences in utilization of the dwelling. This has been possible in an advanced stage for a couple of years through different calculation software. Although, because of the boundary conditions of this study it is not possible to use such a program. Therefore, the model that was developed in this study is explained in *Appendix II*. The hypothesis that was investigated in this study is that a difference in comfortable indoor temperature might be the reason for variation in energy demand between similar dwellings. Therefore, real-life measurements were taken into account during the calculation of the heating demand, in order to include the actual differences in set-point temperatures and other variables such as ventilation flow, wind speed and energy use of appliances and installations. Inverse modelling was used to increase the accuracy of this model and to determine building parameters (e.g. thermal resistance of closed parts, thermal transmittance of transparent parts and air tightness of the dwelling) in practise. Because these parameters might differ from the expected values in practise and deviations might also have a great influence on the energy demand (Rasooli, Itard, & Infante, 2016).

In this study one dwelling was monitored for two years, in the winter of 2015-2016 two female tenants were living in this dwelling. During the summer of 2016 two new tenants (a man and woman) came living in this dwelling and were monitored during the winter of 2016-2017. The measurements showed that there is a linear correlation between the measured energy demand and ΔT in both data sets. The indoor temperature during the winter of 2016-2017 was on average slightly higher than during the winter of 2015-2016, although it was more constant. And the winter of 2016-2017 was on average colder In addition, the occupants during the winter of 2016-2017 were slightly more efficient. In addition, the routine of the tenants in the winter of 2016-2017 was probably more constant, this resulted in a better prediction of the energy demand by the TRECO energy demand model.

Finally, the inverse modelling stage showed that the efficiency of the building façade of the dwelling was worse than expected. The renovation of the monitored dwelling was part of a different TKI-project. This renovation was a pilot for a new renovation principle, and therefore an experiment. From the high measured infiltration rates, it was already known that the dwelling was leak. But the results from the energy model suggested that the joints between different insulation materials are poor as well, which might resulted in major thermal bridges. Multiple calculations and measurements concluded that the building envelop is different than expected.

The experimental nature of the used dwelling might not give unambiguously results, the methods used this study can be used for further research concerning energy demand and occupant behaviour predictions. The energy model described in *Appendix II* can be used as a starting point for more and better energy demand predictions. One of the main advantages of this model is that it can be used as a code only model. Input variables can automatically be retrieved from for example a database. Not only measurement data, but information about the dwelling as well, e.g. dimensions, surfaces, parameters of building parts. In addition, this simplistic energy model used in this study, has great advantages compared to more advanced models such as TRNSYS, VABI or EnergyPlus;

- with the TRECO energy demand model it is possible to directly use data (measurements or information about the dwelling such as dimensions) from databases instead of files.
- One of the well-known type of databases are the BIM databases. At this moment it is time consuming and hard to connect BIM databases to energy models such as TRNSYs or EnergyPlus. Mainly because of bugs in the data export from BIM to an IFC-file and the import in the model. The TRECO energy demand model might be suitable to connect to the BIM database directly without exporting data to a file.
- Finally, the model can automatically be run on a server, without any manual manipulation from a user. The calculated energy demand can automatically be written back to the database, which than can be used for further analysis.

Overall, the energy model can be used to predict energy consumption for specific dwellings with its specific utilization. It is therefore possible to investigate differences in utilization between similar dwellings, which results from differences in set-points.

7.5 Is it possible to predict energy consumption per day for a perticulair dwelling with its utilization pattern?

Yes it is possible to predict energy consumption per day for a dwelling with a certain utilization pattern. The energy model used in this study can be used to calculate the energy demand of a dwelling with its utilization pattern, by means of including real measurements. In this study principal component analysis (PCA) is used to emphasize variation and bring out strong patterns in the datasets. Principal component analysis is often used to make data easy to explore and to visualize.

In addition, PCA can be used the predict the slope of the energy demand line by a specific utilization of a dwelling. Furthermore, PCA can be used to find certain patterns of user behaviour, for example with PCA it is possible to identify a variable that is most influenced by an occupant and to define which variables have the biggest impact on the heating demand calculation. These outcomes can vary between occupants and between dwellings.

The principal component analysis showed that transmission had the greatest influence on the data in this study. This variable is strongly dependent on the measured ΔT and therefore probably in line with the x-axis. Therefore the second greatest influencer, infiltration, is used to determine the slope of the energy demand lines. Different energy demand lines were made by means of the amount of infiltration per day. It was not expected that infiltration had the greatest influence on the slope of the energy demand lines. However, because of the experimental nature of the dwelling it is not implausible that infiltration has the greatest influence on the slope of the energy demand line.

Finally, PCA was used to assess differences in utilization of the dwelling. In this study one dwelling was monitored for two years, in the winter of 2015-2016 two female tenants were living in this dwelling. During the summer of 2016 two new tenants (a man and woman) came living in this dwelling and were monitored during the winter of 2016-2017. The only difference in the PCA of both datasets was the influence of the internal heat load on the heating demand. This suggested that the infiltration was smaller, or the internal heat load was greater compared to the other winter. The outdoor temperature and the wind speed, the depending variables in the calculation of the infiltration, were higher or similar compared the other winter. However, the electricity demand for domestic use was greater compared to the other winter. This is an example of how PCA might show differences in utilization of a dwelling and differences in occupant behaviour.

7.6 Is it possible to explain differences in energy consumption due to differences in thermoregulatory behaviour and comfort of the occupant?

After answering and discussing the secondary research questions it is possible the answer the primary research question:

Is it possible to explain differences in energy consumption due to differences in thermoregulatory behaviour and comfort of the occupant?

Yes it is possible the explain differences in energy consumption due to differences in thermoregulatory behaviour and comfort of occupants. By answering the first three secondary research questions it can be derived that there are differences in thermoregulatory behaviour, comfort and resulting optimal indoor temperatures. When the average calculated optimal temperatures are being compared, differences in optimal indoor temperatures can be distinguished. From these calculations the conclusion can be drawn; test subject 1 is more comfortable at lower temperatures compared to test subject 2. As was seen in the measurements, the set-point temperature of the living room was in the middle of these calculated optimal temperatures. It is not sure if the test subjects would act on their optimal indoor temperature if they would life alone, but it could be that test subject 1 would set a lower indoor temperature as a set-point compared to the set-point that she agreed on with test subject 2. And vice versa. By combining the energy demand lines and the average calculated optimal temperatures per person per day, differences in energy demand can be seen.

By means of the energy demand line it can be derived what approximately would be the difference in energy use per day when the test subjects would act on their optimal indoor temperature instead of the agreed set-point temperature. This study showed that this can differ a factor 2 between the average optimal indoor temperature of test subject 1 and test subject 2. Both test subjects are female and approximately the same age, height and weight. Several studies suggest that there might be great differences in comfort between men and women, lean and obese and young and elderly. When this study already shows that between two almost similar females the energy demand might vary up to a factor 2, the differences between subpopulations might be even greater. This might explain why in some projects the highest measured energy consumption is a factor 5 greater than the lowest measured energy consumption (Borg, 2015; Steen et al., 2010).

References

Ainsworth, B. E., Haskell, W. L., Whitt, M. C., Irwin, M. L., Swartz, A. N. N. M., Strath, S. J., … Leon, A. S. (1995). Compendium of Physical Activities : an update of activity codes and MET intensities, (12).

Air Infiltration and Ventilation Centre. (2016).

Baker, F., Mitchell, D., & Driver, H. (2001). Oral contraceptives alter sleep and raise body temperature in young women. k.n.: k.n.

Baker, F., Waner, J., Vieira, E., Taylor, S., Driver, H., & Mitchell, D. (2001). Sleep and 24 hour body temperatures: a comparison in young men , naturally cycling women and women taking hormonal contraceptives. k.n.: k.n.

Borg, A. (2015). Alexander Borg and Calculated Energy Demand Relationships Between Measured in the Norwegian Dwelling Stock.

Brager, G. S., & de Dear, R. (2000). A standard for natural ventilation, (October).

Brohus, H., Heiselberg, P., Simonsen, A., & Sørensen, K. C. (2010). Influence of Occupants' Behaviour on the Energy Consumption of Domestic Buildings. Proceedings Clima, 0–7.

Dubois , D., & Dubois, E. (1916). A formula to estimate the approximate surface area if height and weight be known. n.k.: Arch Intern Med.

Harris, J., & Benedict, F. (1918). A biometric study of human basal metabolism. Washington: Carnegie institution of Washington.

ISSO. (2008). ISSO-publicatie 50: kwaliteitseisen warmwaterverwarmingsinstallaties. Rotterdam: ISSO.

Jacquot, C., Schellen, L., Kingma, B., van Baak, M., & van Marken Lichtenbelt, W. (2013). Influence of thermophysiology on thermal behavior: the essentials of categorization. Maastricht: Department of human biology Maastricht University.

Jacquot, C. M. C., Schellen, L., Kingma, B. R., van Baak, M. A., & Van Marken Lichtenbelt, W. D. (2014). Influence of thermophysiology on thermal behavior: The essentials of categorization. Physiology and Behavior, 128, 180–187. http://doi.org/10.1016/j.physbeh.2014.01.025

Karjalainen, S. (2011). Thermal comfort and gender: a literature review. Helsinki, Finland.

Kingma, B. (2016). Internal presentation. London: Windsor.

Kingma, B., & Lichtenbelt, W. V. M. (2016). Energy consumption in buildings and female thermal demand Energy consumption in buildings and female thermal demand, (August 2015). http://doi.org/10.1038/nclimate2741

Kingma, B. R. M., Frijns, A. J. H., Schellen, L., Marken, W. D. Van, Kingma, B. R. M., Frijns, A. J. H.,

… Lichtenbelt, W. D. V. M. (2014). Beyond the classic thermoneutral zone Beyond the classic thermoneutral zone Including thermal comfort, *8940*(March 2017). http://doi.org/10.4161/temp.29702

KNMI. (2016, 10 5). Zonsondergang 2016. Retrieved from Zonsondergang: http://www.zonsondergangtijden.nl/tabel-zonsondergang-2016.html

Kramer, R., Schijndel, J. Van, & Schellen, H. (2013). Inverse modeling of simplified hygrothermal building models to predict and characterize indoor climates. Building and Environment, 68, 87–99. http://doi.org/10.1016/j.buildenv.2013.06.001

McCullough, E., Jones, B., & Huck, J. (1985). A Comprehensive Data Base for Estimating Clothing Insulation. Atlanta: ASHRAE.

McCullough, E., Jones, B., & Tamura, T. (1989). A data base for determining the evaporative resistance of clothing. Atlanta: ASHRAE.

Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings, 34, 563–572.

Rasooli, A., Itard, L., & Infante, C. (2016). A response factor-based method for the rapid in-situ determination of wall ' s thermal resistance in existing buildings. Energy & Buildings, 119, 51–61. http://doi.org/10.1016/j.enbuild.2016.03.009

Schweiker, M., Kingma, B. R. M., & Wagner, A. (2017). evaluating the performance of thermal sensation prediction with a biophysical model. Indoor Air, 49(0), 0–3. http://doi.org/10.1111/ijlh.12426

Slimme Meter. (2016, 1 17). Homepage. Retrieved from Slimme meter: http://www.slimmemeters.nl/

Starmer, J. (Director). (2015, 8 15). StatQuest: Principle Component Analysis (PCA) clearly explained [Motion Picture].

Steen, T., Henrik, N., Marie, A., Tove, E., Kvols, P., Larsen, T. S., … Rose, J. (2010). Occupants influence on the energy consumption of Danish domestic buildings - State of the art.

Tohoku University. (2013). Annex 53 Total energy use in buildings. Sendai, Japan: International Energy Agency.

Visser, L. (2016). Occupant behaviour and thermal comfort in buildings; Monitoring the end user, (February).

Wang, D., Zhang, H., Arens, E., & Huizenga, C. (2006). Observations of upper-extremity skin temperature and corresponding overall-body thermal sensations and comfort. Berkeley: University of California.

Zonnepanelen (PV) op je eigen dak. (2016, 9 28). Retrieved from 11duurzaam: http://11duurzaam.nl/zonnepanelen-op-je-eigen-dak/

Appendixes

Appendix I

Matlab code TNZ_static_simple function

```
function [data] = TNZ_static_simple(Ta,Ts,v_air, Rh, A, Icl, M, TcMax,
TcMin, IbMax, IbMin )
n = length(Ta);
Ts_c = zeros(n,n);

Mtot = mean(M)/A;

for i=1:n
    for j=1:n %1st dim = Tclo and 2nd dim is Tair (col,row)

        Pa_res = 0.001 * vapourpressure(Ta(j), Rh);
        Cres = 0.0014 * Mtot * ( 34 - Ta(j) );
        Eres = 0.0173 * Mtot * ( 5.87 - Pa_res );
        Qrsp = Cres + Eres;
        alpha = Qrsp / Mtot;
        %alpha_set =[alpha_set,alpha];
        Mmax = (1-alpha) * max(M);
        Mmin = (1-alpha) * min(M);
        TsMin = TcMin - Mmax*IbMax/A;
        TsMax = TcMax - Mmin*IbMin/A;

        Ts_r = TsMax - TsMin;
        Ts_rc = (IbMax-IbMin)/Ts_r;

        T = Ta(j)+273.15;
        a1 = 0.61*(T/298)^3; %radiative
        a2 = 0.19*sqrt(v_air*100)*(298/T); %convective
        Ia = 0.155/(a1+a2); %m2K/W

        %gagge model for evaporation
        Pa = 0.00750061683 * vapourpressure(Ta(j), Rh); %pascal to mmHg
        Psat_ts = 0.00750061683 * vapourpressure(Ts(i), 1); %pascal to mmHg
        CTC = 1/Ia; %W/m2K
        CHR = a1/0.155; %W/m2K
        HC = (CTC-CHR); %W/m2K

        lewis = 2.2;
        W = 0.06;
        CLO = Icl/0.155; %clo
        Fpcl = 1/(1+0.143*(CTC-CHR)*CLO);

        Ts_c(i,j) =Ts(i);

        if Ts_c(i,j)>TsMax %calculate body insulation as function of Tskin
            Ibf = IbMax-IbMin;
        elseif Ts_c(i,j)<TsMin
            Ibf = 0;
        else
            Ibf =  Ts_rc*(Ts_c(i,j)-TsMin);
        end
        Ibody = (IbMax-Ibf);%1/((If-Ibf)); %convert to conductivity
```

```
        Emax = lewis*HC*(Psat_ts-Pa)*Fpcl;
        Qe = W*Emax; %W/m2
        Tb(i,j) = (Ibody/(1-alpha))*((Ts_c(i,j)-Ta(j))/(Icl+Ia) + Qe) +
                  Ts_c(i,j);


        Qsk_cl(i,j) = (A/(Icl+Ia))*(Ts_c(i,j)-Ta(j)) + A*Qe;

        if( Tb(i,j) < TcMin || Tb(i,j) > TcMax )
            Tb(i,j) = NaN;
        end

        Tcit(i,j) = Tb(i,j);
        Tsw(i,j) = Tb(i,j);


        if( Qsk_cl(i,j) < Mmax )
              Tcit(i,j) = NaN;
        end

         if( Qsk_cl(i,j) > Mmin )
              Tsw( i,j ) = NaN;
        end

        if( Qsk_cl(i,j) < Mmin || Qsk_cl(i,j) > Mmax )
            Tb(i,j) = NaN;
        end


    end
end

%mean(alpha_set)
Q = Qsk_cl;

data.Ta = Ta;
data.Ts = Ts;
data.Tcit = Tcit;
data.Tsw = Tsw;
data.Tb = Tb;
data.Q = Q;
end
```

Matlab code vapourpressure function

```
function vp = vapourpressure(T, rh)
% calculate the vapour pressure for given temperature and relative
% humidity.
psat = 100*exp(18.965 - 4030/(T+235));
vp = rh * psat;
end
```

Matlab code TNZ calculation

```
kcalday2watts = 4184/(24*60*60);
weight = 55; % kg
height = 169; % cm
age = 25;
```

```
S_BMR =  ( 13.397*weight+ 4.799*height - 5.677*age + 88.362 ) *
      kcalday2watts; % men
S_BMR =  ( 9.247*weight+ 3.098*height - 4.330*age + 447.593) *
      kcalday2watts; % women

A = 0.007184 * weight^0.425 * height^0.725; %Dubois (surface area)
S_Wm2 = S_BMR/A; %bmr = 4/5 Met
S_MET_1 = 5/4 * S_Wm2; % 1 met value

N = 100; %grid
Ta = linspace(14,32,N);
Ts = linspace(28,38,N);

TcMax = 37.5;
TcMin = 36.5;
IbMax = 0.112;
IbMin = 0.032;

M = [A*(MET(a)*S_MET_1-1), A*(MET(a)*S_MET_1+1)];
Icl = CLO*0.155;
v_air = 0.09; % m/s
Rh = 0.50; % precent


static_data = TNZ_static_simple(Ta,Ts,v_air, Rh, A, Icl, M, TcMax, TcMin,
      IbMax, IbMin);
[isk,iai] = find(~isnan(static_data.Tb));
%tnz temperature centroid
Top_centroid = mean(static_data.Ta(iai));
Tsk_centroid = mean(static_data.Ts(isk));

Top_centroid_array = [Top_centroid_array,static_data.Ta(iai)];
Tsk_centroid_array = [Tsk_centroid_array,static_data.Ts(isk)];
Top_centroidmean_array =
      [Top_centroidmean_array;mean(static_data.Ta(iai))];
Tsk_centroidmean_array =
      [Tsk_centroidmean_array;mean(static_data.Ts(isk))];

plot(static_data.Ta(iai),static_data.Ts(isk),'o','Color',[1, .2,
      .2],'MarkerFaceColor',[1, .2, .2],'MarkerSize',2);
hold on;

plot(Top_centroid,Tsk_centroid ,'o','Color',[1, 0, 0],'MarkerFaceColor',[1,
      0, 0],'MarkerSize',8);
```

T_{opt} can be calculated with; mean(static_data.Ta(iai))

The corresponding skin temperature would then be; mean(static_data.Ts(isk))

Appendix II

TRECO energy demand model for heating

The dwelling in Heerlen was equipped with an advanced monitoring system as mentioned in 4 Experimental program. The collected data was used to predict the energy use of the dwelling. Wherein real measurements, such as in- and outdoor temperatures, were being used in the calculation of $Q_{predicted}$ [kWh]. In this appendix the energy demand model discussed in Chapter 3 Methodology to calculate energy consumption will be further explained.

The variables 'a, b, c, d, e and f' indicate factors which will be predicted during the inverse modelling stage when the model is going to be optimized, as discussed in 3.1 Inverse modelling. It is important to note that the model was only applied during the colder months of the year, i.e. October through March, because of the major differences between the months when heating is turned on and the period when it is switched off (i.e. colder and warmer seasons in the Netherlands/Heerlen). Therefore, this model still needs to be revised for predictions during warmer months, such as the summer period in the Netherlands.

The total energy demand of a dwelling can be calculated with (1) as mentioned in Chapter3 Methodology to calculate energy consumption.

$$Q_{predicted} = Q_{out} - Q_{in} \qquad [kWh_{th}/day] \qquad (1)$$

Wherein;

$$Q_{out} = Q_{tr\,windows} + Q_{tr\,closed\,parts} + Q_{vent} + Q_{\inf total} \qquad [kWh_{th}\,/day] \qquad (2)$$

$$Q_{in} = Q_{sun} + Q_{int} \qquad [kWh_{th}\,/day] \qquad (3)$$

The outgoing heat flow comprises of the transmission through windows, transmission through closed parts, outgoing heat flow through ventilation, and the outgoing heat flow through infiltration. The incoming heat flow comprises of the incoming solar heat and internal heat load by devices and people. In the following sections, the various components of the model will be further explained.

Outgoing heat flow

Transmission through windows

The transmission through windows can be calculated with (4).

$$Q_{tr\,windows} = \Sigma(q_{tr\,windows} * \Delta T_{zone} * (3600 * 24)/(10^6 * 3{,}6)) \qquad [kWh_{th}\,/day] \qquad (4)$$

With;

$$q_{tr\,windows\,per\,zone} = a * \sum U_{glass} * A_{glass} \qquad [W_{th}/K] \qquad (5)$$

The inside temperature is measured in all rooms of the dwelling. The outside temperature is measured on the north façade ($T_{outside}$). The ΔT is calculated per zone of the dwelling and multiplied with $q_{tr\,windows}$ per zone. The variable 'a' indicates a factor for not intended thermal bridges.

Transmission through closed parts

The transmission through closed parts is calculated with (6).

$$Q_{tr\,closed\,parts} = \sum(q_{tr} * \Delta T_{zone} * (3600 * 24)/(10^6 * 3{,}6)) \qquad [\text{kWh}_{\text{th}}\,/\text{day}] \qquad (6)$$

Wherein;

$$q_{tr\,walls} = \sum A_{walls} * \frac{1}{b * RC_{walls} + \alpha} \qquad [\text{W}_{\text{th}}\,/\text{K}] \qquad (7)$$

$$q_{tr\,floor} = A_{floor} * \frac{1}{c * RC_{floor} + \alpha} \qquad [\text{W}_{\text{th}}\,/\text{K}] \qquad (8)$$

$$q_{tr\,roof} = A_{roof} * \frac{1}{d * RC_{roof} + \alpha} \qquad [\text{W}_{\text{th}}\,/\text{K}] \qquad (9)$$

The heat transfer resistance (α) used in these equations is 0,17. The variables 'b, c and d' indicate factors for not intended thermal bridges.

Outgoing heat flow through ventilation

The outgoing heat flow through ventilation is calculated with (10).

$$Q_{vent} = (e * \sum V_{zone} * \Delta T_{zone} * \eta) * (1{,}2 * 1000 * 24)/(10^6 * 3{,}6) \qquad [\text{kWh}_{\text{th}}\,/\text{day}] \qquad (10)$$

Wherein V stands for the volumetric flow in m^3/h and η the energy efficiency of the heat recovery from ventilation air. The volumetric flow calculation was based on the transformation tables (used electricity to volumetric flow) as provided by the manufacturer. However, these tables might not have been fully accurate for this specific dwelling. The variable 'e' indicates a factor that can indicate deviations in these tables.

Outgoing heat flow through infiltration

The outgoing heat flow through infiltration is calculated with (11).

$$Q_{inf} = Q_{inf\,wind} + Q_{\inf temp} \qquad [\text{kWh}_{\text{th}}\,/\text{day}] \qquad (11)$$

Infiltration through wind

The outgoing heat flow through infiltration due to pressure differences caused by wind is calculated with (12).

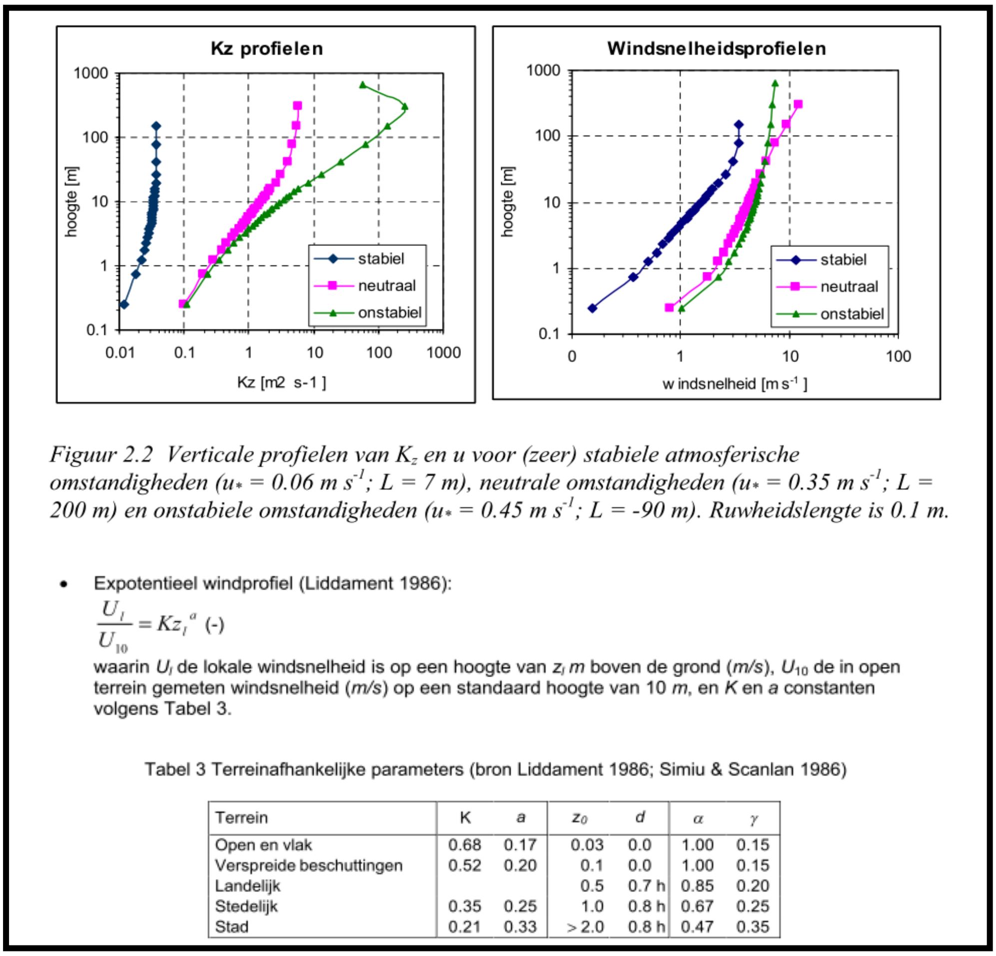
$$Q_{\inf wind} = f * c * \Delta\rho_{wind}^{\;2/3} * 1{,}2 * 1000 * 24 * \Delta T_{average}/(10^6 * 3{,}6) \qquad [\text{kWh}_{\text{th}}\,/\text{day}] \qquad (12)$$

With;

$$\Delta\rho_{wind} = 0{,}5 * 1{,}2 * formfactor * (windspeed * \frac{U_1}{U_{10}})^2 \qquad [\text{Pa}] \qquad (13)$$

$$\frac{U_1}{U_{10}} = k * z^a \qquad [-] \qquad (14)$$

Where c (m3 / h per Pa) is derived from the qv_{50} measurement, converted to 1 Pa. According to AIVC (Air Infiltration and Ventilation Centre, 2016) 0,5 is an average value for the form factor. The variable ‘f’ indicates a factor that stands for the changes which have been made after the qv_{50} measurement. Furthermore, the wind speed from the nearest KNMI weather station is used; this is measured at 10 meters above ground level. To calculate the representative wind speed at building height in the build environment, equation (14) was used. The parameters for this equation are determined on the base of Figure 77.



Figuur 2.2 Verticale profielen van K_z en u voor (zeer) stabiele atmosferische omstandigheden ($u_* = 0.06\ m\ s^{-1}$; $L = 7\ m$), neutrale omstandigheden ($u_* = 0.35\ m\ s^{-1}$; $L = 200\ m$) en onstabiele omstandigheden ($u_* = 0.45\ m\ s^{-1}$; $L = -90\ m$). Ruwheidslengte is 0.1 m.

- Expotentieel windprofiel (Liddament 1986):

$$\frac{U_l}{U_{10}} = Kz_l^{\,a} \ (-)$$

waarin U_l de lokale windsnelheid is op een hoogte van z_l *m* boven de grond (*m/s*), U_{10} de in open terrein gemeten windsnelheid (*m/s*) op een standaard hoogte van 10 *m*, en *K* en *a* constanten volgens Tabel 3.

Tabel 3 Terreinafhankelijke parameters (bron Liddament 1986; Simiu & Scanlan 1986)

Terrein	K	*a*	z_0	*d*	α	γ
Open en vlak	0.68	0.17	0.03	0.0	1.00	0.15
Verspreide beschuttingen	0.52	0.20	0.1	0.0	1.00	0.15
Landelijk			0.5	0.7 h	0.85	0.20
Stedelijk	0.35	0.25	1.0	0.8 h	0.67	0.25
Stad	0.21	0.33	> 2.0	0.8 h	0.47	0.35

Figure 77 Comparison of wind speed profiles (Air Infiltration and Ventilation Centre, 2016)

Infiltration through temperature differences

The outgoing heat flow through infiltration due to pressure differences caused by temperature was calculated with (15).

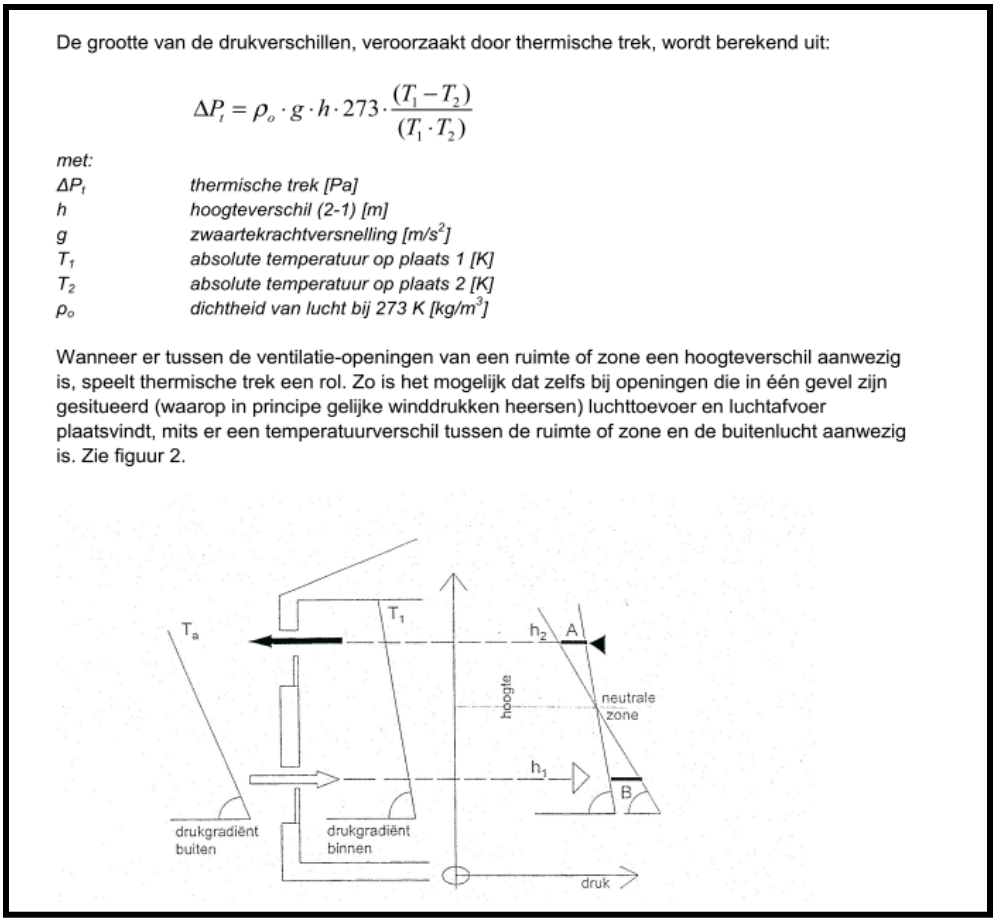
$$Q_{\inf temp} = f * c * \Delta\rho_{temp}{}^{2/3} * 1{,}2 * 1000 * 24 * \Delta T_{average}/(10^6 * 3{,}6) \qquad [\text{kWh}_{\text{th}}/\text{day}] \qquad (15)$$

With;

$$\Delta\rho_{wind} = 1{,}2 * 9{,}8 * z * 273 * \frac{(273+T_{in})-(273+T_{out})}{(273+T_{in})*(273+T_{out})} \qquad [\text{Pa}] \qquad (16)$$

Choosing the c-value was partly arbitrary. At lower heights, the thermal draft played a minor role thus the c-value was not the determining factor. However, pressure differences caused by wind were experienced at all levels. For T_{in} the average measured indoor temperature was used, T_{out} is the measured outdoor temperature.

The source of equation (16) is shown in Figure 78. The same values were used for the variables ‘f’ and ‘z’ as in equation (12).



De grootte van de drukverschillen, veroorzaakt door thermische trek, wordt berekend uit:

$$\Delta P_t = \rho_o \cdot g \cdot h \cdot 273 \cdot \frac{(T_1 - T_2)}{(T_1 \cdot T_2)}$$

met:

ΔP_t	*thermische trek [Pa]*
h	*hoogteverschil (2-1) [m]*
g	*zwaartekrachtversnelling [m/s^2]*
T_1	*absolute temperatuur op plaats 1 [K]*
T_2	*absolute temperatuur op plaats 2 [K]*
ρ_o	*dichtheid van lucht bij 273 K [kg/m^3]*

Wanneer er tussen de ventilatie-openingen van een ruimte of zone een hoogteverschil aanwezig is, speelt thermische trek een rol. Zo is het mogelijk dat zelfs bij openingen die in één gevel zijn gesitueerd (waarop in principe gelijke winddrukken heersen) luchttoevoer en luchtafvoer plaatsvindt, mits er een temperatuurverschil tussen de ruimte of zone en de buitenlucht aanwezig is. Zie figuur 2.

Figure 78 Explanation of pressure differences caused by (Air Infiltration and Ventilation Centre, 2016)

The incoming heat flow

Incoming solar heat

The global radiation measured by the Royal Netherlands Meteorological Institute (KNMI) was used for the calculation of the incoming solar heat. The average global radiation per month was studied over 15 years, see Figure 80.

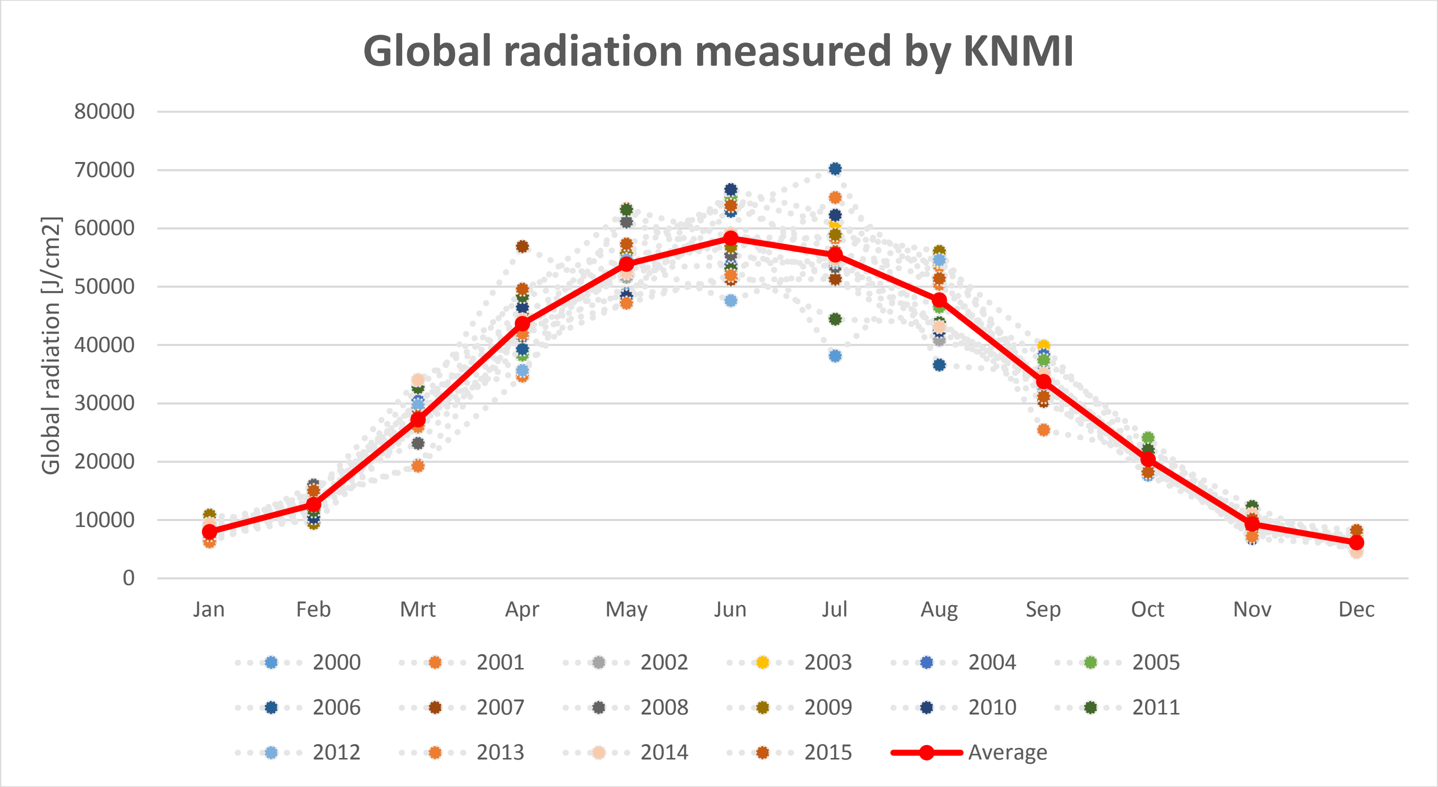


Figure 79 Comparison of the average global radiation over 15 years

As can be seen in Figure 80, the deviation during October till February over a time span of 15 years appeared to be minimal [Std. < 4000 J/cm^2]. Interestingly, these months correspond with the season when heating is turned on. For this period, the average global radiation as calculated over the previous 15 years was applied in the calculation of the incoming solar heat, see Table 14.

Table 14 Average global radiation per month and average hours of daylight per day (KNMI, 2016)

Month	*Average global radiation [J/cm²]*	*Average hours of daylight [p/d]*
January	7993	8
February	12646	10
March	27195	12
April	43628	13.5
May	53835	15.5
June	58301	16.5
July	55438	16.5
August	47714	14.5
September	33697	13
October	20351	11
November	9264	9
December	6135	7.5

Finally, the orientation of the dwelling was equally important. For dwellings that are oriented towards the north or south, the incoming solar heat can be calculated with equation (17). The incoming solar heat for those dwellings that are easterly of westerly oriented can be calculated with equation (18). The factor $\frac{10000}{1000}$ is used to transform $Q_{\text{sun day}}$ from W/cm^2 to kWh/m^2.

$$Q_{sun\ day} = \frac{average\ global\ radiation}{31 \times hours\ of\ daylight \times 3600} \times \frac{10000}{1000} \times A_{windows\_south} \times ZTA \quad [\text{kWh}_{\text{th}}\ /\text{day}] \qquad (17)$$

$$Q_{sun\ day} = \frac{average\ global\ radiation}{31 \times hours\ of\ daylight \times 3600} \times \frac{10000}{1000} \times \sum A_{windows} \times Reduction \times ZTA \ [\text{kWh/day}]\ (18)$$

Wherein the reduction can be derived from Figure 81, for east and west facing windows the reduction is 50%.

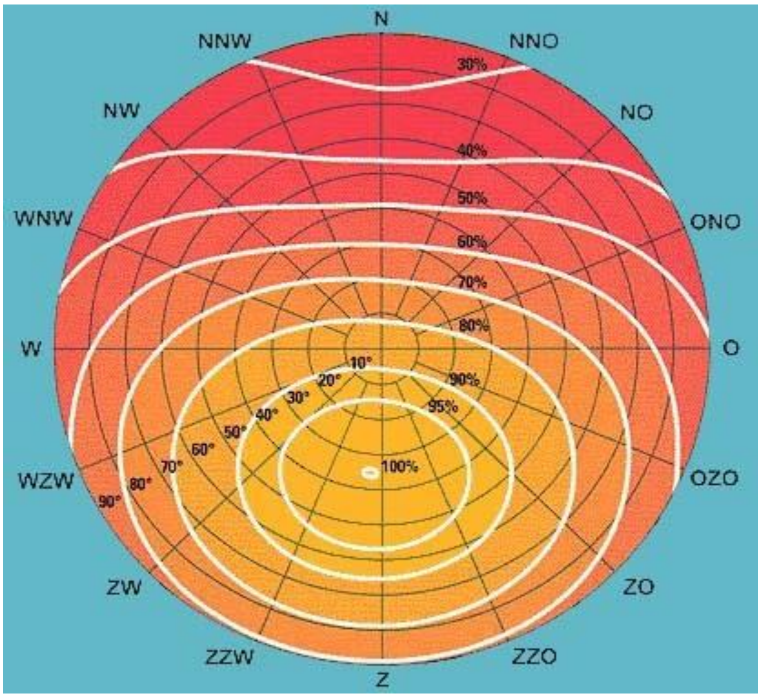


Figure 81 Radiation differences between different orientations (Zonnepanelen (PV) op je eigen dak, 2016)

Internal heat load by devices and people

The internal heat load by devices and people can be calculated with equation (19).

$$Q_{int} = \frac{Total\ electricity\ use\ by\ appliances\ [W/h] \times 0.5 + (number\ of\ occupants \times 80) \times 12}{1000} \text{ [kWh}_{\text{th}}\text{/day] (19)}$$

Occupants produce on average 80 watt per hour per person, in this model is assumed that the occupants are present during the evening and night; corresponding with 12 hours. In this calculation, it is assumed that 50% of the total electricity consumption is converted into effective heat. It is assumed that the other 50% will be produced on placed where no heat is needed, e.g. the bathroom, the attic, the bedrooms, the hallway.

Conclusion

Coming back to the equations (1), (2) and (3), once again repeated below, the total energy demand $Q_{predicted}$ can now be calculated as follows:

$$Q_{predicted} = Q_{out} - Q_{in} \qquad \text{[kWh}_{\text{th}}\text{ /day]} \qquad (1)$$

Wherein;

$$Q_{out} = Q_{tr\ windows} + Q_{tr\ closed\ parts} + Q_{vent} + Q_{\inf total} \qquad \text{[kWh}_{\text{th}}\text{ /day]} \qquad (2)$$

$$Q_{in} = Q_{sun} + Q_{int} \qquad \text{[kWh}_{\text{th}}\text{ /day]} \qquad (3)$$

Appendix III

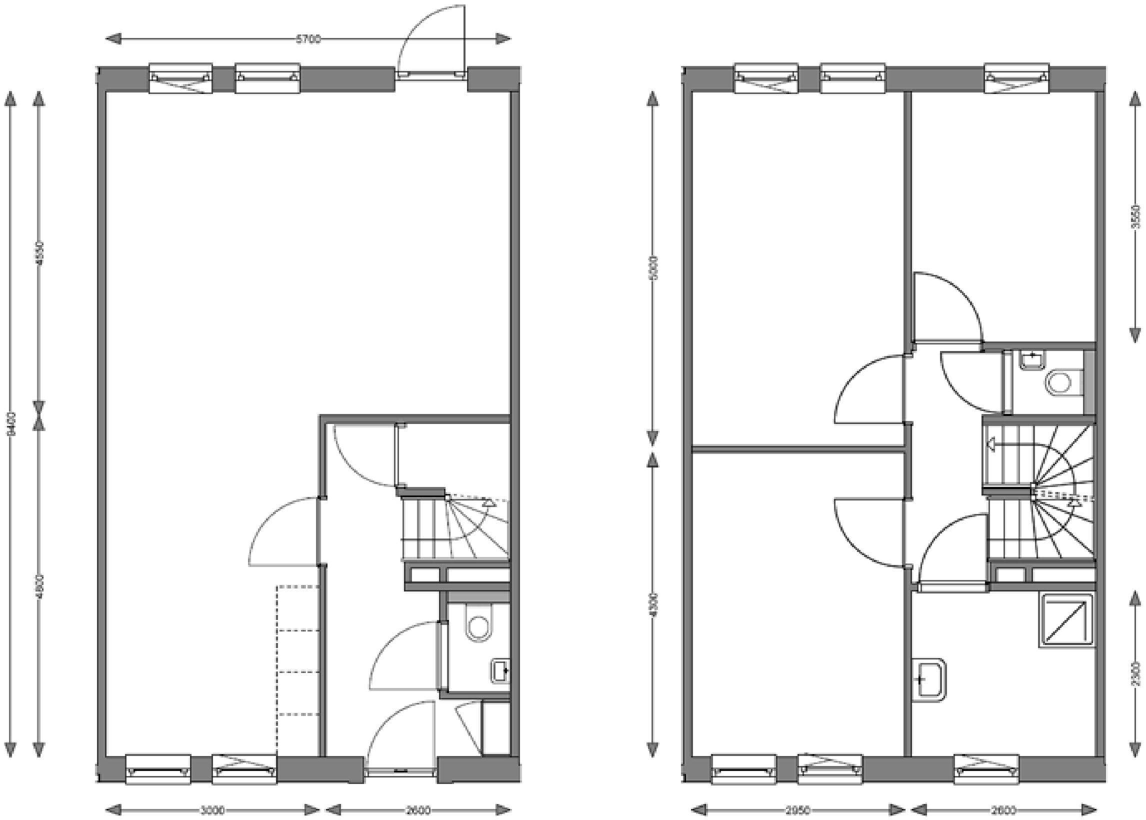


Figure 82 Plan of the measured dwelling

Table 15 Building specifics dwelling in Heerlen

Qv_{10}	1.96 $dm^3/s/m^2$ (minor changes have been made after this measurement)
PV panels	36 m^2 $\eta = 0,14$
Thermal transmittance glass	1.6 $W/(m^2 \cdot K)$ (frames included)
Heat resistance walls	3.5 m^2K/W
Heat resistance floor	2.5 m^2K/W
Heat resistance roof	6.0 m^2K/W
G-value	0.65
Glass A_{total}	16,78 m^2
Walls A_{total}	57.56 m^2
Roof A_{total}	48,24 m^2
Roof angle	45°
Ground floor A_{total}	41.76 m^2
A_{total} dwelling	83.52 m^2
Total volume	173.33 m^3
Orientation	N-Z
Story height	2,3 m
Installations	Air-water heat pump
	Mechanical ventilation (with heat recovery on ground floor)

Appendix IV

Sex: female / male

Age: .... year

Weight: .... , ... kg

Length: .... cm

Do you take any medicine?

○ Yes, namely …………………………………………………..

○ No

Do you have a decease?

○ Yes, namely …………………………………………………..

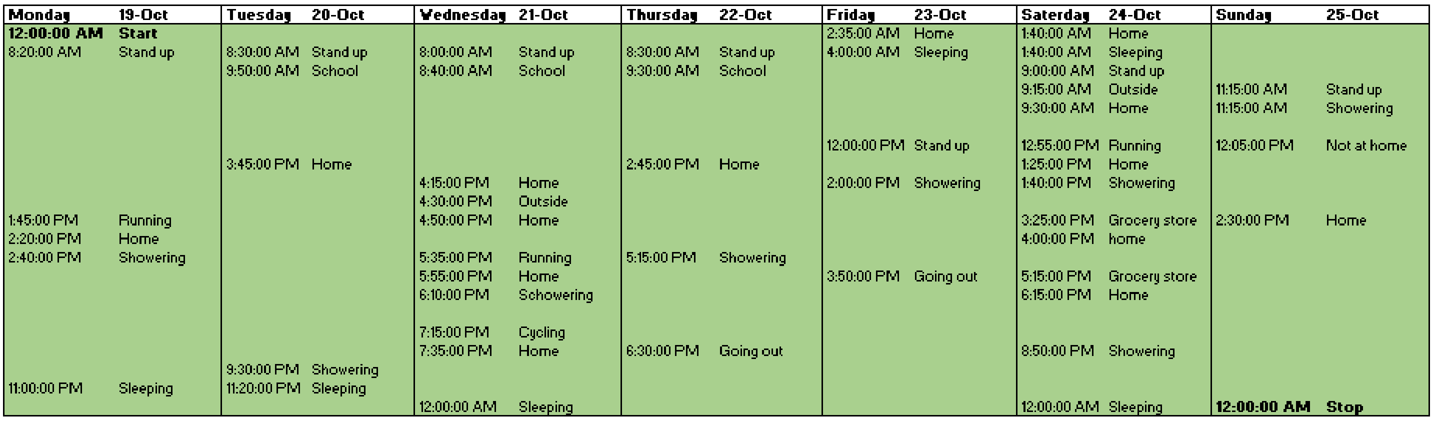
○ No

Do you take any birth control medicine?

○ Yes, namely …………………………………………………..

○ No

Appendix V

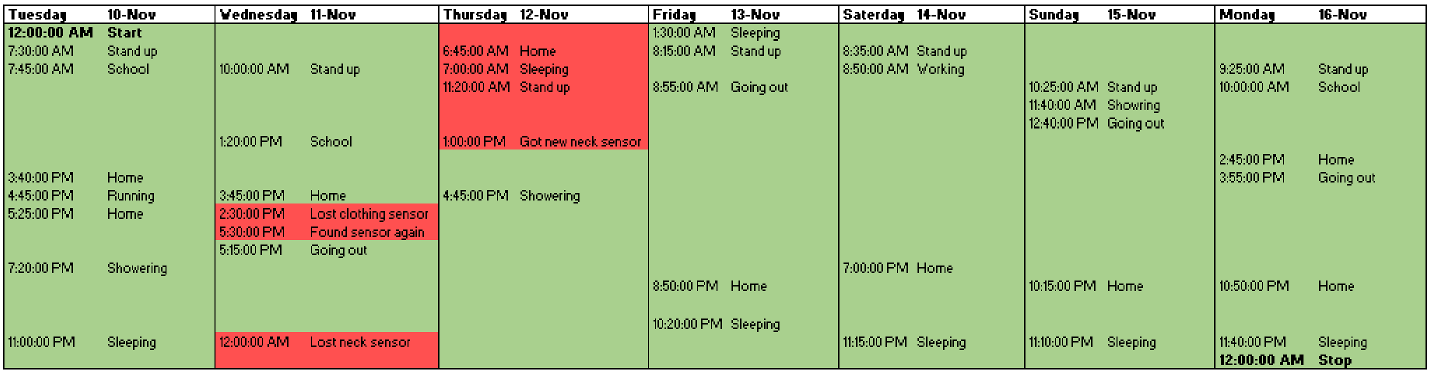


Monday	19-Oct	Tuesday	20-Oct	Vednesday	21-Oct	Thursday	22-Oct	Friday	23-Oct	Saterday	24-Oct	Sunday	25-Oct
12:00:00 AM	**Start**							2:35:00 AM	Home	1:40:00 AM	Home		
8:20:00 AM	Stand up	8:30:00 AM	Stand up	8:00:00 AM	Stand up	8:30:00 AM	Stand up	4:00:00 AM	Sleeping	1:40:00 AM	Sleeping		
		9:50:00 AM	School	8:40:00 AM	School	9:30:00 AM	School			9:00:00 AM	Stand up		
										9:15:00 AM	Outside	11:15:00 AM	Stand up
										9:30:00 AM	Home	11:15:00 AM	Showering
								12:00:00 PM	Stand up	12:55:00 PM	Running	12:05:00 PM	Not at home
		3:45:00 PM	Home			2:45:00 PM	Home			1:25:00 PM	Home		
				4:15:00 PM	Home			2:00:00 PM	Showering	1:40:00 PM	Showering		
				4:30:00 PM	Outside								
1:45:00 PM	Running			4:50:00 PM	Home					3:25:00 PM	Grocery store	2:30:00 PM	Home
2:20:00 PM	Home									4:00:00 PM	home		
2:40:00 PM	Showering			5:35:00 PM	Running	5:15:00 PM	Showering						
				5:55:00 PM	Home			3:50:00 PM	Going out	5:15:00 PM	Grocery store		
				6:10:00 PM	Schowering					6:15:00 PM	Home		
				7:15:00 PM	Cycling								
				7:35:00 PM	Home	6:30:00 PM	Going out			8:50:00 PM	Showering		
		9:30:00 PM	Showering										
11:00:00 PM	Sleeping	11:20:00 PM	Sleeping										
				12:00:00 AM	Sleeping					12:00:00 AM	Sleeping	**12:00:00 AM**	**Stop**

🟩 Sensors worn

Remarks: Sensors worn during showers
Did not worn actiwatch during showers

Figure 83 Week schedule test subject 2 – October 2015



Tuesday	10-Nov	Vednesday	11-Nov	Thursday	12-Nov	Friday	13-Nov	Saterday	14-Nov	Sunday	15-Nov	Monday	16-Nov
12:00:00 AM	**Start**					1:30:00 AM	Sleeping						
7:30:00 AM	Stand up			🟥 6:45:00 AM	Home	8:15:00 AM	Stand up	8:35:00 AM	Stand up				
7:45:00 AM	School	10:00:00 AM	Stand up	🟥 7:00:00 AM	Sleeping			8:50:00 AM	Working			9:25:00 AM	Stand up
				🟥 11:20:00 AM	Stand up	8:55:00 AM	Going out			10:25:00 AM	Stand up	10:00:00 AM	School
										11:40:00 AM	Showring		
										12:40:00 PM	Going out		
		1:20:00 PM	School	🟥 1:00:00 PM	Got new neck sensor								
												2:45:00 PM	Home
3:40:00 PM	Home											3:55:00 PM	Going out
4:45:00 PM	Running	3:45:00 PM	Home	4:45:00 PM	Showering								
5:25:00 PM	Home	🟥 2:30:00 PM	Lost clothing sensor										
		🟥 5:30:00 PM	Found sensor again										
		5:15:00 PM	Going out										
7:20:00 PM	Showering							7:00:00 PM	Home				
						8:50:00 PM	Home			10:15:00 PM	Home	10:50:00 PM	Home
						10:20:00 PM	Sleeping						
11:00:00 PM	Sleeping	🟥 12:00:00 AM	Lost neck sensor					11:15:00 PM	Sleeping	11:10:00 PM	Sleeping	11:40:00 PM	Sleeping
												12:00:00 AM	**Stop**

🟩 Sensors worn
🟥 Sensor(s) not

Remarks Sensors worn during showers
actiwatch not worn during showers

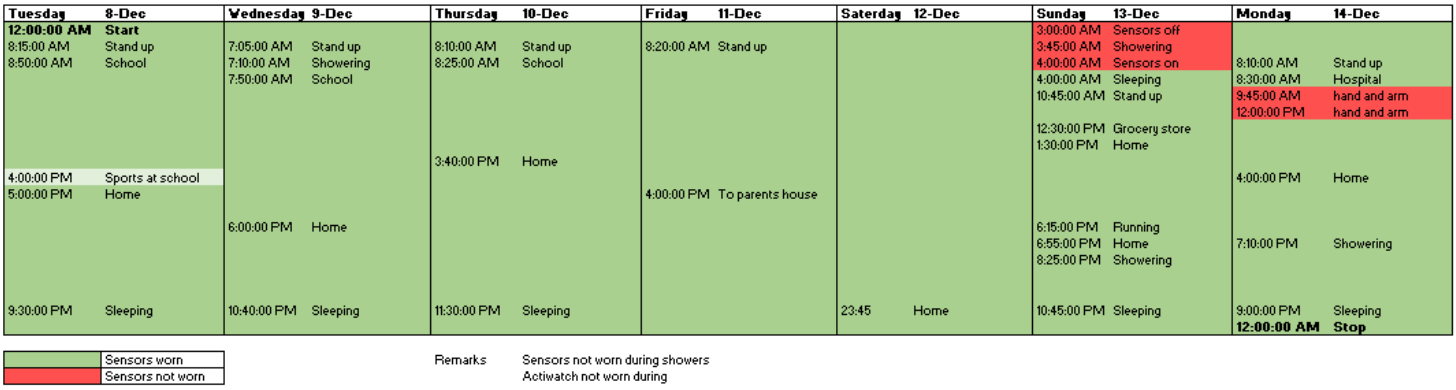
Figure 84 Week schedule test subject 1 – November 2015

Tuesday	10-Nov	Vednesda	11-Nov	Thursday	12-Nov	Friday	13-Nov	Saterday	14-Nov	Sunday	15-Nov	Monday	16-Nov
12:00:00 AM	**Start**			1:45:00 AM	Home	1:30:00 AM	Sleeping						
7:20:00 AM	Stand up	7:45:00 AM	Stand up	2:15:00 AM	Sleeping	8:15:00 AM	Stand up	10:30:00 AM	Stand up	10:30:00 AM	Stand up	9:00:00 AM	Stand up
7:55:00 AM	School	8:15:00 AM	School	8:00:00 AM	Stand up								
				8:25:00 AM	School	8:20:00 AM	Showering			11:55:00 AM	Showering	10:00:00 AM	School
				11:20:00 AM	Home	8:55:00 AM	Not home						
				12:00:00 PM	Sleeping								
								12:40:00 PM	Outside				
		2:45:00 PM	Home					12:50:00 PM	Home				
		3:10:00 PM	Running	3:15:00 PM	Stand up					1:10:00 PM	Going out		
		3:35:00 PM	Home					1:15:00 PM	Showering				
4:50:00 PM	Home			4:00:00 PM	Showering			2:40:00 PM	Grocery store			2:10:00 PM	Home
		4:00:00 PM	Showering					3:40:00 PM	Home			2:55:00 PM	Going out
8:20:00 PM	Showering	5:15:00 PM	Going out										
				6:00:00 PM	Grocery store								
				6:50:00 PM	Home					6:30:00 PM	Home		
						8:55:00 PM	Home						
												10:50:00 PM	Home
11:00:00 PM	Sleeping					11:15:00 PM	Sleeping	11:30:00 PM	Sleeping	11:00:00 PM	Sleeping		
												12:00:00 AM	**Stop**

🟩 Sensors worn

Remarks: Sensors worn during showers
actiwatch not worn during showers

Figure 85 Week schedule test subject 2 – November 2015

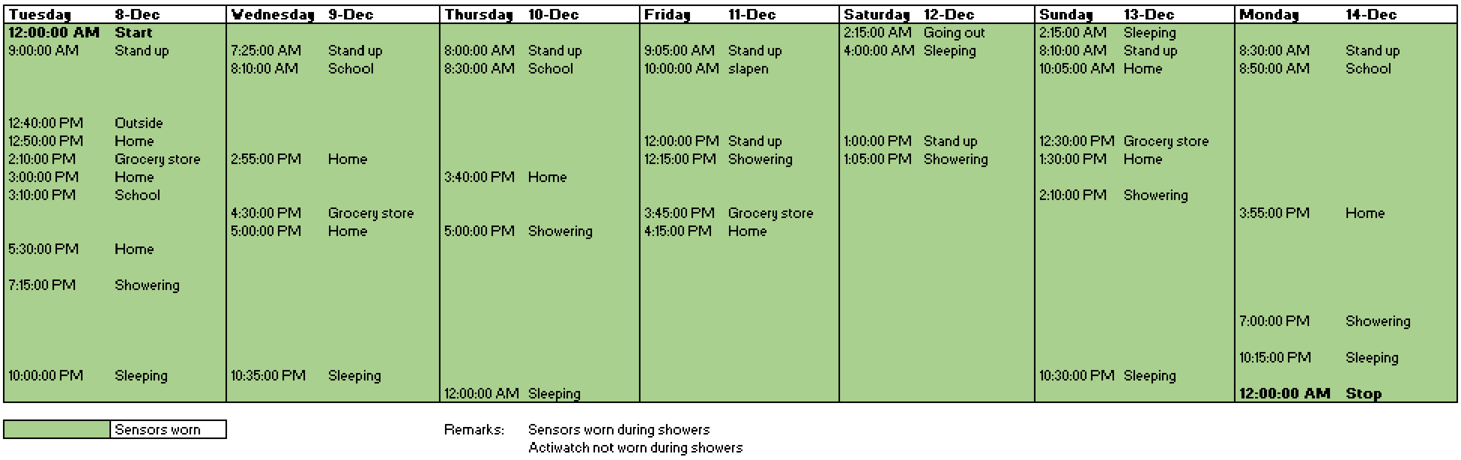


Tuesday	8-Dec	Wednesday	9-Dec	Thursday	10-Dec	Friday	11-Dec	Saterday	12-Dec	Sunday	13-Dec	Monday	14-Dec
12:00:00 AM	**Start**									3:00:00 AM	Sensors off		
8:15:00 AM	Stand up	7:05:00 AM	Stand up	8:10:00 AM	Stand up	8:20:00 AM	Stand up			3:45:00 AM	Showering		
8:50:00 AM	School	7:10:00 AM	Showering	8:25:00 AM	School					4:00:00 AM	Sensors on	8:10:00 AM	Stand up
		7:50:00 AM	School							4:00:00 AM	Sleeping	8:30:00 AM	Hospital
										10:45:00 AM	Stand up	9:45:00 AM	hand and arm
												12:00:00 PM	hand and arm
										12:30:00 PM	Grocery store		
										1:30:00 PM	Home		
				3:40:00 PM	Home								
4:00:00 PM	Sports at school											4:00:00 PM	Home
5:00:00 PM	Home					4:00:00 PM	To parents house						
		6:00:00 PM	Home							6:15:00 PM	Running		
										6:55:00 PM	Home	7:10:00 PM	Showering
										8:25:00 PM	Showering		
9:30:00 PM	Sleeping	10:40:00 PM	Sleeping	11:30:00 PM	Sleeping			23:45	Home	10:45:00 PM	Sleeping	9:00:00 PM	Sleeping
												12:00:00 AM	**Stop**

🟩	Sensors worn
🟥	Sensors not worn

Remarks Sensors not worn during showers
Actiwatch not worn during

Figure 86 Week schedule test subject 1 – December 2015

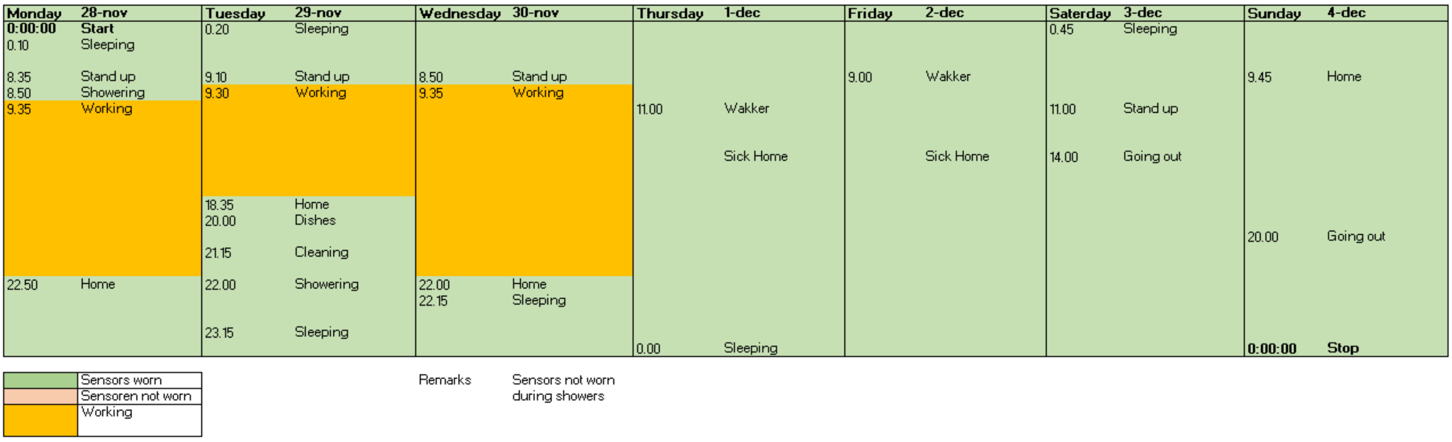


Tuesday	8-Dec	Wednesday	9-Dec	Thursday	10-Dec	Friday	11-Dec	Saturday	12-Dec	Sunday	13-Dec	Monday	14-Dec
12:00:00 AM	**Start**							2:15:00 AM	Going out	2:15:00 AM	Sleeping		
9:00:00 AM	Stand up	7:25:00 AM	Stand up	8:00:00 AM	Stand up	9:05:00 AM	Stand up	4:00:00 AM	Sleeping	8:10:00 AM	Stand up	8:30:00 AM	Stand up
		8:10:00 AM	School	8:30:00 AM	School	10:00:00 AM	slapen			10:05:00 AM	Home	8:50:00 AM	School
12:40:00 PM	Outside												
12:50:00 PM	Home					12:00:00 PM	Stand up	1:00:00 PM	Stand up	12:30:00 PM	Grocery store		
2:10:00 PM	Grocery store	2:55:00 PM	Home			12:15:00 PM	Showering	1:05:00 PM	Showering	1:30:00 PM	Home		
3:00:00 PM	Home			3:40:00 PM	Home								
3:10:00 PM	School									2:10:00 PM	Showering		
		4:30:00 PM	Grocery store			3:45:00 PM	Grocery store					3:55:00 PM	Home
		5:00:00 PM	Home	5:00:00 PM	Showering	4:15:00 PM	Home						
5:30:00 PM	Home												
7:15:00 PM	Showering												
												7:00:00 PM	Showering
												10:15:00 PM	Sleeping
10:00:00 PM	Sleeping	10:35:00 PM	Sleeping							10:30:00 PM	Sleeping		
				12:00:00 AM	Sleeping							**12:00:00 AM**	**Stop**

🟩	Sensors worn

Remarks: Sensors worn during showers
Actiwatch not worn during showers

Figure 88 Week schedule test subject 2 – December 2015

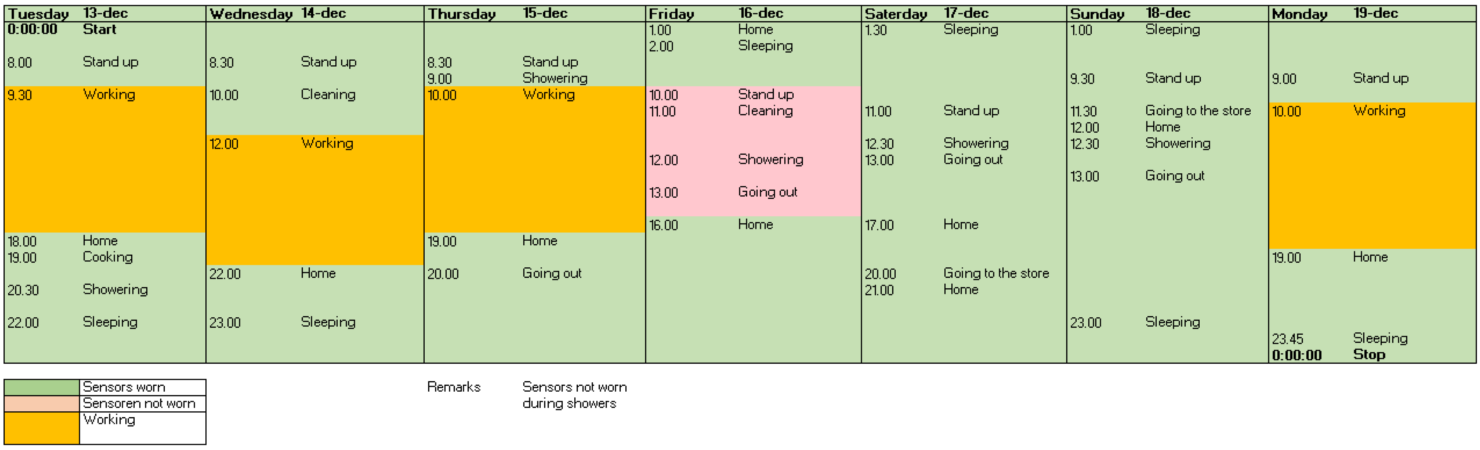


Monday	28-nov	Tuesday	29-nov	Wednesday	30-nov	Thursday	1-dec	Friday	2-dec	Saterday	3-dec	Sunday	4-dec
0:00:00	**Start**	0.20	Sleeping							0.45	Sleeping		
0.10	Sleeping												
8.35	Stand up	9.10	Stand up	8.50	Stand up			9.00	Wakker			9.45	Home
8.50	Showering	9.30	Working	9.35	Working								
9.35	Working					11.00	Wakker			11.00	Stand up		
							Sick Home		Sick Home	14.00	Going out		
		18.35	Home										
		20.00	Dishes										
												20.00	Going out
		21.15	Cleaning										
22.50	Home	22.00	Showering	22.00	Home								
				22.15	Sleeping								
		23.15	Sleeping										
						0.00	Sleeping					**0:00:00**	**Stop**

🟩	Sensors worn
▨	Sensoren not worn
🟧	Working

Remarks Sensors not worn
during showers

Figure 87 Week schedule test subject 3 – November 2016

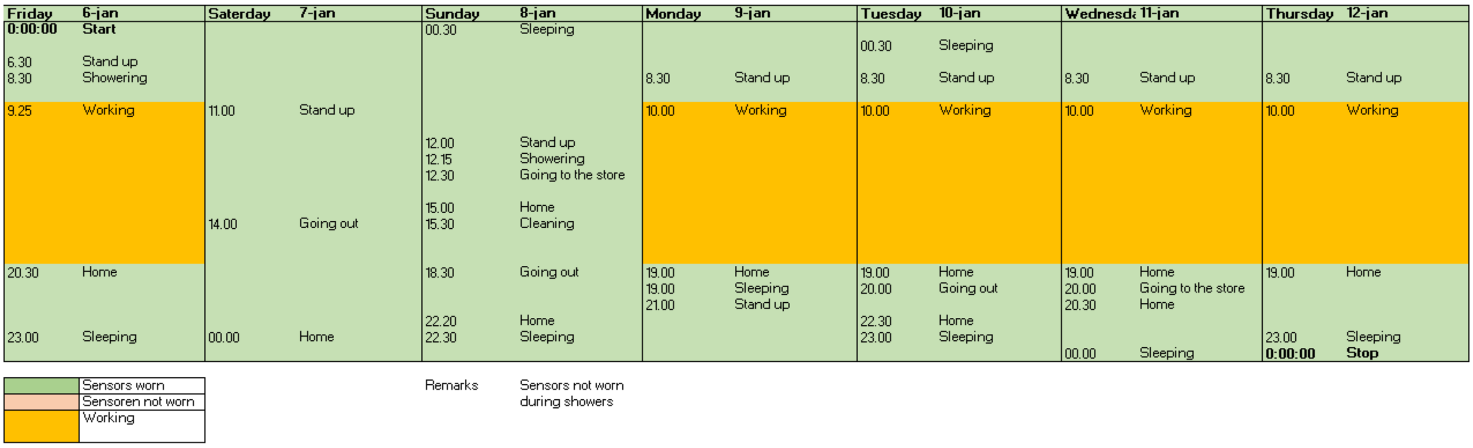


Tuesday	13-dec	Wednesday	14-dec	Thursday	15-dec	Friday	16-dec	Saterday	17-dec	Sunday	18-dec	Monday	19-dec
0:00:00	**Start**					1.00	Home	1.30	Sleeping	1.00	Sleeping		
						2.00	Sleeping						
8.00	Stand up	8.30	Stand up	8.30	Stand up								
				9.00	Showering					9.30	Stand up	9.00	Stand up
9.30	Working	10.00	Cleaning	10.00	Working	10.00	Stand up						
						11.00	Cleaning	11.00	Stand up	11.30	Going to the store	10.00	Working
										12.00	Home		
		12.00	Working					12.30	Showering	12.30	Showering		
						12.00	Showering	13.00	Going out				
										13.00	Going out		
						13.00	Going out						
						16.00	Home	17.00	Home				
18.00	Home			19.00	Home								
19.00	Cooking											19.00	Home
		22.00	Home	20.00	Going out			20.00	Going to the store				
20.30	Showering							21.00	Home				
22.00	Sleeping	23.00	Sleeping							23.00	Sleeping		
												23.45	Sleeping
												0:00:00	**Stop**

🟩 Sensors worn
🟥 Sensoren not worn
🟧 Working

Remarks Sensors not worn during showers

Figure 91 Week schedule test subject 3 – December 2016

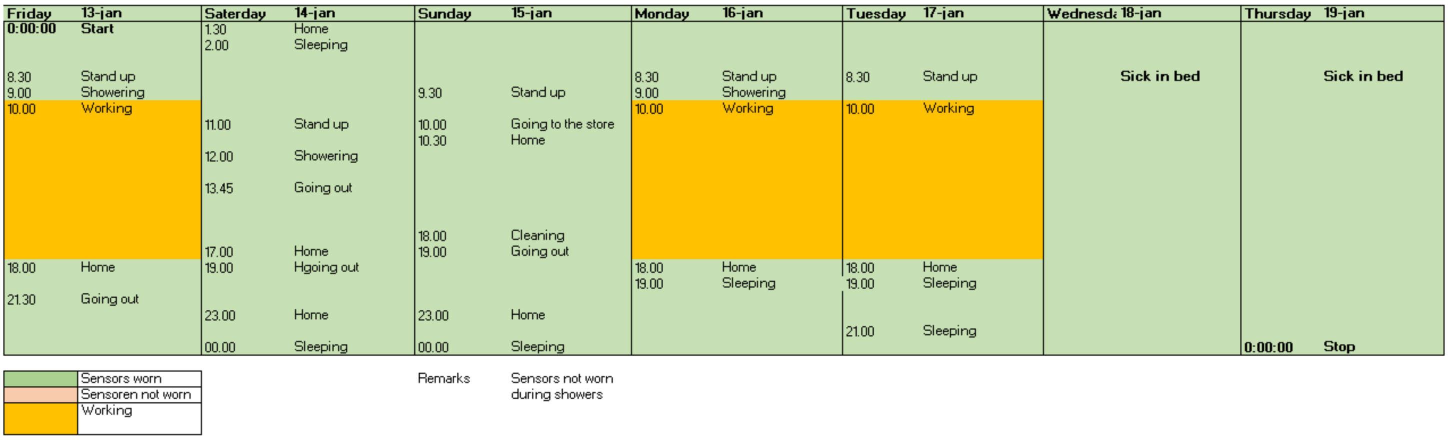


Friday	6-jan	Saterday	7-jan	Sunday	8-jan	Monday	9-jan	Tuesday	10-jan	Wednesd	11-jan	Thursday	12-jan
0:00:00	**Start**			00.30	Sleeping								
								00.30	Sleeping				
6.30	Stand up												
8.30	Showering					8.30	Stand up	8.30	Stand up	8.30	Stand up	8.30	Stand up
9.25	Working	11.00	Stand up			10.00	Working	10.00	Working	10.00	Working	10.00	Working
				12.00	Stand up								
				12.15	Showering								
				12.30	Going to the store								
				15.00	Home								
		14.00	Going out	15.30	Cleaning								
20.30	Home			18.30	Going out	19.00	Home	19.00	Home	19.00	Home	19.00	Home
						19.00	Sleeping	20.00	Going out	20.00	Going to the store		
						21.00	Stand up			20.30	Home		
				22.20	Home			22.30	Home				
23.00	Sleeping	00.00	Home	22.30	Sleeping			23.00	Sleeping			23.00	Sleeping
										00.00	Sleeping	**0:00:00**	**Stop**

🟩 Sensors worn
🟥 Sensoren not worn
🟧 Working

Remarks Sensors not worn during showers

Figure 90 Week schedule test subject 3 – January 2017

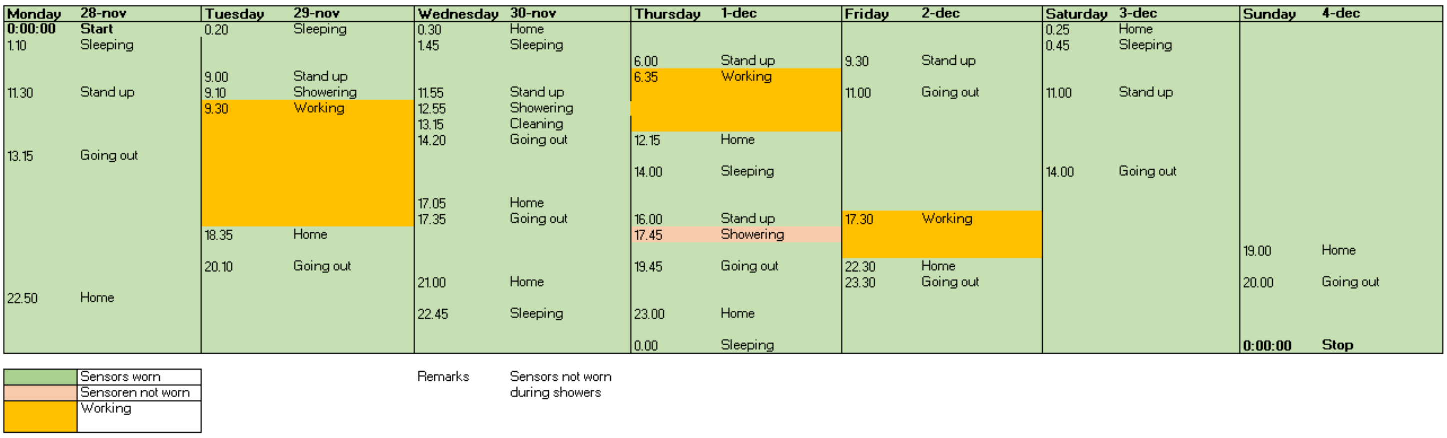


Friday	13-jan	Saterday	14-jan	Sunday	15-jan	Monday	16-jan	Tuesday	17-jan	Wednesd	18-jan	Thursday	19-jan
0:00:00	**Start**	1.30	Home										
		2.00	Sleeping										
8.30	Stand up					8.30	Stand up	8.30	Stand up		**Sick in bed**		**Sick in bed**
9.00	Showering			9.30	Stand up	9.00	Showering						
10.00	Working					10.00	Working	10.00	Working				
		11.00	Stand up	10.00	Going to the store								
				10.30	Home								
		12.00	Showering										
		13.45	Going out										
				18.00	Cleaning								
		17.00	Home	19.00	Going out								
18.00	Home	19.00	Hgoing out			18.00	Home	18.00	Home				
						19.00	Sleeping	19.00	Sleeping				
21.30	Going out												
		23.00	Home	23.00	Home								
								21.00	Sleeping				
		00.00	Sleeping	00.00	Sleeping							**0:00:00**	**Stop**

🟩 Sensors worn
🟥 Sensoren not worn
🟧 Working

Remarks Sensors not worn during showers

Figure 89 Week schedule test subject 3 – January 2017

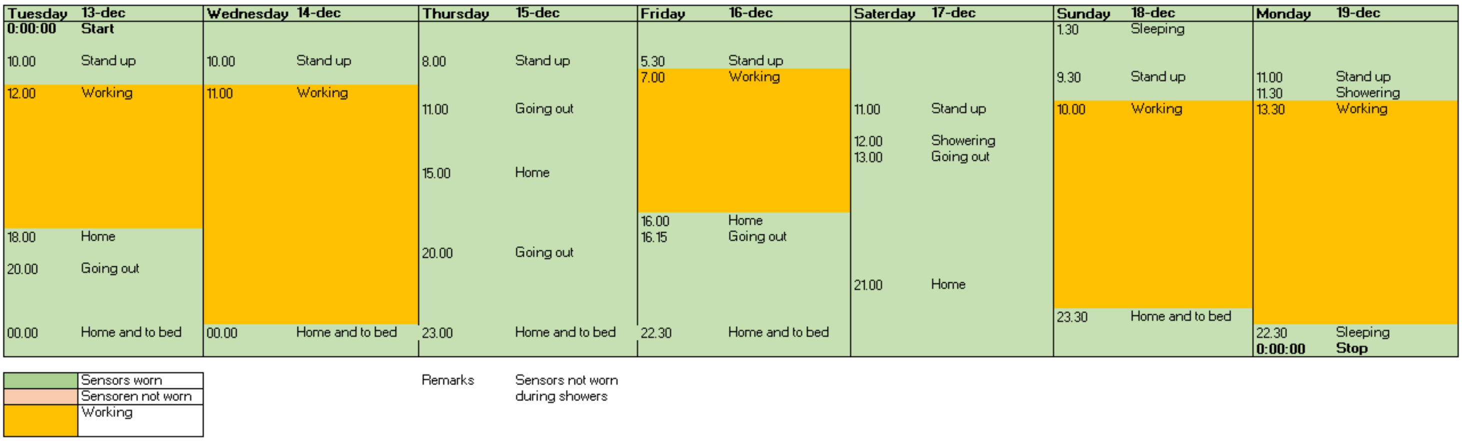


Monday	28-nov	Tuesday	29-nov	Wednesday	30-nov	Thursday	1-dec	Friday	2-dec	Saturday	3-dec	Sunday	4-dec
0:00:00	**Start**	0.20	Sleeping	0.30	Home					0.25	Home		
1.10	Sleeping			1.45	Sleeping					0.45	Sleeping		
						6.00	Stand up	9.30	Stand up				
		9.00	Stand up			6.35	Working						
11.30	Stand up	9.10	Showering	11.55	Stand up			11.00	Going out	11.00	Stand up		
		9.30	Working	12.55	Showering								
				13.15	Cleaning								
				14.20	Going out	12.15	Home						
13.15	Going out												
						14.00	Sleeping			14.00	Going out		
				17.05	Home								
				17.35	Going out	16.00	Stand up	17.30	Working				
		18.35	Home			17.45	Showering						
												19.00	Home
		20.10	Going out			19.45	Going out	22.30	Home				
				21.00	Home			23.30	Going out			20.00	Going out
22.50	Home												
				22.45	Sleeping	23.00	Home						
						0.00	Sleeping					**0:00:00**	**Stop**

🟩	Sensors worn
🟧	Sensoren not worn
🟨	Working

Remarks Sensors not worn during showers

Figure 94 Week schedule test subject 4 – November 2016

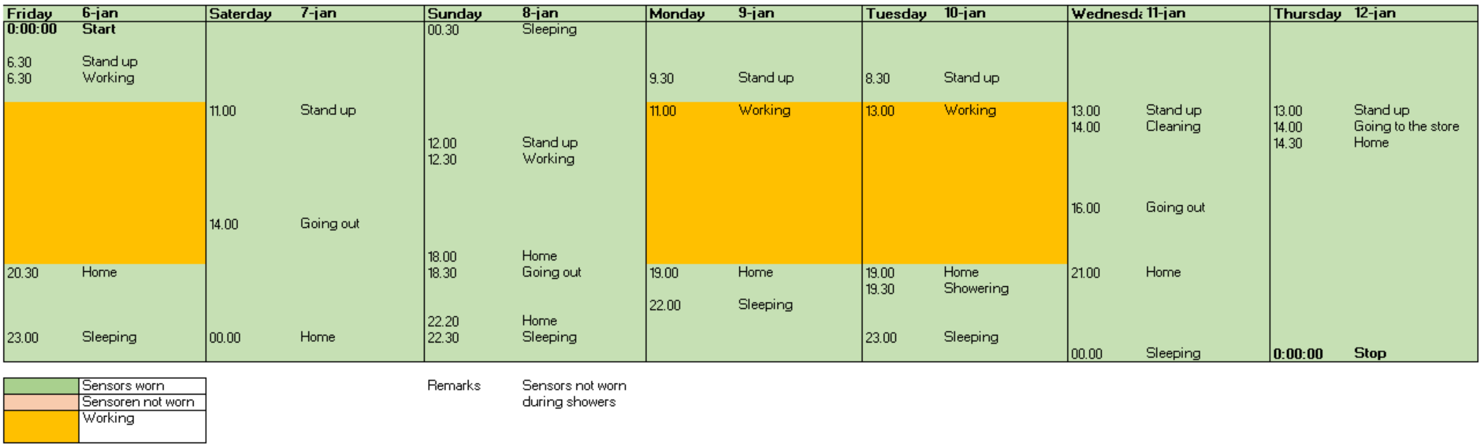


Tuesday	13-dec	Wednesday	14-dec	Thursday	15-dec	Friday	16-dec	Saterday	17-dec	Sunday	18-dec	Monday	19-dec
0:00:00	**Start**									1.30	Sleeping		
10.00	Stand up	10.00	Stand up	8.00	Stand up	5.30	Stand up						
						7.00	Working			9.30	Stand up	11.00	Stand up
12.00	Working	11.00	Working									11.30	Showering
				11.00	Going out			11.00	Stand up	10.00	Working	13.30	Working
								12.00	Showering				
								13.00	Going out				
				15.00	Home								
						16.00	Home						
18.00	Home					16.15	Going out						
				20.00	Going out								
20.00	Going out												
								21.00	Home				
										23.30	Home and to bed		
00.00	Home and to bed	00.00	Home and to bed	23.00	Home and to bed	22.30	Home and to bed					22.30	Sleeping
												0:00:00	**Stop**

🟩	Sensors worn
🟧	Sensoren not worn
🟨	Working

Remarks Sensors not worn during showers

Figure 93 Week schedule test subject 4 – December 2016

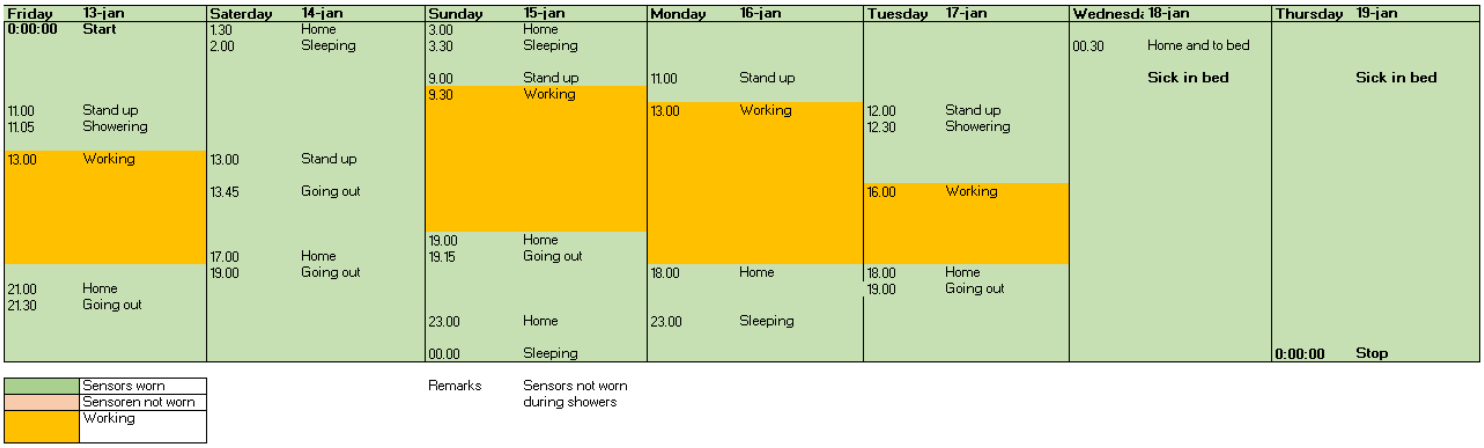


Friday	6-jan	Saterday	7-jan	Sunday	8-jan	Monday	9-jan	Tuesday	10-jan	Wednesd:	11-jan	Thursday	12-jan
0:00:00	**Start**			00.30	Sleeping								
6.30	Stand up												
6.30	Working					9.30	Stand up	8.30	Stand up				
		11.00	Stand up			11.00	Working	13.00	Working	13.00	Stand up	13.00	Stand up
										14.00	Cleaning	14.00	Going to the store
				12.00	Stand up							14.30	Home
				12.30	Working								
										16.00	Going out		
		14.00	Going out										
				18.00	Home								
20.30	Home			18.30	Going out	19.00	Home	19.00	Home	21.00	Home		
								19.30	Showering				
						22.00	Sleeping						
				22.20	Home								
23.00	Sleeping	00.00	Home	22.30	Sleeping			23.00	Sleeping				
										00.00	Sleeping	**0:00:00**	**Stop**

🟩	Sensors worn
🟧	Sensoren not worn
🟨	Working

Remarks Sensors not worn during showers

Figure 92 Week schedule test subject 4 – January 2017



Friday	**13-jan**	**Saterday**	**14-jan**	**Sunday**	**15-jan**	**Monday**	**16-jan**	**Tuesday**	**17-jan**	**Wednesda**	**18-jan**	**Thursday**	**19-jan**
0:00:00	**Start**	1.30	Home	3.00	Home								
		2.00	Sleeping	3.30	Sleeping					00.30	Home and to bed		
				9.00	Stand up	11.00	Stand up				**Sick in bed**		**Sick in bed**
				9.30	Working								
11.00	Stand up					13.00	Working	12.00	Stand up				
11.05	Showering							12.30	Showering				
13.00	Working	13.00	Stand up										
		13.45	Going out					16.00	Working				
				19.00	Home								
		17.00	Home	19.15	Going out								
		19.00	Going out			18.00	Home	18.00	Home				
21.00	Home							19.00	Going out				
21.30	Going out												
				23.00	Home	23.00	Sleeping						
				00.00	Sleeping							**0:00:00**	**Stop**

🟩	Sensors worn
🟧	Sensoren not worn
🟨	Working

Remarks Sensors not worn during showers

Figure 95 Week schedule test subject 4 – January 2017

Appendix VI

11:02

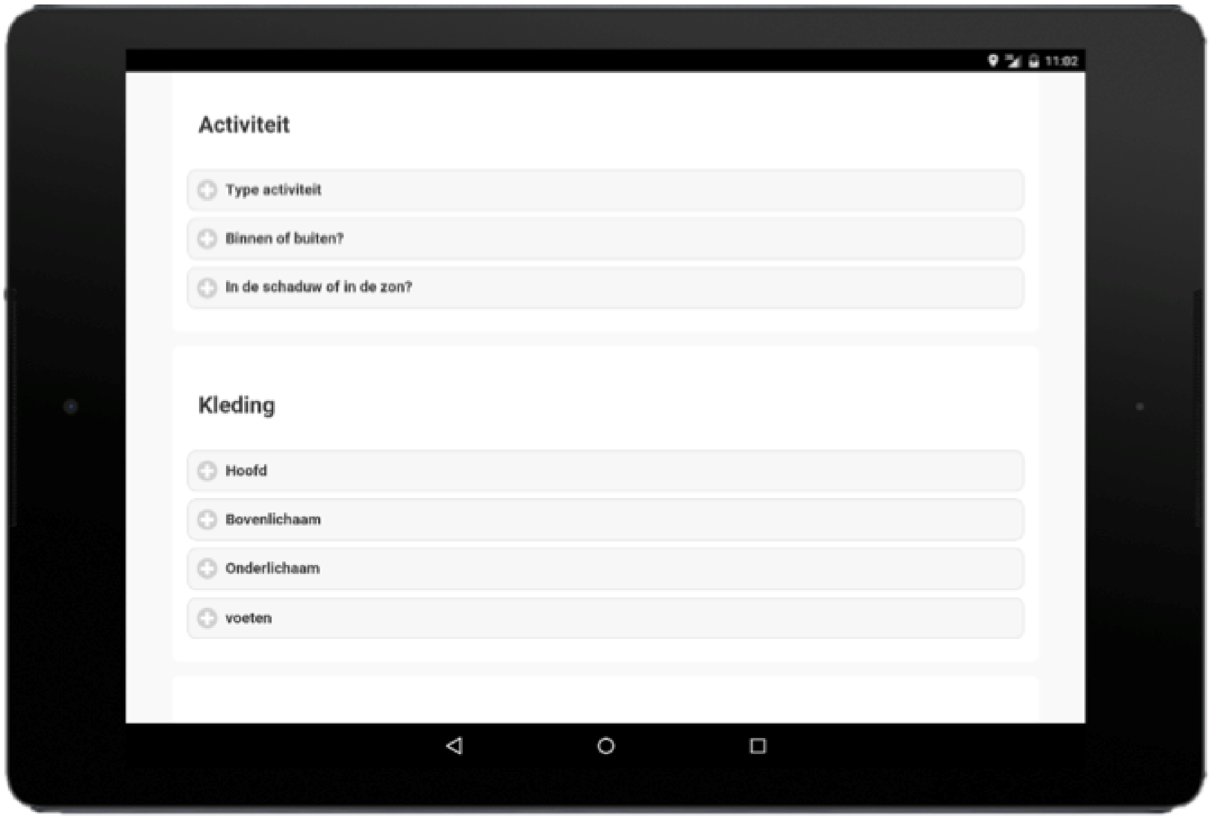
TherMU Questionnaire

weerstation: Maastricht (NL) | 21 °C | Dinsdag 10u

Hoe ervaar je de thermische omgeving?

Is dit comfortabel?

Activiteit



11:02

Activiteit

- Type activiteit
- Binnen of buiten?
- In de schaduw of in de zon?

Kleding

- Hoofd
- Bovenlichaam
- Onderlichaam
- voeten

Appendix VII

Table 16 Clothing with corresponding Clo-value (McCullough, Jones, & Tamura, 1989) (McCullough, Jones, & Huck, 1985)

Clothing		**Clo-value**
Footwear	Nothing	0
	Socks	0.03
	Sandals/ flip-flops	0.03
	Sneakers	0.04
	Normal shoes	0.04
	Higher shoes	0.05
	Walking boots	0.06
	Boots	0.06
Lower body	Nothing	0
	Underwear	0.05
	Shorts	0.12
	Linen trousers	0.21
	Jeans	0.3
	Ribeye trousers	0.4
Upper body (first layer)	Nothing	0
	Shirt (short sleeves)	0.18
	Shirt (long sleeves)	0.33
	Blouse (short sleeves)	0.25
	Blouse (long sleeves)	0.33
	Sweater (thin)	0.28
	Sweater (thick)	0.4
	Dress (no sleeves)	0.34
	Dress (short sleeves)	0.38
	Dress (long sleeves)	0.44
	Dress (thick, long sleeves)	0.59
	Cardigan	0.26
Upper body (second layer)	Nothing	0
	Shirt (short sleeves)	0.18
	Shirt (long sleeves)	0.33
	Blouse (short sleeves)	0.25
	Blouse (long sleeves)	0.33
	Sweater (thin)	0.28
	Sweater (thick)	0.4
	Dress (no sleeves)	0.34
	Dress (short sleeves)	0.38
	Dress (long sleeves)	0.44
	Dress (thick, long sleeves)	0.59
	Cardigan	0.26
Upper body (third layer)	Nothing	0
	Colbert	0.44
	Cardigan	0.26
	Summer coat	0.5
	Wind jacket	0.33
	Rain coat	0.28
	Winter coat	0.63

Appendix IIX

Test subject 2

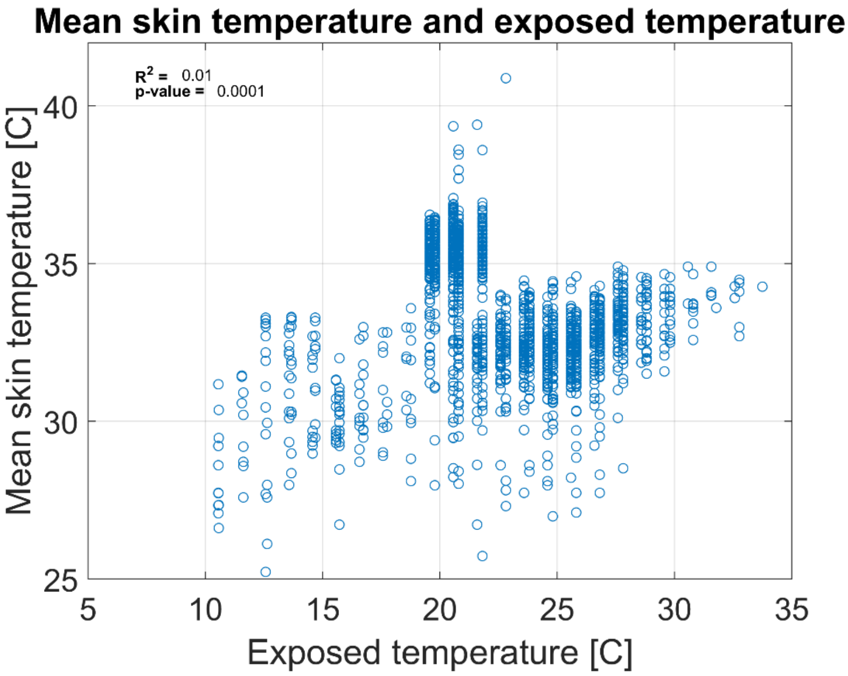


Figure 96 Mean skin temperature and exposed temperature of test subject 2

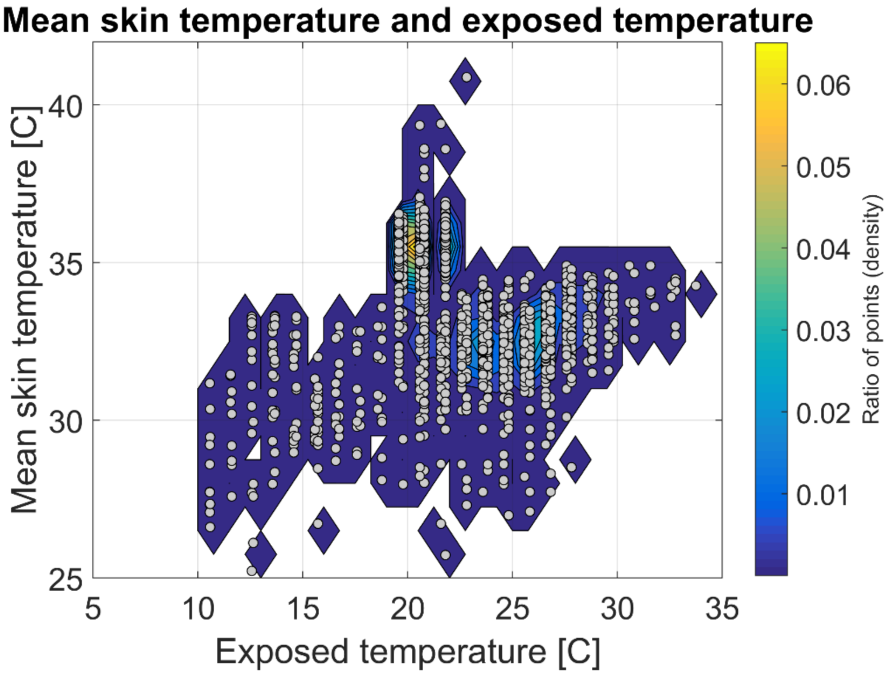


Figure 97 Contour plot of mean skin temperature and exposed temperature data of test subject 2

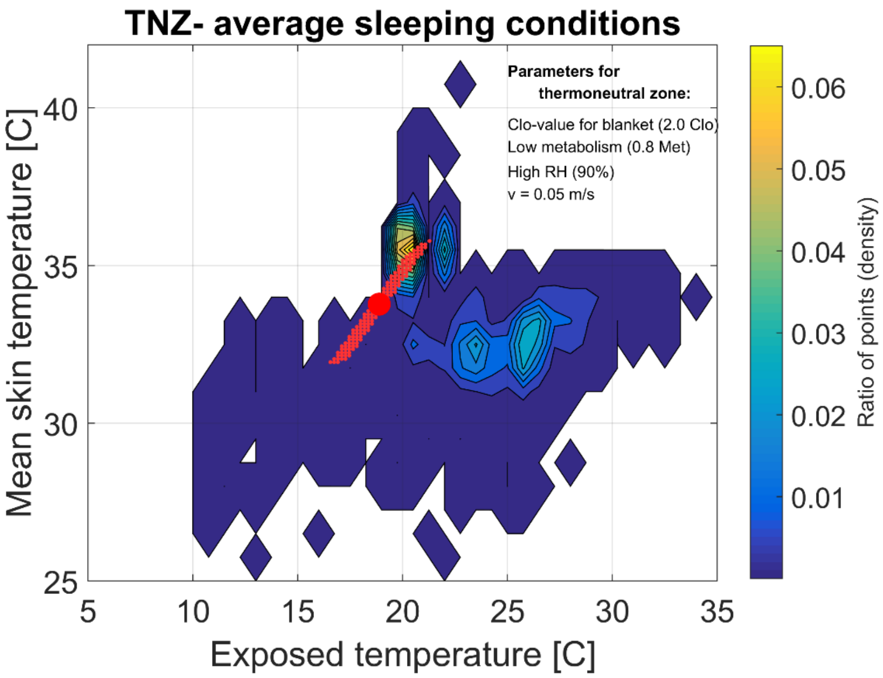


Figure 98 Contour plot of mean skin temperature and exposed temperature data including the thermoneutral zone during the night for test subject 2

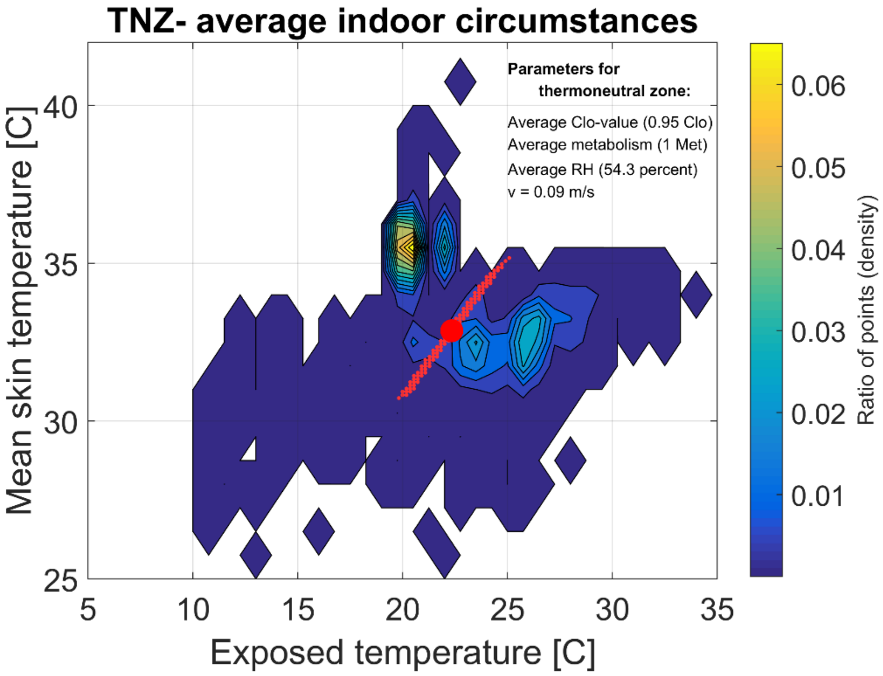


Figure 99 Contour plot of mean skin temperature and exposed temperature data including the thermoneutral zone of test subject 2

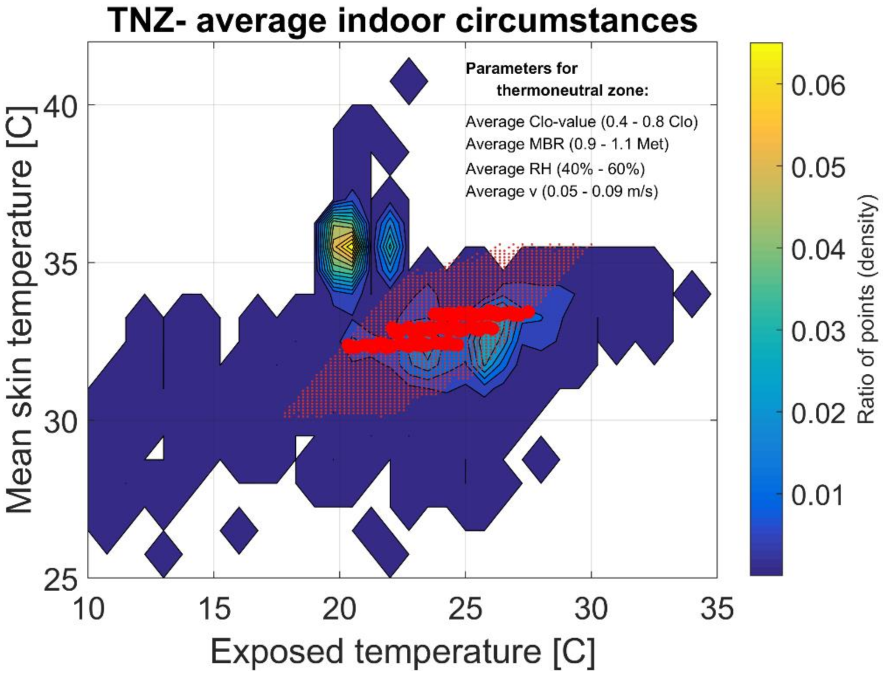


Figure 100 Contour plot of mean skin temperature and exposed temperature data including the dispersion of thermoneutral zones of test subject 2

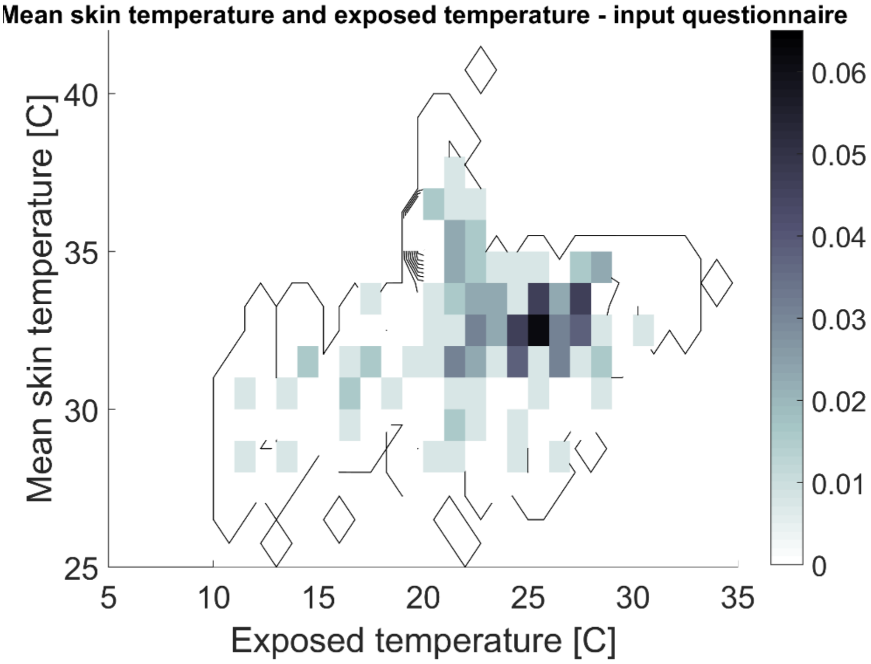


Figure 101 Contour plot of questionnaire entries of test subject 2

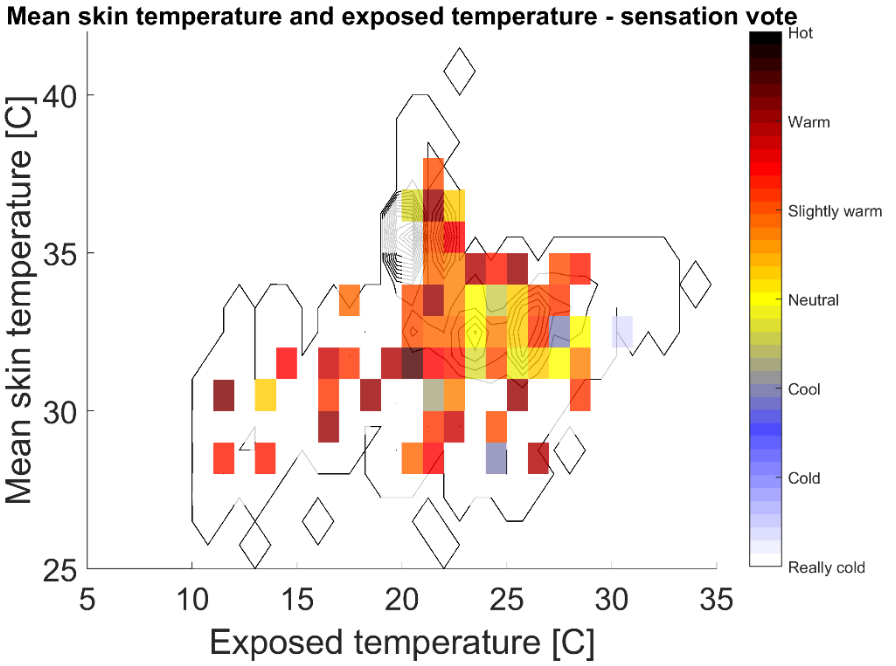


Figure 102 Contour plot of sensation votes of test subject 2

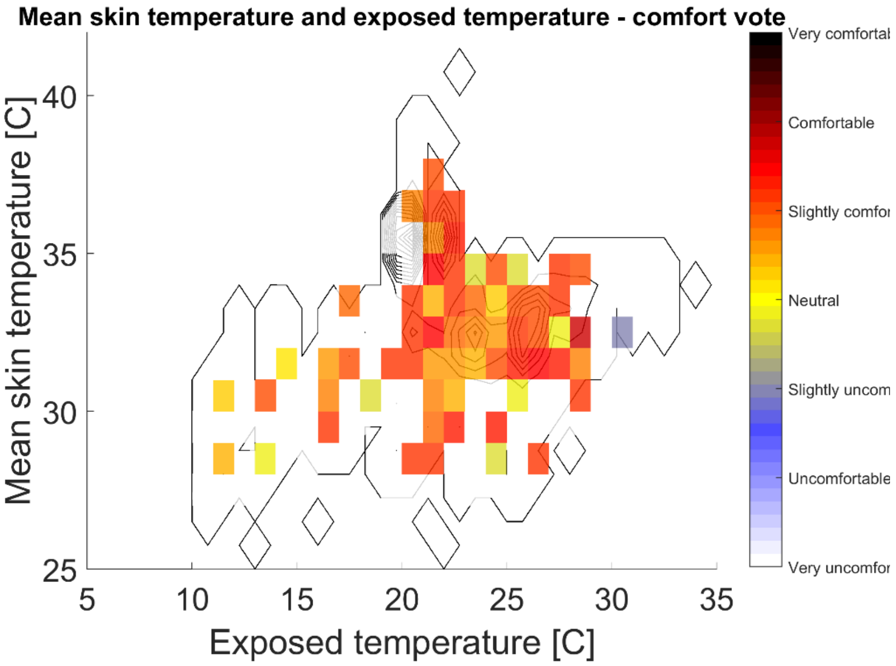


Figure 103 Contour plot of the comfort zones of test subject 2

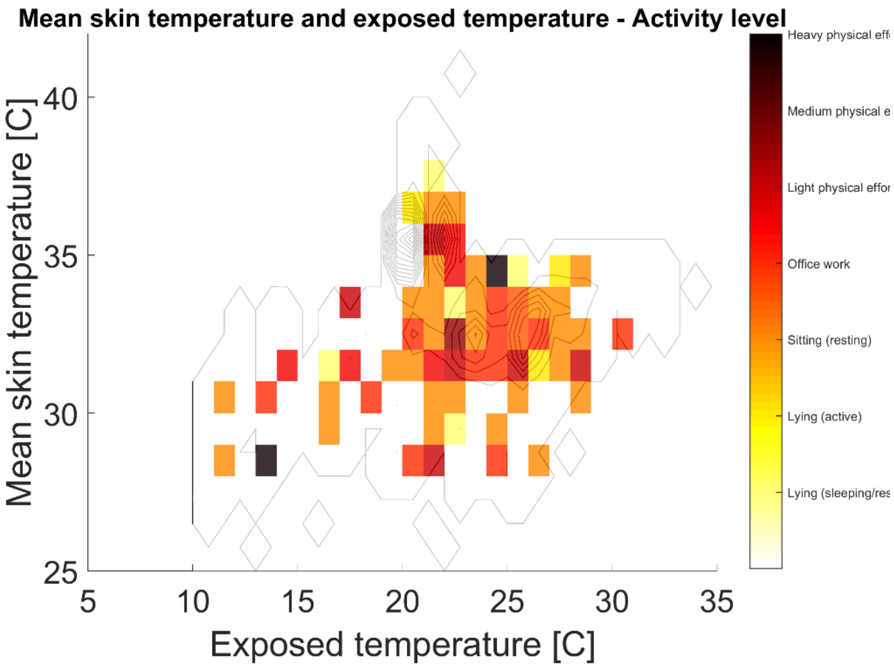


Figure 104 Contour plot of the activity level of test subject 2

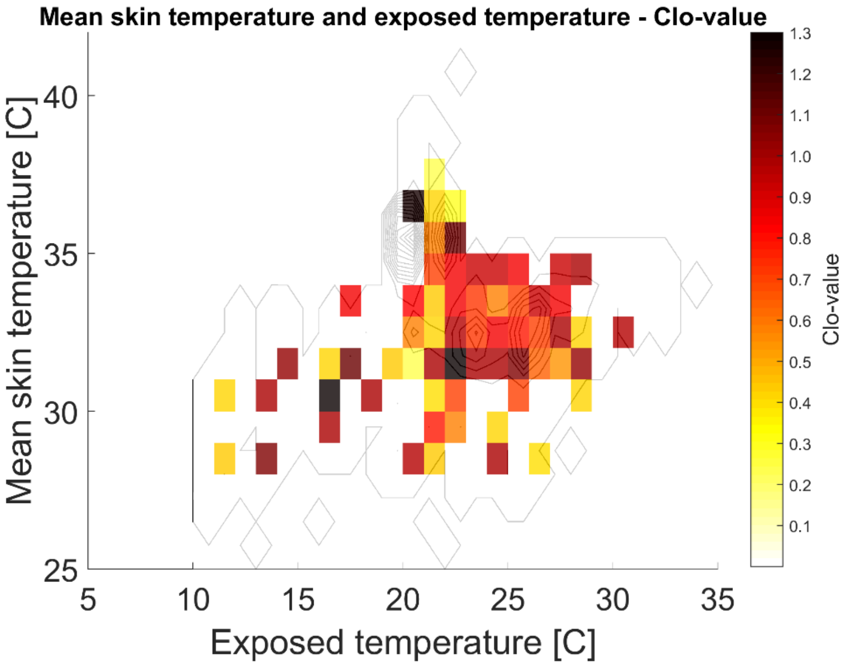


Figure 105 Contour plot of clothing worn by test subject 2

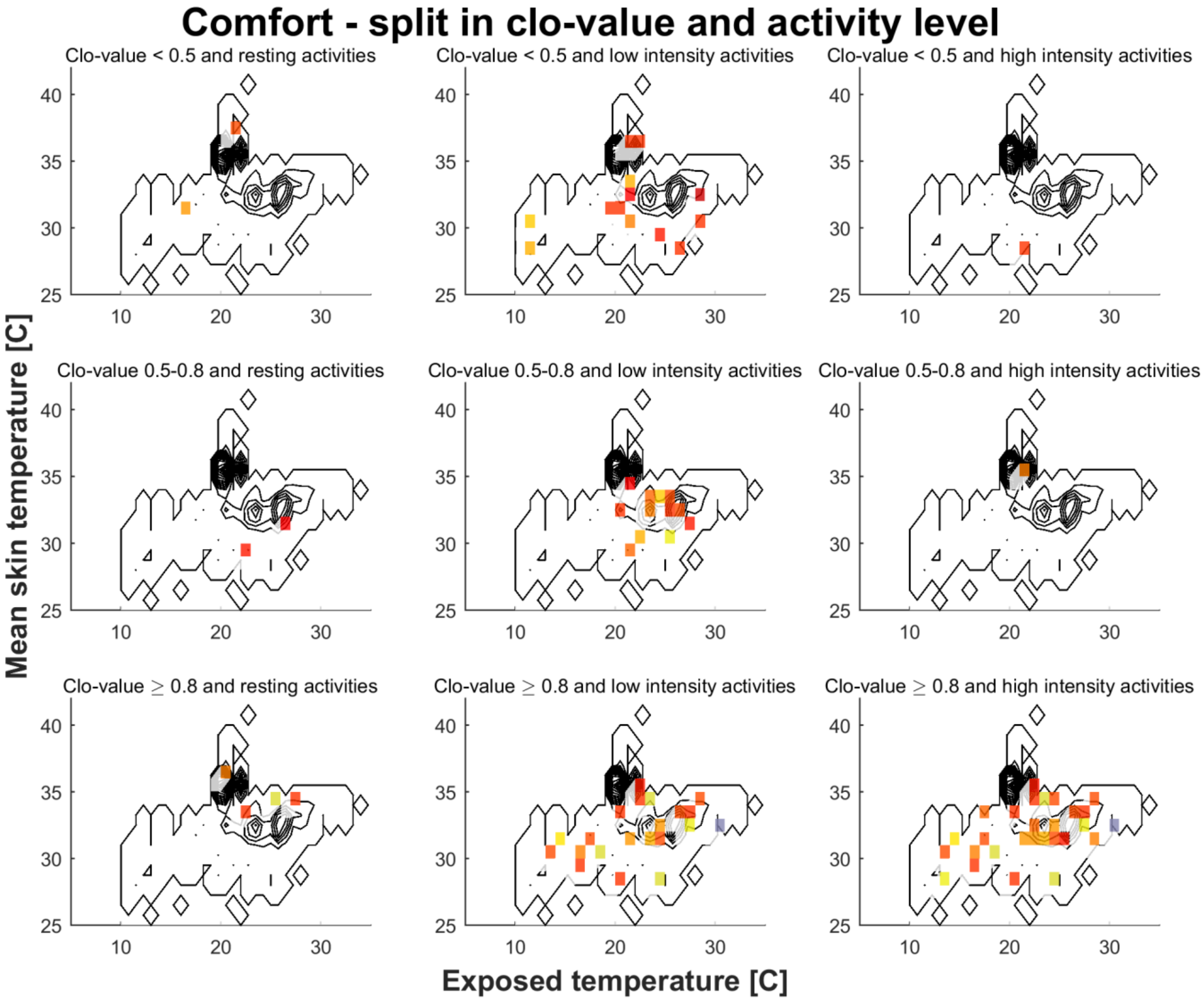


Figure 106 Contour plots of the comfort vote of test subject 2, with boundary conditions for Clo-values and activity levels

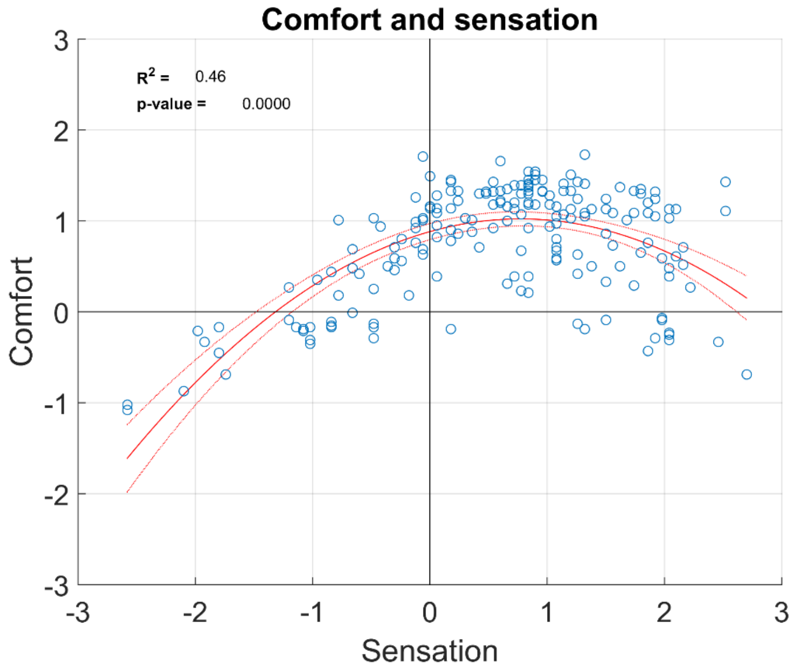


Figure 107 Comfort and sensation vote of test subject 2

Test subject 3

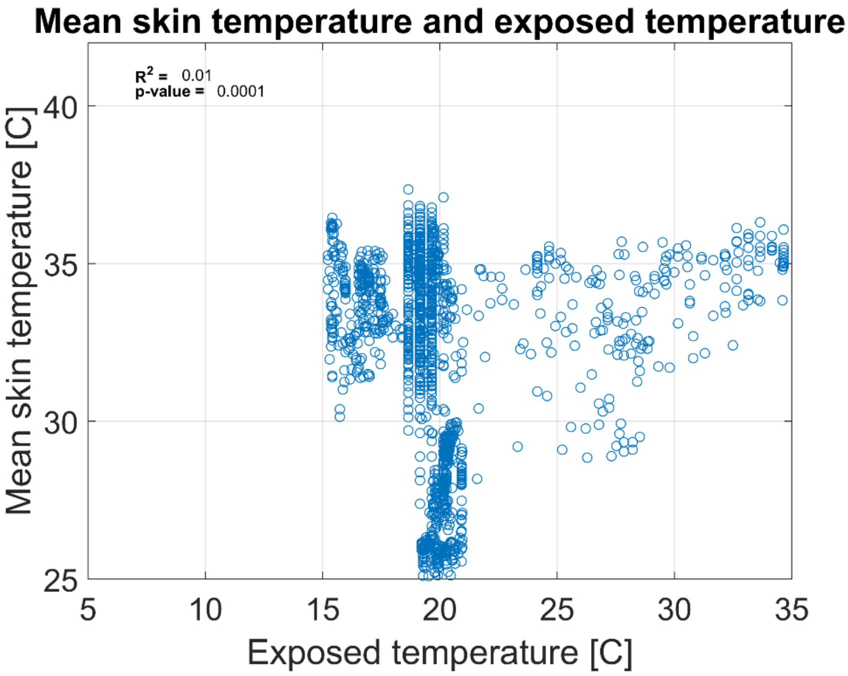


Figure 108 Mean skin temperature and exposed temperature of test subject 3

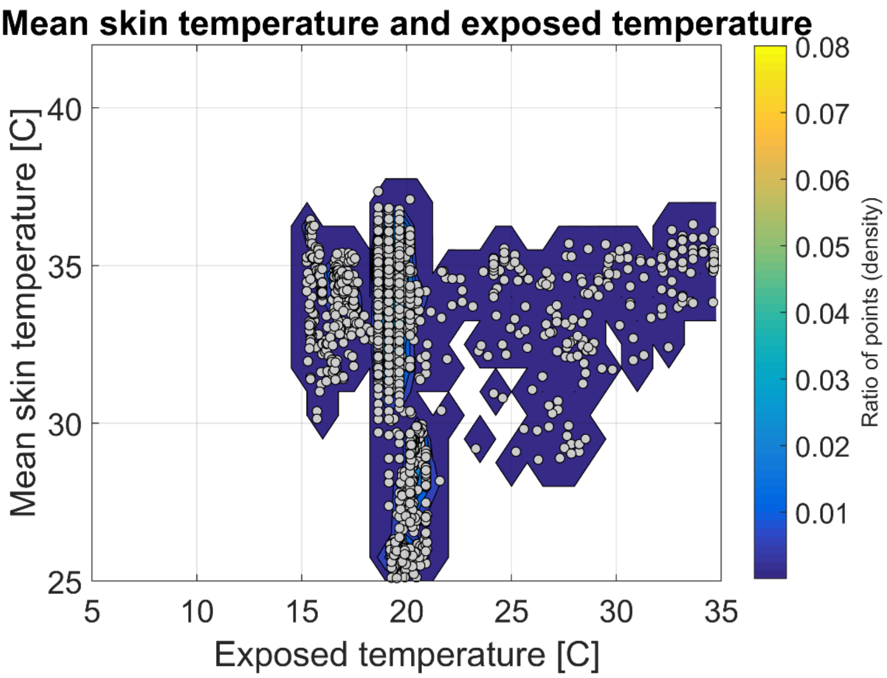


Figure 109 Contour plot of mean skin temperature and exposed temperature data of test subject 3

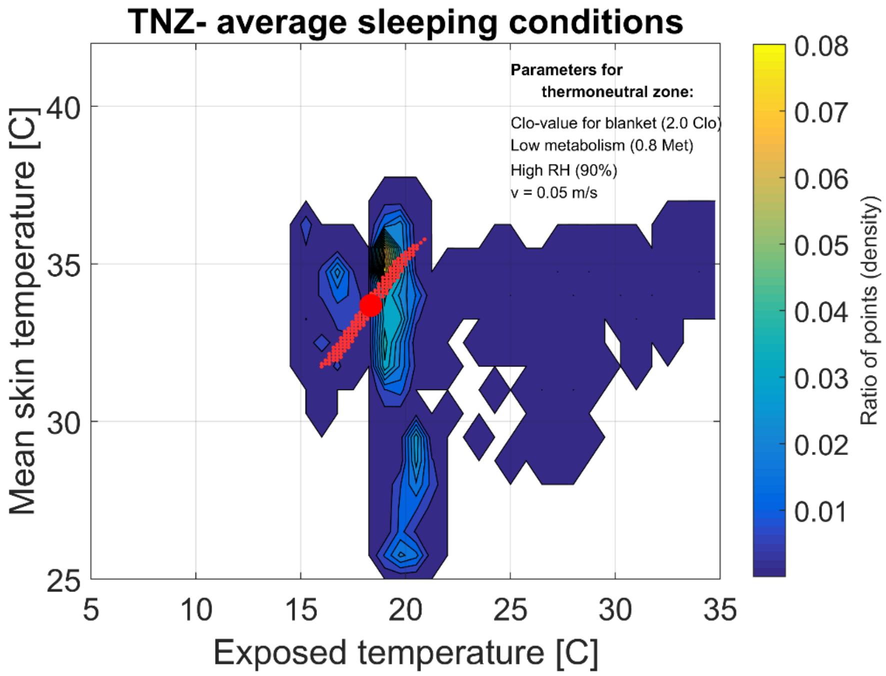


Figure 110 Contour plot of mean skin temperature and exposed temperature data including the thermoneutral zone during the night for test subject 3

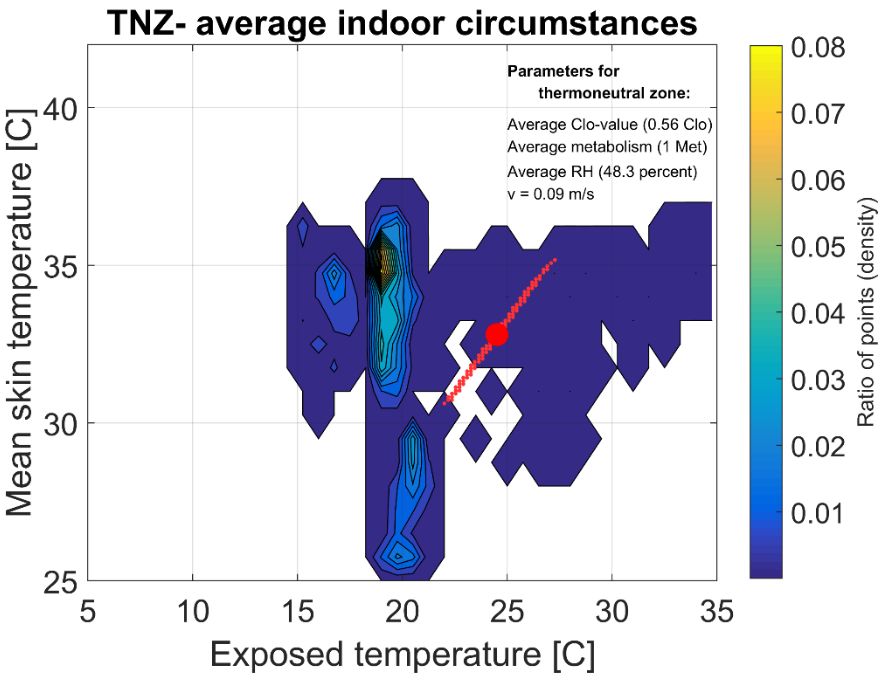


Figure 111 Contour plot of mean skin temperature and exposed temperature data including the thermoneutral zone of test subject 3

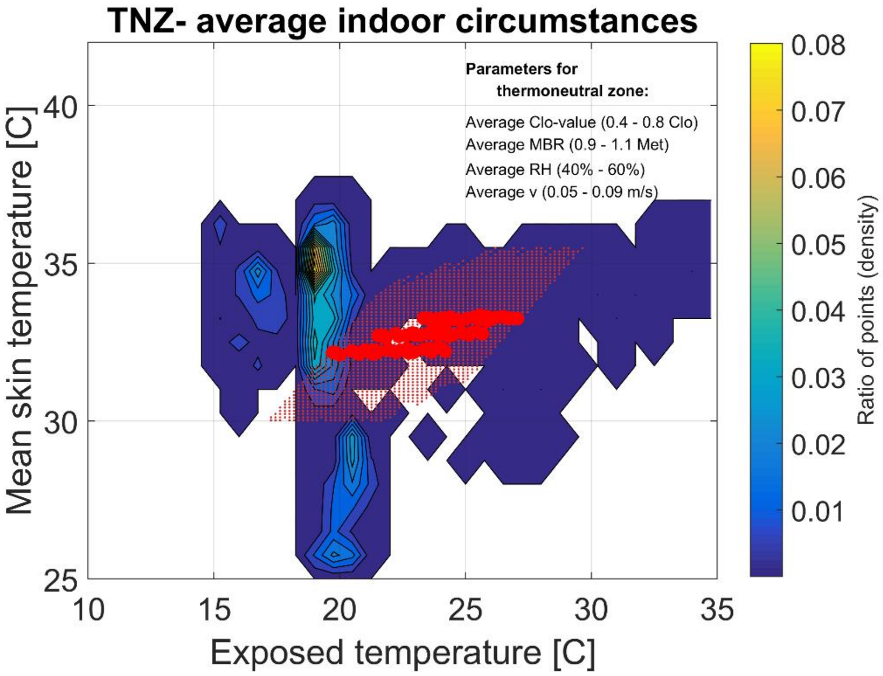


Figure 112 Contour plot of mean skin temperature and exposed temperature data including the dispersion of thermoneutral zones of test subject 3

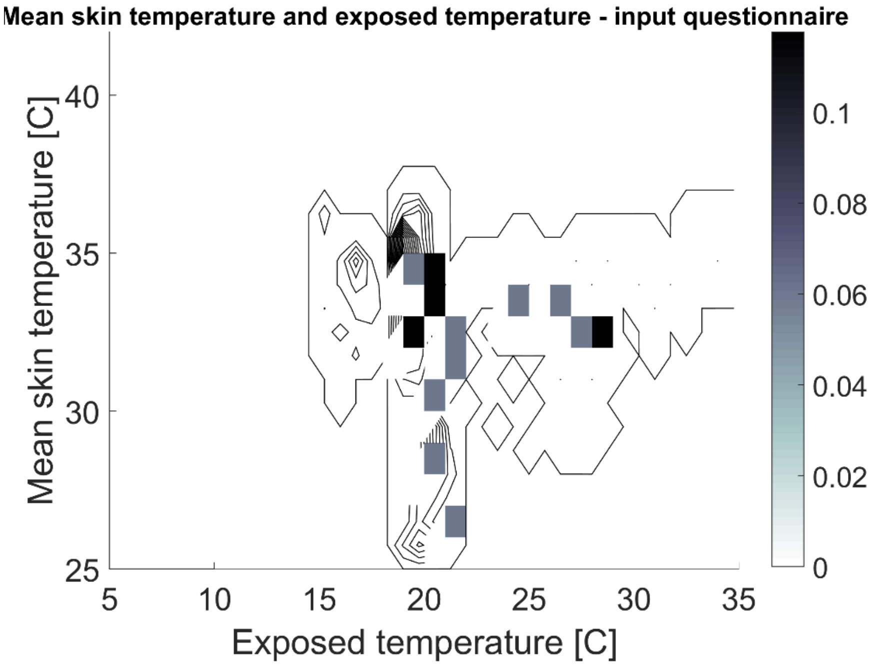


Figure 113 Contour plot of questionnaire entries of test subject 3

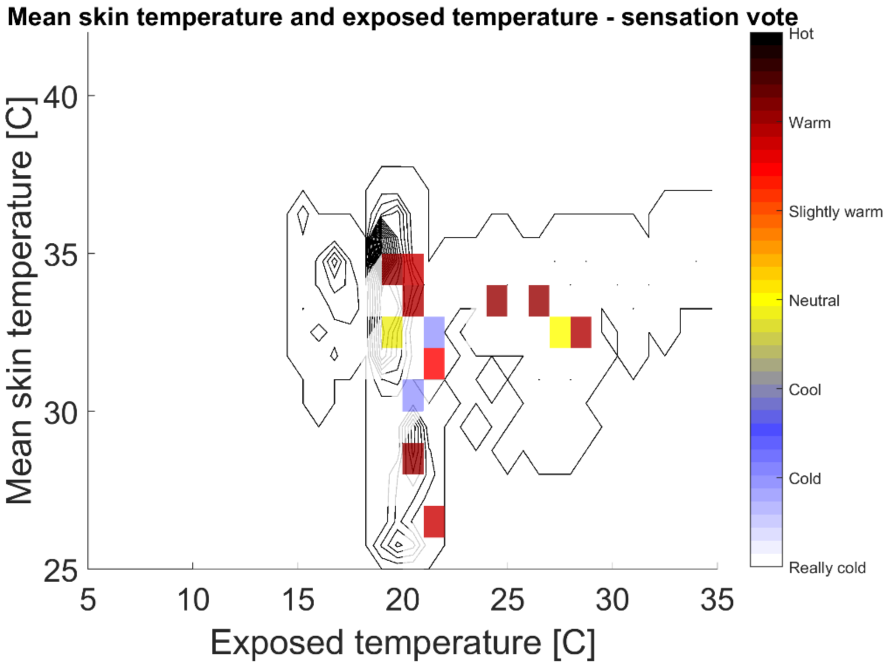


Figure 114 Contour plot of sensation votes of test subject 3

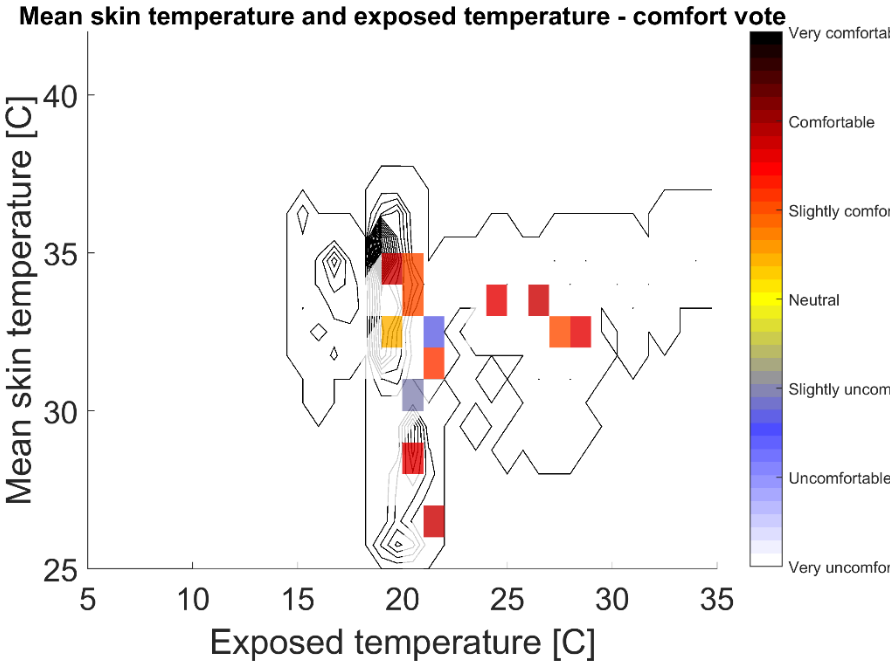

Mean skin temperature and exposed temperature - comfort vote

Figure 115 Contour plot of the comfort zones of test subject 3

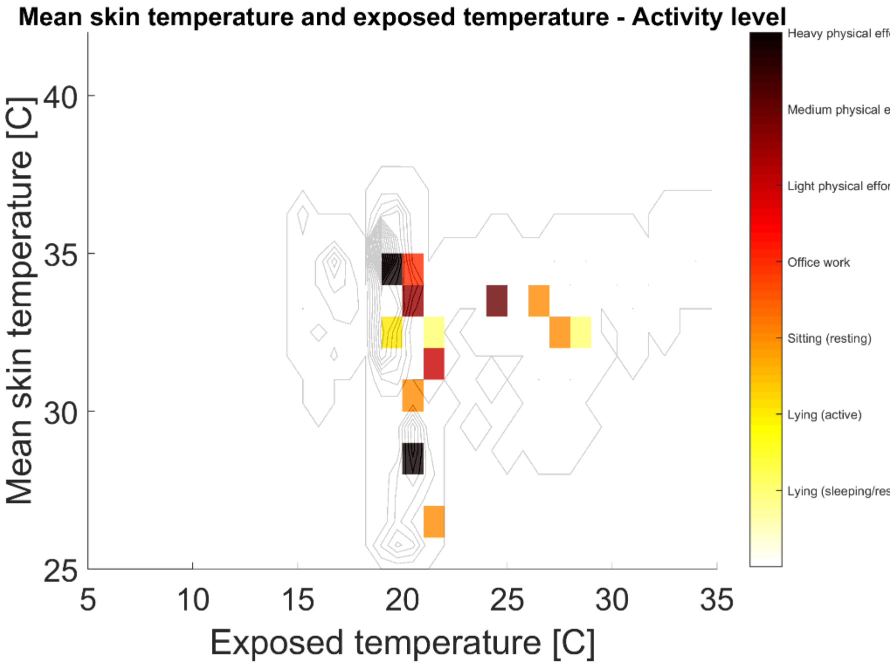

Mean skin temperature and exposed temperature - Activity level

Figure 116 Contour plot of the activity level of test subject 3

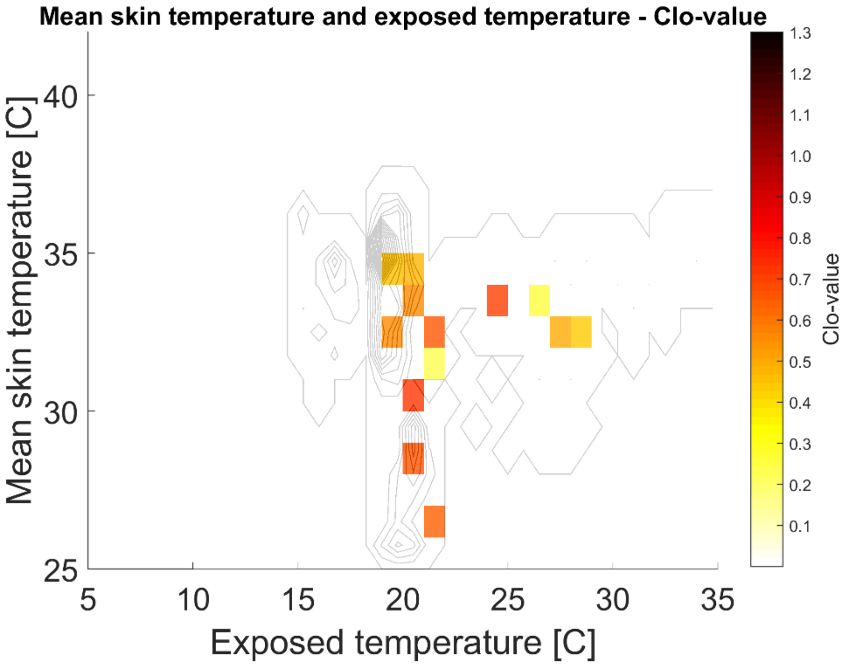


Figure 117 Contour plot of clothing worn by test subject 3

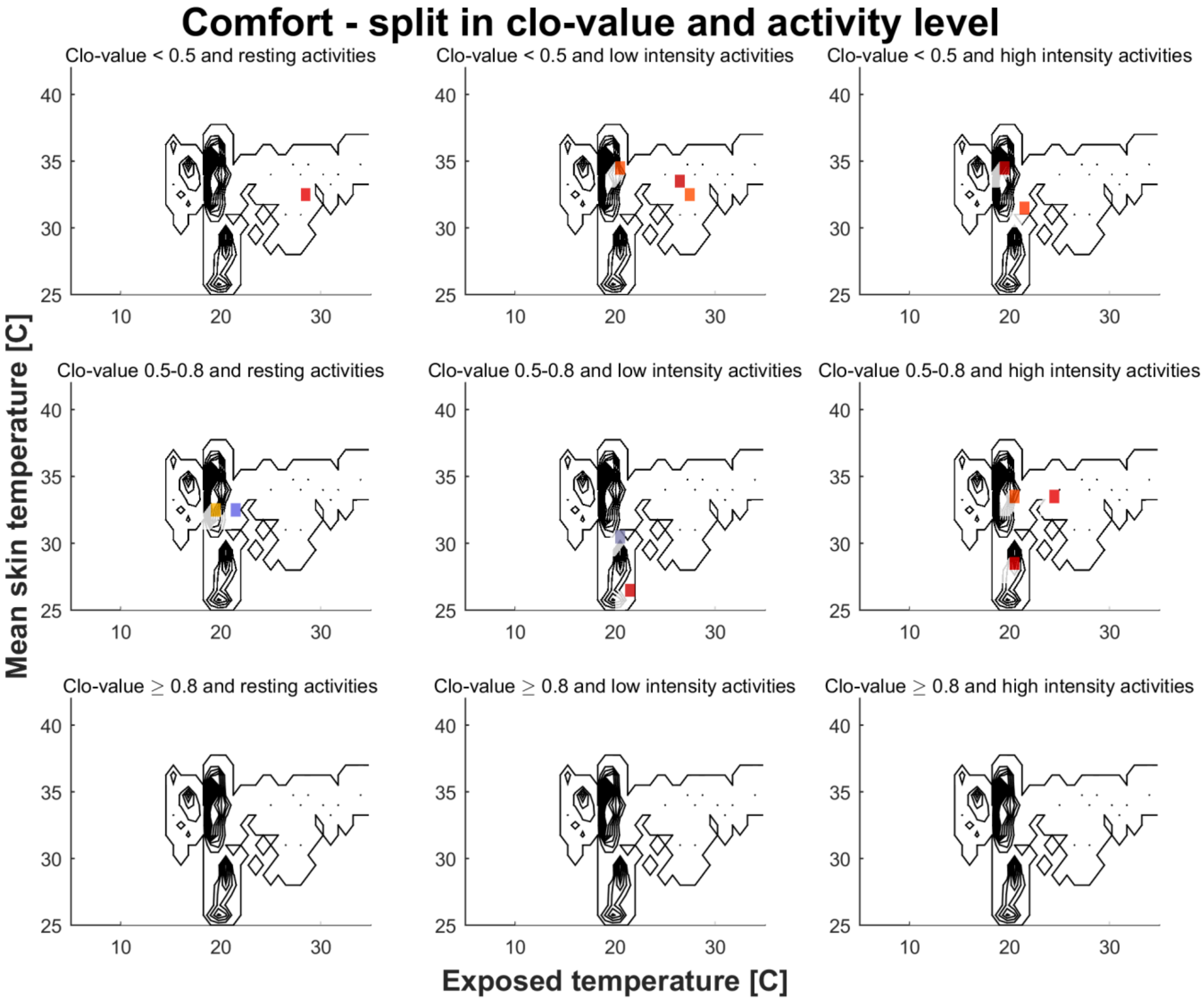


Figure 118 Contour plots of the comfort vote of test subject 3, with boundary conditions for Clo-values and activity levels

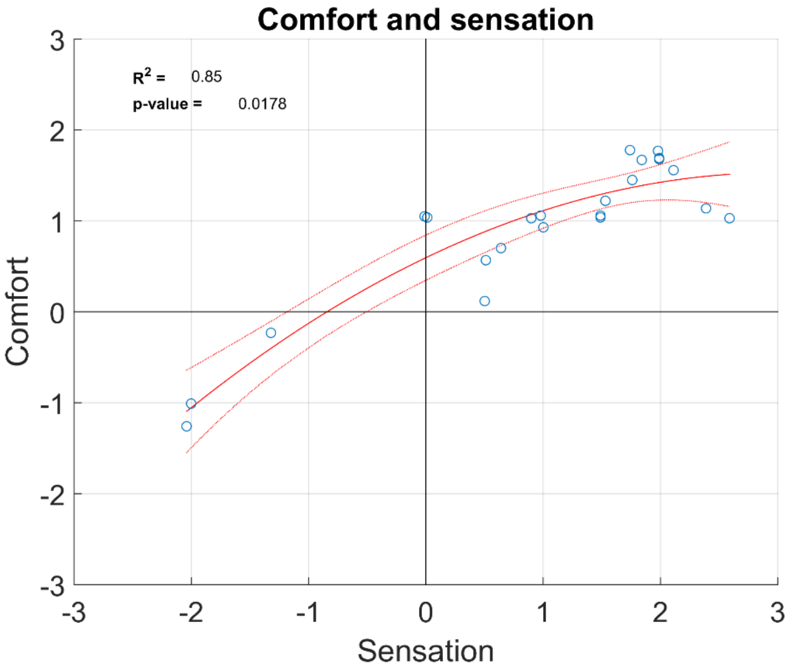


Figure 119 Comfort and sensation vote of test subject 3

Test subject 4

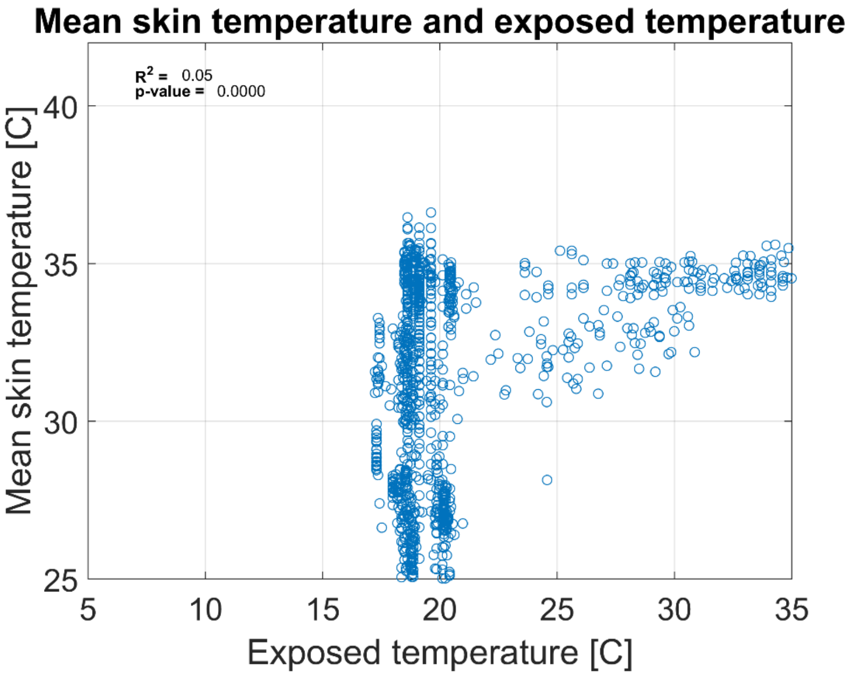


Figure 120 Mean skin temperature and exposed temperature of test subject 4

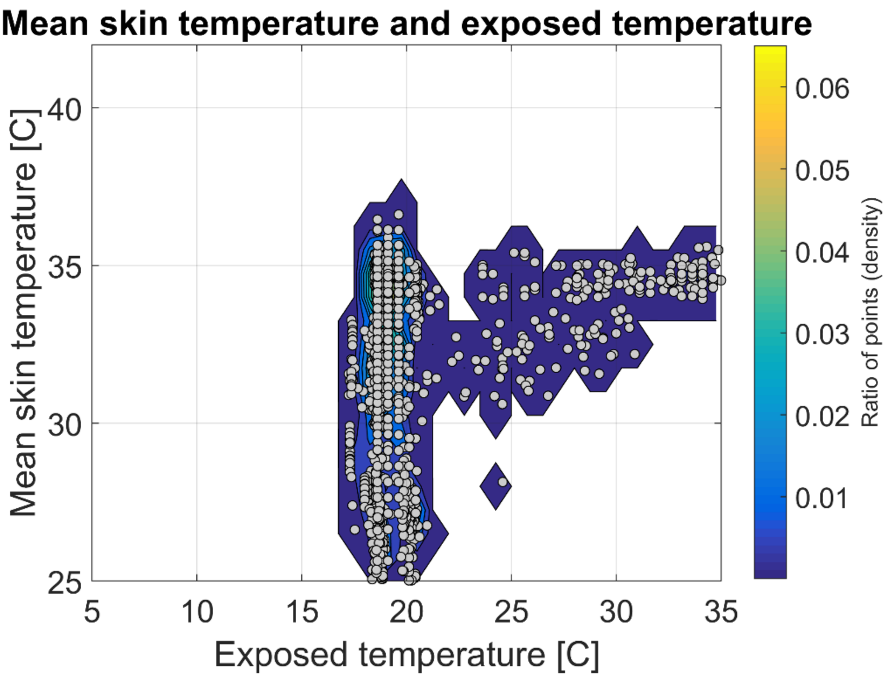


Figure 121 Contour plot of mean skin temperature and exposed temperature data of test subject 4

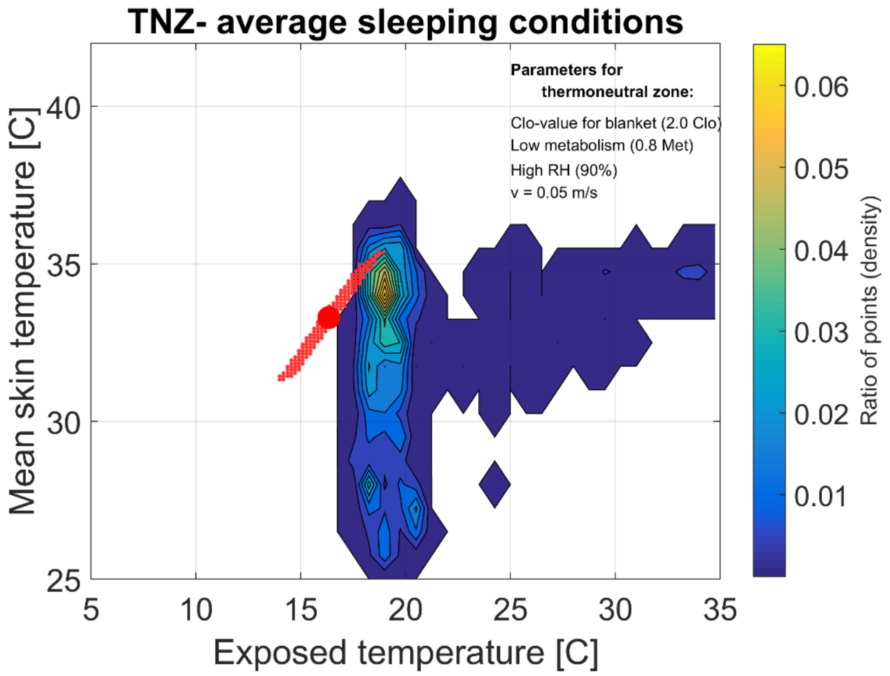


Figure 122 Contour plot of mean skin temperature and exposed temperature data including the thermoneutral zone during the night for test subject 4

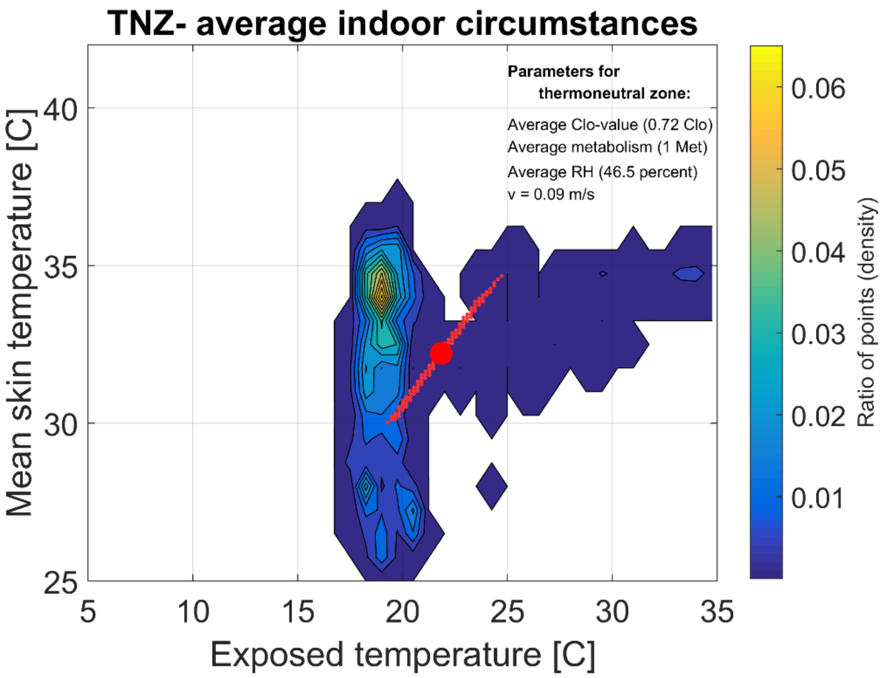


Figure 123 Contour plot of mean skin temperature and exposed temperature data including the thermoneutral zone of test subject 4

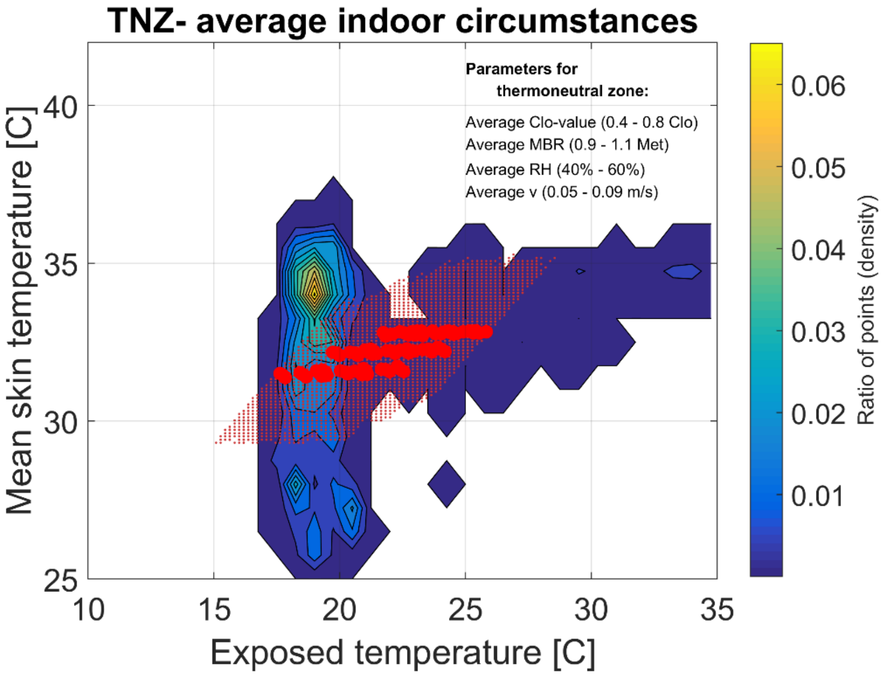


Figure 124 Contour plot of mean skin temperature and exposed temperature data including the dispersion of thermoneutral zones of test subject 4

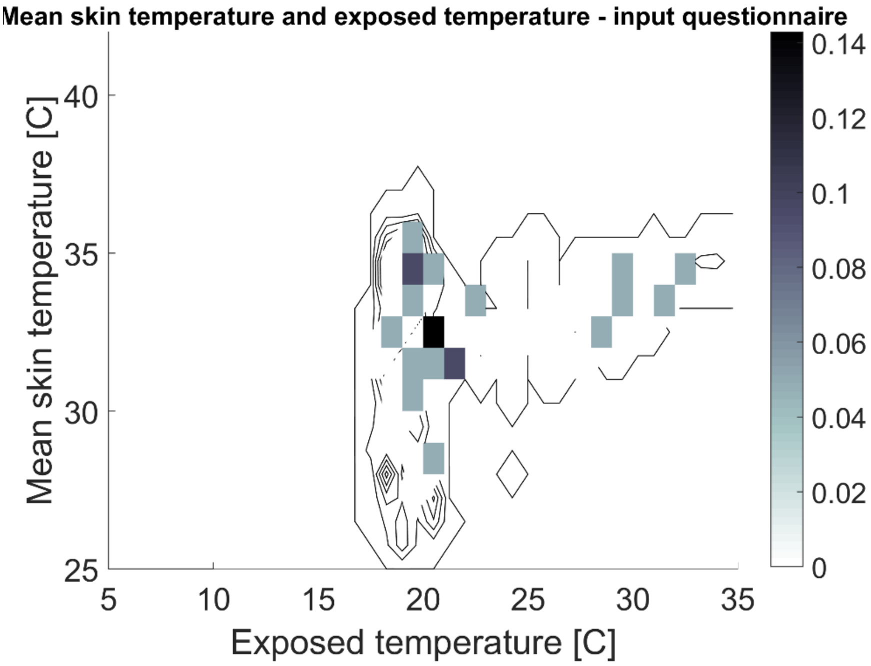


Figure 125 Contour plot of questionnaire entries of test subject 4

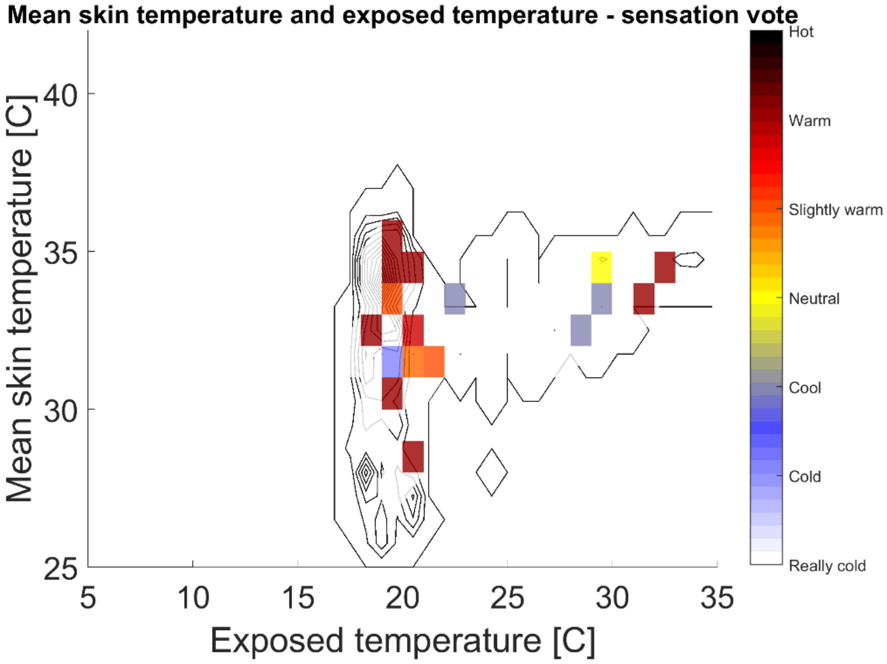


Figure 126 Contour plot of sensation votes of test subject 4

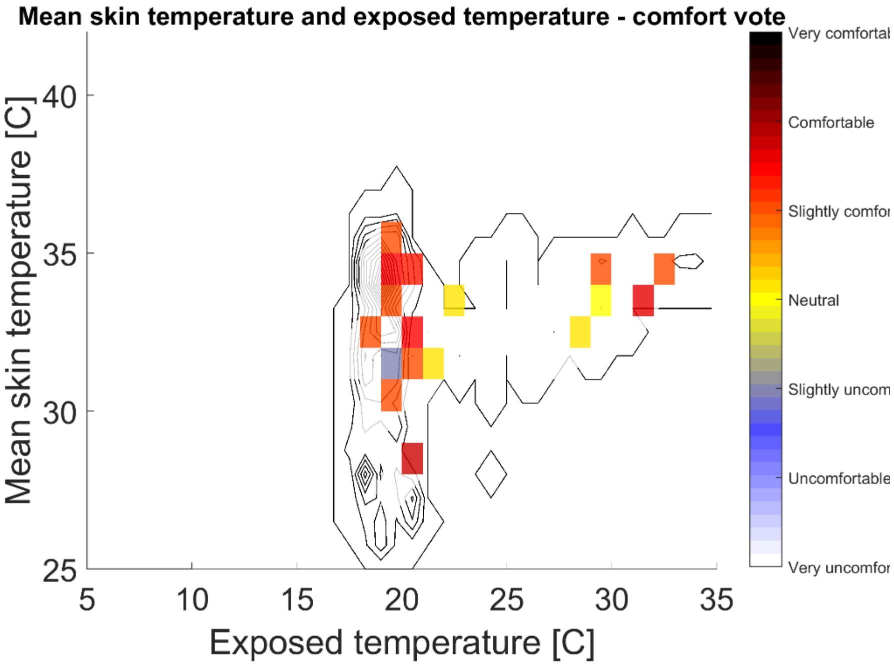


Figure 127 Contour plot of the comfort zones of test subject 4

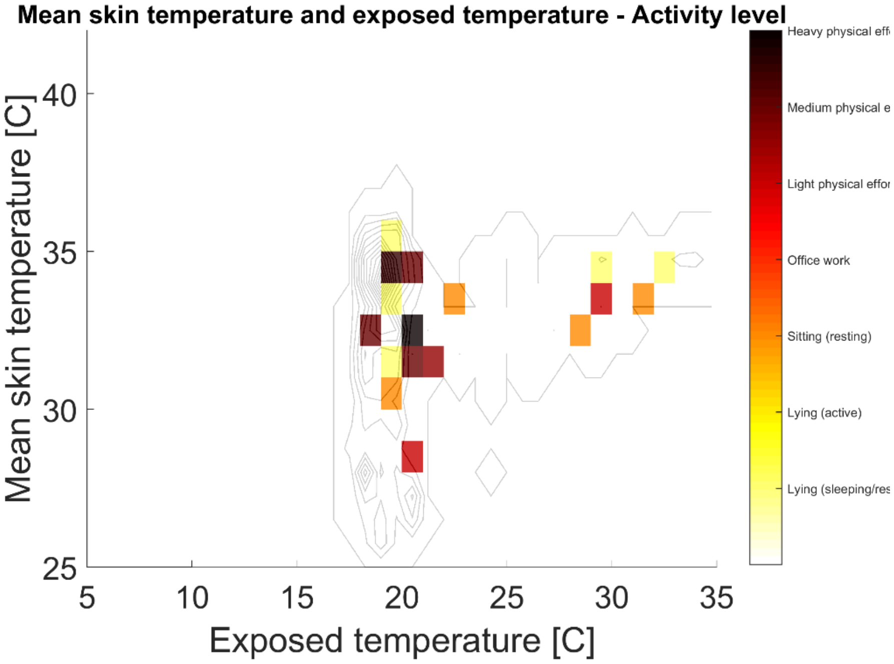


Figure 128 Contour plot of the activity level of test subject 4

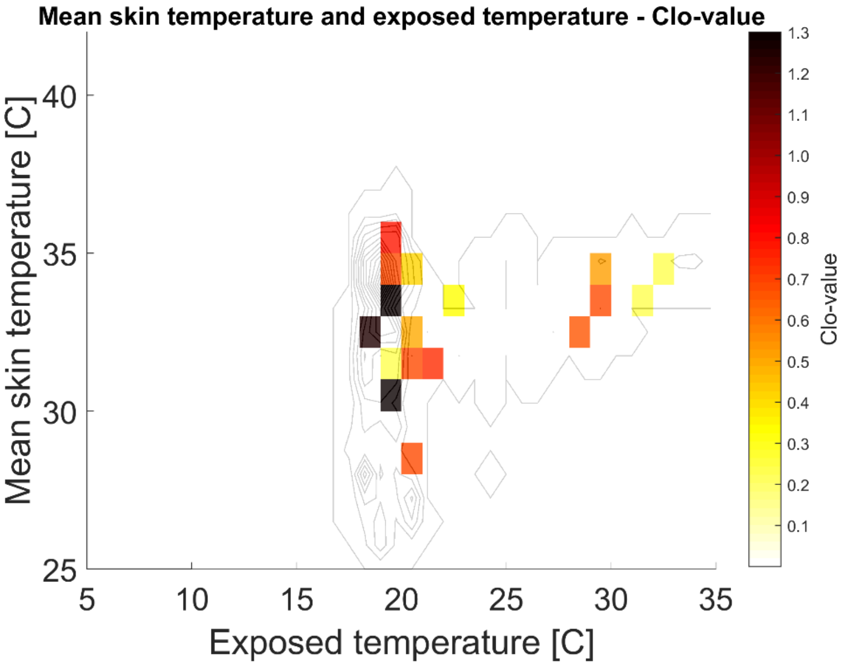


Figure 129 Contour plot of clothing worn by test subject 4

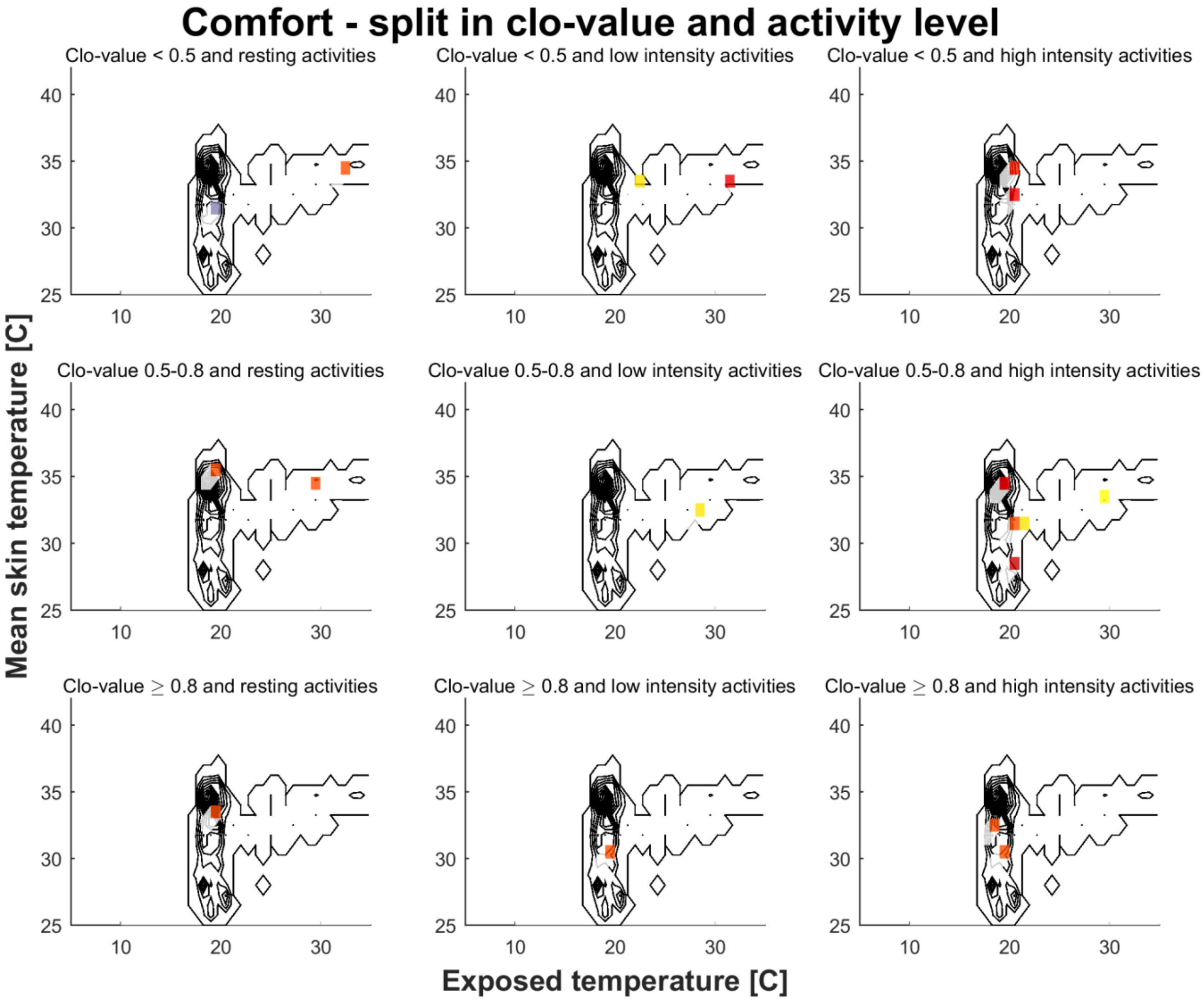


Figure 130 Contour plots of the comfort vote of test subject 4, with boundary conditions for Clo-values and activity levels

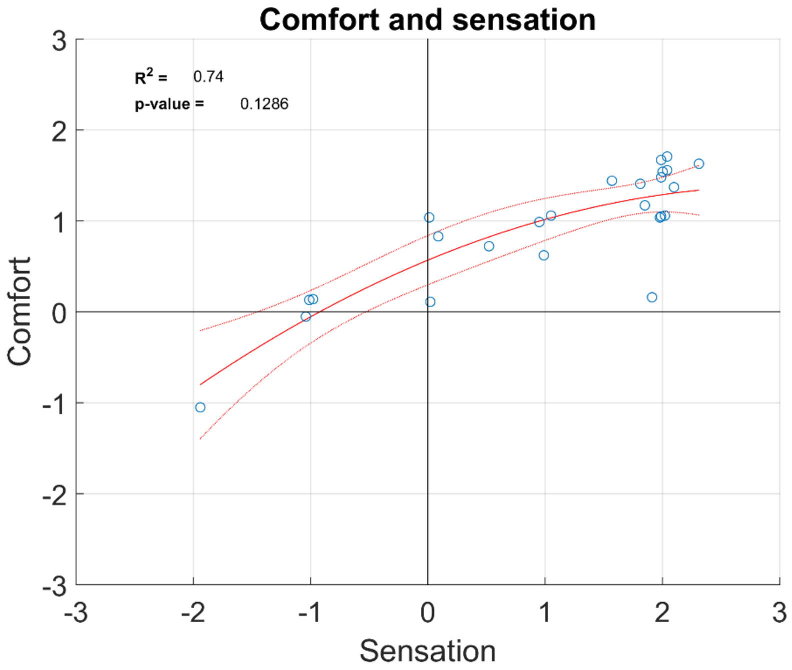


Figure 131 Comfort and sensation vote of test subject 4

Difference in energy demand between test subject 3 and 4

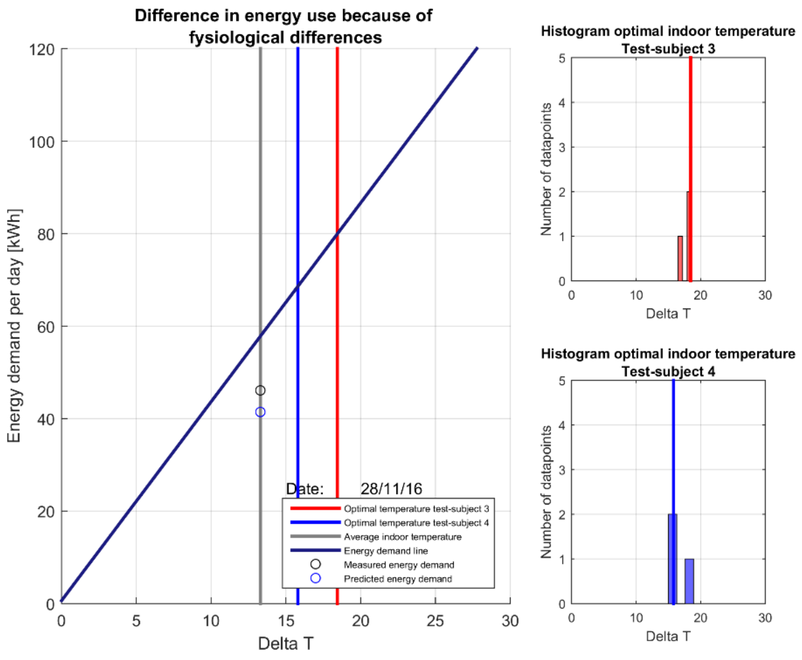


Figure 132 Difference in energy use because of physiological differences – 28th of November 2016

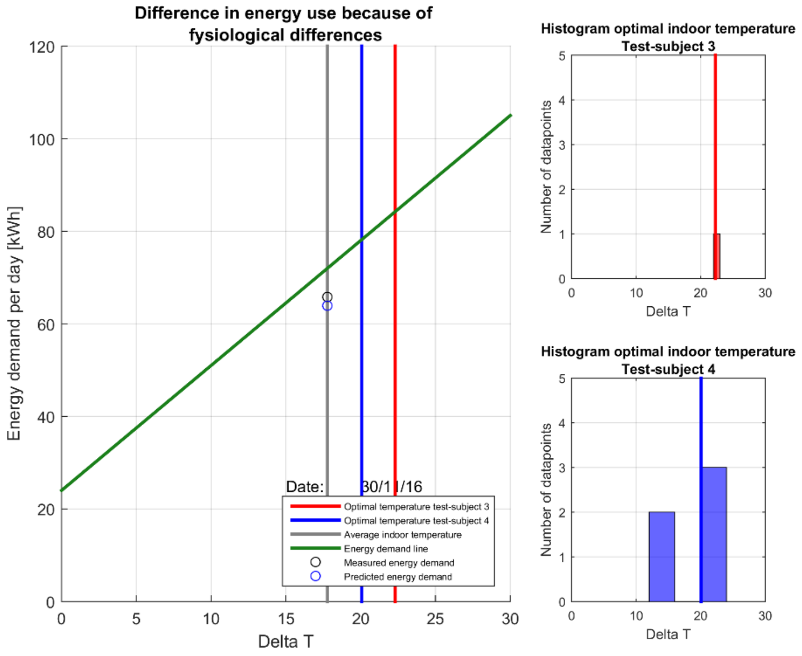


Figure 133 Difference in energy use because of physiological differences – 30th of November 2016

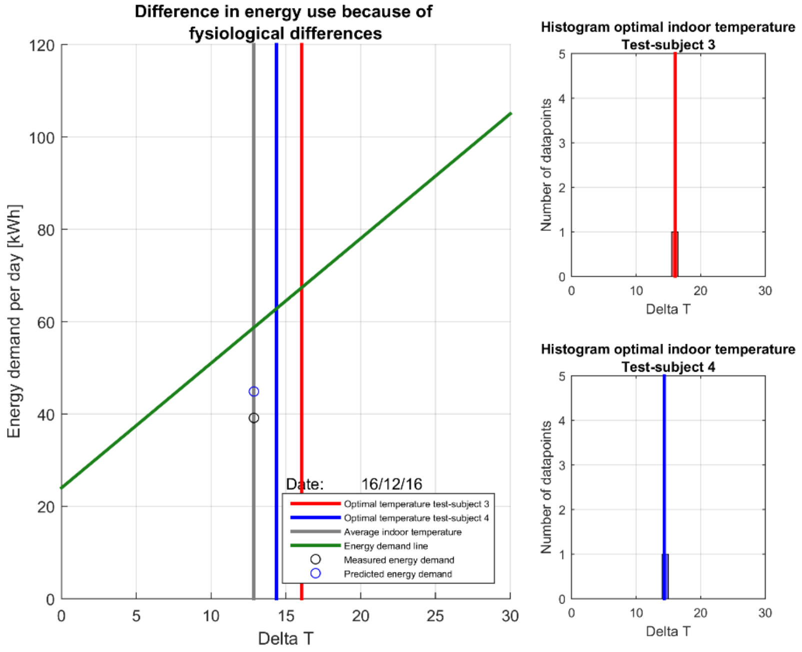


Figure 134 Difference in energy use because of physiological differences – 16th of December 2016

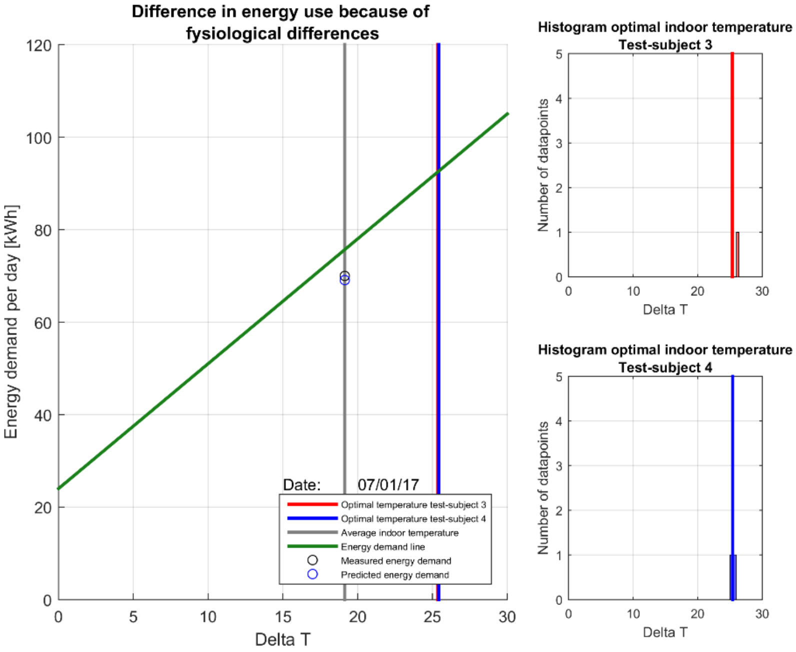


Figure 135 Difference in energy use because of physiological differences – 7th of January 2017

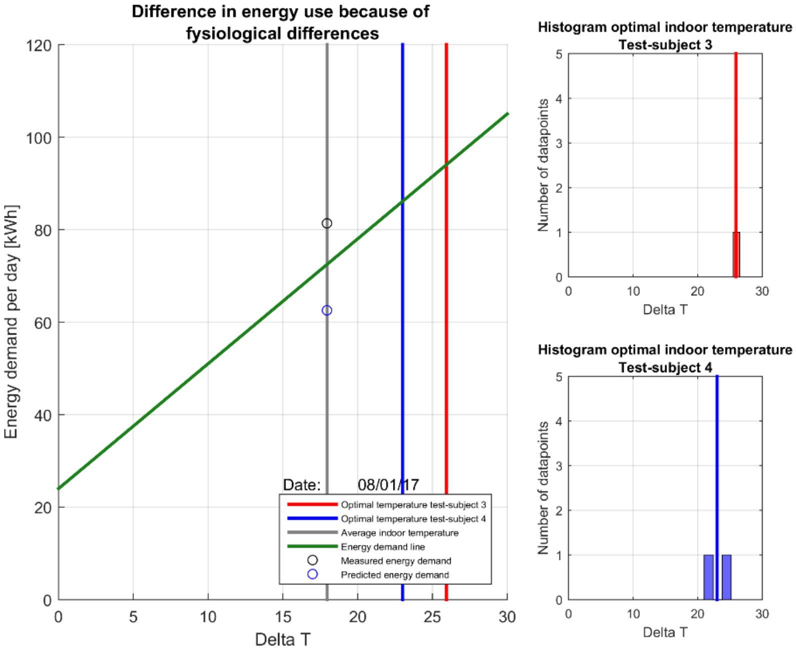


Figure 136 Difference in energy use because of physiological differences – 8th of January 2017

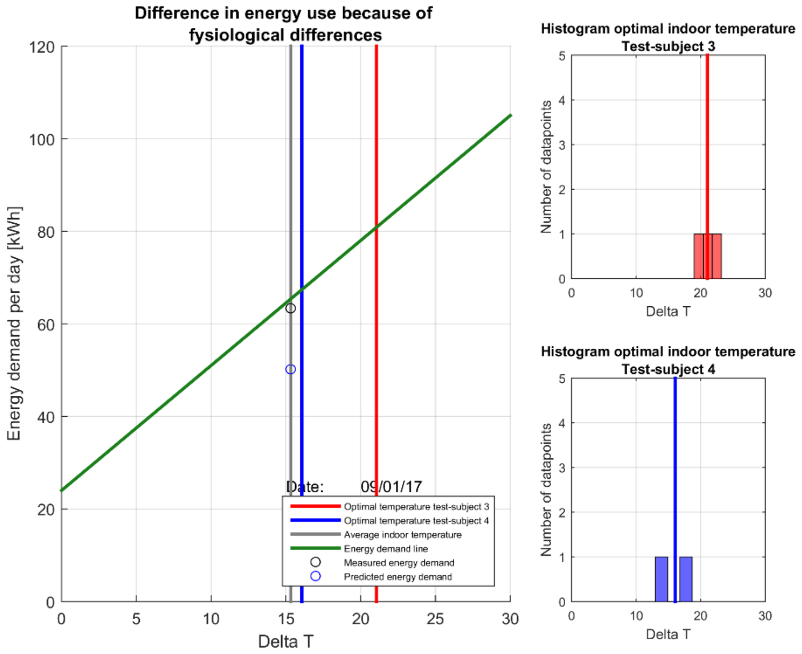


Figure 137 Difference in energy use because of physiological differences – 9th of January 2017

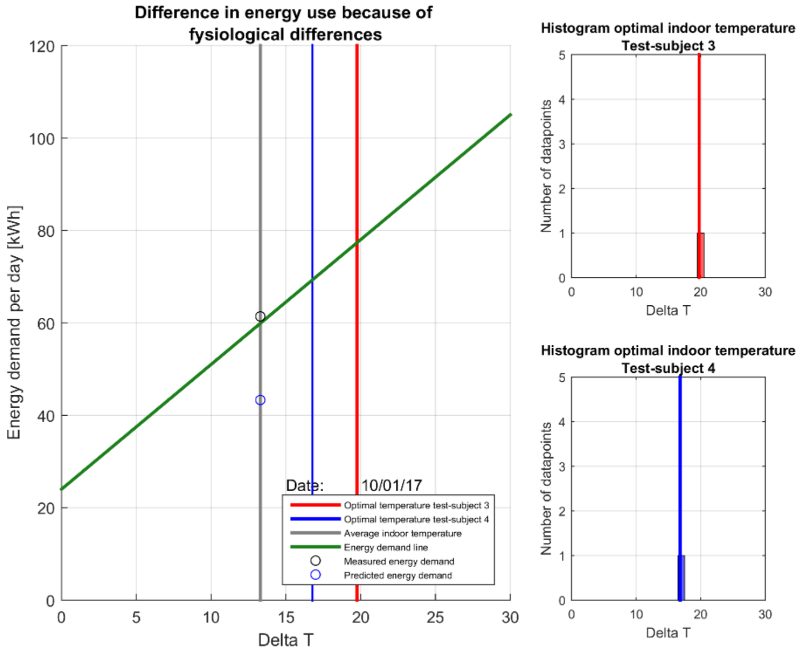


Figure 138 Difference in energy use because of physiological differences – 10th of January 2017

Appendix IX

Table 17 Degree days 2015

2015	Degree days
Month	
Jan	501,4
Feb	463,3
Mrch	364,3
Apr	199,0
May	122,3
Jun	52,5
Jul	25,9
Aug	16,9
Sep	113,7
Oct	256,2
Nov	275,1
Dec	293,8
Total	**2684,4**

Table 18 Degree days 2016

2016	Degree days
Month	
Jan	453,3
Feb	434,2
Mrch	402,5
Apr	223,9
May	92,2
Jun	42,9
Jul	20,0
Aug	22,0
Sep	25,0
Oct	257,0
Nov	396,0
Dec	468,0
Total	**2837,0**

Table 19 Degree days 2017

2017	Degree days
Month	
Jan	594,0
Feb	376,0
Totaal	**970,0**

Appendix X

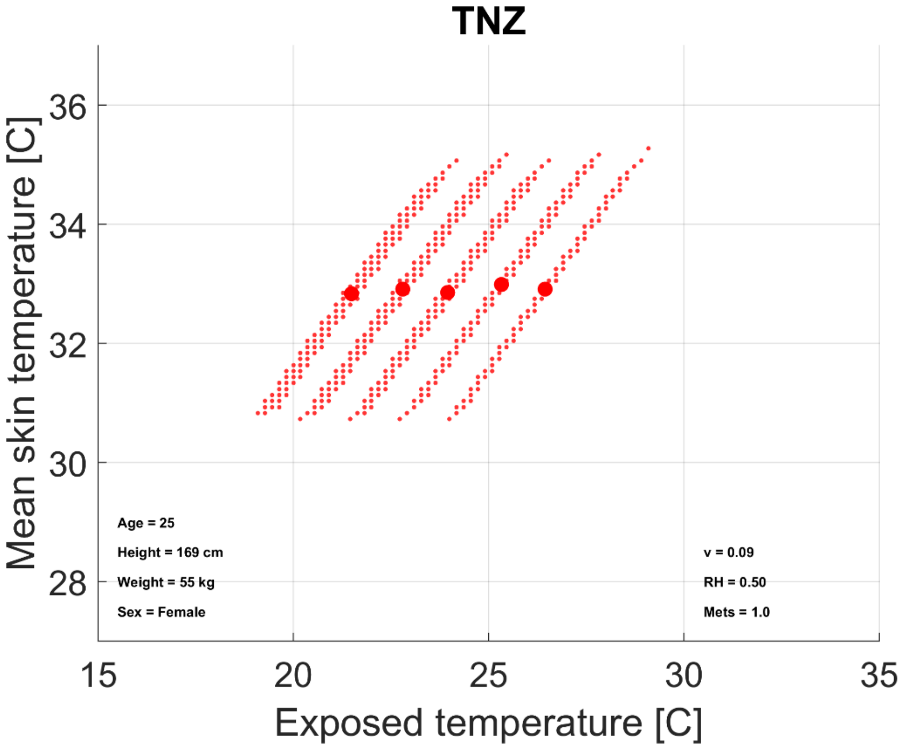


Figure 139 Example of the range of comfortable ambient temperatures at different clo-values – a woman of the age of 25 and an average female height and weight

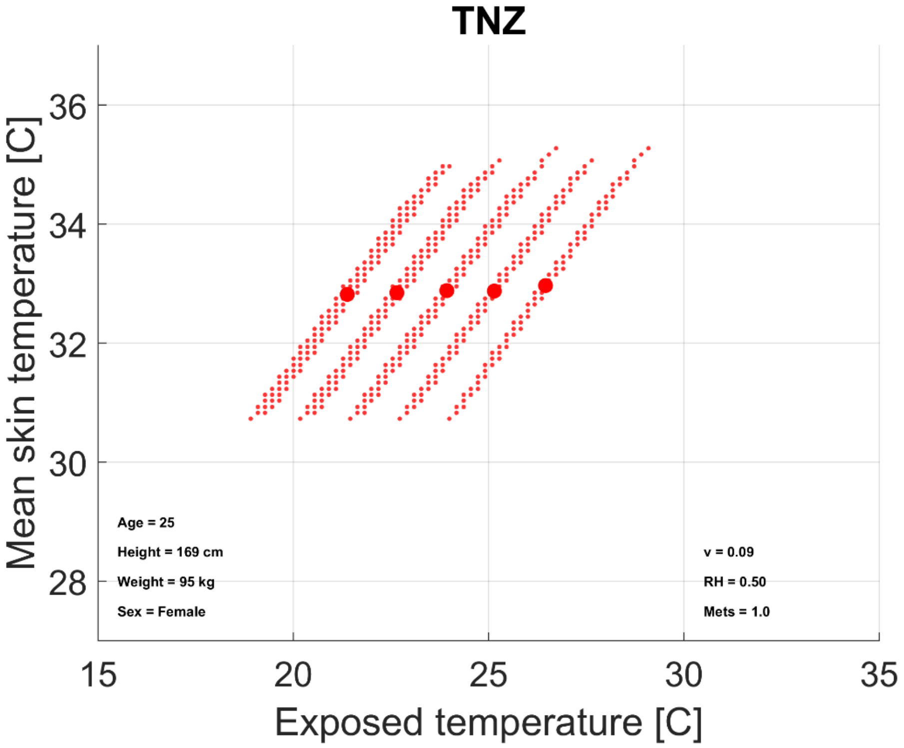


Figure 140 Example of the range of comfortable ambient temperatures at different clo-values – an obese woman of the age of 25 and an average female height

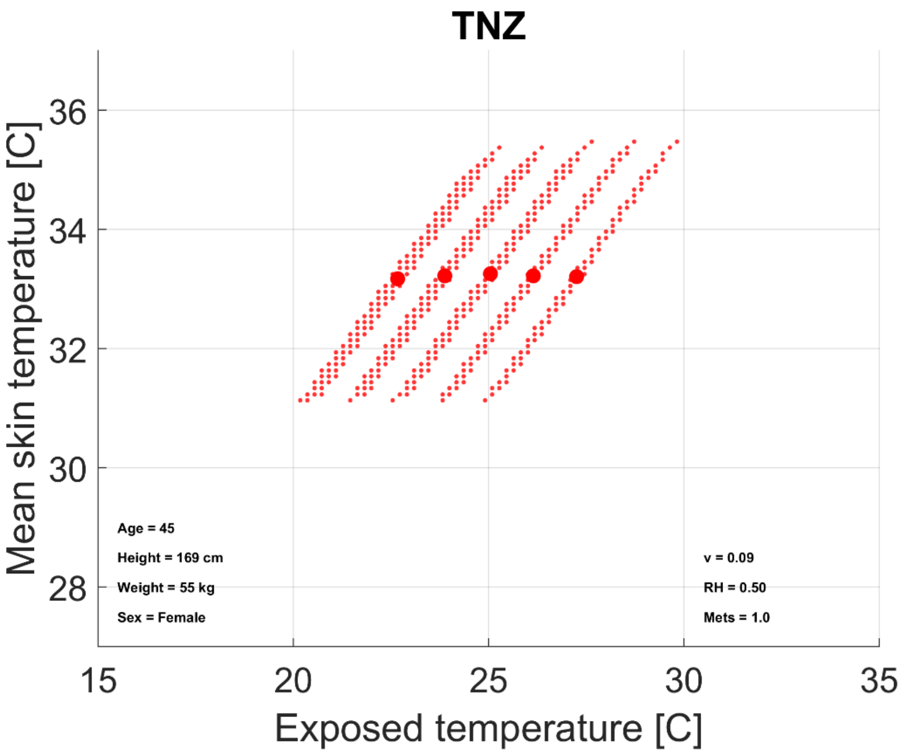


Figure 141 Example of the range of comfortable ambient temperatures at different clo-values – a woman of the age of 45 and an average female height and weight

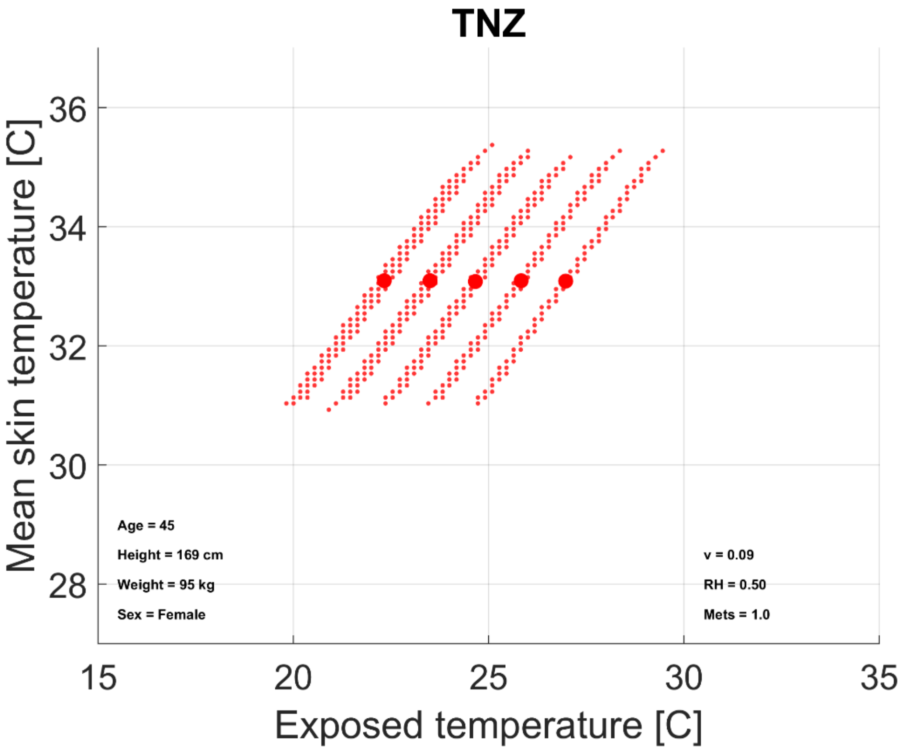


Figure 142 Example of the range of comfortable ambient temperatures at different clo-values – an obese woman of the age of 45 and an average female height

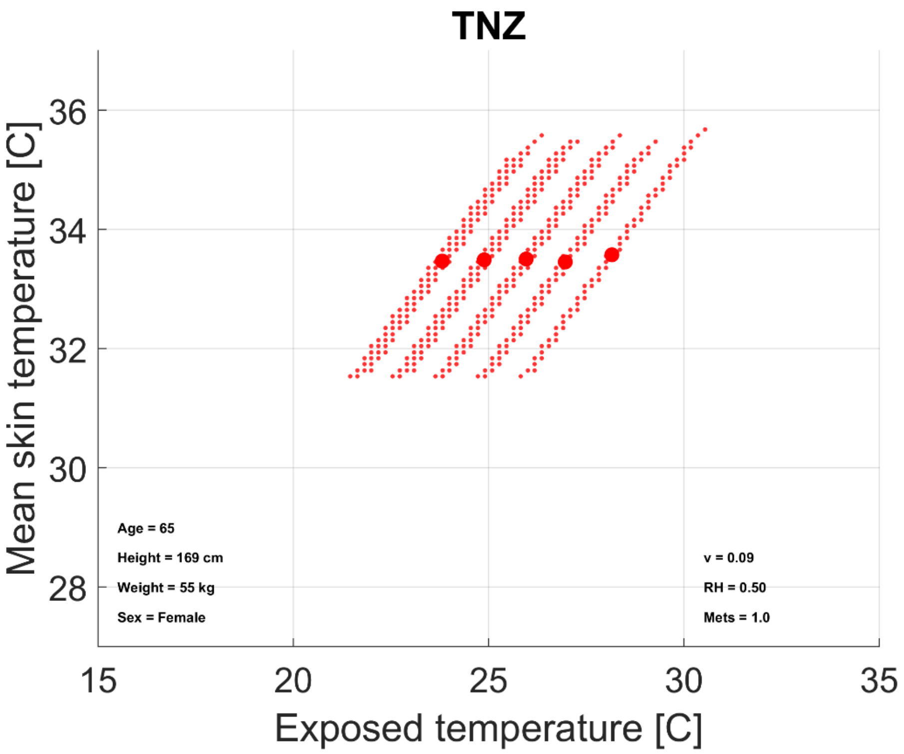


Figure 143 Example of the range of comfortable ambient temperatures at different clo-values – a woman of the age of 65 and an average female height and weight

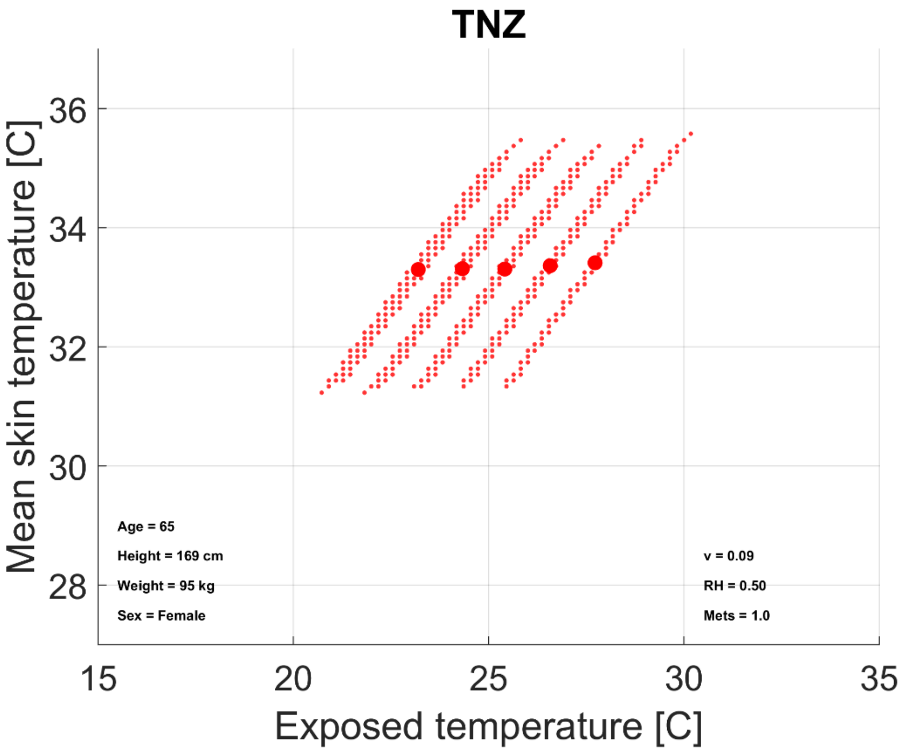


Figure 144 Example of the range of comfortable ambient temperatures at different clo-values – an obese woman of the age of 65 and an average female height

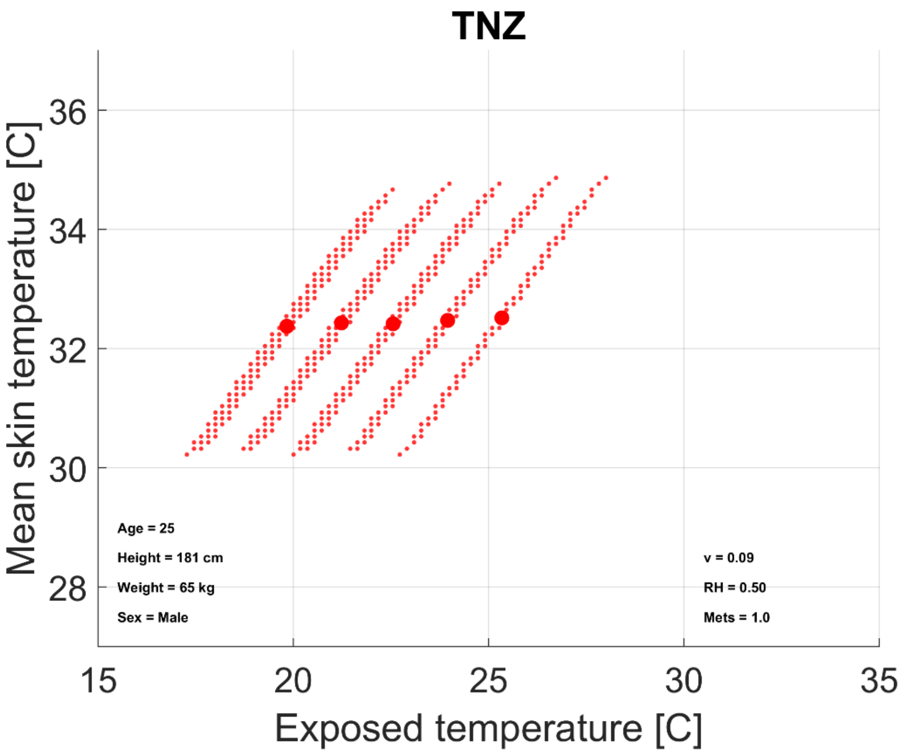


Figure 145 Example of the range of comfortable ambient temperatures at different clo-values – a men of the age of 25 and an average male height and weight

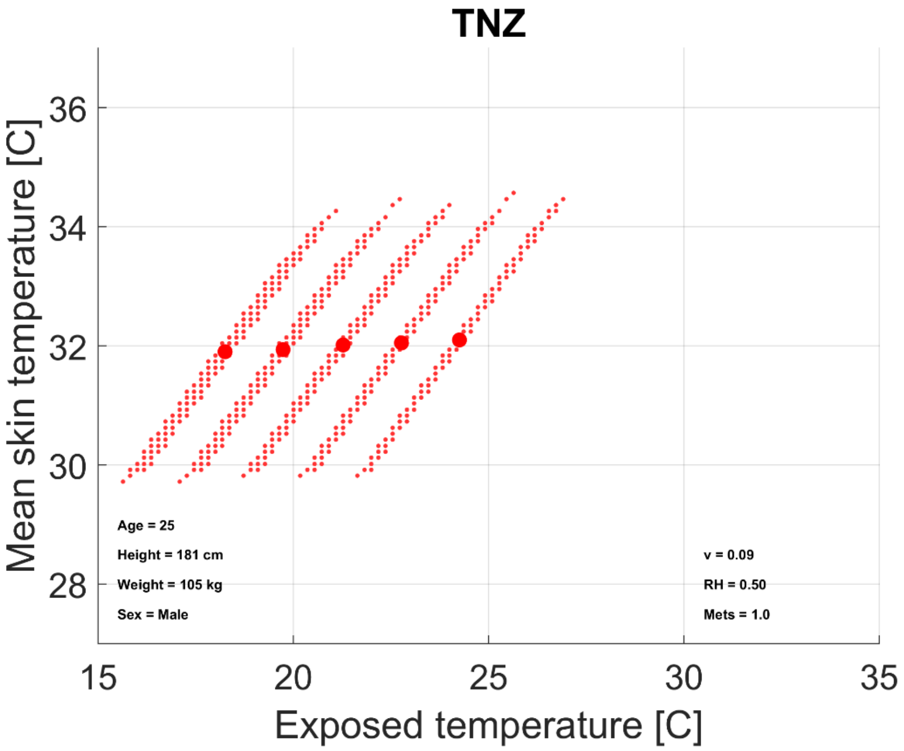


Figure 146 Example of the range of comfortable ambient temperatures at different clo-values – an obese men of the age of 25 and an average male height

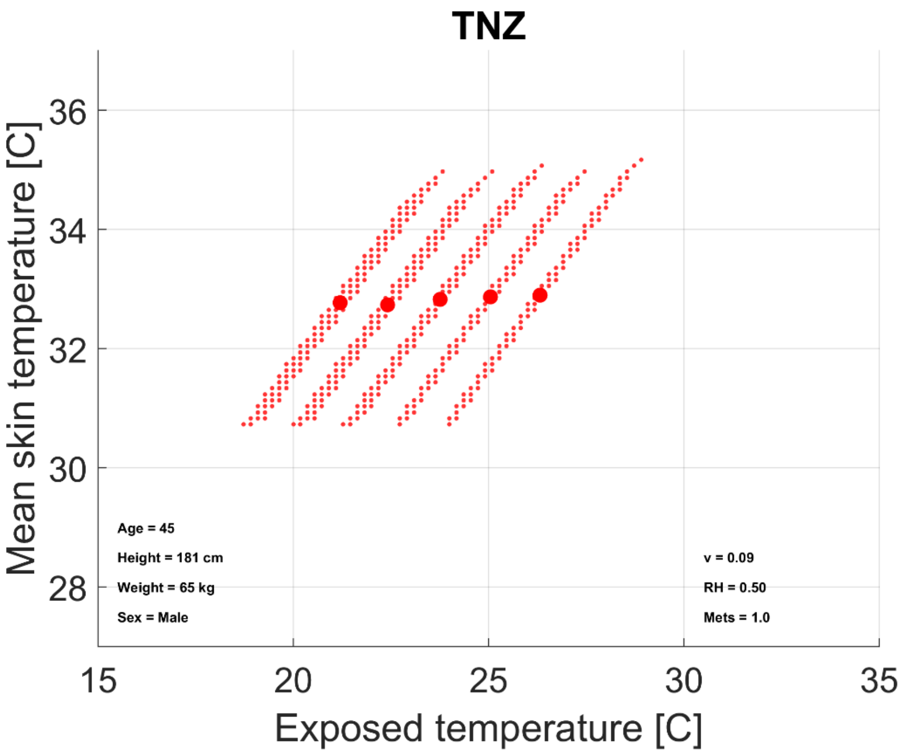


Figure 147 Example of the range of comfortable ambient temperatures at different clo-values – a men of the age of 45 and an average male height and weight

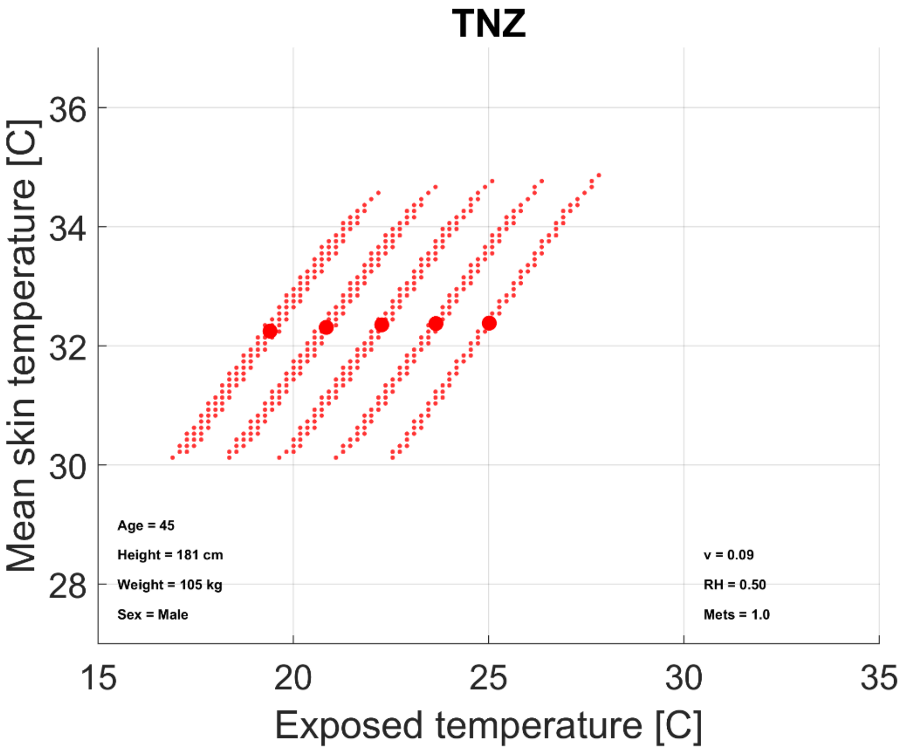


Figure 148 Example of the range of comfortable ambient temperatures at different clo-values – an obese men of the age of 45 and an average male height

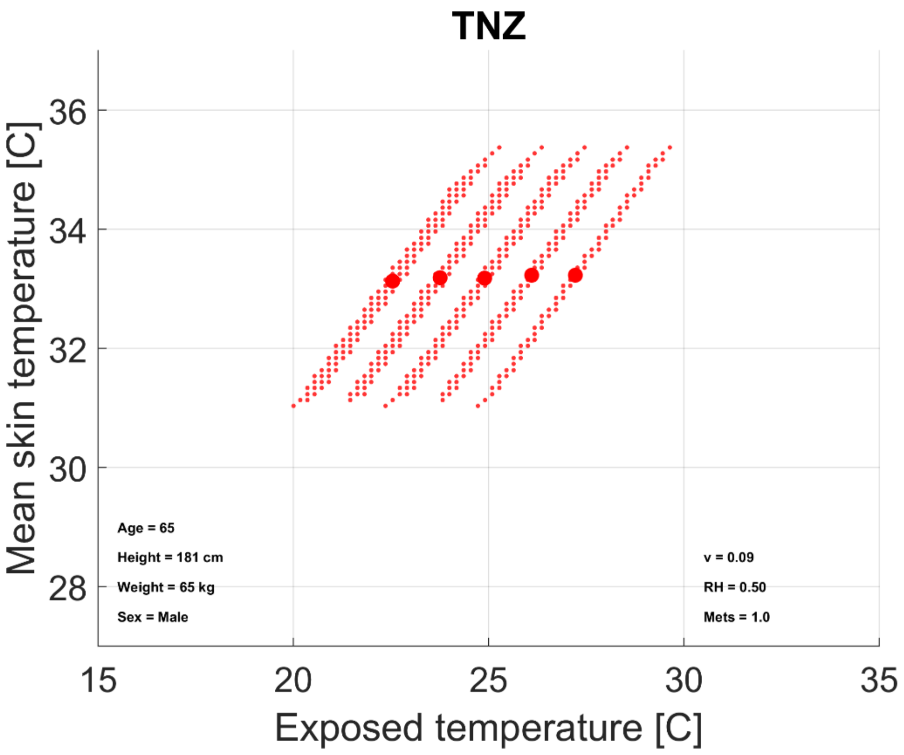


Figure 149 Example of the range of comfortable ambient temperatures at different clo-values – a men of the age of 65 and an average male height and weight

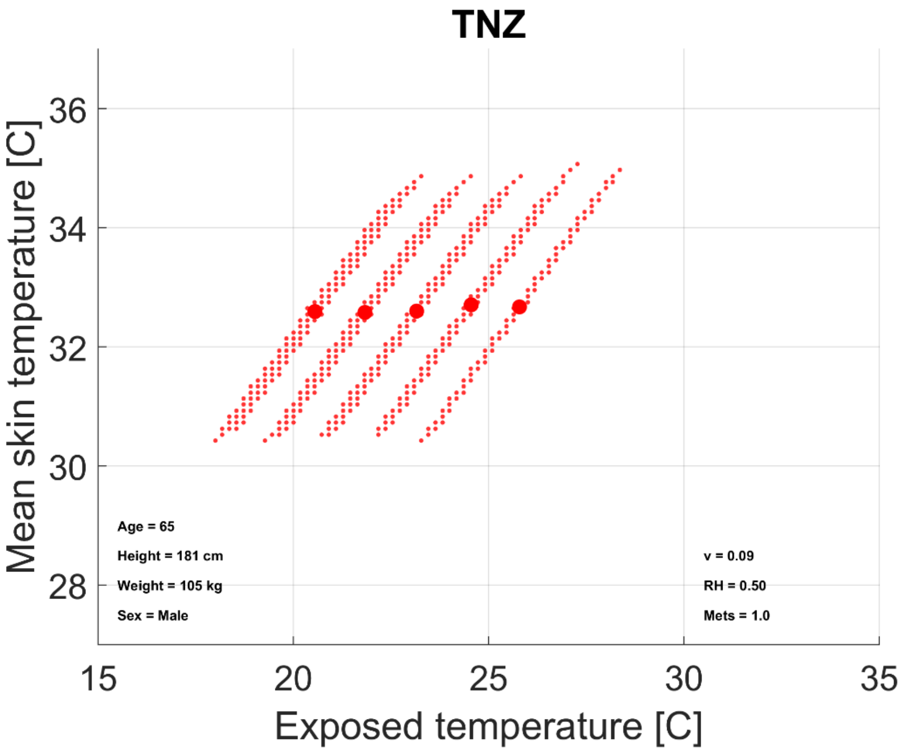


Figure 150 Example of the range of comfortable ambient temperatures at different clo-values – an obese men of the age of 25 and an average male height

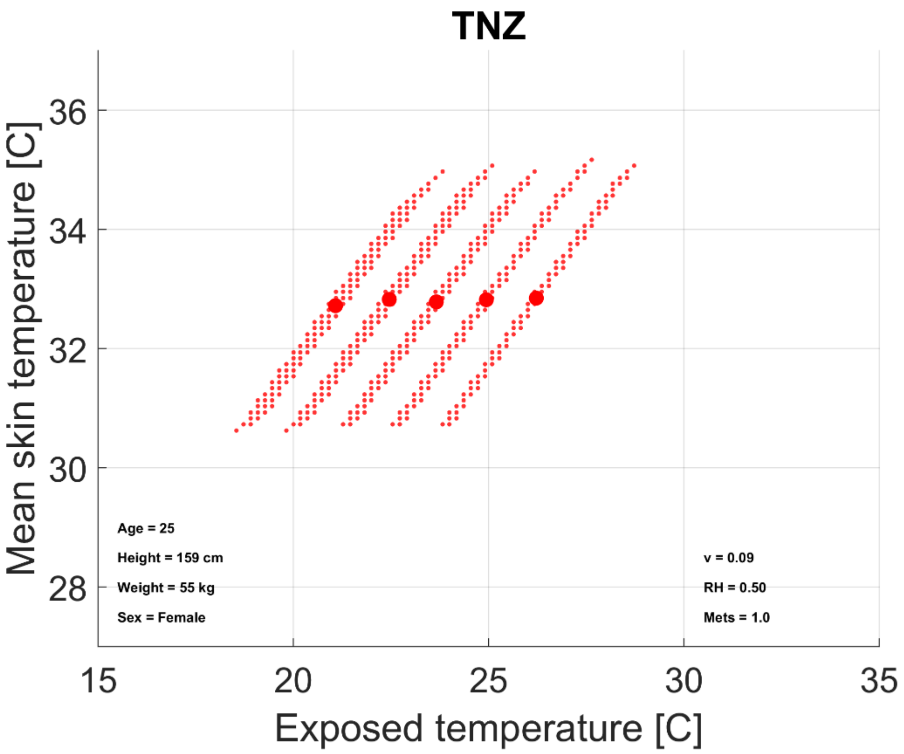


Figure 151 Example of the range of comfortable ambient temperatures at different clo-values – a short woman of the age of 25 and an average weight

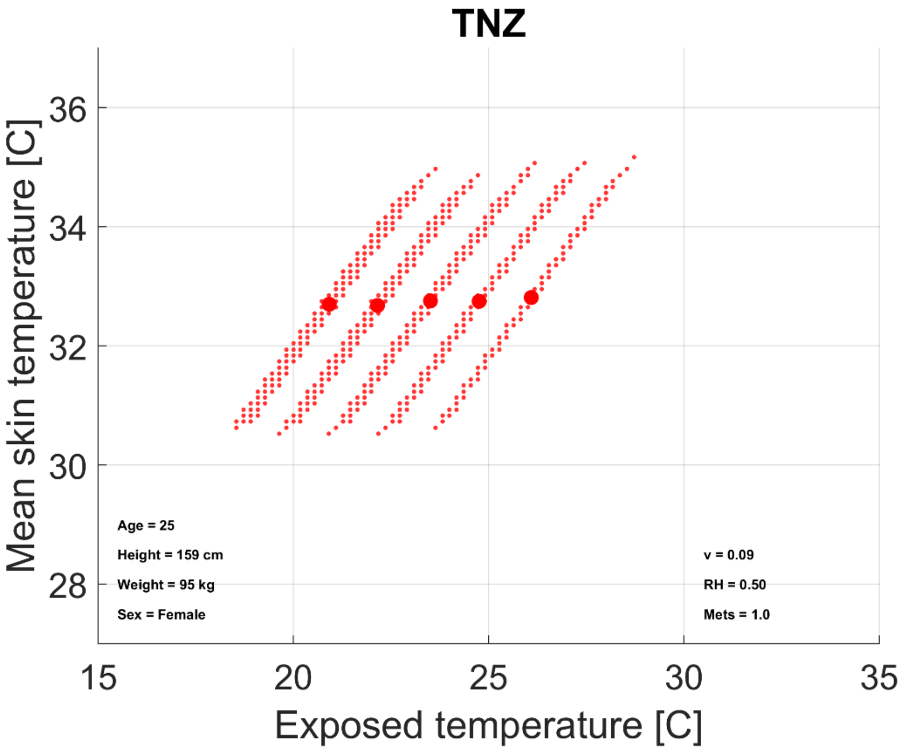


Figure 152 Example of the range of comfortable ambient temperatures at different clo-values – a short obese woman of the age of 25

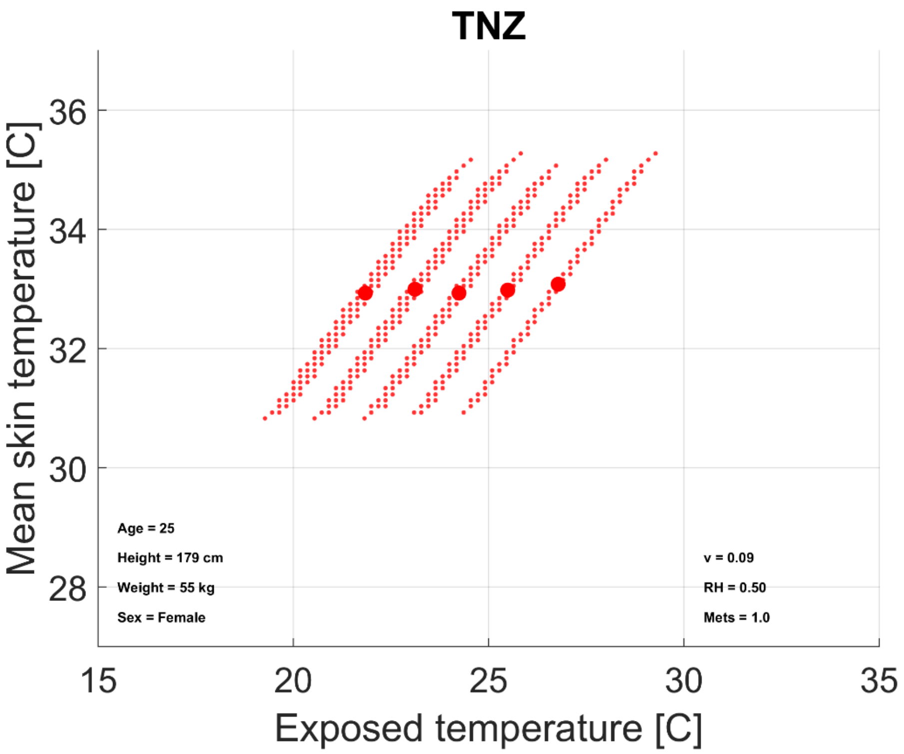


Figure 153 Example of the range of comfortable ambient temperatures at different clo-values – a tall woman of the age of 25 and an average weight

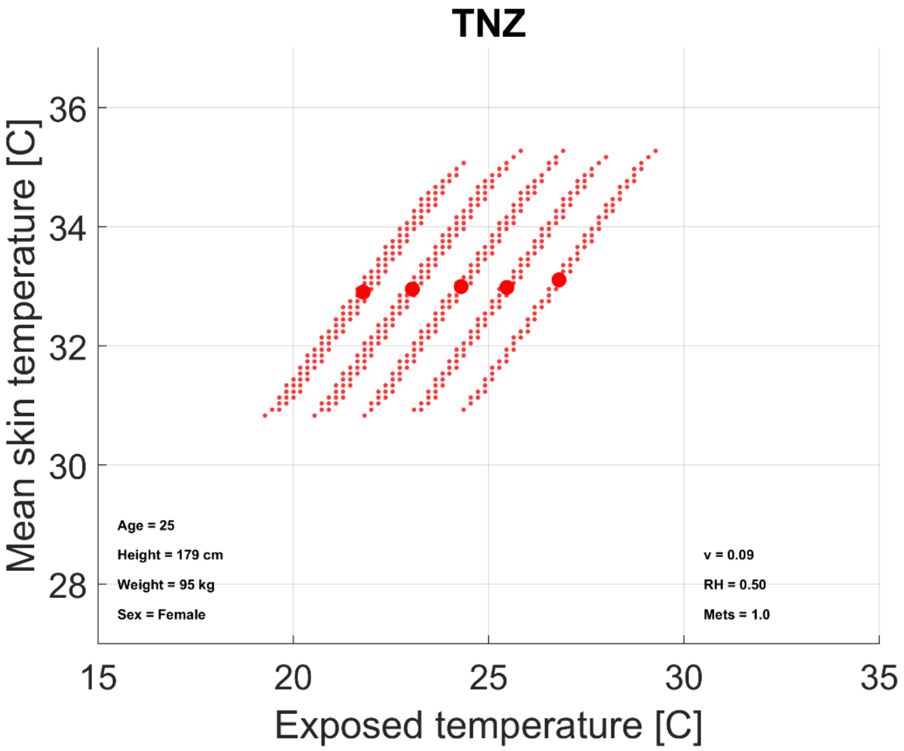


Figure 154 Example of the range of comfortable ambient temperatures at different clo-values – a tall obese woman of the age of 25

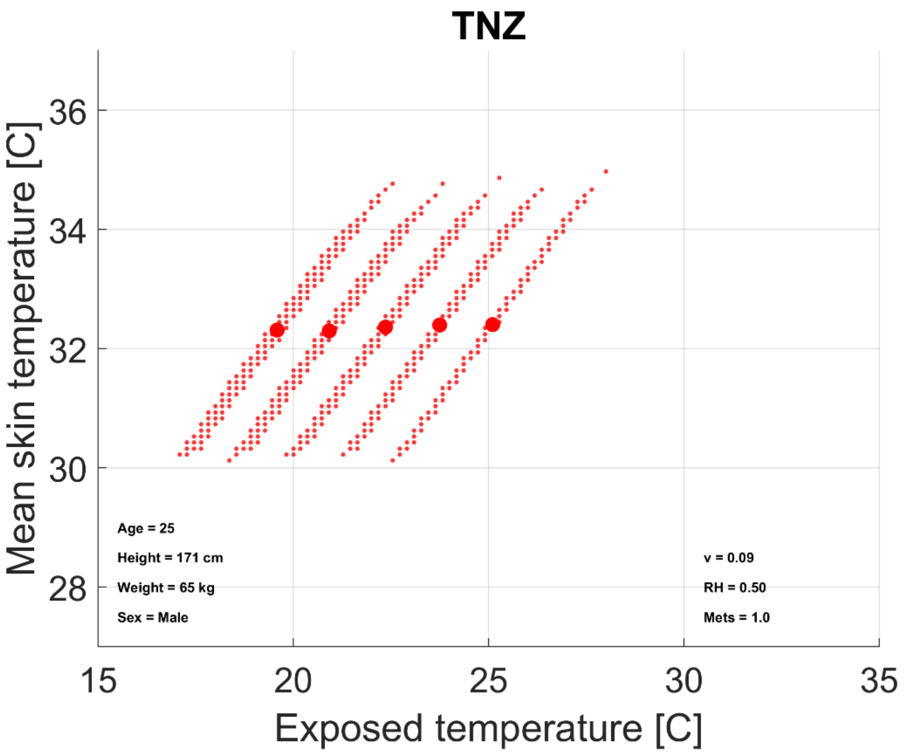


Figure 155 Example of the range of comfortable ambient temperatures at different clo-values – a short man of the age of 25 and an average weight

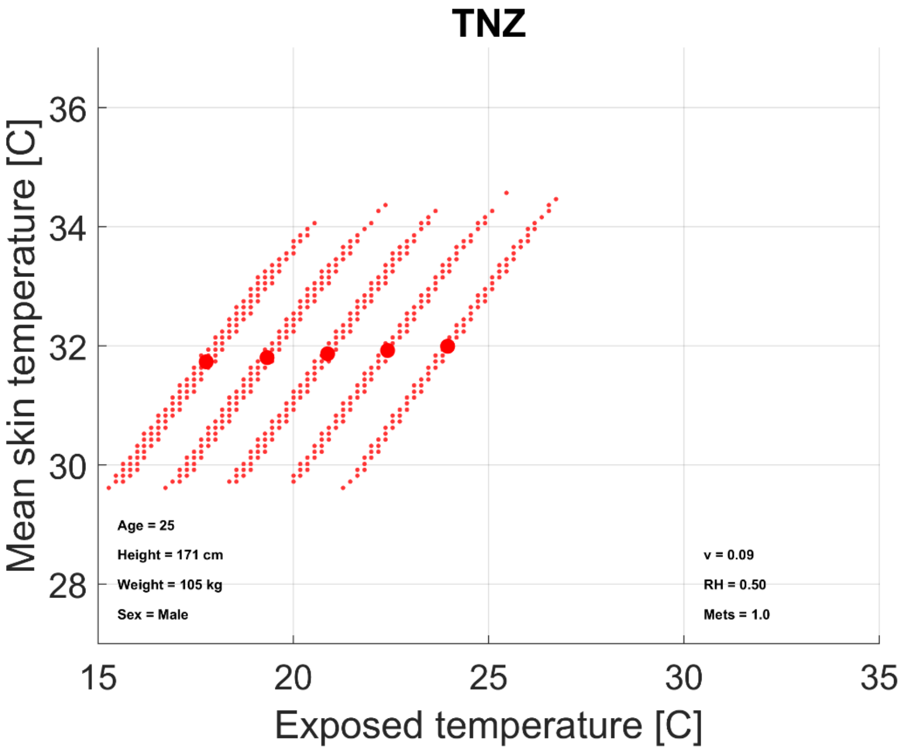


Figure 156 Example of the range of comfortable ambient temperatures at different clo-values – a short obese man of the age of 25

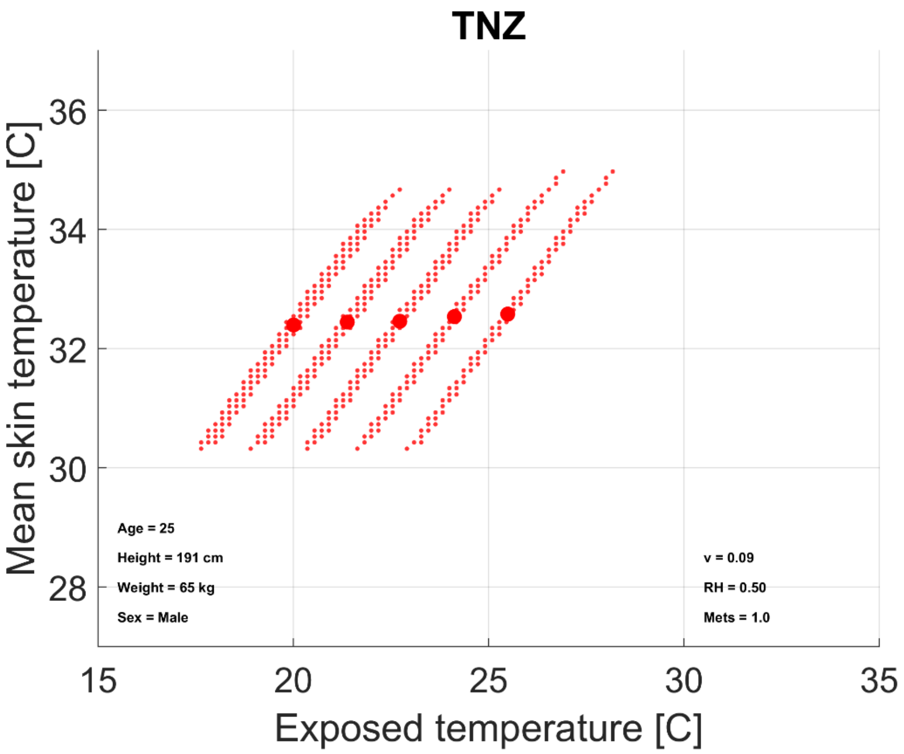


Figure 157 Example of the range of comfortable ambient temperatures at different clo-values – a tall man of the age of 25 and an average weight

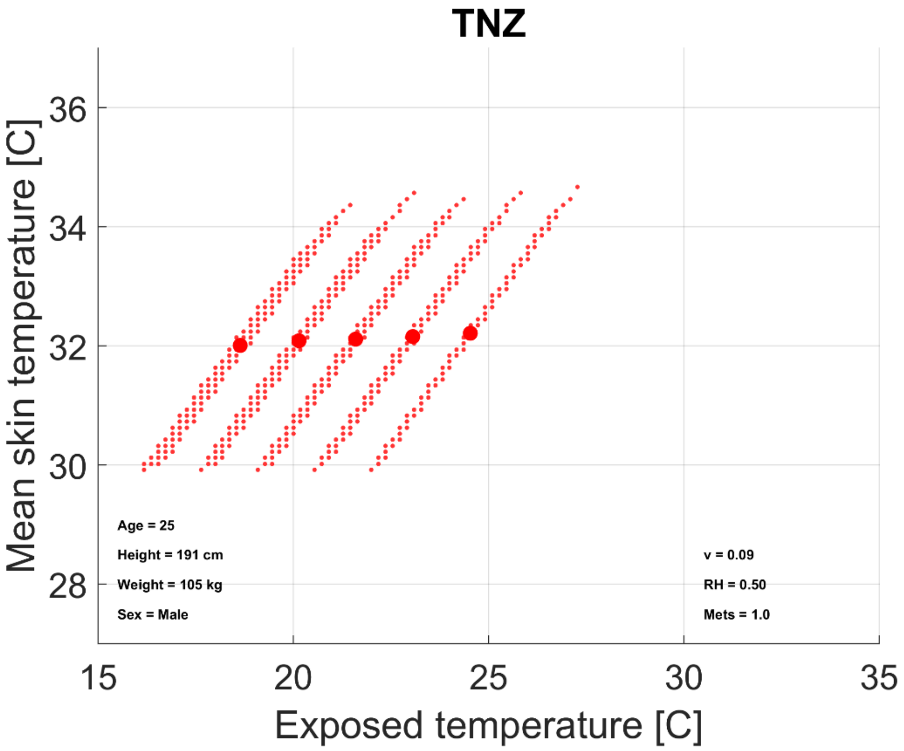


Figure 158 Example of the range of comfortable ambient temperatures at different clo-values – a tall obese man of the age of 25