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Itard, Laure; Ioannou, Taso; Meijer, Arjen; Rasooli, Arash; Kornaat, Wim

Publication date
2016

Document Version
Final published version

Citation (APA)
Itard, L., Ioannou, T., Meijer, A., Rasooli, A., & Kornaat, W. (2016). *Development of improved models for the accurate pre-diction of energy consumption in dwellings*. Delft University of Technology, Onderzoeksinstituut OTB.

OTB – Onderzoek voor
de gebouwde omgeving
Faculteit Bouwkunde

Final report

Development of improved models for the accurate prediction of energy consumption in dwellings

Laure Itard, Tasos Ioannou, Arjen Meijer, Arash Rasooli (TU Delft)
Wim Kornaat (TNO)

17 October 2016

MONICAIR

TU Delft Delft University of Technology

INSTALLATIES 2020

Challenge the future

Development of improved models for the accurate prediction of energy consumption in dwellings

MONICAIR is a research project initiated by the Dutch Ventilation Industry and co-financed by the Dutch Ministry of Economic Affaires within the framework of TKI (Top consortia for Knowledge & Innovation).

Authors:
Laure Itard, Tasos Ioannou, Arjen Meijer, A. Rasooli (TU Delft)
Wim Kornaat (TNO)

17 October 2016
OTB – Research for the Built Environment
Faculty of Architecture, Delft University of Technology
Julianalaan 134, 2628 BL Delft
Tel. (015) 278 30 05
E-mail: OTB-bk@tudelft.nl
http://www.otb.bk.tudelft.nl

MONICAIR

MONICAIR Consortium

Het Moniciar praktijkonderzoek wordt uitgevoerd door toonaangevende producenten, adviesburo's en onderzoekscentra die alle actief zijn in de ventilatiebranche.

Het Monicair consortium bestaat uit de volgende partners:

BRINK Climate Systems	Brink Climate Systems BV
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This research has also been made possible by the participation of Delft University of Technology in the following research programs:

(www.suslabnwe.eu)

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Acknowledgment

This research would not have been possible without the kind collaboration of 32 dedicated households. We would like to thank all of them for their participation in our measurement campaign, their patience when installations or de-installations were delayed, or when the equipment was not working properly and the time they have spent filling the paper logbooks and using the comfort dial. Their commitment contributed greatly to the quality of the research.

Summary

This report presents the results of the second part of the Monicair project[1], which aim was to explore in how far the better determination of a number of parameters, which up to now were measured only seldom, could support the development of better prediction models for the heating energy consumption in dwellings. Energy labelling calculations, as well as energy consumption forecasts, on which energy policies rely, are based on models. In the past years several studies have demonstrated that these models show large deviations from reality, making the prediction of possible energy savings biased. These poor predictions can be hypothesised to be the result of poor estimation of the U–values of walls, poor estimation of the infiltration and ventilation flow rates and poor estimation of the heated surface area and of the temperature preferences of occupants. Additionally, there is very little knowledge on how occupant's perception of comfort influences their ventilation and heating behaviour and finally the total energy use for heating.

This report presents the results of a field study in which monitoring data was collected in order to further analyse parameters that could influence strongly the heating energy consumption and to finally improve energy prediction models. A mix of modern and older dwellings was studied, as this can give a better idea of possible energy savings when renovating dwellings.

In the monitoring campaign the sample was restrained to social housing in order to match earlier research in which most of data was collected for social housing. Furthermore the sample had to be divided into A and F labels and most of housings associations have labelled their dwellings, which is not the case of individual owners. In total 32 houses were monitored between November 2014 and April 2015, ensuring a 6 months monitoring period. These houses had either an energy label A/B or a label F. The label A houses had either a heat pump or a high efficiency boiler, the label B houses all had a high efficiency boiler and the label F dwellings had either a high efficiency boiler or a stove. There were houses with balanced ventilation, houses with natural air supply and mechanical exhaust, and, finally, houses with only natural ventilation. In all houses presence, CO_2 concentrations, temperature and humidity were measured each 5 minutes in all rooms. Gas and electricity were measured at the start of the campaign, at the end and in some houses on a continuous basis as well. The thermal comfort perception of occupants was measured real time during a two-weeks period, using a wireless comfort dial, in combination with a log-book. Additionally, all households had to fill in a survey at the start of measurement period and the dwellings were inspected. The heat resistance (Rc-value) of external walls was measured in-situ in three additional dwellings, in order to determine if the Rc-value was in the same range as the Rc-value estimated in the energy labelling calculations.

In the past, many studies on temperature habits in household were based on surveys. In our survey, almost half of the temperature settings during the day were reported correctly, while approximately one fourth reported too high temperatures and one fourth too low temperatures, both by 1 ^{o}C on average. This shows that when relying on temperature surveys to find correlations between energy use and temperature, one may not find them, while these correlations may be present. Furthermore, even in the case the set point temperatures were correct, these set point temperatures were not an accurate predictor of the actual temperatures measured all along the heating period. However, both

[1] This second part was realized in collaboration with the SuslabNWE project (www.suslabnwe.eu) and the Installaties2020 project (www.installaties2020.weebly.com)

the set point temperatures and the continuously measured temperatures showed in general higher temperatures in A-labelled dwellings than in F-labelled ones.

The continuously measured averaged daily temperature profiles demonstrated a wide spread in the actual temperatures of dwellings. The spread between rooms of one dwelling may also be large. Dwellings with a heat pump had clearly a more constant temperature all over the day than dwellings with boilers or stoves, and also their temperatures in the different rooms were closer to each other. Clear relationships between temperature profile and energy label, ventilation system, number of hours of window opening or number of occupants were not found in our sample, which was rather small. However, it is clear that the temperatures in the bedrooms were in general lower than in the living rooms, but clearly, most bedrooms were heated, also during the night. It is also clear that lower temperature profiles were observed in the dwellings with energy label F (all naturally ventilated) than in the dwellings with label A (all balanced ventilation).

For most mechanical ventilation systems (both balanced and natural supply/mechanical exhaust systems), the flow-rate set points were on the lowest level. In general, the living room and bedrooms were reported to be ventilated through windows or grilles 1-4 hours a day. Most living rooms and bedrooms in dwellings with natural supply/mechanical exhaust ventilation are ventilated longer than 5 hours a day. An important share of people (21 to 50%) report to rely completely on the mechanical ventilation (when present) to ventilate kitchen and bathroom, and notably, also in the naturally ventilated houses more than 28% of people reported not to ventilate the bathroom actively.

No clear pattern between the CO_2 excess hours (threshold 1200 ppm) and the reported ventilation behaviour was found. The household size seems to relate somehow to the excess hours: the larger the household, the more chance to find high excess hours. In our sample the relationship between the CO_2 excess hours and the type of ventilation system was very clear, though. Balanced ventilation systems scored better (i.e. had less excess hours) than mechanical exhaust systems, which scored better than natural ventilation systems. This is in line with the findings from the Monicair report part A, in which the results of another sample of 60 dwellings were described. However, situations with too frequent and too high excess of 1200 ppm were found for each ventilation system or, in other words, despite of the ventilation system. Thus possibilities to improve all the considered ventilation systems need to be examined.

Based upon the combination of motion detection and CO_2-profile, it has been possible to predict presence, also when only slight increases or decreases of the CO_2 concentration are observed. The predicted presence could be explained logically, however, additional validations will be needed in the future. How to construct statistically valid (at building stock level) presence profiles was also demonstrated.

It was observed than, when moving from label A to label F dwellings, the percentage of people experiencing the indoor temperature in winter as being ''too cold'' increases. For the summer the answers concerning overheating are more or less similar in all dwellings, showing that about on fourth of the tenants in the sample experience too high temperature in the summer, regardless of the label. No clear relationship was found between the temperature perception and the type of ventilation system. In general, there were fewer complaints about draft in the dwellings with balanced ventilation than in the other ones and there were more complaints about humidity in the dwellings with natural ventilation. When asked which measure would help to improve their thermal comfort, most respondents in the naturally ventilated dwellings, which were all label F, responded they would like to have a warmer house in winter. Most respondents in the balanced ventilation dwellings, which were all labels A or B wouldn't change anything or would prefer to have faster warm water. In the category of natural supply/mechanical exhaust ventilation, with mixed energy labels, a warmer house and faster warm water where the most often given answers.

The real time comfort perception of the tenants was also investigated. Regardless the facts that a lot of data needs to be analysed further, that the methodology needs to be further developed and that no definitive conclusion could be drawn in this stage of the research, the possibility to measure real time comfort on site and to relate it to real time measureable physical parameters was demonstrated. It was observed that in general people who felt cold at a certain moment were sitting relaxed or doing light desk work, while people feeling warm have been sitting, walking, jogging or running, or a mix of these activities. People who were feeling cold or a bit cool often reported to have set the thermostat up in the last half hour. People who were feeling warm of a bit warm reported quite often to have taken a cold drink or to have set the thermostat down. Not completely expected, but in line with some theoretical studies in literature, no correlation was found between the perceived thermal comfort and the room temperatures. Additionally, the relative humidity was observed to be low in the neutral zone, while it was higher when occupants reported 'warm' or 'cold'. Finally, when people reported 'warm', the CO_2 concentration was higher than when they reported a less warm, neutral or a bit cool feeling. It is of course well known that the comfort zone depends on temperature and humidity, but little is known about the influence of the air quality (CO_2 concentration) on the thermal comfort. Most important, a sensitivity analysis on our data demonstrated that the PMV seems to be able to predict the neutral and cold sensations quite well but not the warm sensations.

The relationship between temperature profile and gas or electricity consumption was not clear. However, the dwellings which consume the most gas are found in the category naturally ventilated dwellings (all label F). The dwellings with balanced ventilation (labels A and B) were not consuming less gas or electricity than the dwellings in the category 'natural supply and mechanical exhaust'. These results show the necessity for an integrated approach, as main parameters like temperature and energy label could not directly be related to the energy consumption. Detailed energy monitoring, with the same time interval of 5 min as the other data, could give better insights in the determinant factors. The detailed analysis of a number of cases made clear that there seems to be room for improving the energy behaviour of households, either by making them aware of the actual temperature in their dwellings, or by reducing it gradually or by changing ventilation habits, although one should be very careful with the last option not to lower the indoor air quality. It was also shown that not only behaviour may be held responsible for high temperature levels, but also the tuning of the system itself, especially when heat pumps and floor heating are used.

The measurement of external wall's thermal resistance was carried out using a transient method, the EPM method, which was fine-tuned during the project and applied to three different dwellings. The EPM method offers the advantage of being very quick in comparison to the current ISO standards for which weeks of measurements are needed. A very good agreement was found between these standards and the EPM method. For two of the three cases the heat resistance of the walls (Rc-values) showed to be extremely underestimated (by more than 70%) in comparison to the standard values from the Dutch energy labelling method.

Finally, recommendations for the improvement of energy simulation models, based on the data collected and earlier studies, were made separately for dynamic models and for regulatory models. For both types of models it was stated that current problems were not caused so much by flaws in the models themselves than by the inaccuracy of the estimation of the input parameters to the models.

For dynamic models (like ESP-r, Energy+ ,TRNSYS, VA114, etc.), it was recommended to improve the quality of the patterns relating to presence, activities in house, thermostat settings and ventilation settings for each zone of the house. Possibilities to relate these data to household types and thermal comfort perception should be researched further. The better determination of ventilation and infiltration flow rates was also argued to be necessary, as well as the better determination of wall's thermal properties and further in-situ studies on thermal comfort.

For regulatory models like the energy labelling one, it was recognize that their aim is to assess the performance of buildings under standardized conditions in order to, on the long term, improve the thermal quality of the building stock. The predictions of these models do not need to be accurate case by case, but must be *on average, at the level of the building stock,* accurate enough in each label or energy index category. The actual inaccuracy of the average predictions, which furthermore differs strongly in each label category, leads to large bias in expected energy savings and can be perceived as misleading by building owners and renters and by those who are willing to thermally renovate their house. Improvements of the models on the subjects of standard values for average temperature and heated area, standard values for presence home, standard values for ventilation, infiltration flow rates and efficiency of heating systems were discussed as well as the revision of the standard U-values of walls, roofs and floors.

As expected, because of the small size of the sample and the experimental character of the measurements, it has not been possible to deliver representative results. The research, however, demonstrated why the type of measurements carried out within Monicair, SuslanNWE and Installaties2020 will be needed in future. A step into the development of analysis methods using large scale monitoring data was made. This is important because large sets of data coming from home automation systems are expected to become common practice in future. However, at the moment of the Monicair study, the meaning of these data for energy simulation software and for a better understanding of the complete home energy system (including building envelope, HVAC, use of the house, thermal behaviour and comfort preferences) had not been studied yet. Although not all collected data could be analysed within the framework of the project, and although the findings were not always conclusive, this study shows the potential of such measurement campaigns. The development of methods for the rapid in situ measurement of U values and for the measurement of the real time comfort perception of occupants, are results that are worth being mentioned as well. It is recommended to go on with such measurement campaigns in order to collect the data and to develop further the methods that are needed for a better understanding and prediction of the home energy system.

1 Introduction

The built environment is responsible for about 40% of the total energy use in Europe. Of these 40%, more than half relates to space heating. European and national regulations like EPBD and specific parts of building codes aim at reducing the energy consumption of buildings. To reduce their heating needs, new and renovated buildings are generally made air-tight, meaning that natural air flow rates by infiltration are minimized. Because of this, the indoor air quality relies for a large part on the quality of the (mechanical) ventilation system.

In the first part of the Monicair research, reported in Holsteijn & Li (2014) and in Kornaat & Joosten (2015), the air quality in each room of dwellings has been studied for several ventilation systems. This study aimed at modern well insulated and air-tight dwellings in which the researchers made sure that the ventilation systems were designed according to the current Dutch norms and were installed properly. 62 dwellings with in total 10 different ventilation systems were measured during more than one year and analysed. The main results of this study are that although the measured ventilation flow rates are large enough to avoid poor air quality, very high CO_2 concentrations and excess hours were observed regularly indicating that the CO_2 is not removed at the place it should be removed. Very large variations between systems were observed, with poorer air quality in completely naturally ventilated houses and better air quality with mechanical ventilation systems where exhaust valves are present in all rooms. It was also observed that low air-tightness does not lead to better air quality because the air leakages are not located at the place where the CO_2 is produced (the living area). Furthermore, it was noted that occupants generally, even when the CO2 concentration is very high, do not use the switch of the ventilation system to increase ventilation or undertake any other action. Finally it was shown that ventilation systems with mechanical supply and exhaust and heat recovery were performing better on air quality and low energy use than the other systems. Systems with CO_2 control were performing worse than systems without CO_2 control except for the systems having CO_2 control at room level instead of a central one.

Kornaat & Joosten (2015) further used the measurement results to validate and improve simulation models for ventilation. They found that it was possible to predict well the CO_2 concentrations at room level, on condition that the input parameters to the model, and in particular occupant behaviour, are correctly determined. It has been possible to characterize the use of ventilation grilles, windows and inside doors and to show, for one system, that the high CO_2 concentration observed were not the result of a wrong use of the ventilation grilles.

This report is about the second part of the Monicair research, which aim was, elaborating on these first results, to explore in how far the better determination of a number of parameters, which up to now were measured only seldom, could support the development of better prediction models of the heating energy consumption in dwellings. Energy labelling calculations, as well as energy consumption forecasts, on which energy policies rely are based on models. In the past years several studies have demonstrated that these models show large deviations from reality, making the prediction of possible energy savings biased. Majcen et al (2013) shown that these poor predictions can be hypothesised – on the basis of a sensitivity analyses- to be the result of poor estimation of the U–values of walls, poor estimation of the infiltration and ventilation flow rates and poor estimation of the heated surface area leading to a poor estimation of the average indoor temperature. Additionally, there is very little knowledge on how occupant's perception of comfort influences its ventilation and heating behaviour and finally the total energy use for heating.

This report presents the results of a field study in which monitoring data was collected in collaboration with two other projects (SusLabNWE (Interreg, www.SusLabNWE.eu) and Installaties2020 (SIA RAAKPRO, www.installaties2020.weebly.com)) in order to further analyse parameters that could influence strongly the heating energy consumption and to finally improve energy prediction models. Opposite to the first part of the Monicair research, the second part is not restricted to modern dwellings but also accounts for older dwellings, as their actual energy performance is essential to determine possible energy savings. Data collection and analysis was made by TU Delft. The analysis in chapter 6.4 was made by TNO, who also contributed to the whole chapter 6 and reviewed the complete report.

The aim of the research is not to deliver representative results (the studied sample, accounting for 32 houses is too small for this) but to explore in how far a number of parameters, which up to now were measured only seldom, could explain the large deviations observed between actual and predicted energy consumption.

In chapter 2 (deliverable D2b1), the state of the art about current models is given, as well as an overview on current insights on the relationship between building characteristics, occupant behaviour, comfort and energy performance. In chapter 3 (deliverables D1b1, D1b2 and D1b3) the monitoring campaign is described. In chapter 4 and 5 (deliverable D1b4 and D1b5) basic descriptive statistics of the sample are given and the comfort perception of the occupants is analysed using the survey data. Chapters 6 to 10 (deliverable D2b2) analyses in detail the monitoring data on the subjects of CO_2 concentrations, temperature profiles, presence home, comfort perception, actual heat resistance of external walls and their relationship with energy use. This analysis is used in chapter 11 (deliverables D2b3 and D3b1), where future improvements of the models presented in chapter 2 are discussed, as well as recommendations for norms and regulatory energy calculation methods. Final conclusions and recommendations are drawn in chapter 12.

2 State of the art models for the prediction of heating energy in dwellings

2.1 Introduction

Models have been used for years now to predict the energy consumption of dwellings. These models are used by consultants and architects as support to building design, in order to size the heating, ventilation and air-conditioning equipment (HVAC), and to optimize the building design itself on the subjects of lighting, energy use or comfort. Researchers also use models to test the performance of new components or solutions or to compare different design options. Examples of well-known and validated models are TRNSYS, ESP-r, Energy+, VA114 etc. It is also well known that the use of these models in practice requires first an extensive and time-consuming calibration procedure because the results are highly dependent of the quality of the input variables to the model. These input variables may be very difficult to collect or estimate. For instance, it is difficult to estimate the air flows by infiltration and data about the presence pattern of occupants are missing. Both have a substantial effect on the calculated energy consumption. Additionally, many assumptions have to be made on how the occupants use and control the technologies simulated (e.g. the lighting or the opening of the windows). Generally, very little is known on this subject.

The level of details needed in aforementioned models is such that they can hardly be used to simulate groups of buildings or the building stock. Generating the needed input data to the model would be an impossible task in terms of time and money. That is why models that are used as support for energy policy studies, or for energy labelling, are generally simplified ones in which the number of input variables is strongly reduced. For instance the model is static instead of dynamic, or the whole building is modelled as one zone instead of multi-zones (the rooms). There is a trade-off between the quality of the model and the quality of input parameters. An accurate model needs detailed input data that are impossible to collect at the needed level of quality. Therefore the benefit of an accurate model is lost by the resulting inaccuracy of the input data. Input data for simplified models is much easier to collect at the desirable level of quality, but the benefit of this is counteracted by a possible lack of accuracy of the simplified model.

In the past years several studies have demonstrated that the models used for energy labelling show large deviations from reality, making the prediction of possible energy savings biased. According to the above, the causes of these deviations relate either to the quality of the model itself or to the quality of the input to the model.

2.2 Observed problems with current models

In this section the focus is on the Dutch energy labelling model, as described in ISSO 82. Up to a few years ago the evaluation of the actual effects of the enforced energy labelling has been hindered by the lack of publicly accessible databases (Perez et al., 2008) containing the information on label certificates on one hand and information about the actual energy consumption of the individual dwellings on the other. That is only since 2010 that these databases have been ready for use in the Netherland, who is a forerunner on that subject.

The studies that have so far been carried out have indicated a discrepancy between the actual and theoretical consumption rates of dwellings, in the Netherlands as well as elsewhere in Europe (Laurent et al, 2013). Recent studies by Cayre et al. (2011) in France, Hens et al. (2010) and Delghust (2015) in Belgium, Sharpe and Shearer (2013) in Scotland and Guerra Santin (2010) and Majcen (2013a, 2013b, 2014) in the Netherlands all showed that actual energy consumption levels were lower in reality than had been predicted theoretically in dwellings with poor labels. The better the label of the dwelling, the smaller the difference between theoretical and actual energy consumption levels. However, in dwellings with very good labels, actual energy consumption can be higher than theoretical levels. For example, Haas and Biermayr (2000) in Austria and Branco et al. (2004) and Khoury (2014) in Switzerland showed that the theoretical energy consumption in dwellings with good labels tends to be lower than is actually used. The disparity between the energy use predicted by the calculation model (theoretical consumption) and the energy use of those buildings in operation (actual consumption) is also referred to as the performance gap (de Wilde, 2014). Figure 2.1 shows the results obtained by Majcen (2013) on a sample of almost 200.000 Dutch dwellings.

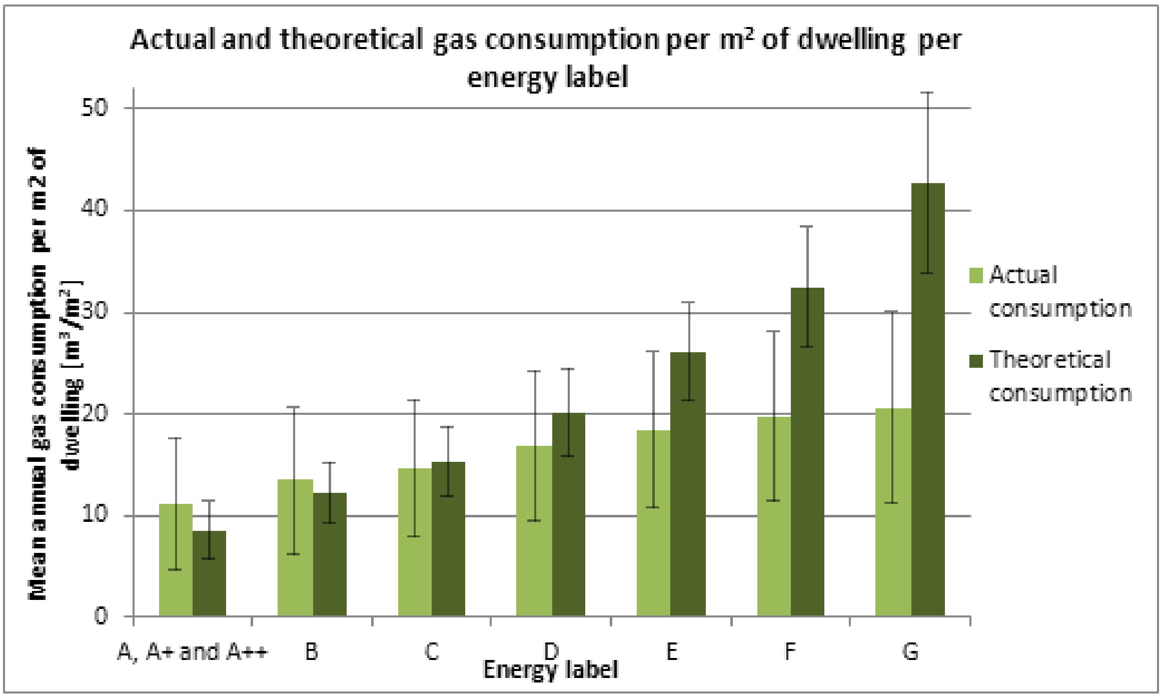


Figure 2.1: comparison of the gas consumption predicted by the Dutch energy labelling model (theoretical consumption) and the actual consumption corrected for degree days, per label category and with 95% confidence intervals (n=193.856).

This performance gap is caused as much by the factors influencing actual energy consumption as it is instigated by the calculation model itself. Unrealistic normalization assumptions can cause the theoretical consumption calculations to be severely flawed. As an example, the Dutch methodology assumes an indoor temperature of 18 degrees over the whole floor area during the entire heating period, while many older Dutch dwellings lack a heating unit in the bedrooms and cannot possibly maintain such a temperature over the winter. The current way in which the model represents reality is inaccurate –either by the model itself or by the input parameters and can be improved by understanding the influencing parameters. This would be also beneficial to other more sophisticated models.

In the following sections a summary is given of the knowledge collected during the past 5 years at Delft University of technology, department OTB-Research for the Built Environment. The findings can be found in Guerra Santin & Itard (2009, 2010a, 2010b, 2012), Majcen & Itard (2013a, 2013b, 2014, 2015, 2016), Ioannou & Itard (2014), Filippidou et al. (2015), with a lot additional literature. The data by Guerra Santin was collected during a field study with more than 250 buildings. The data by the other authors have been collected using several large databases: the national energy label database from RVO (200.000 cases at the time of the study); the SHAERE database of Aedes (~ 2 million of dwellings); subsamples of the SHAERE database varying from a few thousands to a few hundreds of thousands cases; a sample of dwellings from the municipality Amsterdam containing around 9000 renovated dwellings; an occupant survey conducted with the Rekenkamer Amsterdam with almost 1000 respondents; the actual energy database of CBS, containing the yearly gas and electricity use, as reported by the energy companies, of almost all dwellings in the Netherlands and that was coupled at address level to the other databases; several CBS databases with socio-economic data's of households at address level.

Furthermore, in Majcen (2016a, 2016b), the heating energy consumption of a few ten thousands of dwellings renovated between 2011 and 2013 was followed before and after renovation. The results of these so-called longitudinal data analysis showed that most of the renovations are expected to yield larger energy reduction than what materialises. On average in all renovated dwellings, actual gas reduction is about a third lower than expected, however, there are big differences in the energy savings obtained from individual measures. The sample was large enough to identify reasonably large samples of dwellings in which only one renovation measure was taken, which proved to be very useful to assess the efficiency of these individual renovation measures.

2.3 Performance gap: relative influence of building characteristics and occupant behaviour

In all regression analysis performed in order to find out explanations for the differences between theoretical and actual consumptions, it was found that building characteristics (including HVAC) have a much large explanatory power than occupant behaviour and household characteristics. The two last ones have a non-negligible explanatory power, but it is rather low (around 9%, varying between 3 and 15%, although some authors claimed in the past higher potentials, up to 30% or even 80%, which was not validated by our studies). The fact that building and HVAC characteristics dominate the performance gap emphasises the importance of the assumptions made in the calculation method and the values used as input to the model. However, it is also likely that the behavioural parameters that can be studied in large samples do not catch the impact of occupant behaviour sufficiently.

It was also shown that the variables with explanatory power are different when there is underprediction of energy use and when there is overprediction. Basically, in dwellings where the gas consumption is overpredicted (generally the dwellings in poor label categories, see figure 2.1) 51% of the variance was accounted for by dwelling and installation type, age of the building, floor area, and indoor temperature. Furthermore, reported comfort was also a significant predictor. In dwellings where the gas consumption is underpredicted (generally the dwellings in good label categories), only 20% of the variance could be explained and the factors with the highest explanatory power were presence patterns, presence of a programmable thermostat and having or not a water saving shower head.

2.4 Influence of building characteristics

In general the influence of building characteristics is high. In terms of dwelling type, semi-detached houses have the highest performance gap, followed by flats with a staircase entrance, detached houses and finally, gallery flats. The analyses showed that floor area does not affect the performance gap strongly.

The heat resistance of construction elements was shown to have a big impact on the accuracy of the prediction (Majcen 2010a). The fact that this heat resistance is almost never measured, but generally guessed based on the construction year, may lead to a very faulty estimation of the energy consumption due to an inaccurate estimation of the insulation. This likely occurs in many old dwellings, where documentation is not available. A recent paper by Rasooli et al. (2016), in which the heat resistance of three different walls (in the Netherlands) was measured showed that this heat resistance was in reality much higher than assumed in the energy labelling calculation and could explain for a part the gap in dwellings with poor energy labels. Similar results were obtained in UK (Francis et al, 2015). Basically, older dwellings seem to be much better insulated than assumed in the energy labelling regulations.

A longitudinal study in renovated dwellings confirmed the significant influence of insulation value by showing that the largest performance gaps appear in dwellings with poor envelope insulation, followed by those by poor window insulation. The energy prediction was much better after renovation than before. Basically it was shown that overestimation of the energy savings by thermal renovation originates to a large extent from the overestimation of the energy consumption before renovation. However, it could not be excluded that a differing behaviour of the occupants before and after renovation could also have some influence. In Majcen (2016a, 2016b), an inventory of the quality of the energy prediction per insulation category can be found for envelope insulation and for windows.

2.5 Influence of HVAC on performance gap

Regression analysis has shown that heating system and ventilation types both have an explanatory power on the heating energy. The performance gap differed in dwellings with different installation types (Majcen 2015). Dwellings with a local heater in the living room (gas stove) have the highest performance gap, followed by combined boiler with η<83 % (CR boilers) and then each higher efficiency boiler have a smaller performance gap.

In the longitudinal study were renovated dwellings were followed (Majcen 2016a) it does seem again that the heating energy of dwellings is better predicted after renovation than before, meaning that theoretically better performing installations are better predicted. Some interesting findings are worth to be highlighted:

- The predictions for local gas heater are very poor as are the predictions of gas savings when upgrading these heaters. This phenomenon is thought to arise from the definition of the normalized heating area in the energy labelling calculation method. When a local gas heater is installed, the heated surface area is much smaller than indicated in the method.
- Improvements within the category of non-condensing boilers (η<83 (CR) and η>83 (VR)) are reasonably well predicted and seem to generally lead to more savings than expected.
- Improvements within the categories of condensing boilers (η< 90 to η< 96 (HR)) were found, and although the results are not completely conclusive (large 95% confidence interval), these improvements seem to lead to more savings than expected.
- However, improvements between categories (from non-condensing to condensing boiler) were poorly predicted.

Heat pumps were excluded from this study, because the study concentrated on gas use. Considering the ventilation systems, a sensitivity analysis (Majcen 2013b) has shown that increments in ventilation rates (up to 40% smaller or larger than current assumption) can explain the performance gaps in energy label classes A to C, but only partly the performance gap in lower labels. When following renovated dwellings in which only the ventilation system was changed (Majcen, 2016), energy savings when changing from natural to mechanical exhaust ventilation (4479 cases) were found to be at least three times as high as expected. The theoretical gas consumption barely reduces after the renovation, while the actual gas consumption dropped. When looking at the calculation method this makes sense, since mechanical and natural ventilation both use exactly the same air flow rates. It was observed that the performance gap after renovation was higher than before, indicating that the actual ventilation flow rates are much smaller when mechanical exhaust is used than with natural ventilation. It could therefore be that the energy savings are obtained at the expense of indoor air quality.

Opposite, when changing the system from mechanical exhaust to balance ventilation (279 cases), high theoretical reductions were obtained because of the heat recovery, while the actual reduction was by far much less (5 times lower), which could indicate that heat recovery does not work at the rate assumed by the calculation method. However, some doubts were also raised about the quality of the input data in SHAERE. It couldn't be excluded that balanced ventilation systems were mistaken for mechanical exhaust systems and vice versa.

2.6 Influence of household characteristics

Household characteristics and occupant behaviour are two different notions. Household characteristics are socio-economic parameters like household size, incomes, age, being employed or being present a lot home. This parameters form the context in which occupants behave and therefore may influence their thermal behaviour.

The study by Guerra-Santin (2010) indicated that the hours of presence home was a good predictor of heating energy. The presence of elderly in the household proved to be a determining factor in the way of using heating system and ventilation. Elderly used more intensively both. The presence of elderly was also associated with the number of hours spend at home. The presence of children had a significant effect on ventilation use (people with children ventilated less). Other characteristics related to a more intensive use of the heating system were average education levels compared to high education levels and having previously lived in a single-family dwelling.

The simulation study in Majcen (2013a) showed that the number of occupants in the house had an influence on the prediction gap, but this influence is much smaller than the one of buildings and HVAC characteristics. This influence is much more important for electricity consumption than for heating consumption (Bedir et al. 2013). Number of occupants, salary, price of the house and type of ownership (rental of owner-occupied) has also been found to influence the actual heating energy consumption. The study from 2015 indicated again that number of occupants, but also education level and reported ability to pay the energy bills were correlated to the heating energy consumption.

2.7 Influence of occupant behaviour

Occupant behaviour, in terms of building and HVAC use, is not an easy parameter to catch in large scale studies. Furthermore the delimitation between occupant behaviour and characteristics of heating and ventilation systems is not clear and may lead to confusions. For instance the fact that the indoor temperature seems to be higher in modern houses than in older ones is not necessarily a consequence of behaviour like rebound effect (people allowing themselves to use higher indoor temperatures because they know the house is well insulated). It can also be the consequence of the heating system itself: in modern houses low temperature systems are used much more often than in older houses. These low temperature systems (e.g. heat pumps with floor heating) must generally be maintained 24 hours a day at a constant temperature and can often not be controlled per room, leading automatically to higher indoor temperatures than would be achieved with a conventional system with boiler and radiators in each room. These higher indoor temperatures have in that case little to do with occupant behaviour.

Majcen (2013a) showed in a sensitivity analysis, that an indoor temperature 2,7 degrees higher than assumed by the labelling method (18 degrees) can explain the performance gap observed in label A and an indoor temperature 5,6 degrees lower than 18 degrees can account for the gap in label G. Both these temperature deviations are realistic, since people in well insulated dwellings could be suspected to heat their house more due to the small increment this causes in their monthly bill (rebound effect). However, it was observed that the installation system itself might be encouraging the occupants to heat more or less with for example low temperature floor heating installation in case of A labelled dwelling and with a local gas stove placed only in the living room in case of dwelling G. In the normalised calculation, all rooms are assumed to be heated.

The importance of the technological component of behaviour was also stressed by Guerra Santin (2010), who indicated that, in comparison to households having a programmable thermostat, in households having a manual thermostat the temperature at night time was lower, the radiators were on fewer hours and people ventilated less.

In a study by Ioannou & Itard (2015) it was shown using a Monte-Carlo sensitivity analysis that if behavioural parameters are not taken into account, the most critical parameters affecting heating energy consumption are the window U value, window g value (solar factor) and wall conductivity. However the most important finding was that when behavioural parameters like thermostat use and ventilation habits are added to the analysis, they dwarf the importance of the building parameters.

Delghust (2015) analysed in his thesis for the first time temperature profiles at room level in a large amount of different houses. Large variations in heating and ventilation profiles were found, but clearly more lavish profiles were found in the better performing houses (the more modern ones), especially in houses with low temperature central heating systems. Additionally he showed that variations of technical characteristics of the ventilation systems (e.g. nominal ventilation flow rate) had more effect than variations in control settings chosen by the user. He also showed that the Belgian regulatory performance assessment method overestimates the ventilation flow rates in old houses with natural ventilation because it doesn’t take into account the fact that the windows that are opened are meanly those of the unheated bedrooms. He therefore stressed the importance of multi-zone modelling.

Finally, in the first part of the Monicair project, Kornaat et al (2015) studied the influence of the use of grilles, windows and indoor doors on the CO_2-levels in houses with different ventilation systems. Too high CO_2-levels were shown not to be the result of an insufficient use of the grilles. It was also demonstrated that the mechanical ventilation systems were not controlled (by switches or buttons) by the household members like assumed in the regulations and in the supporting models. In fact, the mechanical ventilation systems seemed not to be controlled at all and to be always in the lowest position.

2.8 Influence of comfort perception

There is very little known about the influence of comfort perception on the heating energy consumption. Majcen (2015) showed in a sample of a few hundreds of dwellings that households who consider their dwellings to be too cold consumes significantly more gas than the households who consider the dwellings' temperature to be good. This raised the question of the influence of comfort experience on the heating energy use. It was shown that there was no correlation between feeling cold and having lower or higher reported temperature set points but in Majcen & Itard (2014) it appeared that most people feeling cold were living in houses with poor energy labels. Apparently, people in the sample heat their house at a 'usual' temperature level, but still feel cold because the operational temperature (the resultant of the radiation temperature from the walls/floor/ceiling and the air temperature, according to Fanger's comfort theory) is low because the walls/floor/ceiling temperature is low due to poor insulation.

Next to the comfort perception, it was shown in Majcen & Itard (2014)that people perceiving themselves as begin energy conscious were using less electricity that people perceiving themselves has having an average energy behaviour. This couldn't be found for the heating energy, probably because of the small size of the sample.

In a study by Ioannou & Itard (2015) it was demonstrated on the basis of a Monte-Carlo analysis that the most influential parameters for comfort (measured as PMV index) were metabolic activity and clothing, while the thermostat had only a secondary impact. Obviously the thermostat settings push both energy consumption and PMV upwards (except for the low temperature floor heating system, for which the thermostat settings are off-set by the control systems and the fact that the response time in such a system is very long). The parameter that influences heating the most was shown to be the thermostat. Therefore the thermostat plays a large role in the heating energy and a minor one in the sensation of thermal comfort. It was argued that people may be trying to regulate their comfort by adjusting the thermostat which could result in an increase in heating consumption but will not necessarily produce an increase in the occupants 'comfort because this comfort is essentially sensitive to metabolic activity and clothing.

2.9 Conclusion

This chapter demonstrated that there is a clear gap between actual and theoretical consumption in dwellings. Regarding the causes of the discrepancies, they can party be explained by the features of the dwelling itself, meaning that the input of calculation model does not represent the reality accurately. The results seem to indicate that overprediction relates strongly with the fact that older installation and ventilation systems and the dwelling itself perform differently than expected. There is a need to generate better input values for the heat resistance of walls, floors and ceiling and for infiltration and ventilation flow rates. Underprediction on the other hand is more difficult to explain and probably more dependent on occupant practices than on the accuracy of the standardisation model. The behavioural part is difficult to quantify statistically. A part of the discrepancy between actual and theoretical consumption arises from too little knowledge on household and occupant behaviour: what are the temperature and ventilation preferences of different groups of people in different rooms and how do these preferences relate to physical building and HVAC characteristics? How does the thermal comfort sensation impact these temperature preferences and the heating energy consumption?

The study presented in the next chapters aims at testing a methodology to give answers to these questions.

3 Monitoring campaign

Of course, not all variables from chapter 2 could be tested within the framework of Monicair. It was also not the aim of the monitoring campaign to produce statistically valid data for input parameters of the energy labelling model, like average indoor temperature or presence patters. The monitoring campaign serves the major goal of testing if it is possible to find out causalities between the measured parameters (presence, comfort, temperatures, CO_2 concentrations, humidity) and building or HVAC characteristics, causalities between theses parameters and the energy consumption and finally to test how to develop patterns of use that can be used in building simulation models.

In this chapter, the design of the monitoring campaign is explained first, followed by a description of the four data acquisition sets used, a description of the surveys and inspections and a description of the databases. Finally the practical realization of the monitoring campaign is described.

The monitoring campaign is refereed as Ecommon campaign (Energy & Comfort Monitoring). The web site for the occupants can be found at www.otb.tudelft.nl/ecommon.

3.1 Initial design of the monitoring campaign

In the first stages of the research design there were many options on the classification of the dwellings: energy class, income of the tenants, type of heating system or type of ventilation system and the thermal envelope of the building. The data that were planned to be gathered could be categorized in two big groups: data related to comfort and additional data related to energy consumption of components and energy systems. Data related to comfort were the air temperature, radiant temperature, humidity, air speed, CO_2 concentration, natural light, wall/floor/ceiling temperatures and controls of windows, doors, blinds, curtains, thermostats, fans and electric heaters. Additionally it was planned to collect the total electricity consumption of the dwellings, the total gas and water consumptions, hot water and boiler (if not combined) supply and return temperatures, energy consumption of fans, pumps and boilers. The initial design of the measurement campaign can be seen in figure 3.1.

In order to be able to address energy labelling models, the classification of the buildings was decided to be based on the labels of the dwellings and for that purpose two extremes were chosen, class A and class F dwellings. Class F was chosen instead of G because from the studies in chapter 2, it appears that there are little dwellings in category G. Further in the classification process these two groups were divided into two subgroups each. The class A dwellings were split into a group with efficient boilers and a group with heat pumps. The class F buildings were split into a group with efficient boilers and one with old inefficient boilers. These subgroups in turn were divided again into groups of houses with manual and programmable thermostat except for the group containing heat pumps as only one type of thermostat was used. The groups are described in the upper part of figure 3.2.

The lower part of figure 3.2 shows that the campaign was divided in 4 periods of 3 months each, from September 2014 to March 2016. For each period of 3 months the total amount of houses that would be equipped with sensors was 60. The reason for this was the limitation in the number of measurement sets available. The data used for Monicair would be the data up to March 2015, resulting in a sample of 120 dwellings. As will be described in section 3.5, due to the limitations of the equipment, only 32 dwellings were measured in the end.

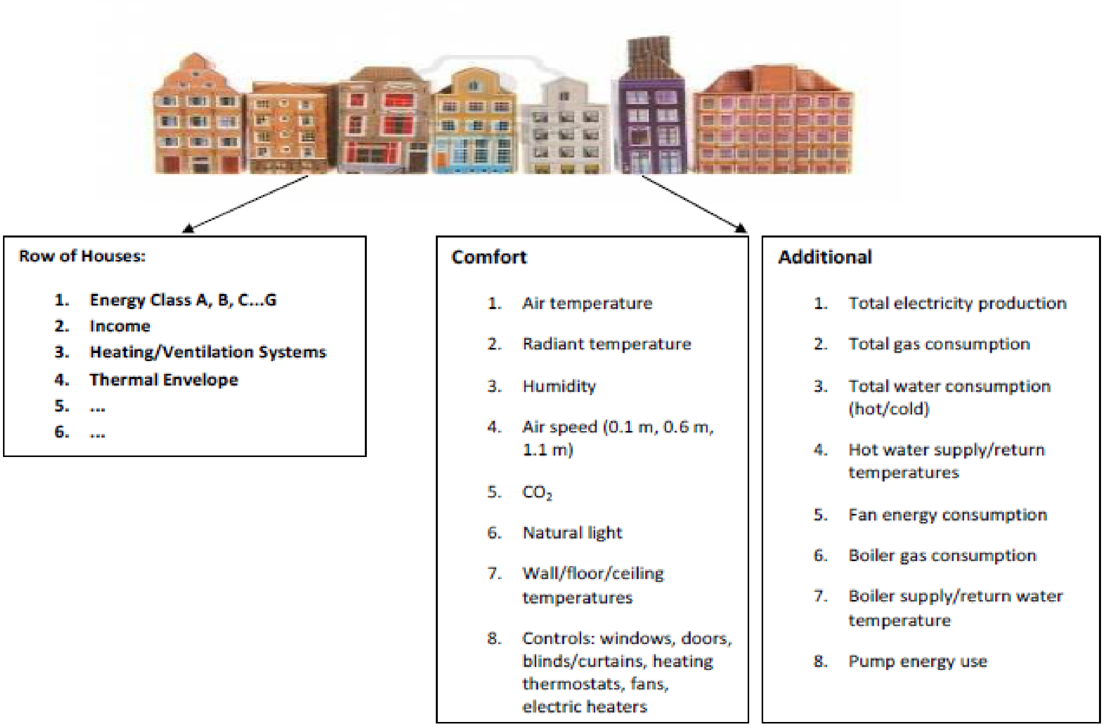
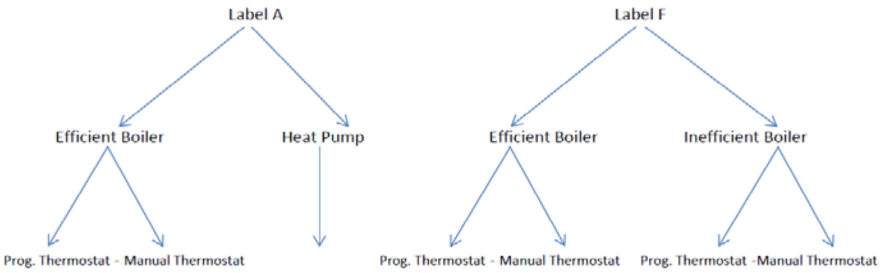


Figure 3.1: Initial research design for the Ecommon campaign, classification of dwellings and data planned to be gathered.



	Label A			Label F			
	Efficient Boiler		Heat Pump	Efficient Boiler		Inefficient Boiler	
	Prog. Thermostat	Manual Thermostat		Prog. Thermostat	Manual Thermostat	Prog. Thermostat	Manual Thermostat
October-December 2014	15	15		15	15		
January-March 2015	15		15	15		15	
October-December 2015			30			15	15
January-March 2016		15	15		15		15

Figure 14: Initial group formation for the dwellings that would participate in Ecommon measurement campaign.

3.2 Data acquisition equipment

3.2.1 Indoor climate parameters: Honeywell set

The system that was used to gather temperature, relative humidity, CO_2 and presence data was a custom made combination of sensors developed by Honeywell. The same set of sensors was used in part A of Monicair. The sensors for temperature, humidity and CO_2 were all fit in a single box that was installed in every habitable room (living room, bedrooms, study room and kitchen) of each of the houses that participated in the measuring campaign (figure 3.1). This box was not powered by batteries and had to be plugged in the electricity system of the house.

Figure 3.1: Temperature, Relative Humidity and CO_2 sensor box

The CO2 was an NDIR type sensor with +/- 50 ppm accuracy. NDIR sensors (nondispersive infrared sensors) are simple spectroscopic sensors that are widely used as gas detectors. An infrared lamp directs waves of light into the atmospheric sampling chamber of the sensor. A filter, with an infrared detector, blocks all the other wavelengths of the light that are not absorbed by the CO2 while the remaining wavelength is absorbed by the CO2 molecules. Next, an infrared detector measures the light that is not absorbed by the CO2 molecules and the difference between the total amounts of infrared light the infrared lamp directs into the sample chamber enter and the amount of light received by the detector gives the concentration of CO2.

The humidity sensors were based on the capacitive sensing principle. They consist of a hygroscopic dielectric material (in this case thermo set polymer) placed between a pair of electrodes forming a small capacitor. In absence of moisture, the dielectric constant of the hygroscopic dielectric material and the sensor geometry determine the value of capacitance. At equilibrium conditions, the amount of moisture present in a hygroscopic material depends on both the ambient temperature and the ambient water vapour pressure. This is true also for the hygroscopic dielectric material used on the sensor. By definition, relative humidity is a function of both the ambient temperature and water vapour pressure. Therefore there is a relationship between relative humidity, the amount of moisture present in the sensor, and sensor capacitance. This relationship governs the operation of a capacitive humidity instrument.

The temperature sensors used were silicon temperature sensors. These are common forms of sensors used in electronic equipment. It can be integrated into a silicon integrated circuit and the principle behind the sensor is that the voltage of a silicon diode is temperature dependent.

For the measuring of the relative humidity in the bathroom, a separate battery powered sensor was used. The reason behind this was safety of the tenants participating in the measurement campaign, the presence of plug in cables in a wet environment such as the bathroom could pose potential threats for the tenants and therefore a battery model of the same relative humidity sensor was used.

For the presence detection a PIR (passive infrared sensor) sensor was used similar to the ones that are commercially available for home security (figure 3.2). These sensors are detecting the infrared radiation that is emitted or reflected from another object. Humans are emitting heat in the form of radiation which is captured by the PIR sensor. In order to ensure that the radiating heat that was detected was emitted by humans, the sensor was built with animal immunity systems in order to avoid presence data which belong to animals instead the human tenants of the dwellings.

Figure 3.2: PIR sensor mounted above a door

The placement of the sensors was quite a challenging task since there are many limitations on how and where to install the sensors in order to gather data that describes the real indoor environment of a dwelling. In that sense the T, Hu, and CO_2 sensors box was always mounted on non-external walls, at least 1.5 meters height and 0.5 meters from the adjacent walls. Moreover the sensor box was installed on parts of the wall that were not coming in contact with direct solar radiation and away (as much as possible) from bookshelves, alcoves, lamps, radiators and chimney walls. Furthermore the sensor boxes were not installed directly next to doors or windows or behind curtains.

The frontal detection pattern of the PIR sensor can reach up to 11 meters and the rear detection pattern (as measured from 2.3 meters height) can detect movement in an area that starts almost immediately under the sensor and reaches up to the 11 meters of the frontal detection pattern. This means that in rooms were the distance between the walls is equal or smaller than 11 meters the best place to mount the sensor is one of the upper corners (2.3 meters of higher) of the room. In the case of larger rooms (large living rooms, combination of kitchen-living room, L shaped rooms etc.) a combination of sensors could be used

The measuring frequency of all the sensors was 5 minutes. This means that the value that was recorded for every 5 minutes interval was the average value for temperature, relative humidity and CO_2 for these 5 minutes. Temperature was recorded in ^{o}C, relative humidity in % and CO_2 in ppm (parts per million). The PIR sensor data were in binary form (0 and 1), 0 zero means that in the specific 5 minutes interval no movement was detected while 1 means that for a specific 5 minutes interval there was at least 1 time movement recorded.

3.2.2 Electricity consumption of appliances: Eltako

Parallel to the Honeywell sensors, another type of wireless sensor was installed in each of the dwellings of the Ecommon measurement campaign. This sensor was developed by Eltako Electronics for measuring electricity consumption of specific installations. Although in principle the device could measure electricity consumption of every appliance (television, coffee machine, toaster etc.) its large size, figure 5, makes it more suitable for measuring the consumption of larger home installations such as a balance ventilation system or a boiler. In our case the sensor was used for measuring the electricity consumption of the pump of the combined heat and hot water boiler, see figure 3.3. The idea was that by combining data on gas consumption and data on the pump, we should be able to differentiate between space heating and tap water heating. In houses with a balance ventilation system, the Eltako was also used to measure the electricity use of the ventilators and in houses with heat pumps it was used to measure the specific electricity use of the heat pump.

Figure 3.3: Eltako Electricity meter used for measuring in real time the combi-boiler's pump energy consumption

3.2.3 Gas and electricity consumption: Youless

Apart from the atmospheric data (T, RH and CO2), presence, and electricity of the combi-boiler's pump, ventilation and heat pump, the total electricity consumption of each dwelling was monitored in real time with the Youless system. The Youless energy meter can be attached on the electricity meter (figure 3.4) and its sensor can count the number of pulses that the meter is emitting. Its technology allows it to work with analog, dial gauges, as well as newer digital meters, which was very important in this project, as we expected to have almost no smart meters in the sample. A specific number of meter pulses each time interval (minute, quarter, hour etc.) is related to a specific number of kWh. The Youless sensor counts the amount of pulses, translates them into kWh of electricity consumption and then stores the data online. The Youless energy meter plugs into a home network using the supplied network so that the tenants, with the use of a smart phone, computer or tablet can view the current or historical energy usage. These possibilities, however, were masked during our measurement campaign, in order to not influence the behaviour of the occupants.

Figure 3.4: Youless electricity meter sensor mounted on a) a new digital meter b) an old gas meter

3.2.4 Qualitative Data: comfort dial and log book

The Ecommon measurement campaign was not limited in gathering only quantitative data but qualitative ones as well. Data on the comfort perception were gathered with the help of a device developed by TU Delft Department of Industrial Design under the umbrella of the European Interreg project Sustainable Laboratories North West Europe (www.SusLabNWE.eu). This Comfort Dial, figure 3.5, was allowing the tenants to record their thermal comfort perception in different hours of the day by choosing between a 7 point scale, from -3 to +3 with -3, figure 3.6.

Figure 3.5: Comfort Dial used to capture comfort perception of the residential tenants

Figure 3.6: Thermal Comfort 7 point scale (PMV index)

Parallel to the comfort dial, a paper log book was given to the tenants, see figure 3.7. This log book was developed from the TU Delft Industrial Design Department along with the Comfort Dial. Initially it was designed to be in online format where people could log in their computer, smart phone or tablet and fill in various qualitative data such as:

- Comfort perception: 7 point scale as mentioned above.
- The room they are situated at that particular moment: kitchen, living room, bedroom etc.
- Clothing combination: they could choose any combination between t-shirt without sleeves, t-shirt with sleeves, knit sport shirt, long sleeve sweatshirt, jacket and jacket with hood.

- Actions they took related to comfort and energy consumption: opening or closing the windows, drinking a cold or hot drink, putting on or off clothes, increasing or decreasing the level of the thermostat and having a warm or cold shower.
- Their activity: lying /sleeping, sitting relaxed, doing light desk work, walking, jogging, running. This activity can then be related to their metabolic rate.

However, we finally used a paper version of the log book because of the combination of financial limitations (not enough available tablets to provide to all the occupants) with the fact that many of the people that participated in our campaign were elderly, and a paper log was much easier for them. To guarantee uniformity among data gathering the paper format of the log book was chosen.

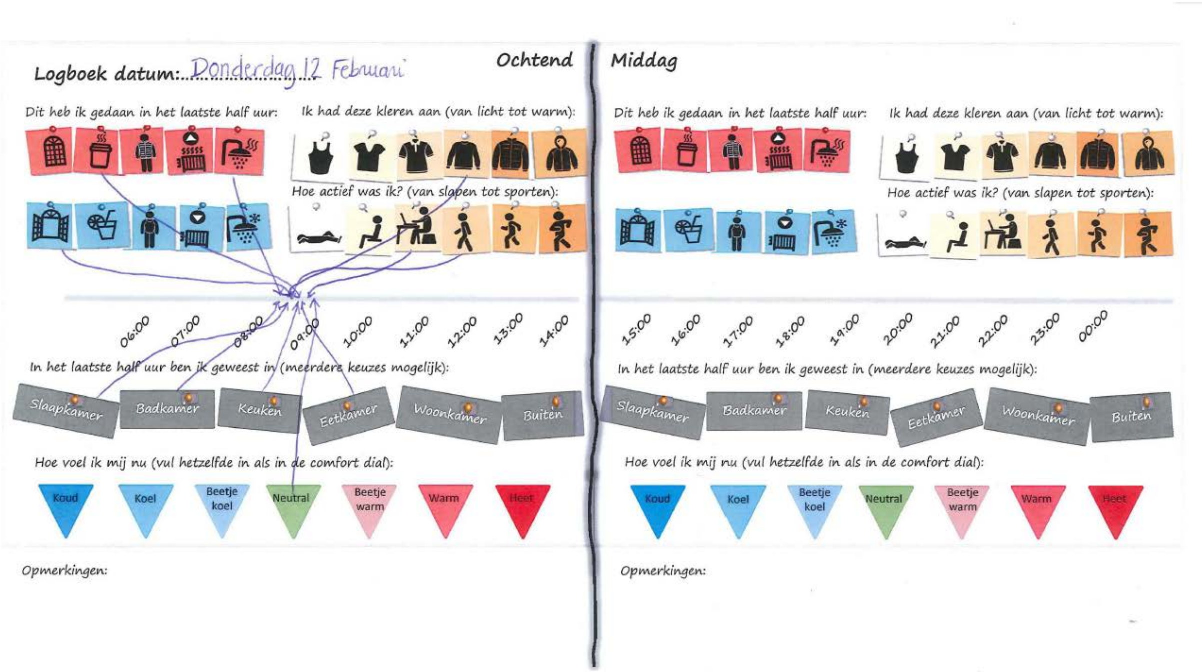


Figure 3.7: Qualitative Data Paper Log Book

The comfort dial was given to the occupants of some of the houses for a period of one or two weeks. The main respondent was asked to use the comfort dial as many times as he/she wanted per day with a minimum of three times per day (preferably in the morning, midday and evening). Additionally they had to fill in the paper log at least at the moments they were using the comfort dial.

3.3 Data storage and management

3.3.1 Honeywell Data

The data that were gathered from the Honeywell sensors were managed by software that was developed by Honeywell. In figure 3.8 a screen shot of the sensors manager software is shown. In the upper right corner there are 4 green coloured tabs. These are having the code name of the sensor set that is installed in each room (in this case: kitchen, living room, bedroom 1 and bedroom 2).
The software provided the possibility to change the measurement frequency at any time between 1, 2, 5, 10 or more minutes. For this project the 5 minute interval was chosen. In the data log panel we can see the string of data recorded every 5 minutes, in the first column there is a detailed timestamp that includes date and time. The second column shows the code of the sensor kit which refers to a

room and then the next columns are the actual data (CO_2, Temperature, Relative Humidity, Relative Humidity of the Bathroom, and presence. The column with the indication 255 denotes an error which in our case was just that this column was not in use. The interface was also providing the possibility to download in csv format the total amount of data recorded or data from specific days.

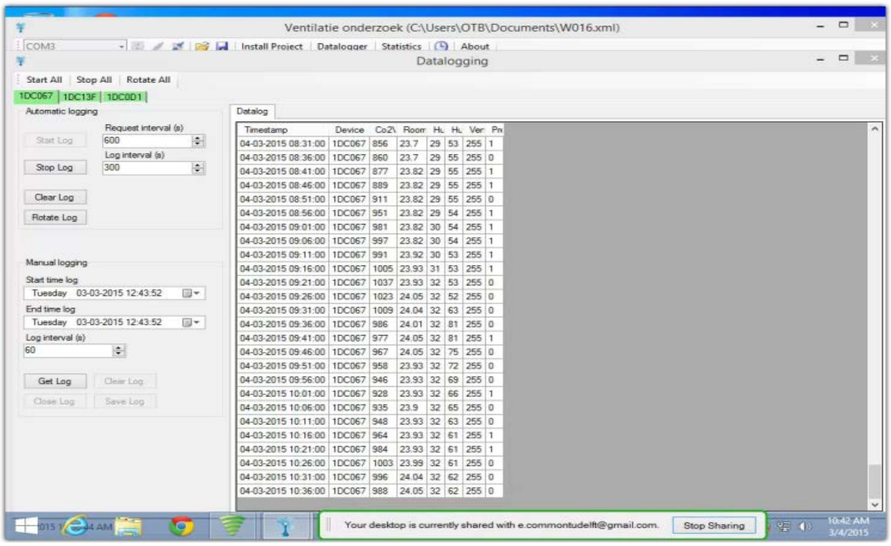


Figure 3.8: Honeywell interface for managing the sensor data.

All the data were wirelessly transmitted from the sensors to a locally installed mini-pc which was equipped with software running on Windows and with proper adjustments in IOS that Honeywell developed for this project. From the mini-pc the data were regularly copied to our TU Delft SQL database. In that way the data were stored both locally, on the mini-pc hard drive, and centrally in the TU Delft database. Additionally each week another digital copy of was saved in the Google drive of the Ecommon account.

Another point worth mentioning is that each of the Honeywell sensor boxes (containing the temperature, relative humidity and CO_2 sensors) was also acting as a wireless transmitter for the closest sensor box. At the same time each of the local mini-pc could accommodate the sensor boxes of 6 houses. That means that if there were 6 row houses, one mini pc installed in the middle house could serve the data gathering of all 6 houses since the sensor boxes of the furthest away houses could send the data to the mini pc bouncing from sensor box to sensor box from house to house.

3.3.2 Eltako

The Eltako sensor had also its own software, developed by Eltako Electronics which can be downloaded for free from the company site (figure 3.9).

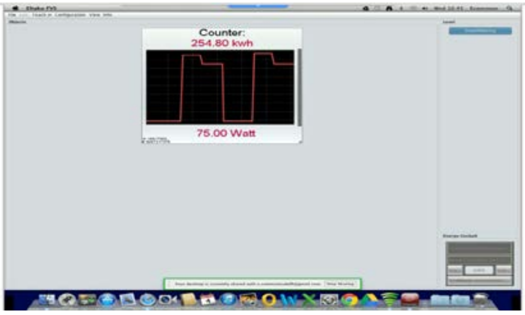


Figure 3.9: Eltako interface and consumption display in real time.

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

3.3.3 Youless

The Youless data were the only data that were not stored in the TU Delft own servers. Enelogic, the company that has developed the system has its own servers and when buying a Youless sensor this comes with a reserved space in the company's servers for the data of that sensor. In figure 3.10 the Enelogic interface for the management and display of the data is shown. The data can be displayed or exported in a daily, weekly, monthly or yearly interval.

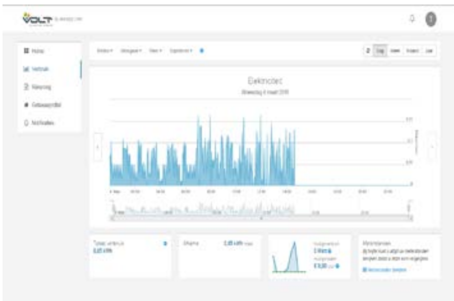


Figure 3.10: Enelogic online interface for the management of the Youless sensor and data display.

3.3.4 Comfort dial data

The comfort dial data were sent by connect ports through the Internet or 3G to a TU Delft database constructed by the Faculty of Industrial Design during the SuslabNWE project (www.suslabnwe.eu). In case of no response to the URL request, the connect port keeps trying to send the data up to the moment it succeeds.

3.4 Inspection of the dwellings and occupant survey

3.4.1 Occupant Survey

During installation of the sensors at their house the occupants were asked to fill in a survey. The questions of this survey were divided in four categories, the first about general characteristics and information of the households, like household composition and age, the second about their heating and ventilation habits, the third about the overall comfort perception of their dwellings. The survey can be found in appendix A.

3.4.2 Inspection list

During the installation campaign, an inspection was conducted for each dwelling. The elements that were inspected were:

1) Type of space heating system
2) Type of hot tap water heating system
3) Type of glazing
4) Electricity meters A, B (night tariff if applicable) and gas meter readings at the time of installation of the equipment, when the comfort dial was delivered, and finally at the time of de-installation of the equipment.
5) Types of ventilation present in the dwelling (extraction point in the kitchen, other mechanical ventilation usually present in the kitchen or bathroom and Balanced ventilation).
6) Thermostat patterns concerning: settings, schedule and type of thermostat.

3.5 Measurement of the heat resistance of external walls

As described in section 2.4, there is some theoretical evidence that the heat resistance (Rc) of external walls (and roofs and floors) is not correctly estimated, especially in older dwellings. The main reason for this is that in older dwellings the construction details and materials are generally unknown, leading to inaccurate guesses, based on construction year (ISSO 60). In-situ measurements would improve greatly the quality of the estimations, but are generally not carried out because, according to the international ISO 9869 and ASTM C1155-95 standards, weeks of measurements are necessary to compensate for the transient behaviour of walls and climate. During the Monicair project, a new transient method, the Excitation Pulse Method (EPM), much more rapid, developed in Rasooli (2014) was further fine-tuned and tested in three houses. The details of the method can be found in Rasooli & Itard (2016).

The idea behind EPM is based on the theory of response factors (RF). In the past, the RFs method was used as an alternative to solving sets of partial differential equations. The benefit of the method is that it is independent from the wall's internal temperature. The RFs are calculated from the wall thermo-physical properties. The heat fluxes $\dot{q_1}$ and $\dot{q_2}$ at two surfaces of the wall can be calculated then as a function of surface temperatures, X being the inner heat flux time-series RFs to a triangular surface temperature pulse of 1 K, and Y being the outer heat flux time-series RFs to the same pulse In Figure 3.11, the concept is illustrated, with $\dot{q_1}$ the heat flux from the excitation pulse, and $\dot{q_2}$ the heat flux on the wall's outer surface.

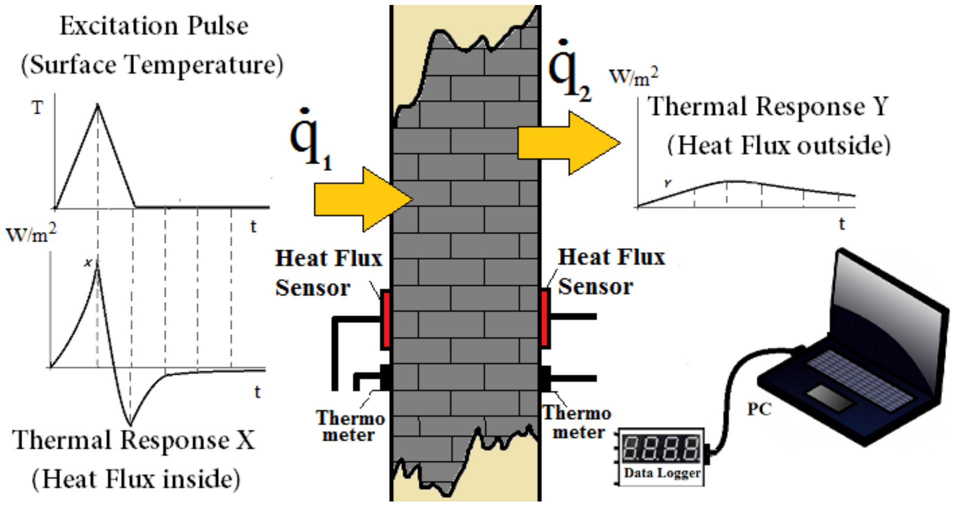


Figure 3.11: The general concept of EPM – applying a triangular temperature pulse to the surface and measuring heat flux responses on two sides of the wall

In EPM, the problem is reversed: if it is possible to control the wall's surface temperature to form a triangular profile, then it is possible to determine the RFs X and Y by measuring the heat fluxes $\dot{q}_1$ and $\dot{q}_2$. Therefore, in EPM, the wall's interior surface is linearly heated and cooled, generating a triangular surface temperature profile. Meanwhile, the heat fluxes on two sides of the wall are measured leading to the RFs to this excitation pulse. Not only can these RFs be used directly in dynamic simulations, but also they can lead to the determination of the Rc-value and other thermal properties. In actual conditions, temperature and heat flux fluctuations always exist on the surface of the walls. Temperature fluctuation range, generally higher than 1 K, prevents measurements to take place accurately. However, since the RF method is based on Fourier's conduction equation and Laplace transform, it allows applying the superposition principle, allowing generation of a triangular pulse with a magnitude much greater than 1 K. Having a greater magnitude allows neglecting the small magnitude temperature and heat flux fluctuations while easing the application and control, assuring sufficient heat penetration through the wall. Of course, the magnitude should be such that it doesn't affect the inside finishing of the wall (e.g. paint or wallpaper). According to the superposition principle, the measured heat flux should be divided by the magnitude of the triangular pulse in order to obtain the RFs of the equivalent wall (RFs are defined for a triangular pulse with a magnitude of 1 K). The Rc-value can be obtained by the sum of the measured RFs:

$$Rc = 2 \times \left(\sum_{i=0}^{n} (X_i + Y_i) \right)^{-1}$$

The exterior surface of the wall is exposed to various thermal disturbances such as forced convection, solar radiation, etc. and is therefore isolated by a protective shield (box). A triangular pulse (up to 80 °C) is generated by a radiant heater. Right after linear heating, linear cooling takes place immediately by increasing the distance between the heater and the wall, followed by cooling with a fan and an ice bag respectively. Two heat flux sensors (EKO MF-180) with individual calibration certifications are mounted on both sides of the wall under study, see figure 3.11 and 3.12 According to the temperature dependency of these sensors, a maximum error of 1.8% in high levels of heat flux has been possible. Two T-type thermocouples with an accuracy of 0.1 K are attached at the same spots of heat flux sensors. The data logger has an accuracy of 0.5 K in the temperature junction (reference temperature). Therefore, a maximum total error of 0.6 K in the temperature measurement is expected. The surface of the heat flux sensors and the thermocouples are covered with a layer of tape with the same colour of the wall's surface for sake of radiative heat transfer. The linearity of the signal is controlled every 10 seconds. According to the chosen time interval, the data is read and analysed to obtain the RFs.

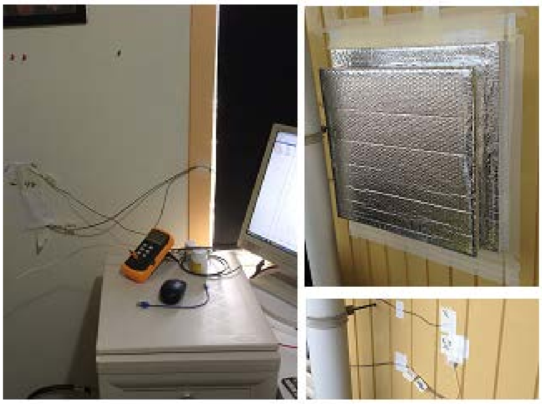


Figure 3.12: Measurement set up

3.6 Final realization of the monitoring campaign

As described in section 3.1, the total amount of houses that would be equipped with sensors was 60 in each period of 3 months, meaning that we expected to be able to monitor 120 dwellings. We had at our disposal only 10 mini-PC's for the local storage of data. These mini PCs were designed to collect the data of 6 houses each. In the first part of the Monicair project, the monitored dwellings were close enough to each other and allowed the measurement of 60 dwellings.

In the Ecommon monitoring campaign we chose to restrain the sample to social housing in order to match this research to earlier research (see chapter 2) in which most of data was collected for social housing. Furthermore the sample had to be divided into A and F labels and most of housings associations have labelled their dwellings, which is not the case of individual owners. We could have approached housing associations to ask for their collaboration in order to choose the dwellings and to approach the tenants, but we chose not to do so because experience from previous projects has showed that when housing organisations are involved, tenants feel less free, are afraid of the housing association getting too much information about them, and participation therefore drops. People tend to be more active and embracing such initiatives when they are contacted directly with a personal letter.

We decided therefore to contact tenants individually by a letter of intent. More than 2000 such letters were sent to households in several neighbourhoods of a selected large urban area in the Netherlands. The selection of the neighbourhoods took place by selecting areas with a high percentage of social housing. In these area's we used the publicly available energy label atlas to select addresses that were mentioned as having labels A/B or F. To make sure we would have enough dwellings, we broadened the focus from A to A/B.

The response rate was about 10% and then a careful selection had to take place in order to maximize the amount of useful data that we could collect. For this selection, we made use of the SHAERE database from Aedes, to select respondents on the basis of their heating system. Additionally, we tried to select dwellings close to each other, to overcome the limitation of having only 10 mini-PCs.

Eventually, the spread of the dwellings remained too large and we had to dedicate almost one mini pc per house. Some of the houses were next to each other (when tenants were asked if they did this in cooperation with their neighbours, they all replied that they had no idea that their next door neighbour wanted to participate in the project), but also in a lot of these cases, an individual mini-PC was needed because the data transmission from an apartment to another was too weak.

In total 32 houses were selected for the first measurement period of 3 months and 7 pairs of them, adjacent to each other, had 7 mini pc allocated to them (14 houses). We finally bought 13 extra mini-PC and borrowed 2 to be able to equip the rest of the houses. The equipment was planned to be installed in October 2014, but due to several problems with the equipment, the installations were carried at the beginning of November, leaving 1,5 months of monitoring instead of the expected 3 months. It was therefore decided to continue the campaign with the same dwellings in order to be sure to have a long enough monitoring period, meaning that the planned second measurement campaign of 3 months was skipped. The 32 selected houses were monitored between November 2014 and April 2015, ensuring a 6 months monitoring period. On average, the installation of the equipment took 2,5 hours per home and the de-installation half hour.

As for the heat resistance measurements, it has not been possible to measure them in the dwellings described above. Reason for this is that the development of the method was at an experimental stage at that moment and we didn't want to bother the occupants during the installation more than was already the case. Instead we chose to measure the heat resistance in three additional dwellings, being owned or rented by members of the staff. The dwellings were chosen according to their construction period. There were two apartment buildings, one from 1933 and one from 1964, and one historical row house from 1680.

4 Basic statistical description of the sample

4.1 Global description of the final sample and data collected

The final sample of the dwellings for the Ecommon measurement campaign contains 32 dwellings and can be seen in table 4.1. All dwellings belong to the social housing sector, 28 of them were apartments and four were row houses. According to the SHAERE data base from Aedes some of these houses should have old inefficient boilers but the inspection during the installation of the sensors showed that all the houses had substituted the old CR boilers with new or relatively new HR ones. Two of the houses still had old gas stoves.

Heating System / Energy Label	Heat Pump	Condensing boiler	Local stove
A/B	4	10	
F		15	3

Table 4.1: Number of dwellings per label category and type of space heating system

In table 4.2 the total amount of dwellings that participated in the measurement campaign is shown together with information on the heating system, the type of data gathered in each house, the type of installation for warm water, type of glazing, type of ventilation and finally the number of rooms monitored and number of people for each household. The data concerning the sensors installed is summarized in figure 4.1. These data differ from the ones of the initial project design. Limitations in budget, time, availability of specific sensors and integration of these sensors to the existing Honeywell system and database, lead us to redefine some of the initial targets of the project and narrow down the amount of data that had to be gathered.

Figure 4.1 shows the histograms of the amount of houses equipped with Honeywell, Eltako and Youless sensors. The Honeywell system was installed in the majority of the houses. From two of the houses we finally had no data, due to missing antenna's and because the tenants wanted to be polite and uninstalled the sensors for us but unfortunately did it the wrong way. The sensors were transmitting the data wirelessly via an antenna that was installed with each mini-pc. In these two dwellings, no antennas were used because of budget limitations. In the absence of such an antenna the sensors were storing the data locally in the internal storage memory of the sensors. At the end of the measuring campaign in these two dwellings, an antenna would be plugged in the mini pc to dump the data from the sensor to the mini pc and from there the mini pc would send the data to the database. The sensors hold the data while they are plugged in the electrical system of the dwelling. Once they are unplugged all the data are erased. Because the tenants had already unplugged the equipment when we arrived, all data were lost. Note that some dwellings belong to the same building blocks or rows: W001&W002; W003&W004; W005&W006; W007&W008; W010&W011, W012&W013 (row houses); W015&W016&W017&W018; W19&W20 (row houses); W21&W22, W26&W27.

	Energy label	Space heating	Measurement devices placed			Warm Water				Glazing		Ventilation		
House no.			Honeywell	Eltako	Youless	Combi-ketel	Geiser (kitchen)	Electrical boiler	Heat pump	Double	Single	Natural ventilation	Mechanical exhaust	Balanced Ventilation
W001	F	HR Boiler	yes	no	no	yes	no	no	no	yes	no	no	yes	no
W002	F	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	no	yes	no
W003	A	Heat Pump	yes	yes	yes	no	no	no	yes	yes	no	no	no	yes
W004	A	Heat Pump	yes	yes	yes	no	no	no	yes	yes	no	no	no	yes
W005	A	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	no	no	yes
W006	A	HR Boiler	yes	yes	yes	yes	no	no	no	yes	no	no	no	yes
W007	A	Heat Pump	yes	no	yes	no	no	no	yes	yes	no	no	no	yes
W008	A	Heat Pump	yes	no	no	no	no	no	yes	yes	no	no	no	yes
W009	A	HR Boiler	no	yes	yes	yes	no	no	no	yes	no	no	yes	no
W010	A	HR Boiler	yes	no	yes	yes	no	no	no	yes	no	no	yes	no
W011	A	HR Boiler	yes	no	yes	yes	no	no	no	yes	no	no	yes	no
W012	F	HR Boiler	yes	yes	yes	yes	no	no	no	no	yes	yes	no	no
W013	F	HR Boiler	yes	yes	no	yes	no	no	no	yes	yes	yes	no	no
W014	F	Moederhaard	yes	yes	no	no	yes	no	no	yes	no	yes	no	no
W015	B	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	no	yes	no
W016	B	HR Boiler	yes	yes	yes	yes	no	no	no	yes	no	no	yes	no
W017	B	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	no	yes	no
W018	B	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	no	yes	no
W019	F	HR Boiler	yes	yes	yes	yes	no	no	no	yes	yes	yes	no	no
W020	F	HR Boiler	yes	yes	yes	yes	no	yes	no	yes	no	yes	no	no
W021	F	HR Boiler	yes	yes	yes	yes	no	no	no	yes	no	no	yes	no
W022	F	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	no	yes	no
W023	F	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	yes	no	no
W024	F	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	no	yes	no
W025	F	Moederhaard	yes	no	no	no	yes	no	no	yes	no	yes	no	no
W026	F	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	yes	no	no
W027	F	Moederhaard	yes	no	no	no	yes	no	no	yes	no	yes	no	no
W028	F	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	no	yes	no
W029	F	HR Boiler	yes	yes	no	yes	no	no	no	no	yes	no	yes	no
W030	F	HR Boiler	no	yes	no	yes	no	no	no	yes	no	yes	no	no
W031	F	HR Boiler	yes	no	no	yes	no	no	no	yes	no	no	yes	no
W032	B	HR Boiler	yes	yes	no	yes	no	no	no	yes	no	no	yes	no

Table 4.2: Overview of the dwelling's characteristics in the Ecommon measurement campaign (Note that in all dwellings, it was possible to open the windows. Natural ventilation=System A; Mechanical exhaust = System C; Balanced ventilation = System D)

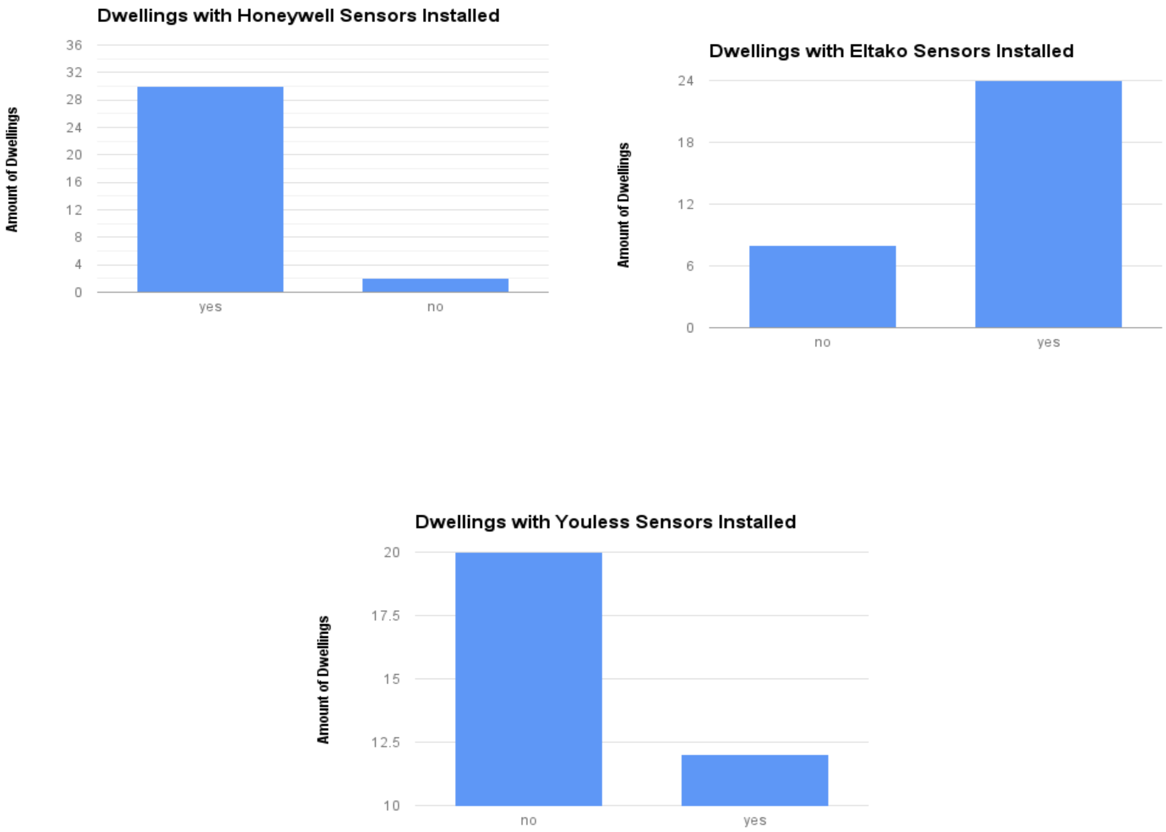


Figure 4.1: Number of houses equipped with Honeywell, Eltako and Youless sensors.

4.2 Dwelling and installation characteristics

4.2.1 Type of glazing

The types of glazing per energy label can be seen in figure 4.2. The majority of dwellings, regardless of labels were equipped with double glass windows. Only four dwellings had single glass windows, all of them class F. In this way, the sample is very representative of Dutch dwellings that generally have double glass (Filippidou, 2014).

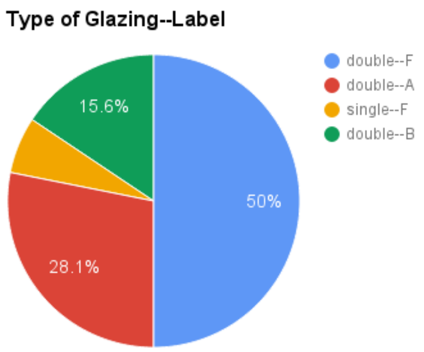


Figure 4.2: Types of glazing and energy label per dwelling participated in Ecommon campaign

4.2.2 Heating equipment

The majority of the dwellings were using combined space heating and hot tap water boilers, 4 houses had heat pumps (all of the houses with heat pump had energy Label A) for space heating and hot water and 2 houses had a local stove in combination with geyser for hot tap water (both houses had label F), see figure 4.3.

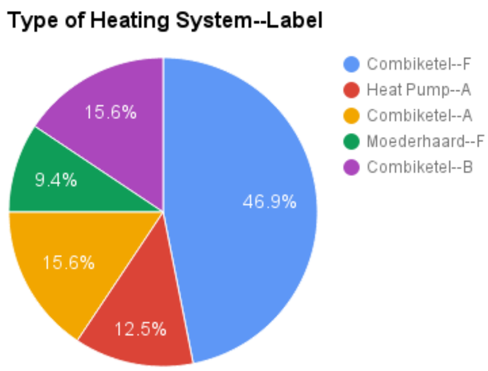


Figure 4.3: Distribution of heating systems per energy labels in the Ecommon sample

4.2.3 Type of thermostat

Figure 4.4 shows the type of thermostat per energy label category. Most of the houses, almost 72%, have a manual thermostat, 28% have a programmable thermostat and 6.3% have a programmable thermostat used as a manual one (referred as 'Manual/programmable' in figure 4.4). Some of the programmable thermostats were programmed to give a constant temperature all over the day (referred as 'Programmable/always on') and in some others a heating profile was programmed, corresponding to the working hours of the tenants (referred as 'Programmable/working week'). Very few dwellings have no thermostat at all.

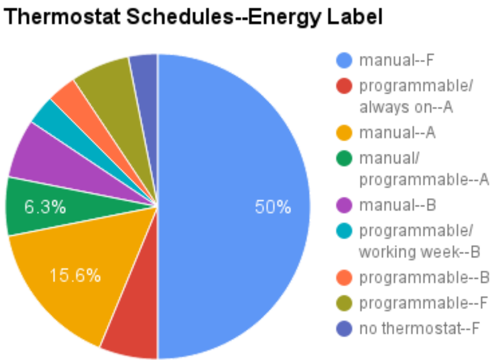


Figure 4.4: Type of thermostat per energy label

4.2.4 Ventilation system

The houses in the sample had either natural supply and exhaust ventilation (with or without a kitchen hood), natural supply and mechanical exhaust (referred in the figures as 'mechanical extraction, extraction points being in kitchen, bathroom and/or WC) or balanced ventilation.
The proportion of houses with balanced ventilation, natural ventilation, and mechanical extraction is shown in figure 4.5. A bit less than one fifth of the houses have balanced ventilation (System D) , about one third have completely natural ventilation (System A) and about half have natural supply and mechanical exhaust (System C). Figure 4.6 shows the ventilation systems in relation to the energy label categories. In figure 4.6 and the rest of this report, 2 dwellings have been excluded (W009 (Labe A, mechanical exhaust) and W030 (label F, natural ventilation)) because finally no data from the Honeywell system could be recorded (see section 4.1). So finally the sample ends up with 6 balanced ventilation dwellings, 9 naturally ventilated dwellings and 15 dwellings with natural supply and mechanical exhaust. All balanced ventilation systems are found in energy labels A or B. All natural ventilation systems are found in label F. Mechanical exhaust systems are found in all label categories.

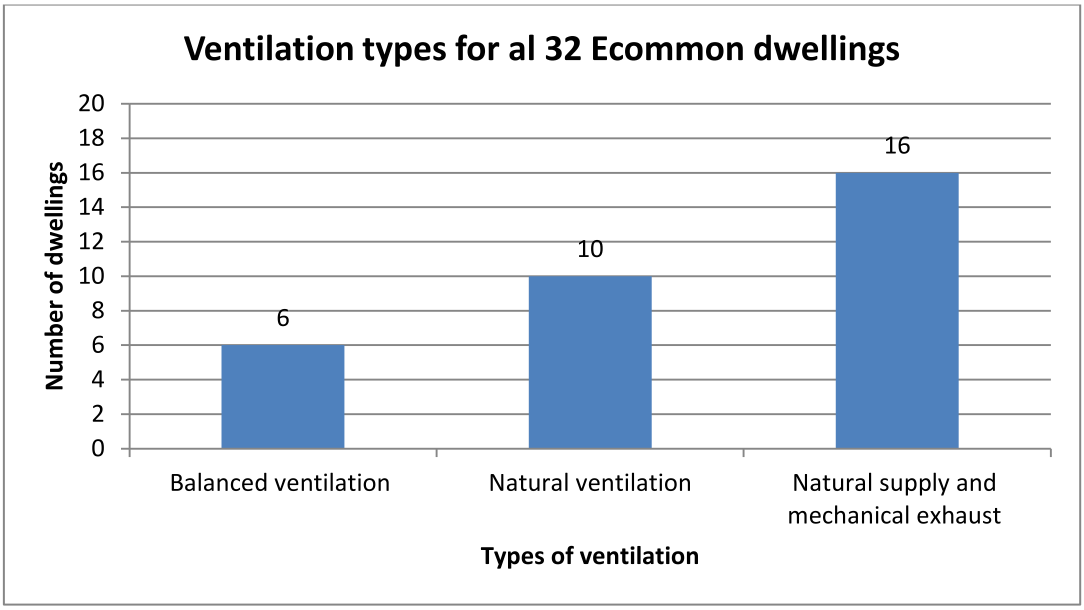


Figure 4.5: Types of ventilation systems in the Ecommon sample

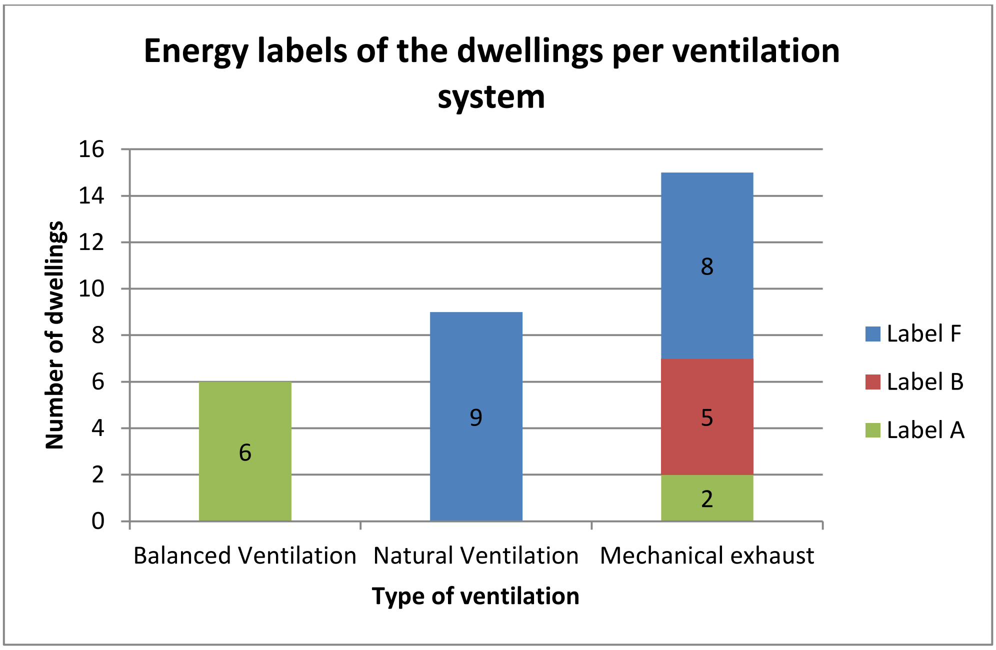


Figure 4.6: Energy labels of the dwellings per ventilation system

4.3 Household characteristics

This chapter presents some data that could be needed in further studies on energy consumption, or to test representativeness of the sample.

4.3.1 Number of people per dwelling

The majority of dwellings were inhabited by two persons, while the least amount of dwellings had 4 people as shown in the histogram in figure 4.7.

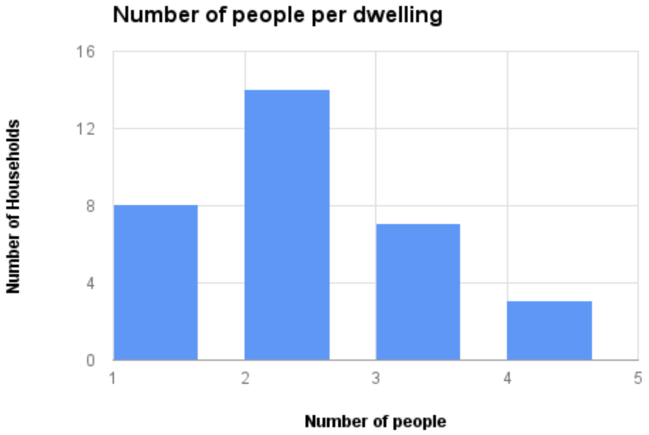


Figure 4.7: Histogram of the number of people per dwelling.

4.3.2 Age of the members of the household

The age of people can be seen in figure 4.8. We can see that the age of person 1 (the respondent) and 2 is concentrated mostly between 40 to 70 years old. While the age of person 3 and 4 is between

3 and 25. The respondent was usually one of the senior members of the household, the person 2 was the husband or wife of the prior and persons 3 and 4 usually were the children.

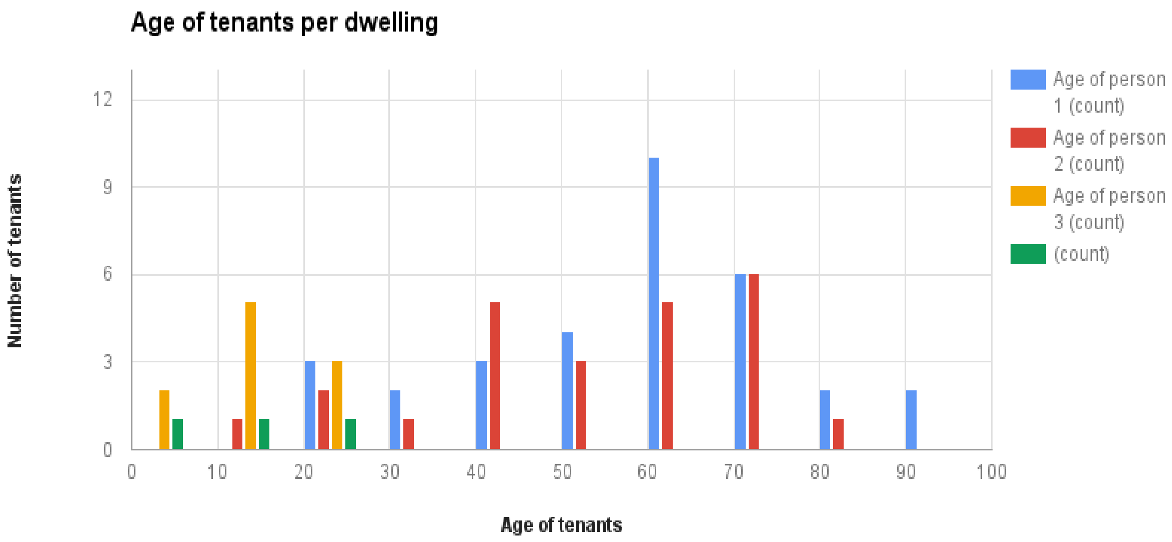


Figure 4.8: Age of occupants

4.3.3 Education level of the respondents

Concerning the educational level of the tenants that participated in the measurement campaign the survey revealed a variety of levels (see figure 4.9) with the two largest groups being the WO (higher academic education) and the HBO (higher professional education).

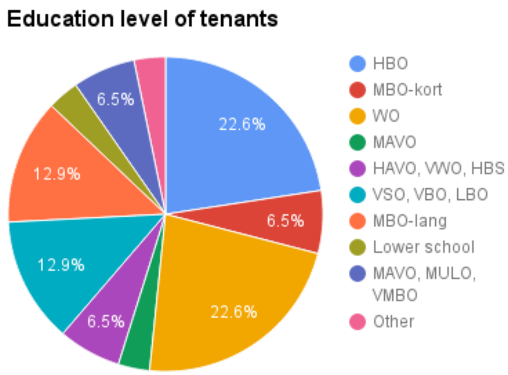


Figure 4.9: Educational Level of respondents

4.3.4 Incomes and ability to pay the energy bills

Figure 4.10 shows the reported net monthly incomes per household. The majority of the households are concentrated in the lower end of the income, which was expected since the dwellings belong to social housing.

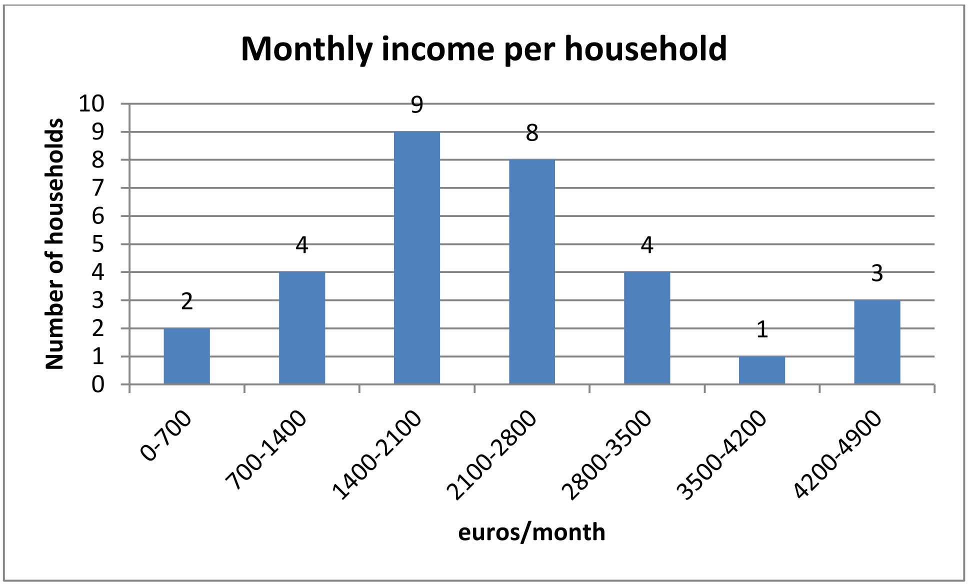


Figure 4.10: Reported net monthly income of households participating in Ecommon campaign

In figure 4.11 the answers the tenants gave to the question how the difficult it was for them to pay the energy bill are shown. The answers are shown in combination with the energy label of their dwelling and their total energy consumption as measured during the 6-months measurement campaign. In some of the houses the total energy consumption data were not available and so they are not displayed in the graph. The majority of the tenants found it easy or fairly easy to pay their monthly energy bill. Only three houses (all of the label F) said that they find it a bit hard, but as can be seen in figure 4.12 these houses have some of the lowest incomes per month and some of the highest energy consumption. It should be noted, though, that lower incomes were found in other categories, as well as high energy consumptions. Some other households, despite the fact they also have some of the lowest incomes and highest energy consumptions stated that it is easy or fairly easy to pay the monthly energy bill. A clear relationship between difficulty to pay the bill and low income or high energy consumption was not found.

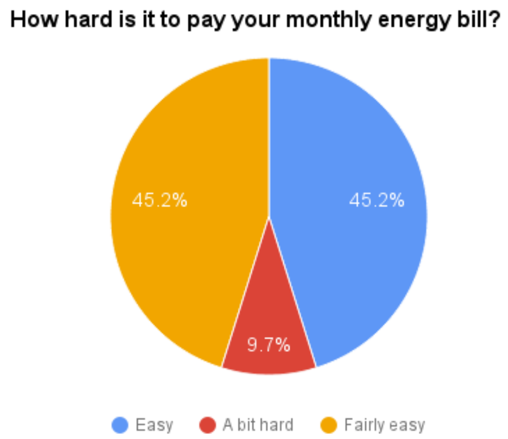


Figure 4.11: Distribution of the answers to the question ''How difficult is it for your household to pay the monthly energy bill?''

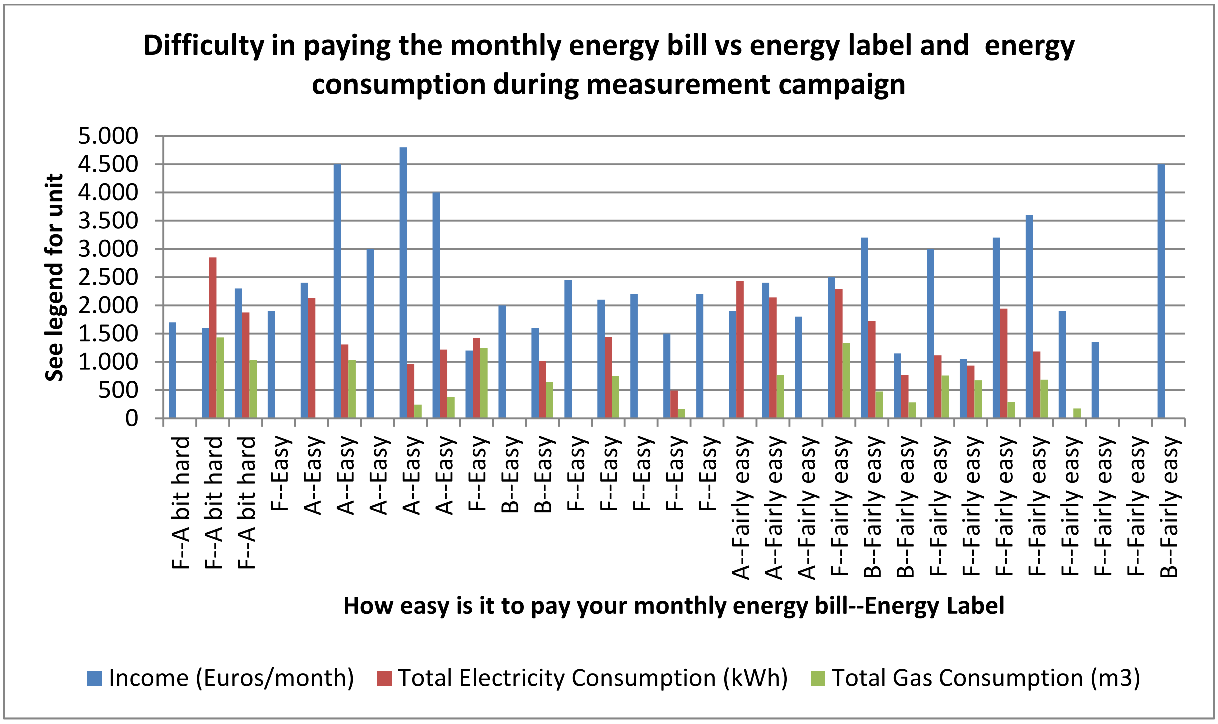


Figure 4.12: Difficulty to pay the energy bill in combination with the energy label and energy consumption during the measurement campaign.

4.4 Reported bathing and showering behaviour

The showering and bathing behaviour of the tenants is given in figure 4.13, based on the Ecommon survey data. The majority of the answers were 1 shower per day, followed by 2 and 3. Some of the tenants answered that they had no showers at home. Most of the showers last for 10 minutes, followed by 5 minutes. Finally bathing is not a common practice in the monitored sample. One tenant answered that he/she is having 7 baths per week. A few more tenants said they were bathing twice per week and the rest had no baths.

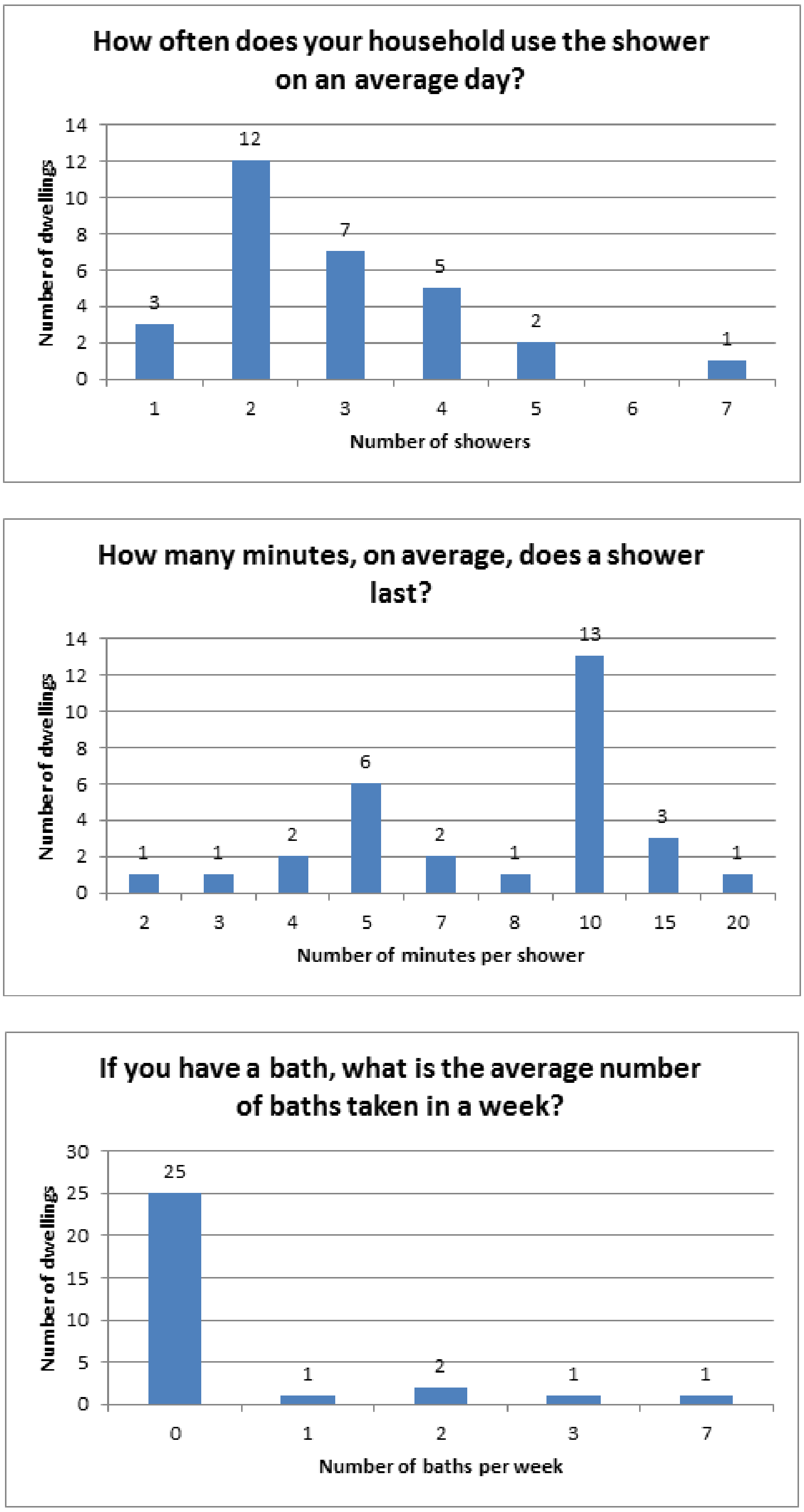


Figure 4.13: Showering and bathing habits on the survey

5 Behaviour and Comfort perception: results of the survey

In this chapter the main results of the survey that was carried out at the start of the measurement campaign are described. During the inspection of each dwelling and the installation of the sensors, which all together took approximately 2 hours, the tenants (one respondent per household, an adult) were asked to fill in the survey (see Appendix A). The results of the survey are expected to be useful to place the data analysis into perspective.

5.1 Reported set point temperatures

Figure 5.1 shows for each house thermostat the temperature set points that were recorded during the inspection of the dwellings at the time of the installation of the sensors. Figure 5.2 shows the settings that were reported by the tenants in the survey. The bars in figure 5.1 should correspond to the red bars in figure 5.2 (day temperature during presence).

From figure 5.1 it is clear that the set point temperatures in label A dwellings are higher than in the other houses. In the label A dwellings the recorded settings vary between 21 and 24 ^{o}C, while these settings are between 17.5 and 21 in the other dwellings. This is in agreement with the temperatures reported by the tenants (figure 5.2), except for the last house, with local stove, in which the temperature setting is 22^{o}C. The comparison between both figures shows that in 48% of the cases the recorded and reported temperature are identical, in 28% of the cases the reported temperature is lower than the recorded one (on average by 1.1oC, varying between 0.5 and 2) and in 24% the opposite is true (on average by 0.9, varying between 0.5 and 1.5), showing that on average the respondents are able to give accurate answers on their thermostat setting- although difference up to 2 degrees can be observed. No correlation with the energy label of the house was found.

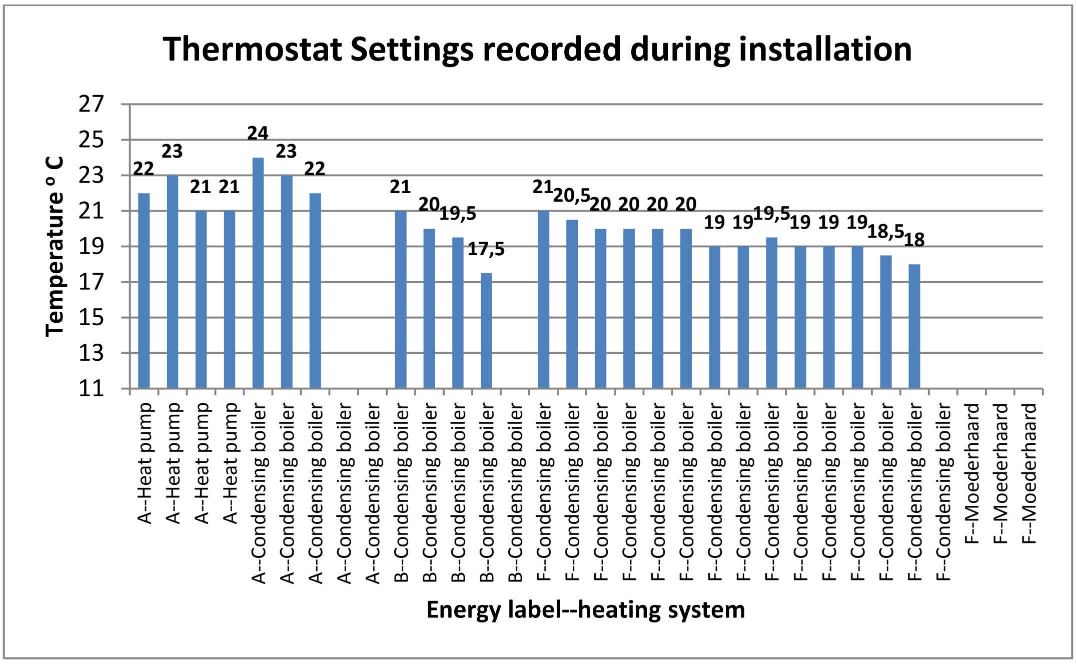


Figure 5.1: Recorded thermostat settings at the moment of inspection per label category, for each dwelling

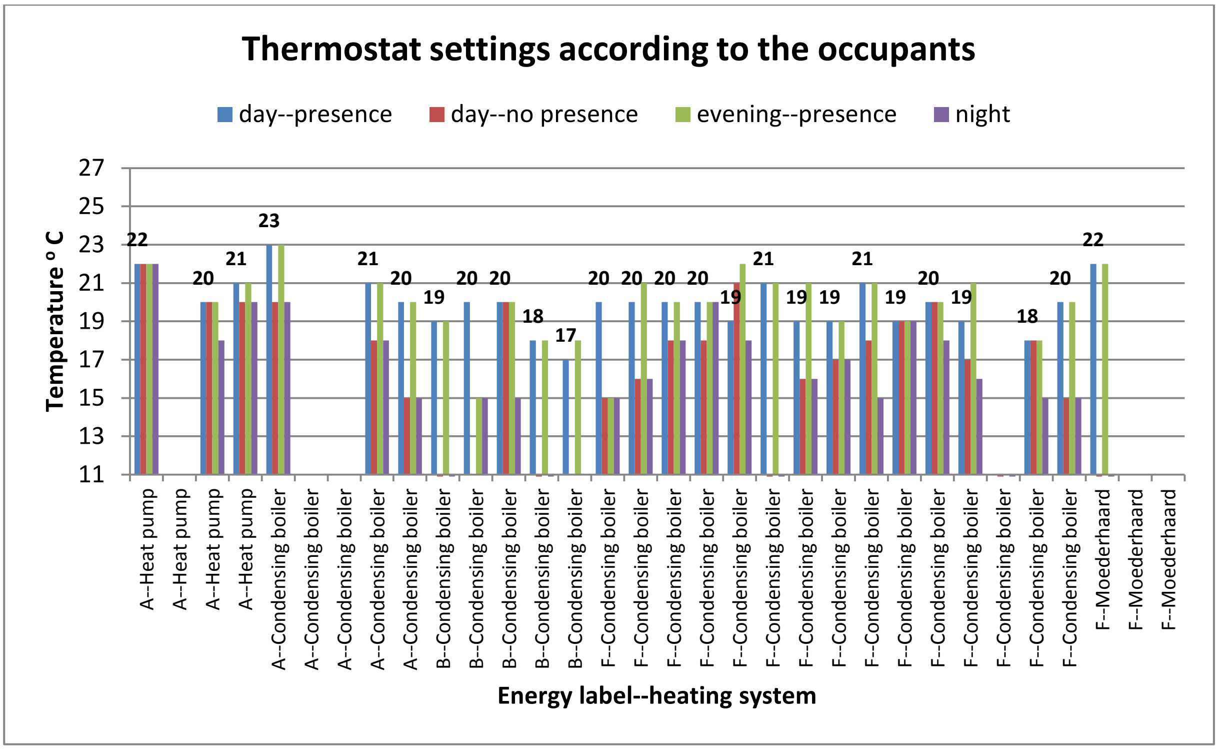


Figure 5.2: Thermostat settings according to the occupants, as filled in the initial Ecommon survey.

5.2 Reported ventilation behaviour

5.2.1 Use of the mechanical ventilation

People reported on the setting of the balanced ventilation in 4 of the 8 dwellings (generally the set points are from 1 to 3, 1 being the lowest ventilation flow rate). In 3 of these 4 dwellings the setting was 1 and in one of them 2. In the dwellings with natural supply and mechanical exhaust, only 5 tenants responded, in all cases the setting was 1. These findings are in good accordance with the findings of Monicair report Part A.

5.2.2 Use of windows and grilles

Figures 5.3, 5.4 and 5.5 show the reported ventilation patterns (windows and grilles) for each type of room per ventilation system. For the living room and bedrooms of the balanced ventilation dwellings the most common answer (43%) was 1-4 hours. Same results were obtained for the category natural ventilation, with a much higher percentage (71% for the living room and 50% for the bedrooms). For the dwellings with natural supply and mechanical exhaust it is not easy to distinguish a pattern since many answers are found in all rooms, although a large majority of bedrooms (52%) in this category are ventilated longer than 5 hours a day, while the living rooms is in 57% of the cases ventilated less than 5 hours a day.
Regarding the ventilation of the kitchen and bathroom a lot of tenants (33% in kitchens and 43% in bathroom) with balanced ventilation report not to ventilate through windows or grilles (generally they have chosen the option 'non applicable', meaning that they are no windows or grilles in these rooms, relying on the mechanical ventilation. For houses with natural supply and mechanical exhaust, this percentage is high as well (28% in kitchen, 50% in bathrooms, of which 21% have chosen 'not applicable'). Interesting is that also in the naturally ventilated houses more than 28% of people report not to ventilate the bathroom, in half of the cases they chose for 'non applicable'.

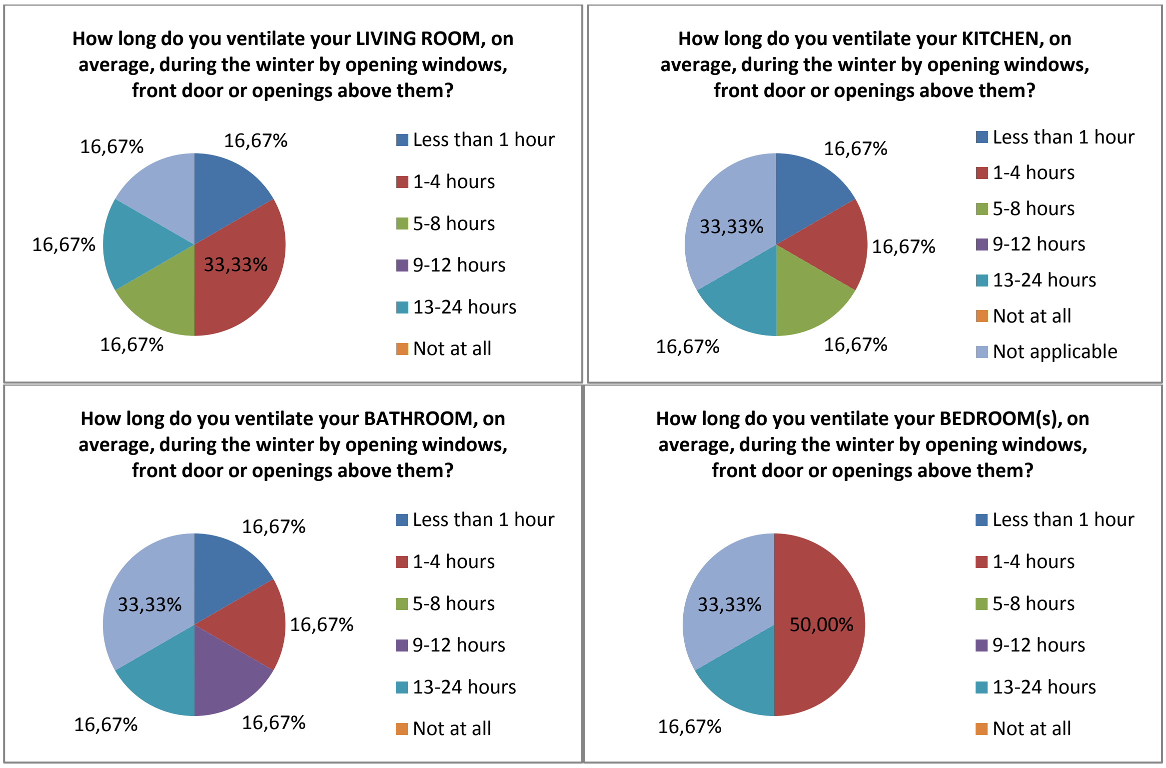


Figure 5.3: Ventilation patterns based on the survey—Dwellings with balanced ventilation

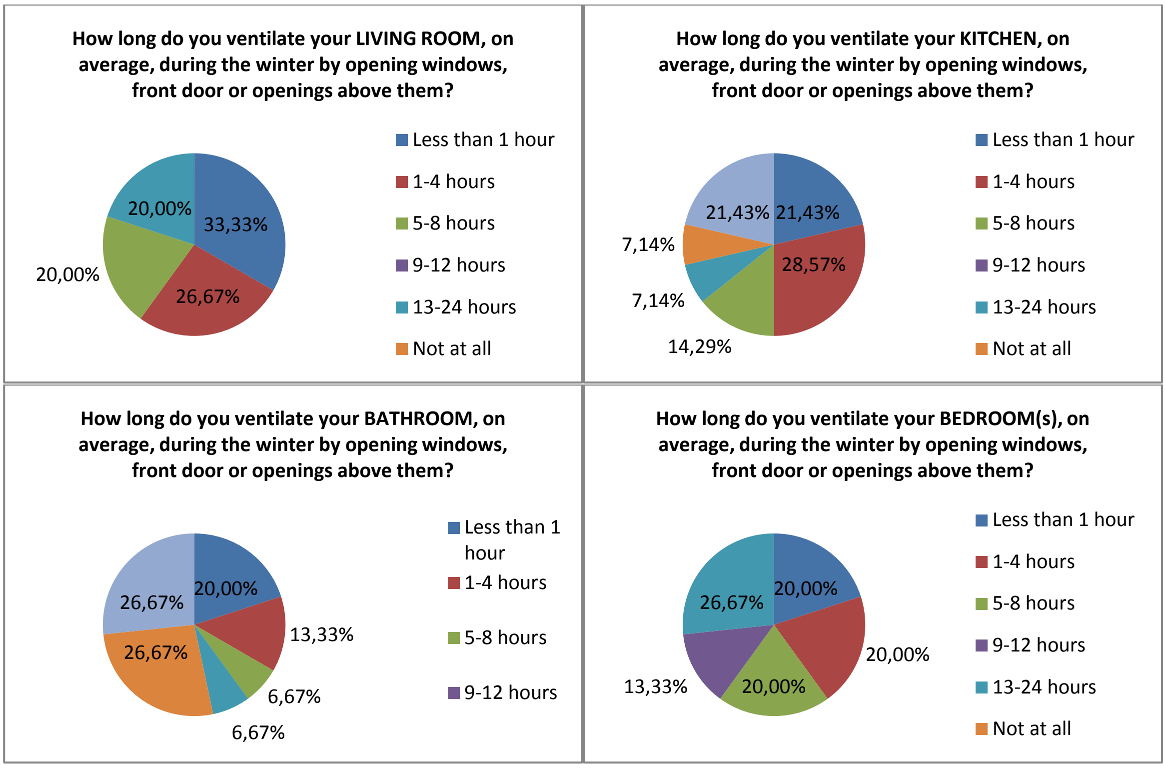


Figure 5.4: Ventilation patterns based on the survey—Dwellings with natural supply and mechanical exhaust ventilation

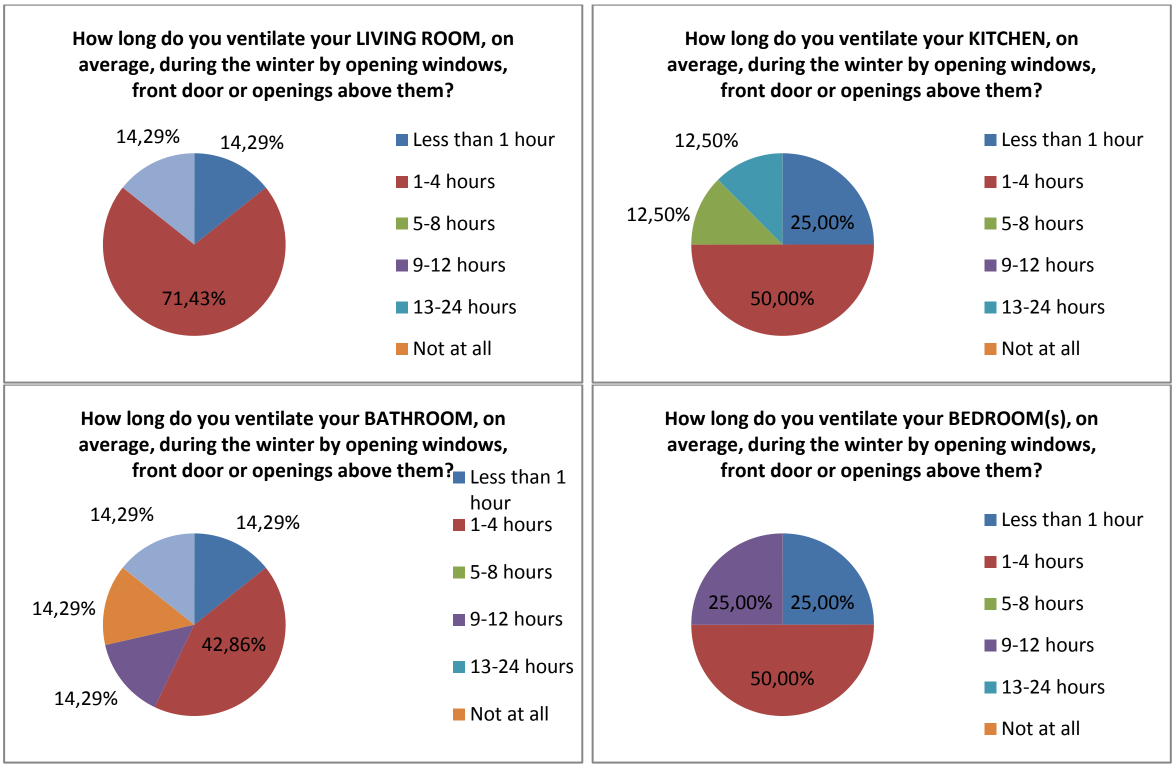


Figure 5.5: Ventilation patterns for living room, kitchen, bedrooms and bathroom based on the survey—Dwellings with natural ventilation

5.3 Thermal Comfort perception

The initial survey that was used at the start of the Ecommon measurement campaign contained some questions regarding the comfort perception of the tenants. Specifically they were asked about their perception of the temperature of the dwelling during the winter and the summer, the humidity and draft during the winter and what would they like to change in the apartment.

5.3.1 Temperature perception in relation to the energy label

Figure 5.6 shows the answers to the questions ''How do you feel about the temperature of the apartment during the winter and in the summer'' per dwelling's energy label. We can see that as we move from label A to label F the percentage of ''too cold'', concerning the temperature of the winter, increases. Similar types of results were also reported in Majcen 2015 and relate probably to the degree of insulation and air tightness of the houses. For the summer the answers concerning overheating are more or less similar in all dwellings, showing that about on fourth of people experience too high temperature in the summer.

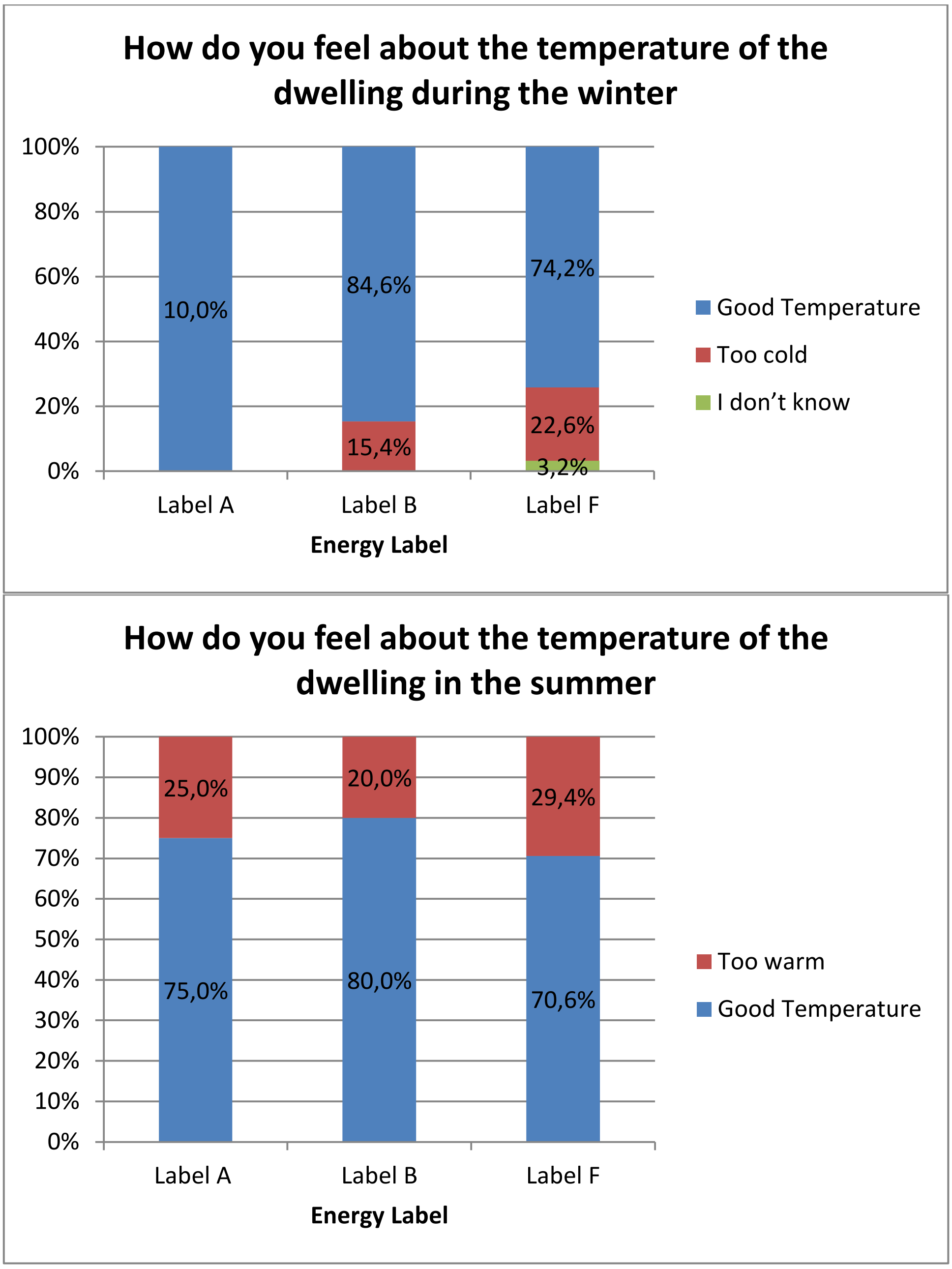


Figure 5.6: Temperature perception in the winter and in the summer per energy label.

5.3.2 Humidity and draft

The answers on the questions about humidity and draft, per energy label, during the winter can be seen in figure 5.7. The humidity was perceived to be good in almost half of the dwellings with the exception of the label B ones where the percentage of ''good humidity'' drops to 40%. In labels B and F dwellings, two tenants answered ''too humid'', one had a balanced ventilation system and the other a mechanical exhaust one. No tenant in label A house found his house too humid.
The tenants of labelled A dwellings considers that there is no problem with the draft during the winter. For the labels B and F on the other hand, approximately 40% of the tenants complain about the draft.

In the question ''what would you like to change in your house to make it more comfortable in winter'' the majority of the label A dwellings answered that they want faster warm water, the majority of label B that they want warmer dwellings, and the tenants of label F dwellings that they want their homes warmer and also faster warm water.

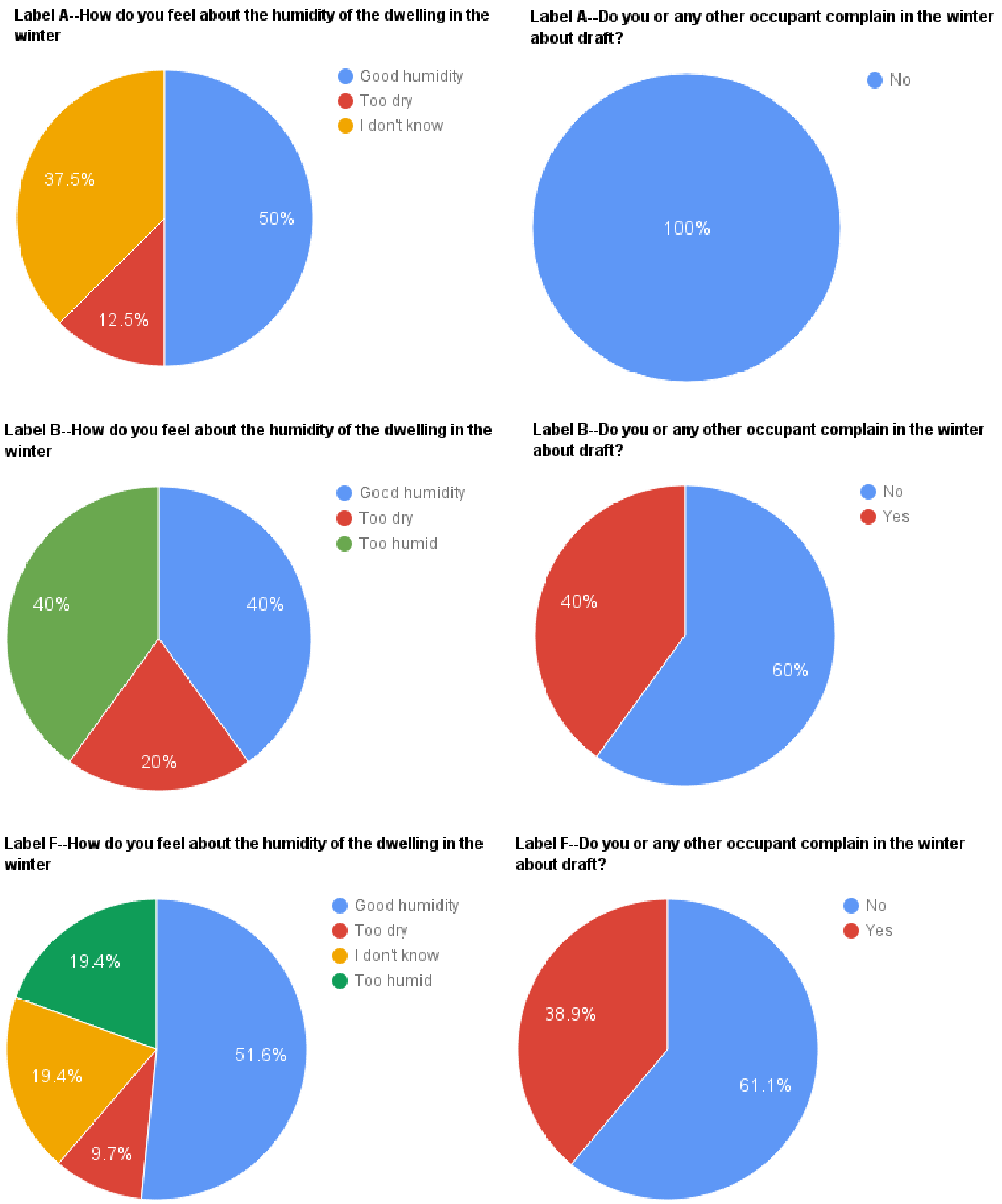


Figure 5.7: Perceived humidity and draft during the winter per energy label.

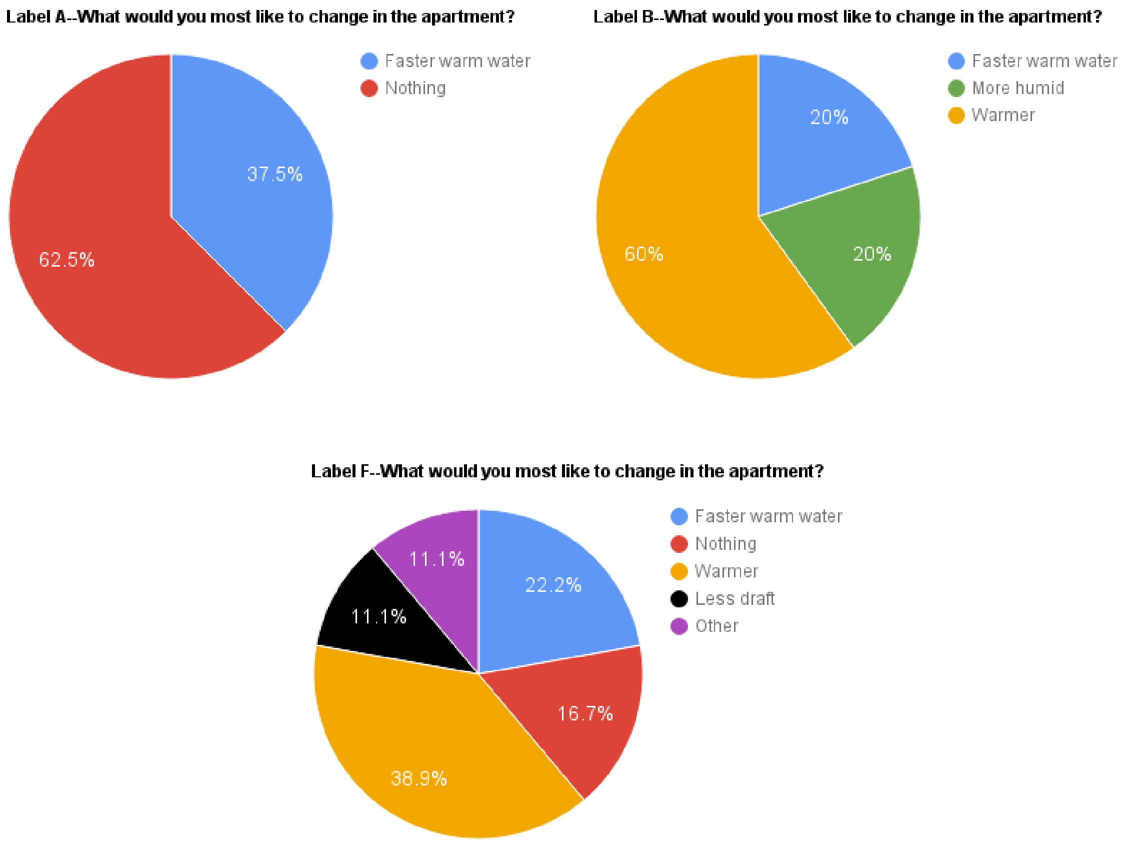


Figure 5.8: Answers on the question ''what would you like to change in your house to make it more comfortable in winter'' per energy label.

5.4 Temperature perception in relation to ventilation system

Figure 5.9 shows the answers of the tenants to the questions concerning the temperature of the houses during the winter and the summer. The tenants of the dwellings with balanced ventilation had the highest percentage (85.7%) in considering the temperature during the winter to be good. All these dwellings had also an energy label A or B, see section 4.2.4., so these results could be expected and relate more to the label than to the ventilation system. The tenant who answered 'too cold' had the only label B dwelling. In houses with mechanical exhaust ventilation, the tenants answered that they consider the temperature to be good with a bit smaller percentage, 71% for label A and 75% for label F. Further in this section the relationship with the energy label will be shown for this category. The completely naturally ventilated dwellings had a significantly smaller percentage considering the temperature to be good (55.5%). In the naturally ventilated dwellings, there were three houses with a stove. All three answered that they found the temperature good.

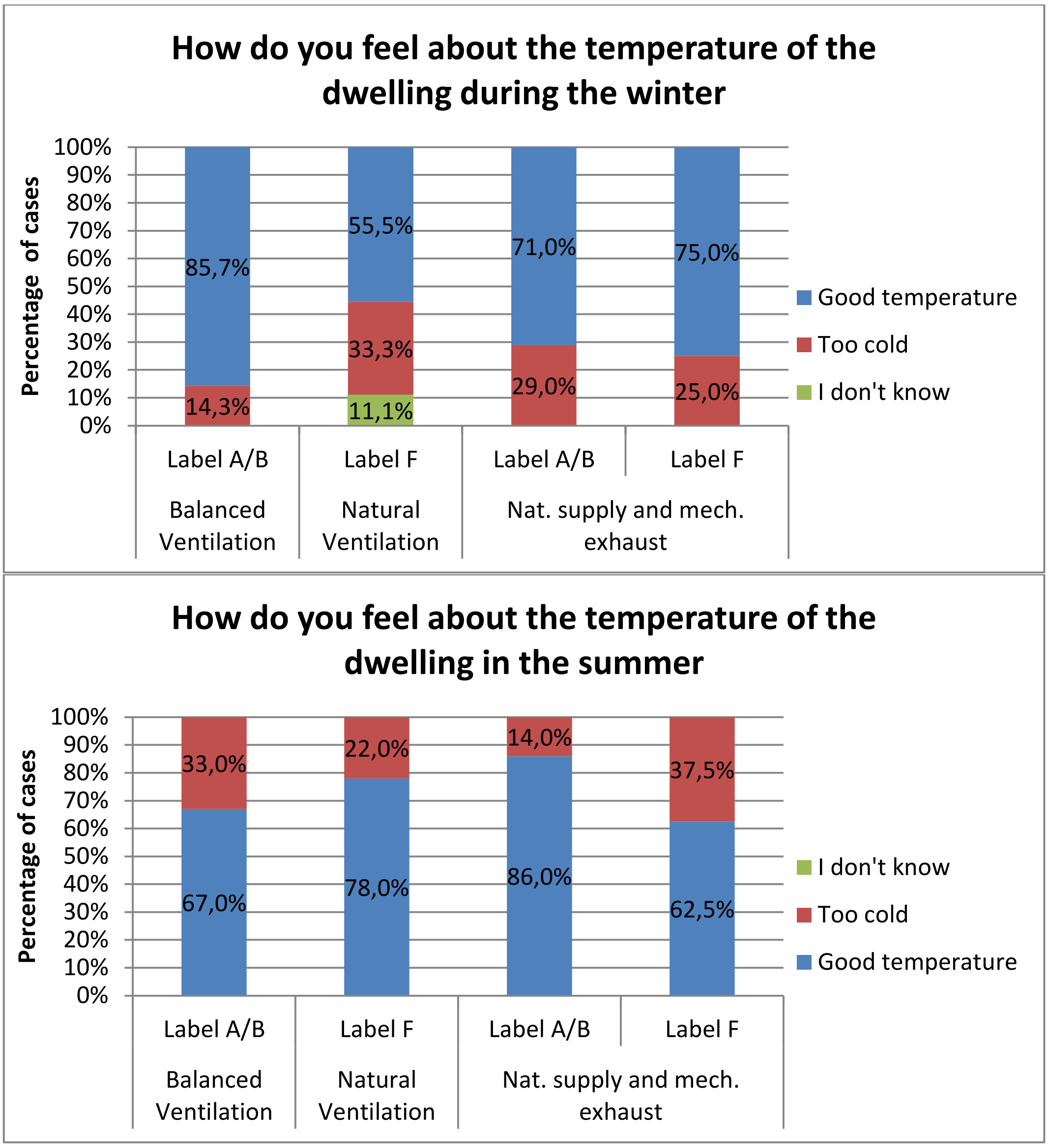


Figure 5.9: Temperature perception during winter and summer periods for all dwellings, per type of ventilation system and per label

In the category of dwellings with natural supply and mechanical exhaust there is a combination of label A, B and F dwellings (figure 4.6). From the 14 houses only 3 said that the temperature was too cold, one of these 3 was a label B dwelling and 2 were labelled F. The tenants of the remaining 11 houses all said they experienced the temperature to be good. Two of these dwellings were label A, three label B and six label F (see table 5.1).

It would be logical that the temperature perception during the winter is more related to the energy label than to the type of ventilation. However in the dwellings with natural ventilation and mechanical exhaust, which is the category in which, in our sample, different labels were observed, the answers seem to be random. In dwellings with good labels, the temperature feeling can be 'too cold' while in dwellings with a poor label the temperature can be 'good'. Further investigation is needed to the actual energy consumption of these dwellings to see if these answers are related to excessive energy use on behalf of the low labelled dwellings or very small consumption of the better labelled dwellings.

Table 5.1: Energy label and temperature perception of dwellings with natural air supply and mechanical exhaust

House Number	Energy Label	How do you feel about the T of the dwellings during the Winter
W010	A	Good Temperature
W002	F	Too cold
W001	F	Too cold
W011	A	Good Temperature
W015	B	Good temperature
W016	B	Good Temperature
W017	B	Too cold
W021	F	Good Temperature
W022	F	Good Temperature
W024	F	Good Temperature
W028	F	Good Temperature
W029	F	Good Temperature
W031	F	Good Temperature
W032	B	Good Temperature

Concerning the temperature during the summer the answers are more unanimous this time. All the houses answered with more than 70% that they consider the temperatures to be good and the naturally ventilated buildings had the biggest percentage of all the other buildings.

5.5 Humidity and draft perception in relation to ventilation system

In figures 5.10 and 5.11 the answers the tenants gave concerning the draft and humidity during the winter are shown per ventilation type and per energy label. The label F dwellings with mechanical exhaust seem to have the most satisfied occupants about humidity during the winter, with 75%. The balanced ventilation dwellings are performing a lot worse with only 43% of the tenants considering the humidity to be good. Balanced ventilation dwellings' tenants thought that during the winter their houses are too humid or two dry with the same percentage (14.3%) while natural supply and mechanical exhaust dwellings' tenants found their houses too humid or too dry with a percentage of 12.5%. Finally in the naturally ventilated buildings tenants answered ''good humidity'', ''too humid'' and ''I don't know'' with the exact percentage (33.3%) while the answer ''too dry'' was absent.

Concerning the draft complaints, the dwellings with balanced ventilation scored the best with no complaints at all about t draft. In the naturally ventilated buildings the complaints about draft were 33.3 % while in the dwellings with mechanical exhaust they were 28.6% and 50% for the label A/B and F ones respectively.

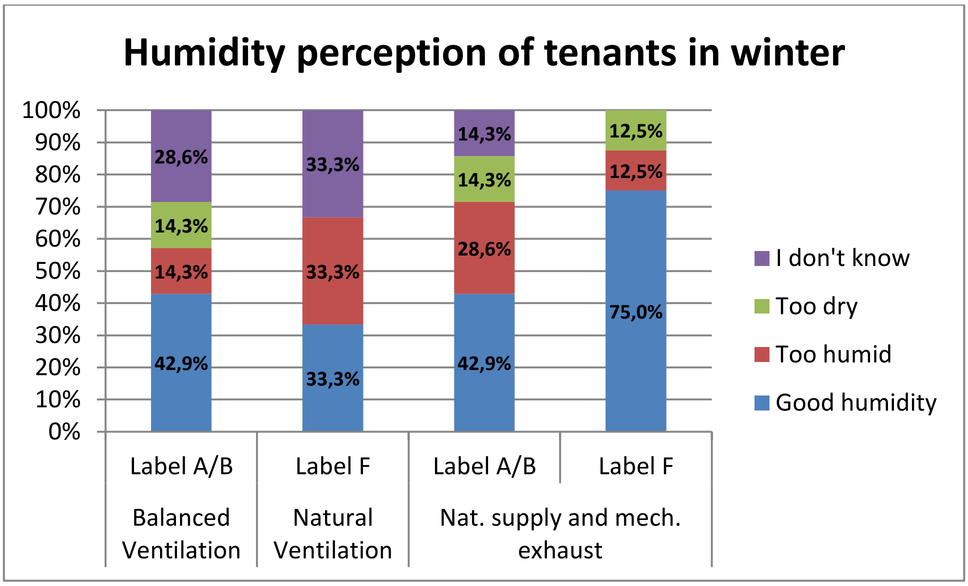


Figure 5.10: Humidity perception of tenants during winter.

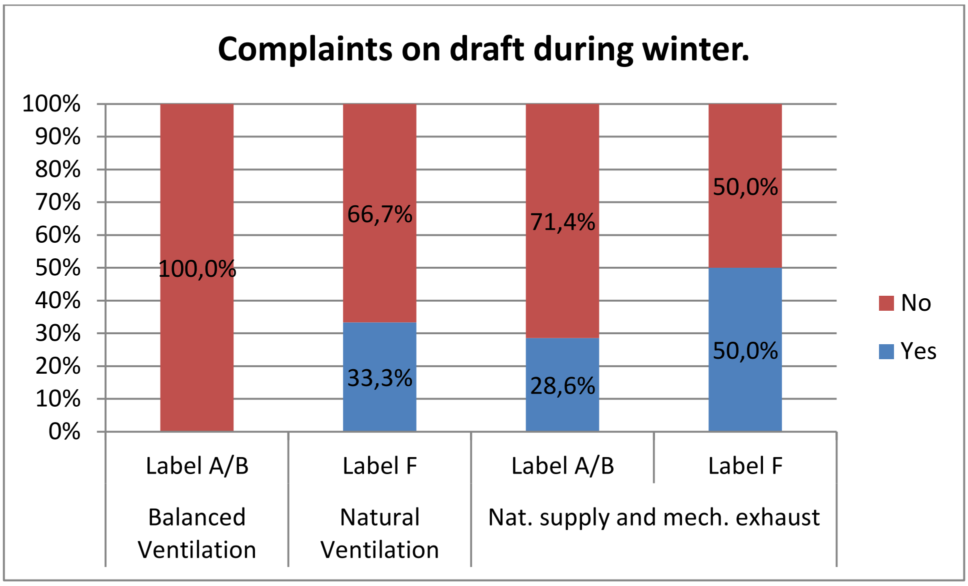


Figure 5.11: Draft perception of tenants during winter

5.6 Wanted improvements to the apartments

Finally the answers to the question ''what would you most like to change in your home?'' can be seen in figure 5.12 for the dwellings with balanced ventilation, mechanical exhaust point and the naturally ventilated ones. The wishes of the tenants were different for the three categories of dwellings. The ones living in balanced ventilation dwellings (all labels A or B) said in majority that nothing should be changed (66.7%), followed by a wish for faster warm water (33.3%). The dwellers of the houses with mechanical exhaust and label F answered that they want faster warm water (37.5%) followed by warmer indoor environment and less drat with 25%. The ones with label A answered that they would like to have a warmer house with 37.5%.

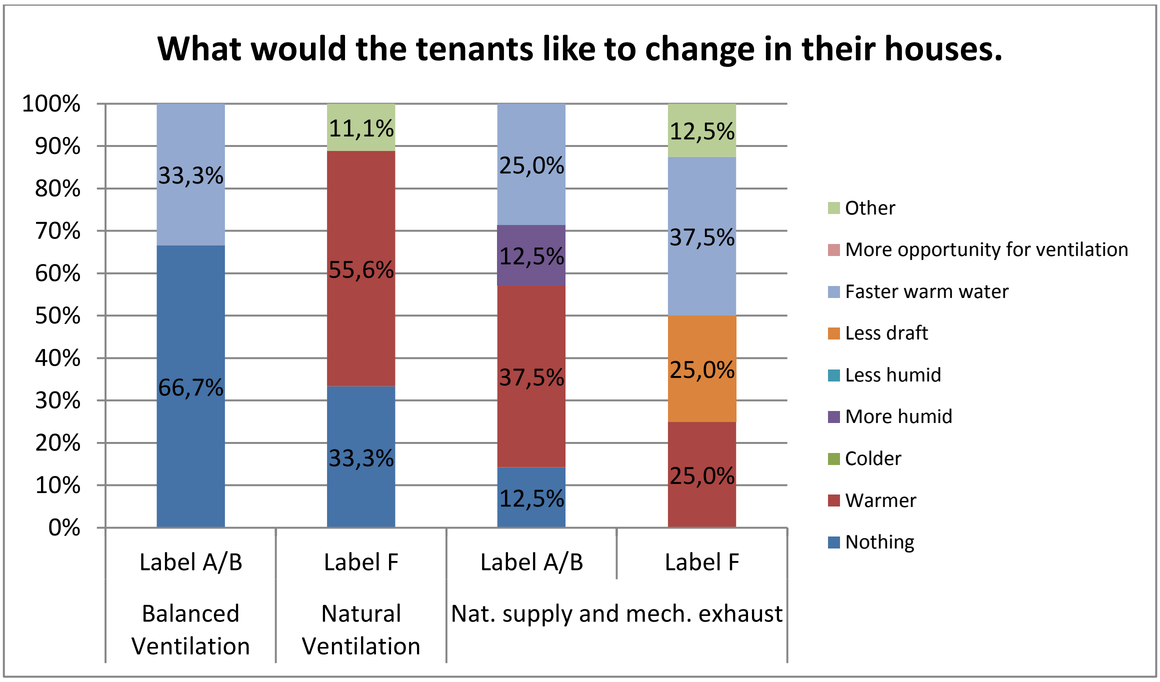


Figure 5.12: What would the tenants like to change in their houses.

Opposite to the former, 55.6% of the tenants in the naturally ventilated dwellings want a warmer house, followed by a quite big 33.3% (considering the increased complaints on the temperature, humidity and draft during the winter period) that do not want to change anything.

5.7 Conclusions

In this chapter the main results of the survey that was carried out at the start of the measurement campaign were described. In the past many studies on temperature habits in households were based on surveys. In our survey, almost half of the temperature settings during the day were reported correctly, while approximately one fourth reported too high temperatures and one fourth too low temperatures, both by 1 ^{o}C on average. This shows that when relying on temperature surveys to find correlations between energy use and temperature, one may not find them, while these correlations may be present.

For most mechanical ventilation systems (both balanced and exhaust only), the flow-rate settings were on the lowest level. In general, the living room and bedrooms are ventilated through windows or grilles 1-4 hours a day (in dwellings with balance ventilation 33% of living rooms and 50% of bedrooms and in naturally ventilated dwellings 71% of living rooms and 50% of bedrooms). Most living rooms and bedrooms in dwelling with mechanical exhaust ventilation are ventilated longer than 5 hours a day. An important share of people (7 to 27%) report to rely completely on the mechanical ventilation (when present) to ventilate kitchen and bathroom, and notably, also in the naturally ventilated houses more than 14% of people report not to ventilate the bathroom actively – in some of the houses there was not even a possibility to ventilate it actively.

It was observed than when moving from label A to label F dwellings the percentage of people experiencing the indoor temperature in winter as being ''too cold'' increases. For the summer the answers concerning overheating are more or less similar in all dwellings, showing that about on fourth of the tenants in the sample experience too high temperatures in the summer, regardless of the label. No clear relationship was found between the temperature perception and the type of ventilation system.

In general, in our sample, there were fewer complaints about draft in the dwellings with balanced ventilation than in the other ones and there were more complaints about humidity in the dwellings with natural ventilation. Most respondents in the naturally ventilated dwellings, which were all label F, would like to have a warmer house in winter. Most respondents in the balanced ventilation dwellings, which were all labels A or B wouldn't change anything or would prefer to have faster warm water. In the category of mechanical exhaust ventilation, with mixed energy labels, a warmer house and faster warm water where the most often given answers.

6 CO_2 concentrations and presence patterns

The aim of this chapter is twofold. First, we want to see in how far the actual CO_2 concentration levels correlate with the ventilation behaviour reported by the tenants during the survey. This would give an indication if survey data can be used safely to estimate ventilation habits that, in turn have an influence on the energy use. Second, we present a method how to construct presence profiles based on a combination of CO_2 measurements and PIR movement sensor. Presence home is believed to be an important determinant of energy consumption in dwellings and a more accurate determination of presence profiles could lead to better energy estimates.

The measurement period taken into account in chapters 6 to 9 is a short period of two weeks between 6 and 18 March 2015. Although this choice is disputable (we could have chosen for the total measurement period of 6 months), we chose for this two-weeks period because that is the only period in which uninterrupted data (including comfort dial and the logbook) were present for all 32 dwellings.
As can be observed in figure 7.1, the weather in this period was rather cold with an average daily temperature between 4 and 9 degrees, therefore we can expect the people to ventilate as they normally do in winter.

6.1 Excess hours of CO_2 concentrations

The total hours of CO_2 excess concentrations were calculated by counting all the 5 minute intervals for which a CO_2 value higher than 1200 ppm was recorded for each room during the complete measurement period. These intervals multiplied by 5 minutes gives the total amount of minutes with CO_2 concentrations above 1200 ppm. Finally the total amount of minutes divided by 60 gave the total hours of CO_2 excess per room. The complete measurement period entails 312 hours. The value 1200 ppm is disputable, but was chosen because it is considered as the hygienic threshold value in the Dutch building code. It is assumed in the building code that with concentrations below the hygienic threshold value, pollution and odours by persons are removed sufficiently.

Figures 6.1 to 6.3 give the number of excess hours per ventilation system in the living room, the kitchen and the 2 main bedrooms, a well as the average excess concentration (the part of the CO_2 concentration that is above 1200 ppm.) It is very clear from these figures that, in our sample, the dwellings with balanced ventilation performed much better than the ones with natural supply and mechanical exhaust, which in turn, performed much better than the naturally ventilated dwellings.

In the dwelling with balanced ventilation the CO_2 concentration in kitchens and living rooms had almost never exceeded the acceptable limits. We have to note here that, in these houses, kitchen and living room were joined together with no separating door or wall. The bedrooms also had a very good performance considering that for three houses there was no excess of CO_2 in any of the bedrooms and one house (W006) had a mere 2.4 hours of excess. Only bedroom 1 and bedroom 2 of W007 and W008 respectively surpassed the 40 hours of CO_2 excess for this period of 13 days. Very interesting is to note that the dwellings with the lowest excess hours (W004, 5 and 6) all reported to almost not ventilate through windows or grilles and therefore rely completely on the mechanical system. No data for dwelling W007 was reported, but for W008 and 3, more hours of window opening were reported (1-8 and 13-24 respectively). As these dwellings have higher CO_2 excess rates, it may be that people feel the need to open the windows to compensate for a poor working balanced ventilation system. It is also worth noting that these two dwellings belong to the same complex (dwellings 3 and 4 also belong to one apartment block and dwellings 5 and 6 as well). Very important is to note that in the dwellings with the less CO_2 excess hours, the household size is small (1 to 2 people), while in the dwellings with the highest excess hours the household size is 2 to 4 people (4 in dwelling 7 and 2 in dwelling 8).

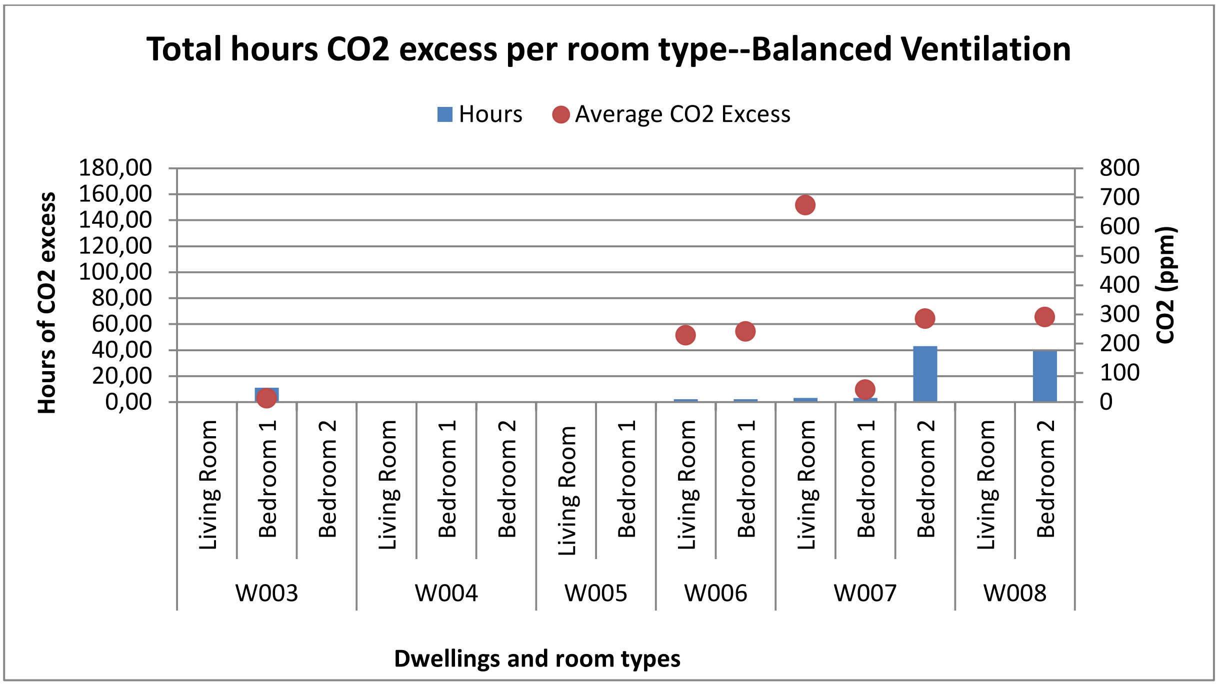


Figure 6.1: Total hours of CO_2 excess per room type in dwellings with balanced ventilation (312 hours of measurement)

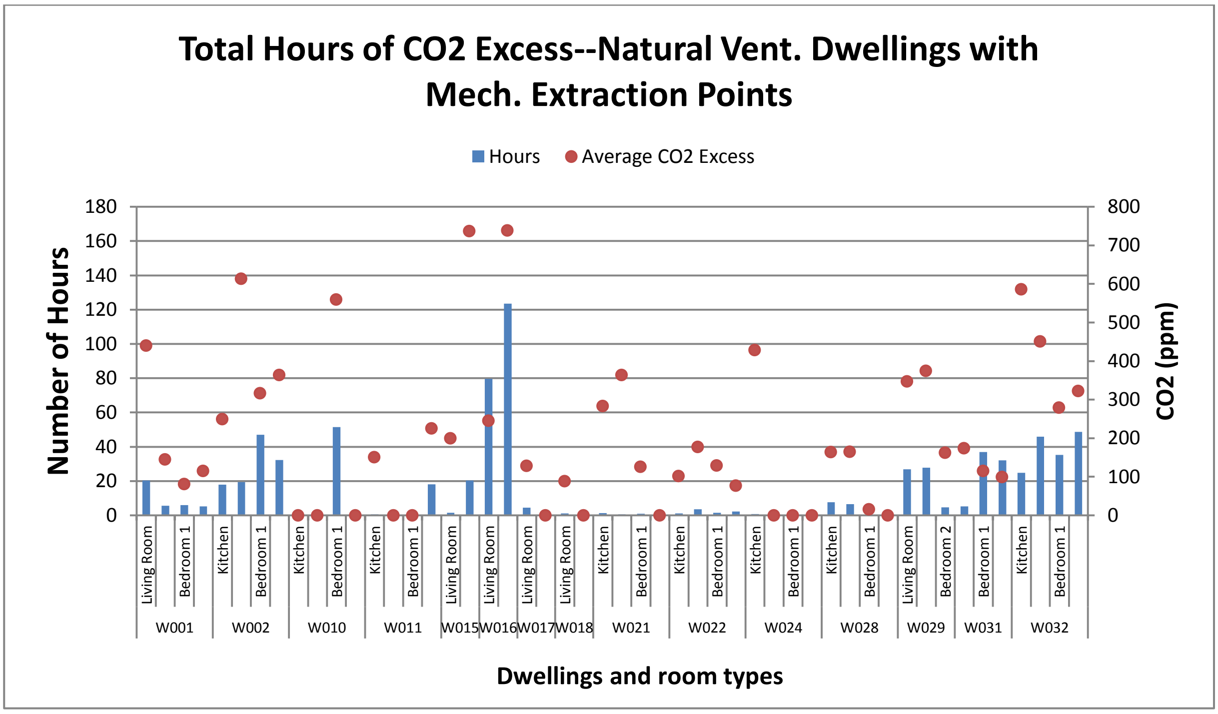


Figure 6.2: Total hours of CO_2 excess per room type in dwellings with natural supply and mechanical exhaust ventilation (312 hours of measurement)

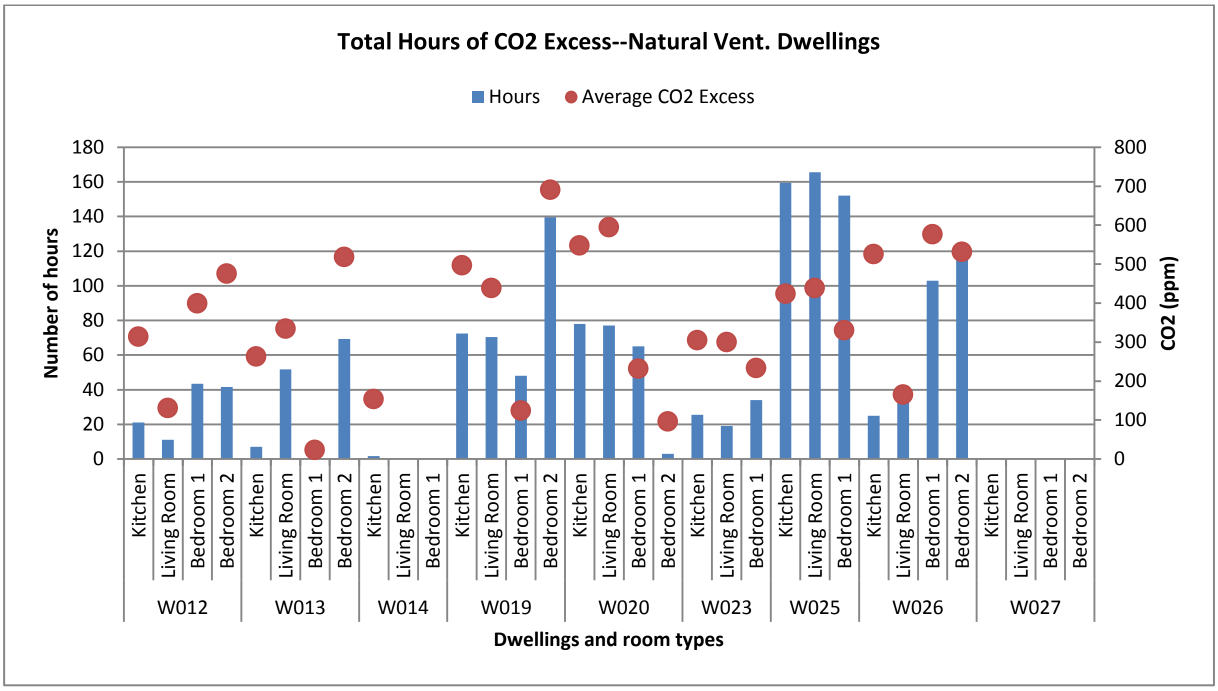


Figure 6.3: Total hours of CO_2 excess per room type in dwellings with natural ventilation (312 hours of measurement)

In the dwellings with natural supply and mechanical exhaust the hours for which the CO_2 concentration exceeds the threshold of 1200 ppm are a lot more. Though, half of the dwellings have no or minimal excess of CO_2 (11, 15, 17, 18, 21, 22, 24, 28), which could imply that the occupant behaviour (ventilation, presence patterns) could play a very important role. There seems to be here no correlation between, the number of hours of ventilation reported by the tenants and the hours of CO2 excess. For instance, for dwellings 01 and 02, who belong to the same complex, 01 has less excess hours than 02 but reported to open the windows less. The reverse happens in dwellings 10 and 11, also belonging to one complex. Dwellings 15, 16 and 17 belong all three to the same building block; 15 and 16 reported a lot of hours of window opening (9-12; 13-24 respectively) but have more CO_2 excess hours than 17. Dwellings 21 and 22, also located in one building show almost no CO_2 excess hours, but in one the windows are open only few hours, while in the other the windows are opened for more than 13 hours a day. This lack of trends may have something to do with occupancy. There are three dwellings with 3 occupants (02, 31, 32) and they show higher excess hours. However, the dwelling with the highest amount of excess hours (W016) has only 2 occupants, like many others without excess hours. In the dwellings with only 2 occupants (W001, 17, 24 and 29) the picture is very mixed as well.
When looking at the energy labels (see Table 4.2), a mix of A (W010, W011), B (W015, 16, 17, 18 and W032) and F, no clear correlations are found, although the dwellings with the lowest number of excess hours all fall under label F, which could relate to higher infiltration rates.

The performance of the naturally ventilated dwellings concerning the excess hours of CO_2 concentrations (see figure 6.3) was clearly the worst. These dwellings are all label F, with –probably -high infiltration rates. These high infiltration rates, however, do not seem to be beneficial for the CO_2 concentration, as the CO_2 excess hours are much higher than in the labels with balanced ventilation (all A-labels). The occupant of dwelling 27 was abroad for the whole time of the two-weeks monitoring campaign and that's why his house appears to have a low CO_2 concentration (identical to the outdoor one). Next to high excess hours in living rooms and bedrooms, excess hours were also observed in the kitchens. Apartment 14 is the only inhabited by one person (elderly) and performs the best (but no data was reported about the ventilation behaviour). Apartments 19 and 25, both with 3 occupants and quite high excess hours, have also different number of window opening (e.g. 1-4 hours in the bedrooms of W025 and 9-12 hours in W019). W020 and 23 have only 2 people and ventilate very little. W026 and W012 have the largest households (4 and 5 people respectively), ventilate very little and have different CO_2 excess hours.

Concluding, there is no clear pattern between the CO_2 excess hours and the reported ventilation behaviour. The household size seems to relate somehow to these excess hours: the larger the household, the more chance to find high excess hours. In our sample the relationship between the CO_2 excess hours and the type of ventilation system was very clear. Balanced ventilation systems seem to score better than mechanical exhaust systems, which score better than natural ventilation systems. This is in line with the findings from the Monicair report part A, in which the results on another sample of 60 dwellings were described.

6.2 Averaged day-CO_2 profiles

For the calculation of the 24-hour profiles of the CO_2 concentration (and temperature in chapter 7) the following procedure was followed: the 5 minute interval data strings for CO_2 and temperature were first aggregated hourly for each room of each house, producing the average hourly values for all the days of the monitoring campaign (in this chapter only from 6 to 18 march). Then, for each hour of the day, the average of all days for this specific hour was taken, resulting in the average 24-hour profile. All profiles can be found in Appendix B, per ventilation system per room. For the sake of readability the standard deviations are not presented, but will be shown for a few examples in section 6.3.

6.2.1 Differences between ventilation systems

The differences between ventilation systems are illustrated below by comparing the CO_2-profiles in the living rooms of dwellings with balanced ventilation and with natural ventilation. As seen in section 6.1, the dwellings with natural supply and mechanical exhaust behave in-between (see also Appendix B). Next to showing higher CO_2 concentrations, the naturally ventilated dwellings have in general less constant concentrations during the day, see figures 6.4 and 6.5. Only one dwelling (W014 - we exclude W027 because there was nobody home during the campaign) shows a pattern similar to balanced ventilation dwellings.

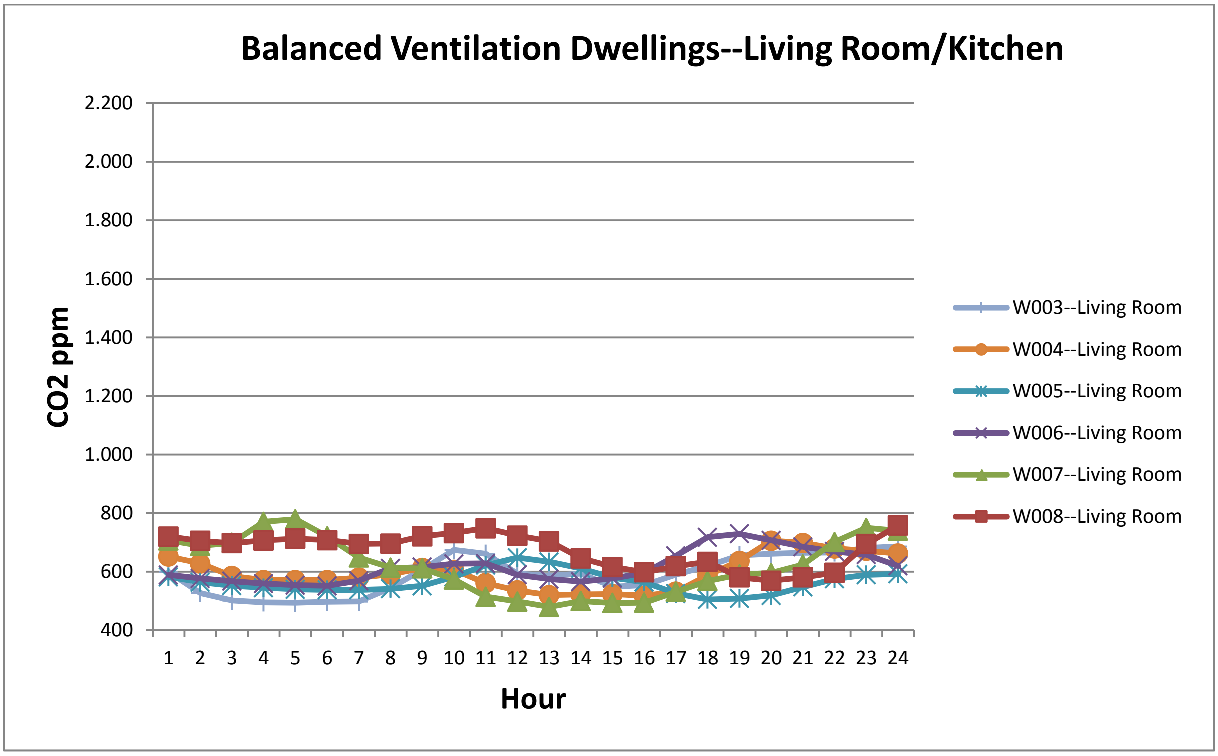


Figure 6.4: 24-hour CO_2 profiles of the living room for the dwellings with balanced ventilation.

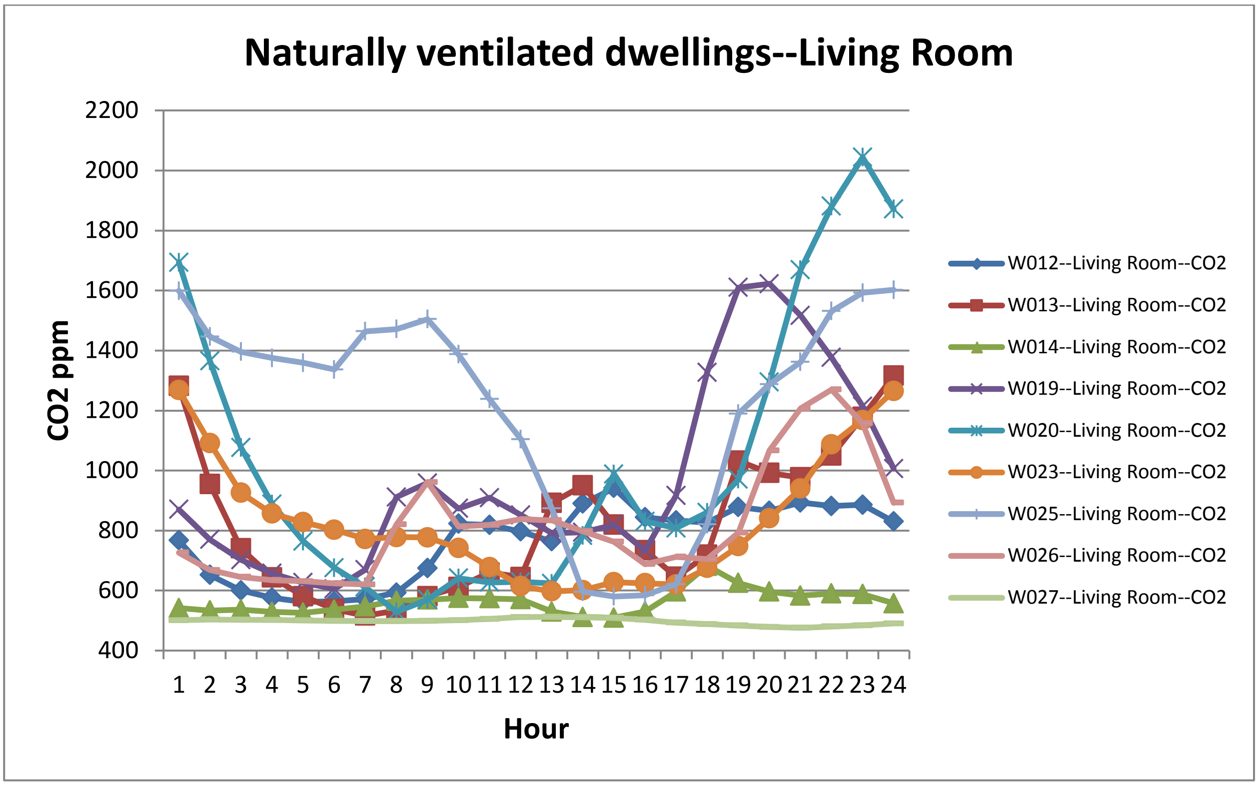


Figure 6.5: 24-hour CO_2 profiles of the living room for the naturally ventilated dwellings.

Apparently, in the dwellings with balanced ventilation, the air flow rates are enough to maintain a reasonable air quality all over the day.

In the dwellings with natural ventilation, the minimum concentrations during the day are similar to the ones in balanced ventilation, but at other moments the CO_2 concentration is much higher. The highest observed concentrations are in dwellings W019, WO20 and W025, which have, as already explained in section 6.1, no specific features. Dwellings with high occupancy (W012 and WO26 with 5 and 4 people respectively) both have a reasonable CO_2 profiles. Note that the peaks that are responsible for the excess hours, see figure 6.3, are not visible in figure 6.5 which presents averages over 2 measurement weeks.

6.2.2 Differences between rooms

As could be expected from section 6.1, large differences are observed between rooms within one dwelling. Figure 6.6 shows the CO_2 profile in the same dwellings as figure 6.4, but this time for the master bedroom (bedroom 1) instead of the leaving room. Obviously, the spread and the concentrations are much larger in the bedrooms than in the living rooms and it seems that the balanced ventilation system is being much more effective in the living room than in the bedroom. The CO_2 profiles in bedroom2 (see figure B.3 in Appendix B) show similar trends, but are, however, clearly different from the profiles in the master bedroom.

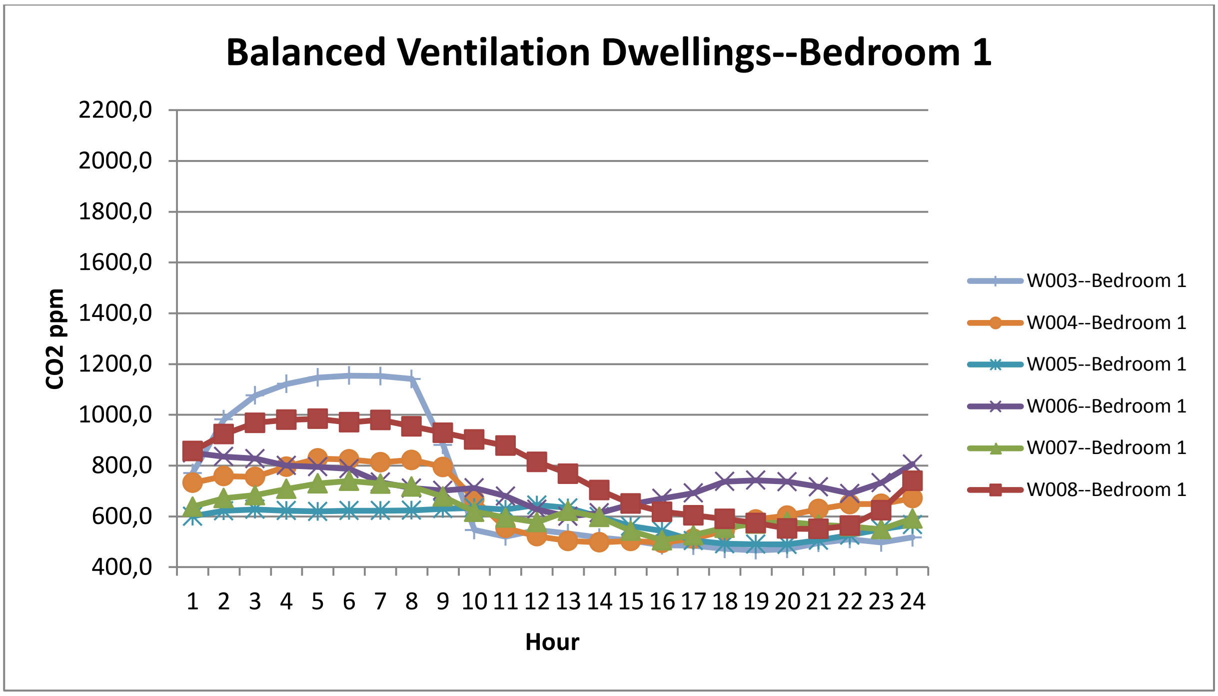


Figure 6.6: 24-hour CO_2 profiles of the master bedroom for the dwellings with balanced ventilation

Figures 6.7 and 6.8 shows the CO_2 profiles for the kitchen and the master bedroom in the naturally ventilated dwellings. Here too it is clear that the profiles are very different per room.

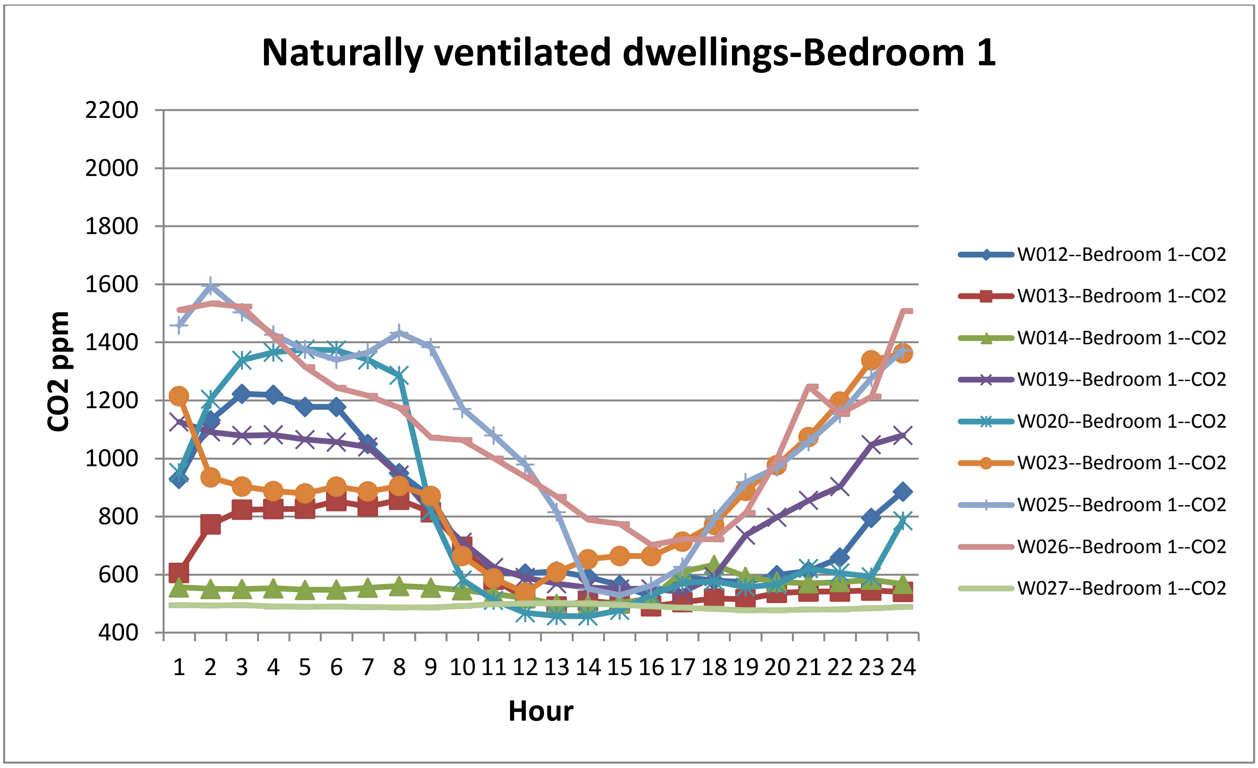


Figure 6.7: 24-hour CO_2 profiles of bedroom 1 for the naturally ventilated dwellings.

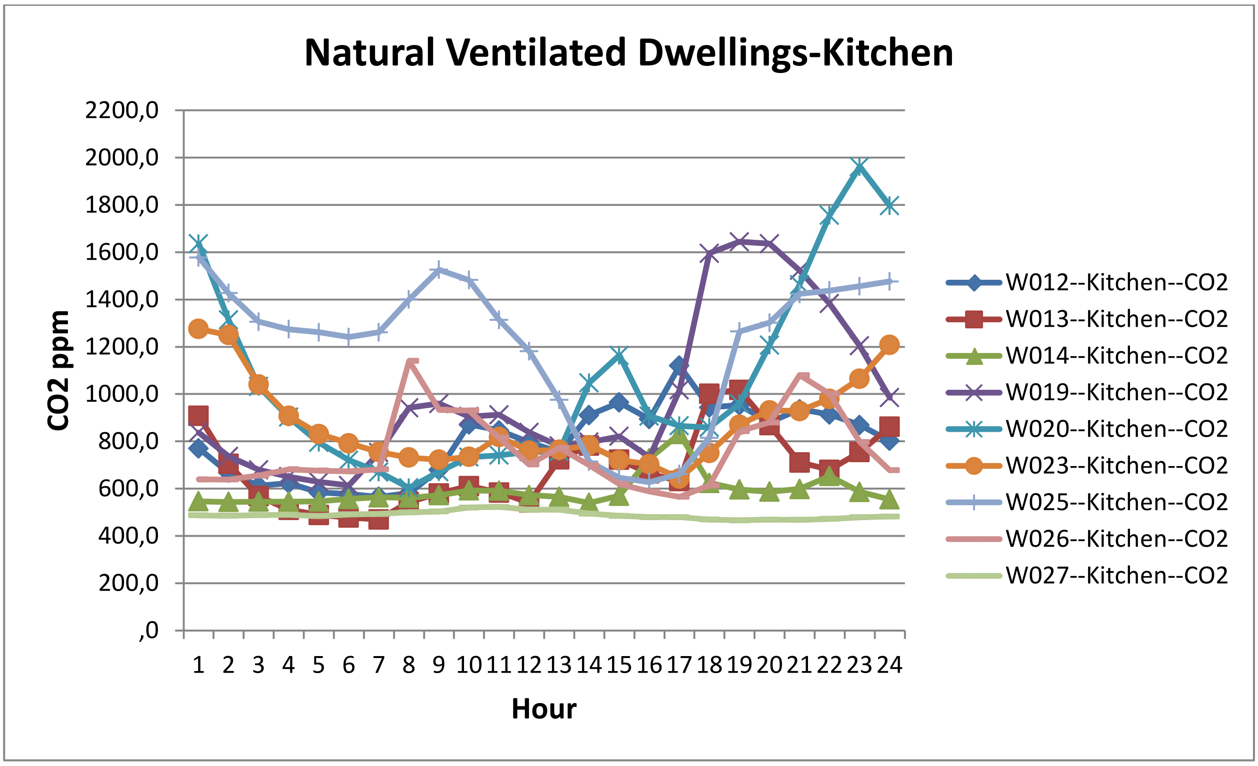


Figure 6.8: 24-hour CO_2 profiles of the kitchen for the naturally ventilated dwellings.

6.2.3 Qualitative interpretation of the CO_2 profiles

Figures 6.4 to 6.8 and Appendix B may also be interpreted in the light of occupancy patterns.
If we take figure 6.5, living room of naturally ventilated dwellings, a CO_2 concentration drop is generally observed at night from 22:00-23:00 to approximately 7:00 in the morning (although in dwelling

W019, this drop starts already at 19:00 and corresponds to an increase of CO2 concentration in the bedrooms, that are probably used as study room as well). There is generally a small peak in the morning, between 7:00 and 10:00, followed in most cases (but not all) to a strong decrease, corresponding to people leaving the house to go to work or to school. After 17:00 there is again a peak: people come back home. Similar observations can be made on figure 6.4 (balanced ventilation) but the profiles are much flatter.

Concerning the master bedrooms, we observe a clear increase of the CO_2 concentration at night in most of the balanced ventilation dwellings (figure 6.6), when it is most likely that the tenants are sleeping in this room. The concentration starts dropping during the morning hours and start increasing again during the evening. The different slopes of the CO_2 increase may relate to the amount of people present, to the effectiveness of the ventilation system, and to the opening of windows. However, the highest CO_2 concentration at night is found in dwelling W003, in which the tenants reported to open the windows a lot (13-24 hours). Dwelling W006 is the only one who shows a deviating profile for which no good explanation could be found.

As for the master bedrooms in the naturally ventilated houses (figure 6.7), the profiles are very clear, showing an increase in CO_2 concentration from 17:00 in the afternoon, therefore a bit earlier than in the balanced ventilation dwellings. The bedrooms in these dwellings may also be used as hobby or study room. Note also that we didn't check for the opening of indoor doors between rooms. Habits about opening or closing them should influence also the CO_2 concentrations.

6.3 Detailed analysis of the CO_2 levels in a few dwellings

In addition to the analysis of the CO_2-levels over a period of about 2 weeks, the CO_2-levels are also analysed over the whole measuring period for a couple of dwellings. The whole measuring period concerns the period from roughly November 2014 up until April 2015. For this purpose from each group of dwellings, with a specific ventilation system, 2-4 dwellings were selected. A dwelling with low, average and high CO_2-levels, based upon the analysis over the period of 2 weeks, were selected.

The selected dwellings from the group with balanced ventilation system (system D) are: W003 and W007.

From the group with natural supply and mechanical exhaust (system C), W002, W011, W016 and W018 were selected.

From the group of dwellings with natural ventilation (system A) we selected W014, W023 and W025.

Based upon the measured CO_2-levels, the CO_2-curve is derived per room and for each day of the week, following the same method as described in section 6. 2. The average CO_2-level is determined for each time of the day, together with the standard deviation and the minimum and maximum values. The data however showed little or no difference per day, also when week days were compared to weekends. Therefore in this report the CO_2-curves are given as an average of all days together.

The results are shown in figures 6.9 to 6.11 for a dwelling with balanced ventilation. The data for the other dwellings can be found in appendix C.

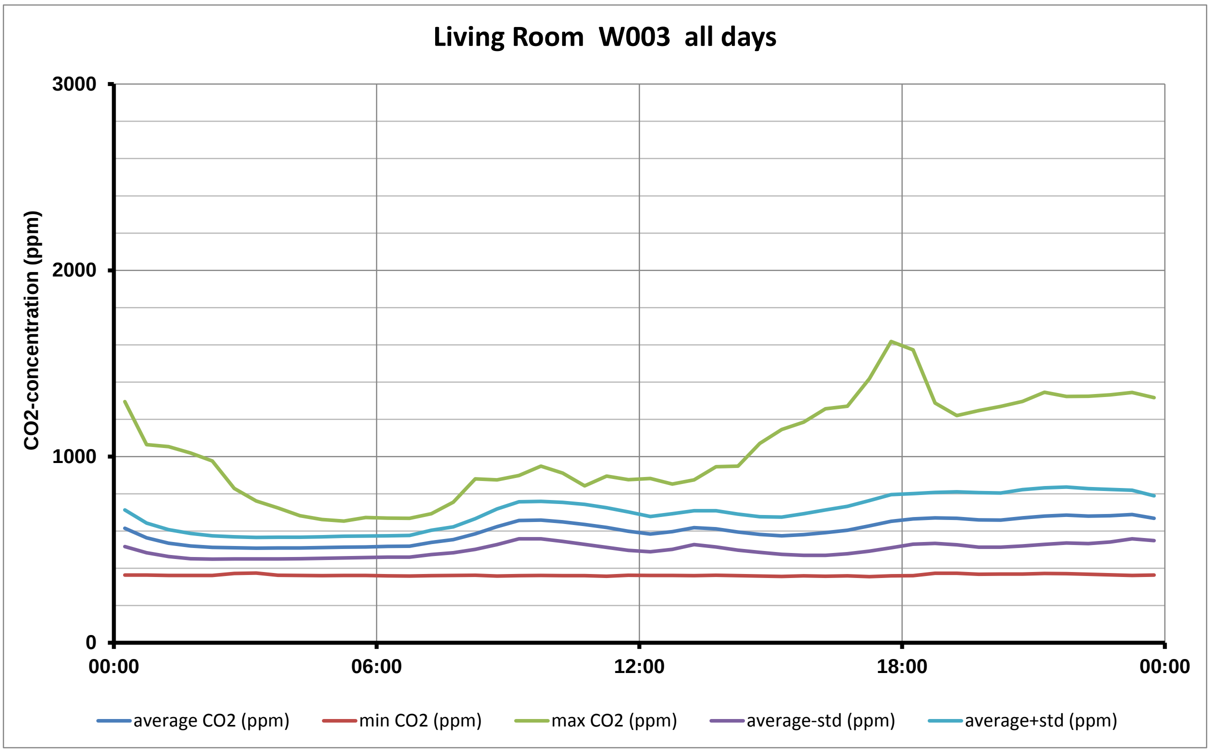


Figure 6.9: CO_2-profile living room dwelling W003 (balanced ventilation) over the complete 6 months of measurement

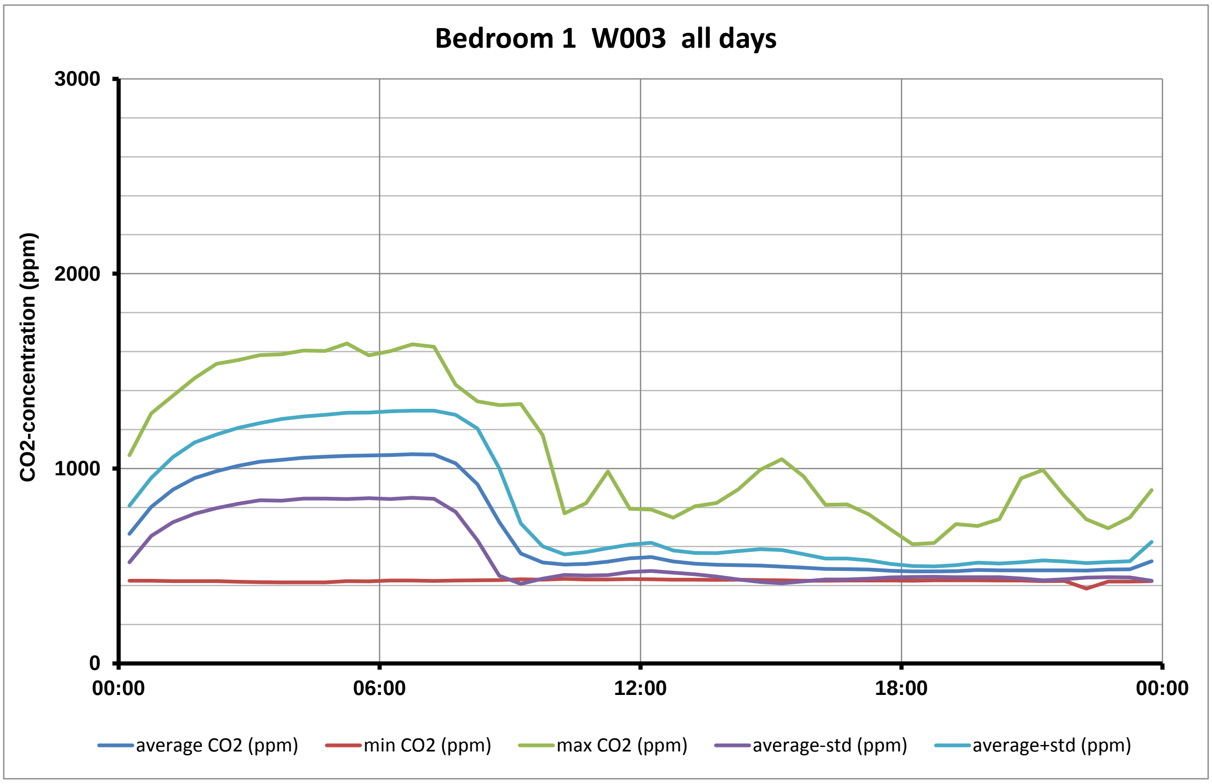


Figure 6.10: CO_2-profile bedroom 1 dwelling W003 (balanced ventilation) over the complete 6 months of measurements

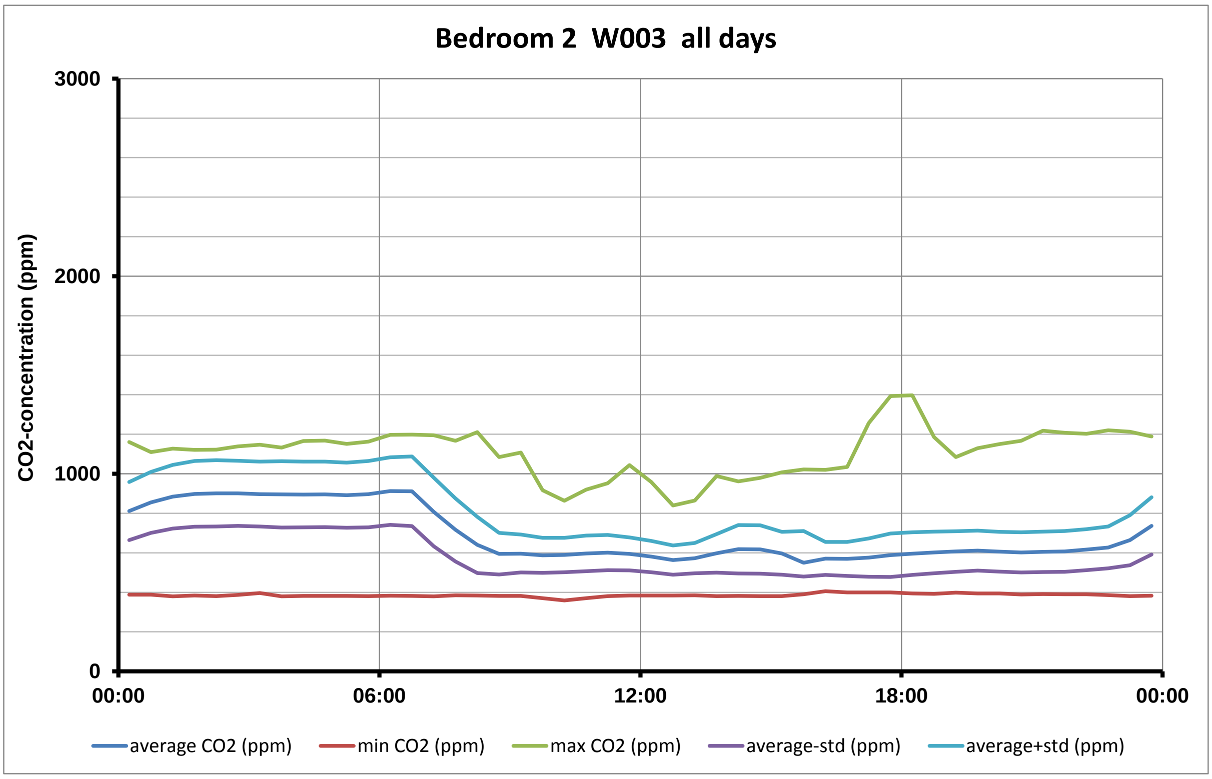


Figure 6.11: CO_2-profile bedroom 2 dwelling W003 (balanced ventilation) over the complete 6 months of measurement.

6.3.1 Balanced ventilation dwellings (system D)

A first observation is that average profile over the 6 months period are very similar to the average profile over the two weeks period that was used in sections 6.1 and 6.2, although the 6 months average is flatter than the 2 weeks average.

From figures 6.8 to 6.10 and appendix C can be derived that in a lot of the rooms the CO_2 profile of the averaged CO_2 value plus one times the standard deviation, lays below 1200 ppm. From the figures can be derived that in a lot of the rooms even the averaged value plus two times the standard deviation (86% probability) is below 1200 ppm. In these situations, maximum CO_2-level higher than 1200 ppm may occur for a short period. It is noted however that the CO_2-concentrations are not log-normal distributed, which can be seen from the fact that the averaged value minus the standard deviation can be lower than the minimum value, which shouldn't happen if the distribution was log-normal. This indicates that some reserve needs to be taken into account when analysing the data in relation with the standard deviation.

In the following dwellings and rooms, too frequent and too high excess hours (>1200 ppm) are found.

- Bedroom 1 in dwelling W003: Figure 6.10 shows excess of 1200 ppm during the night. The CO_2-profile of the averaged value plus one time the standard deviation can increase up to 1300 ppm. The maximum level is below 1600 ppm.
- Living room and bedroom 2 of dwelling W007: Figures C.1 and C.3 (Appendix C)show that the CO_2-profile of the averaged value plus once or twice the standard deviation exceeds 1200 ppm, while maximum values occur up to 2000 or 3000 ppm.

Thus in total in 3 of the 6 considered rooms in the dwellings with balanced ventilation, situations with insufficient ventilation were found. A reason, for the above mentioned excess hours of 1200 ppm can be an incorrect use of the ventilation system. Figure 6.10 clearly shows a daily repeating use of bedroom 1 during the night. The CO_2-levels increase every night up until the morning. It may be that the ventilation level (manual control) was not set at the right position leading to higher CO_2-levels, however this household was the only one reporting using level 2 of the ventilation (instead of 1 in all others, see also analysis in sections 6.1 and 6.2). In MONICAIR part A it was found that occupants often do not set the ventilation system in a higher position for ventilating the bedrooms during the night, but keep the system in low position, which (normally) results in too low ventilation of the bedrooms. This is also in agreement with the survey filled in by these occupants. They answered that they did not control the ventilation or did not even know whether they were controlling the ventilation.

6.3.2 Dwellings with natural supply and mechanical exhaust (system C)

The figures C.4 to C.16 indicate that, in general, the CO_2-profile of the averaged value plus twice the standard deviation, lays roughly below 1200 ppm while higher maximum values are observed for short periods. Note that in these figures only the CO_2-profile of the averaged value plus once the standard deviation is shown, but the profile with twice the standard deviation can easily be estimated based upon this. This concerns the living room and kitchen in both dwelling W002 (figures C.4 and C.5) and W011 (figures C.9 and 11). The highest CO_2-level hereby seems to be a result from cooking on gas (high CO_2-production). This could indicate a poor efficiency of the exhaust ventilation in the kitchen.

In the following dwellings and rooms, too frequent and too high excess of 1200 ppm are found.

- Bedroom 1 and 2 in dwelling W002: Figures C.6 and C.7 indicate that the CO_2-profile of the averaged value plus once the standard deviation can exceed 1200 ppm, while a maximum value up to 2000 ppm may occur.
- Bedroom 2 in dwelling W011: Figure C.11 shows that the CO_2-profile of the averaged value plus once the standard deviation can exceed 1200 ppm, while a maximum value up to 3000 ppm may occur.
- Living room and bedroom 1 and 2 in dwelling W016: Figures C.12 to C.14 indicate that the averaged value plus once the standard deviation (or twice in bedroom 2), can exceed 1200 ppm, while a maximum value up to 3000 ppm may occur. This happens especially in bedroom 1.

Thus in total in 6 of the 13 considered rooms in the dwellings with mechanical exhaust and natural supply, situations with insufficient ventilation are found. One of the reasons for this can be an incorrect use of the ventilation system. In case of systems with mechanical exhaust in the wet rooms (kitchen, bathroom and toilet), occupants are triggered to some extend to use the bedroom grids or windows, but are little or not triggered to switch the mechanical exhaust higher during the night, leading to low ventilation rates. It is well known that not using the system during the night is also something that happens with balanced ventilation systems. With balanced systems however a 'higher' basic ventilation of the bedrooms usually takes place.

6.3.3 Naturally ventilated dwellings (system A)

For the dwellings with natural exhaust and natural supply, the figures C.17 to C.27 show that only in dwelling W014 the CO_2-profile of the averaged value plus twice the standard deviation (86% probability), lays below 1200 ppm while higher maximum values are observed during short periods. In the other dwellings, too frequent and too high excess of 1200 ppm occurs (see figures C.20 to C.27).

This is especially the case for dwelling W025. A part of this can be explained by cooking on gas in the kitchen. Figure C.25 shows extreme high CO_2-levels in the kitchen up to 7000 ppm and thus poor exhaust efficiency. This seems to affect the other rooms via air exchange (see also analysis in sections 6.1 and 6.2). Figure C.27 shows that in bedroom 2 the CO_2-level can increase further during the night by 1500 ppm (average+ standard deviation).
Thus in total in 8 of the 11 considered rooms in the dwellings with natural exhaust and natural supply, situations with insufficient ventilation were found.

6.3.4 Conclusions

The results discussed above lead to similar conclusions as the outcome of the analysis performed over 2 weeks. Situations with too frequent and too high hours of excess of 1200 ppm are found for each ventilation system or, in other words, despite of the ventilation system. Thus possibilities to improve all the considered ventilation systems need to be examined.

However, it is clear that much less CO_2 excess is found with balanced ventilation systems than with naturally ventilated ones. Although the starting point of the analysis was dwellings with low, average and high CO_2-levels from each type of ventilation system, the analysis shows that the number of rooms in which threshold values are exceeded together with the level and duration of excess, increase from ‘balanced system’ to ‘mechanical exhaust with natural supply’ to ‘natural exhaust and natural supply’.

In a couple of dwellings high CO_2-levels are observed in the kitchen, probably due to cooking on gas. This shows a poor efficiency of the exhaust in the kitchen. This especially occurred in dwelling W025 with natural exhaust (and natural supply), leading to extreme high CO_2-level up to 7000 ppm and, perhaps more disturbing (although not measured), high levels of related combustion and cooking gases/particles.

These findings are also in agreement with the findings in Part A of Monicair. The main difference between the CO_2-profiles determined in part A of MONICAIR and the profiles determined in section 6.3 is that averaged values are considered in section 6.3. In part A no averages were used, thus giving, too some extend, insight in the variation of the CO_2-levels per dwelling per day. In part A it was found that, although averaged values might be reasonable, instantaneous values could exceed threshold values too much.

6.4 Determination of the presence of occupants by analysis of movement and CO_2 concentrations

For the analysis of monitoring data in dwellings, it is necessary to have a good insight in the presence of occupants. This can explain, for instance, changes due to occupant behaviour or can be needed to analyse energy consumption.

To determine the presence of occupants, motion sensors are commonly used. Such a sensor (PIR sensors in our case), as the name illustrates, however only detects motion. Thus it is not clear if somebody has entered or left the room. If after motion detection, no further motion is detected, this can mean that the person is no longer present or is seated at rest or, in case of a bedroom, is sleeping. This section presents the results of a study about the possibility to predict presence by using a combination of motion sensors and CO_2 measurements.

6.4.1 Movement detection

This section describes a way to produce average movement profiles during a period for a certain type of dwellings or household. For the sake of demonstration, we illustrate the method on dwellings having balanced ventilation – although this grouping may not be the most relevant one. The 5 minute interval data strings from the movement sensors for each room type (living room, kitchen, bedroom 1 and bedroom 2), for all the dwellings having balanced ventilation were gathered together in a worksheet. For each one of the 5 minute intervals the total amount of cases was counted forming a new data string column. Again for each of the 5 minutes interval the number of times that movement was detected was recorded in a new adjacent column, while in a second column the number of times that movement was not detected was recorded. Then all data strings were aggregated and averaged hourly just like described in section 6.2. Figures 6.12 and 6.13 show the average percentage of time for which movement was detected in each hour of the day, during the two weeks measurement period in March (see also section 6.1), in each specific room type of the dwellings with balanced ventilation. Evidently, the same method can be used to produce profile per house or per type of household or any other relevant category.

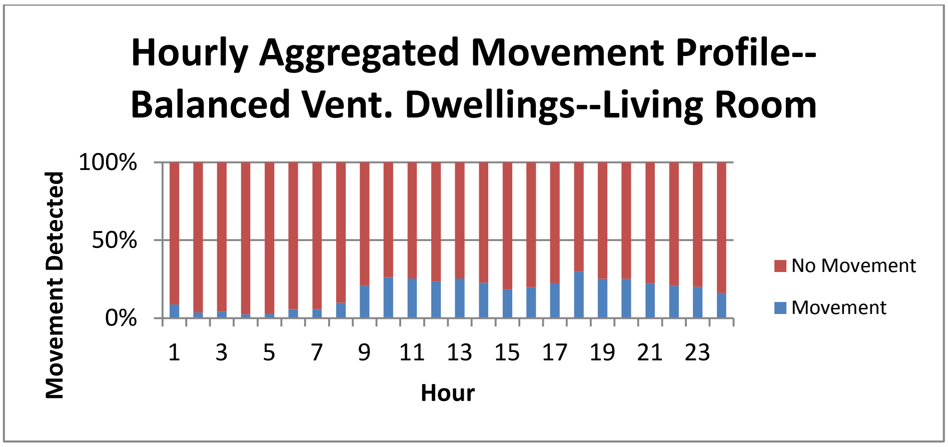


Figure 6.12: Aggregated movement profile for the living rooms (all balanced ventilation dwellings).

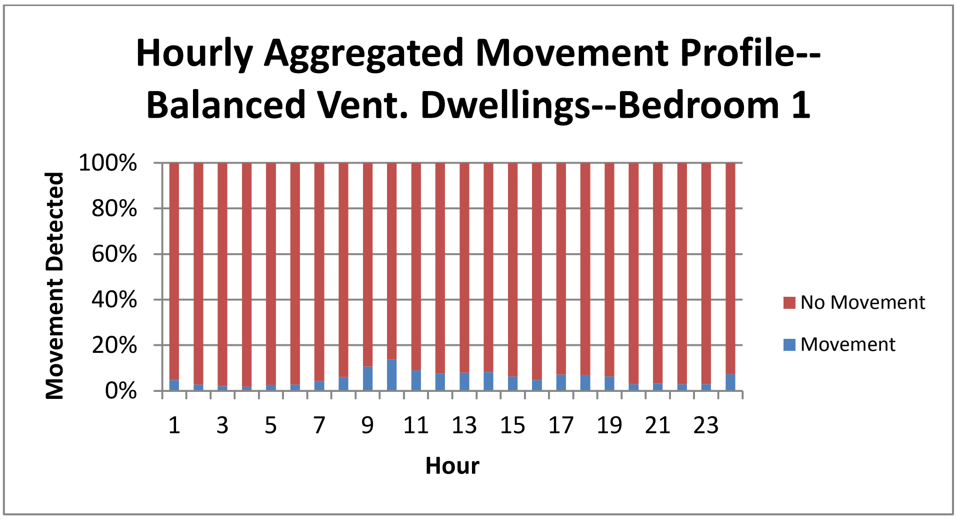


Figure 6.13: Aggregated movement profile for bedroom 1 (all balanced ventilation dwellings).

At night, almost no movement is detected in the main bedroom (bedroom1), but in most cases people are present, sleeping there. The figures show very well the average time were people wake up: movement is detected between 7:00 and 10:00, and again in the evening, after 23:00. In the living room, the absence of activity at night probably means that there are no people present. A lot of movement is detected during the day, which is logical.

In case of a bedroom, things can however be reasonably clear. If during the course of the evening, motion is detected and later on motion is detected in the morning, one might assume that a person has slept in that bedroom. For a living room, however, it is not that clear if somebody is present or not in between motion detection. The same goes for bedrooms used for study or hobby. There is therefore a strong need to develop a method to detect presence instead of movement.

6.4.2 Presence prediction

Within this project an algorithm was written to define the presence of occupants based upon (1) the motion sensor, (2) the fact that somebody was assumed present or not at previous time intervals and (3) the slope of the CO_2 profile.

Determination is done in the following iterative way:

1) if motion is detected, at that moment somebody is considered present. This is unquestionable and regardless the fact whether somebody was assumed present or not previously.
2) if no motion is detected, while previously somebody was assumed present, the CO_2 profile is checked. If the CO_2 concentration decreases in a way that might be expected when nobody is present, the algorithm assumes that nobody is present (the people previously present have leaved the room). If the CO_2 concentration do not decrease, the assumption will be that somebody is still present in the room, but do not move (e.g. seat on the coach). The increase and decrease of the CO_2 level is evaluated based upon an estimated ventilation time constant.
3) if no motion is detected, while previously nobody was assumed present, the CO_2 profile is checked as well. If the CO_2 concentration increases as might be expected when people are present, there is a contradictory situation (no motion, no previous presence but CO_2 increase), the assumption of 'no presence' must be corrected. This is necessary because situations were found in which the motion sensor misses the motion.

The above focusses on the presence and not on the number of persons present. In case the number of persons in the household is known, rules can be added for this purpose. For instance if a person is detected in a bedroom, there should be at least one occupant less in, for instance, the living room. Furthermore 1 and 2 person bedrooms can be defined. This would give additional information about the possible number of persons when there is presence predicted in a room.

In section 6.4.3 some results are given about the predicted presence during a specific day within the measuring period. In section 6.4.4 the results are given averaged over the complete measuring period. This way an average presence profile per day for the 6 months heating period is derived.

6.4.3 Presence prediction for a specific day

In figures 6.14 and 6.15 the predicted presence (blue line indicated with 'Presence_') is shown, based upon the motion sensor signal (purple dots indicated with 'Presence') and the measured CO_2-curve, for the living room and bedroom 1 in dwelling W003. The prediction is done according to the method described in section 6.4.2.

Figure 6.14 shows motion detection spread over the day from about 7:40 in the morning until 23:20 in the evening for the living room of dwelling W003 on the 13th of January 2015. In combination with the CO_2 curve, the predicted presence seems very likely. From about 7:40 in the morning the CO_2-level increases until about 9:15, indicating presence. Up to about 12 hour, the CO_2-levels fluctuates a bit, thus presence and no presence alternate based upon the signal of the motion sensor. From about 12:00 the CO_2-levels increases again, thus presence is likely. From 16 hour to 21 hour, the CO_2-level increases as well, thus a longer period with presence seems likely. From about 22:00 the CO_2-level stays constant, while motion is now and then detected and thus, again, presence is predicted.

Figure 6.15 shows the situation for bedroom 1 in the same dwelling over the same day. During the night little motion is detected. Nevertheless based upon the CO_2-increase, presence is predicted for a longer period until 7:35 in the morning. This is likely to be correct. This bedroom seems to be used typically as a bedroom, while during the day no motion is detected. The increase of CO_2 at 11:10 seems to indicate presence, although no motion is detected by the motion sensor.

In general, based upon the results shown in figure 6.14 and 6.15, it may be concluded that the presence predicted by the algorithm seems to be logical. However the prediction is based upon several assumptions, especially an estimation of the ventilation time constant. When a window is opened, this might result in the incorrect assumption that someone has left.

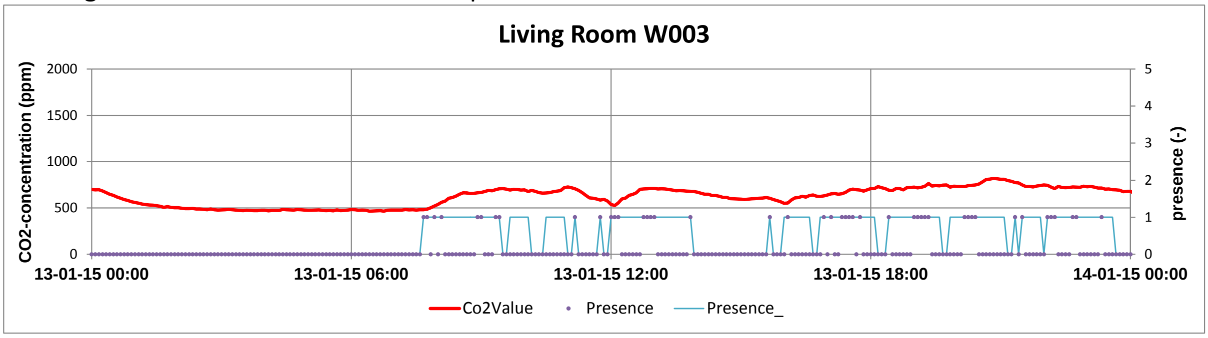


Figure 6.14: Predicted presence (blue line, right axis) based upon motion sensor (purple dots, right axis) and CO_2-course (red line, left axis) for the living room of dwelling W003 on the 13th of January 2015.

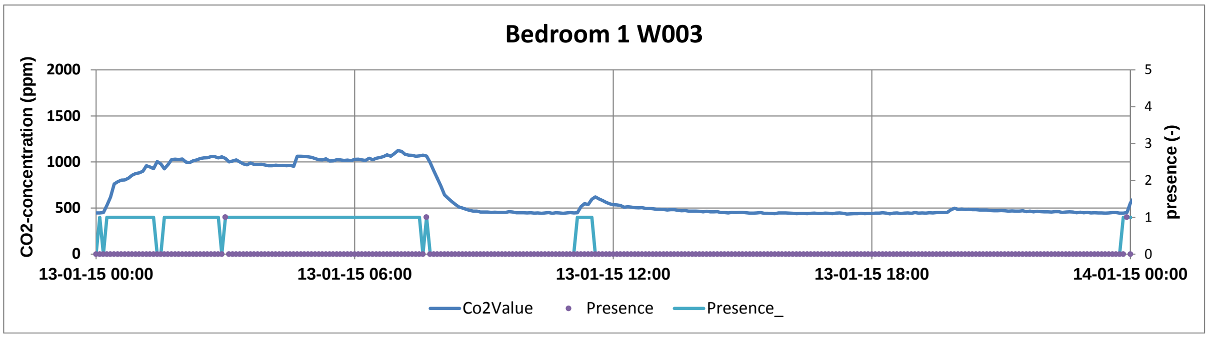
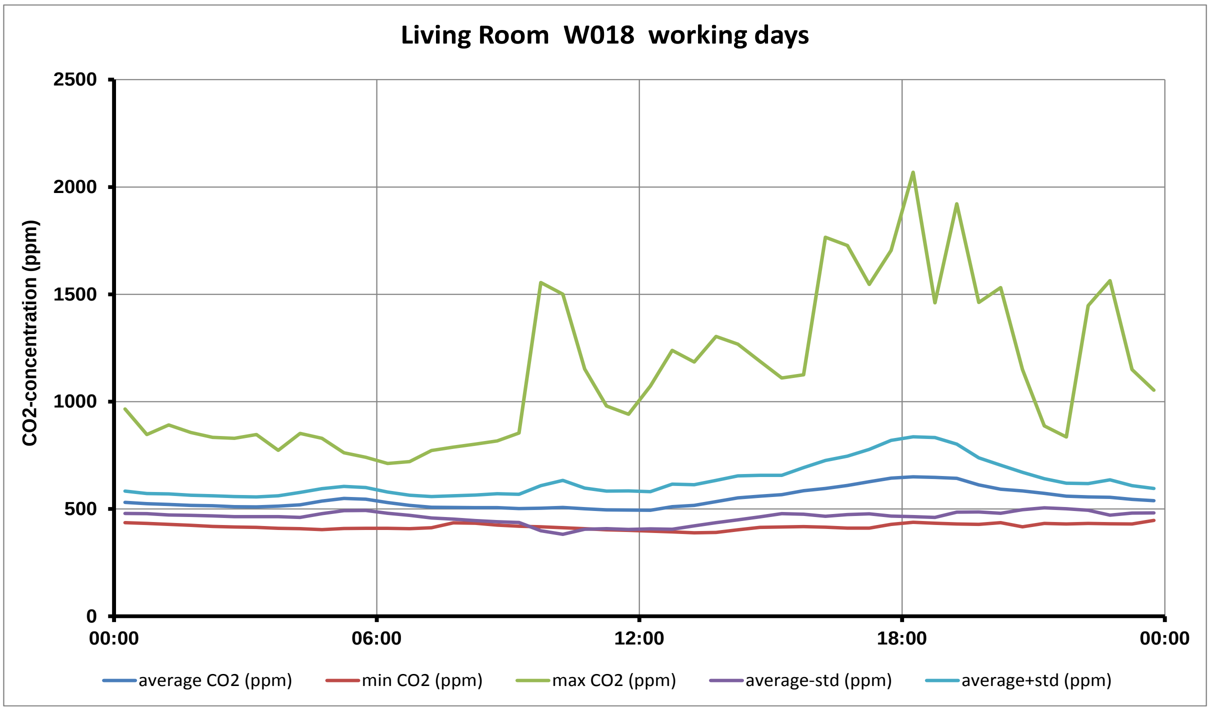


Figure 6.15: Predicted presence (blue line, right axis) based upon motion sensor (purple dots, right axis) and CO_2-course (red line, left axis) for bedroom 1 of dwelling W003 on the 13th of January 2015.

6.4.4 Presence profile on an average working day

In this paragraph, the average presence profiles per working day (Monday to Friday) are shown for the living room and the master bedroom of dwelling W018 (natural supply and mechanical exhaust). The average is calculated for the complete 6 months measurement period. The figures for the weekend were also determined and, as already state for the CO_2-profiles, the differences between workings days and weekend were minimal in our sample. In Appendix D the graphics for dwellings W03 (balanced ventilation), W016 (natural supply and mechanical exhaust) and W014 (natural ventilation) can be found.



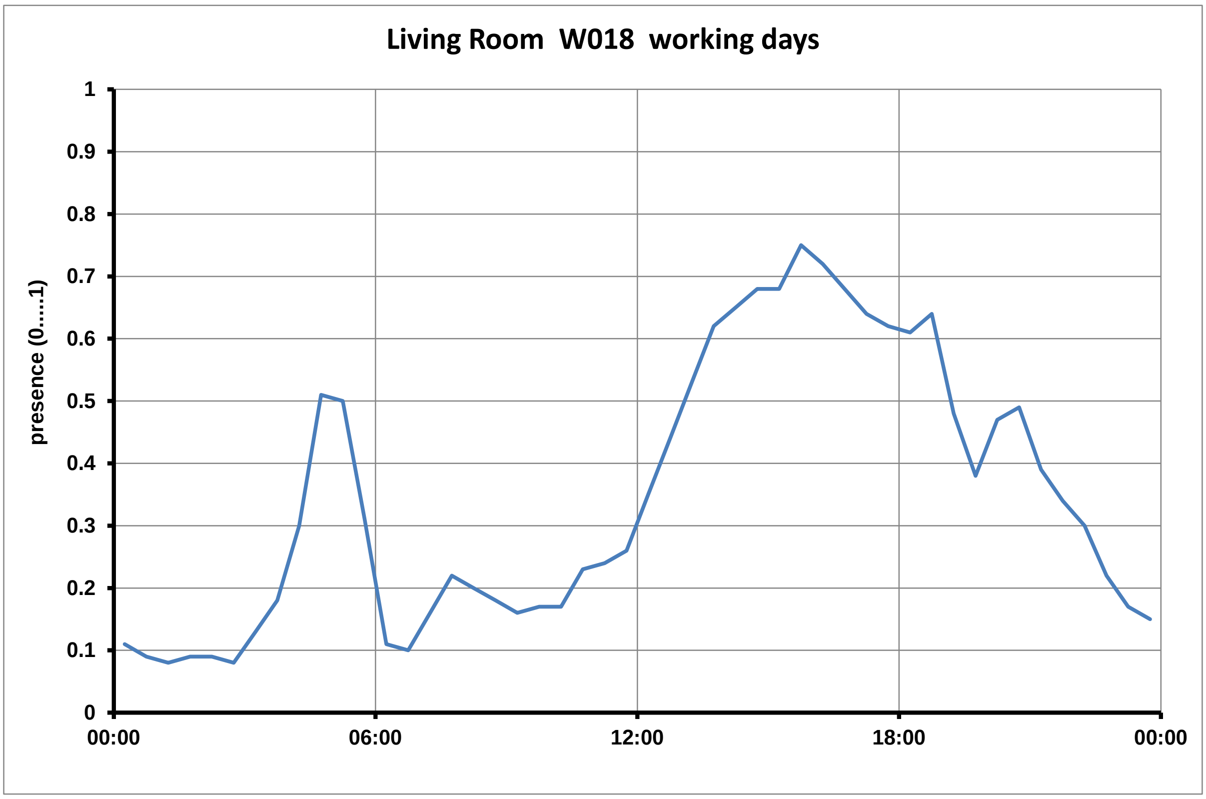
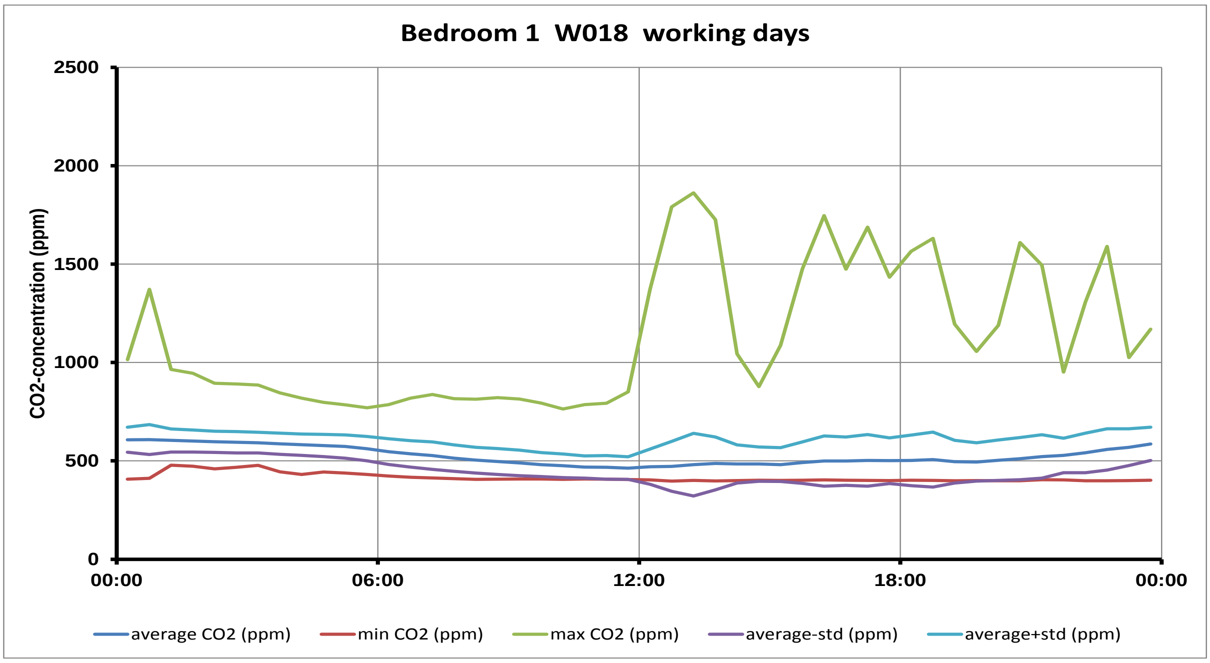


Figure 6.16: CO_2-profile and presence profile for the living room in dwelling W018 for working days based upon the complete 6 months measuring period

In figures 6.16 and 6.17 and in Appendix D the presence fluctuates between 0 and 1. Because several days are evaluated (period from November 2014 to April 2015), the presence at a certain time during the day in fact becomes the probability that somebody is present. So a presence of 0.8 at a certain hour means that in 80% of all studied cases (that certain hour for all working days of the measurement period), there was presence.



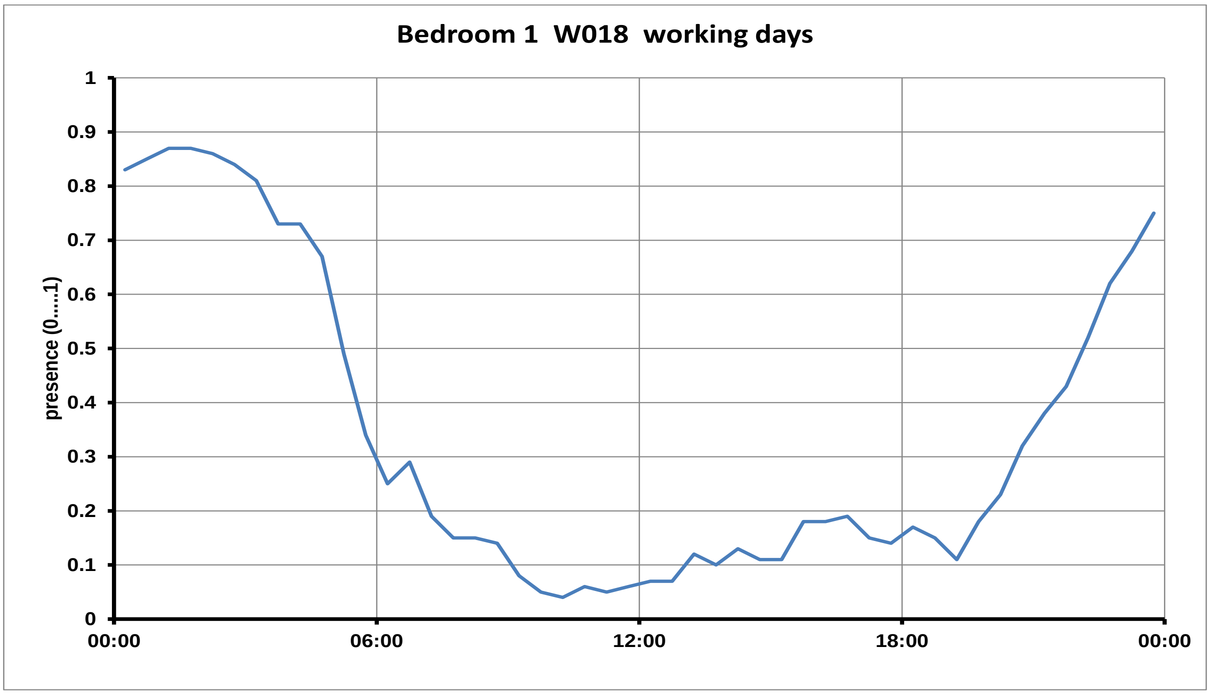


Figure 6.17: CO_2-profile and presence profile for bedroom 1 in dwelling W018 for working days based upon the complete 6 months measuring period

Figures 6.16 and 6.17 indicate that, although the CO_2-profile is not always very concluding about presence, the combination of the profile with the data from the motion produces a presence profile that seems reasonable: presence in the living room (see figure 6.16) is predicted in the afternoon and evening and presence in the bedroom (see figure 6.17) is predicted during the night. The presence peak in the living room at about 5:00 in the morning seems less common, but the CO_2-profile consistently has a small increase at that time, which definitely might be the result of presence. It could indicate that the tenant (there is only one person in the household) wake up early in the morning and uses for a short time the living room or the kitchen.

In figure D.1 (Appendix D) the presence profile (working days) for bedroom 1 of dwelling W003 is given. This shows that during the night, from about 23:00 in the evening until 7:15 in the morning, the algorithm predicts presence for about 90% of the time. During the day there is hardly presence. This meets the CO_2-profile which clearly indicates (and is already mentioned before) that this bedroom is used only for sleeping at regular times. Figure D.2 shows data from the living room in dwelling W016, which shows a clear distinction between presence during the day and no presence during the night. This is what might be expected and also meets the distinct CO_2-curve over night and day. Figure D.3 shows data from bedroom 1 in dwelling W014. Here the CO_2-profile gives little or no distinction between night and day. This is also the case for the predicted presence.

Based upon the combination of motion detection and CO_2-profile, it seems possible to predict presence, also when only slight increases or decreases of the CO_2 concentration are observed. The predicted presence could be explained logically, however, additional validations will be needed in the future by a careful monitoring of the actual presence, possibly by using a logbook or a camera in the dwelling. In particular the predictions are based upon several assumptions, especially an estimation of the ventilation time constant. When a window is opened, this might result in the incorrect assumption that someone has left. Additional information about the household could also improve the prediction, such as: number of occupant, age of the occupants, which bedrooms are used by which occupant. Based upon this, assumptions can be added about the number of people present and the probabilities of presence or absence during the day.

7 Analysis of the temperature profiles and the energy consumption

Temperature levels and profiles in dwellings are expected to have an important effect on the heating energy use. However up to now very few studies have been realized to determine such temperature profiles. The only one is Delghust (2015), who did it for around 50 dwellings in Belgium.

In the following sections the temperature profiles are analysed in the different categories of ventilation systems, although this might not be the most relevant categorisation. However, all dwellings with balanced ventilation had an energy label A or B and a heat pump or a condensing boiler, which are relevant parameters for the analysis. All dwellings with natural ventilation had a label F and a condensing boiler or a local stove. In the dwellings with natural supply and mechanical exhaust, the labels are mixed between A, B and F, but all dwellings in this category have a condensing boiler. It should then be possible to get an idea about the influence of these parameters on the temperature profiles.

The temperature profiles are calculated over the two-week measurement period (8-13 march 2015) the same way as described in section 6.2. As already mentioned in chapter 6, this is a reasonably cold period, and as such, quite representative of the heating season. The results for the 6 months measurement period could have been presented as well, but we chose for the short measurement period for which we also had comfort data (see chapter 9). In figure 7.1, the average, minimum and maximum outdoor temperatures during the measurement period are given.

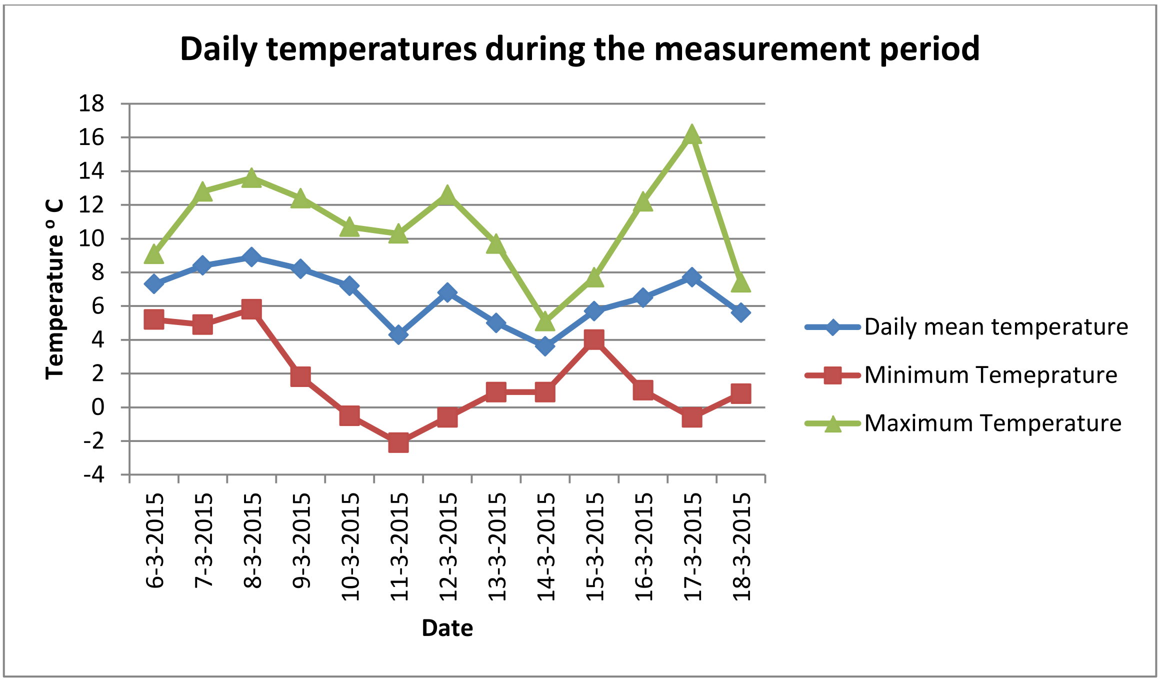


Figure 7.1: Daily outdoor temperatures in the measurement area during the two-week measurement period.

7.1 Dwellings with balanced ventilation

7.1.1 Analysis of the temperature profiles

Figure 7.2 shows the hourly temperature profiles for the living rooms of the balanced ventilation dwellings, all label A dwellings. Two patterns can be recognized, one for the dwellings with heat pump and one for the dwellings with condensing boilers. Houses W003, 4, 7 and 8 are equipped with heat pumps coupled with floor heating and so the temperature fluctuation is small through all the hours of the day reflecting the continuous operation of the heat pump with the low temperature hydronic system. On the other hand, dwellings W005, and 6, equipped with condensing boilers show a clear increase of the temperature during the morning hours, probably reflecting the occupancy pattern of the tenants. The temperatures in all living rooms were above 21^{o} C for all the hours of the day with dwelling W003 having a temperature between 25 and 26^{o} C all over the day.

The 24-hour profiles for the master bedrooms can be seen in figure 7.3. Again two patterns can be distinguished. Dwellings with heat pumps have a minimal fluctuation in the hourly temperature during the day while the houses with condensing boilers show a clear increase of more than one degree Celsius, during the morning hours.

Especially for the buildings with efficient boilers this could be an indication of energy wasting practices. The presence patterns of the master bedrooms of these houses should be investigated and if it proven that the rooms are not really occupied then this could be evidence of energy saving opportunities since the temperature of these rooms is constantly above 20 ^{o} C through the whole day. However, in these dwellings, the occupants reported to apply a lower thermostat setting at night and during absence (see section 5.1). Therefore it seems that the behaviour of the occupants in these houses is energy conscious, but because the houses are very well insulated, the temperature doesn't decrease.

In the houses with heat pumps, what happens is a bit different due to the nature of the heating system. Low hydronic systems with heat pump have continuous operation through the whole day and the thermostat does not play such an important role compared to houses with boilers, the delay from the moment the thermostat is set to a new temperature and the moment this temperature is achieved, can be several hours, so it is generally advised to keep a constant temperature all over the day.

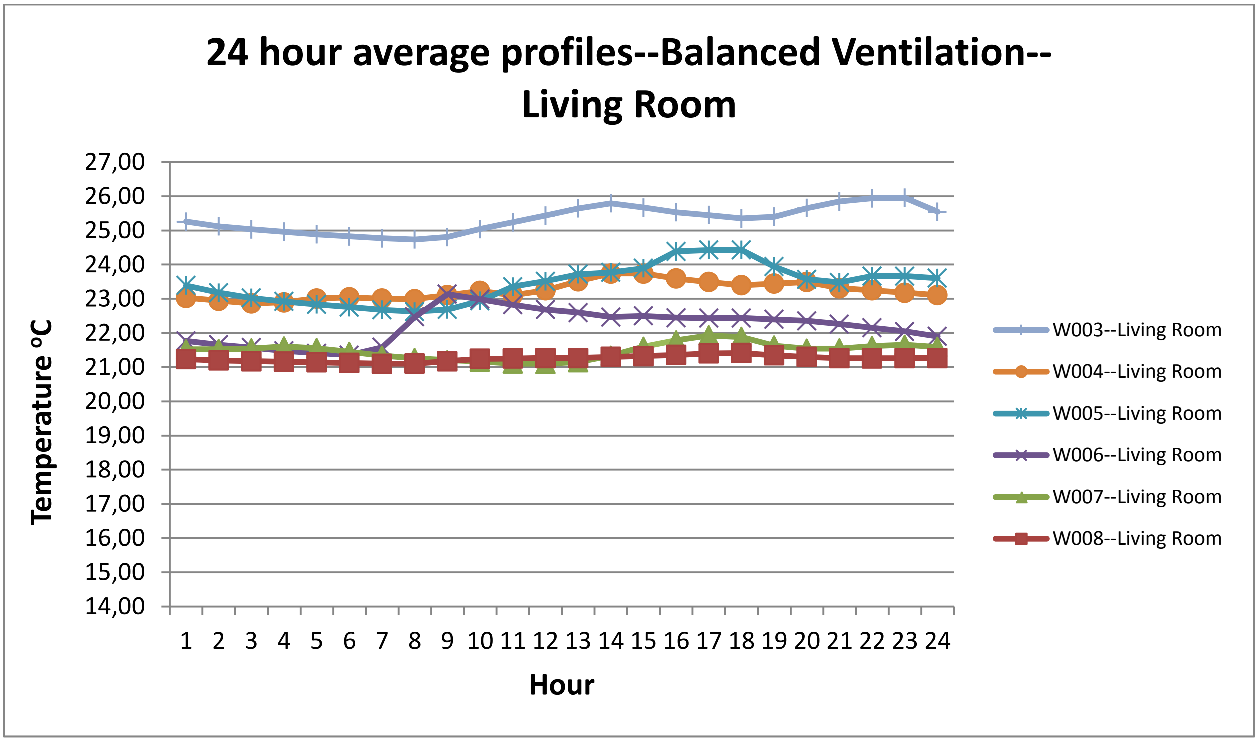


Figure 7.2: 24-hour temperature profiles of living rooms for the balanced ventilation dwellings

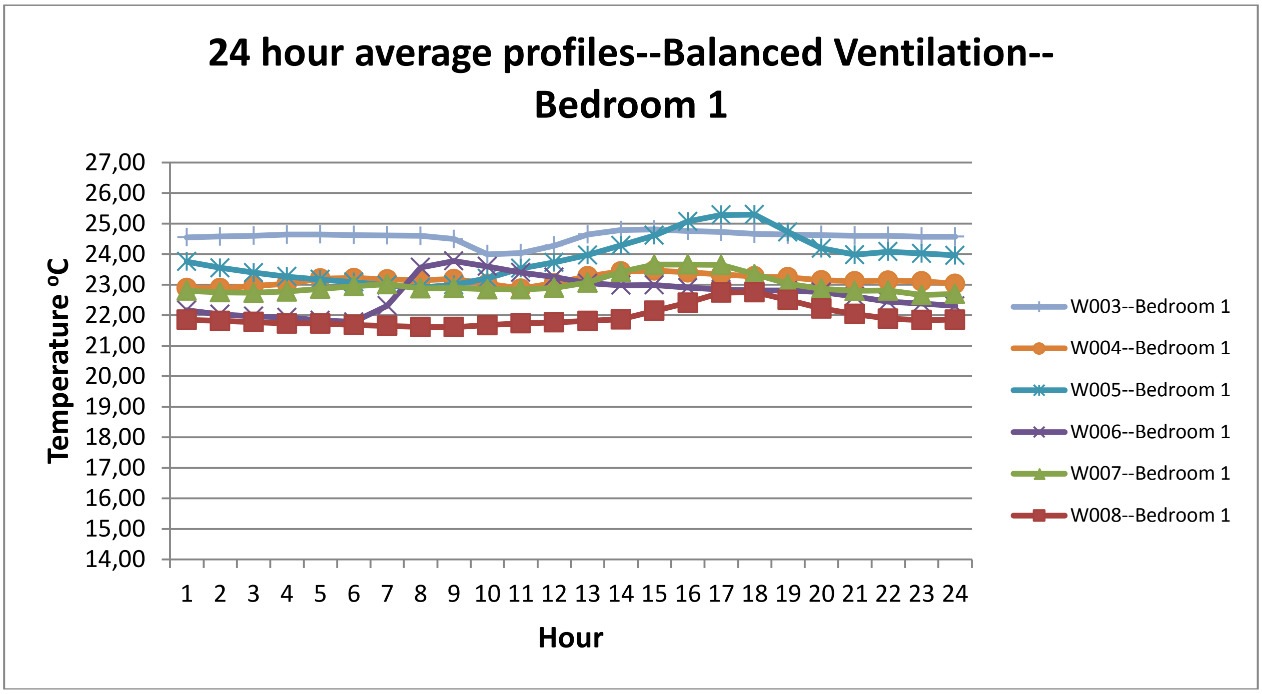


Figure 7.3: 24-hour temperature profiles of bedroom 1 for the balanced ventilation dwellings.

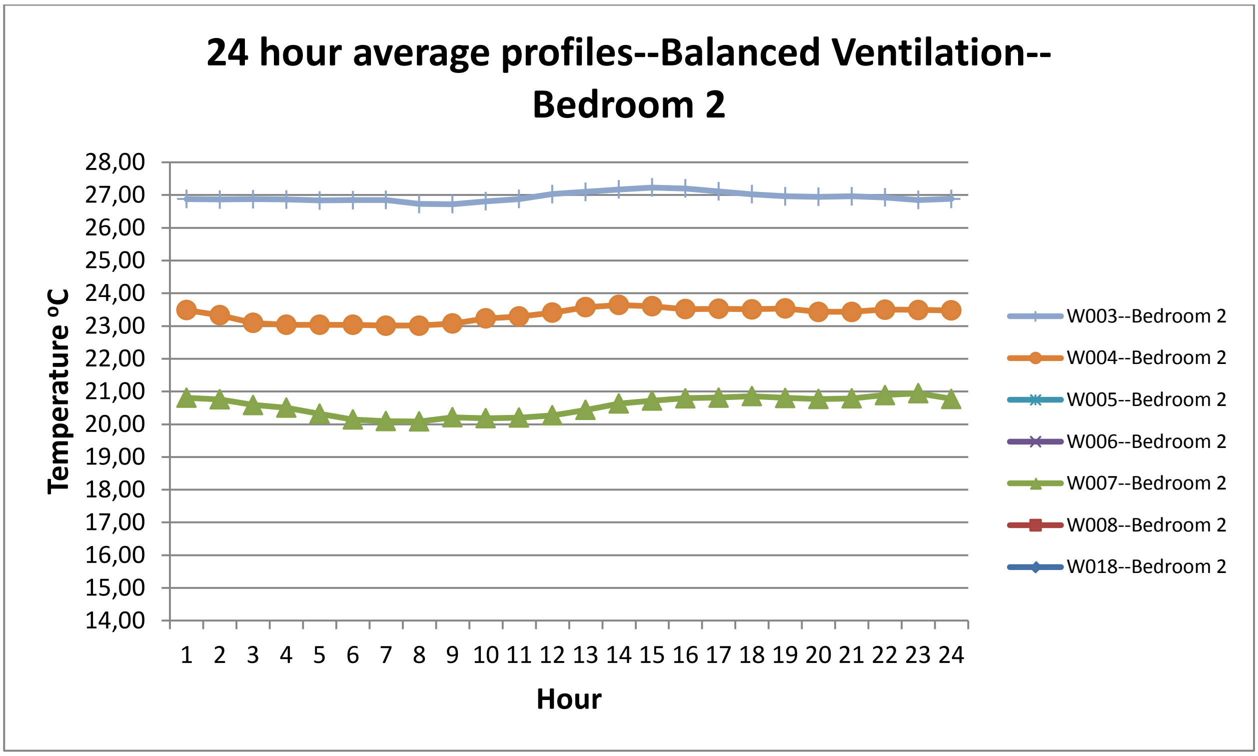


Figure 7.4: 24-hour temperature profiles of bedroom 2 for the balanced ventilation dwellings.

The temperature profiles for the second bedroom can be seen in figure 7.4. The three dwellings with a second room were W003, 4 (study rooms) and 7 (child's bedroom), all equipped with a heat pump. The temperature is almost stable for the whole day, with minimal fluctuations.

When comparing the profiles in the three rooms, we observe that for dwelling W004 the temperature fluctuates between 23 and 24 ^{o} C in all rooms. For the other dwellings with heat pump, however, difference van be noted:

- In dwelling W007, the temperature in bedroom 2 is 1 ^{o}C lower than the temperature in the living room, which is also 1 ^{o}C lower than in bedroom 1.
- In dwelling W003, the reverse is observed: the child's bedroom (bedroom 2) has the highest temperature (around 27 ^{o}C).

In how far occupants were able to control the temperature is not clear from the inspection or the survey, the temperature levels and the differences between rooms may be attributed to occupant behaviour as well as to the design of the heat distribution system.

7.1.2 Relationship between temperature profiles and energy consumption

In figure 7.5, the total energy use for the 6 months measurement period is given. It would have been better to have it also for the 2-weeks period, but this data was missing. With the hypothesis that the temperature profiles generated during the two weeks will not be very different from the 6 months periods (for the CO_2 level, it was found that the profiles were quite similar, see chapter 6), it is possible to look if any correlation is visible between the indoor temperature and the energy consumption. Due to time limitations, the energy consumption results in this report have not been corrected yet for small variations of duration of the campaign in the different dwellings. However, the corrections are expected to be very small because it is about a few days only on 6 months of measurement.

For the dwellings with heat pumps, using therefore only electricity, the data for dwellings W007 and 8 is unfortunately missing. However, dwelling W003, which had much higher temperatures than dwelling 4, consumes clearly more electricity. Both dwellings had the same number of occupants (2), but the occupants of dwelling W003 reported to open the windows a lot (windows open for 13-24 hours a day) and to have mostly the balanced ventilation on level 2. They also reported to be energy conscious, to put their thermostat at 22 ^{o}C , which was in accordance with our observations during the inspection, (see chapter 5) and to have no problem with the temperature or the humidity. Probably, because the thermostat is set on 22 ^{o}C, they have no idea that the temperature is that high in their dwelling (~27 ^{o}C). It may be therefore that not their behaviour is responsible for the high temperature, but the heat distribution system and/or the thermostat which controls it.

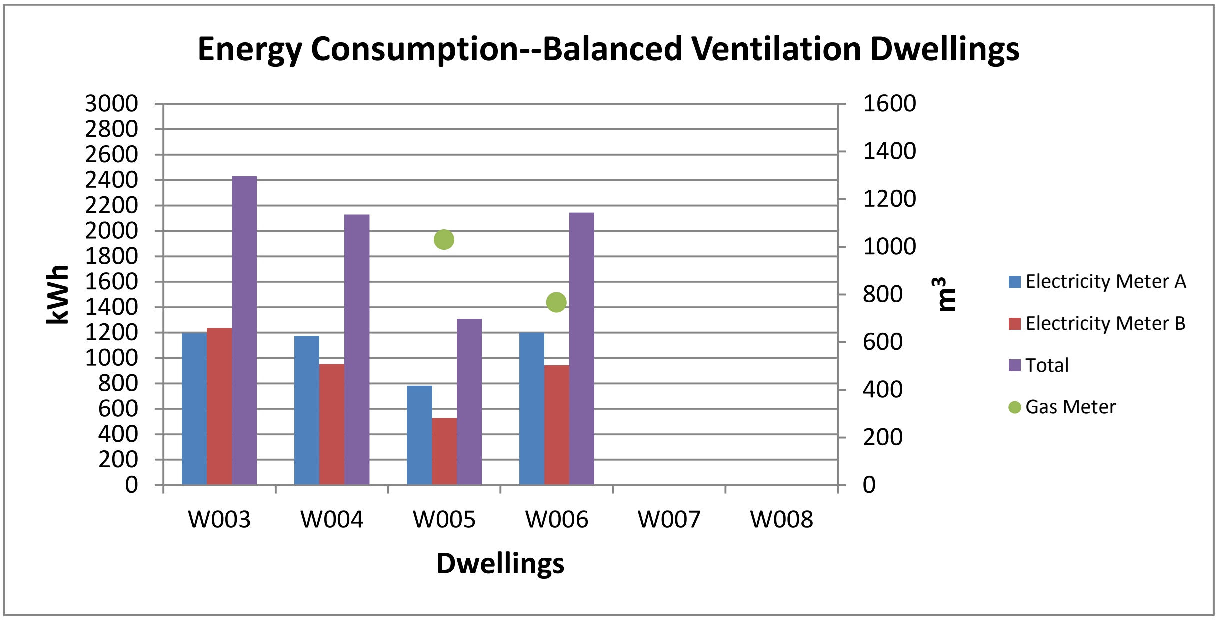


Figure 7.5: Energy consumption of balanced ventilation dwellings for the 6 months period.

For the three dwellings with a condensing gas boiler, there also seems to be a clear relationship between the gas consumption and the temperature profiles. During almost all 24 hours, dwelling W005 has higher temperatures than dwelling W006 in the bedroom. In the living room that is only the case during the day, and, as expected, dwelling 5 (1 occupant) has a higher gas use than dwelling 6 (2 occupants). To go further in the analysis, the average temperature (weighted based on the floor area) should be calculated, which couldn't be done during the short time span of the project. Another factor of influence that was not measured, but was shown in earlier studies to be important (Guerra Santin, 2010) is the heating behaviour in spaces like corridor, entrance hall and bathroom.

Also interesting to note is the fact that the dwellings with a heat pump (W003 and W004) have much higher electricity consumption than the dwellings with a gas boiler, which is as expected, but their electricity consumption is hardly higher than the one of dwelling W006, which also has a gas boiler. The respondent of dwelling W006 reported, like most others, to almost never have the lights on in rooms where no people are and leave devices on standby only sometimes. The respondent also reported not to have special electrical appliances (like aquarium of sauna), except for an induction plate for cooking. However, opposite to the occupants of dwellings W005, the respondent reported not to know if the lighting bulbs were energy saving ones.

7.2 Dwellings with natural supply and mechanical exhaust

7.2.1 Analysis of the temperature profiles

The dwellings with natural air supply and mechanical exhaust all have a condensing boiler, but different energy labels:

- Label A: W010 and W011 (same building complex)
- Label B: W015, W016, W017, W018 (all four in same building complex), and W032
- Label F: W001 & 02 (both in same building), W021 & 22 (both in same building) and W024 28, 29 and 31.

Figures 7.6 to 7.9 show the temperature profiles in the different rooms.

A first observation is that there is a large spread of profiles. The maximum temperature profile observed in the living room is similar to the one in the former section, however, much lower profiles are observed. In general, the temperature profiles in the bedrooms show lower temperature levels. The spread of temperatures is clearly the highest in the living rooms, varying from 16.5 to 25 ^{o}C for its lowest part, and from 19.5 to 26.5 ^{o}C in the highest part. In the kitchen and the master bedroom lower temperatures are observed (except for W018 in the kitchen). In bedroom 2, the pattern is more similar to the one of the living room, but seems to reflect very different functions of this bedroom (child's bedroom, study etc…).

In the kitchen and the living room the pattern is the same for all houses, temperature decreases during the night and starts increasing in the morning, depending on when people wake up. In some dwellings it keeps increasing till dinner time and in the rest, after the morning increase, it stabilizes before increasing again around dinner time. Then it finally decreases again in the night hours. What differs between the houses is the timing of the increases and decreases of temperature (people may have similar patterns but start earlier or later) and the level of temperature.

There is no clear relationship between the temperature profile in the living room and the energy label. The spread is large in each label. Dwellings with label F may have one of the lowest profiles (W031), just as the highest (W01 or W024). Dwellings with label B are in between with a large spread and the two label A dwellings are grouped in the middle (W010, W011).Very characteristic is the case of dwellings 10 and 11. These two dwellings were identical and next to each other. One was inhabited by a young couple and one by a couple of pensioners. As we can see in figure 7.7, dwelling 11 has 1 ^{o} C higher temperature for each hour of the day, which leads to higher energy consumption (see section 7.22)

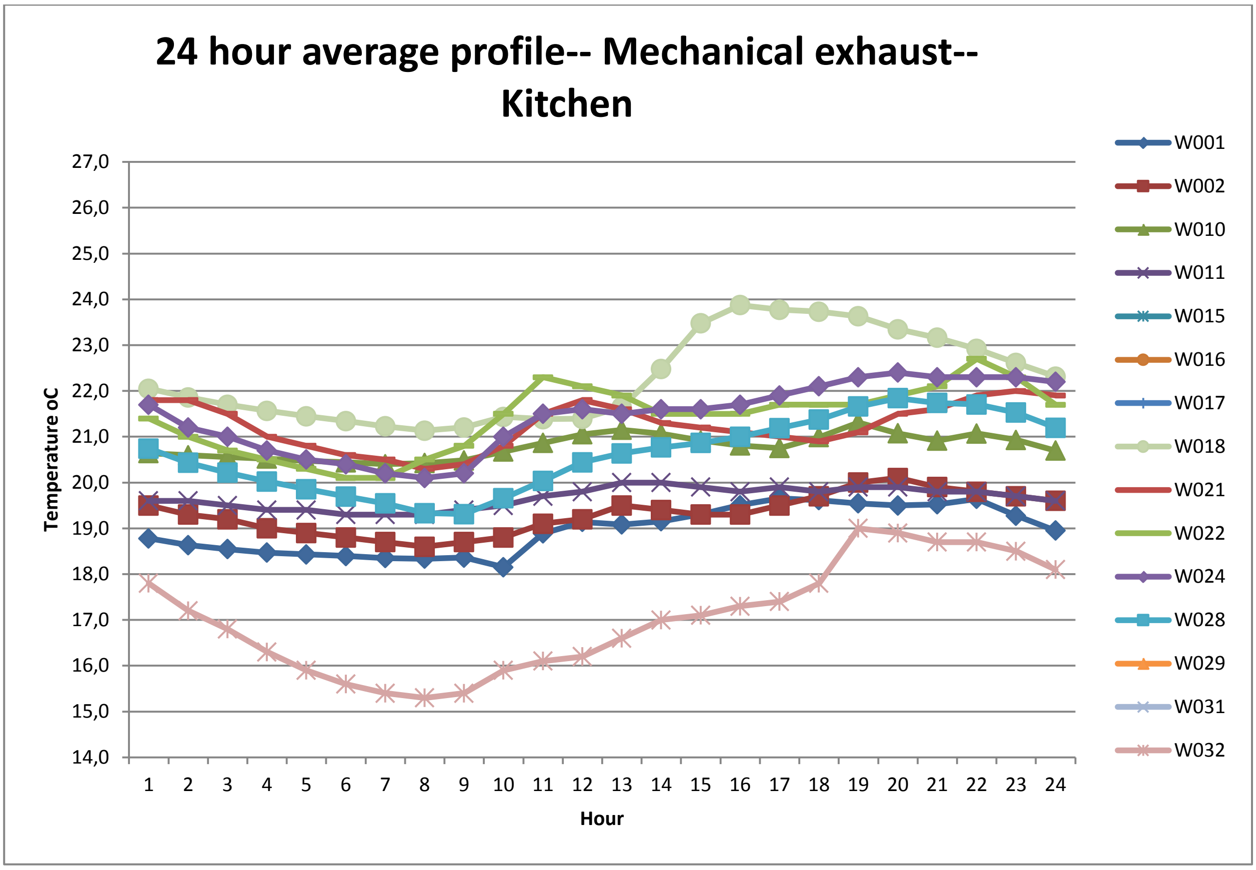


Figure 7.6: 24-hour temperature profiles for the kitchens of the dwellings with natural air supply and mechanical exhaust.

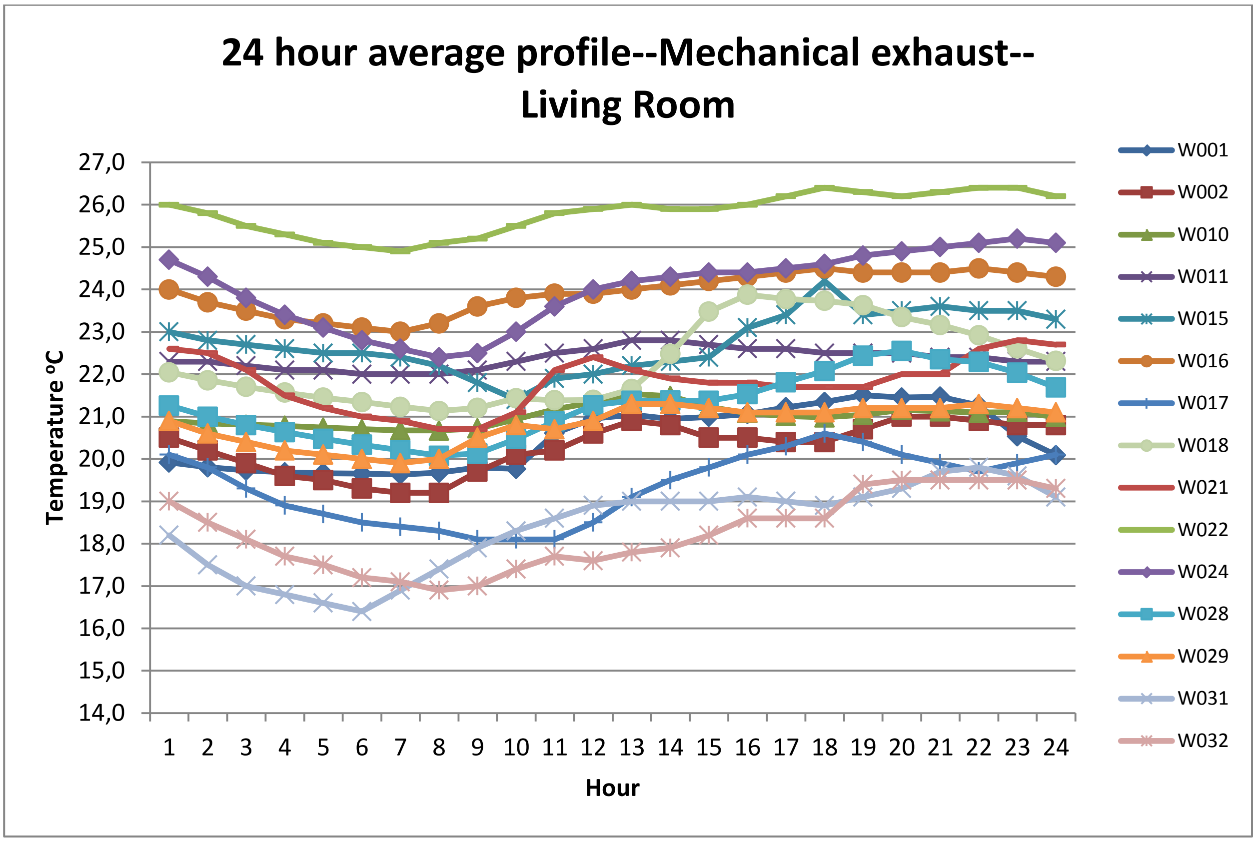


Figure7.7: 24-hour temperature profiles for the living rooms of the dwellings with natural air supply and mechanical exhaust.

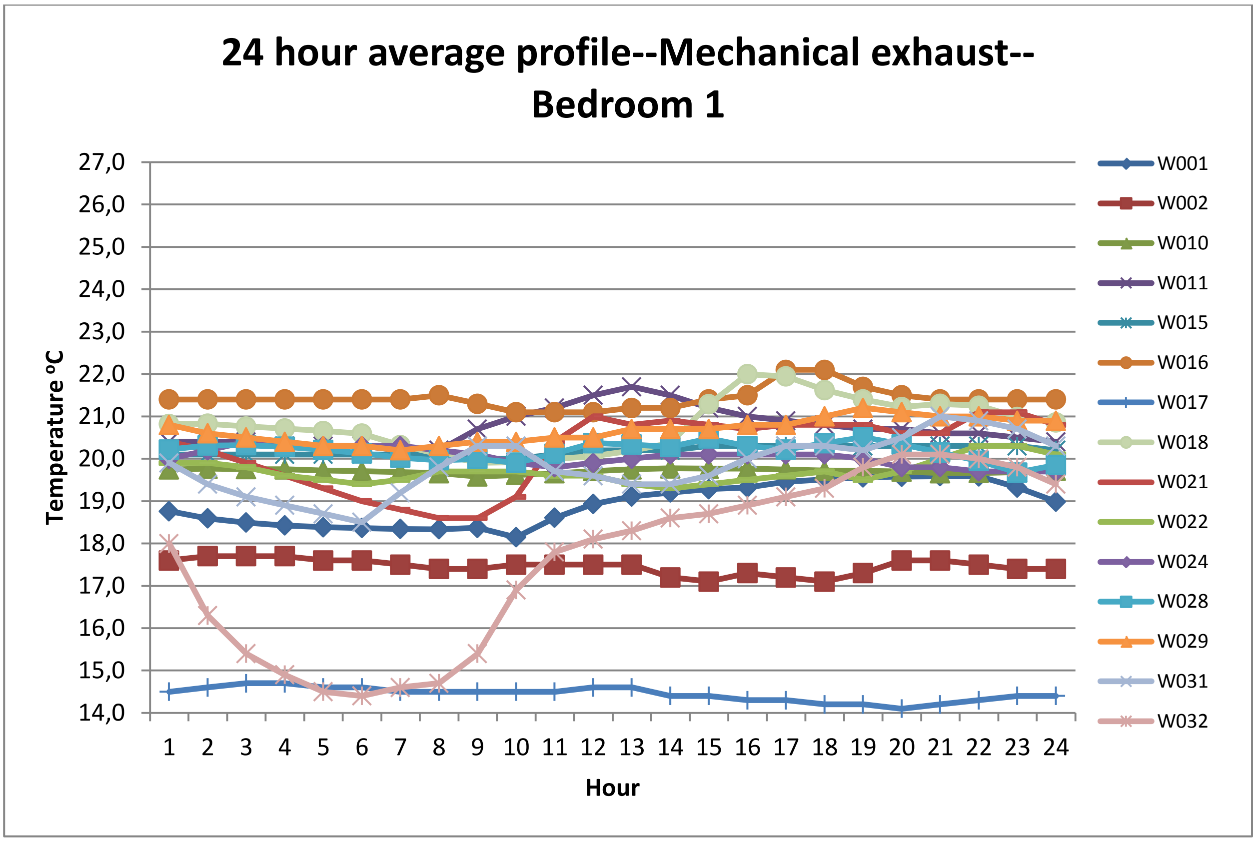


Figure 7.8: 24-hour temperature profiles for the master bedrooms of the dwellings with natural air supply and mechanical exhaust.

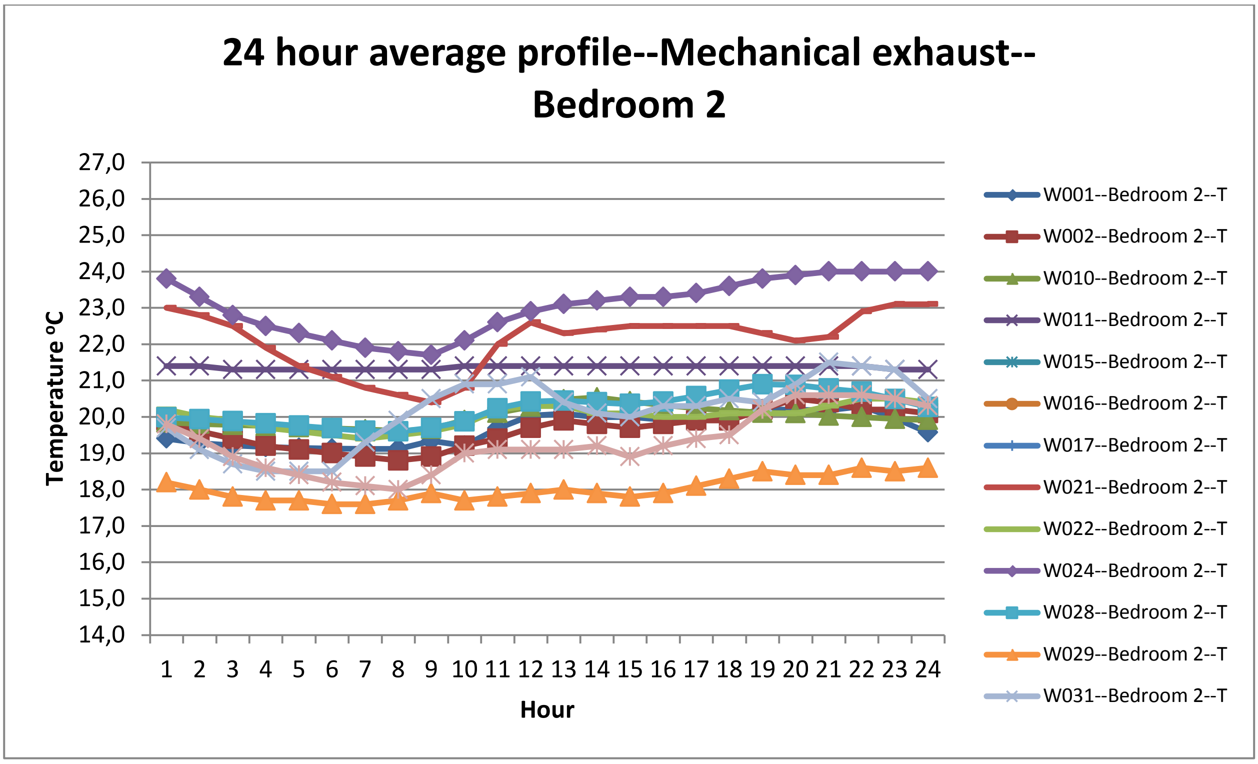


Figure 7.9: 24-hour temperature profiles for bedroom 2 of the dwellings with natural air supply and mechanical exhaust.

In the master bedrooms two patterns can be recognized (figure 7.8). In the first temperature stays stable (with minor fluctuations) for the whole day and in the second one temperature drops during the night and increases again in the morning until the hours after dinner when it peaks. Then it starts dropping again till the next morning. This temperature drop takes place in 4 of the 15 dwellings. It seems therefore that in our sample the majority of occupants do not lower the temperature at night in the master bedroom (or the temperature just does not decreases). With the exception of dwelling 17 where the temperature is constantly around 14.5 ^{o} C and dwelling 32 where the temperature during the sleeping hours drops gradually to 14.5 ^{o} C all other dwellings have 24 hour temperature profiles between 18 ^{o}C and 21.5 ^{o} C.

The temperature pattern for the second bedroom (figure 7.9)is in between the one of the master bedroom and the one of the living room. Temperature is either stable for the whole day or drops during the night and starts increasing from the morning on. In some of the second pattern houses it stabilizes after a few hours until the evening hours when it increases again or gradually increases until sleeping hours when it starts decreasing again. Here too, no relationship with the energy label could be found.

7.2.2 Relationship between temperature profiles and energy consumption

There is no clear correlation between electricity and gas consumption, although this correlation has been observed many times in the past (e.g. Guerra Santin, 2010, Majcen 2013). With the exception of W018, which has a label B, the three dwellings with by far the highest gas consumption (W021, 22 and 24) all have an energy label F. In W018 the temperatures were quite high. In dwellings W022 and 24 the highest temperature profiles were observed in the living rooms (and in W024 also in bedroom 2). Dwelling W021 had a quite average temperature profile in the living room; while in the other rooms it was quite high in comparison with other dwellings. It is difficult at that stage of the research to determine whether the high temperatures are the result of occupant preferences or a necessary compensation of possibly too low wall surface temperatures (because of poor insulation). It is well known from the comfort theory that the comfort temperature is determined by both air and wall temperatures. Unfortunately it has not been possible to measure the wall temperatures in this project.

The three dwellings with the lowest gas consumption, W010, 17 and 28, have label A, B and F respectively, so there seems to be no correlation here. However, all three dwellings have a rather average or even low temperature profile in the living room and the bedrooms.

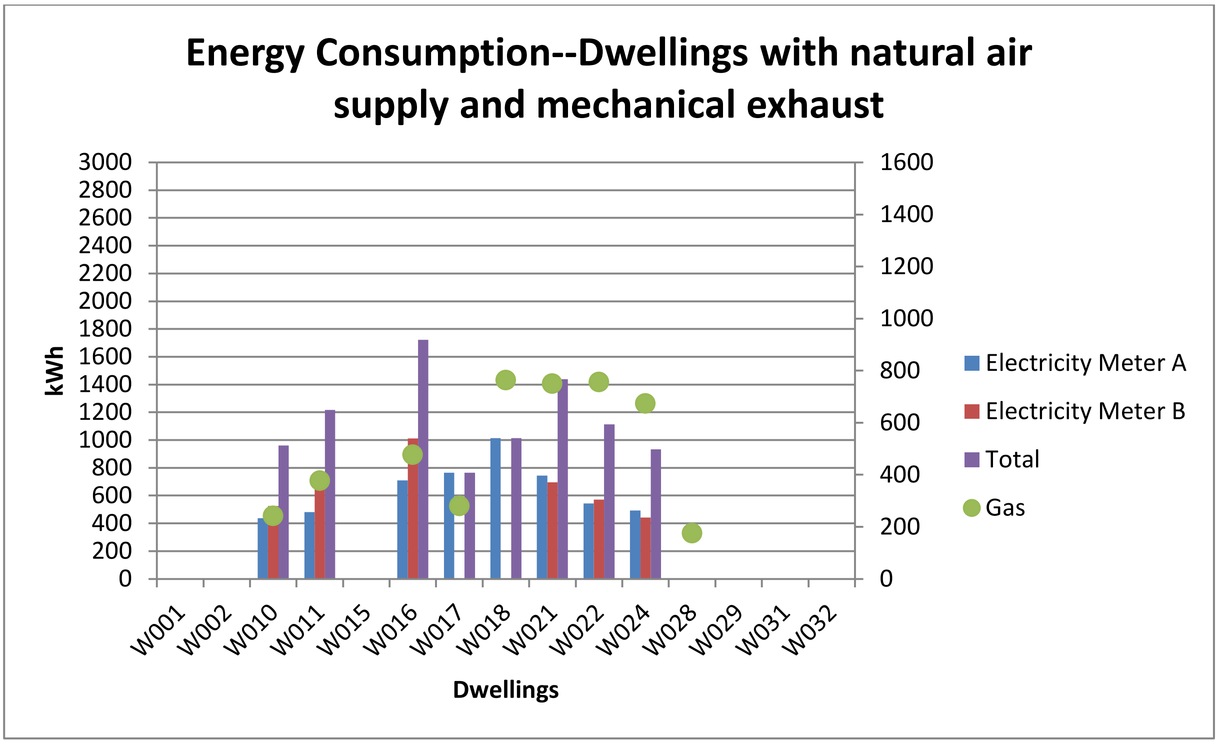


Figure 7.10 Energy consumption of dwellings with natural air supply and mechanical exhaust for the 6 months period.

7.3 Naturally ventilated dwellings

7.3.1 Temperature profiles

Figures 7.11 to 7.14 show the temperature profiles in the different rooms of the naturally ventilated dwellings. All this dwellings have an energy label F and a condensing boiler, except W014, 25 and 27 which had a stove. These stoves do not heat one room only, but are connected to radiators in all rooms (they act as central heating). In the group of naturally ventilated dwellings, the temperature profiles, although very similar to the ones of section 7.2, are more grouped around 20-21 ^{o}C: a smaller spread is observed. The occupant of W027 reported to be abroad during a long period, including the two-week period reported in the graphics. However, the temperature profiles in his house were quite high; Because his gas consumption was very low (see section 7.3.2) we can deduce that he didn't left the stove on, but that, due to the poor thermal quality of the apartment complex, his apartment was heated by the surroundings apartments.

Here again, in the kitchen as in the living room temperature decreases during the night, increases in the morning when people wake up, after a few hours it stabilizes in some of the dwellings and then increases again in the afternoon or the evening (if people are working and come home after 17:00). Minimum temperatures in the living room vary between 16.5 ^{o}C and 21.7 ^{o}C while maximum temperatures vary between 20.7 ^{o}C and 23.8 ^{o}C.

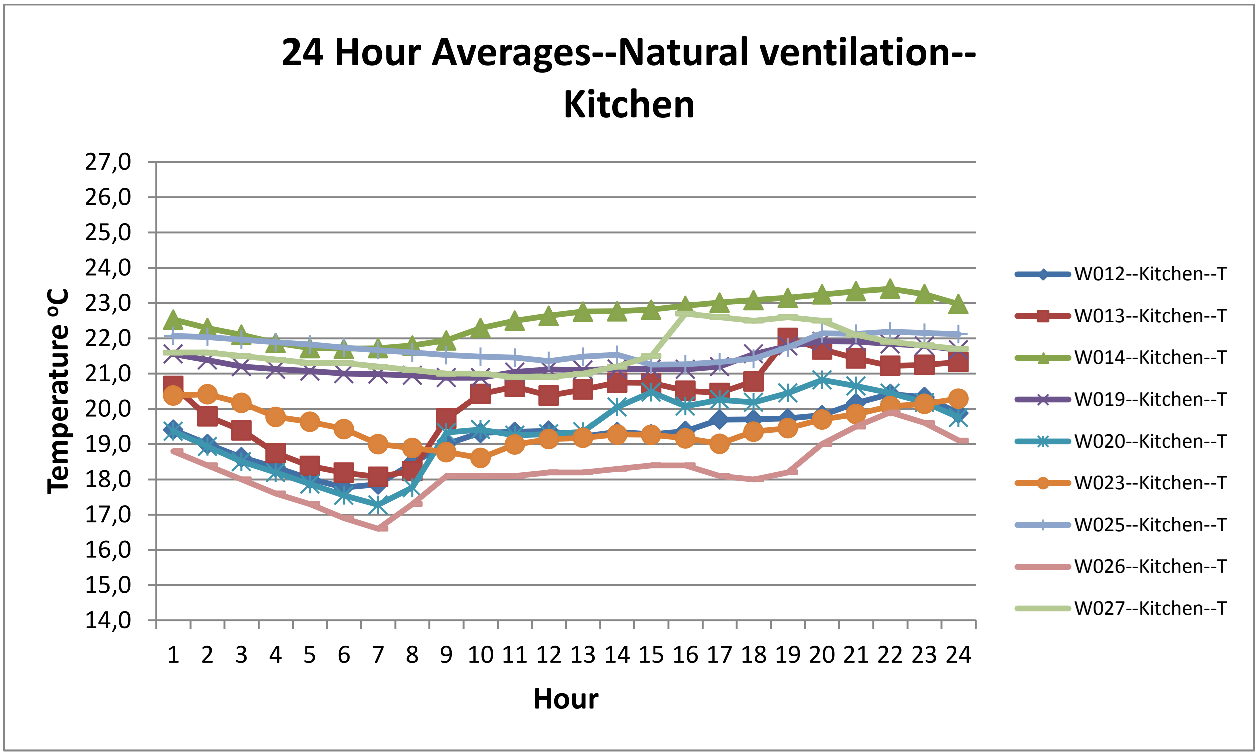


Figure 7.11: 24-hour temperature profiles for the kitchens of the naturally ventilated dwellings.

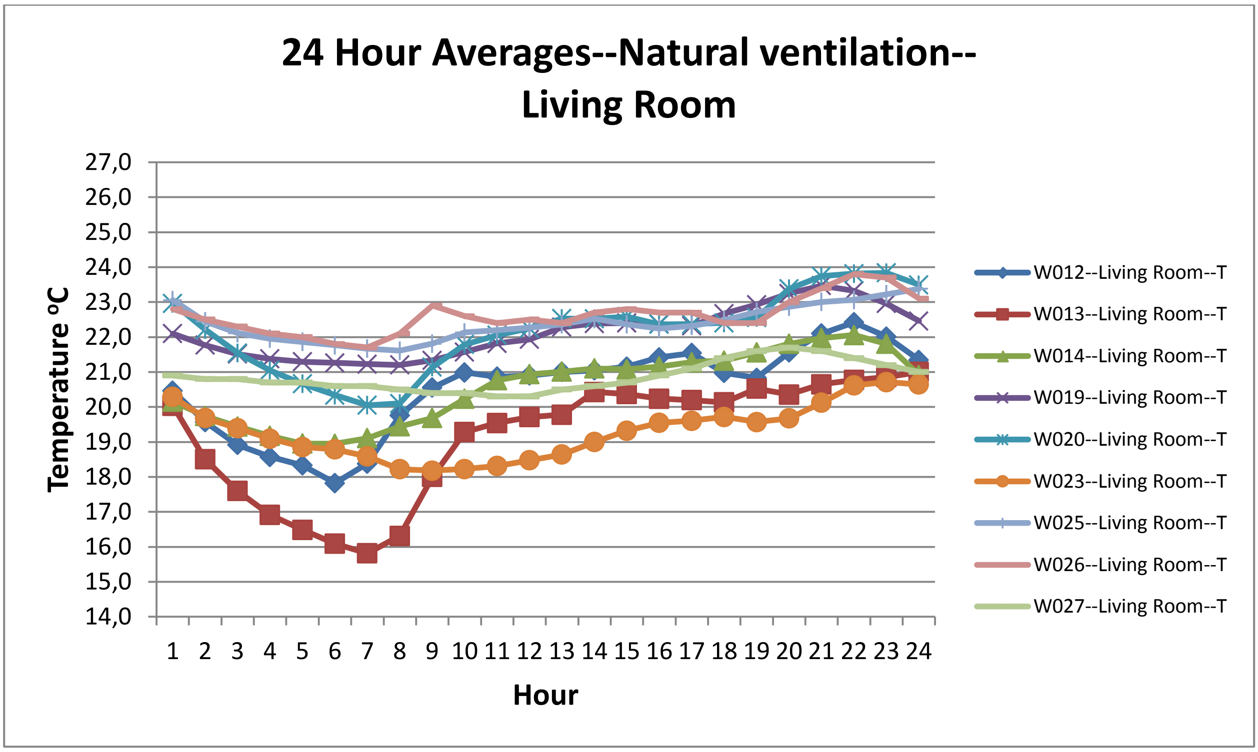


Figure 7.12: 24-hour temperature profiles for the living rooms of the naturally ventilated dwellings.

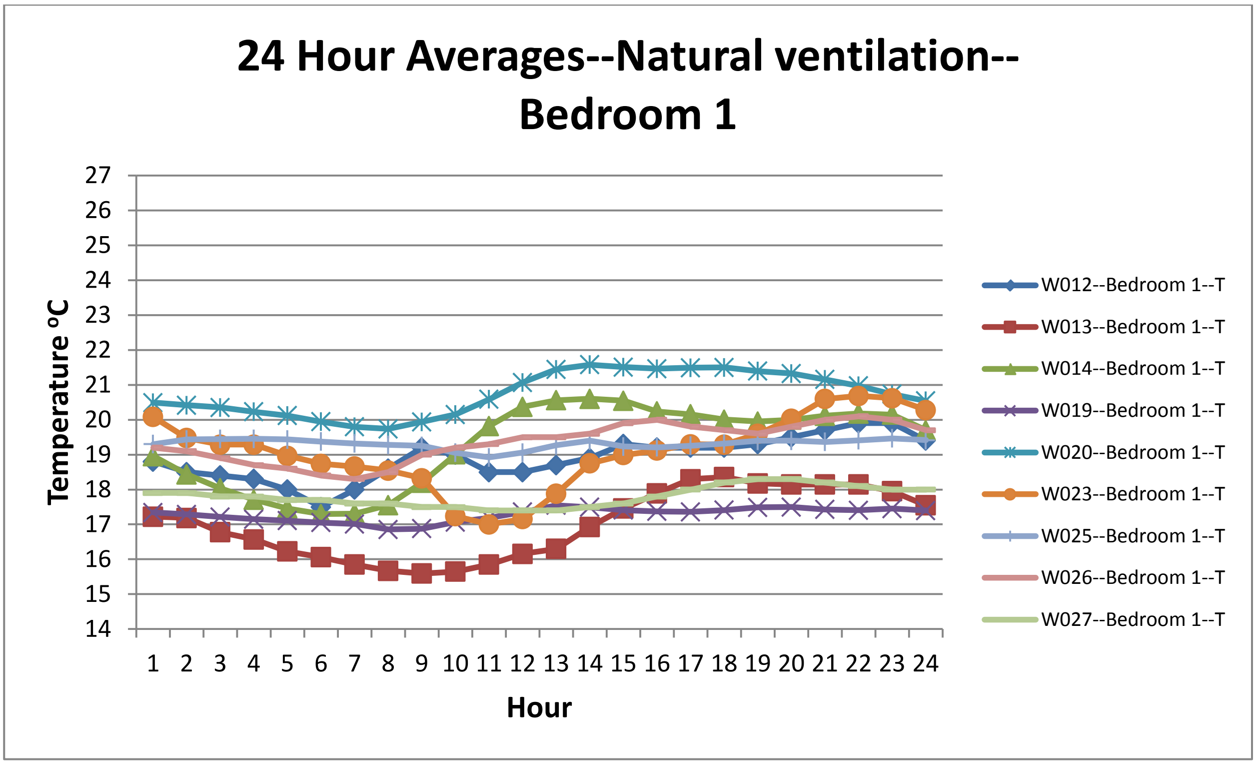


Figure 7.13: 24-hour temperature profiles for bedroom 1 of the naturally ventilated dwellings.

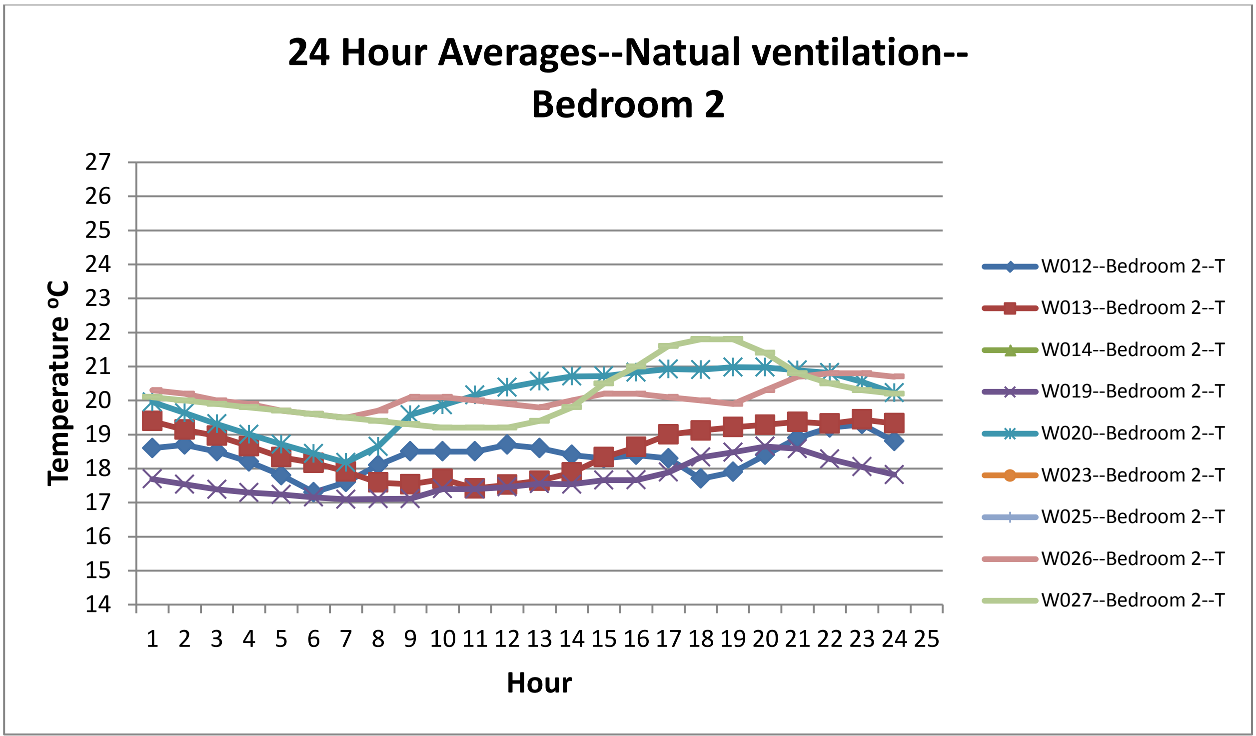


Figure 7.14: 24-hour temperature profiles of bedroom 2 of the naturally ventilated dwellings.

The temperature profiles for the bedrooms (figure 7.13 and 7.14) showed again that temperatures drop slightly during sleeping hours. In the first morning hours for some dwellings, and in the hours before midday for some others, temperature starts rising again for a few hours. Then it stabilizes till the night hours and it starts to drop when people go to bed. Lower temperatures vary between 15.6

°C and 19.7 °C. Highest temperatures vary between 17.5 °C and 21.6 ° C. This pattern, as found in sections 7.1 and 7.2 go against the commonly believed notion that in the Netherlands people do not heat their bedrooms. The results show that clearly the bedrooms start getting heated in the morning when people are most probably not in the rooms. Many of these dwellings are inhabited by one person, or by a child that during the day go to school. Despite this, temperature seems to rise during the hours that the room is not in use. It seems that, in our sample, bedrooms are not treated individually: people do not go to the individual heating body and turn off the valve but are commanding the heating of the bedrooms from the central thermostat that manages the whole house.

Three dwellings didn't had a condensing boiler but a stove (W014, 25 and 27). The temperature pattern they show is not significantly different from the other ones, not even in the one that was empty during the measurement period (W027).

7.3.2 Relationship between temperature profiles and energy consumption

Figure 7.15 shows a clear correlation between electricity and gas consumptions. The energy consumption of dwelling W027 is extremely low, because the occupant was away for a long period. The three highest gas consumptions (W012, 13 and 14) do not correlate at all with the level of the temperature profile in the living room. The - by far- highest temperature profiles were found in dwellings W019, 20, 25, and 26. The spread of energy consumption for these four dwellings is very high. Apparently it does also not correlate with the temperatures in the other rooms, except may be for dwelling W014 that has a quite high temperature in kitchen and bedroom 1. Dwelling W012, with the highest energy consumption for both electricity and gas also had the highest occupancy (5 people). Dwelling W026 had 4 occupants, but shows a much lower energy consumption. The reported ventilation behaviour was similar in both dwellings.

The dwellings with a stove (W014 and W025) have a lower consumption than W012, 13 and 14, but a higher one than W026. Dwellings W012, 13, 19 and 20 were row houses.

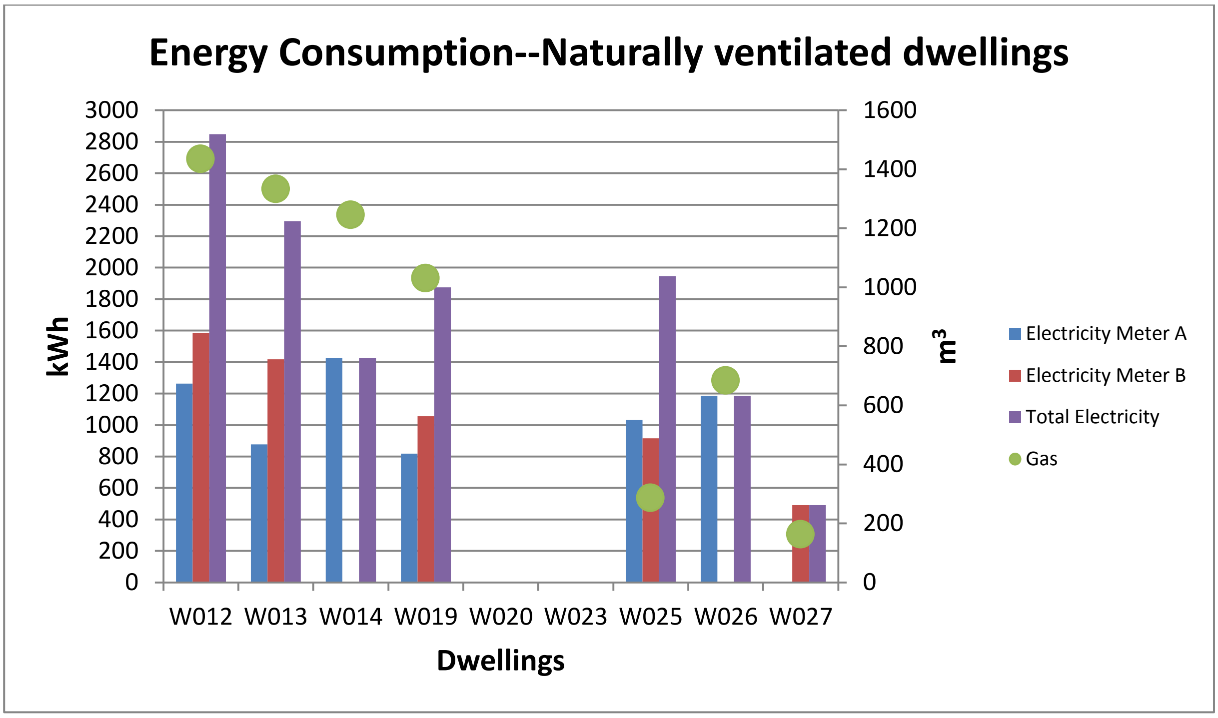


Figure 7.15: Energy consumption of naturally ventilated dwellings for the 6 months period.

7.4 Conclusions

This chapter showed, using averaged daily temperature profiles, that there is a wide spread in the actual temperatures of dwellings. The spread between rooms may also be large. Dwellings with heat pump had, as expected, a clearly more constant temperature profile than dwellings with boilers or stoves. Clear relationships between temperature profile and energy label, ventilation system, number of hours of window opening or number of occupants were not found in our sample. The temperatures in the bedrooms were in general lower than in the living rooms, but clearly, most bedrooms are heated, also during the night.

The relationship between temperature profile and gas or electricity consumption was not clear. However, because of time limitation for this study, the daily average temperature profiles were based on a two-week measurement period, while the energy data were for the complete 6 months period. Although the two-week period was quite representative of the whole period, the result may be biased. Further study should demonstrate if the 6 months temperature profiles are similar to the two-week one. It was however clear that most gas consuming dwellings are found in the category naturally ventilated dwellings (all label F). The dwellings with balanced ventilation (labels A and B) were not consuming less energy than the dwellings in the category ‘natural supply and mechanical exhaust’.

These results show the necessity for an integrated approach, as main parameters like temperature and energy label could not directly be related to the energy consumption. Probably, detail energy monitoring, with the same time interval of 5 min as the other data could give better insights in the determinant factors. Unfortunately, the collection of these data with the Youless partly failed.

8 Detailed overall analysis of a number of dwellings

For this chapter we chose to analyse in detail and in a holistic way a few comparable dwellings in order to get further insights into the relationships between the parameters studied in the former chapters. We chose dwellings for which the energy consumption was known as well. Four groups of dwellings will be studied: W003&W004 (balanced ventilation and heat pump, located in the same complex); W010&W011 (label A with condensing boiler, located in the same complex); W021&W022 (Label F with a condensing boiler) and finally W014 (an old dwelling with a stove);

8.1 Dwellings W003 and W004

These two dwellings are identical, they have the same size, they are both sited in the same building complex and they are equipped with floor heating coupled with a heat pump and the same balanced ventilation system. Both dwellings have other apartments in the sides, below and on top and they have very high temperature profiles for the whole day, for all rooms. Both dwellings accommodate pensioners, the first in their seventies and the second ones in their sixties.
The tenants of dwelling W003 answered in the initial survey that they have their thermostat fixed on 22 degrees and the tenants of W004 on 23 ^{o} C while the ventilation system settings were 2 and 1 respectively.

As we can see in figures 6.6 and appendix D, the CO_2 levels of W003 compared to the levels of W004 do not reflect the difference in ventilation setting. Most of the hours of the day the CO_2 levels of W003 are actually higher than those of W004. The tenant from W003 reported to ventilate a lot through the windows (almost all day). It may be that the balanced ventilation system does not work properly because the windows are open too often, but it may also be that the ventilation system is not working properly and that the tenants have to open the windows to get some fresh air.

The answer of the tenants of W003 on the thermostat setting were in agreement with our inspection but not verified by the measured temperatures. In the living room of W003 temperatures are slightly fluctuating between 25 and 26 ^{o} C (figure 7.3), in bedroom 1 temperatures are 1 degree lower (figure 7.4) while in bedroom 2 the temperature is 27 ^{o} C for the whole day (figure 7.5). These numbers are significantly higher compared to the thermostat set point of 22 ^{o} C. There is a strong possibility that the tenants are not aware at all of the very high temperature they have in their dwelling. It may be that the heat pump distribution system is wrongly tuned or that the thermostat is malfunctioning. In W004 temperatures are between 23 and 24 ^{o} C for every room for the whole day which is in agreement with the thermostat settings and with the answers the tenants gave during the initial survey.

Tenants from both houses have answered that they consider indoor temperatures during the winter to be very good. Here we see a clear difference in the level of temperature that the tenants consider comfortable. These two houses have floor heating and we know from previous research (Ioannou et al 2015) that changing the thermostat has a very limited impact in the energy consumption of these dwellings or the indoor temperature due to the delay of the system's heat in reaching the indoor environment. So in fact these tenants have no control of the indoor temperature, they probably just get for granted the temperature that technicians set up for them, got used to this temperature and considered it to be comfortable. Even in the case of overheating they have the option of reducing the clothes they wear in order to feel comfortable but not decreasing the thermostat setting since this will have no immediate effect.

Considering the fact that the electricity consumption of both dwellings was not excessively high (see figure 7.6) and the fact that the tenants of W003 answered ''fairly easy'' and of W004 ''easy'' to the question ''how easy is it to pay your monthly energy bill'', a very important issue seems to be that in energy efficient dwellings with very good building envelope and state of the art heating and ventilation system , energy is still wasted by poor tuning of the installation (poor occupant behaviour was not demonstrated in this case) and the tenants have no incentive to correct this due to the very low monthly energy bill.

8.2 Dwellings W010 and W011

Dwellings W010 and W011, are completely identical, both label A, recently built and with condensing boiler which provides the space heating and the hot tap water. The mechanical exhaust ventilation, according to the tenants' answers during the initial survey, is for both dwellings set at 1. The only difference between these two dwellings is that W010 is inhabited by a young couple (in their early thirties) while W011 is inhabited by a couple of pensioners (in their late sixties). The incomes of both households were among the highest and both couples said that it is easy for them to pay the monthly energy bill.

Despite the similarities between the two dwellings, W011 has higher consumption in categories electricity and gas.

The CO_2 concentrations in the kitchen and living room of both dwellings are almost identical (figures B.4 and B.5, appendix B) and among the lowest in the category mechanical exhaust. The differences lie on the two bedrooms (figures B.6 and B.9) where differences in ventilation practice between the two couples are visible. The young couple probably doesn't ventilate the bedroom a lot during the night. As a result the CO_2 grows until the time they wake up (for the whole period of the analysis 51.5 hours exceeded the threshold of 1200 ppm CO_2). The older couple maintains better ventilation during the sleeping hours which results in only 18 hours of CO_2 excess above the 1200 ppm threshold. Bedroom 2 is the only room in which the CO_2 concentrations in the old couple's dwelling were higher than in the young couple's one. The reason for that is that bedroom 2 in W011 was used as a study room while it was used just as a storage room in the young couple's dwelling. It may be that the fact that W011 is ventilated more than W010 leads to the observed higher energy consumption.

The temperature patterns of the two dwellings are quite different (figures 7.6 to 7.9). The kitchen is the only room in which dwelling W010 has higher temperature (approximately 1 ^{o}C higher each hour of the day) for the whole day compared to dwelling W011. The reason for this is that the young couple are using the kitchen as study room, some days of the week they work from home and they are doing so at the kitchen table. In all other rooms the temperatures in dwelling W011 are higher. The living room has approximately 1.5 ^{o} C higher temperature for each hour of the day. The patterns for these two rooms are identical. The temperature patterns in the bedrooms though differ. The young couple's bedroom has more or less stable temperature throughout the whole day, a little below 20 ^{o}C. The older couple's master bedroom has stable temperature during the sleeping hours, a bit above 20 ^{o}C and in the morning, when they wake up, the temperature increases 2 degrees until midday when it starts falling again until it stabilizes again a bit above 20 ^{o} C. Bedroom 2 has the exact opposite pattern. The second bedroom of the old couple remains stable for the whole day a little below 21.5 ^{o} C while the bedroom 2 of the young couple drops slightly during the sleeping hours (from 20 ^{o}

C to 19.5 ^{o} C) and then increases about 1 degree when people wake up in the morning until midday when it starts to gradually drop to 20 ^{o} C. As already mentioned the use of bedroom 2 is completely different in the two dwellings, in W010 it serves as a storage room while in W011 it serves as study room. All temperatures from all rooms in both dwellings are well above 19 ^{0} C, during the whole day.

The differences in energy consumption between these two dwellings can at least partly be attributed to occupant behaviour and they are reflected in the temperature profiles of the rooms. Both couples replied that they consider the indoor temperatures during the winter as ''good''. But clearly the old couple has higher temperature profiles in 3 out of 4 rooms which means that their perception of ''good temperature'' is different (and higher) than what the young couple defines as good. Maybe this is due to the age difference but on the other hand it may be just conditioning. Maybe the old couple is just used to having a different occupancy behaviour and, when asked, they consider this as comfortable. Maybe if they were adjusting (or if someone else was adjusting) their temperature profiles towards a lower level they would give the same ''good temperature'' answer.

Despite the fact that these two dwellings are among the best performing from an energy consumption point of view (figure 7.10), there is still room for improvement. Especially bedroom 2 is a room that has rarely presence in W010 since it is a storage room for clothes, and for W011 it serves as a study which means that, at least during the sleeping hours, it has no presence. The temperatures though, despite the limited presence are still high and this could be characterized as an energy wasting practice. Especially the young couple's practice concerning the second bedroom is worse since in the morning the temperature of the room increases (when the heating system is turned on). The same can be seen for bedroom 1 of dwelling W011. The temperature starts to increase in the morning when people are awake and no longer in the bedroom. However, it may also be that the heating system is not turned on in this room, but the room is heated passively by the other rooms. This could be the case if the doors between rooms are left open.

8.3 Dwellings W021 and W022

Both dwellings W021 and W022 are identical, next to each other and occupied by couples of pensioners. Both couples said that it is easy to pay the energy bill and their incomes were middle to high compared to the 32 dwellings that participated in the campaign. Both dwellings have a label F and a condensing boiler.

From the CO_2 profiles (figures B.4 to B.7, appendix B) we can see that these two dwellings are very well ventilated. The CO_2 concentrations never come above 1200 ppm and rarely exceed 800 ppm. In the bedrooms the CO2 concentration in W021 is lower than in W022, which could indicate a higher rate of ventilation in W021. However, the tenants of W022 indicated to ventilate a lot (13 to 24 hours a day), while the occupants of W021 indicated to ventilate much less.

The temperature patterns (figures 7.6 to 7.9) in the kitchen are identical with slightly higher temperature for dwelling W022 during the day and slightly higher temperature for dwelling W021 during sleeping hours. Both temperature profiles are above 20 ^{o} C for the whole day. Dwelling W022 has one of the highest living room temperatures from all the dwellings in the campaign. The temperature drops gradually during sleeping hours from 26 ^{o} C to 25 ^{o} C and in the first morning hours it starts increasing again until midday when it stabilizes at 26 ^{o} C till midnight. Dwelling W021 has similar pattern but the temperatures are between 23 ^{o} C and 21 ^{o} C. The reason for this is that the tenant of dwelling W022 had a major surgery during the measurement campaign and declared to have chosen temporarily for a high temperature in order to have a smoother recovery. The bedroom 1 pattern for dwelling W022 is stable at 20 ^{o} C for the whole day. For W021 the temperature drops during sleeping hours but rises again in the morning and stabilizes after midday till the night at 21 ^{o} C. The bedroom 2 temperature patterns for dwelling W022 were steady for the whole day at 20 ^{o} C just like in bedroom 1. Temperature drops at midnight gradually from 23 ^{o} C to 20.5 ^{o} C and during the first morning hours its starts increasing again until it stabilizes at 23 ^{o} C around midday for the rest of the day. All temperatures are well above the 18 ^{o} C average that is assumed for the national standard energy label calculations.

The two dwellings have similar energy consumption, especially for gas. Probably the higher temperatures observed in W021 during the two-week measurement period have not affected very much the total gas consumption during the 6 months period, but this will have to be proved in a later stage of this research. Dwelling W022 has lower electricity consumption with the night electricity being higher than the day one (which is a sign of good practice,) while dwelling W021 has higher electricity consumption and morning tariff higher than the night one.

8.4 Dwelling W014

Another very interesting case is that of dwelling W014. This dwelling is labelled F, is between other apartments at the sides, below and on top, its heating system is an old stove with no thermostat and it is inhabited by an old man in his eighties.

In figures 6.5 and 6.7, and in appendix B) we can see the ventilation patterns of this dwelling. The CO_2 levels for the kitchen, the living room and the bedroom are the lowest from all the naturally ventilated dwellings, steadily just below 600 ppm for all hours of the day. The only time that CO_2 increases above 600 ppm in the kitchen and living room is around dinner time and it is most likely attributed to the cooking since the dwelling has no mechanical exhaust for cooking steam removal. It is striking that the CO_2 profile of W014 is almost the same with that of W027 which was uninhabited for the whole period of the monitoring campaign.

Having very good ventilation in one's home is something that is encouraged by the majority of health, research and housing organizations. The striking feature of this case though is that this apartment together with the lowest CO_2 levels also has some of the highest temperature levels from all the naturally ventilated dwellings (figures 7.11, 7.12 and 7.13). The kitchen temperatures are above 22 ^{o} C for almost all the hours of the day. Only for some hours during the night it drops just below 22 ^{o} C. The living room temperatures are above 19 ^{o} C during the night and from the early morning they increase and fluctuate between 20 and 22 ^{o} C for the rest of the day. In the bedroom, during the sleeping hours temperature drops to 17 ^{o} C and in the morning, despite the limited presence of the occupant in this space, it starts increasing and eventually it fluctuates above 20 ^{o} C for the rest of the day.

Naturally, very high ventilation rates and relatively high indoor temperatures result in high energy consumption as we can see in figure 7.14. This dwelling has the third biggest gas consumption and the only two dwellings that have bigger gas consumption are W012 and W013 which are also naturally ventilated but were larger and accommodated families of 5 and 3 people respectively. Another interesting characteristic of this dwelling is that its tenant has the third smallest income among the 32 dwellings and in the question ''how easy is it to pay your monthly energy bill'' he answered ''easy'' despite the fact that he has the third highest gas consumption and one of the highest in electricity.

In this dwelling there could be room for decreasing the energy consumption by decreasing a little bit the ventilation rate, the temperature and, may be, changing the stove by a condensing boiler.

8.5 Conclusions

The detailed analysis of a number of cases made clear that there seems to be room for improving the energy behaviour of households, either by making them aware of the actual temperature in their dwellings, or by reducing it gradually or by changing ventilation habits, although one should be very careful with the last option not to lower the indoor air quality. It was also shown that not only behaviour may be held responsible for high temperature levels, but also the tuning of the system itself, especially when heat pumps and floor heating are used.

It also became visible that there is little consistency in the relationship between energy behaviour and actual energy use, although one could argue that this may come from the different periods used for the energy consumption and the temperature and CO_2 profiles. Further more detailed study with the data collected during this research is needed.

9 Real time comfort perception

Comfort perception can be expected to be a very important determinant of the choices made by occupants regarding temperature set points and ventilation, and therefore regarding their energy use. Unfortunately, the on-site real time collection of data about comfort perception is almost non-existent in literature. Generally, comfort perception is collected in climate rooms under strict conditions. We however suspect that actual comfort perception may be totally different from the perception during lab tests. That is why, apart from the quantitative data that were gathered during the Ecommon campaign (temperatures, CO_2 concentrations, relative humidity, movement, gas and electricity consumptions), also qualitative data about comfort perception were collected using the comfort dial and the comfort log book described in section 3.2. The qualitative data that were gathered were:

- Comfort perception on a 7 point scale (PMV scale)
- Activities corresponding to categories of metabolic rates (from sleeping to running, see figure 3.7) during the last half an hour before using the comfort dial (therefore before recording the comfort perception
- Actions taken during the last half hour possibly influencing the comfort sensation (e.g. opening a window, taking a warm shower, drinking a hot beverage, putting clothes on or off)
- Room in which the tenants were the last half hour, or if they were outside
- Their comfort perception (as a validation of the comfort dial data)

Chapter 9 presents the first results from these qualitative data analysis for four of the six parameters being known to influence the sensation of thermal comfort: clothing, (metabolic) activity, air temperature and humidity. Unfortunately, radiant temperature and air velocity, the remaining two of the six parameters could not be measured during the project. An additional analysis on the relationship between thermal comfort and CO_2 concentration is carried out.

9.1 Methodology

The dwellings that participated in the campaign were divided into groups of 7 due to limitations concerning the equipment: only 7 comfort dials were available. Each dwelling was given a comfort dial, starting mid-February, and a paper log book. The tenants were instructed to use the comfort dial at least 30 minutes a 1 hour after waking up and then at any moment of the day (but by preference at least four times) when they felt their thermal comfort was changing. They were also instructed to fill in the logbook at least twice a day, in the morning and in the afternoon, just after they used the comfort dial.

The comfort dial have an automatic time stamp feature and records only comfort perception (from cold to hot). Comfort perception coupled with time stamp and in combination with the movement sensor is enough to know the comfort of the tenant in a specific time and specific room and to couple it with the timestamped quantitative data. The logbook asked for much more qualitative information. The time line provided with the paper log book was a time-numbered straight line (see figure 3.7). The tenant had to draw a line from the icons representing metabolic activity, actions towards comfort, clothing or the room he was situated to the time line. This was not so accurate timewise, but we wanted to capture activities in the last half hour only, as we expect this period would be of influence on the perceived level of comfort. The main respondent of each household had to use the comfort dial and the comfort log book for two weeks. Then the equipment was gathered and given to the next group of dwellings. Eventually, data were gathered from 19 dwellings. For the rest of the dwellings, either the data were lost due to technical reasons or to little data was recorded to be meaningful.

Due to the time limitations of the project, only aggregated results over the whole comfort measuring period are presented in this report. Note that the number of cases in each comfort level differ in each of the following sections, because not all respondents filled each of the categories in the log-book.

9.2 Type of Clothing

The clothing ensembles that the tenants could choose in the logbook are given in table 9.1. These clothing ensembles are the one used in literature to define the clo-values (heat resistance) of clothing, with the assumption that in all cases socks, underwear and pants were worn – which couldn't be verified from our logbook. There is also a possibility that, because of the graphics (figure 3.7), some tenants interpreted 'long sleeved sweat shirt' as sweater, or 'jacket/sweater' as a jacket to be worn outside. These possible inconsistencies would have to be decreased in new measuring campaigns by improving the graphics in the logbook.

Table 9.1: Clothing ensembles the tenants could choose during the qualitative data collection period

Ensemble	Clo-value
(Socks, underwear, pants), sleeveless t-shirt	0,5
(Socks, underwear, pants), t-shirt	0,55
(Socks, underwear, pants), knit sport shirt	0,57
(Socks, underwear, pants), long sleeved sweat shirt	0.61
(Socks, underwear, pants),jacket or sweater	0,91
(Socks, underwear, pants), jacket or sweater with hood	1

All times during the 2-week measurement period that people recorded through the comfort dial that they were filling 'cold' (for instance) were added and the type of clothing they wore, known from the logbook, was analysed. Figure 9.1 shows the results of the analysis for each comfort level. For instance, during the whole measurement period, over the whole dwellings sample, it happened in total 6 times that one of the tenants recorded 'cold'. In four of these 6 times (67%) the tenants who recorded 'cold' were wearing long sleeved sweat shirt and in 2 of these 4 times (33%) the tenants wore a jacket/sweater.

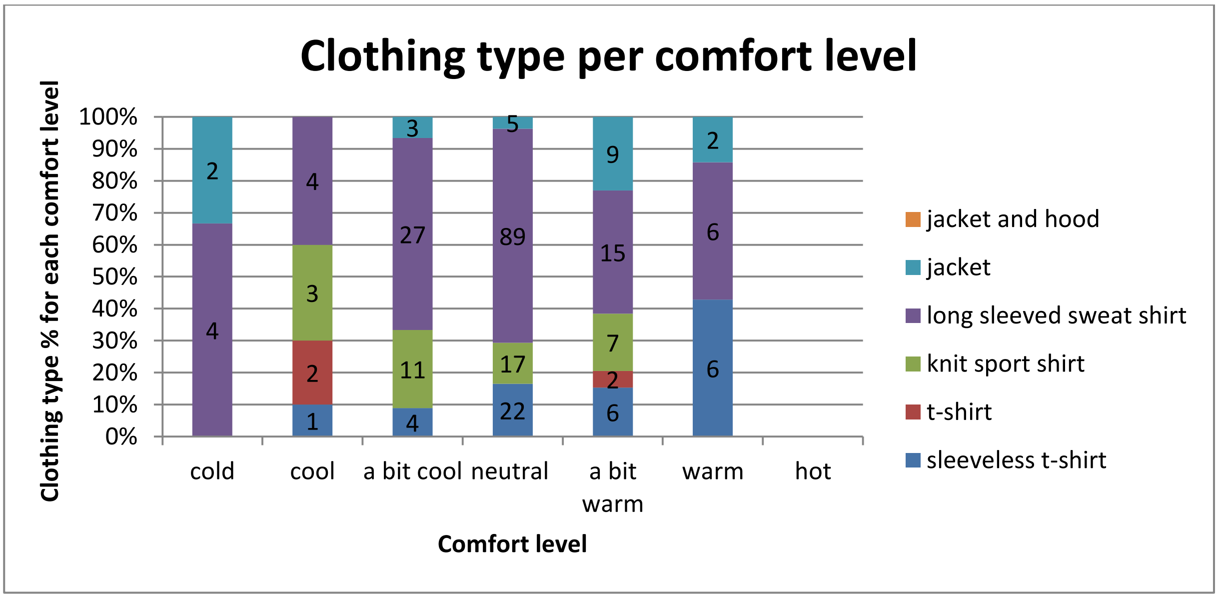


Figure 9.1: Clothing type per comfort levels from all dwellings participating in the qualitative phase of the campaign.

As can be seen in figure 9.1, in all comfort levels (7 points PMV scale from cold to hot) the clothing ensemble that is mostly found is the one with long sleeved sweat shirt, followed by the ones with the sleeveless t-shirt and then by the knit sport shirt. Less variation in the clothing is found at the extreme comfort levels (cold and warm). It is interesting to see that all kind of clothes are worn (from sleeveless T-shirt to jacket) in the categories 'a bit cool', 'neutral' and 'a bit warm', indicating that the combination of clothes with other parameters like temperature of activity are of importance. People who reported 'cold' were not wearing light clothes, like a T-shirt. From the people who reported 'warm' only 43% wore a T-shirt and the others wore warm clothes. The figure therefore tends to show some adaptation of the clothing to the thermal feeling.

9.3 Metabolic activity

Figure 9.2 shows the activities the respondent reported to have been busy with during the half hour before using the for comfort dial. The activities are shown per comfort level. These activities can easily be related to metabolic rates and are therefore referred as 'metabolic activities'.

The most common answer all over all comfort levels was 'sitting relaxed', with the exception of the comfort level cool where 'lying/sleeping' was the answer given the most. Walking was the second most common answer overall, followed by light desk work and lying/sleeping. Jogging and running had a much smaller occurrence in the answers.

It can be observed that, in general, the variety of activities increases when going from 'cold' to 'hot'. The people who felt cold were all sitting relaxed or doing light desk work, while the people feeling 'warm' have been sitting relaxed, walking, jogging or running.

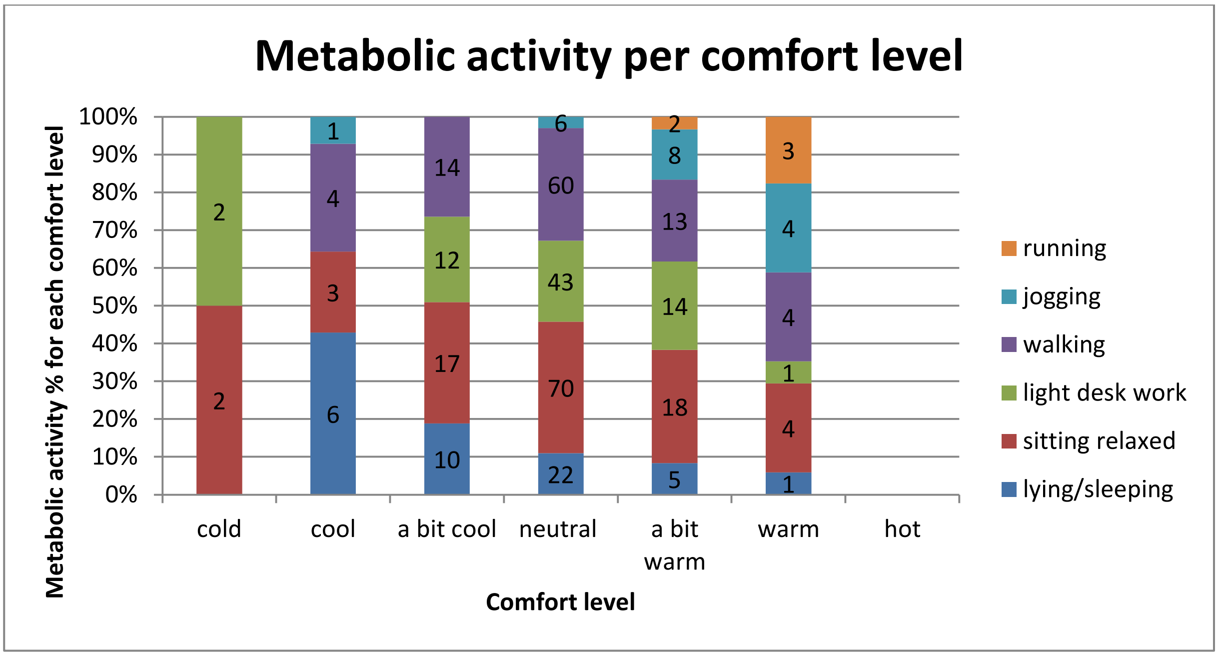


Figure 9.2: Metabolic activity for per comfort levels from all dwellings participating in the qualitative phase of the campaign.

9.4 Actions taken during the past half hour

Next to the metabolic activity it can be interesting to look at other actions undertaken in the past half hour before reporting on the comfort perception. Figure 9.3 shows the answers given by the tenants.

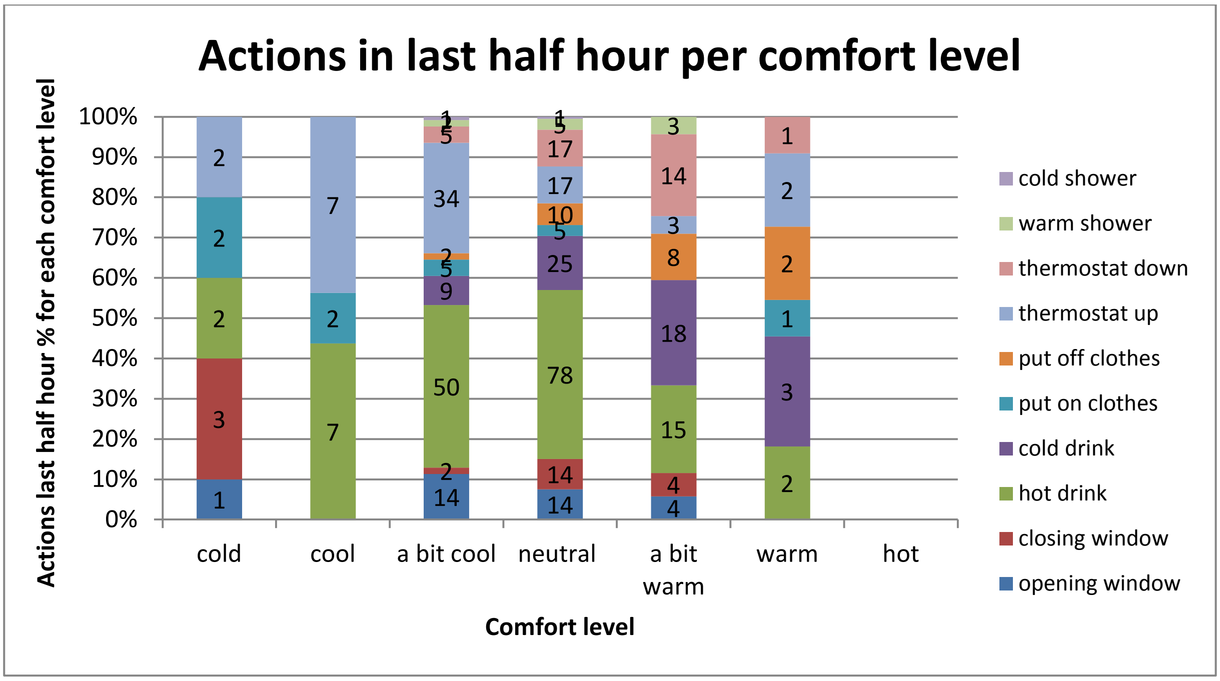


Figure 9.3: Actions taken during the past half hour per comfort levels from all dwellings participating in the qualitative phase of the campaign.

The answer that was most commonly found was having a hot drink. This answer was present across all comfort levels and it appears more intensively in the comfort levels around ''neutral'', ''a bit cool'' and ''cool''. However, as drinking thee or coffee all over the day is a Dutch habit, it is difficult to say in how far this action is undertaken with the aim of increasing the personal thermal comfort. The second most given answer overall was thermostat up, which appears mostly in the left side of the comfort scale, particularly in the ''cold'', ''cool'', ''a bit cool'' and even ''neutral'' comfort levels. Notably, this answer appears also in the level 'warm'. One cannot totally exclude that people who felt nicely warm reported 'warm' instead of 'neutral'. This is the well-known difference between thermal feeling and satisfaction (PMV and PPD) in Fanger's theory, which was not captured sufficiently by the comfort dial. This should be improved in a next version of the comfort dial. On the other hand, the third most given answer overall, having a cold drink, appears mostly in the right side of the comfort scale, particularly in the ''warm'', ''a bit warm'' and ''neutral'' levels. The next most taken action was to put the thermostat down which appears, as would be expected, mostly in the right side of the scale, in the levels ''neutral'', ''a bit warm'' and ''warm'', but also 5 times in the comfort level ''a bit cool''.

9.5 Average room temperatures per comfort level

Room temperature is generally believed to be a main factor in the sensation of comfort. It was shown in chapters 7 and 8 that large temperature variations are observed between dwellings and it is therefore interesting to look in how far it relates to the thermal comfort experienced by the tenants.

It seems very likely that the temperature in the specific room the tenants are when reporting their comfort with the comfort dial is less important than the overall temperature in the house. This is because in general the tenants have been doing different things during the past half hour and walked al lot through the dwelling (see figure 9.2). Choosing to analyse the temperature of all rooms in the dwelling at the same time may introduce a large uncertainty in our analysis, especially when people have reported to be sleeping, lying or sitting relaxed (they were then probably for a long time in the same room). That is why an analysis on the rooms in which movement was recorded will also be conducted. In the same way, only average temperatures all over the dwellings having reported a certain level of comfort have been used. Further data analysis will be needed to determine the bandwidth (sigma) of these temperatures, which is expected to be of greater importance for the analysis than the average temperature itself.

Figure 9.4 shows the average temperature at the same timestamp the tenants were using the comfort dial, regardless of the presence in a certain room. This timestamp has duration of 5 minutes (see also chapter 2). Further study of the data should demonstrate if this timestamp is the most relevant one to use. One could argue that the average temperature during the half hour before using the comfort dial may show more correlation with the thermal comfort sensation that the instantaneous temperature at the precise moment of filling. However, figure 9.4 is interesting for the sake of demonstration.

Surprisingly, the temperature in the living room is the highest at the comfort level 'neutral' and then decreases steadily with negative as well as positive deviations from this state. The same happens in the two bedrooms, but temperatures in the states 'neutral' and 'a bit warm' are quite identical. In the living room and both bedrooms it is notable that the temperatures at the 'cold' level are higher than at the 'cool' level. The kitchen show a more flattened profile: the temperatures in the levels ‘cool’, ‘a bit cool’ and ‘’neutral’ are quite similar. In fact it seems that this average temperature is not really connected to the comfort levels, although one could argue that the left part of the graphic, from cold to neutral shows a logical pattern were the temperature increases. The feeling of warmth at lower temperatures in the right part of the graphic could logically be imputed to the increased activity levels that were observed in figures 9.2 and 9.3.

Figure 9.5 shows the results when only the rooms were movement was detected at the time of filling the comfort dial are taken in to account. Although differences are observed, especially in bedroom 2, the results are basically similar to those of figure 9.4.

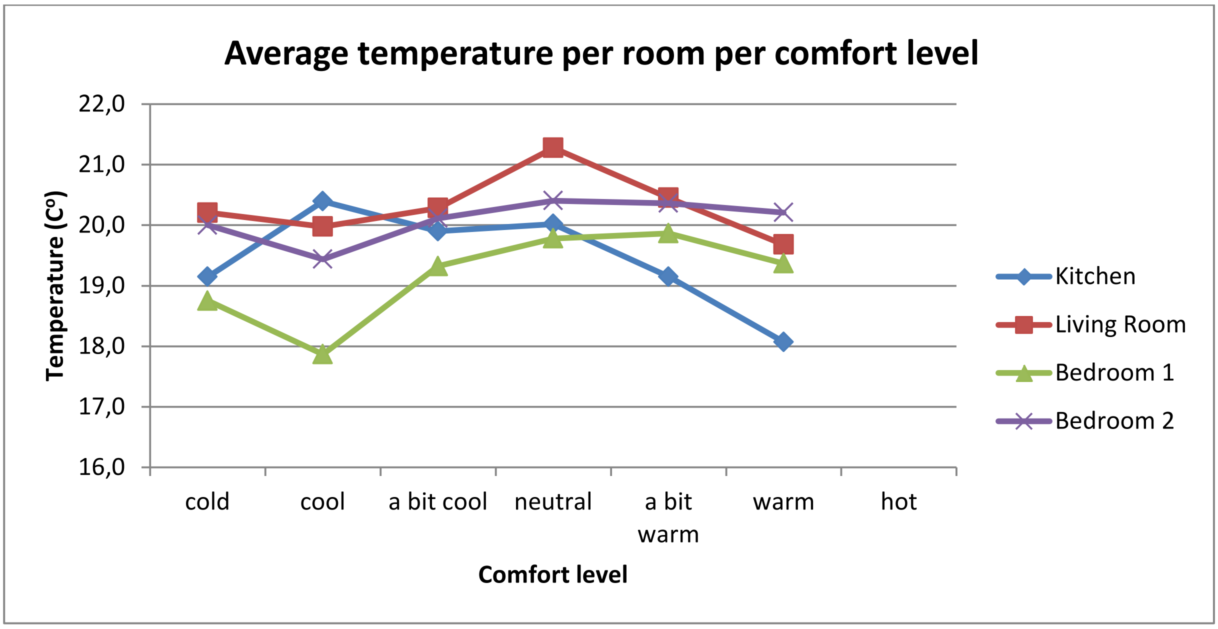


Figure 9.4: Average temperature per room per comfort level from all dwellings participating in the qualitative phase of the campaign.

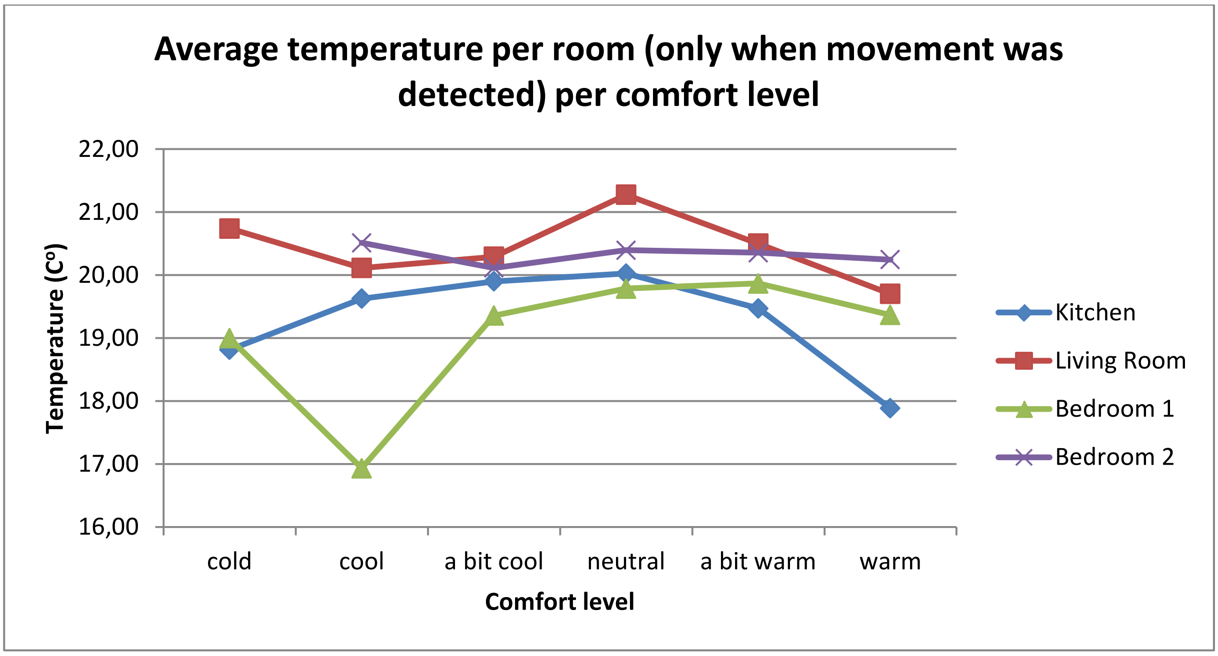


Figure 9.5: Average temperatures per room (when movement was detected) per comfort level from all dwellings participating in the qualitative phase of the campaign.

9.6 Relative humidity per comfort level

In figure 9.6 the fluctuation of humidity is displayed across the comfort scale for all types of rooms, using the same methodology as for figure 9.4. The figure shows a reverse trend. Except for the kitchen, the humidity is lowest in the comfort level 'neutral' and increases at lower and higher comfort levels.

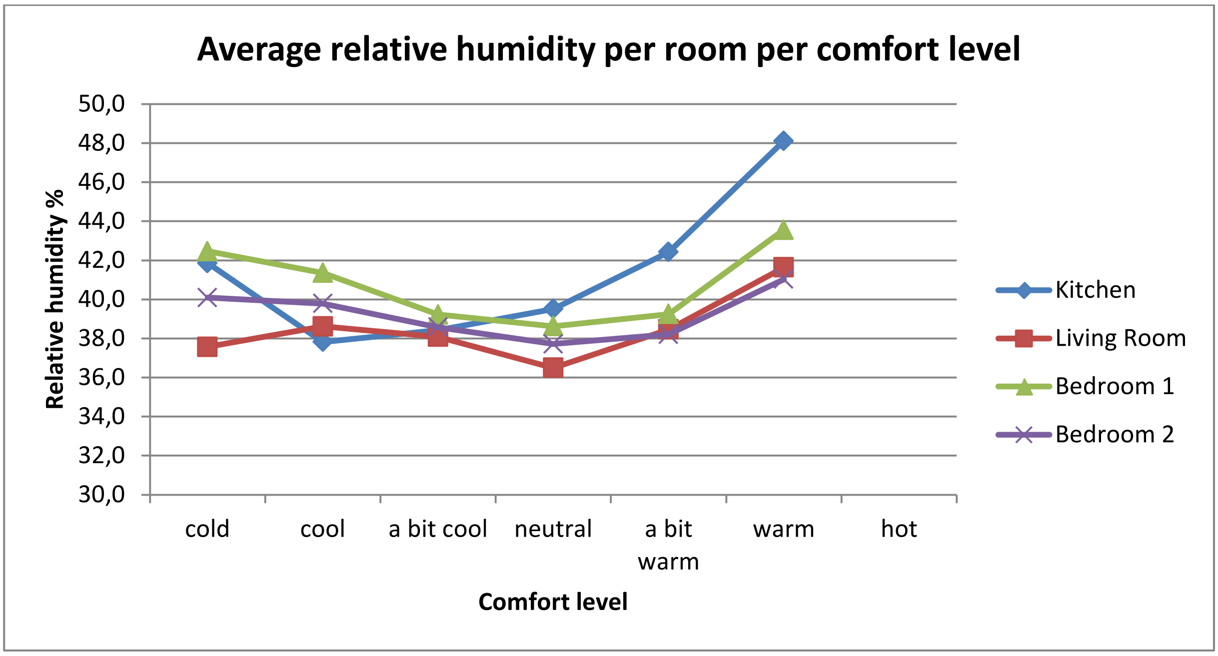


Figure 9.6: Average relative humidity per room per comfort level from all dwellings participating in the qualitative phase of the campaign.

9.7 CO_2 concentrations per comfort level

Although CO_2 concentration is not known from literature to relate to the thermal sensation of comfort, it could be that the perception of air quality does influence the thermal comfort perception. In fact, it was already discovered by Fanger that perceived indoor air pollution (in decipols) does influence the percentage of people dissatisfied (PPD).

In figure 9.7 the CO_2 levels per comfort level per room types are given. Here two different patterns are observed. The first pattern is for the two bedrooms. The CO_2 levels increase between comfort level ''cold'' to comfort level ''cool'' and then they keep on dropping till ''a bit warm''. Then there is a very steep increase for the comfort level ''warm''. The kitchen and the living room follow a different path, the CO_2 levels drop between levels ''cold'' and ''cool'' and then they keep on increasing till level ''warm''. In general, it seems that the CO_2 levels are increasing as we go from the comfort level ''neutral'' to the right side of the comfort scale while it is more erratic in the cold side of the comfort scale, as we go from ''neutral'' to ''cold''.

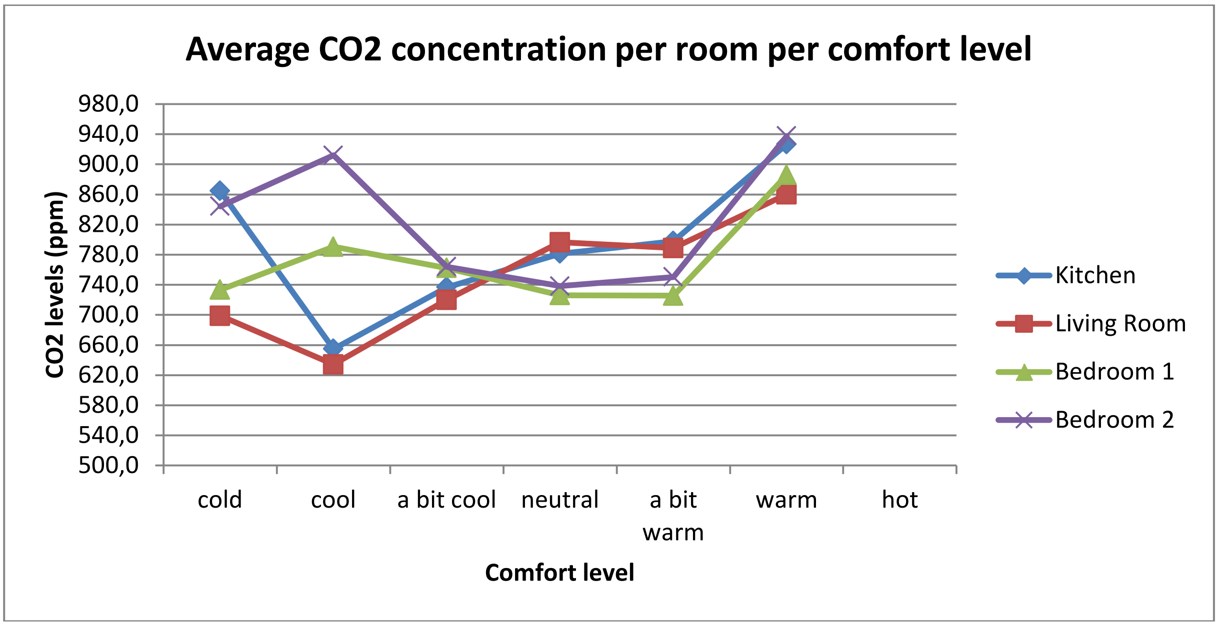


Figure 9.6: Average CO_2 concentration per room per comfort level from all dwellings participated in the qualitative phase of the campaign.

9.8 PMV and comfort level

It is well known from comfort theory that all parameters studied in the previous sections (except for the CO_2) are interrelated. For example, the comfort temperature strongly depends on the relative humidity and on the radiation temperature. These interdependencies are caught into the so-called PMV: the predicted mean vote, calculated on the basis of clothing, activity, air temperature, relative humidity, radiation temperature and air velocity. The predicted mean vote predicts the thermal comfort experienced by most of people, it is therefore a statistical concept, used in building design and post-occupancy studies to assess the quality of the indoor thermal environment.

As the last two parameters in the list above were not measured, we based our PMV calculations on the assumption that the radiation temperature is equal to the air temperature. As for the air velocity we added a sensitivity analysis. Figure 9.7 shows the PMV for the living room, calculated for each comfort level, on the basis of the average data described in sections 9.1 to 9.6 and the assumption of radiative temperature begin equal to air temperature. Each comfort level (from cold to warm) is divided into three categories: low, average and high. In the category 'low', the air velocity is supposed to be 0.3 m/s, in the category 'average' it is 0.2 m/s and in the category 'high' it is 0.1 m/s.

The comfort perception as recorded by the respondents with the comfort dial, is shown in orange. According to the theory, 'cold' corresponds to a PMV of -3, 'cool' to -2, 'a bit cool' to -1, 'neutral' to 0, 'a bit warm' to 1, and finally 'warm to '2'. The calculated PMV is given in blue, each time for the three air velocities.

The perceived thermal sensations 'cold', 'cool', 'a bit cool' and 'neutral' seems to be quite well predicted by the PMV, when adjusting for the air velocity (0.3 m/s for 'cold; between 0.3 and 0.2 m/s for 'cool'; between 0.2 and 0.1 m/s for ' a bit cool' and 'neutral'). For the thermal sensations 'warm' and 'a bit warm', the prediction goes wrong by predicting a quite cold sensation while the tenants seem to experience enough thermal comfort.

Of course, no definite conclusions can be drawn from this exercise. The sensitivity analysis should be extended to radiation temperature taking into account a realistic bandwidth for it. This bandwidth depends on the insulation of the walls, the outdoor temperature and the temperature in the apartments next, the temperature of the heating devices (radiators/floor heating) and their size.

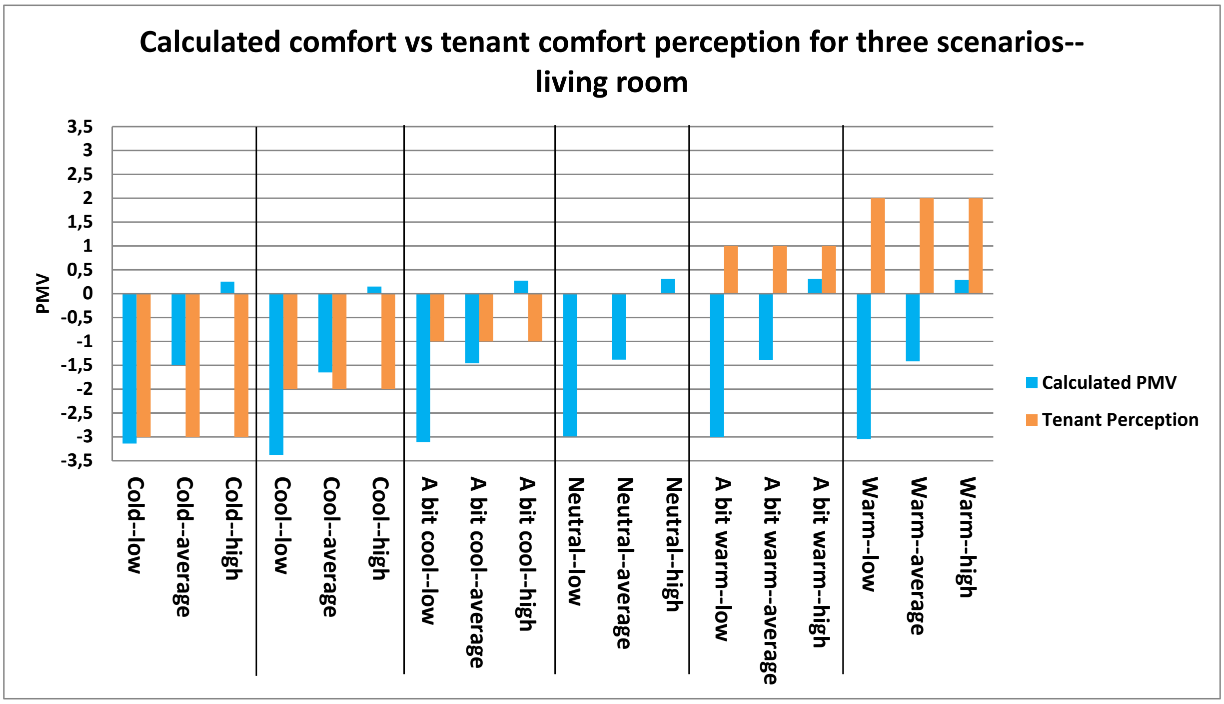


Figure 9.7: Comparison between predicted and reported thermal comfort per comfort level per category of air velocity (low: 0.3 m/s; average: 0.2 m/s; high: 0.1 m/s)

9.9 Conclusions

In this chapter we investigated the real time comfort perception of the tenants. Although a lot of data need to be analysed further, the methodology needs to be further developed and we couldn't draw any definitive conclusion in this stage of the research, we demonstrated regardless the possibility to measure real time comfort on site and to relate it to real time measureable physical parameters. Additionally, some improvements of the comfort dial and the logbook were proposed. It was observed that in general people who felt cold at a certain moment were sitting relaxed or doing light desk work, while people feeling warm have been sitting, walking, jogging or running, or a mix of these activities. People who were feeling cold or a bit cool often reported to have set the thermostat up in the last half hour. People who were feeling warm of a bit warm reported quite often to have taken a cold drink or to have set the thermostat down. Not completely expected, but in line with the findings of the theoretical study described in section 2.8, no correlation was found between the perceived thermal comfort and the room temperatures. Additionally, the relative humidity was observed to be low in the neutral zone, while it was higher when they reported 'warm' or 'cold'. Finally, when people reported 'warm', the CO_2 concentration was higher than when they reported a less warm, neutral or a bit cool feeling. It is of course well known that the comfort zone depends on temperature and humidity, but little is known about the influence of the air quality (CO_2 concentration) on the thermal comfort. Most important, a sensitivity analysis on our data demonstrated that the PMV seems to be able to predict the neutral and cold sensations but not the warm sensations.

10 U-value of external walls

10.1 Description of the measured dwellings

Three case studies were investigated. The first case study investigated in this research is an old 97 m^2 semi-detached house located in Delft. The wall under study is at the end of a corridor connected to a terrace. The energy label of this house is F and the construction is very old (1680). The thickness of the wall is 27 cm and the construction is unknown. The photos of this case study are shown in Figure 10.1.

Figure 10.1- Case study 1- The whole building (left), the inside surface of the wall (middle), and the outside surface and sensors covered by the box (right). Location: Delft, the Netherlands

The second case study is a wall with known construction (Dutch brick). This wall is 21 cm thick, made from Dutch red bricks with thermal conductivity of 1.2 W/mK. Hence, for this case the results can also be compared to the theoretical value of conductive thermal resistance. The tests took place on two sides of one brick (on the length) to assure that there is a single layer in the direction of one dimensional heat flow. The wall in this case is located at the kitchen of a 93 m^2 house (construction year: 1933) with energy label F in Den Haag, see Figure 10.2.

Figure 10.2: Case study 2- The whole building (left), the inside surface of the wall (middle), and the outside surface covered by the box (right). Location: Den Haag, the Netherlands.

The third case study investigated in this research is a wall of a bedroom in an 84 m^2 apartment located in Delft with an energy label of E. The construction in this case is unknown and there is no information about the material used in the wall. The wall is 8.5 cm thick and the year of construction is 1964, see figure 10.3

Figure 10.3: Case study 3- The whole building (left), the inside surface of the wall (middle), and the outside surface and sensors covered by the box (right). Location: Delft, the Netherlands.

10.2 Results of the measurements

The results of the three experiments are summarized in this section. For the three case studies EPM and the method based on ISO standard 9869 were applied. The results are summarized in Table 10.1. For the case study in which the construction of the wall was known (Dutch brick wall), the measured Rc-values are compared to the calculated Rc-value (k=1.2 W/mK [40] and l=0.21 m).

Table 10.1. Comparison between the Rc-values by ISO 9869 and by EPM for three case studies

Case Study	Location	Duration ISO 9869	Rc by ISO 9869 (Duration >2 weeks)	Rc by EPM (Duration 1.5 hr)	Calculated Rc	Departure
1	Delft	16 Days	0.77 m2K/W	0.78 m2K/W	-	+1.2%
2	Den Haag	14 Days	0.173 m2K/W	0.172 m2K/W	0.175 m2K/W	-0.6%
3	Delft	14 Days	1.57 m2K/W	1.60 m2K/W	-	+2.0%

As illustrated in Table 10.1, the results of EPM show a good agreement with the ones obtained by applying the method based on ISO standard 9869 . The results for these three walls therefore show that it is possible to measure in-situ in 1,5 hour the heat resistance of walls. In comparison with the actual standards, it is an enormous time saving, as more than two weeks were needed for measurement according to these standards. This may open the way for systematic in-situ measurements.

10.3 Comparison with standard values used in the energy labelling method

In Table 10.2, the results of the Rc-values by EPM are compared to the ones stated in the energy labelling method for unknown constructions. According to ISSO 82.1 and ISSO 82.3, the Rc-value will be assumed (if no measurement is made, which is mostly the case) based on construction period which is the same in all three cases (before 1965). Accordingly, the Rc-value for all three cases is supposedly equal to 0.19 m^2K/W.

As shown in Table 10.2, the estimation of the Rc-value using ISSO 82.3 can result in a considerable error. Taking convective heat transfer coefficients of 7.6 W/m^2K and 25 W/m^2K for indoor and outdoor respectively in accordance with ISSO 60 and ISSO Kleintje, the U-values for the three cases according to energy labelling method and to EPM are given in Table 10.3.

Table 10.2. Comparison between the Rc-values calculated according to the Dutch energy labelling method and the measured values for three case studies

Case Study	Location	Construction year	Rc by energy labelling method	Rc measured by EPM	Departure
1	Delft	1964	0.19 m2K/W	0.78 m2K/W	-76%
2	Den Haag	1933	0.19 m2K/W	0.172 m2K/W	+10%
3	Delft	1680	0.19 m2K/W	1.6 m2K/W	-88%

Table 10.3. Comparison between the U-values calculated according to the Dutch energy labelling method and the measured values for three case studies

Case Study	Energy Label	U-value by energy labelling method	U-value by measurement (EPM)	Departure
1	E	2.76 W/m^2K	1.05 W/m^2K	+163%
2	F	2.76 W/m^2K	2.92 W/m^2K	-6%
3	F	2.76 W/m^2K	0.56 W/m^2K	+393%

As shown in Table 10.3, by using the standard values from the Dutch energy labelling method, the U-values of walls can be extremely overestimated. This also might explain the overestimation of gas consumption in old dwellings with poor energy labels that was observed in section 2. However, three case studies are far from enough to prove so and further study is recommended.

11 Recommendations for the improvement of energy simulation models and for regulatory energy calculation methods

The aim of the Monicair study was to investigate in how far detailed and high resolution data on occupant behaviour, buildings' physical characteristics and HVAC characteristics could help in refining current energy models and increasing the quality of their input data, in order to improve the quality of the prediction of energy consumption, which was shown in section 2 to be far from satisfactory.

Section 11.1 focuses on energy models in general (like ESP-r, Energy+ ,TRNSYS, VA114, etc., all dynamic models), while section 11.2 addresses more specifically the regulatory, often static, energy calculation models, like the one used for energy labelling.

11.1 Improvements of dynamic energy models

In the precedent chapters it was shown that a large variety of occupancy patterns in terms of presence, temperature preferences and ventilation patterns is found. The size of the sample limited the quality of the analysis with regard to the relationship of these patterns with the actual energy usage, however we expect that larger samples will be more easily achievable in the future due to the emergence of cheap sensors and their wide application in, for instance, smart phones and all kind of appliances. Therefore the kind of data we started to collect in the Monicair project will be more widely available in the future.

Dynamic energy models are used in simulation research to study, develop and test new buildings or HVAC components and can also be used during building design or renovation to estimate energy saving potentials of specific systems and renovation measures. The models in itself are generally accurate and have been extensively validated using procedures like BESTEST or BRL 9501. Regardless their validation, these models require extensive and time consuming case by case calibration when applied to a specific building. This is because the input data needed by the model needs to be precisely known in order to produce an accurate output: garbage in, garbage out as known from computer sciences.

At that point, there is a trade-off between accuracy of the model and accuracy of the input data. Detailed dynamic models need much more input parameters than simple static models. For instance knowing the overall U-value of a wall is sufficient for a static model, while the conductivity, specific heat, and density of each layer of the wall are needed in a transient model. These data may be very difficult to gather, especially in older buildings where the exact construction is not known. If it is not possible to generate accurate enough input data for detailed dynamic models, then the potentially more accurate predictions by using a more precise model will be offset by the low quality of the input data. Therefore, it may be that a simple static model, which needs input data at a more aggregated level, delivers the same final quality as a transient model.

There are two common practices observed when using dynamic models to calculate energy saving potential. The first one is to try to calibrate them by fitting the calculated energy use to the real ones

-if measured- by playing with input data like occupancy or ventilation flow rates and indoor temperatures. This is generally a very time consuming procedure and many combinations of parameters can be found that would lead to a reasonable fit, but there is no way in practice to determine which combination is the right one. So, generally, the work stops at the first found combination, no matter if it is the right one. However, it should be noted that more and more research is carried out in this area, and one can expect he improvements in the future. The second practice is not to calibrate, but just to use standard values, based on experience or the standard values already filled in the software.

In both cases there seems to be a huge need in the building simulation community to get access to well validated input data. The type of study carried out in Monicair could in the future deliver this validated input data. The main fields of improvement are described below:

Comfort and activity patterns

Our results indicate that the current calculation of thermal comfort in houses using (adaptive) PMV leads to indoor temperatures that are higher than needed. In our sample, people were reporting they were feeling warm while PMV indicated they should feel cold. Further research on thermal comfort perception in dwellings could lead in the future to the revision of the PMV method and to the adaption of building simulation software on that point. Additionally, comfort was shown to depend more on metabolic activity and clothing than on temperature. Having 24-hours activity patterns of household members coupled to metabolic rates could improve the quality of the simulations. Based on the same type of study as explored in Monicair, it may be possible to produce activity patterns on the basis of household characteristics, like number and age of people in the household and if they are physically active people or more quite ones. Further studies on the variation of metabolic rates within the same type of activity, depending on age, gender, weight etc. could also help explaining variations in comfort perception.

Thermostat settings

In dynamic models, temperature patterns are not an input but a result of the calculations, based on HVAC, buildings' physical characteristics and thermostat settings. In our sample a relationship was found between the thermostat settings and the thermal quality of the house: the temperature set point was in general higher in label A than in label F. This should be accounted when choosing the set point temperatures for a building simulation, as well as the day/night and present/absence set points of the thermostat. Our study shows here differences in the settings relating to the type of heating system.

Presence patterns

The determination of presence patterns, as was done in chapter 6, would be very helpful in relation to the thermostat settings and the use of the ventilation systems. It would also help the models to estimate better the internal heat load all along day and seasons. One could think of a presence patterns library, in which a suitable presence pattern could be chosen based on household size, age or hours of work or study outside.

Multi zone models

Our study showed different temperature levels and different ways of ventilating different rooms. This mean that, on the basis of further research, databases with different patterns per type of room, type of heating and ventilation system and type of households could be set up. In one-zone models, the results of studies like ours would lead to a better estimation of average temperatures and ventilation low rates.

Natural ventilation and infiltration flow rate patterns

Our study and the one by Delghust (2015) have shown different use of windows and grilles per room and in different households. The most ventilated rooms are often the unheated ones, therefore assuming one ventilation pattern for the whole house could lead to overestimation of heating energy use. Maybe it could be possible in the future to determine ventilation patterns depending on household characteristics. Continuous CO_2 measurements becoming more common will also give the possibility to estimate year-round infiltration flow rates, which could improve greatly the energy predictions.

Patterns of use of mechanical ventilation systems

When modelling mechanical ventilation systems it would be good to account for the fact that, up to now and unlike the thermostat of the heating system, the control possibilities of the system seem not to be used by the occupants: most systems are always in the lowest position. This of course could change in the future if smarter control is offered and possible noise problems relating to these systems are solved.

Walls thermal properties

Chapter 10 has shown that it is likely that in many old buildings the estimation of the thermal properties of the external walls (and roofs/floors) is very inaccurate. As this estimation is essential for the calculation of energy savings when insulating buildings, the recommendation here is to measure it whenever possible. Furthermore, the thermal properties of the wall and of the different layers it consists of are very important in dynamic models. However, they are very difficult to determine in existing buildings. The EPM method described in section 3.5 and tested in chapter 10 allows for the quick determination of the overall thermal properties of the wall and therefore for dynamic calculations based on a homogeneous equivalent wall.

Household type

In many of the variables described above the possible relationship with household characteristics was stressed. This is because household characteristics could offer an easy way to generate and structure these variables, while maintaining an acceptable level of abstraction. A first step was set by Guerra Santin (2010), but at that time too little data could be collected to go further. Almost everything can be measured nowadays, new possibilities will therefore arise in the near future and it will be possible to define specific occupancy patters for different household groups. Last but not least, by defining household typologies, a better determination of model's input parameters like internal heat load by appliances will be possible.

As a concluding remark we can state that the next generation of dynamic building simulation models needs to include behavioural models to assist with the generation of the right input data. However, as behaviour has a strong stochastic component, future model should be able to cope with these probabilistic properties and to offer not only one answer (the energy consumption) but a probability distribution of this energy consumption.

11.2 Norms and regulatory energy calculation models

Regulatory models are often simple, static models. The aim of regulatory models like the energy labelling model (ISSO 82) is not to provide an accurate case by case prediction of the energy consumption, but to assess the performance of buildings under standardized conditions in order to, on the long term, improve the thermal quality of the building stock. It is therefore important that, on average, the predictions in each label category are accurate enough. The actual inaccuracy of the average predictions, which furthermore differs strongly in each label category (see figure 2.1, section 2), leads to large bias in expected energy savings and can be perceived as misleading by building owners and renters and by those who are willing to thermally renovate their house.

Of course, it is logical that there is a wide range of variation of actual energy consumptions within one label category, or even within dwellings having similar energy-indexes. Everyone can understand that behaviour and household composition plays a role in energy consumption. However, regulatory models could profit from a broader societal support is their accuracy at the level of averages per label category or per range of energy-index was increased.

In Majcen et al. (2015) it has been proposed to improve the energy labelling method by applying correction factors based on statistical large scale data on actual energy consumption, as these data are becoming widely available. The paper demonstrated that better accuracy could be achieved by doing so. The advantage of the use of these correction factors is that the calculation method remains unchanged. However, one can argue that an improved method would be a purer way and would help understanding the underlying factors of energy consumption and therefore would lead to better predictions of energy savings. This is the path we followed in the Monicair project.

Keeping in mind that regulatory methods used to assess the thermal quality of buildings must offer a certain degree of standardization concerning behaviour and household size, the following areas of improvement are proposed:

- Revision of the standard value for average temperature and heated area;
- Revision of the standard values for presence home;
- Revision of the standard values for ventilation and infiltration flow rates;
- Revision of the standard efficiency of heating systems;
- Revision of standard U-values per construction year.

Revision of the standard value for average temperature and heated area

In static models like the energy labelling one, pre-defined temperature patterns are used as input for the calculation. In our sample a relationship was found between the temperature profile and the thermal quality of the house: the temperatures were in general higher in label A than in label F. Different profiles were also observed for different types of heating systems and seemed to relate more to the heating system than to occupant behaviour. For instance in houses with a heat pump, the temperature was more constant all over the day and all over the houses than in houses with a boiler or a stove. Furthermore, it could be that houses with heat pumps and low temperature systems have a higher heated area than houses with a boiler and radiators in rooms, which in turn have a higher heated area than houses with only a local stove.

The main reason to use the same average indoor temperature for all types of houses and heating system in the energy labelling method (ISSO 82) is the idea that the houses should be compared at the same level of comfort. However, different types of houses and of heating systems do not deliver the same levels of comfort. It would help the consumer more to provide him with a realistic estimation of his energy consumption and a separate estimation of the thermal comfort than to try to combine both as is the case now. In the current method, the heating energy estimation is very inaccurate and the level of comfort is hidden in the calculation and not communicated to the consumer.

It therefore seems logical to make the standard temperature dependent of house typology and heating system. This could be based on further statistical analysis of temperature profiles in combination with realistic heated areas. The calculation of the heated area could also be made dependent of the presence of absence of a heat distribution system in the different rooms of the dwelling.

Revision of the standard values for presence home

In the current method, the size of the household depends on the surface area of the dwelling, which seems logical. This number of persons is used to calculate the hot tap water demand. The internal heat gains are considered to be 6 W/m^2, regardless the number of persons in the household, which may introduce inaccuracy in the calculation of the space heating demand. Furthermore, the temperature profiles observed may be very dependent of the way of living of the persons in the household: are they a retired couple being home all time, a young person working all week outside of the house or a family with young children?

Keeping in mind that user behaviour should be standardized in a regulatory instrument, the point here is to define presence patterns that match with reality on average. Therefore further studies should be conducted to show if certain types and sizes of houses correlate with certain income levels and with employment figures. A minimum accuracy level here is to try at least to base the data on nationally correct statistics.

Revision of the standard values for ventilation and infiltration flow rates

Like happens with indoor temperature, the current energy labelling method applies the principle that the hygienic ventilation flow rates are identical in all types of dwellings. The CO_2 measurements have shown that it is very likely that houses with natural ventilation are much less ventilated than the ones with mechanical systems. Here again, the assessment of energy use on the basis of identical ventilation is confusing for the consumer and leads furthermore to the overestimation of energy saving potentials. It would be much better to estimate realistic flow rate averages per type of ventilation system in order to obtain realistic energy use and to further warn consumers about the shortcomings of their ventilation system, instead of trying to aggregate these parameters on an artificial way.

Revision of the standard efficiency of heating systems

Although the data couldn't be measured during the Monicair study, the data by Majcen (2016a, 2016b) gives evidence that the efficiency of diverse heating systems seems no to be realistically estimated. The problems seem to take place more in older systems than in new ones, and the efficiency of these older systems seems to be systematically underestimated, leading here too, to ways to optimistic estimation of energy savings by renovation. Therefore, a revision of the standard efficiency of older systems is recommended.

Revision of standard U-values per construction year

Chapters 2 and 10 gave indications that the U-value of external wall is overestimated in older buildings, leading to the overestimation of their heating energy consumption. It seems that the insulation quality of older walls is better than expected and assumed in the documents the energy labelling method refers to (ISSO 60, ISSO-Kleintje). Apparently, the data from ISSO 60 is outdated. The in-situ measurement of the thermal resistance of walls during the dwelling's inspection would probably lead to a much better estimation of this U-value. However, this is not easy to realise within the inspection context (time and costs). Another solution is to start a measurement campaign in order to determine the thermal resistance of existing walls (ad roofs or floors) based on representative samples of houses.

To conclude this section on the improvement of regulatory models, a reflection on current developments in the CEN TC 371 commission relating to models for the Energy Performance of Building Directive is being called for. In order to increase the predictive power of the simulation method, a choice was made to use dynamic hourly simulation models. According to the findings in this chapter, a doubt is raised if this will really result into an improvement. As stated in section 11.1 dynamic models need more detailed input parameters. As these input parameters are in practice very difficult or even impossible to estimate, they will not be measured, but replaced by standard values, leading to new inaccuracies. The same problems will arise if using multi-zone models instead of one-zone models. For regulatory models, applied for the whole building scope, the detail level of the models should be in accordance with the accuracy of the input data that can be collected in practice.

12 Conclusions and recommendations

This chapter provides a summary of the main results of the Monicair project.

12.1 Set point temperatures and actual temperature profiles

In the past, many studies on temperature habits in household were based on surveys. In our survey, almost half of the temperature settings during the day were reported correctly, while approximately one fourth reported too high temperatures and one fourth too low temperatures, both by 1 ^{o}C on average. This shows that when relying on temperature surveys to find correlations between energy use and temperature, one may not find them, while these correlations may be present. Furthermore, even in the case the set point temperatures were correct, these set point temperatures were not an accurate predictor of the actual temperatures measured all along the heating period. However, both the set point temperatures and the continuously measured temperatures showed in general higher temperatures in A-labelled dwellings than in F-labelled ones.

The continuously measured averaged daily temperature profiles demonstrated a wide spread in the actual temperatures of dwellings. The spread between rooms of one dwelling may also be large. Dwellings with heat pump had a clearly more constant temperature 24-hours profile than dwellings with boilers or stoves, and also their temperatures in the different rooms were closer to each other. Clear relationships between temperature profile and energy label, ventilation system, number of hours of window opening or number of occupants were not found in our sample, which was rather small. However, it is clear that the temperatures in the bedrooms were in general lower than in the living rooms, but clearly, most bedrooms were heated, also during the night. It is also clear that lower temperature profiles were observed in the dwellings with energy label F (naturally ventilated) and the dwellings with label A (balanced ventilation).

12.2 CO_2 concentration and ventilation systems

For most mechanical ventilation systems (both balanced and mechanical exhaust systems), the set points were on the lowest level. In general, the living room and bedrooms were reported to be ventilated through windows or grilles 1-4 hours a day. Most living rooms and bedrooms in dwelling with mechanical exhaust ventilation are ventilated longer than 5 hours a day. An important share of people (21 to 50%) report to rely completely on the mechanical ventilation (when present) to ventilate kitchen and bathroom, and notably, also in the naturally ventilated houses more than 28% of people reported not to ventilate the bathroom actively.

No clear pattern between the CO_2 excess hours and the reported ventilation behaviour was found. The household size seems to relate somehow to the excess hours: the larger the household, the more chance to find high excess hours. In our sample the relationship between the CO_2 excess hours and the type of ventilation system was very clear, though. Balanced ventilation systems scored better (i.e. had less excess hours) than mechanical exhaust systems, which scored better than natural ventilation systems. This is in line with the findings from the Monicair report part A, in which the results of another sample of 60 dwellings were described.

Situations with too frequent and too high excess of 1200 ppm were found for each ventilation system or, in other words, despite of the ventilation system. Thus possibilities to improve all the considered ventilation systems need to be examined. However, it is clear that much less CO_2 excess is found in balanced ventilation systems than in naturally ventilated ones. The analysis shows that the number of rooms in which threshold values are exceeded together with the level and duration of excess, increases from 'balanced system' to 'mechanical exhaust with natural supply' to 'natural exhaust and natural supply'.

In a couple of dwellings high CO_2-levels were observed in the kitchen, probably due to cooking on gas. This shows a poor efficiency of the exhaust in the kitchen.

Based upon the combination of motion detection and CO_2-profile, it has been possible to predict presence, also when only slight increases or decreases of the CO_2 concentration were observed. The predicted presence could be explained logically, however, additional validations will be needed in the future.

12.3 Comfort perception

It was observed than when moving from label A to label F-dwellings the percentage of people experiencing the indoor temperature in winter as being ''too cold'' increases. For the summer the answers concerning overheating are more or less similar in all dwellings, showing that about on fourth of the tenants in the sample experience too high temperature in the summer, regardless of the label. No clear relationship was found between the temperature perception and the type of ventilation system.

In general, in our sample, there were fewer complaints about draft in the dwellings with balanced ventilation than in the other ones and there were more complaints about humidity in the dwellings with natural ventilation. Most respondents in the naturally ventilated dwellings, which were all label F, would like to have a warmer house in winter. Most respondents in the balanced ventilation dwellings, which were all labels A or B wouldn't change anything or would prefer to have faster warm water. In the category of mechanical exhaust ventilation, with mixed energy labels, a warmer house and faster warm water where the most often given answers.

We also investigated the real time comfort perception of the tenants. Regardless the facts that a lot of data needs to be analysed further, the methodology needs to be further developed and we couldn't draw any definitive conclusion in this stage of the research, we demonstrated the possibility to measure real time comfort on site and to relate it to real time measureable physical parameters.
It was for instance observed that in general people who felt cold at a certain moment were sitting relaxed or doing light desk work, while people feeling warm have been sitting, walking, jogging or running, or a mix of these activities. People who were feeling cold or a bit cool often reported to have set the thermostat up in the last half hour. People who were feeling warm of a bit warm reported quite often to have taken a cold drink or to have set the thermostat down. Not completely expected, but in line with the findings of the theoretical study described in section 2.8, no correlation was found between the perceived thermal comfort and the room temperatures. Additionally, the relative humidity was observed to be low in the neutral zone, while it was higher when they reported 'warm' or 'cold'. Finally, when people reported 'warm', the CO_2 concentration was higher than when they reported a less warm, neutral or a bit cool feeling. It is of course well known that the comfort zone depends on temperature and humidity, but little is known about the influence of the air quality (CO_2 concentration) on the thermal comfort. Most important, a sensitivity analysis on our data demon-

strated that the PMV seems to be able to predict the neutral and cold sensations but not the warm sensations.

12.4 Relation with energy consumption in theory and in practice

The relationship between temperature profile and gas or electricity consumption was not clear. Because of time limitation for this study, the daily average temperature profiles were based on a two-week measurement period with 5 minutes time interval, while the energy data were for the complete 6 months period and no continuous energy data was available. Although the two-week period was quite representative of the whole period, the result may be biased. It was however clear those dwellings which consume the most gas are found in the category naturally ventilated dwellings (all label F). The dwellings with balanced ventilation (labels A and B) were not consuming less gas or electricity than the dwellings in the category 'natural supply and mechanical exhaust'.

These results show the necessity for an integrated approach, as main parameters like temperature and energy label could not directly be related to the energy consumption. Detailed energy monitoring, with the same time interval of 5 minutes as the other data, could give better insights in the determinant factors. Unfortunately, the collection of these data with the Youless partly failed.

The detailed analysis of a number of cases made clear that there seems to be room for improving the energy behaviour of households, either by making them aware of the actual temperature in their dwellings, or by reducing it gradually or by changing ventilation habits, although one should be very careful with the last option not to lower the indoor air quality. It was also shown that not only behaviour may be held responsible for high temperature levels, but also the tuning of the system itself, especially when heat pumps and floor heating are used.

12.5 Actual heat resistance of walls

A transient method, the EPM method was fine-tuned and applied to measure the actual het resistance of the external walls of three different dwellings. The EPM method offers the advantage of being very quick in comparison to the current standards for which weeks of measurements are needed. A very good agreement was found between these standards and the EPM method. For two of the three cases the U-values showed to be extremely overestimated (by more than 150%) in comparison to the standard values from the Dutch energy labelling method.

12.6 Improvement of energy simulation models

The improvement of energy simulation models, based on the collected data and earlier studies, was discussed separately for dynamic models and for regulatory models in the framework of the EPBD. For both types of models it was stated that current problems were not caused so much by flaws in the models themselves than by the inaccuracy of the estimation of the input parameters to the models.

For dynamic models (like ESP-r, Energy+ ,TRNSYS, VA114, etc.), it was recommended to improve the quality of the patterns relating to presence, activities in house, thermostat settings and ventilation settings for each zone of the house. Possibilities to relate these data to household types and thermal comfort perception should be researched further. The better determination of ventilation and infiltration flow rates was also argued to be necessary, as well as the better determination of wall's thermal properties and further in-situ studies on thermal comfort.

For regulatory models like the energy labelling one, it was recognize that their aim is to assess the performance of buildings under standardized conditions in order to, on the long term, improve the thermal quality of the building stock. The predictions of these models do not need to be accurate case by case, but must be *on average* accurate enough in each label or energy index category. The actual inaccuracy of the average predictions, which furthermore differs strongly in each label category leads to large bias in expected energy savings and can be perceived as misleading by building owners and renters and by those who are willing to thermally renovate their house. Improvements of the models on the subjects of standard values for average temperature and heated area, standard values for presence home, standard values for ventilation, infiltration flow rates and efficiency of heating systems were discussed as well as the revision of the standard U-values of walls, roofs and floors.

12.7 Specific recommendations for housing associations

All dwellings in the sample belong to housing associations. Based on the results described in earlier chapters of this report, the following general recommendations are proposed:

- The calculation of the potential energy savings when renovating dwellings should be made based on historical, measured energy data. There is evidence that new systems are reasonably well predicted, but the energy consumption of older dwellings and systems seem to be systematically over-predicted. By using historical data, the estimated energy saving potential is more realistic. Housing associations could use energy data at building block level, or at postcode 4 level, in combination with data from the SHAERE database from AEDES.
- Natural ventilation systems should be supported by a mechanical system. In the MONICAIR sample, this seemed to lead to better air quality. The air quality was the best in dwellings with a balance ventilation system. Evidently, the system must be correctly designed, with large enough ventilation flow rates and with good acoustic insulation, in order to avoid well-known problems with these systems (see report MONICAIR part A).
- The (automatic) monitoring of heating installations is recommended, especially when heat pumps and floor heating are used. These systems are often poorly controlled, especially in collective systems. Thermostats may also be defect.
- When thinking of using heat pumps and floor heating, one should be aware that the distribution system should be divided into zones, in order to give occupants the possibility to control the temperature separately in each room. This may be a more expensive investment, but will lead to more comfort and open possibilities for a lower energy use.
- The occupants should be regularly informed about possible energy savings in their dwellings. Smart feedback technology could be used. It may be that the temperature in an apartment is very high because the occupants do not know their thermostat is broken, and got used to the high temperature, thinking it is lower.

12.8 Reflections on the present study and recommendations for further studies

The second part of the Monicair research had the aim to explore in how far the better determination of a number of parameters, which up to now were measured only seldom, could support the development of better prediction models of the heating energy consumption in dwellings. In the past years several studies have demonstrated that these models show large deviations from reality, making the prediction of possible energy savings biased. These deviations are believed to be the result of poor estimation of the U–values of walls, poor estimation of the infiltration and ventilation flow rates and poor estimation of the heated surface area leading to a poor estimation of the average indoor temperature. Additionally, there is very little knowledge on how occupant's perception of comfort influences its ventilation and heating behaviour and finally the total energy use for heating.

This report presented the results of a field study in which monitoring data was collected in order to further analyse these parameters. The aim of the research was not to deliver representative results (the studied sample, accounting for 32 houses is too small for this) but to explore in how far a number of parameters, which up to now were measured only seldom, could explain the large deviations observed between actual and predicted energy consumption.

Because of material, budget and time limitations, instead of the initial plan of measuring 60 houses during 3 months, 32 houses were measured during 6 months. During these 6 months a few hundreds of thousands of data points were collected about indoor temperatures, humidity, CO_2 concentrations, gas and electricity consumption, real time comfort perception and U values of walls. As expected, because of the small size of the sample and the experimental character of the measurements, it has not been possible to deliver representative results. We however demonstrated why this type of measurements will be needed in future and we were also able to make a first step into the development of analysis methods using these large scale monitoring data. This is important because large sets of data coming from home automation systems are expected to become common practice in future. However, at the moment of the Monicair study, the meaning of these data for energy simulation software and for a better understanding of the complete home energy system (including building envelope, HVAC, use of the house, thermal behaviour and comfort preferences) had not been studied yet. Although not all collected data could be analysed within the framework of the project, and although our findings were not always conclusive (for instance we could not find a clear relationship between gas consumption and temperature profiles), this study shows the potential of such measurement campaigns. The developments of a method for the rapid in situ measurement of U values and for the measurement of the real time comfort perception of occupants are worth mentioning results as well. It would be of great interest to go on with such measurement campaigns in order to collect the data and to develop further the methods that are needed for a better understanding and prediction of the home energy system.

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Appendix A: Occupant survey

GEGEVENS HUISHOUDEN

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

Ja
Nee
Weet ik niet

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

_____ kamers

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

_____ personen

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

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

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

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

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

Heel zuinig

Zuinig

Gemiddeld zuinig

Niet zo zuinig

Helemaal niet zuinig

Weet ik niet

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

Ja, namelijk energielabel _____

Nee

GEGEVENS VERWARMEN EN VENTILEREN

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

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

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

Handmatige thermostaat

Automatische, programmeerbare thermostaat

Geen thermostaat

Weet ik niet

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

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

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

Ja, vaak
Ja, soms
Nee

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

Afbeelding 1 (een ventiel)

Afbeelding 2 (Installatie voor balansventilatie)

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

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

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

Ja
Nee → ga na vraag 15
Weet ik niet → ga naar vraag 15

14 Op welke stand heeft u het ventilatiesysteem staan? ____

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

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

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

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

17 Wilt u hieronder aangeven welke van de volgende apparaten u gebruikt? Wij willen graag het aantal weten.

Als in uw huishouden 3 telvisies gebruikt worden, dan mag u 3 invullen bij televisie.

	Aantal		Aantal
Televisie	_____	Vaatwasser	_____
Computer, laptop, tablet	_____	Wasmachine	_____
Draadloos internet	_____	Droger	_____
Draadloze huistelefoon	_____	Voordeurverlichting of tuinverlichting	_____
Koffiezetapparaat/waterkoker	_____	Zonnebank, jacuzzi of huissauna	_____
Elektrische grill of oven	_____	Waterbed	_____

Cooker in de keuken	_____	Aquarium of terrarium	_____
Magnetron	_____	Airco unit of ventilator (plafond/staand)	_____
Inductie of elektrische kookplaat	_____	Terras- of balkonverwarmer	_____
Gasfornuis/oven	_____	Extra elektrische radiatoren	_____
Vriezer	_____	Afzuigkap	_____
Koelkast	_____	Close-in boiler (extra boilertje in de keuken)	_____
Koel-vriescombinatie (koelkast en vriezer in 1)	_____		_____

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

18 **Hoe vaak wordt er in uw huishouden gebruik gemaakt van een douche op een gemiddelde DAG?**

Als er 4 mensen 1 keer douchen op een dag, dan vult u hier 4 in. Douchen er 2 mensen 3 keer op een dag, dan vult u hier 6 in. Is er minder dan 1 douche per dag vult u 0 in.

_____ aantal douches per dag

19 **Hoeveel minuten doucht men gemiddeld per keer?**

_____ minuten

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

_____ aantal baden per week

Er is geen bad

VRAGEN OVER UW ENERGIEGEBRUIK

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

Zuinig/energiebewust

Gemiddeld

Niet zuinig/energiebewust

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

Ja

Nee

Weet ik niet

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

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

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

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

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

Te koud
Goede temperatuur
Te warm
Weet ik niet

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

Te vochtig
Goede vochtigheid
Te droog
Weet ik niet

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

Ja
Nee

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

Te koud
Goede temperatuur
Te warm
Weet ik niet

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

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

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

_____ euro per maand
Weet ik niet, of geen antwoord

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

Heel gemakkelijk
Redelijk gemakkelijk

Een beetje moeilijk
Heel moeilijk

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

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

Anders, namelijk ____

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

__________ euro per maand

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

Appendix B: Daily average CO_2 profiles per ventilation system per room (6 to 18 march 2015)

B.1 Balanced ventilation systems

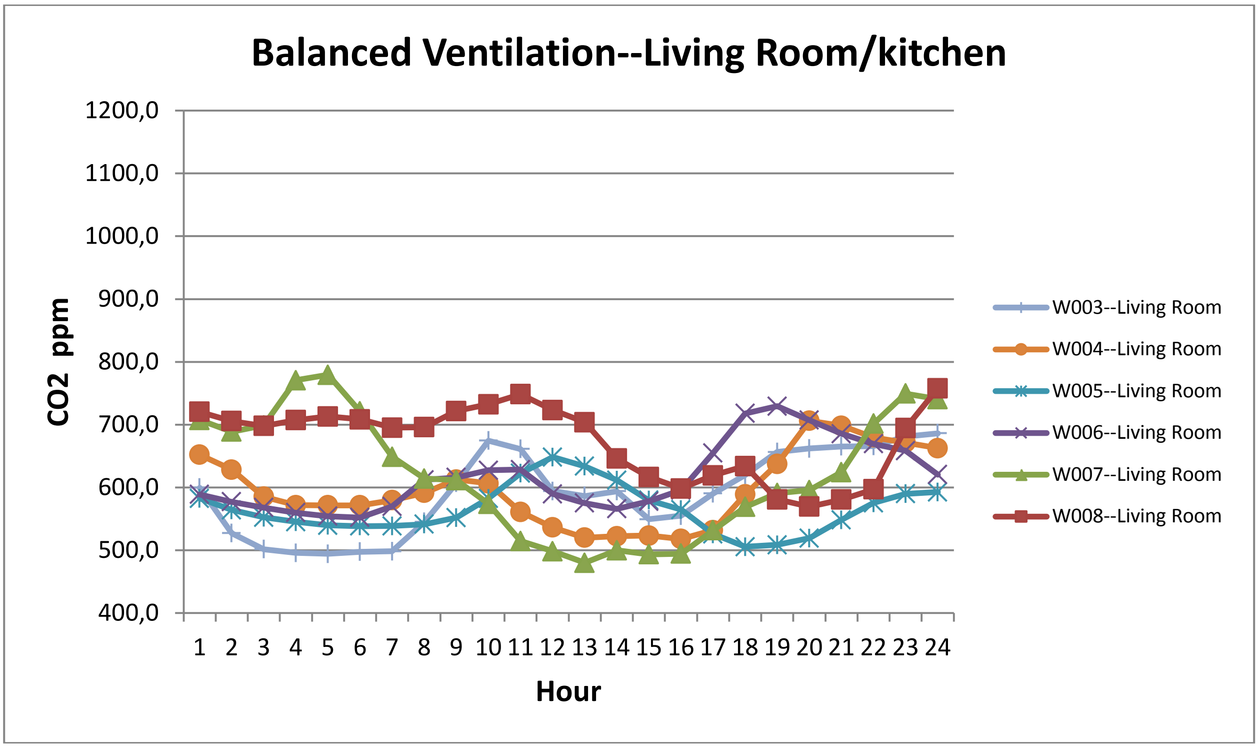


Figure B.1: 24-hour CO_2 profiles of the living room for the dwellings with balanced ventilation.

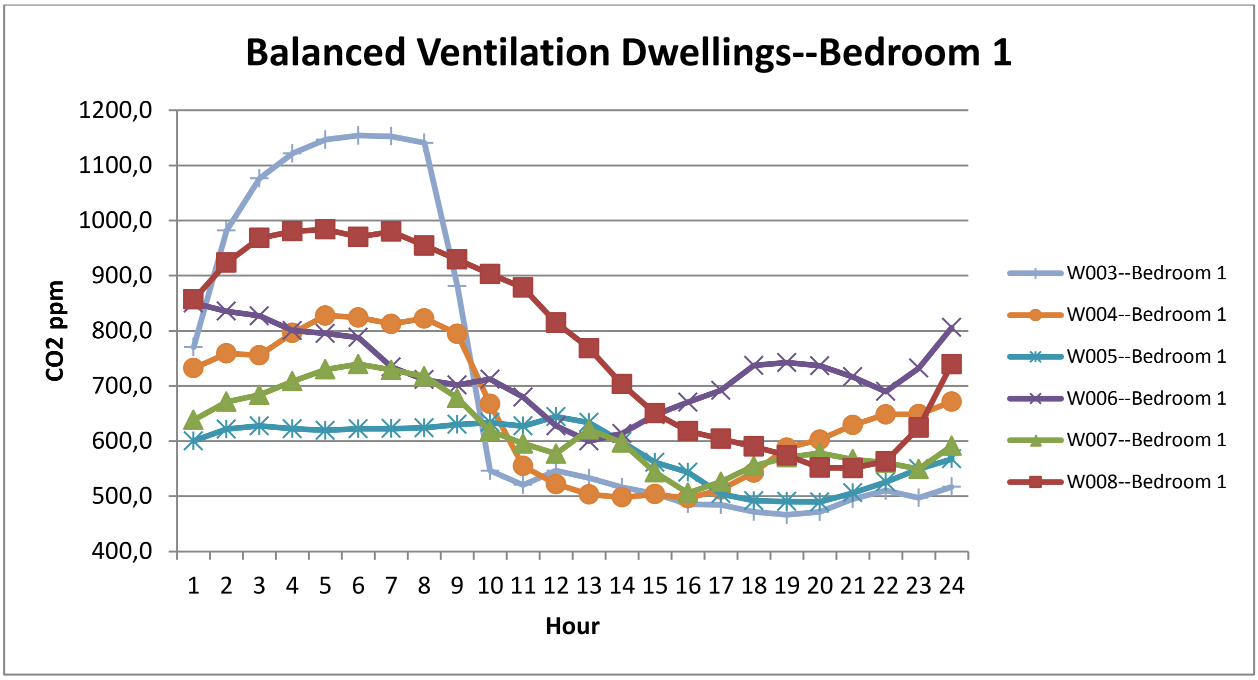


Figure B.2: 24-hour CO_2 profiles of bedroom 1 for the dwellings with balanced ventilation.

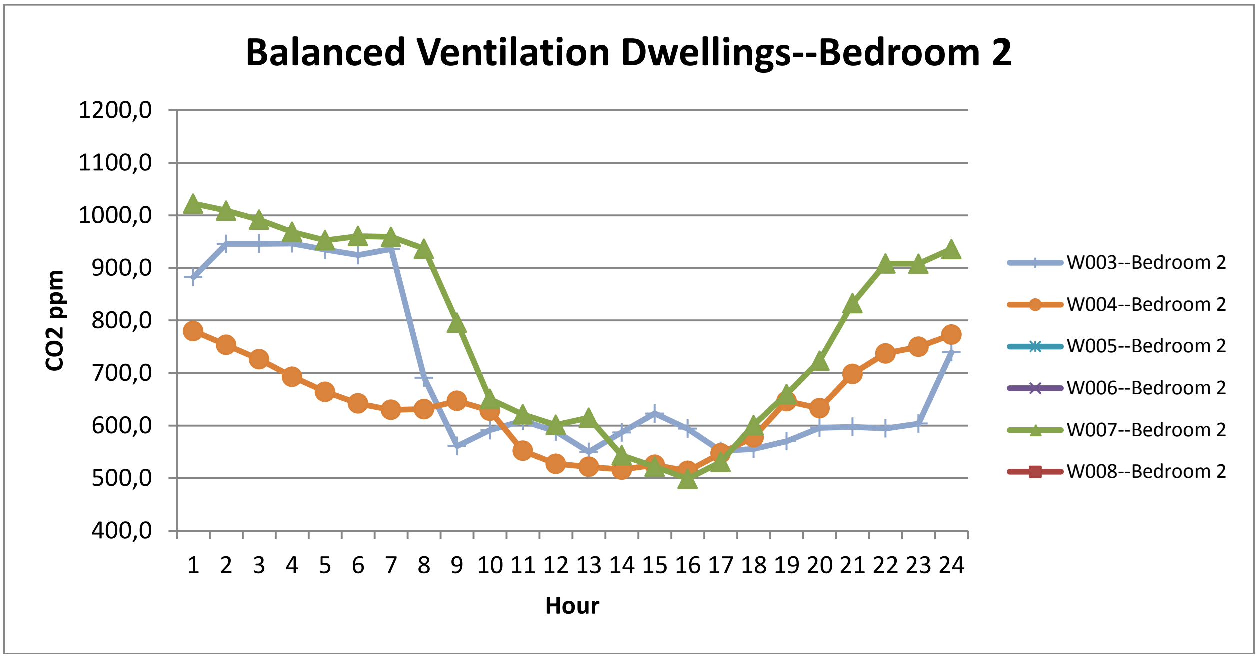


Figure B.3: 24-hour CO_2 profiles of bedroom 2 for the dwellings with balanced ventilation.

B.2 Dwellings with natural supply and mechanical exhaust

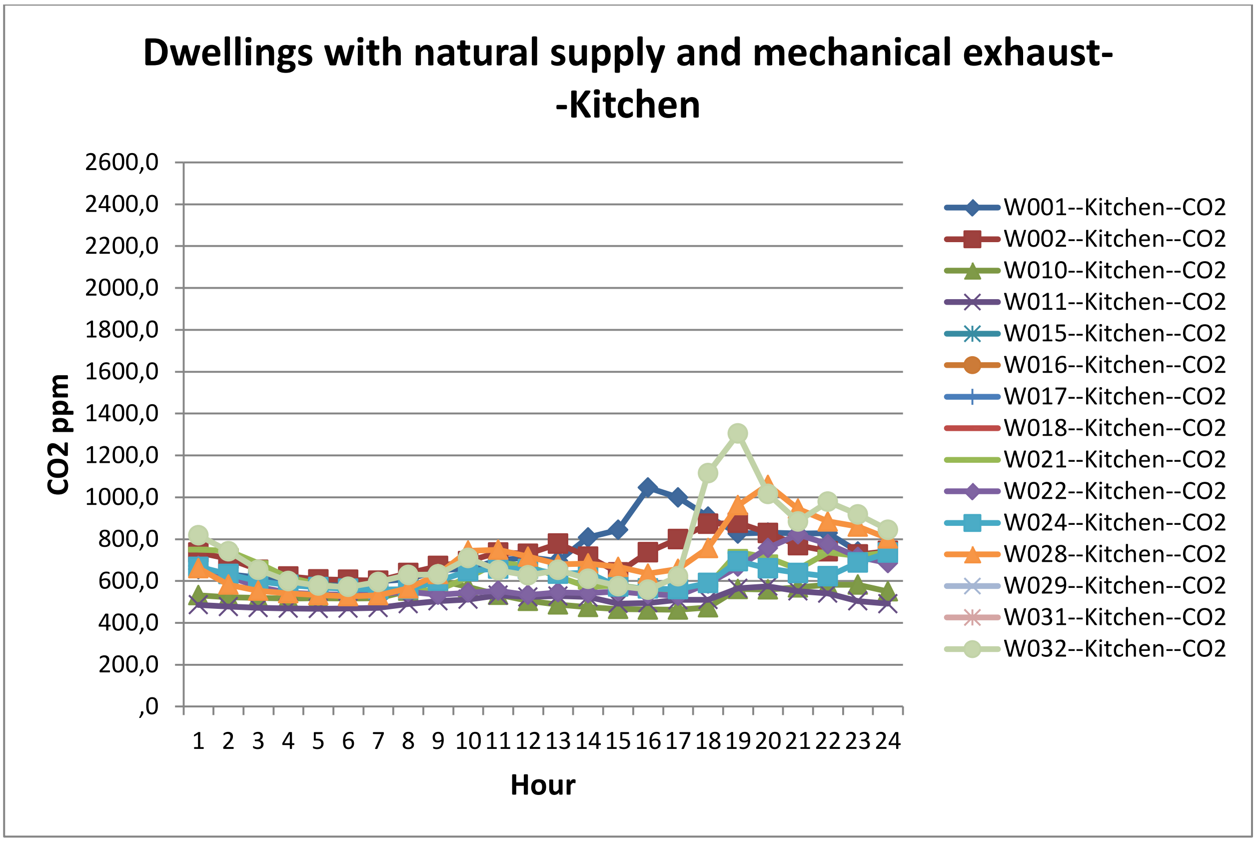


Figure B.4: 24-hour CO_2 profiles of kitchens for the dwellings with natural supply and mechanical exhaust.

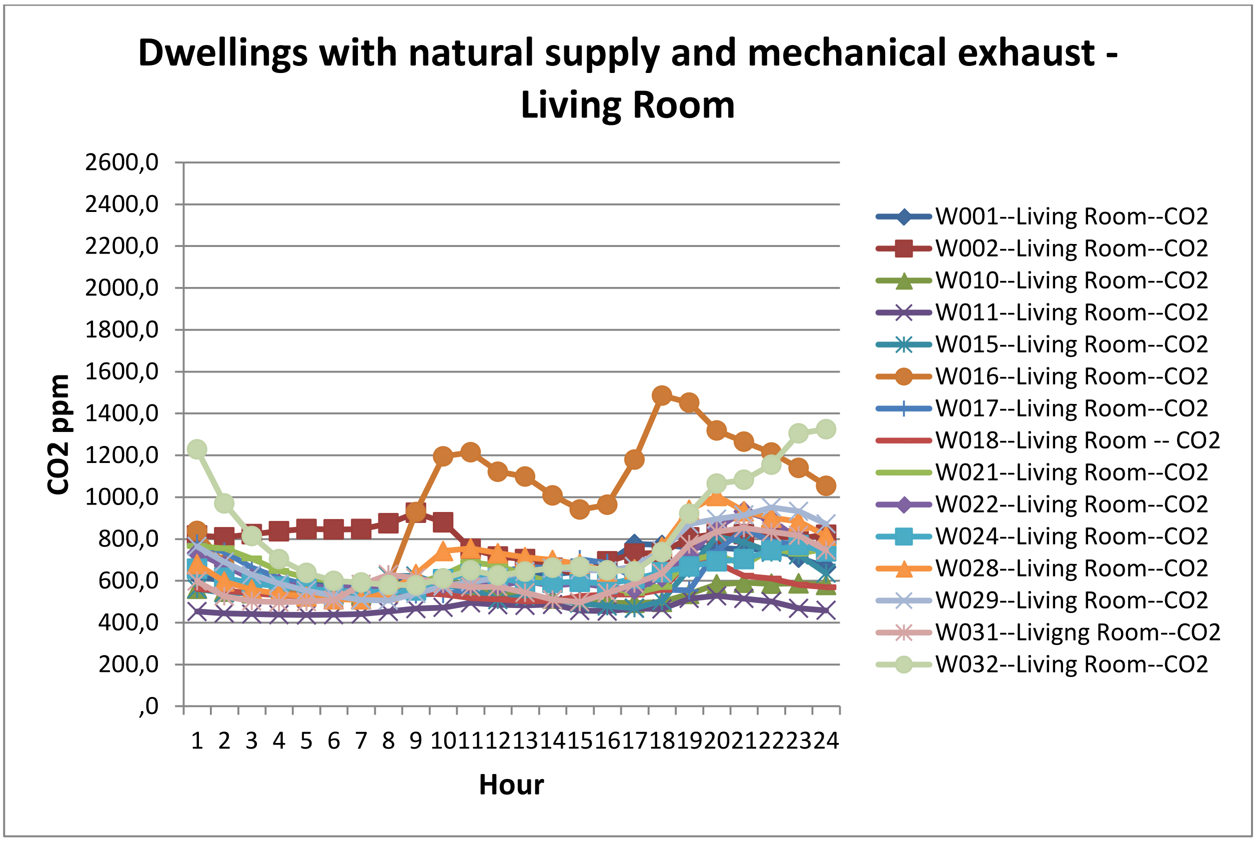


Figure B.5: 24-hour CO_2 profiles of living rooms for the dwellings with natural supply and mechanical exhaust.

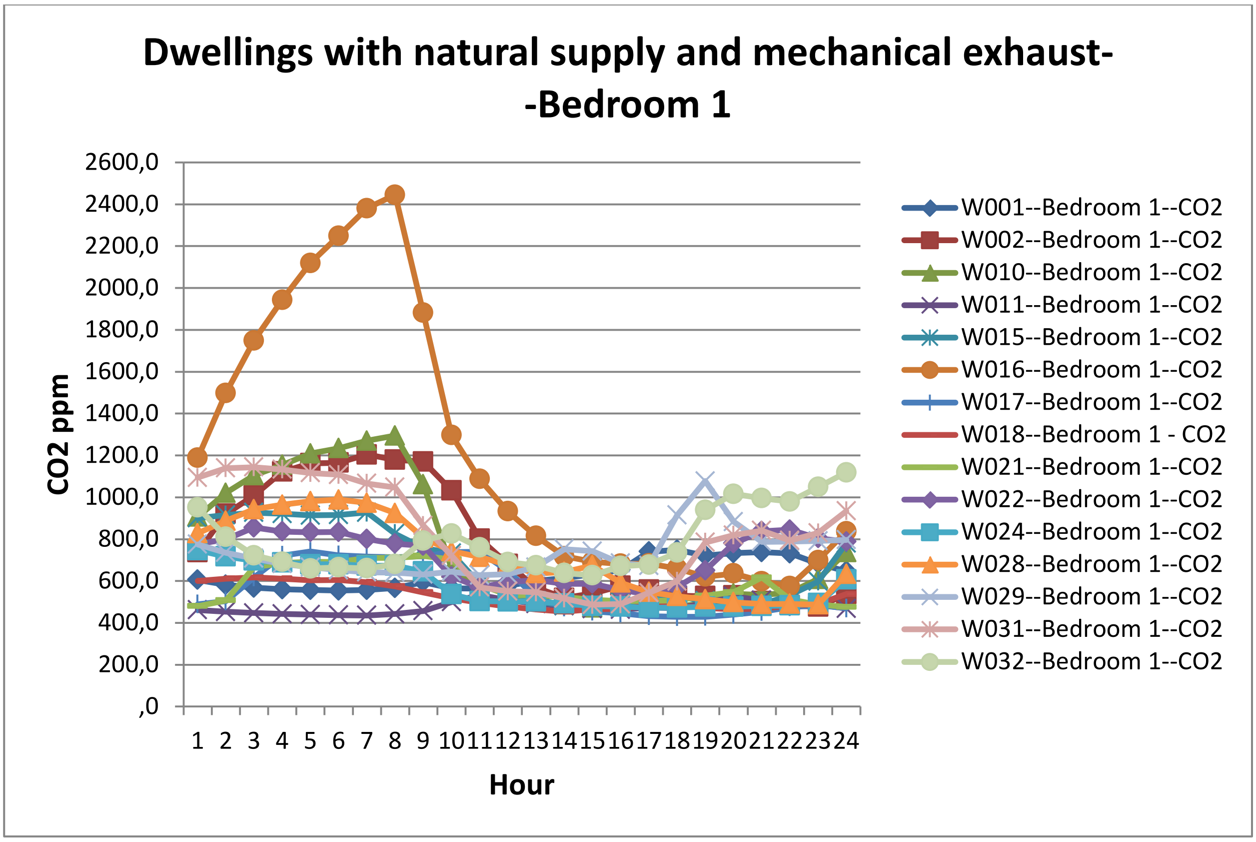


Figure B.6: 24-hour CO_2 profiles of bedroom 1 for the dwellings with natural supply and mechanical exhaust.

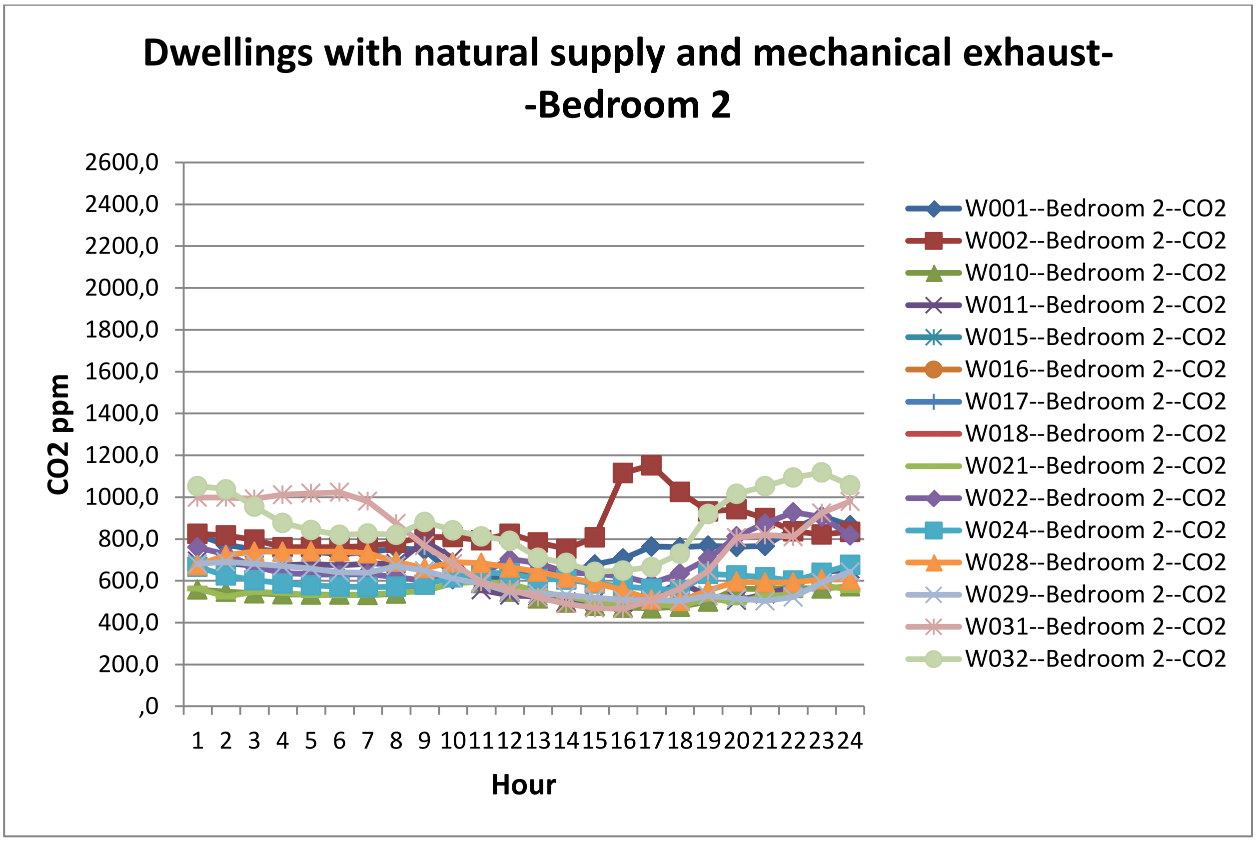


Figure B.7: 24-hour CO_2 profiles of bedroom 2 for the dwellings with natural supply and mechanical exhaust.

B.3 Naturally ventilated dwellings

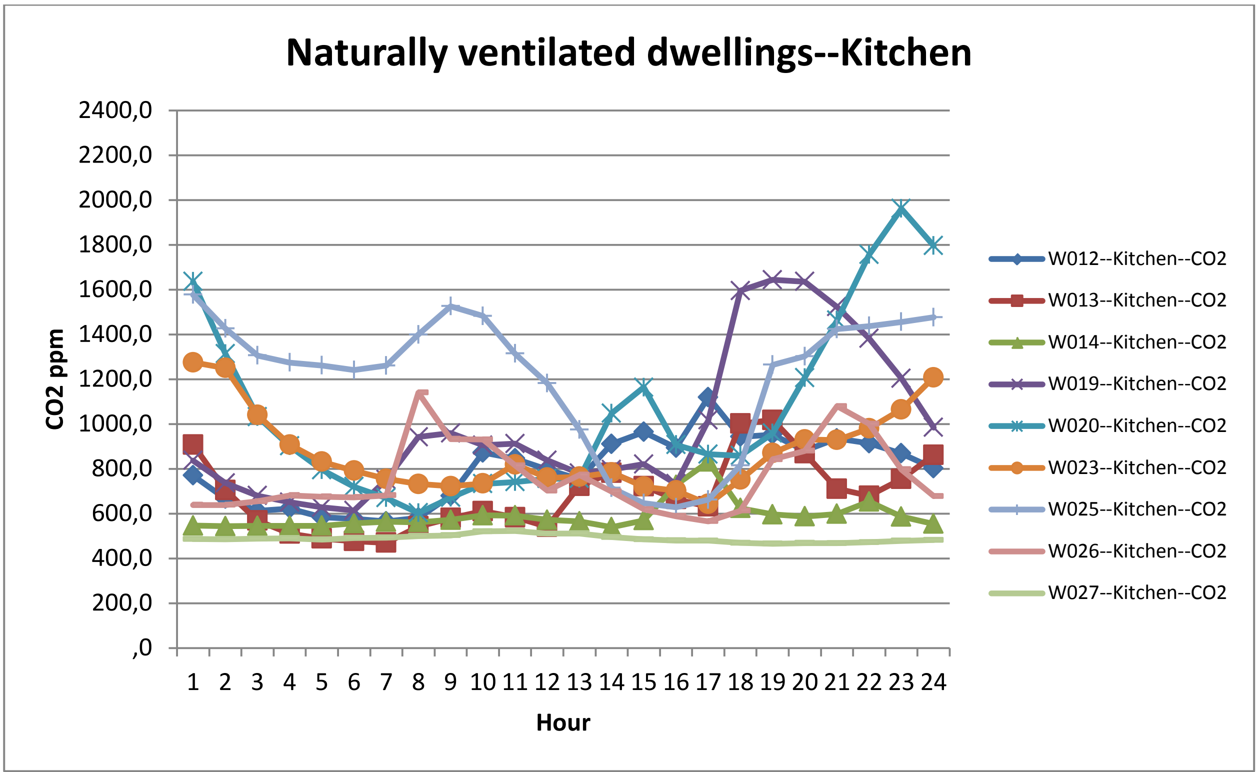


Figure B.8: 24-hour CO_2 profiles of kitchen for the naturally ventilated dwellings.

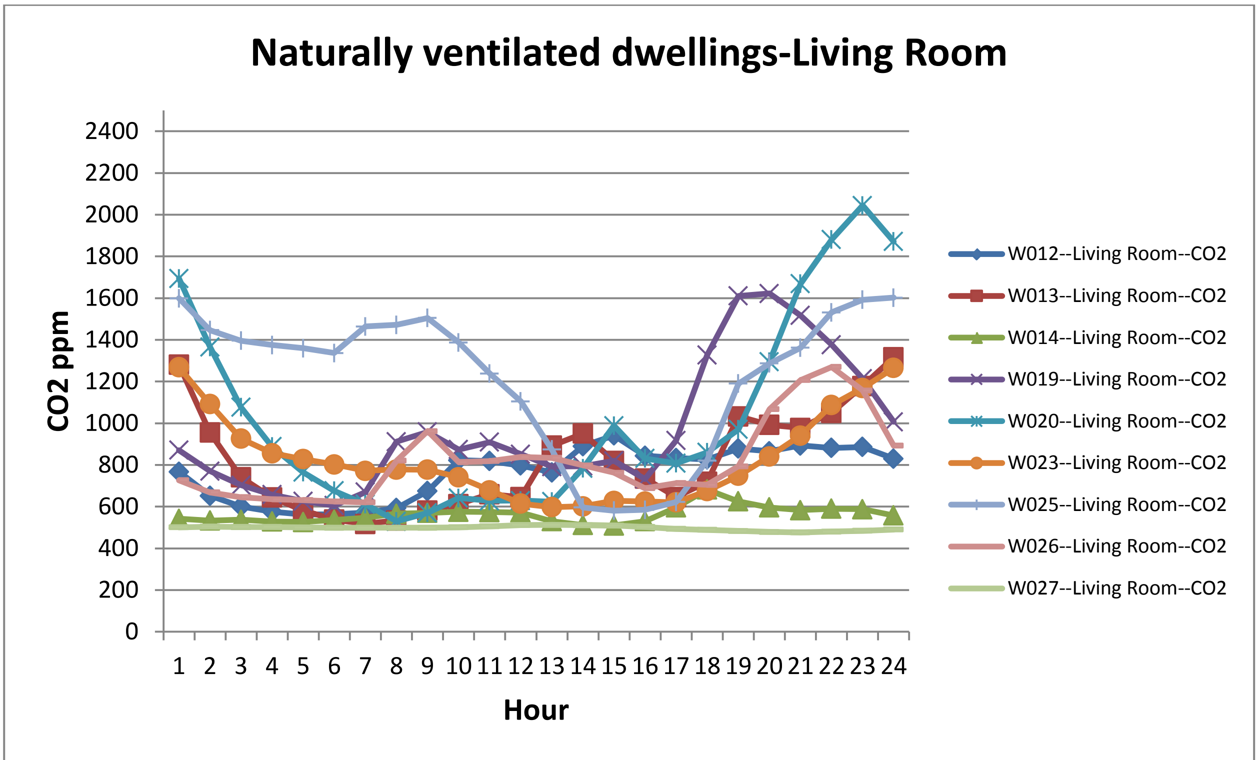


Figure B.9: 24-hour CO_2 profiles of living room for the naturally ventilated dwellings.

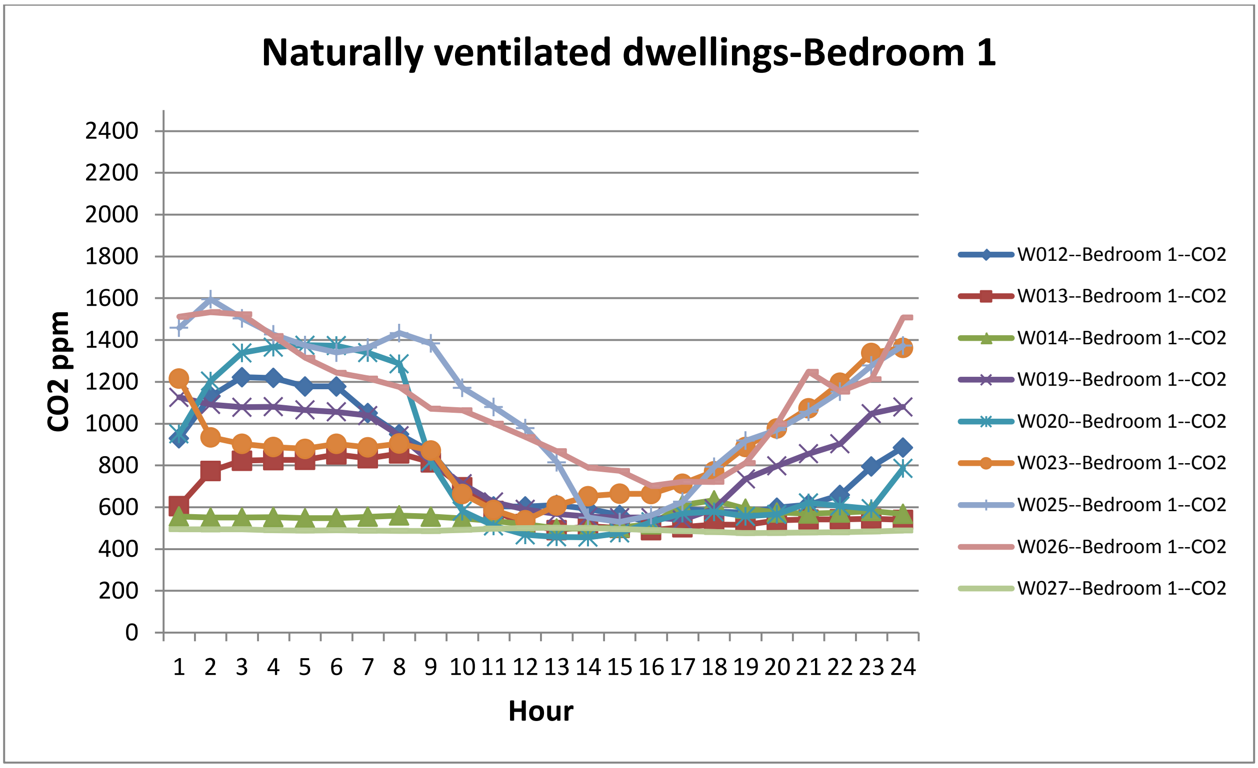


Figure B.10: 24-hour CO_2 profiles of bedroom 1 for the naturally ventilated dwellings.

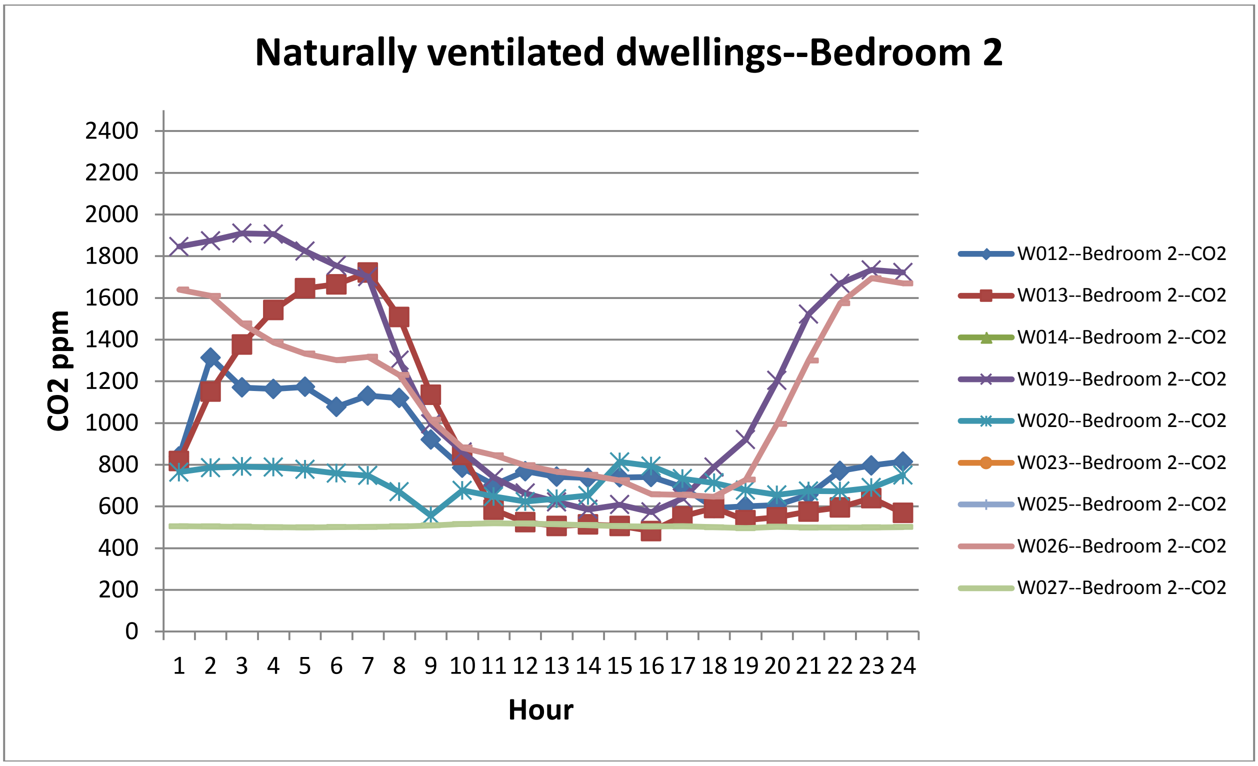


Figure B.11: 24-hour CO_2 profiles of bedroom 2 for the naturally ventilated dwellings.

Appendix C: Daily average CO_2 profiles per ventilation system per room (6 months heating season)

C.1 Dwellings with Balanced ventilation (system D): W007

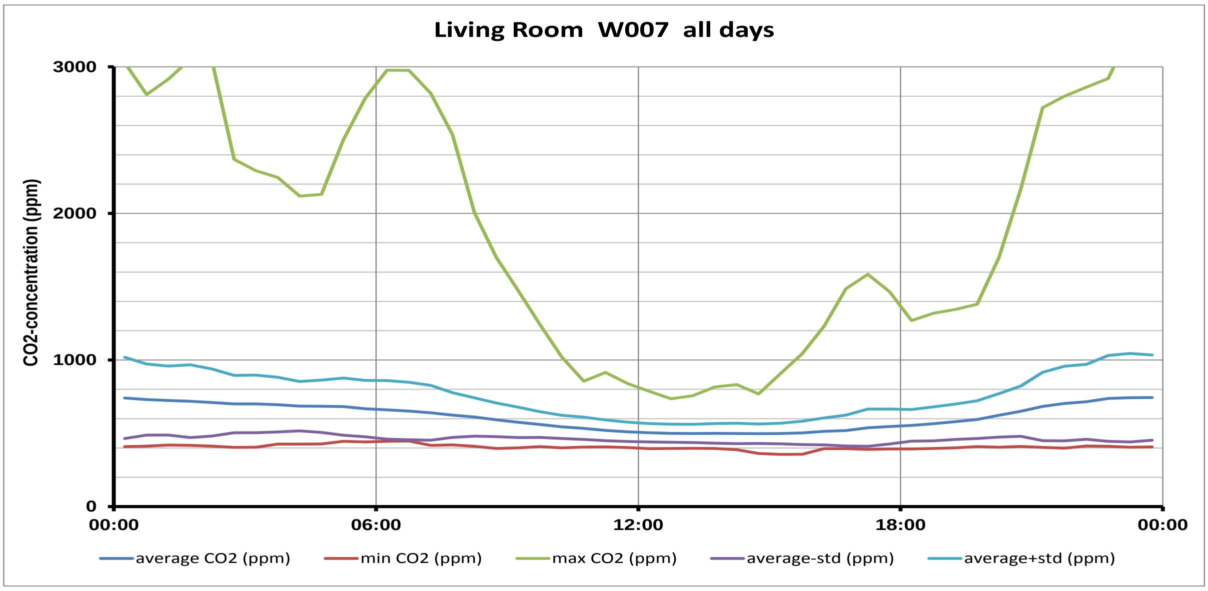


Figure C.1: CO_2-profile living room dwelling W007 over the monitored period

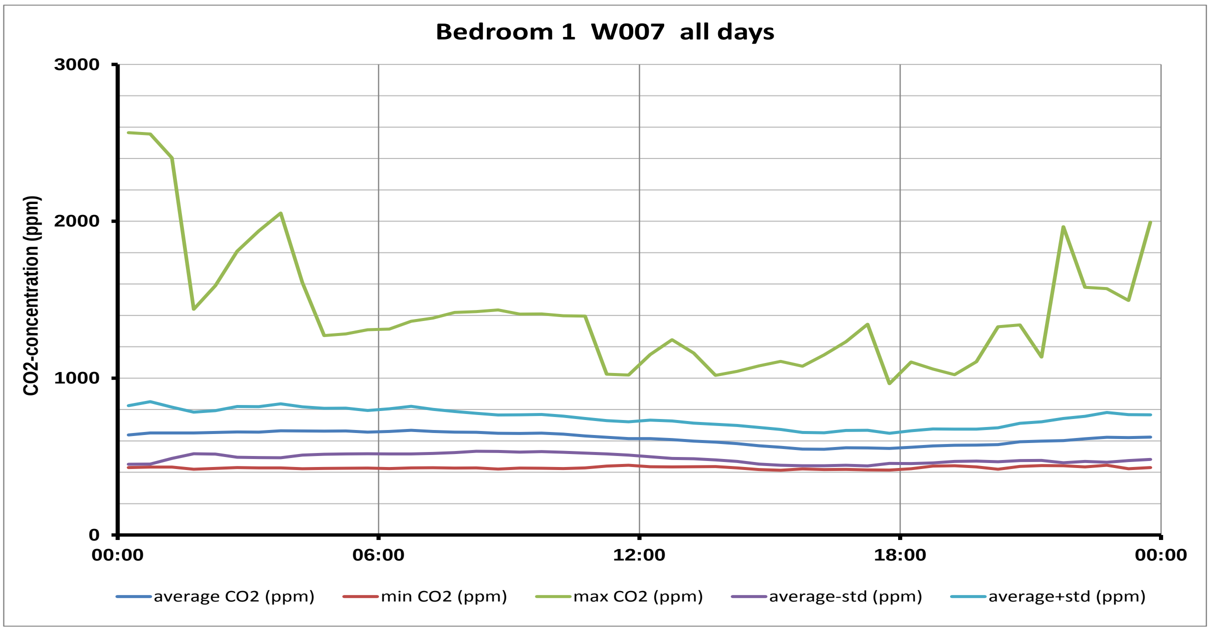


Figure C.2: CO_2-profile bedroom 1 dwelling W007 over the monitored period

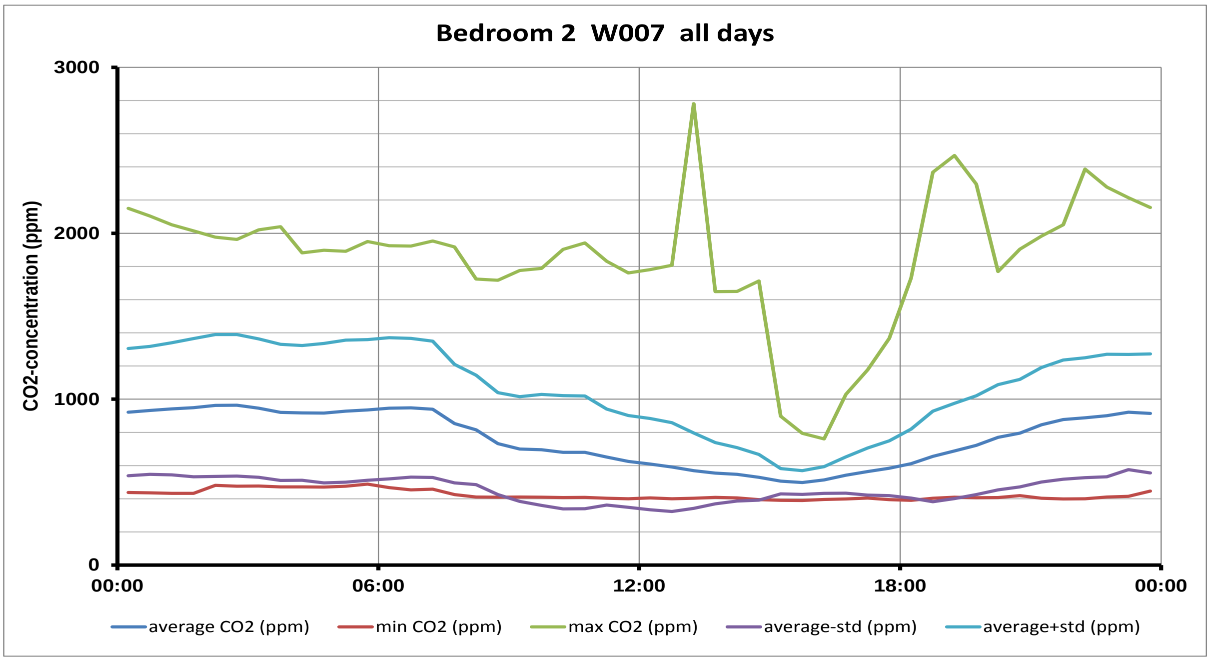


Figure C.3: CO_2-profile bedroom 2 dwelling W007 over the monitored period

C.2 Dwellings with natural supply and mechanical exhaust (system C)

C.2.1 Dwelling W002

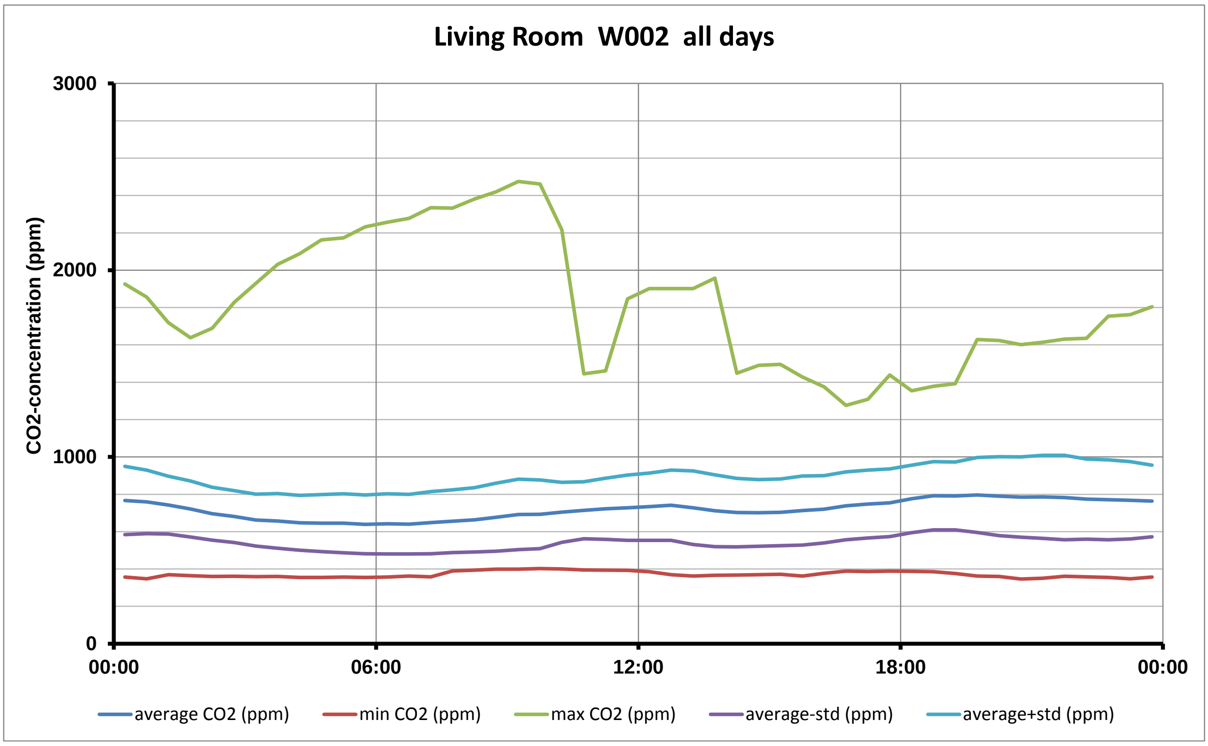


Figure C.4: CO_2-profile living room dwelling W002 over the monitored period

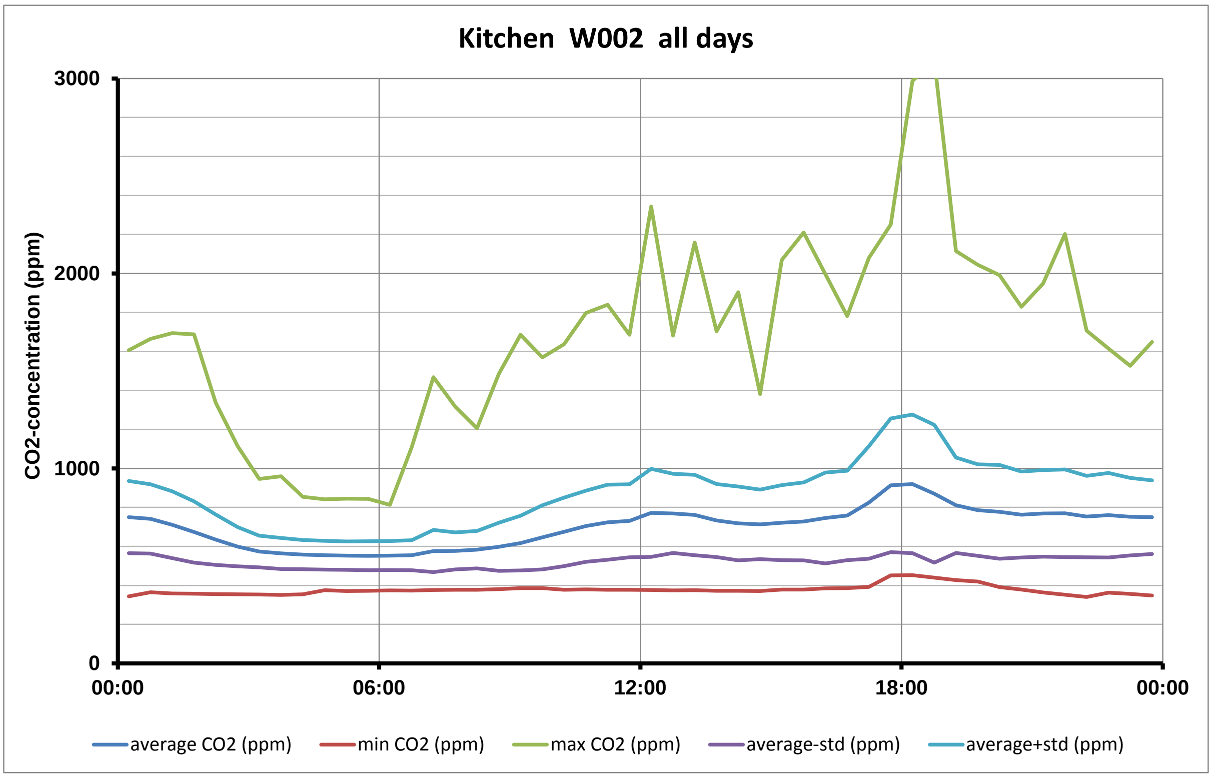


Figure C.5: CO_2-profile kitchen dwelling W002 over the monitored period

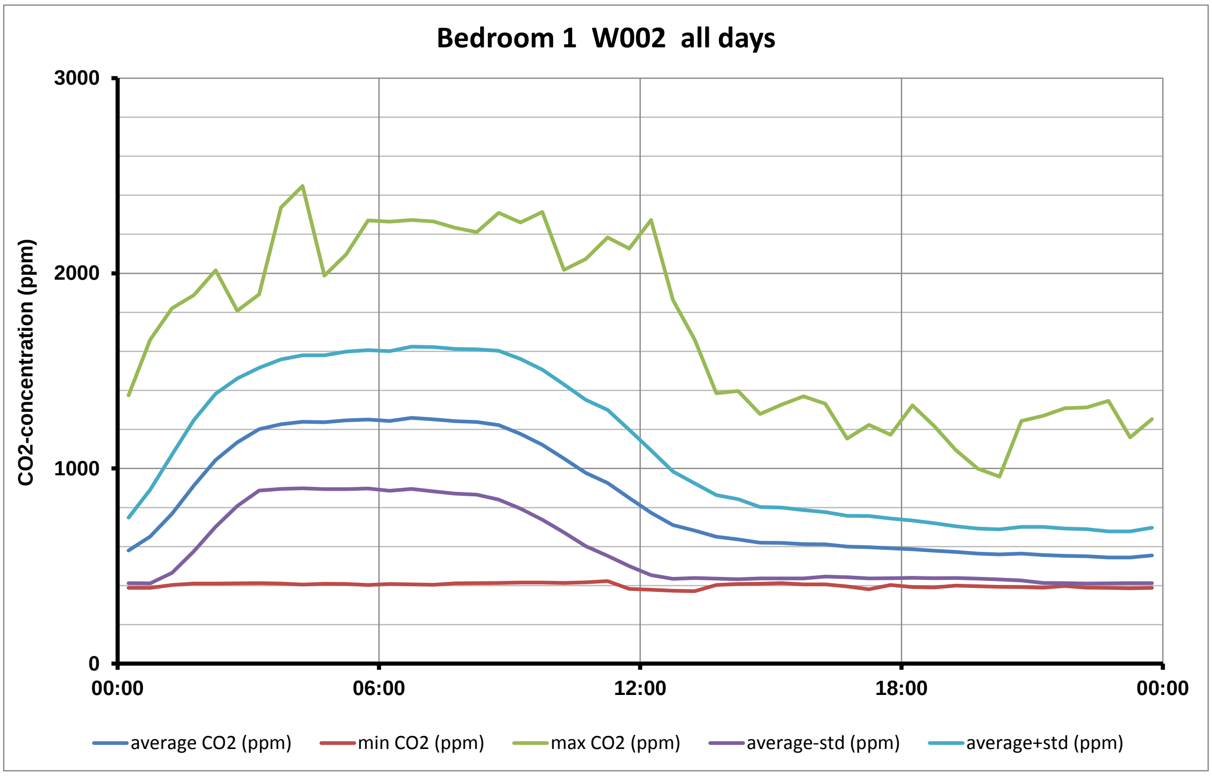


Figure C.6: CO_2-profile bedroom 1 dwelling W002 over the monitored period

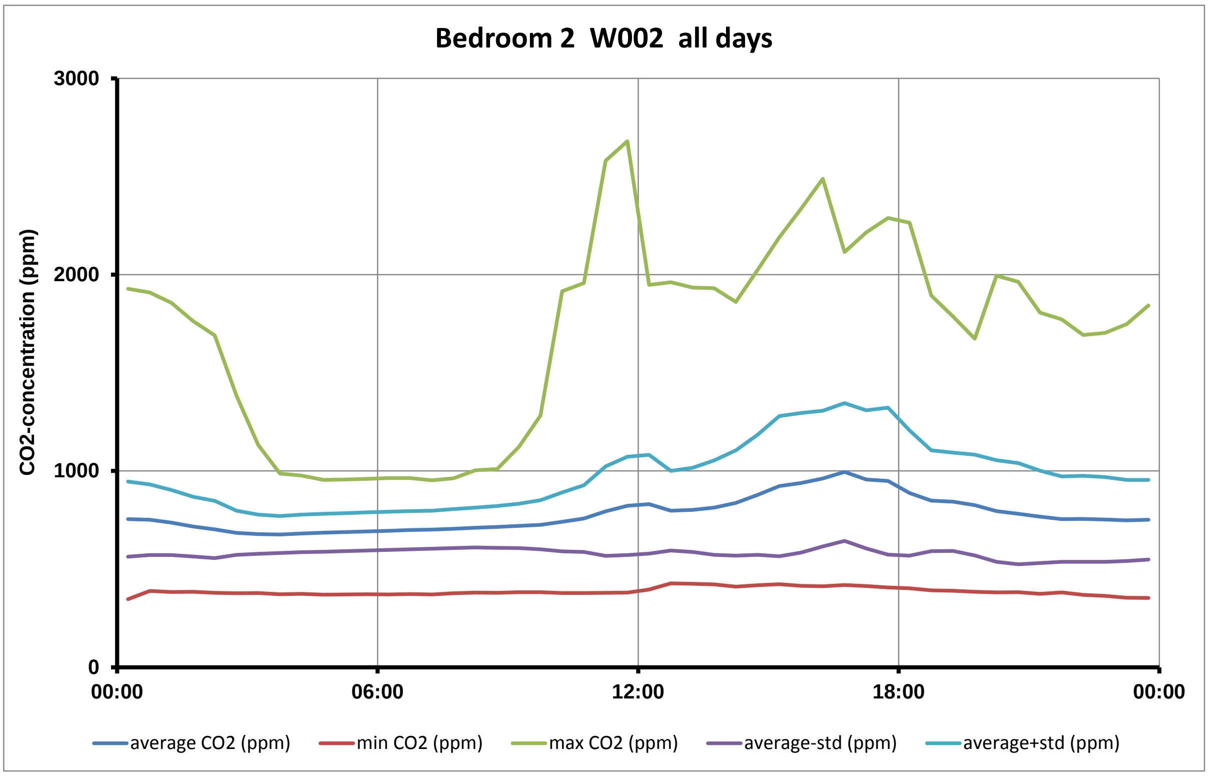


Figure C.7: CO_2-profile bedroom 2 dwelling W002 over the monitored period

C.2.2 Dwelling: W011

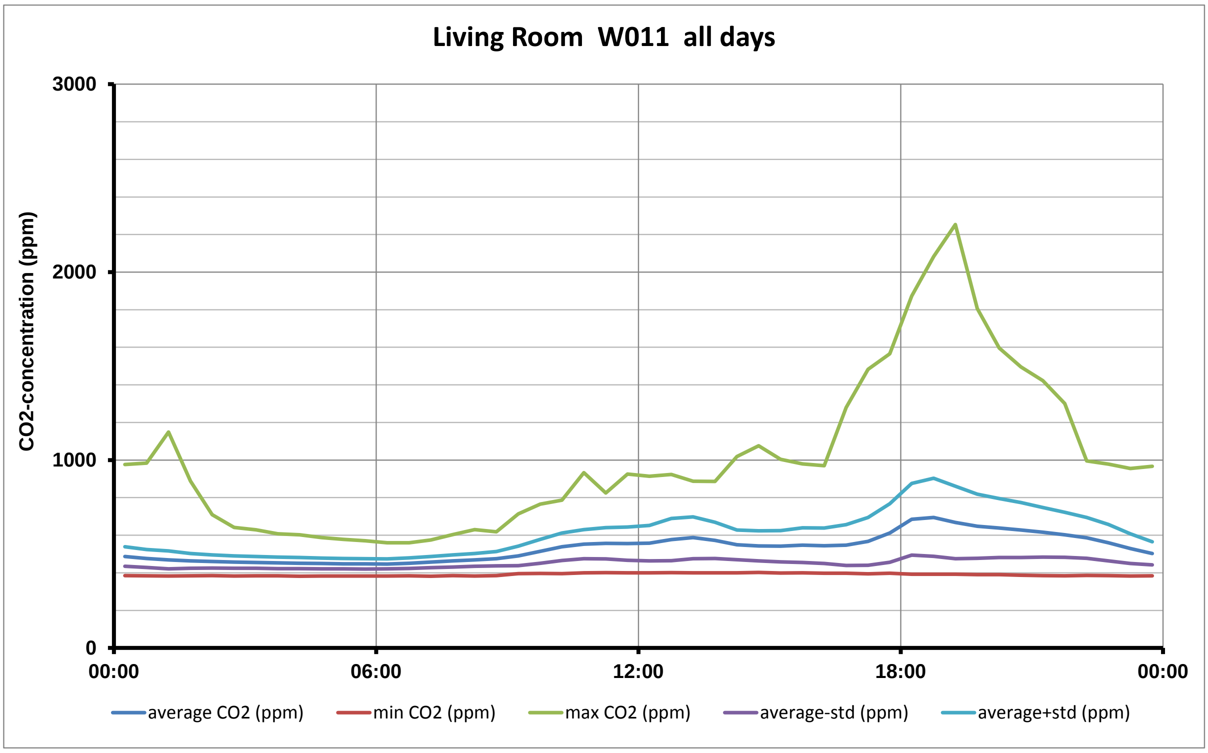


Figure C.8: CO_2-profile living room dwelling W011 over the monitored period

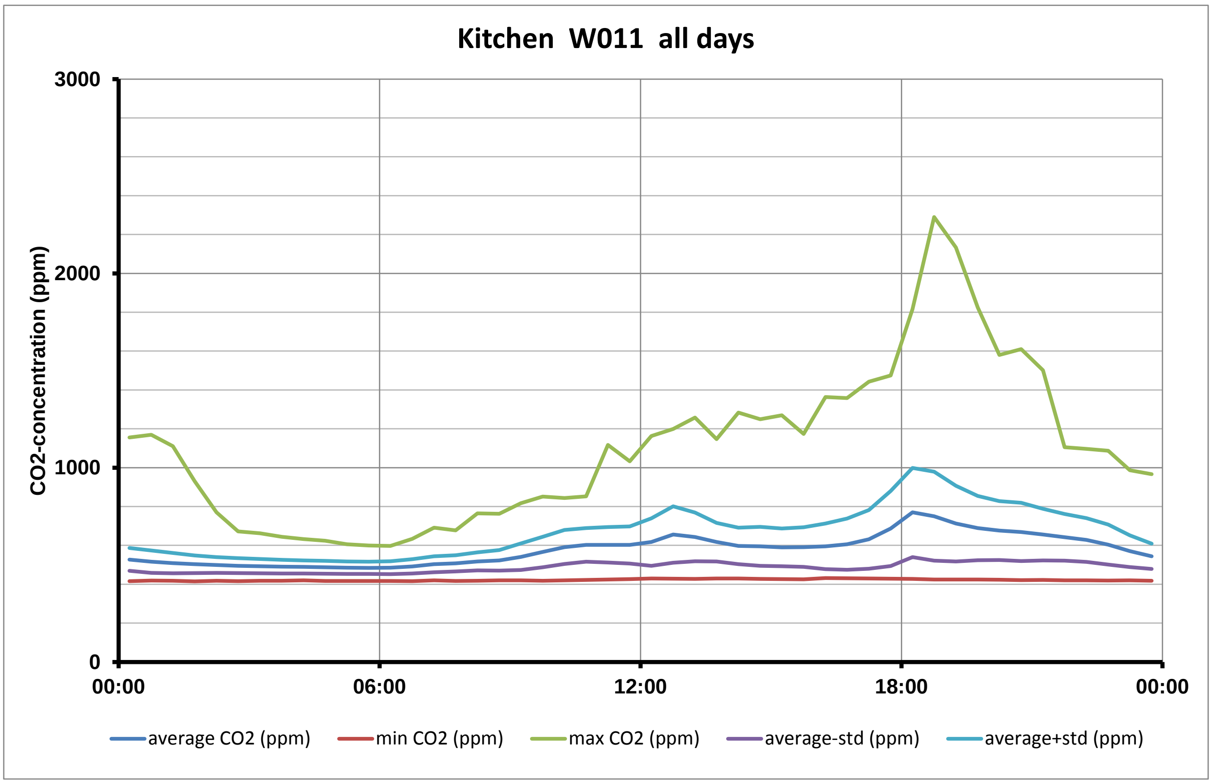


Figure C.9: CO_2-profile kitchen dwelling W011 over the monitored period

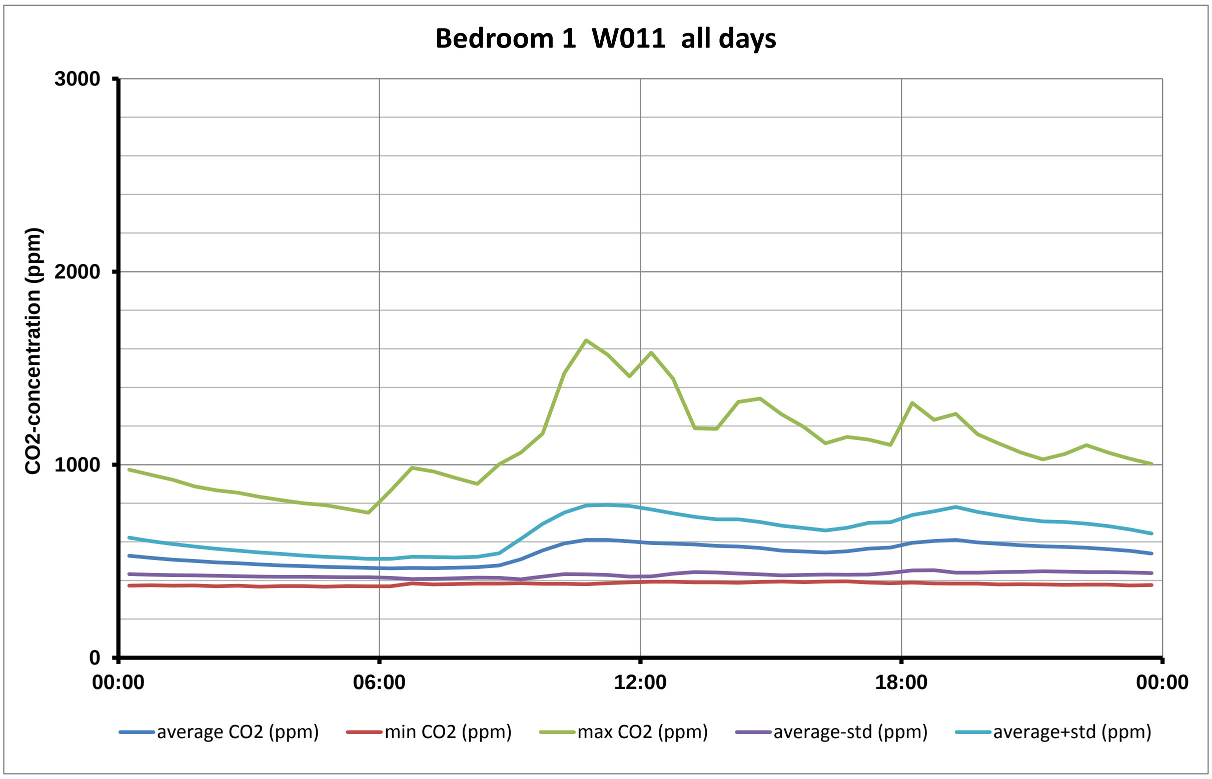


Figure C.10: CO_2-profile bedroom 1 dwelling W011 over the monitored period

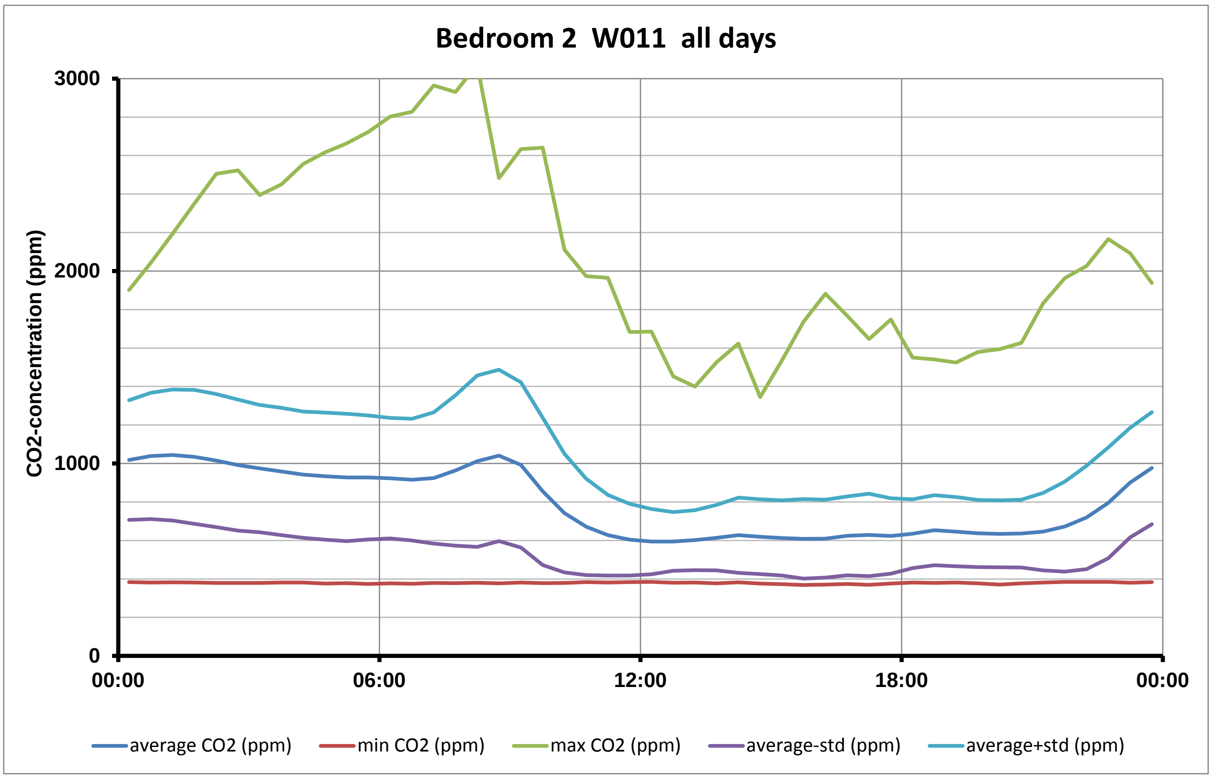


Figure C.11: CO_2-profile bedroom 2 dwelling W011 over the monitored period

C.2.3 Dwelling W016

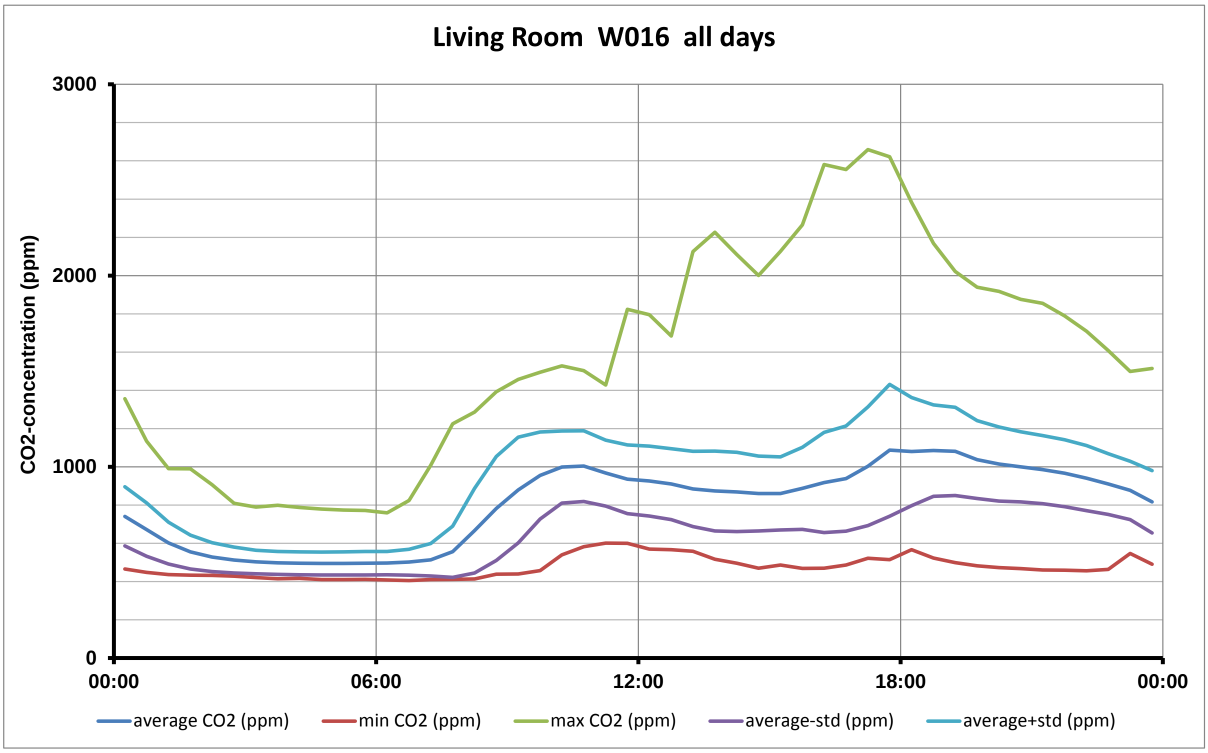


Figure C.12: CO_2-profile living room dwelling W016 over the monitored period

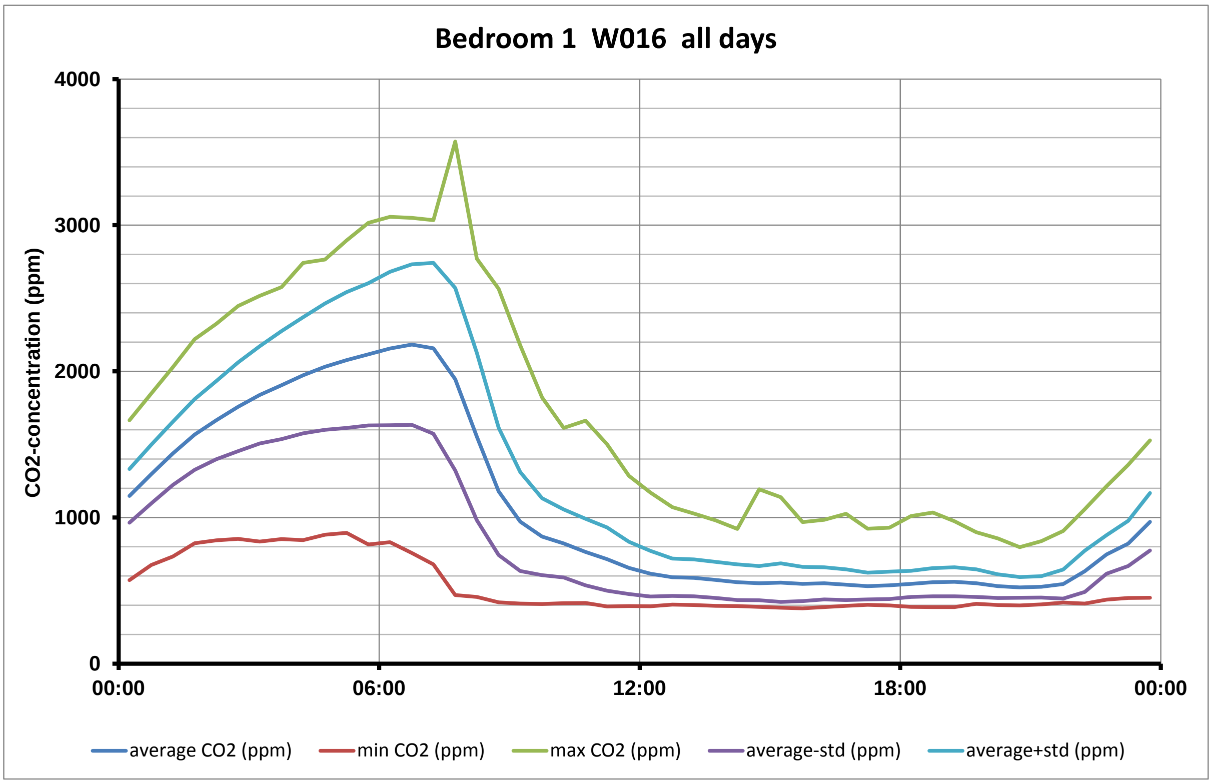


Figure C.13: CO_2-profile bedroom 1 dwelling W016 over the monitored period

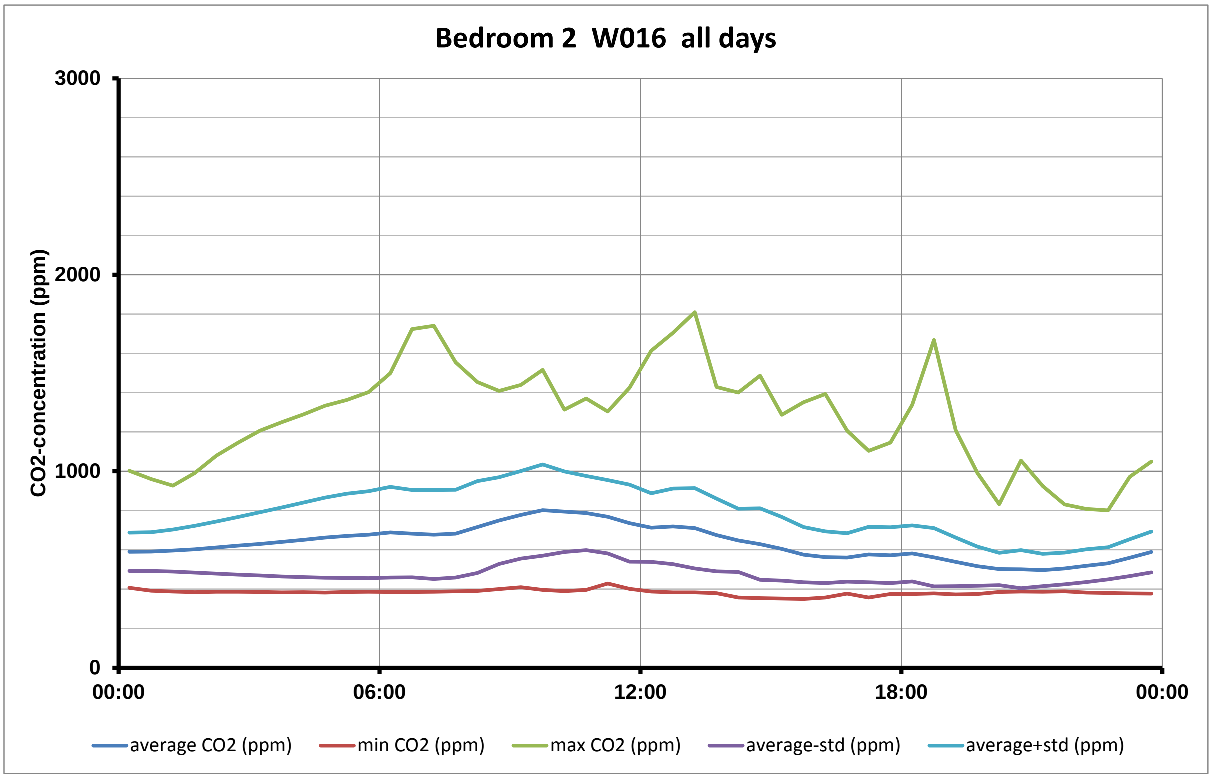


Figure C.14: CO_2-profile bedroom 2 dwelling W016 over the monitored period

C.2.4 Dwelling W018

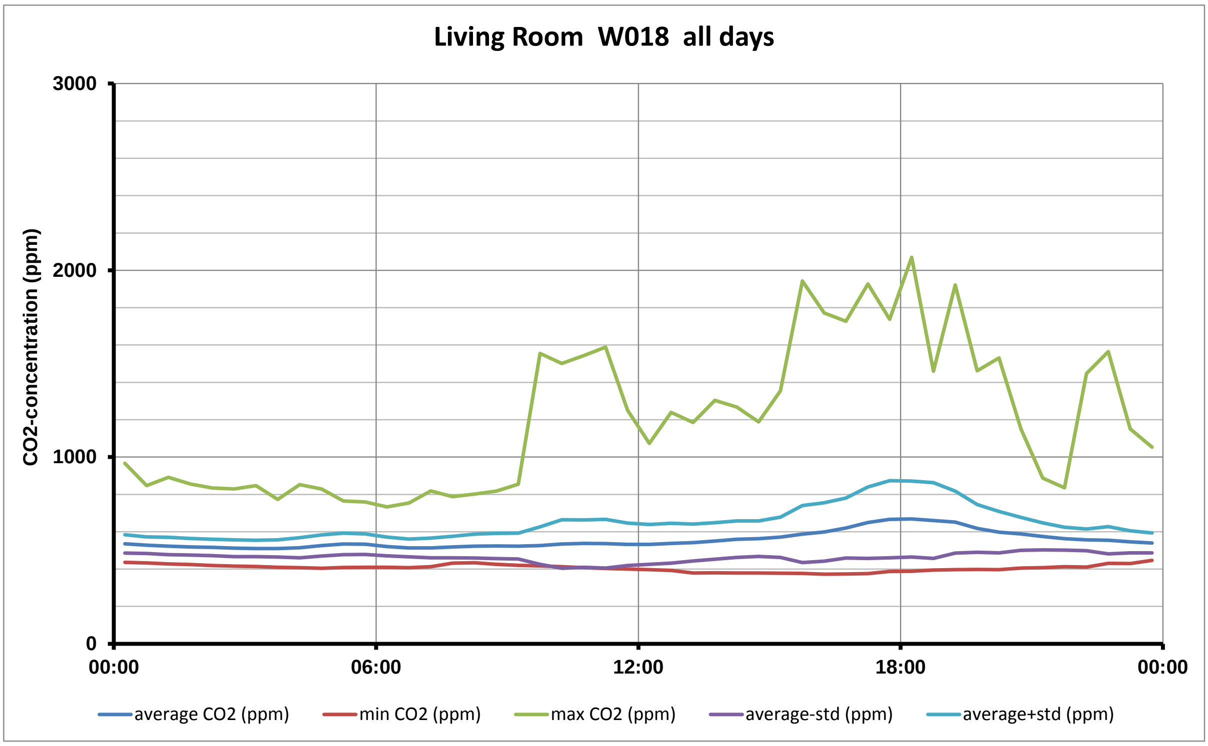


Figure C.15: CO_2-profile living room dwelling W018 over the monitored period

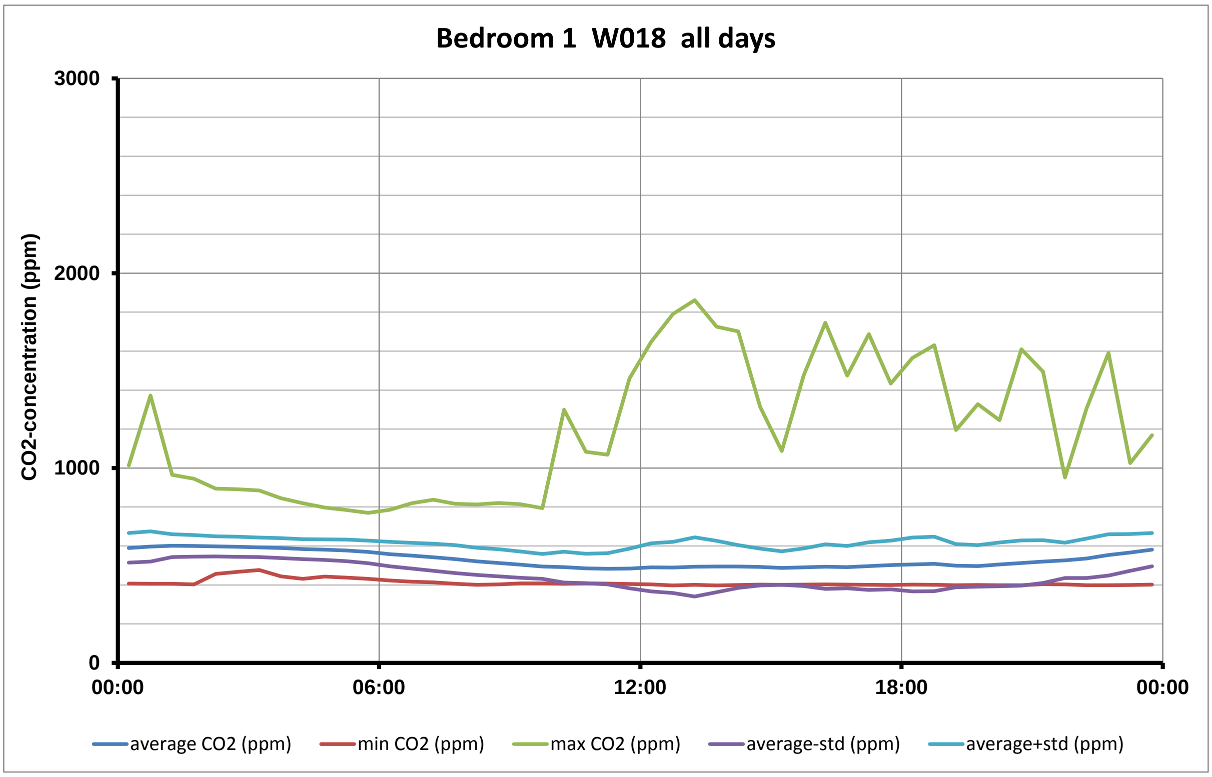


Figure C.16: CO_2-profile bedroom 1 dwelling W018 over the monitored period

C.3 Naturally ventilated dwellings (system A)

C.3.1 Dwelling W014

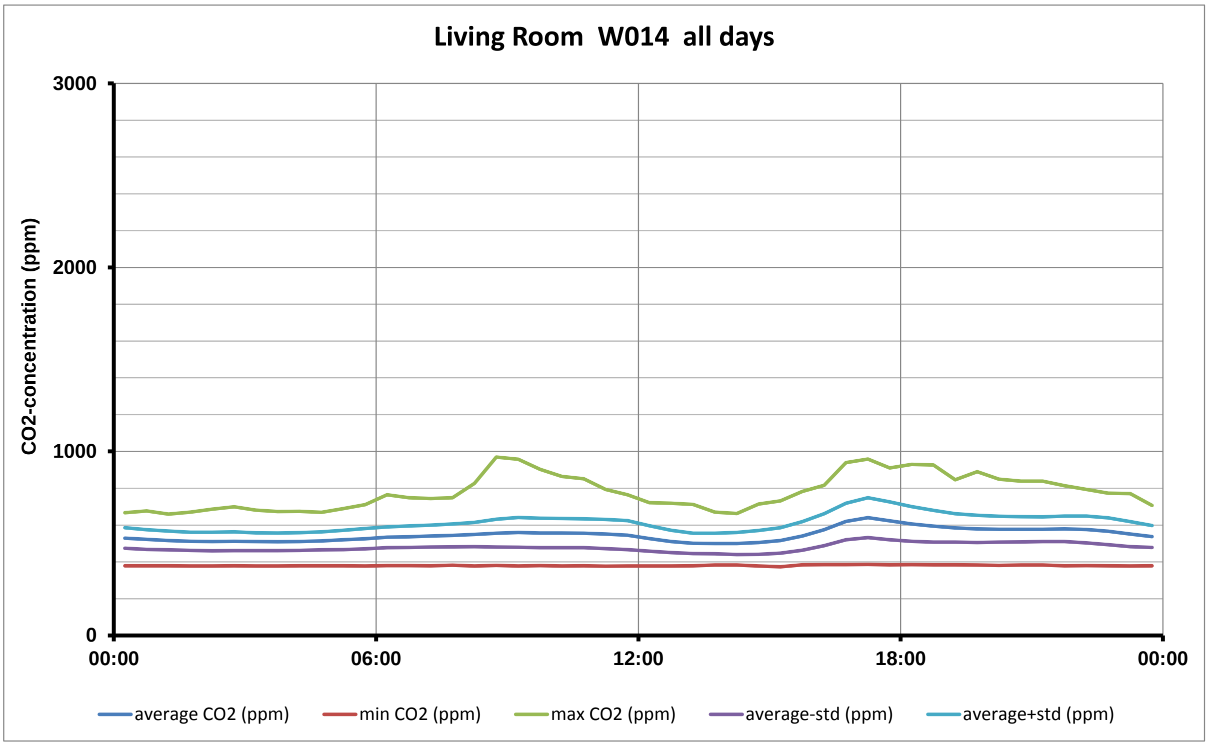


Figure C.17: CO_2-profile living room dwelling W014 over the monitored period

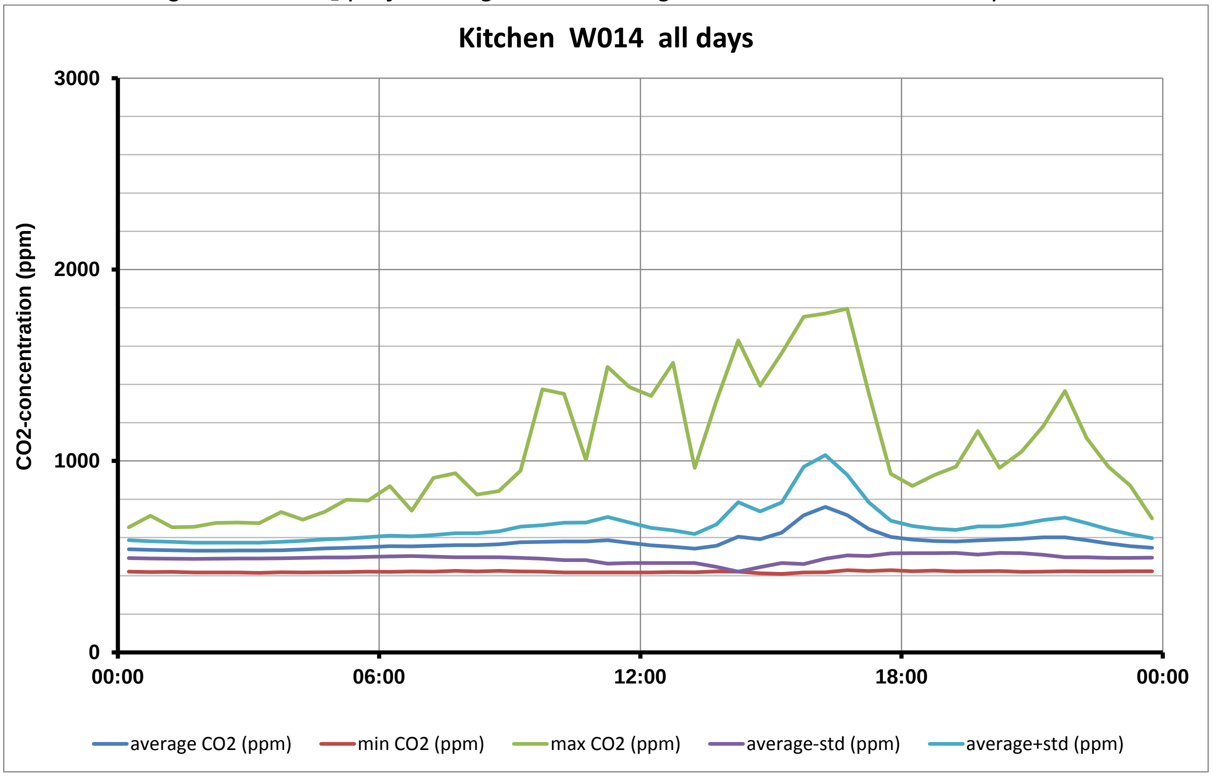


Figure C.18: CO_2-profile kitchen dwelling W014 over the monitored period

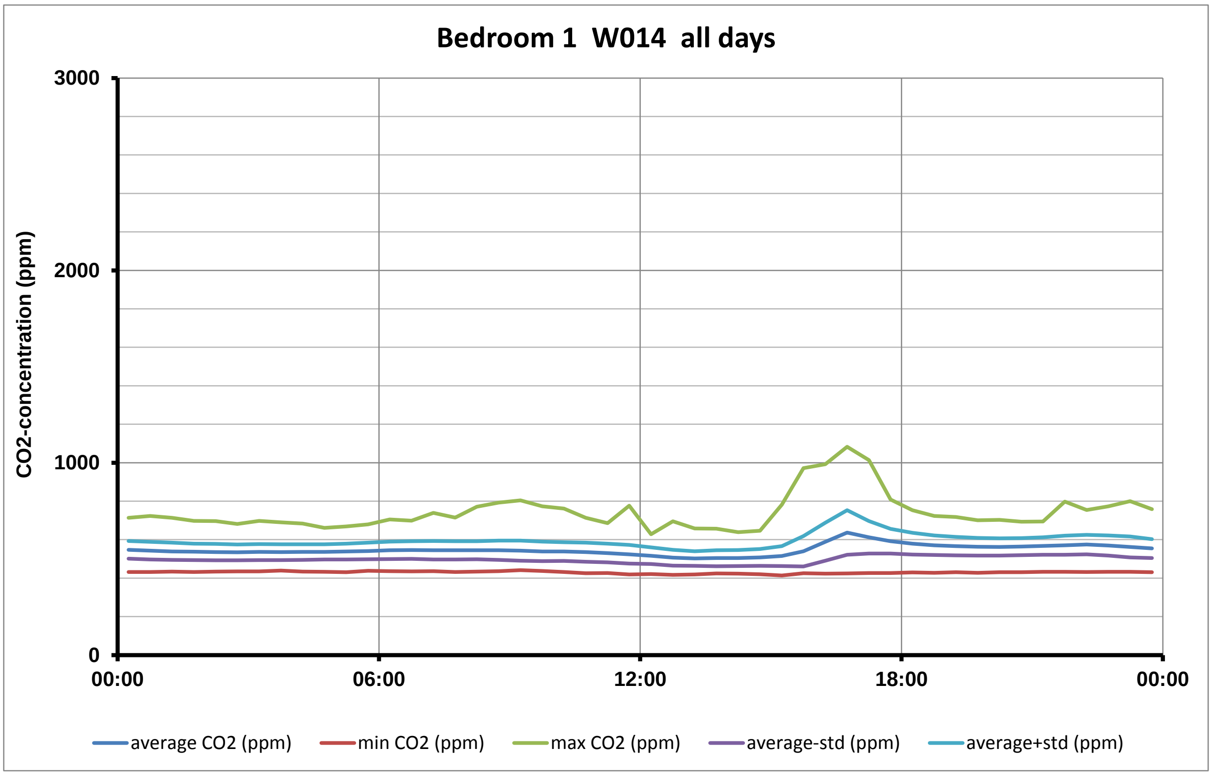


Figure C.19: CO_2-profile bedroom 1 dwelling W014 over the monitored period

C.3.2 Dwelling W023

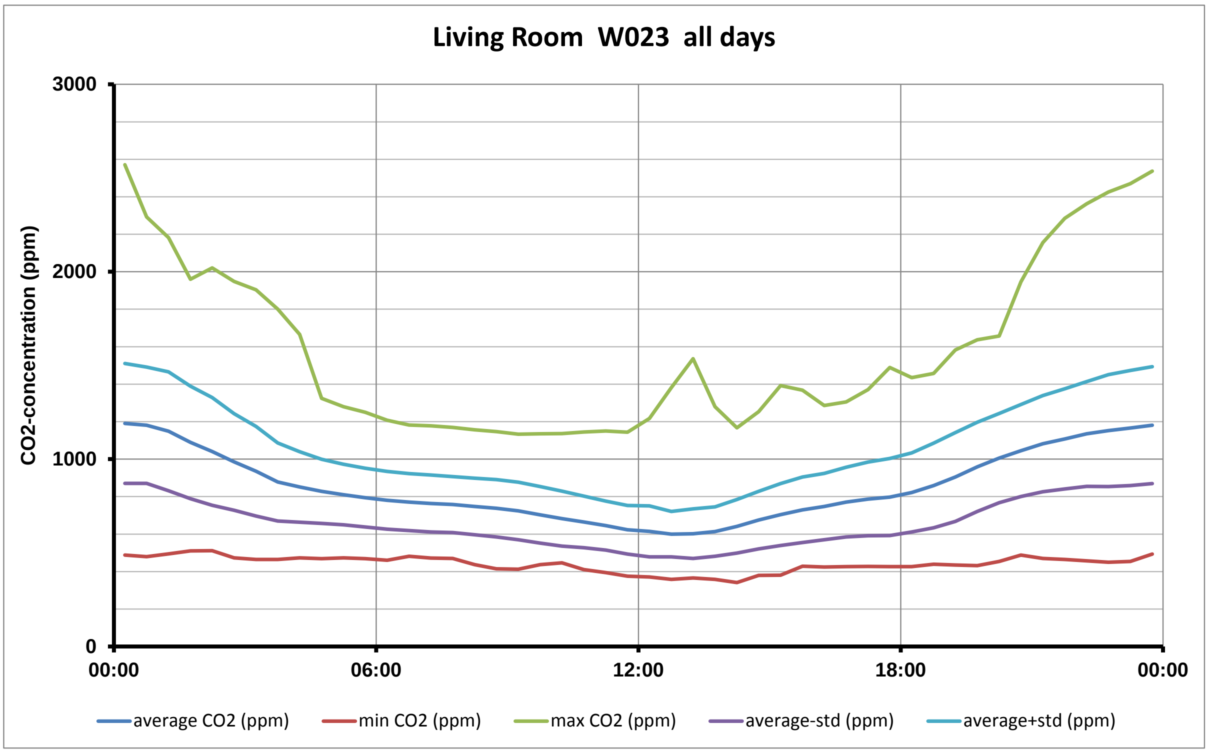


Figure C.20: CO_2-profile living room dwelling W023 over the monitored period

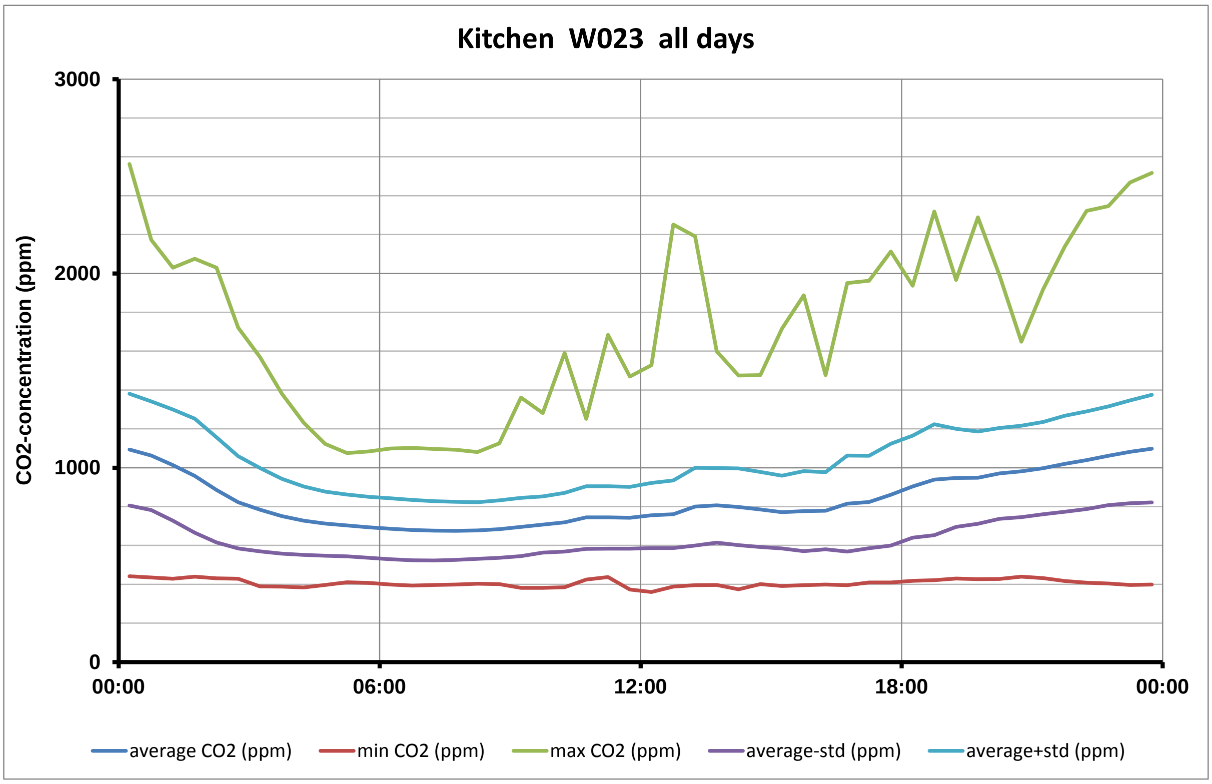


Figure C.21: CO_2-profile kitchen dwelling W023 over the monitored period

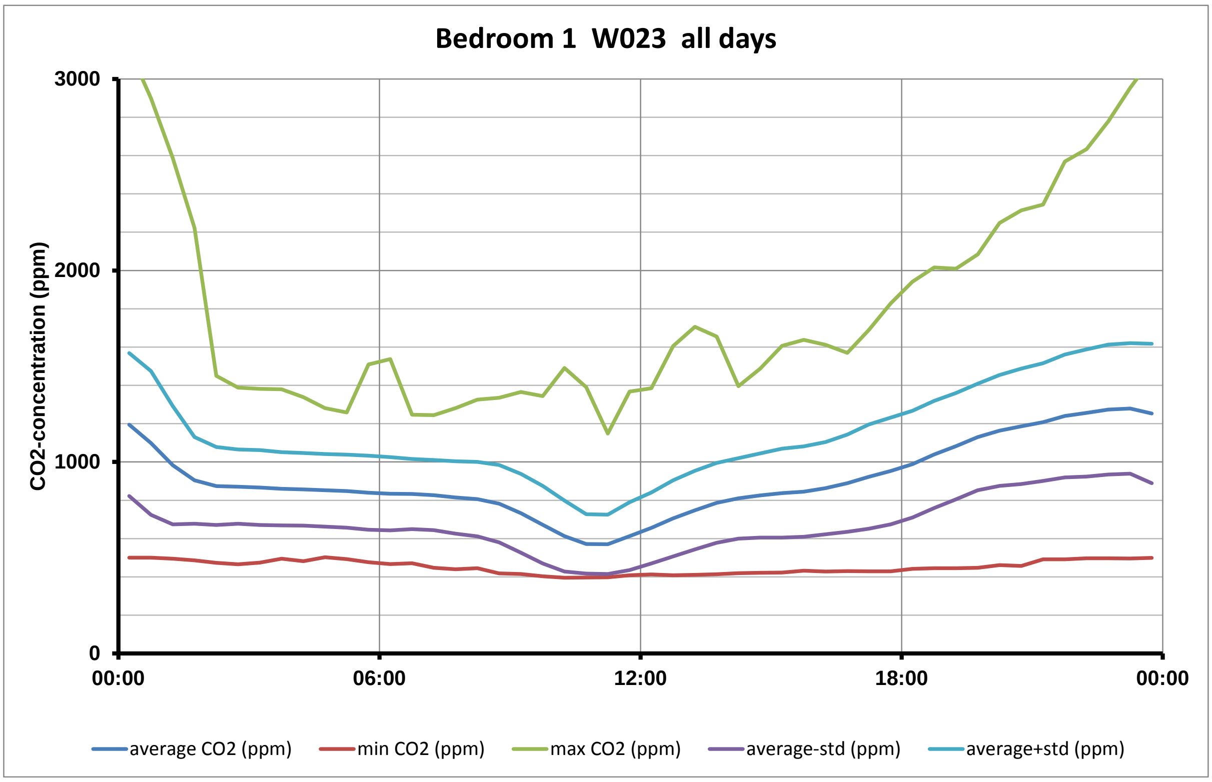


Figure C.22: CO_2-profile bedroom 1 dwelling W023 over the monitored period

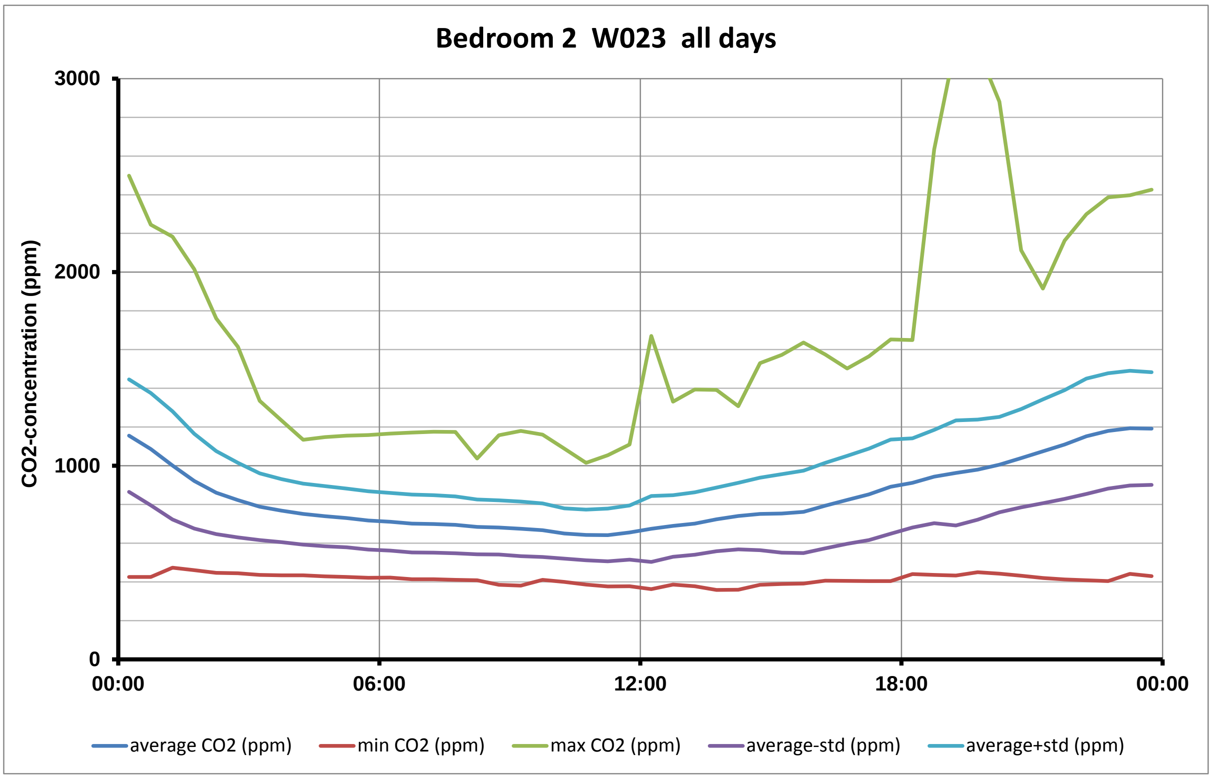


Figure C.23: CO_2-profile bedroom 2 dwelling W023 over the monitored period

C.3.3 Dwelling W025

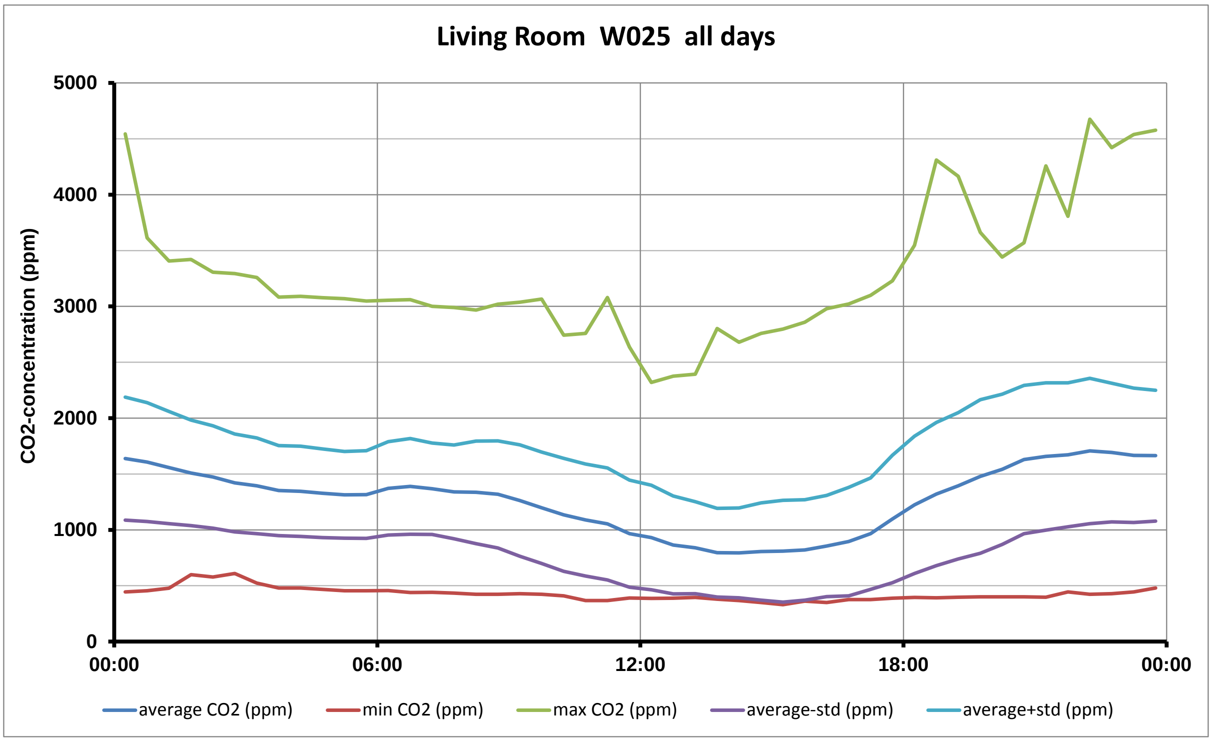


Figure C.24: CO_2-profile living room dwelling W025 over the monitored period

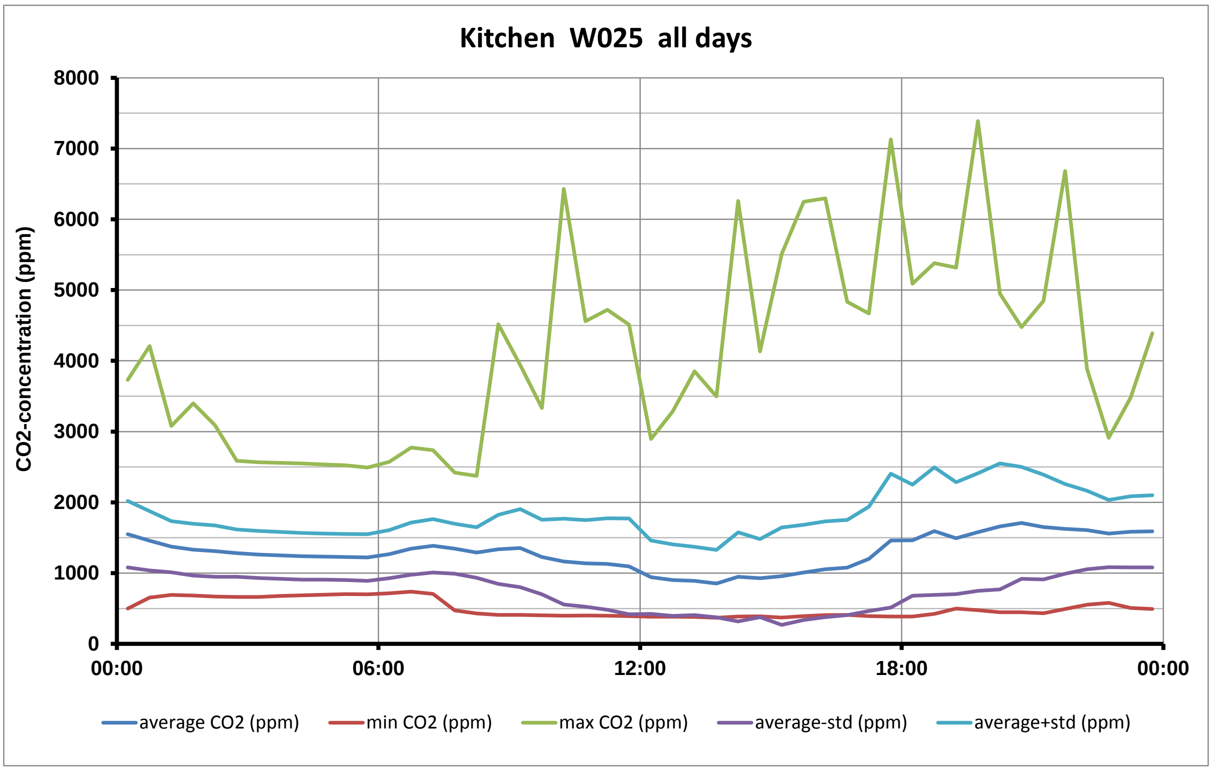


Figure C.25: CO_2-profile kitchen dwelling W025 over the monitored period

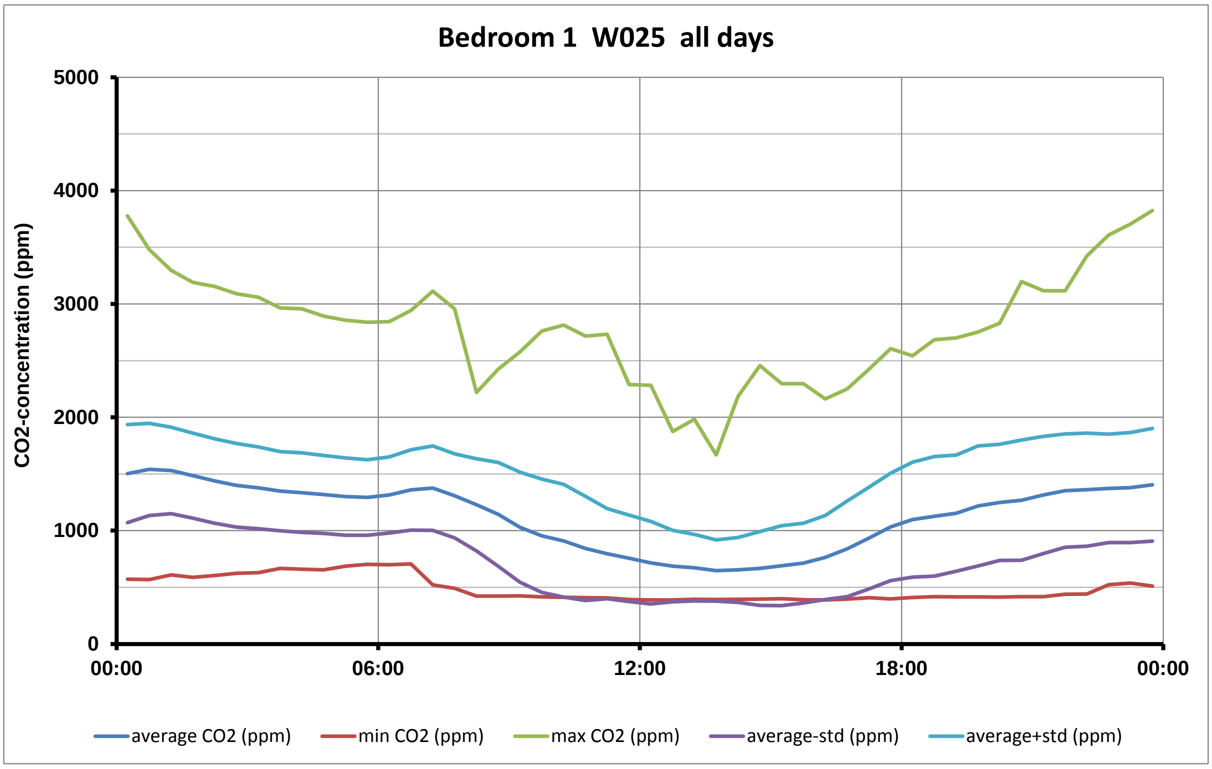


Figure C.26: CO_2-profile bedroom 1 dwelling W025 over the monitored period

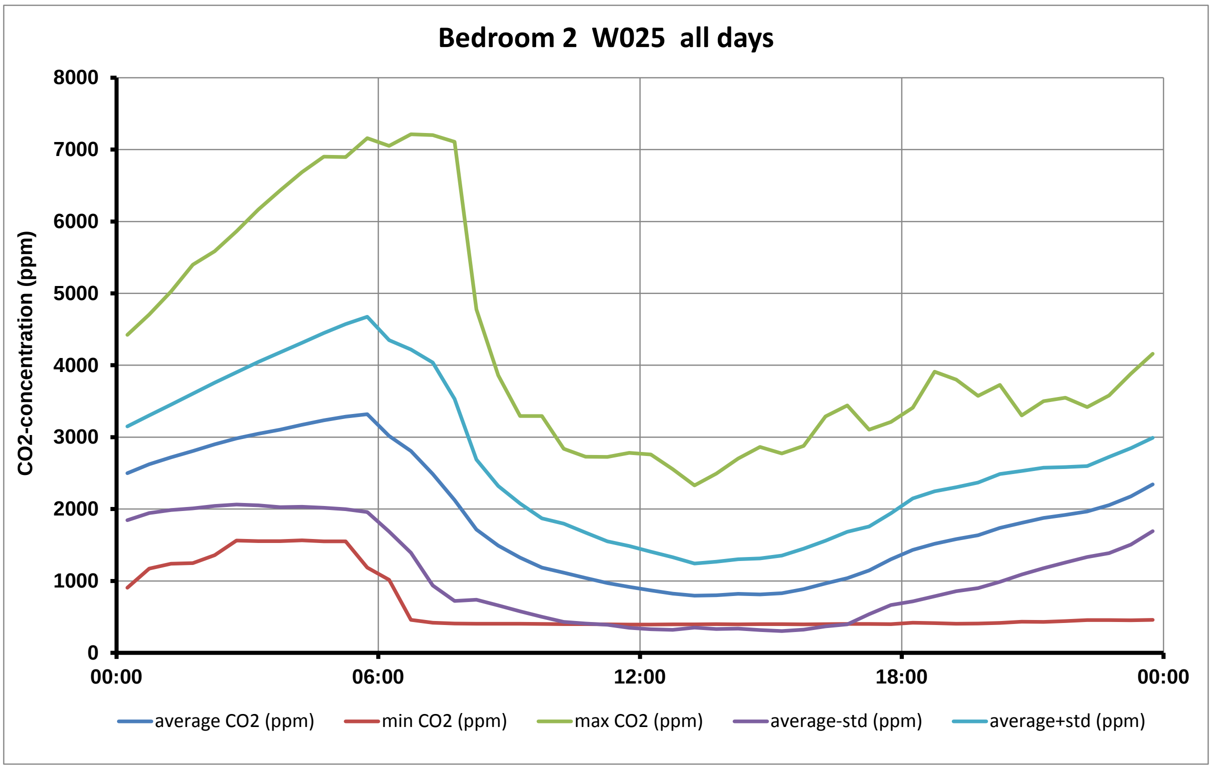
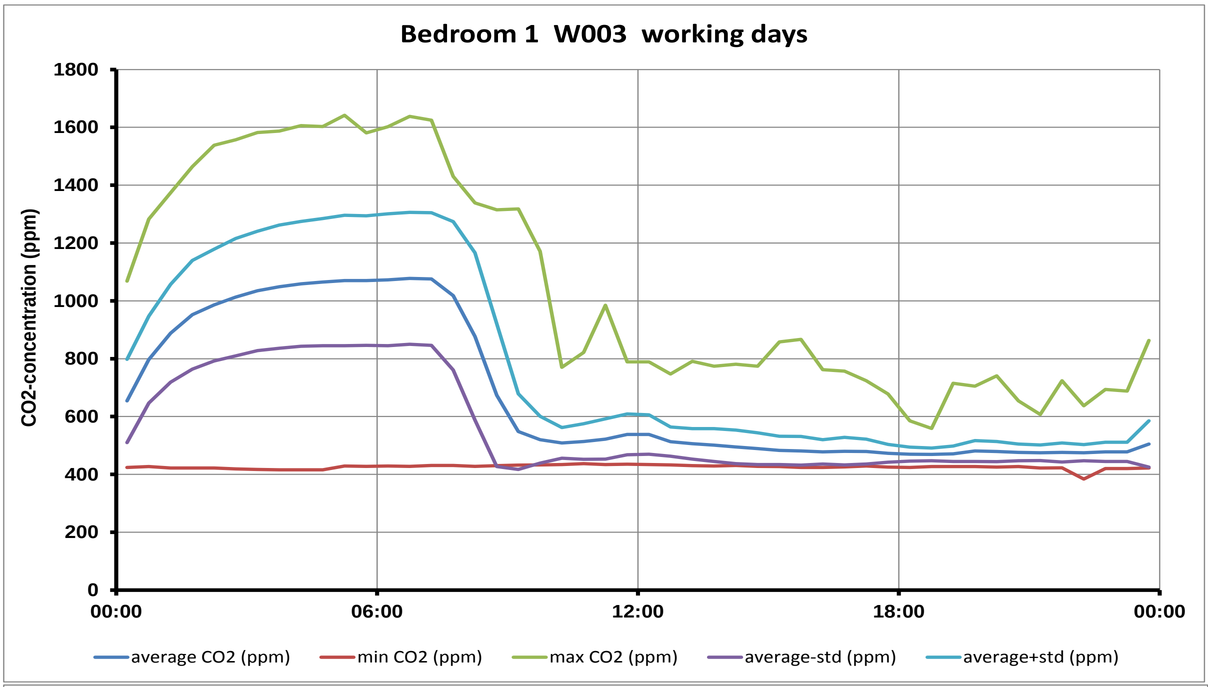


Figure C.27: CO_2-profile bedroom 2 dwelling W025 over the monitored period

Appendix D: Average presence profiles based on CO_2 and movement profiles

D.1 Dwelling W003 (balanced ventilation)



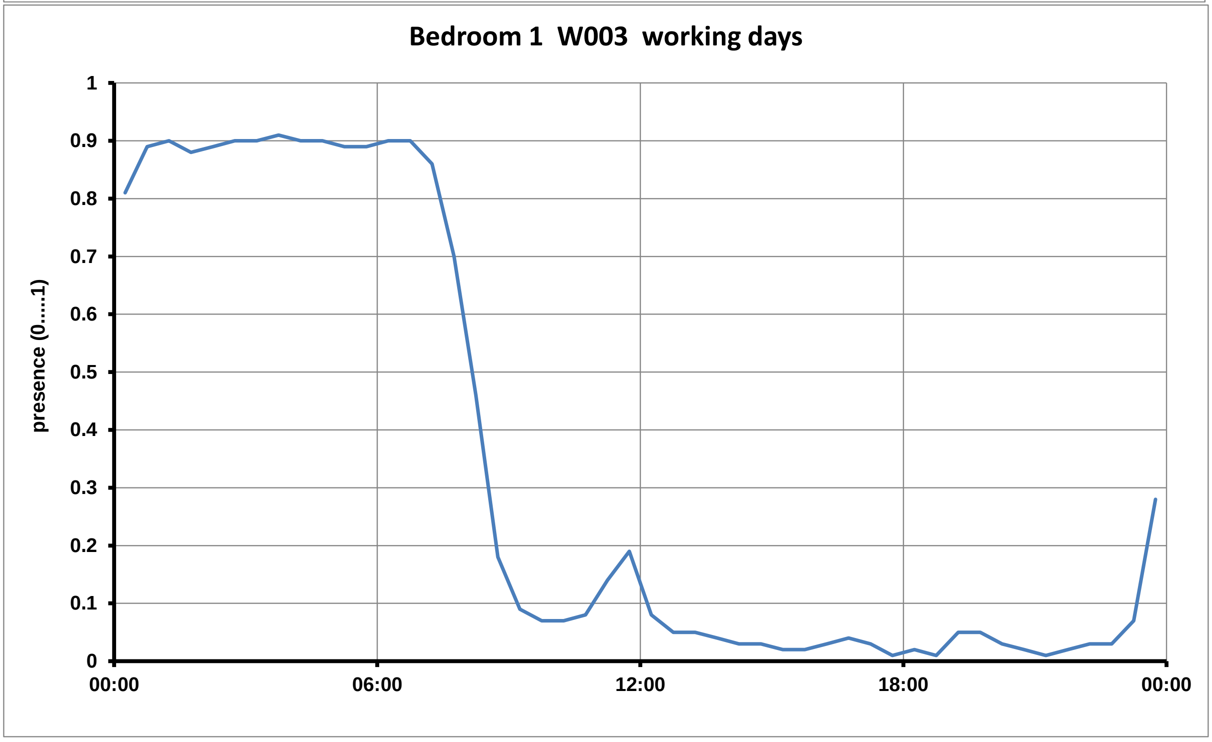
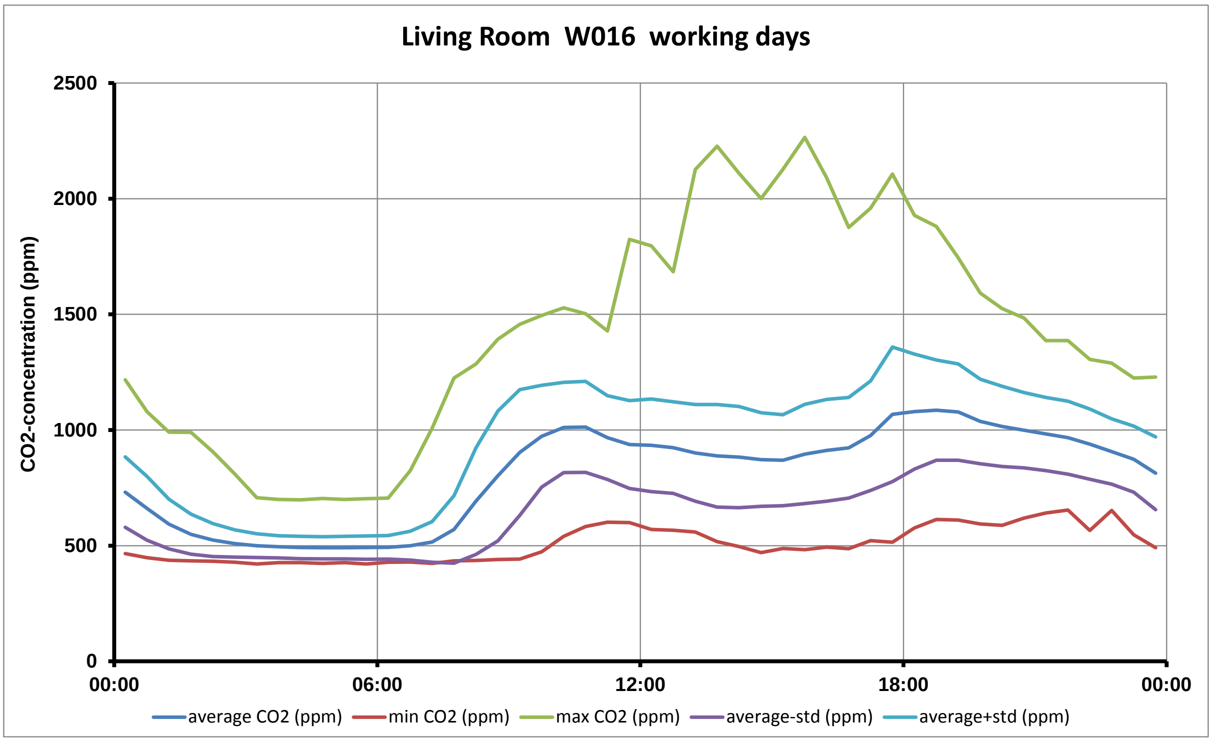


Figure D.1: CO_2-profile and presence profile for bedroom 1 in dwelling W003 for working days based upon the complete 6-month measuring period.

D.2 Dwelling W016 (natural supply, mechanical exhaust)



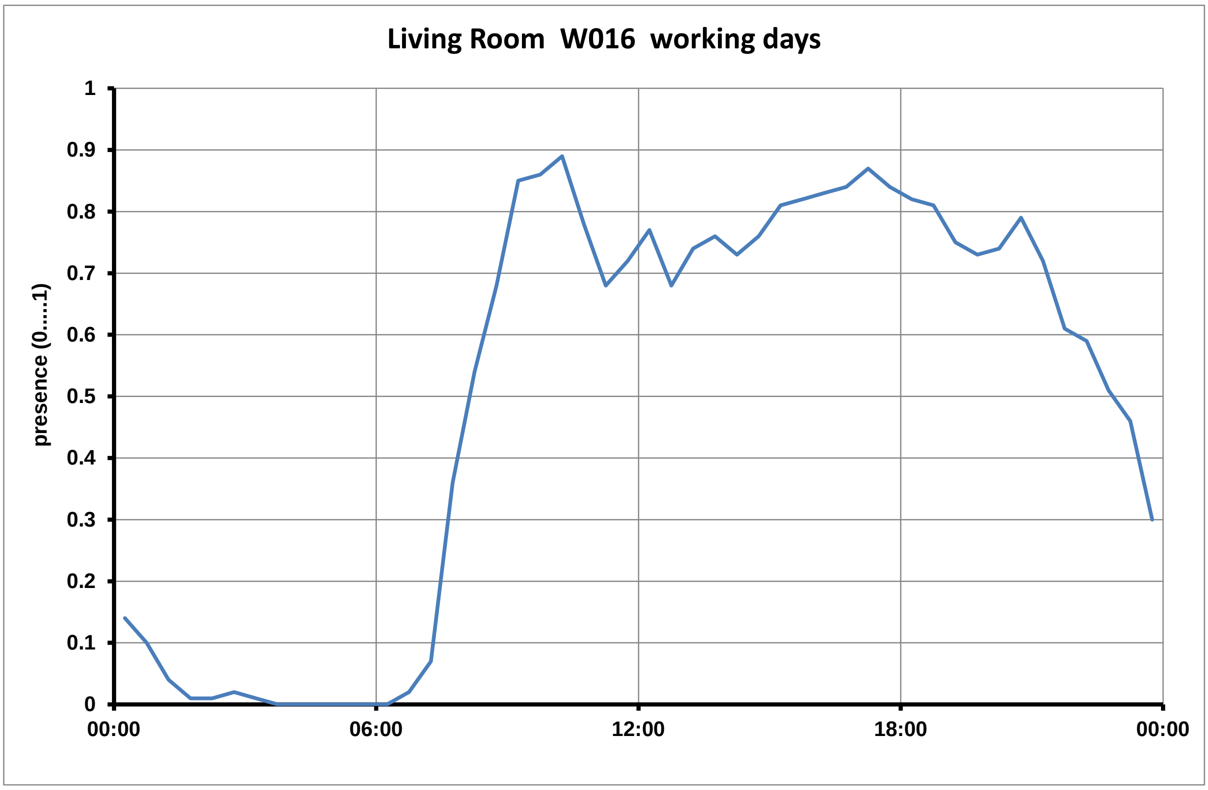
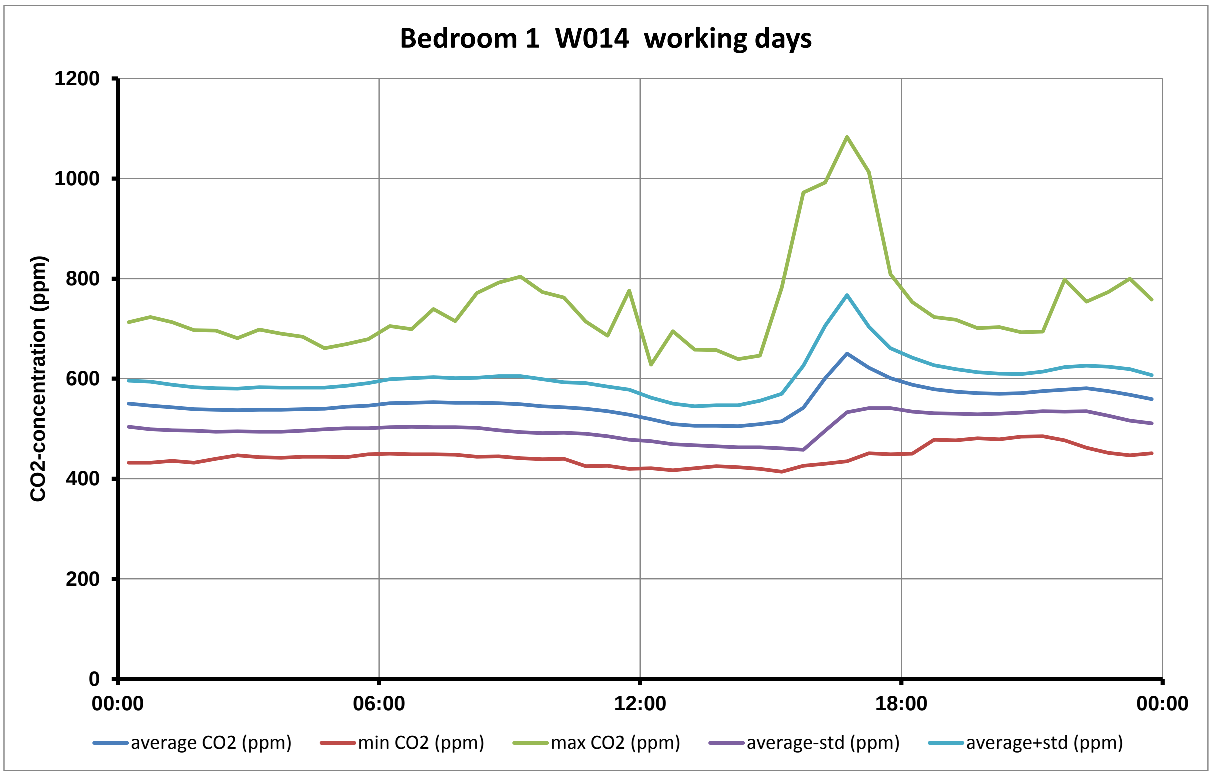


Figure D.2: CO_2-profile and presence profile for the living room in dwelling W016 for working days based upon the complete 6-month measuring period

D.3 Dwelling W014 (natural ventilation)



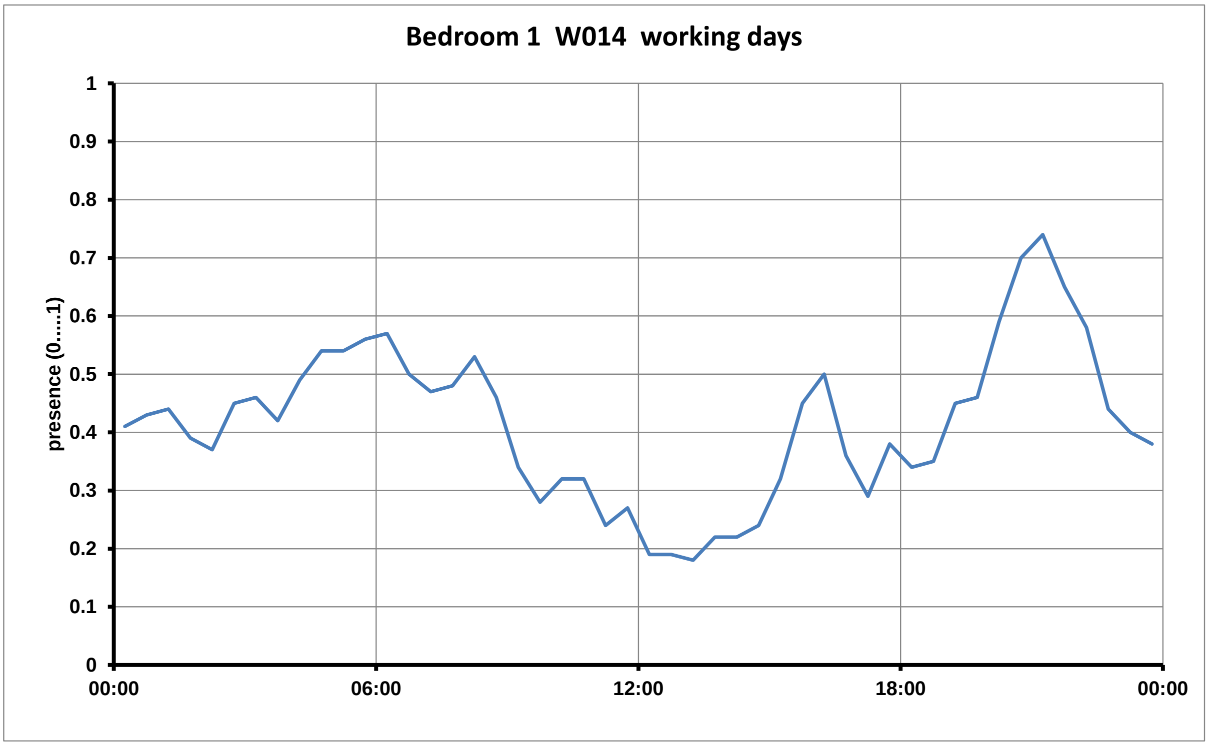


Figure D.3: CO_2-profile and presence profile for bedroom 1 in dwelling W014 for working days based upon the complete 6-month measuring period

OTB – Onderzoek voor de gebouwde omgeving
Faculteit Bouwkunde, TU Delft
Jaffalaan 9, 2628 BX Delft
Postbus 5030, 2600 GA Delft

Telefoon: +31 (0)15 278 30 05
E-mail: OTB-bk@tudelft.nl
www.otb.bk.tudelft.nl