TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

MASTERARBEIT

INDOOR CLIMATIC CONDITIONS IN A RESIDENTIAL BUILDING WITH A HUMIDITY-RESPONSIVE VENTILATION SYSTEM

ausgeführt zum Zwecke der Erlangung des akademischen Grades einer Diplom-Ingenieurin

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1 Introduction

The following sections give a short overview of the motivation of this study, an introduction to recent and previous research on ventilation systems inside residential buildings and an overview of the established state-of-the-art in this research area.

1.1 Summary

The present thesis contains the evaluation of the indoor climatic conditions in a residential building that is equipped with humidity-responsive ventilation. Humidity-responsive ventilation is a type of demand controlled ventilation that reacts to the amount of humidity inside the apartment. The observed building is part of a residential neighbourhood that is located in the 22th district of Vienna. The building contains 12 apartments whereof 11 participate in this case study. The number of inhabitants in the different apartments is almost the same. Furthermore the floor plans of the different apartment types are rather similar, which makes them reasonable to compare.

To evaluate the indoor climatic conditions, temperature, relative humidity and in some apartments carbon dioxide concentration or light were measured over a period of nearly five months. The measurement took place in the winter months from 16.11.2010 – 01.04.2011, because during this time most of the complaints of the inhabitants regarding thermal comfort occur. Due to the fact that relative humidity is beside the temperature one of the most important factors that influence thermal comfort in a room, this thesis is especially directed to the evaluation of the relative humidity inside the apartments. The measured carbon dioxide values are representing the indoor air quality in a room and were measured in the bedroom of five of the participating apartments. Light measurements were conducted to detect the presence of the inhabitants.

In addition to the objective measurements, subjective data was collected by a paper based questionnaire handed out to the inhabitants of the apartments weekly. The occupants had to evaluate their actual feeling of comfort concerning relative humidity and temperature, give information about their ventilation behaviour and their overall thermal comfort. It was attached importance not to influence the inhabitants too much by questions about the ventilation system, to avoid different ventilation behaviour during the case study.

Relative humidity values, temperature and CO_2 concentrations were compared between the apartments.

Although the building has demand controlled ventilation, the possibility of user-operated natural ventilation is established. The results suggest that the humidity-responsive control works properly concerning the reduction of humidity

inside the apartments, but is due to different reasons partly not accepted by the inhabitants.

1.2 Motivation

In the past few years humidity as indicator of health and comfort inside buildings became more important. Regarding ventilation as influencing value in terms of energy saving issues, the discussion of basic ventilation occurred. Low-energy buildings usually have a very tight envelope and so the air exchange trough the building parts and via infiltration (as in older buildings available) is reduced to a minimum. The increasing insulation of buildings leads to the fact that the problem of ventilation losses comes to the fore (Künzel 2009).

Furthermore control of indoor climatic conditions in terms of self-determination by occupants according to their individual needs, compared to the energy efficiency of building systems are a growing topic. Demand controlled ventilation in residential buildings is rather new but nowadays more and more in use to cope with the management of the relative humidity in well insulated buildings. These systems have to be scrutinized regarding their efficiency and influence on indoor climatic conditions. The present work contributes to this discussion and evaluation of ventilation systems inside residential building, based on empirical data.

The DIN 1946-6 was changed in May 2009. One important issue that was faced is the relative humidity inside buildings. Cross-ventilation for humidity control was established as new ventilation system. It is a natural ventilation system, based on the wind pressure that brings the outside air into the building through passive air inlets. The modernisation of the standards regulate whether a ventilation is necessary inside a building or not, based on the evaluation of the volume flow rate for humidity control, compared to the flow via infiltration. If ventilation is necessary it can be established via the so called “freie Lüftung” and the “ventilatorgestütze Lüftung” (DIN 2009).

The awareness and acceptance from the side of the technical standards concerning the importance of humidity inside buildings represents another intention of this work.

Indoor air quality is one of the most important factors that affect feeling comfortable inside a building. Regarding the energy-efficiency the resident’s satisfaction with living there has to be ensured too.

Concluding, this work is also motivated by the observation that there are complaints about relative humidity and draught inside the analysed building. The inhabitants communicate that the air inside the rooms is either too dry or too humid. The reasons for this constrain concerning the comfort inside the apartments has to be figured out.

1.3 Background

In the following recent research on indoor climatic conditions in residential buildings that are equipped with ventilation systems is presented. Main attention was given to the relative humidity as an important factor affecting indoor climate and the feeling of comfort. Especially in terms of basic ventilation in low-energy houses also DIN standards and guidelines are discussed.

1.3.1 Ventilation systems in residential buildings

Leitzinger et al claim that: "The success of sustainable energy efficient buildings depends mostly on the acceptance of the occupants, who expect an increase in comfort as well as substantial energy savings." (Leitzinger et al. 2008).

Part of a previous program called "Haus der Zukunft" was the study of „Akzeptanzverbesserung von Niedrigenergiehauskomponenten" in 2000 under the direction of the interuniversitary research centre in Graz, Austria. Amongst others they figured out that most problems in terms of the acceptance of a ventilation system inside residential buildings occur in multi-storeyed dwelling houses. The reason is that the inhabitants have no possibility to decide on the ventilation system and therefore are more sceptically. They also highlight that it is important to consider the energy-efficiency, the acoustic noise exposure and the long term effect in terms of hygienic aspects (Leitzinger et al. 2008).

Therefore they established the "8 Bedingungen für Nutzerzufriedenheit", in the following five for the present work interesting points of the "8 criteria for occupants' satisfaction" are mentioned (Leitzinger et al. 2008):

- The air volume is adapted to the hygienic needs
- The design of the system enables a permanent good supply air without the feeling of draft
- The operating noise of the system does not be perceived as disturbing in the living room or bedroom
- In air-tight build houses the heating demand can be reduced by a multiple of the energy demand of the system
- The operator can change possible filters on demand easily by himself

Demand controlled ventilation systems respond to the first mentioned point concerning the adaption to the hygienic needs. Due to the fact that relative humidity is a major factor that influences hygienic conditions, the demand controlled system driven by the local indoor relative humidity is important.

In Germany the VFW (Bundesverband für Wohnungslüftung e.V.) declared in 12.2010 that the occupant's independent ventilation is the state-of-the-art, because nowadays the sufficient ventilation of apartments by only natural ventilation via windows cannot be established without restrictions in the everyday life of the occupants (VFW 2010). Also the district court of Vienna decided in 2007 that the occupant's presence for sufficient ventilation by short-term window opening spread over the day, cannot be taken for granted (Komfortlüftung.at 2010).

In the DIN 1946-6 four variants are exposed that can be related to the DIN 18017-3 (VFW 2010). The DIN 18017-3 applies for the ventilation of rooms without windows, whereas the DIN 1946-6 takes the ventilation of the whole apartment into account. Here there are more requirements regarding the installation of air inlets and the operating levels of the ventilation systems. The DIN 1946-6 has to be applied if the amount of removed air by the fans is bigger than the supply with fresh air established by infiltration (DIN 2009).

The DIN 1946-6 established four basic ways of ventilation (DIN 2009):

- Ventilation for humidity control
- Reduced ventilation
- Basic ventilation
- Intensive ventilation

Humidity control attracted attention and is now explicit mentioned in the actual DIN 1946-6.

1.3.2 Controlled ventilation

To provide a hygienic thermal environment it is necessary to ventilate directed and conscious. In the past as well as today ventilation by chance through leak windows is absolutely insufficient. The directed ventilation via windows is based on an active behaviour of the inhabitants (Künzel 2009). As mentioned in the previous chapter (1.3.1) this is maybe not an unfailing method. Due to the fact that not only the windows getting tight, but also the building envelope, ventilation systems become necessary.

Ventilation of internal space faces a lot of different problems. In the following Figure (Figure 1) these difficulties are enumerated.

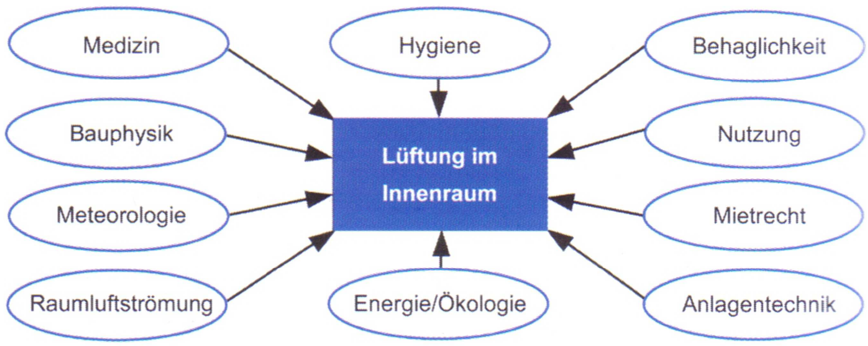

Figure 1: Factors that influence the ventilation of an internal space (Künzel 2009)

Factors like hygienic issues, thermal comfort, building physics as well as the type of use, the energy efficiency and aspects in terms of ecology have to be taken into account. To quantify the ventilation's effect, the air change rate can be calculated. The air volume flow applies to the air volume of the room. One problem is that the air exchange does not adapt to the different circumstances. (Künzel 2009).

Demand controlled ventilation systems try to fill this gap by adapting to different indoor climatic conditions. The analysed building is equipped with demand controlled ventilation reacting to the indoor relative humidity and so is called humidity-responsive ventilation in this thesis.

1.3.3 Relative humidity

Most of our lifetime people spend inside buildings. Indoor air quality affects the feeling of comfort inside rooms as a major factor.

According to VDI 4706 the relative humidity should lie in the area between 30%-65% (absolute humidity 11.5 g/kg) (VDI 2009). In the ASHRAE Standard 55-2004 no minimum humidity value is established. However, non-thermal comfort factors like for example skin drying, irritation of mucus membranes or static electricity generation may place limits on the acceptability of very low humidity environments (ASHRAE 2004).

In the VDI 4706 it is stated that high relative humidity values significantly negatively influence the perceived indoor air quality (VDI 2009).

Relative humidity from the ventilations point of view:

Comfort is perceived different from the occupants. Besides temperature, relative humidity and light also clothing values and the degree of activity as well as air velocity are influencing factors on the satisfaction with the indoor environmental conditions. Previous studies show that a better ventilation of rooms raises significantly the subjective assessment of indoor air quality and causes therefore fewer complaints of the inhabitants.

This awareness was shown in a research study in Canada where 52 single family houses with controlled ventilation and 53 without were compared. They evaluated the results based on the appearance of the Sick Building Syndrome (SBS). Other results bring out that buildings with mechanical ventilation systems and therefore with a higher air exchange rate, have a lower degree of pollutant concentration (Hutter et al. 2005).

In apartments with a ventilation system, but without an air humidifier low relative humidity values can appear, especially in the cold seasons after the streamed in untreated outside air is heated up (Hutter et al. 2005).

1.3.4 CO_2 concentration

One of the most known benchmark for residential buildings concerning the amount of CO_2 is the so called Pettenkofer-value (1858) with 1000 ppm. Concentrations below 10 000 ppm may not cause severe health problems, but have a negative impact on the indoor air quality in a room and the perception of comfort. Besides decreasing peoples' concentration, for example headache can be a typical consequence of higher CO_2 concentrations (Hutter et al. 2005).

The following table (Table 1) displays the relationship between the indoor air quality and the CO_2 concentration according to DIN EN 15251 (DIN 2007).

Table 1: Indoor air quality in relationship to different CO_2 concentrations (DIN 2007)

CO_2 concentration above outdoor air	Indoor air quality
350 ppm	Recommended in rooms with inhabitants that have special needs (for example: very young children, old or ill people)
500 ppm	Standard expected air quality, recommended for new or renovated buildings
800 ppm	Acceptable concentrations
> 800 ppm	Values out of the above mentioned range, concentrations should not lie in this category for a long time

2 Method

In the following sections the observed building and the apartments are described. Furthermore the humidity-responsive ventilation system and the measurement equipment are explained. Finally the methods to evaluate the measured data are presented.

2.1 Overview

The building of interest is partially funded by the WWFSG 1989 (Wiener Wohnbauförderungs- und Wohnhaussanierungsgesetz) and therefore declared as low-energy building. It has an annual heating demand of 38,9 kWh/(m²a) which lies under the maximum value for partially funded low energy buildings in Vienna (Project organiser 2008).

The present thesis does not evaluate the energy efficiency of the building, but takes this for granted.

The analysed building is located in the 22th district of Vienna. The site lies about 142 m above sea level.

In the following Figure 2 the 22th district is highlighted.

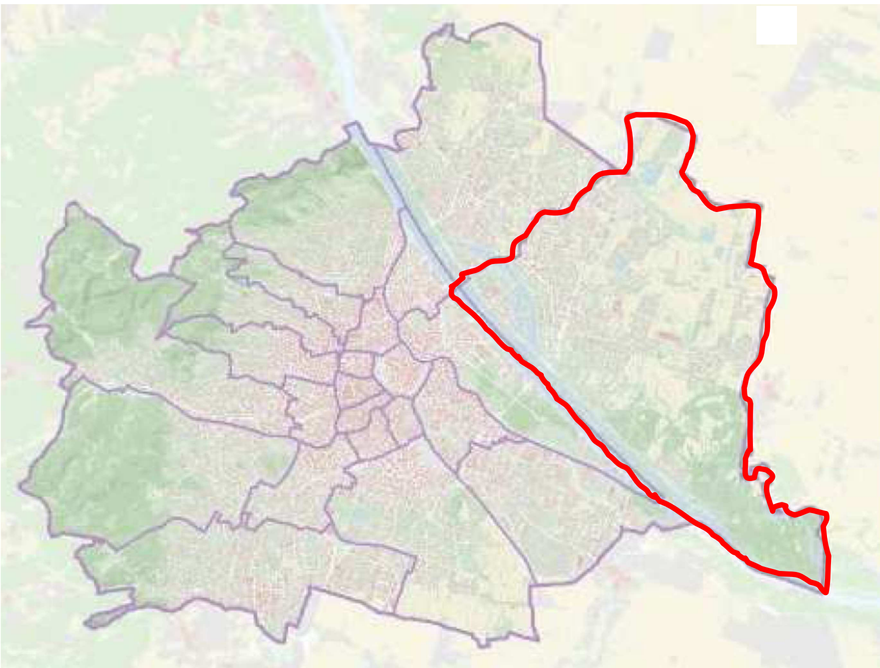

Figure 2: Map of Vienna (wien.gv.at 2011)

The residential neighbourhood was finished in November 2008. Soon after it was completed the inhabitants moved in.

The selected building belongs to the mentioned residential neighbourhood which includes nine buildings. Eight of them are similar in size and construction. One differs in the size. The buildings are low-energy houses with a total of 100 flats. All apartments are equipped with a humidity-responsive ventilation system.

The apartment sizes range from 56 to 107 m^2 living space. Each apartment contains of two to five rooms. Some of them are developed as maisonettes.

The residential neighbourhood was planned for families. Therefore all of the buildings are surrounded by private gardens that belong to the flats on the ground floor. At the northwest end of the site a large children's playground as well as a smaller one, which is especially for the younger children, is provided (Project organiser 2008).

The main entrance, which is also the emergency access road and the gateway to the basement garage, are situated at the east side. All of the buildings are connected by the garage. The second important access to the site is a small footpath in the north that leads directly to the buildings at that part.

In the building that faces the street a storage room for bicycles and strollers is situated. The building next to the playground contains a laundry room. Each building is equipped with an elevator. The storage rooms are in the basement. In the building with the laundry room also a common room is situated.

There are five buildings in a row which are north-south orientated. Two buildings next to the playground also and the remaining two are directed to east and west. Most of the flats face north and south, so cross-ventilation is established. The staircase can be naturally ventilated too (Project organiser 2008).

2.2 Selected Object

Figure 3 displays the selected object. It is the westernmost and faces the large children's playground in the south.

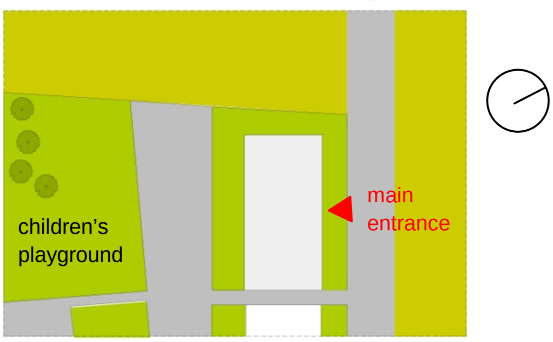

Figure 3: Map of the site

2.2.1 Description of the participating apartments

The building is three storeys high. In 11 (out of 12) flats measurements of the temperature and the relative humidity were conducted, CO_2 and light only in some of them.

Table 2 displays an overview of the participating apartments showing information concerning the area, the number of inhabitants, main orientation, the number of rooms and the floor level. In the following the flats are numbered sequential from the ground floor to the top as well as from the east to the west.

Table 2: Overview of the selected apartments (Project organiser 2008)

Floor level	**Apartm.**	**Area [m²]**	**No. of inhabitants**	**No. of rooms**	**Main orientation**	**Eat-in kitchen**
Ground floor+ 1st floor	101	103.66	2	5	North-south	-
Ground floor	102	71.50	3	3	North-south	x
Ground floor	103	56.14	1	2	South	x
Ground floor	104	71.50	2	3	North-south	x
Ground floor+ 1st floor	105	107.64	4	5	North-south	-
1st floor	112	69.25	2	3	North-south	x
1st floor	114	69.25	2	3	North-south	x
2nd floor	121	88.90	2	4	South-east	x
2nd floor	122	88.90	3	4	South-west	-
3rd floor	131	88.90	3	4	South-east	-
3rd floor	132	89.40	3	4	South-west	-

Two of the selected apartments are maisonettes (101 and 105). The remaining flats in the ground floor and the 1st floor are almost similar (102,104,112 and 114). The type 103 appears only once, because the inhabitant at the 1st floor with the same apartment did not participate in this study. The apartments 121,122,131 and 132 are similar. The only difference is that the flats in the 2nd floor have an additional terrace.

The following two Figures (Figure 4 and Figure 5) show the apartments 101 and 105. Both apartments are maisonettes.

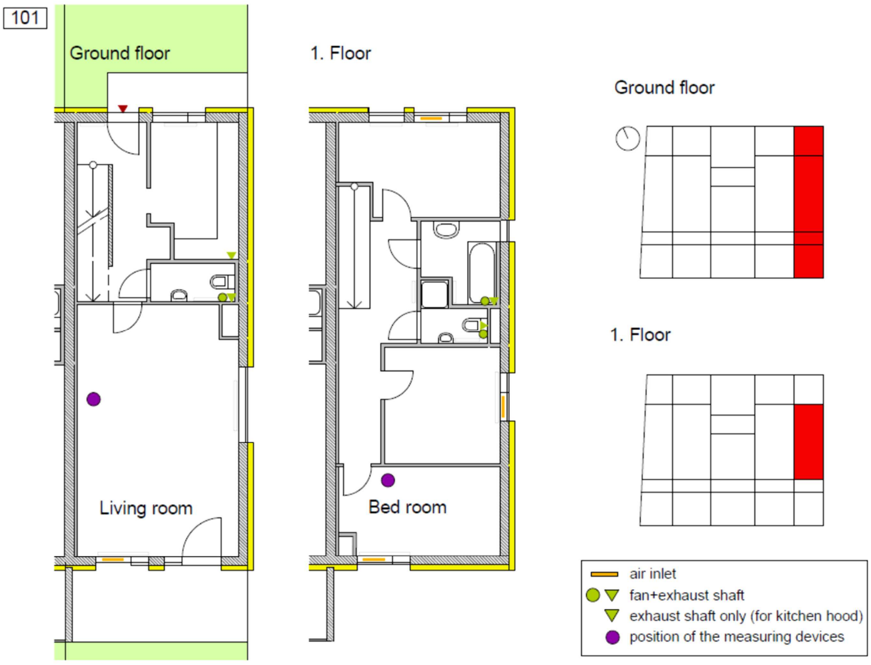

Figure 4: Floor plan, 101

Figure 5: Floor plan, 105

Apartment 101 has a total area of 103.66 m² separated on two floors and is occupied by two residents. The flat faces north and south.

The entrance is situated in the north. In the ground floor the living room is connected to the attached garden in the south.

The sensors were placed in the living room on a dresser on the right hand side of the door and at the first floor in the bedroom left hand side of the entrance door on a nightstand. The device in the bedroom additionally measured CO_2. The exact sensor locations are shown in the floor plan of Figure 4. In Figure 4 also the location of the air inlets and the fans is displayed.

The second maisonette (105) is mirrored from the 101 and therefore at the west part of the building which is shown in Figure 5. With a total of 107.64 m² it is a little bit larger than the first mentioned maisonette. This flat is occupied by four persons.

Again the measuring devices were positioned in the living room at the ground floor and in the bedroom in the first floor. In both rooms the sensors were placed on the side of a wardrobe. Exact locations can be checked up in the floor plan shown in Figure 5. Again CO_2 measurements were conducted in the bedroom.

The type of the next apartment presented in Figure 6 occurs only once in this case study.

Figure 6: Floor plan, 103

One resident lives in the apartment of 56.41 m². The two rooms are orientated to the south. One measuring device was placed in the living room on a shelf, the other one in the bedroom right hand side of the entrance door on a wardrobe. Figure 6 displays the location of the sensors.

As mentioned before the flats (102,104,112 and 114) in the ground floor and the 1st floor are almost similar. The following four Figures (Figure 7 – Figure 10) display the apartments 102 and 104. The description of the different flats is written in each case beneath the floor plan.

Figure 7: Floor plan, 102

This apartment (102) is occupied by three persons. The living area accounts 71.50 m². The sensor in the living room was placed on a rack beside the workplace. The one in the bedroom was positioned on a dresser in front of the bed. CO_2 was measured only in the bedroom. Figure 7 displays the exact location of the devices.

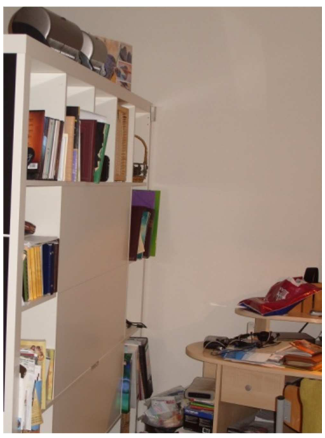

Figure 8: Living room of apartment 102

Figure 9 shows apartment 104, which is similar in size and orientation like the before (Figure 7) presented flat 102.

Figure 9: Floor plan, 104

The apartment, sized 71.50 m² houses two residents. The measuring devices were located on a shelf above the bed in the sleeping room and on a wall unit in the living room. In this flat CO_2 was not measured. In Figure 9 the exact location of the sensors is denoted by a violet dot.

Figure 10 shows a view of the mounted HOBO in the living room of apartment 104.

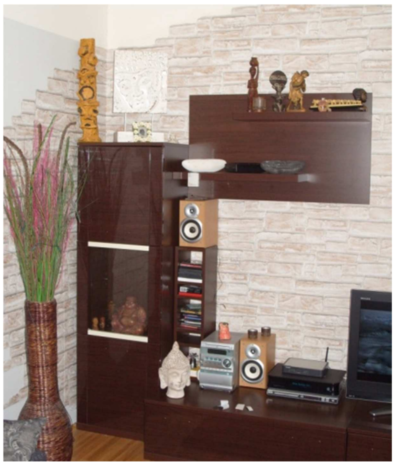

Figure 10: Living room of apartment 104

The following figures (Figure 11 and Figure 13) show the floor plans of the apartments 112 and 114. They are almost similar in size and orientation like the before described apartments. The only difference is that they are in the first floor.

Figure 11: Floor plan, 112

The apartment in the first floor is occupied by two persons. With a size of 69.25 m² it contains three rooms. The loggia is orientated to the south and can be accessed from the living room. The bedroom is located in the north of the apartment. One CO_2 sensor was placed on a dresser on the left hand side of the entrance door of the bedroom. The sensor in the living room was placed above the occupant's workplace. Figure 11 displays the exact positions.

The following picture (Figure 12) shows a view of the bedroom and the living room of apartment 112.

Figure 12: Bedroom and living room of apartment 112

Figure 13 displays the floor plan of apartment 114.

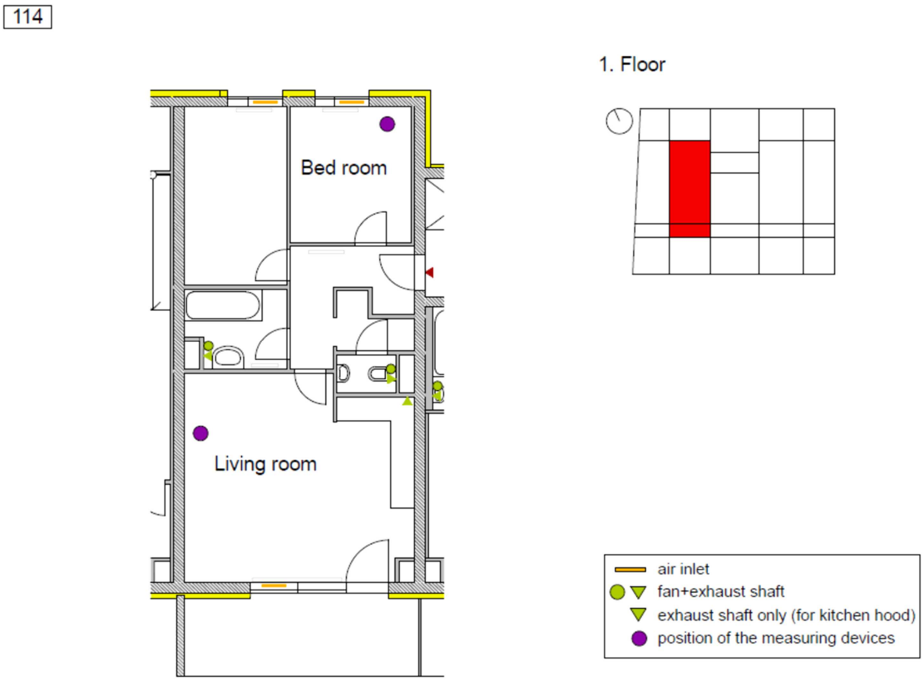

Figure 13: Floor plan, 114

As apartment 112, this one is also sized with 69.25 m². Two residents live there. The measurement devices were located in the bedroom on a nightstand and in the living room mounted on a vitrine next to the couch. The violet dots in Figure 13 show the locations.

In the following (Figure 14) a view of the living room of apartment 114 is displayed.

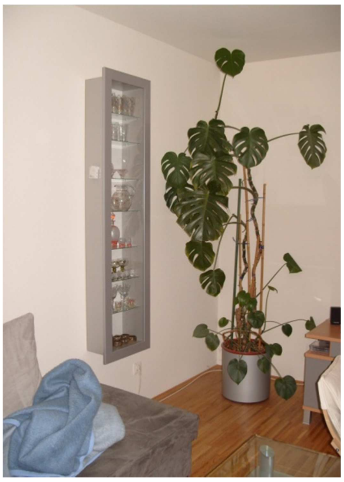

Figure 14: Living room of apartment 114

The following figures (Figure 15 – Figure 20) display the apartments in the second and third floor (121, 122, 131 and 132). Size and the number of inhabitants are described beneath the floor plans.

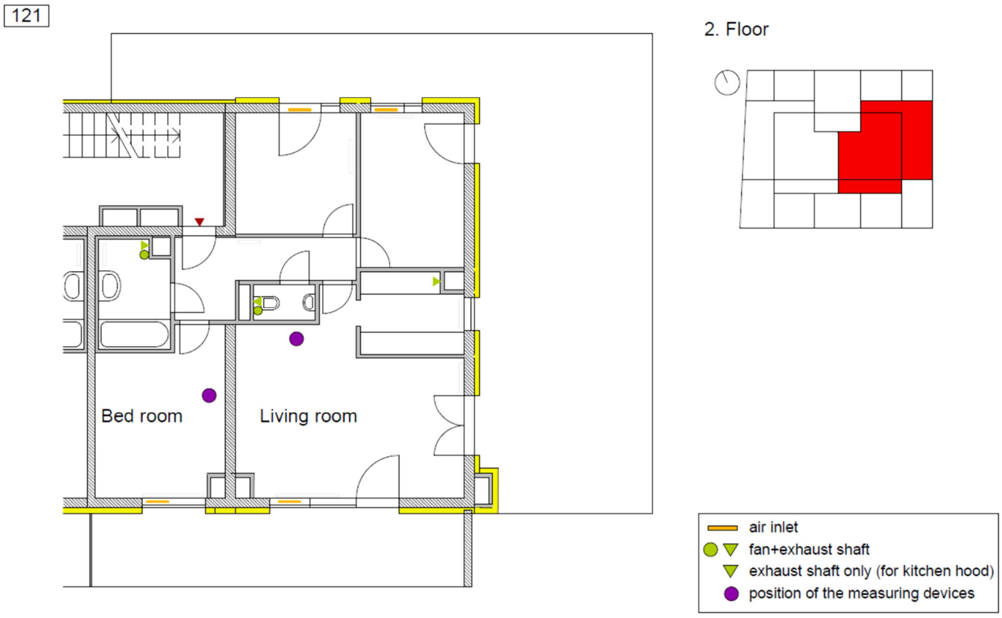

Figure 15: Floor plan, 121

Apartment 121 is occupied by two residents and measures 88.90 m². The living room and the bedroom where the measurements were taken are orientated to the south. The measuring devices are placed once in the living room above the TV set and in the bedroom on a nightstand. The location is visible in Figure 15, marked with violet dots. Figure 16 shows a view of apartment 121.

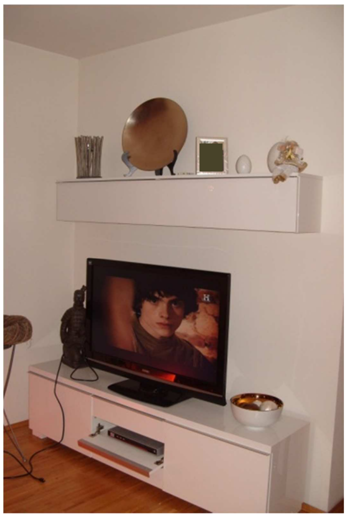

Figure 16: Living room of apartment 121

Figure 17 and 18 show the floor plans of apartment 122 and 131.

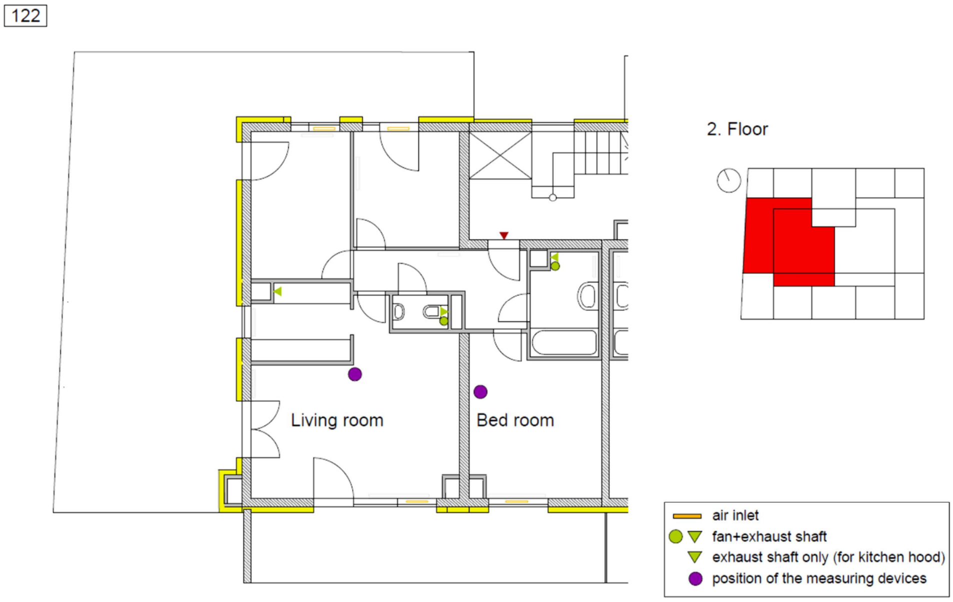

Figure 17: Floor plan, 122

The apartment 122 sizes 88.90 m² and is occupied by three persons. It is at the 2nd floor, the same floor level as 121. The sensors were located in the living room on the door frame of the kitchen door and in the bedroom on the side of a wardrobe. Figure 17 shows the position in the floor plan.

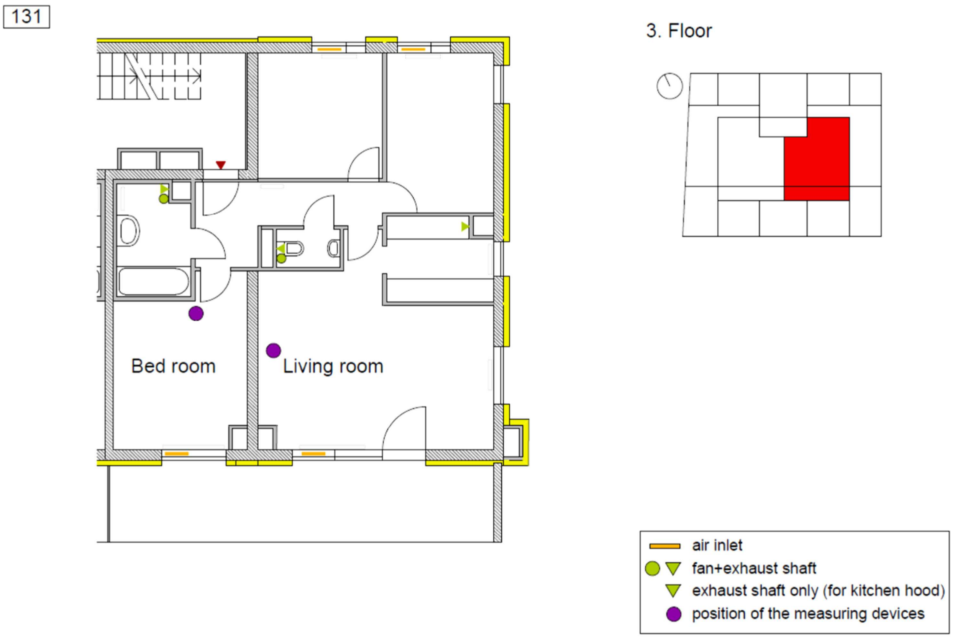

Figure 18: Floor plan, 131

In apartment 131 three occupants live on 88.90 m². One measurement device was placed in the living room on a shelf next to the dining table. In the bedroom the sensor was located on the right hand side of the entrance door. The windows are orientated to the south and to the east, as shown in Figure 18.

The next Figure (Figure 19) displays the floor plan of apartment 132.

Figure 19: Floor plan, 132

This apartment is occupied by three persons and sizes 89.40 m². The location of the sensors is marked in the floor plan of Figure 19. In Figure 20 the location of the HOBO in the living room of apartment 132 is shown.

Figure 20: Living room of apartment 132

2.2.2 Superstructure and heating

The heating of the building is provided by a district heating network (Project organiser 2008).

The construction includes two different types of exterior walls. The main exterior walls consist of reinforced concrete (25 cm) and 10 cm insulation with a U-value of 0,23 W/m²K. The other exterior walls consist of 25 cm Durisol and 10 cm insulation, here the U-value amounts 0,21 W/m²K.

The U-value of the window is 1,10 W/m²K. The g-value of the glazing is 0,51 (Project organiser 2011).

2.2.3 Demand controlled ventilation system

Elements in demand controlled ventilation systems can be activated and controlled in different ways. The aim of these systems is to adapt the airflow to the needs in each room and for each occupancy pattern. A sensor measures the amount of the relative humidity. The system reacts to these measured values. Also the activation of the system by presence or by movement detection is possible (Aereco 2011).

The observed building is equipped with a humidity-responsive ventilation system. The supply air is demand controlled and regulates the amount of fresh air which is coming in according to the local indoor relative humidity. The sensor that measures the height of the relative humidity is applied to the air inlet. Regarding the exhausted air, the remove is constantly maintained by the help of a fan in the bathroom. Additionally a fan in the toilet can be manually activated by the inhabitants on demand. To ensure the air circulation between the rooms there is a larger than usual gap under the interior doors (Aereco 2011).

The next Figure (Figure 21) presents a schema of the air distribution taking the whole apartment into account.

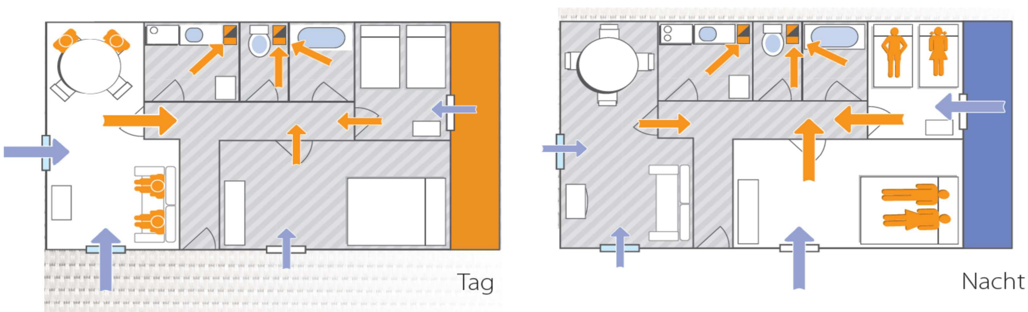

Figure 21: Distribution of air inside the apartment (Aereco 2011)

During daytime (Figure 21, left hand side) most of the supply air is needed in the living room, because it is typically the most occupied room at that time. According to the questionnaire which was given to the inhabitants at the beginning of this case study, the living room was also evaluated as the room where the inhabitants spend most of their time when they are at home.

The demand of fresh air changes during the night. The occupants produce more humidity in the bedroom while they are sleeping. At night the airflow minimises in the living room and therefore heat losses can be reduced (Aereco 2011).

The following Figure (Figure 22) displays how the supply and exhaust units work together.

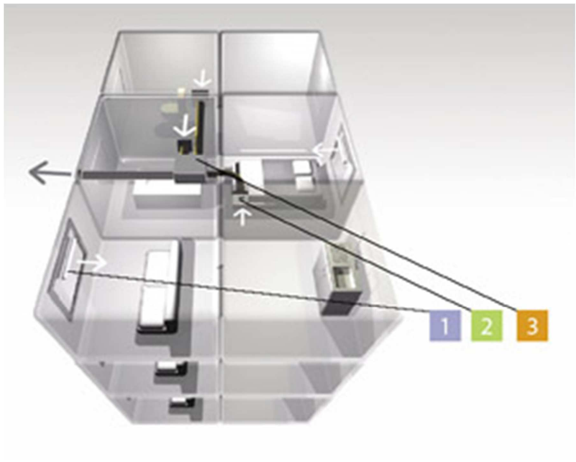

Figure 22: Demand controlled ventilation_schema (Aereco 2011)

As shown in the above presented schema (Figure 22), the system consists of air inlets (1), extract units (2) and a fan (3) (Aereco 2011). In the following these elements are explained more detailed.

Air inlet:

In airtight constructions it is necessary to control the ventilation, because ventilation through leakages or by infiltration does not take place anymore.

The air inlets are provided by Aereco ("AERation ECOnomique" – translated: economical ventilation) (Aereco 2011).

The humidity sensitive air inlets are installed on the window frames in each recreation room. Figure 23 shows an example of installation and Figure 24 a picture of an installed air inlet in apartment 112 of the selected object.

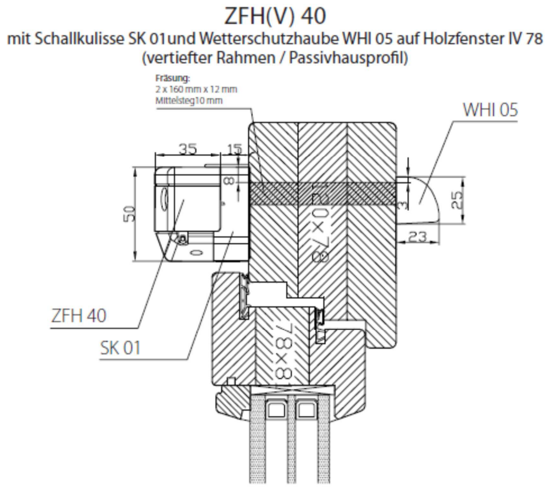

Figure 23: Installation example_ air inlet (Aereco 2011)

Figure 24: Air inlet of apartment 112

As in Figure 23 displayed the windows of the selected building have wooden frames. Figure 24 shows the important parts of the air inlet. On the internal side of the window (left picture of Figure 24) the air inlet is equipped with bands that contract and expand due to the relative humidity. With the help of these bands a shutter opens and closes. So the opening cross section changes according to the relative humidity and determines the air flow. The higher the relative humidity the wider the shutter opens (Aereco 2011).

To establish the air flow, a hole in the window frame is necessary. Hence, also acoustical and hygienic concerns have to be taken into account. The right picture of Figure 24 shows a mounted canopy on the outside part of the window. It protects the inner parts of the window and the wall against flying insects, bad weather conditions and water infiltration. Additionally an acoustical protection is installed at the inner part of the window (Aereco 2011).

Regarding the airflow Figure 25 displays a diagram of the minimum and maximum possible airflow as a function of the relative humidity at 10 Pa pressure difference.

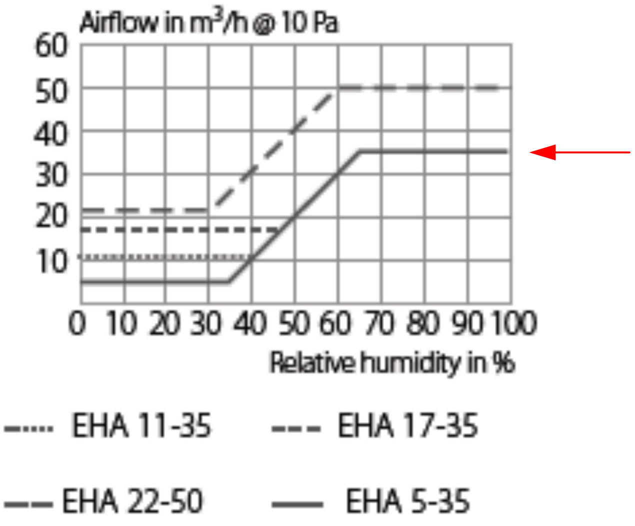

Figure 25: Airflow (Aereco 2011)

Due to the fact that there is no manual closing device, the minimum airflow is always at 5 m³/h. The highest airflow is reached at about 65% relative humidity and amounts 35 m³/h, as displayed in Figure 25.

The distribution of the incoming air is on the one hand driven by the pressure difference created by the fan in the bathroom, on the other hand especially in winter due to thermal reasons. Air inlets are installed above the windows, mounted on the window frames. Cold untreated outside air streams through these air inlets and descents to the floor. Through gaps under the interior doors it supplies for example the bathroom with fresh air. Figure 26 shows the distribution of the incoming air (Aereco 2011).

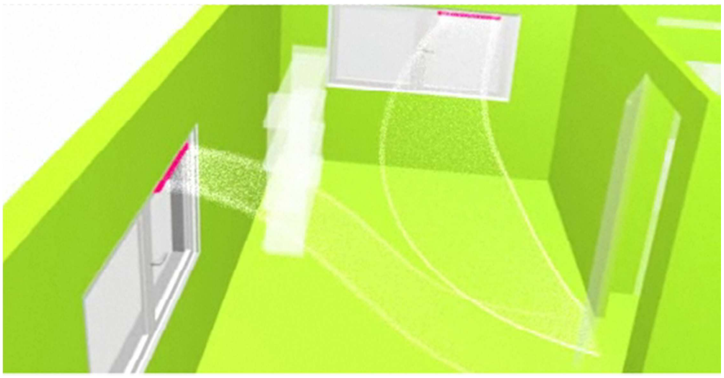

Figure 26: Automatic dispatching of the incoming air (Aereco 2011)

One problem that can occur in this context is that in the winter months the dispatched cold air maybe leads to the feeling of draft and bad comfort because of vertical temperature differences.

Aereco mentioned that to establish balanced indoor climatic conditions the extract units and fans should also be amongst others equipped with humidity sensors (Aereco 2011). The observed building in this thesis solves the problem by constant exhaust air conduction with a manually shift able increasing fan power possibility.

Extract units and fans:

A fan in the bathroom removes constantly 35 m³/h of the exhausted air. The inhabitants have the possibility to increase the air flow to 60 m³/h on demand (Helios 2010).

Additionally a fan in the toilet can be switched on. It is connected to the light switch and runs with a delay of 1-2 minutes. The fan continues running for 6-12 min after the ventilation is switched off.

The fans are provided by Helios Ventilation GmbH.

Compared to a central exhaust ventilation system the fans are situated in the bathroom and the toilet of every apartment. The main difference is that the filters have to be maintained by the inhabitants. On the one hand it is positive that if one fan is defect it does not influence the power of the other ones, on the other hand a higher effort by the inhabitants is required.

Figure 27 shows an installed fan in apartment 112.

Figure 27: Fan in the bathroom of apartment 112

In terms of the fans also the noise level should not be neglected. Helios advertises the “ultraSilence” series. At 35 m³/h 26 dB(A) are reached. At the increased power it goes up to 35 dB(A) at 60 m³/h (Helios 2010).

The questionnaire revealed that there was no disturbance because of the fan.

2.3 Measurement equipment

The indoor climatic conditions were analysed in the 11 apartments of the low-energy building. To observe the thermal comfort in the apartments, temperature and relative humidity were measured in the living room and the bedroom of every flat. The sensors were placed in these two rooms, because they represent a main role concerning the indoor environmental conditions. Additionally in every living room of the observed apartments the amount of light was measured to detect the presence of the inhabitants.

In the bedroom of apartment 101, 102, 105, 112 and 114 a CO_2 measurement device recorded the CO_2 concentrations, to be able to evaluate the indoor air quality later on. The bedroom was chosen, because especially during the night CO_2 concentration can reach high values. Hence, it is more important to observe the indoor air quality in the bedroom than in the living room. In the remaining apartments light was also measured like in the living room.

The data was collected over a period of almost five months. The first sensor was placed in apartment 103 in the middle of November. Please note that in November the results are not fully available in some apartments, due to the fact that the inhabitants were not reachable at that time. At the end of March the measurements were finished.

The inhabitants’ circumstances of living are comparable and there was no noteworthy absence during the whole measuring period.

Outdoor temperatures and relative humidity values were provided by the ZAMG (Zentralanstalt für Meteorolgie und Geodynamik). The data was collected by a weatherstation in the 22th district. Due to the fact that the weather station is near the selected object, this data displays the actual weather conditions at the building of interest very good.

Equipment:

For the measurement of the temperature, relative humidity and light HOBOs, provided by the TU Wien were used. The CO_2 measurements were performed with CO_2 sensors which were also provided by the TU Wien.

Twenty-two HOBOs (Figure 28, left side) were in use. The data loggers were placed in the bedroom and living room of each apartment. Five out of them were connected to the CO_2 sensors (Figure 28, right side) in the bedroom. Attention was given to the placement of the HOBOs. It was ensured that they are not exposed to direct sunlight and protected from water.

In an interval of five minutes the data was recorded. To read out the logged values the software "Greenline" was used. Every two weeks the battery of the HOBOs was checked and the data was saved on a PC.

Figure 28: HOBO (Onset 2011) and CO_2 sensor (Vaisala 2011)

Please note that the CO_2 sensors cannot measure values above 2100 ppm. The measured CO_2 concentration was evaluated by histograms and a box plot.

2.4 Questionnaire

To provide an evaluation of the occupants' habits and their expectations to thermal comfort a paper based questionnaire was designed. During the measurements the inhabitants had to answer questions every week concerning their satisfaction with the thermal comfort in their rooms. This questionnaire can be found in the appendix.

Also at the beginning of this study a general questionnaire was handed out to the inhabitants where information like gender, age, clothing and general ventilation behaviour in winter as well as quantity of plants, animals and aquariums in the room were gathered.

2.5 Types of analysis

In order to ensure the probands' anonymity and to recognize the position of the apartment in the building at first sight the following legend was created:

For example: 101

101 … building (only one building observed, so all numbers start with 1)

1**0**1 … The flat is situated at the ground floor (1= first floor …)

10**1** … It is situated in the east part of the building (east 1,2,3,4,5 west)

The different types of analysis: cumulative histograms, histograms, PMV and PPD, box plots, scattered plots and bar charts were used. In the following sections these are presented and described.

2.5.1 Histograms

Histograms and cumulative histograms show the frequency distribution of for example temperatures and relative humidity values at certain categories. This way to present data makes them comparable among each other. The results are presented in [%] of the time span that should be evaluated. The categories are called "bins".

In the present thesis the temperature, the relative humidity and the CO_2 concentration is evaluated and presented by the help of cumulative histograms, histograms, box plots and scattered plots.

Table 3 shows the bins for the cumulative histograms.

Table 3: Bins for the cumulative histograms

	Bins
Temperature	<12 <13 <14 <15 <16 <17 <18 <19 <20 <21 <22 <23 <24 <25 <26 <27 <28
Relative humidity	<18 <19 <20 <21 <22 <23 <24 <25 <30 <35 <40 <45 <50 <55 <60 <65 <70 <75 <78
CO_2	<200 <400 <600 <800 <1000 <1200 <1400 <1600 <1800 <2000 <2500

The temperature and the relative humidity were evaluated by histograms too.

The following table (Table 4) shows the bins that were used for the histograms.

Table 4: Bins used for histograms

	Bins
Temperature	11-12 12-13 13-14 14-15 15-16 16-17 17-18 18-19 19-20 20-21 21-22 22-23 23-24 24-25 25-26 26-27 27-28
Relative humidity	<18 18-19 19-20 20-25 25-30 30-35 35-40 40-45 45-50 50-55 55-60 60-65 65-70 70-75 75-78

2.5.2 PMV and PPD

PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) are calculation methods to assess thermal comfort. On a scale from minus three to plus three the thermal comfort is evaluated. Negative values indicate that the person feels rather cold, positive values the opposite. Values between -0.5 and 0.5 are considered as comfortable. Temperature, mean radiant temperature and relative humidity with respect to the air velocity, clothing values and metabolic rates are the parameters of the PMV and PPD evaluation (DIN 2006).

The PPD displays the percentage of people that are dissatisfied with the temperature. This value never can fall below 5% (DIN 2006).

Regarding the mean radiant temperature, calculations were conducted. The mean radiant temperature was calculated in two apartments (112 and 121) in the living room. These flats represent a case were the apartment is surrounded by other apartments (112) and a case where there is a large area of glazing and two outside walls (121). The difference to the measured indoor air temperature was maximal 0.5°C. The reason is that this building is very well insulated. Due to the fact that materials and U-values of the windows and walls are the same in every apartment and the size of the rooms is rather similar the mean radiant temperature was assumed to be the same as the measured air temperature for the calculation of PMV and PPD in all apartments.

The clothing value in the bedroom is considered to be higher, because of the existence of blankets.

To assume an adequate value of the air velocity, additional measurements were conducted. The air velocity was measured at working height in the middle of the living room and the bedroom in apartment 112. Due to the fact that the flats are rather similar the measured values can be taken for every apartment of this building. The measured values lay most of the time in both rooms beneath 0.1 m/s. Hence, this value was taken for the calculation of PMV and PPD.

Concerning the metabolic rate it was distinguished between active living in the living room and sleeping in the bedroom.

A summary of the assumptions for the PMV and PPD calculation mentioned above is presented in Table 5.

Table 5: Assumptions for the calculation of PMV and PPD

	Room	Clo [-]	Met [-]	Air velocity [m/s]
All apartments	LR	1.0	1.2	0.1
	BR	2.0	0.8	0.1

3 Results

According to the before described types of analysis the collected data was evaluated. Cumulative histograms, histograms, box plots, bar charts, PMV and PPD as well as the analysis of the questionnaire are presented in the following.

The sections are divided in the evaluation of the air quality by investigating the CO_2 concentrations and the thermal comfort analysis by the assessment of the measured temperature and relative humidity data. Finally the subjective evaluation by the inhabitants is presented.

3.1 Air quality – CO_2 concentrations

CO_2 was measured in the bedrooms of five apartments.

As a first approach the main CO_2 distribution tendency of the apartments during the whole measurement period is observed. This is done to see if the CO_2 concentration generally is rather high or low.

The following cumulative histogram (Figure 29) displays the results. Thereby the percentage of the time is shown (y-axis) for which the CO_2 concentration level was above a certain level (x-axis).

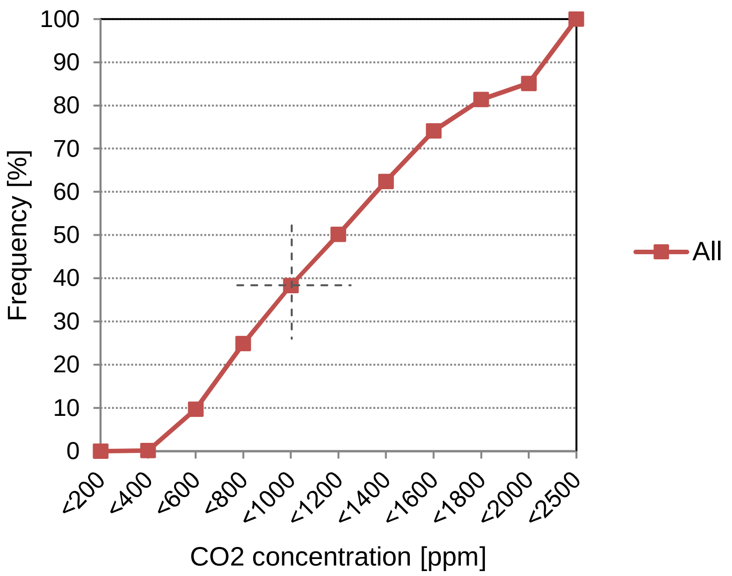

Figure 29: Cumulative frequency distribution of CO_2 concentration levels in all 5 apartments

38% of the time the measured CO_2 concentrations are below the Pettenkofer threshold of 1000 ppm.

As a next step a distinction can be established between the CO_2 concentration levels during day time and night.

Figure 30 shows a cumulative histogram that represents the differences of the CO_2 concentrations during day and night.

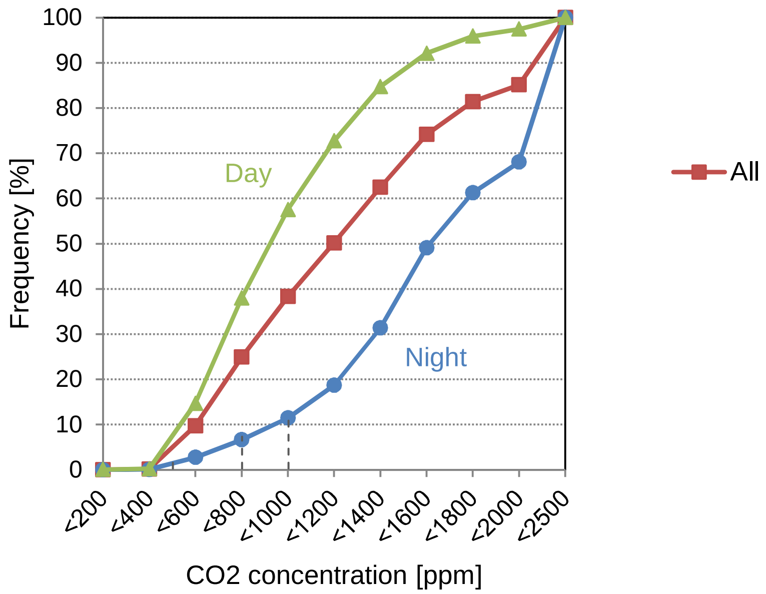

Figure 30: Cumulative frequency distribution of CO_2 concentration levels in all 5 apartments (day and night)

In the following table (Table 6) the percentage of the CO_2 concentration in the night at important benchmarks is displayed.

Table 6: Percentage of CO_2 concentration at important boundaries in all apartments at night

CO_2 concentration	Friction of time at this level
< 500 ppm	< 1%
< 800 ppm	7%
< 1000 ppm	11%

To get an overview of the frequency distribution of the CO_2 concentrations the following figure (Figure 31) shows a statistically evaluation of the concentration levels hourly, by the help of a five-number summary presented as a box plot.

The minimum, maximum, median, first and third quartile of the CO_2 concentration is displayed (y-axis) during a reference day (24 hours).

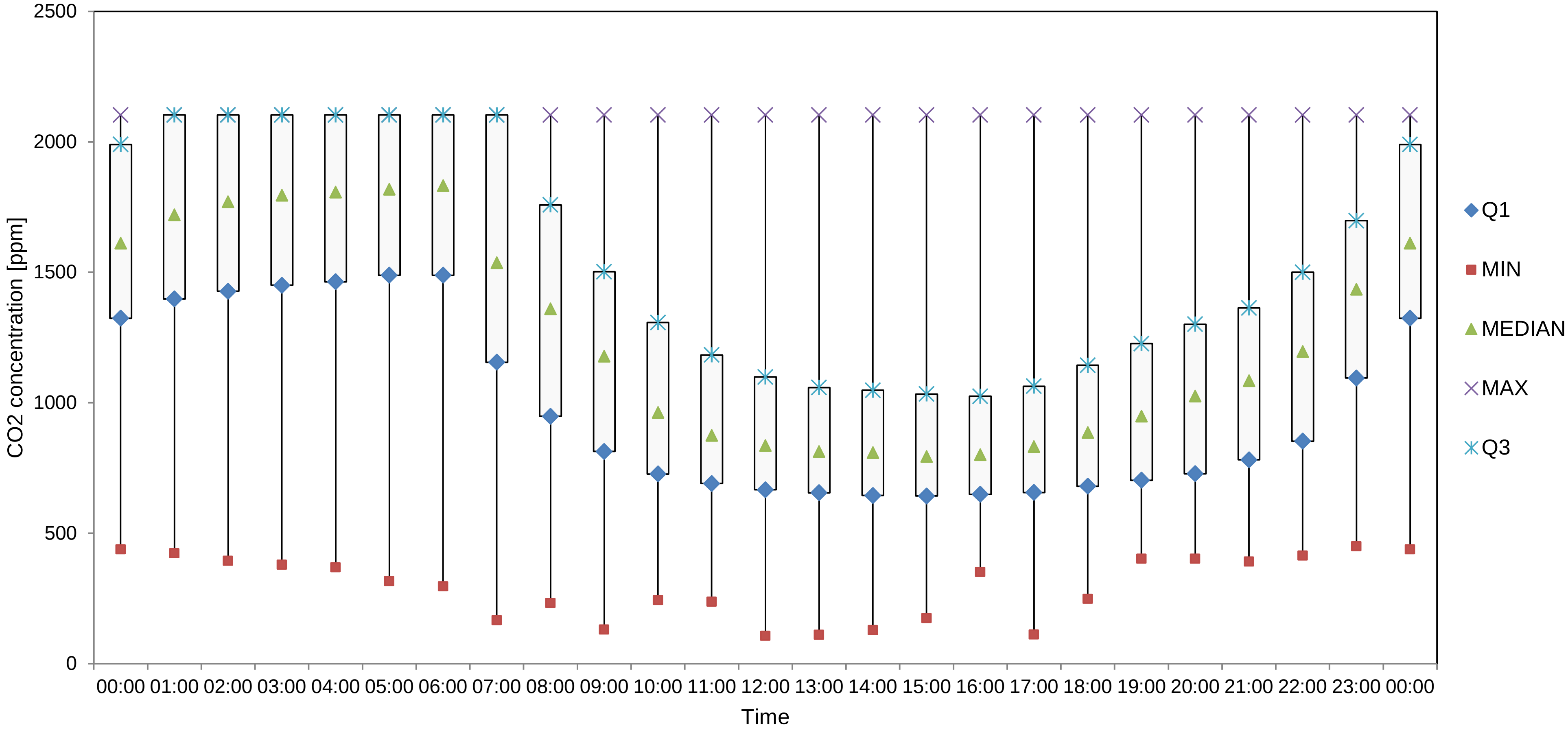

Figure 31: CO_2 concentration levels during a reference day represents the entire mean period

(Note that the maximal concentration levels in this Figure (Figure 31) are constrained due to the sensor's upper measurement range of 2100 ppm).

The scattered plot presented in Figure 32 displays the mean CO_2 concentration (x-axis) with respect to the indoor relative humidity (y-axis) in all five apartments. The correlation coefficient and the squared correlation coefficient were also calculated.

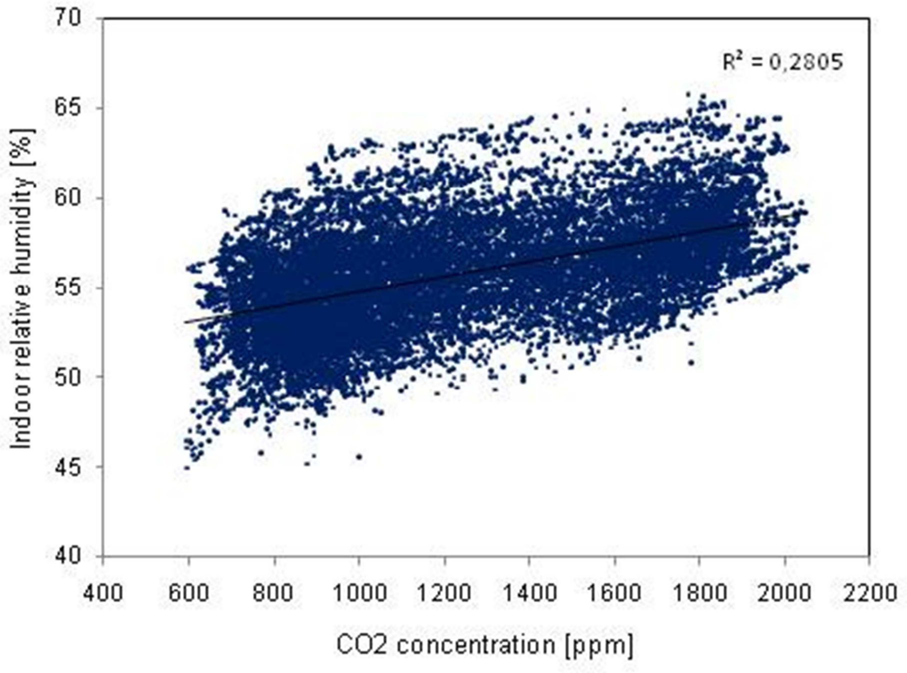

Figure 32: Correlation between the CO_2 concentration and the indoor relative humidity in all 5 apartments

The correlation coefficient between the CO_2 concentration and the indoor relative humidity in the five apartments separately is listed in Table 7.

Table 7: Correlation coefficients of the CO_2 concentration and the indoor relative humidity

Apartment	R^2 ($CO_2 – RH_i$)	R ($CO_2 – RH_i$)
101	0.3325	0.58
102	0.2094	0.46
105	0.3220	0.57
112	0.1803	0.42
114	0.1907	0.44

R ... Correlation coefficient
R^2 ... Correlation coefficient squared
CO_2 ... CO_2 concentration [ppm]
RH_i ... Relative humidity indoor [%]

The correlation between the mean CO_2 concentration in all five apartments and the external relative humidity is displayed in the scattered plot of Figure 33.

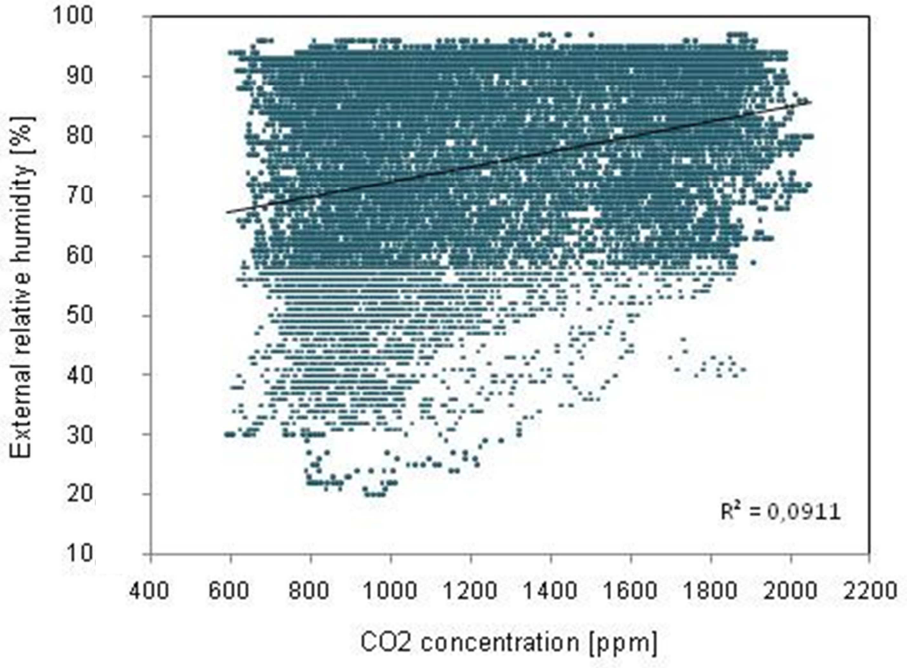

Figure 33: Correlation between the CO_2 concentration and the external relative humidity in all 5 apartments

The correlation coefficient between the CO_2 concentration and the external relative humidity in the five apartments separately is listed in Table 8.

Table 8: Correlation coefficients of the CO_2 concentration and the external relative humidity

Apartment	R^2 ($CO_2 – RH_e$)	R ($CO_2 – RH_e$)
101	0.0779	0.28
102	0.0379	0.19
105	0.0653	0.26
112	0.025	0.16
114	0.0694	0.26

R ... Correlation coefficient
R^2 ... Correlation coefficient squared
CO_2 ... CO_2 concentration [ppm]
RH_e ... External relative humidity [%]

The correlation between the mean CO_2 concentration in all five apartments and the indoor air temperature is displayed in the scattered plot of Figure 34.

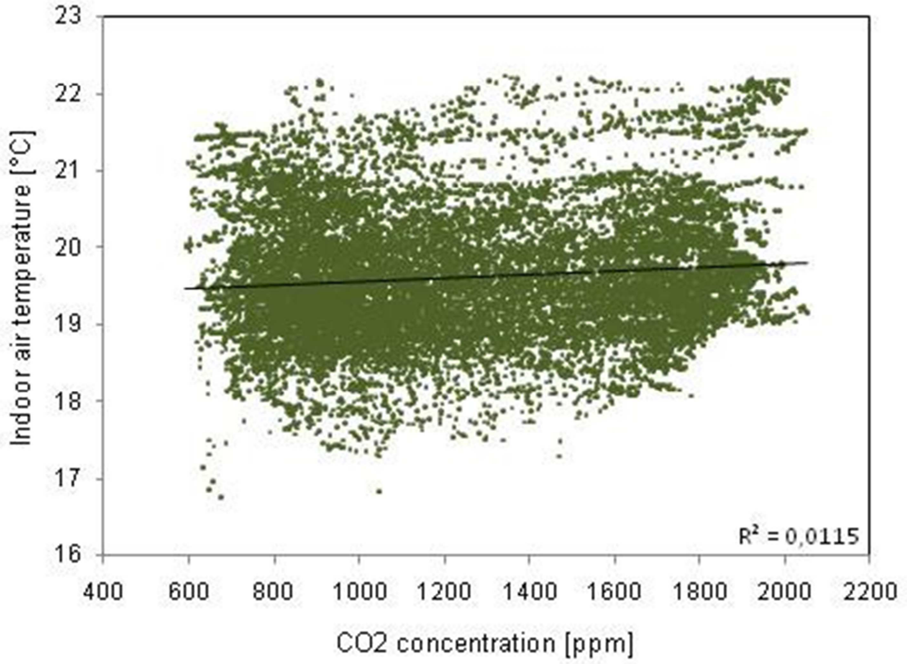

Figure 34: Correlation between the CO_2 concentration and the indoor air temperature in all 5 apartments

The correlation coefficient between the CO_2 concentration and the indoor air temperature in the five apartments separately is listed in Table 9.

Table 9: Correlation coefficients of the CO_2 concentration and the indoor air temperature

Apartment	R^2 ($CO_2 – T_i$)	R ($CO_2 – T_i$)
101	0.0002	-0.014
102	0.0999	0.35
105	0.1902	0.44
112	0.0089	0.09
114	0.0073	0.09

R ... Correlation coefficient
R^2 ... Correlation coefficient squared
CO_2 ... CO_2 concentration [ppm]
T_i ... Indoor air temperature [℃]

The correlation between the mean CO_2 concentration in all five apartments and the external temperature is displayed in the scattered plot of Figure 35.

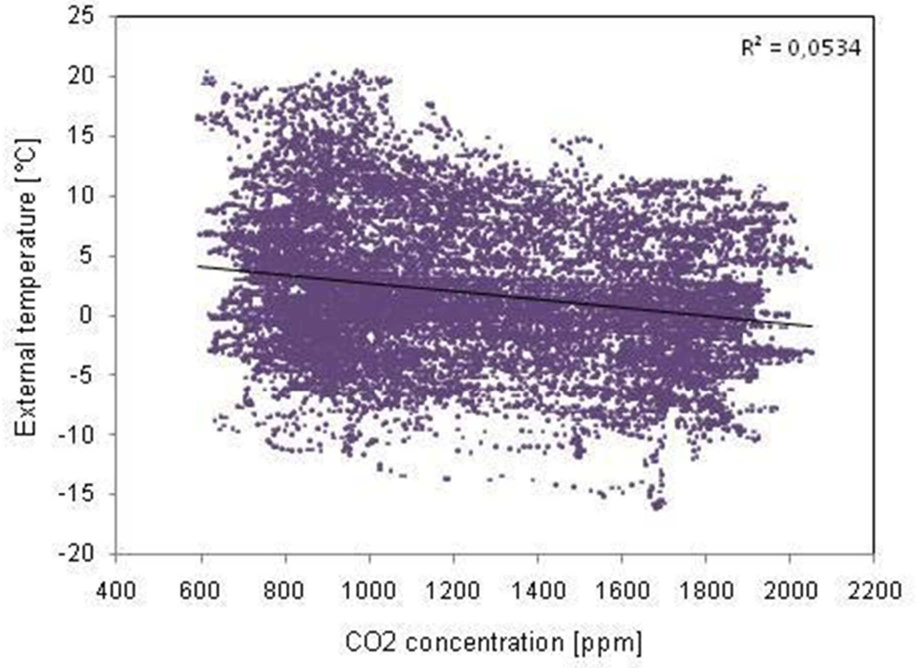

Figure 35: Correlation between the CO_2 concentration and the external temperature in all 5 apartments

The correlation coefficient between the CO_2 concentration and the external temperature in the five apartments separately is again listed in the following table (Table 10).

Table 10: Correlation coefficients of the CO_2 concentration and the external temperature

Apartment	R^2 ($CO_2 - T_e$)	R ($CO_2 - T_e$)
101	0.0851	0.29
102	0.016	0.13
105	0.0477	0.22
112	0.019	0.14
114	0.0168	0.13

R ... Correlation coefficient
R^2 ... Correlation coefficient squared
CO_2 ... CO_2 concentration [ppm]
T_e ... External temperature [°C]

In the next diagram (Figure 36) the frequency distribution of the CO_2 concentrations during the night in the apartments is shown in a cumulative histogram. The apartments are displayed separately to observe differences between each other.

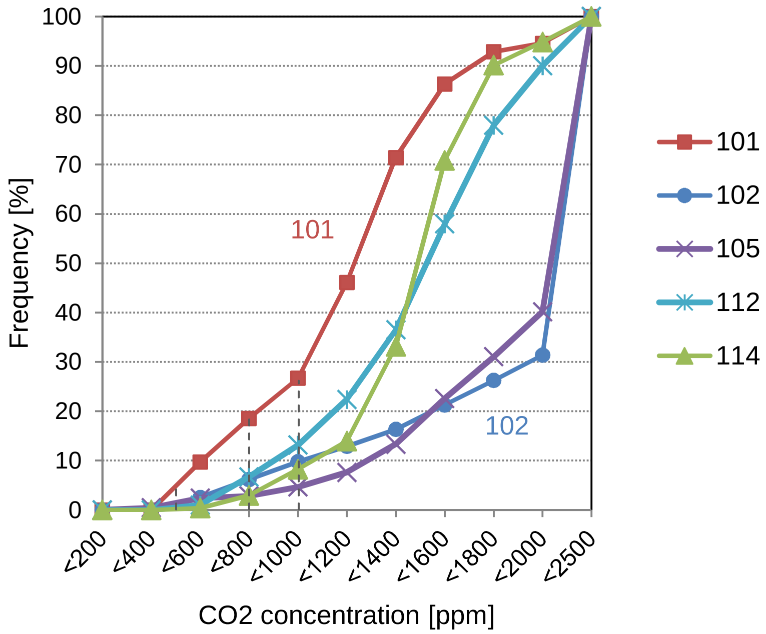

Figure 36: Cumulative frequency distribution of CO_2 concentration levels in all 5 apartments (night)

In Table 11 the most important information from the cumulative histogram in Figure 36 is summarised. The two highlighted apartments represent the apartment that performs the best (apartment 101) and the worst (102) compared to the others.

Table 11: Percentage of CO_2 concentration at important boundaries in two apartments at night

	Friction of time at this level	
CO_2 concentration	Apartment 101	Apartment 102
< 500 ppm	1%	< 1%
< 800 ppm	19%	6%
< 1000 ppm	27%	10%

3.2 Thermal comfort – Temperature and relative humidity

The two major factors that influence thermal comfort in a room are the temperature and the relative humidity. In the following two sections these factors are evaluated. The results of the temperature measurements as well as the ones of the relative humidity are presented.

At the beginning the next two figures (Figure 37 and Figure 38) show the thermal conditions outside. The mean outdoor temperatures and external relative humidity values of the observed months are displayed by bar charts.

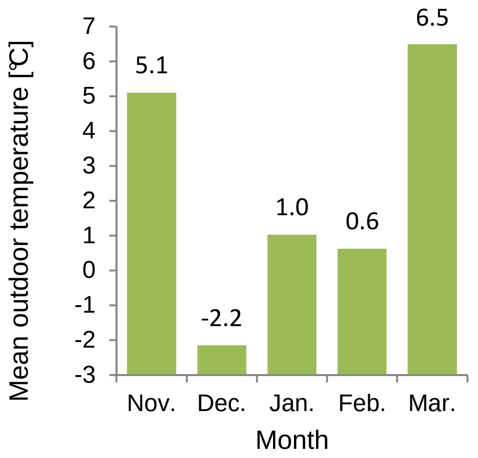

Figure 37: Mean outdoor temperature

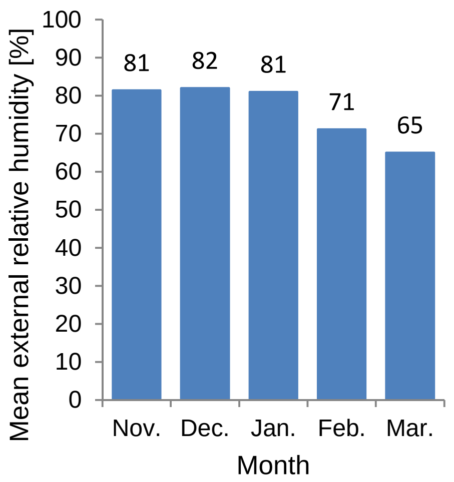

Figure 38: Mean external relative humidity

The mean outdoor temperatures differ during the measurement period with a maximum of 8.7℃. The mean external relative humidi ty differs by 17 %.

3.2.1 Temperature

This section contains the evaluation of the temperature in the observed apartments. At first a summary of all flats over the whole measuring period is presented. From the beginning the living rooms and bedrooms were evaluated separately, because the activity patterns in these two rooms as well as temperature preferences differ a lot.

First the cumulative temperature distribution of all apartments in the living room and the bedroom was explored over the whole period to show the boundaries of the measured data. The next figure (Figure 39) shows the results.

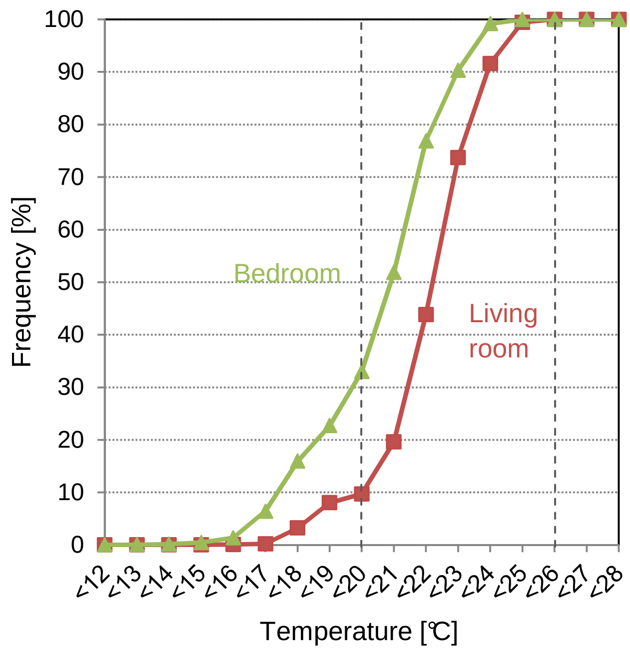

Figure 39: Cumulative frequency distribution of temperature in all apartments

In the majority of the apartments the measured temperature in the bedrooms lay most of the time about one degree lower than in the living rooms.

In the following table (Table 12) the percentage of all measured temperature values at important benchmarks is displayed.

Table 12: Percentage of temperature at important boundaries

Temperature	Friction of time at this level	
< 20 ℃	Living room: 10%	Bedroom: 33%
> 26 ℃	Living room: <1%	Bedroom: <1%

Figure 40 shows the frequency distribution of the temperature differences in one apartment (102) in the bedroom and the living room with the help of a histogram. It is an example of a flat where this difference is clearly visible.

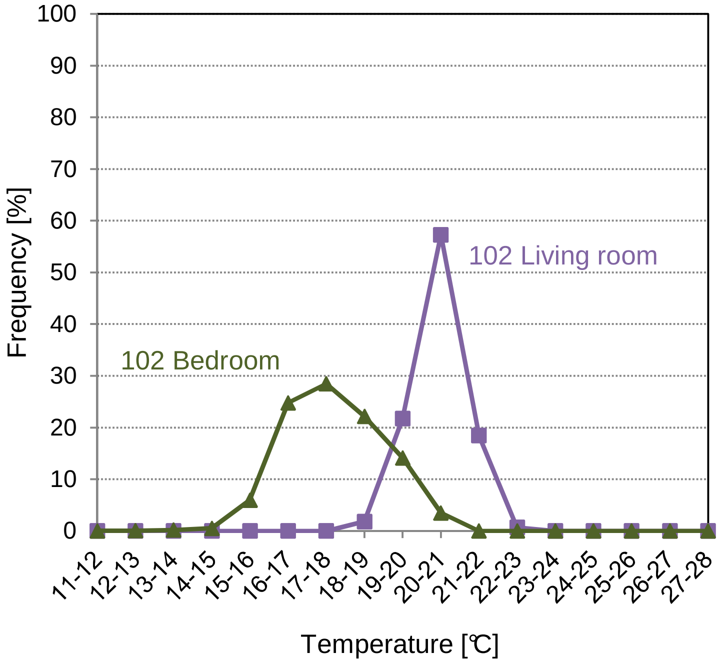

Figure 40: Frequency distribution of temperature in one apartment

As shown in Figure 40 in apartment 102 there is a broad shift towards lower temperatures in the bedroom. The temperature difference between the living room and the bedroom is 3℃.

As a next step the temperature distribution in the living room of each apartment is displayed in the following cumulative histogram (Figure 41).

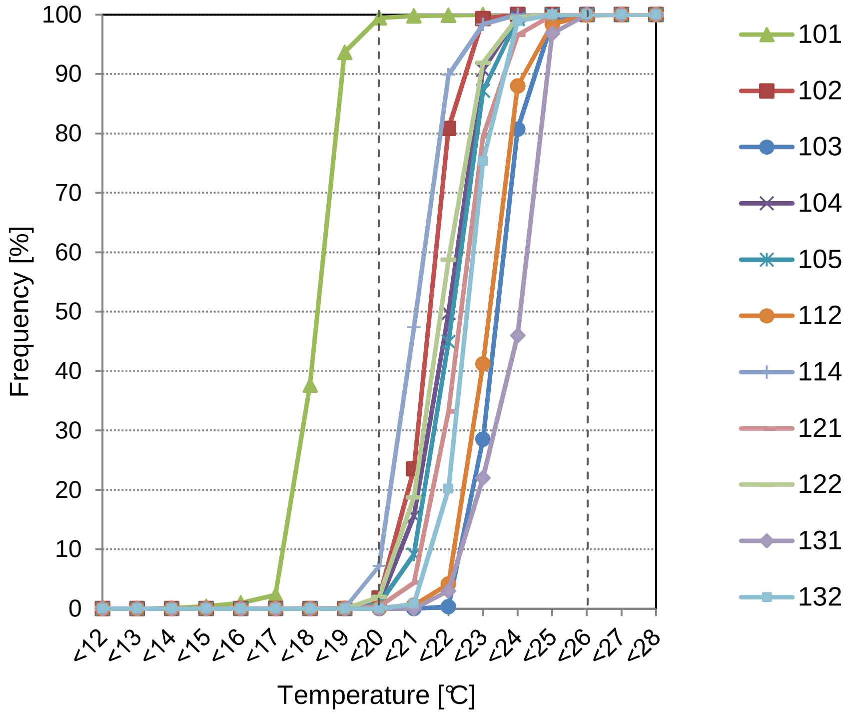

Figure 41: Cumulative frequency distribution of temperature in all apartments (living room)

The temperature is widely distributed and varies between 19℃ and 23℃ most of the time.

Noticeable is the frequency distribution of the temperature in apartment 101. In this apartment 56% of the temperatures lay between 18℃ and 19℃.

Temperatures lower than 20℃ could be measured in every apartment except in apartment 131 and 132. Values above 26℃ can be measured in apartment 103 and 112.

The widest temperature distribution was observed in apartment 121. Temperatures below 12℃ as well as values between 24℃ and 25℃ were detected.

The following figure (Figure 42) displays a statistical evaluation of the temperatures in the living room of each apartment. Results are presented by a five-number summary with the help of a box plot.

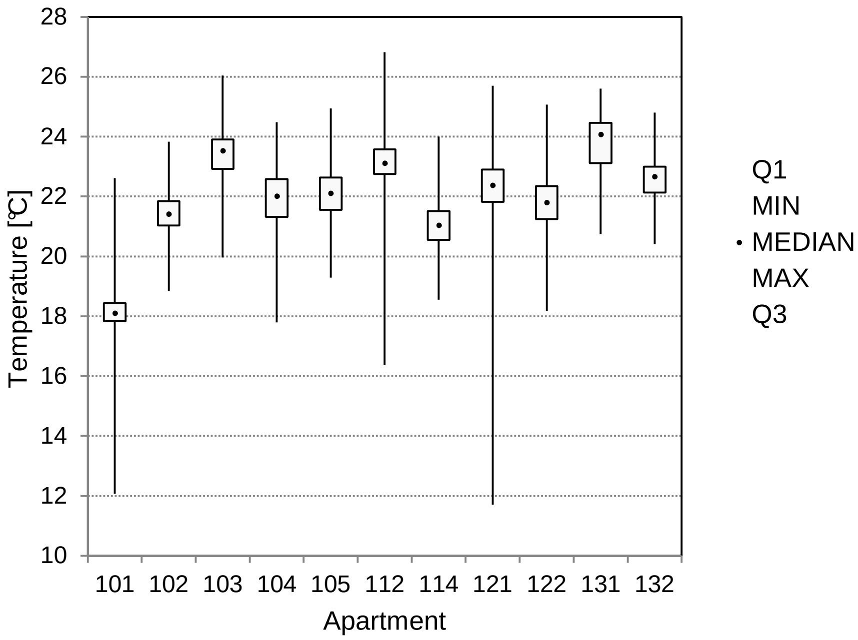

Figure 42: Statistical evaluation of the temperature in all apartments (living room)

The next diagram (Figure 43) shows the cumulative frequency distribution of the temperatures in the bedroom of all apartments during the whole measurement period.

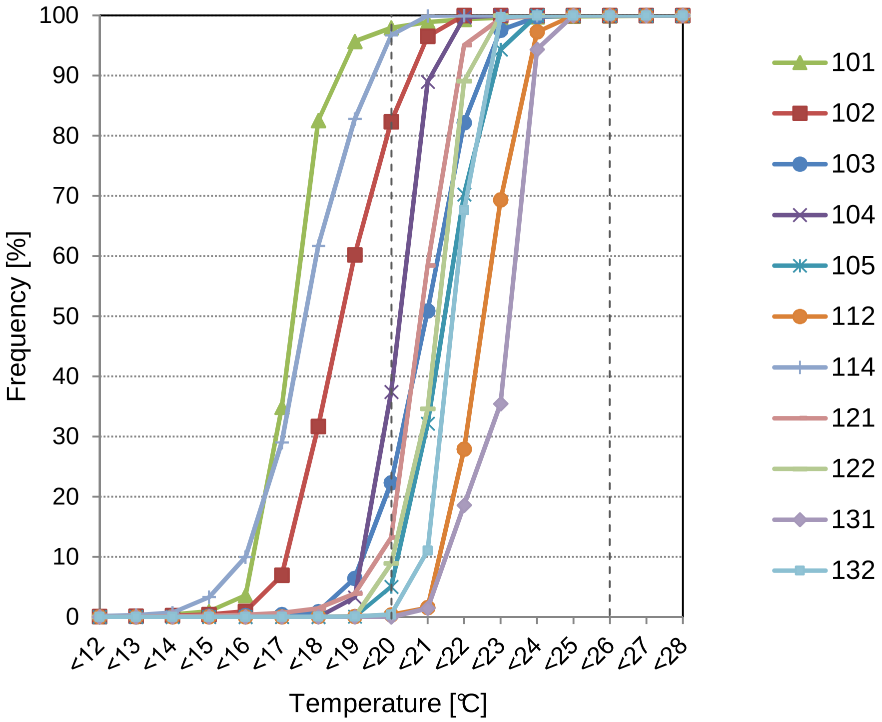

Figure 43: Cumulative frequency distribution of temperature in all apartments (bedroom)

The frequency distribution of the temperature is more widely spread than in the living rooms and varies between 15℃ and 23℃ most of the time.

Values higher than 26℃ could be detected in apartment 101 and 112. Values lower 20℃ were measured in every apartment except in apartment 131.

In apartment 101 temperatures below 8℃ as well as above 26℃ were recorded.

A statistical evaluation of the temperatures in the bedroom of each apartment is presented in the following (Figure 44). Again results are presented by a five-number summary with the help of a box plot.

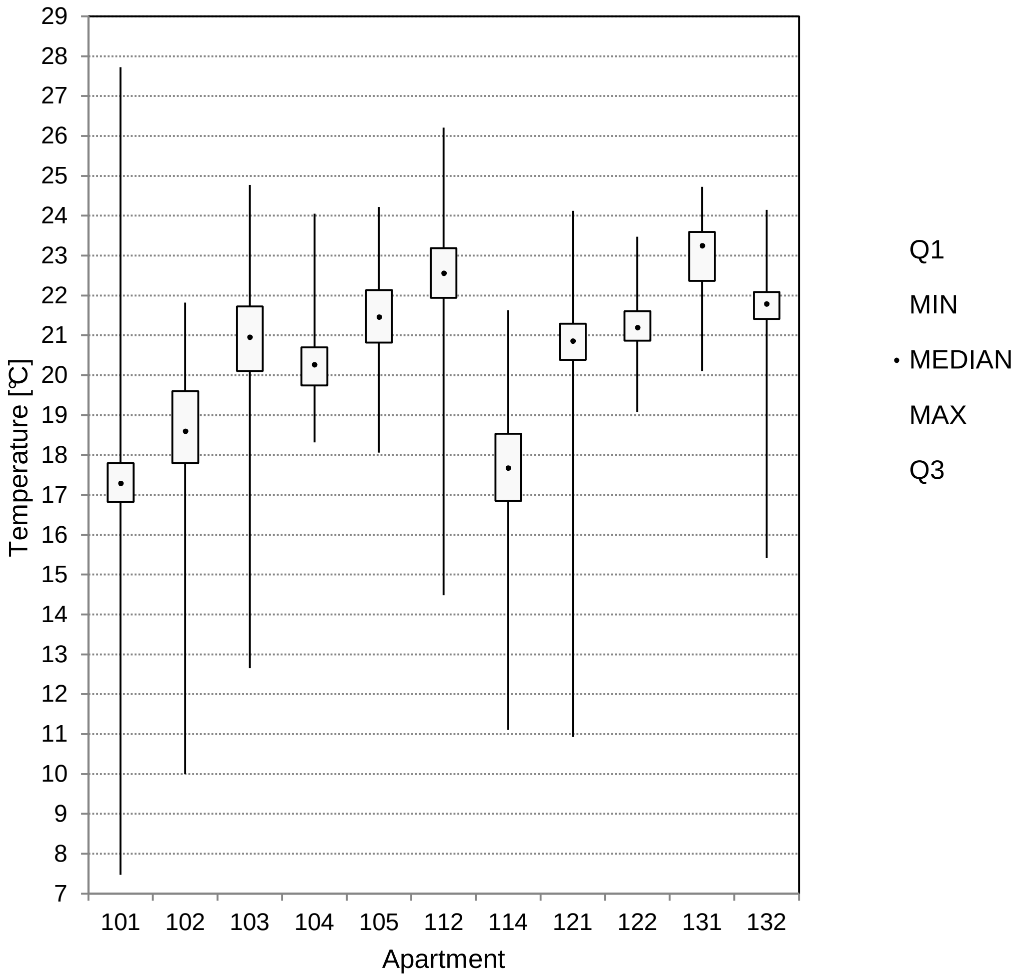

Figure 44: Statistical evaluation of the temperature in all apartments (bedroom)

3.2.2 Relative humidity

The following section contains the evaluation of the relative humidity in the observed apartments. At the beginning a summary of all flats over the whole measuring period is presented.

In Figure 45 the cumulative frequency distribution of the relative humidity values in the living room and the bedroom of all apartments over the whole measurement period can be found. The range of all occurring relative humidity values is shown by a cumulative histogram.

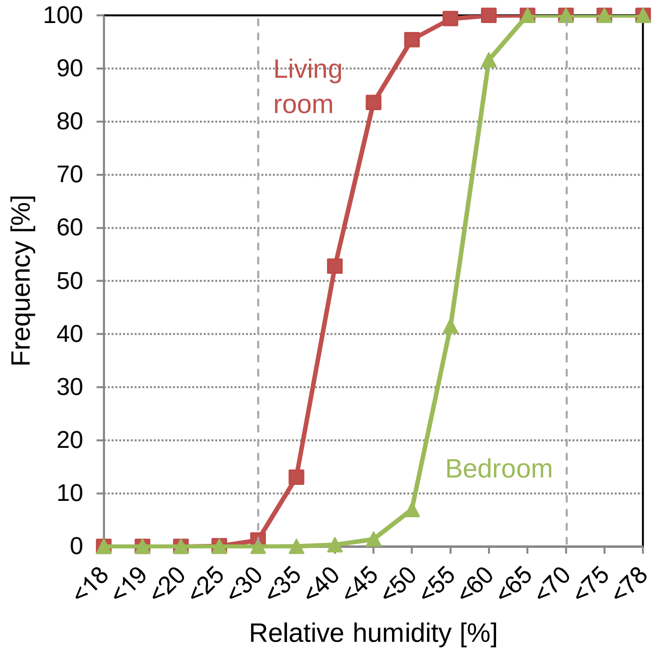

Figure 45: Cumulative frequency distribution of the relative humidity in all apartments

Relative humidity values between the range of 18.3% and 77.3% were measured.

In the following table (Table 13) the percentage of all measured relative humidity values at important benchmarks is displayed.

Table 13: Percentage of relative humidity values at important boundaries

Relative humidity	Friction of time at this level
< 30%	2%
> 70%	<1%

From the beginning the living rooms and bedrooms were evaluated separately, because the inhabitants have very different activity patterns in these two rooms. Another reason is that the results reveal that they are different in terms of the relative humidity distribution in most of the apartments which must not be neglected.

The histogram in Figure 46 shows the relative humidity distribution in apartment 105 in the bedroom and the living room as example to show the difference between these two rooms.

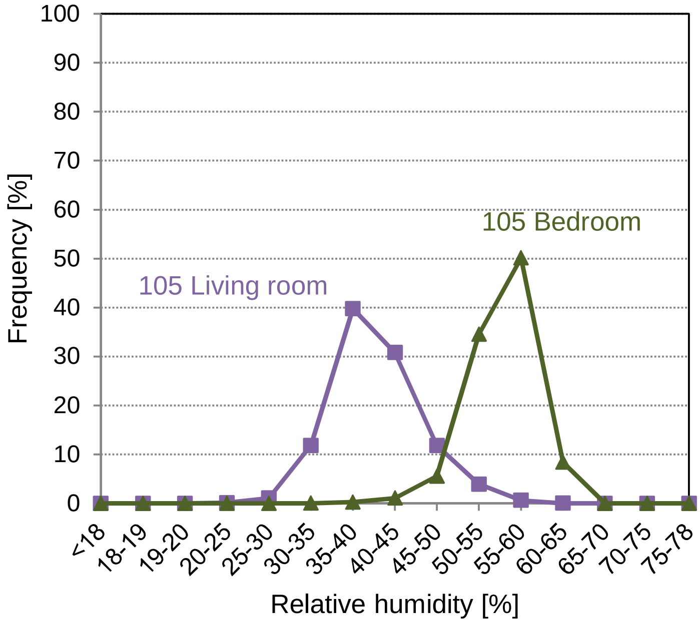

Figure 46: Frequency distribution of the relative humidity in one apartment

The results that are presented in Figure 46 reveal that for example in apartment 105 a broad shift towards higher relative humidity values in the bedroom was detected. The difference between the living room and the bedroom is 20% relative humidity.

As a next step the frequency distribution of the relative humidity in the living room of each apartment is visualised in the following cumulative histogram (Figure 47).

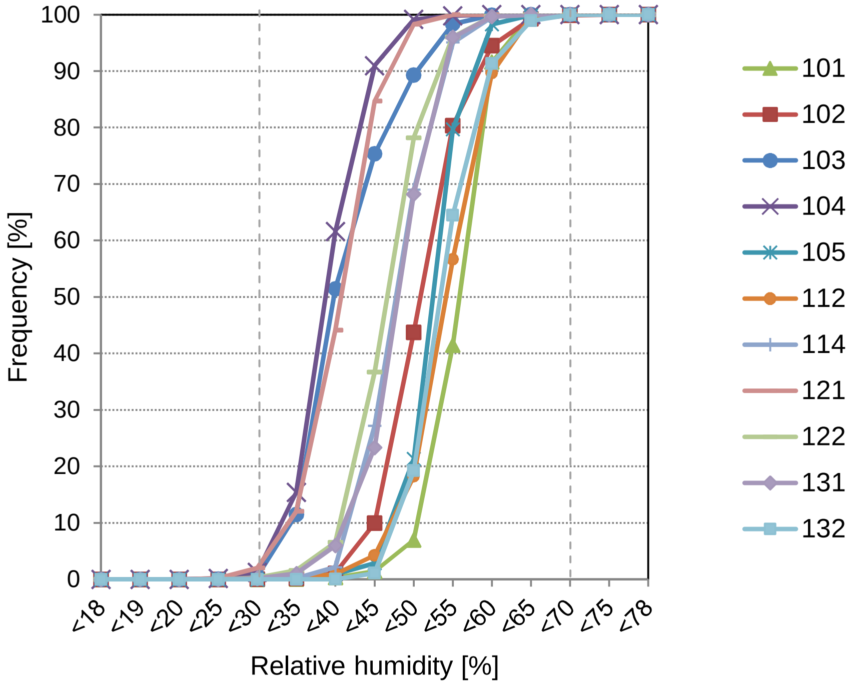

Figure 47: Cumulative frequency distribution of the relative humidity in all apartments (living room)

As displayed in Figure 47 relative humidity values are widely distributed and vary between 35% and 65% most of the time.

Relative humidity values lower than 30% could be identified in every apartment except in apartment 105 and 132.

The widest distribution was observed in apartment 102. Relative humidity values below 30% as well as values between 75% and 78% were measured.

The following diagram (Figure 48) displays the measured relative humidity values in the bedroom of each apartment.

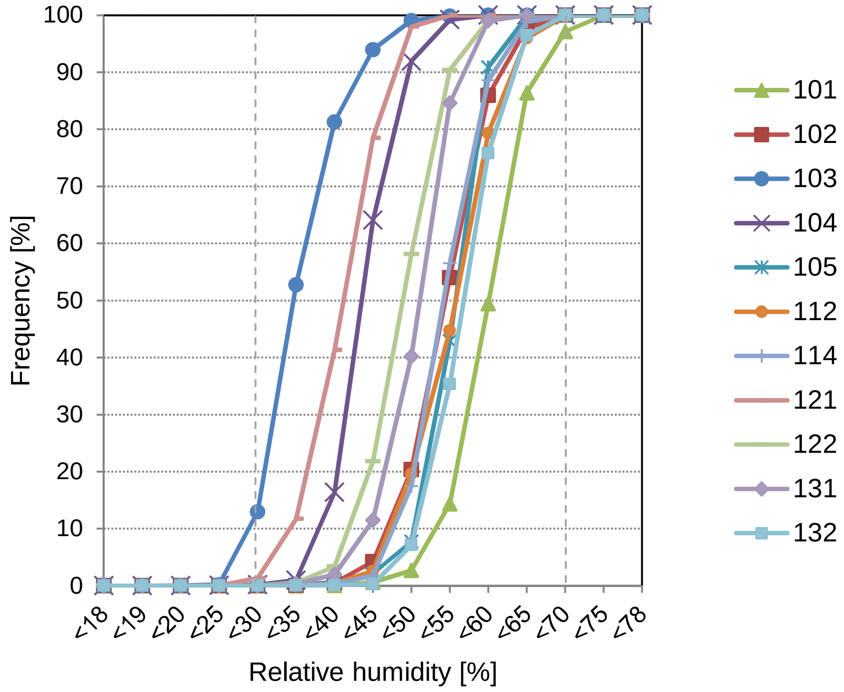

Figure 48: Cumulative frequency distribution of the relative humidity in all apartments (bedroom)

Relative humidity values in the bedrooms are more widely distributed than in the living rooms.

In apartment 103 the relative humidity is noticeable lower than in the other apartments.

Relative humidity values lower than 30% could be identified in six apartments (102, 103, 104, 112, 121 and 122).

3.2.3 Absolute humidity

The results displayed in the previous sections (3.2.1 Temperature and 3.2.2 Relative humidity) reveal that some apartments have indeed high relative humidity values, but at the same time rather low temperatures for example. Due to this fact it is reasonable to show the gram of moisture per kilogram of dry air, so to say the absolute humidity values in all apartments.

The following cumulative histogram (Figure 49) displays the frequency distribution of the absolute humidity in the living room and the bedroom of all apartments.

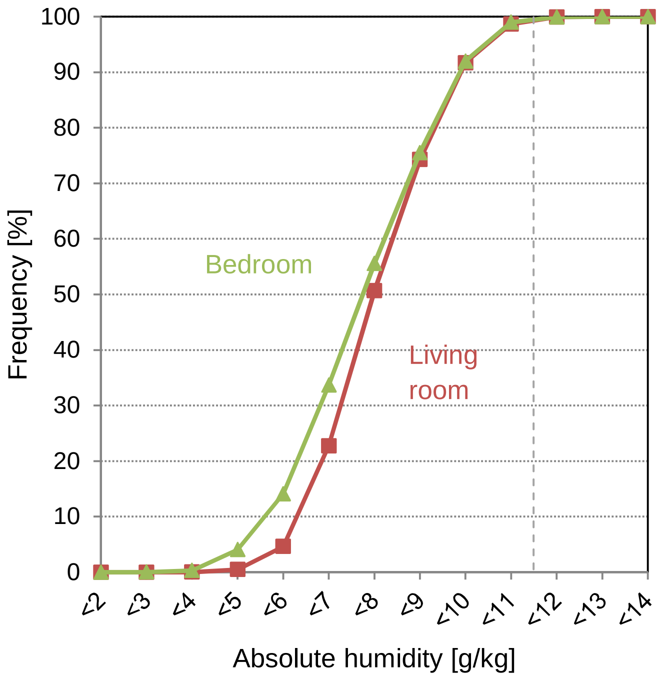

Figure 49: Cumulative frequency distribution of the absolute humidity in all apartments

According to VDI 4706 the absolute humidity should not lie above 11.5 g/kg. (VDI 2009).

In the following table (Table 14) the percentage of all calculated absolute humidity values at an important benchmark is displayed.

Table 14: Percentage of absolute humidity values at an important benchmark in all apartments

Absolute humidity	Friction of time at this level
> 11.5 g/kg	Living room and Bedroom: <1%

The cumulative frequency distribution of the absolute humidity in the living room of each apartment is displayed in the following figure (Figure 50).

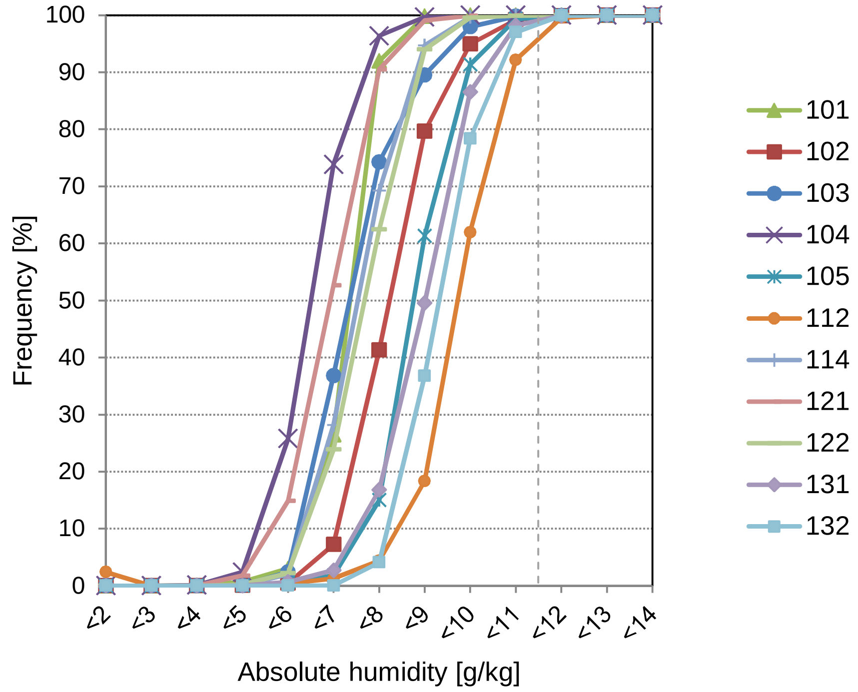

Figure 50: Cumulative frequency distribution of the absolute humidity in all apartments (living room)

The distribution of the absolute humidity is in the range from 3 g/kg to 13.3 g/kg.

In the following table (Table 15) the percentage of the calculated absolute humidity values in the living room of two apartments at an important benchmark is displayed.

Table 15: Percentage of absolute humidity values at an important benchmark in two apartments (living room)

Absolute humidity	Friction of time at this level
> 11.5 g/kg	Apartment 112: 2%
	Apartment 131: 1%

The following cumulative histogram (Figure 51) displays the cumulative frequency distribution of the absolute humidity in the bedroom of each apartment.

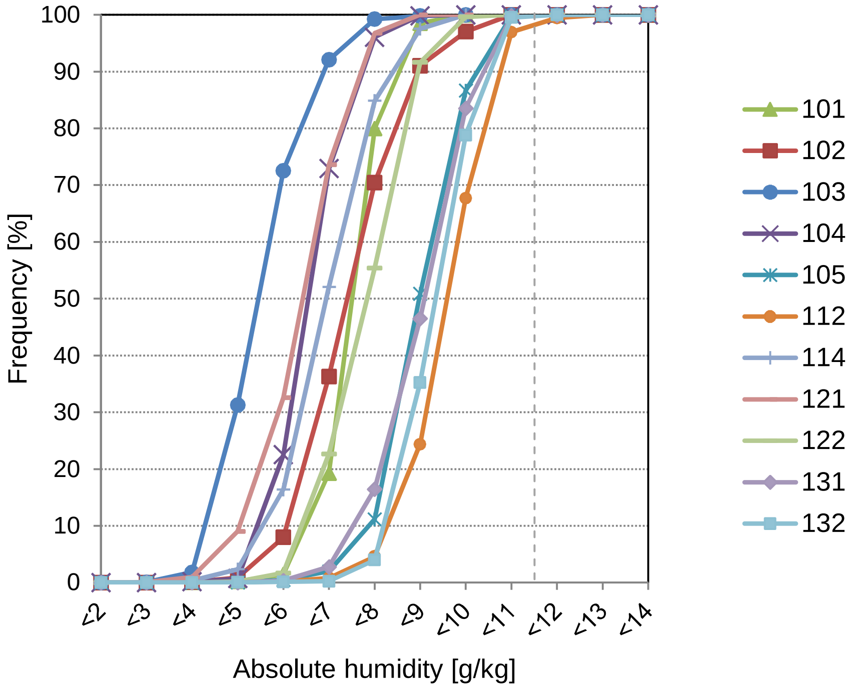

Figure 51: Cumulative frequency distribution of the absolute humidity in all apartments (bedroom)

The minimum amount moisture per kilogram of dry air in the bedroom is 2.3 g/kg and the maximum absolute humidity is 13 g/kg.

In the following table (Table 16) the percentage of the calculated absolute humidity values in the bedroom of two apartments at an important benchmark is displayed.

Table 16: Percentage of absolute humidity values at an important benchmark in two apartments (bedroom)

Absolute humidity	Friction of time at this level
> 11.5 g/kg	Apartment 112: 3%
	Apartment 131: <1%

3.3 Thermal comfort – PMV and PPD

PMV and PPD are approaches to assess thermal comfort. PMV calculation takes the clothing value, the metabolic rate and the air velocity into account (DIN 2006). In the following sections the frequency distribution of the calculated PMVs is displayed by the help of histograms. At the end the PPD results are listed in a table.

3.3.1 PMV

The PMV can be described in a scale from minus three to plus three. In terms of temperature negative values indicate that the inhabitant will evaluate the temperature as rather cold, whereas positive values represent that the person feels rather warm. Values between -0.5 and 0.5 are considered as comfortable (DIN 2006).

The evaluation was done for the living rooms and bedrooms of each apartment separately, because activity patterns, clothing values as well as the relative humidity and the temperature differs between these two rooms.

Figure 52 displays the PMVs of the living rooms of apartment 101, 102, 103, 104 and 105 over the whole measuring period valued at assessed frequencies. Apartment 101 and 105 are maisonettes. The other apartments are situated at the ground floor of the building.

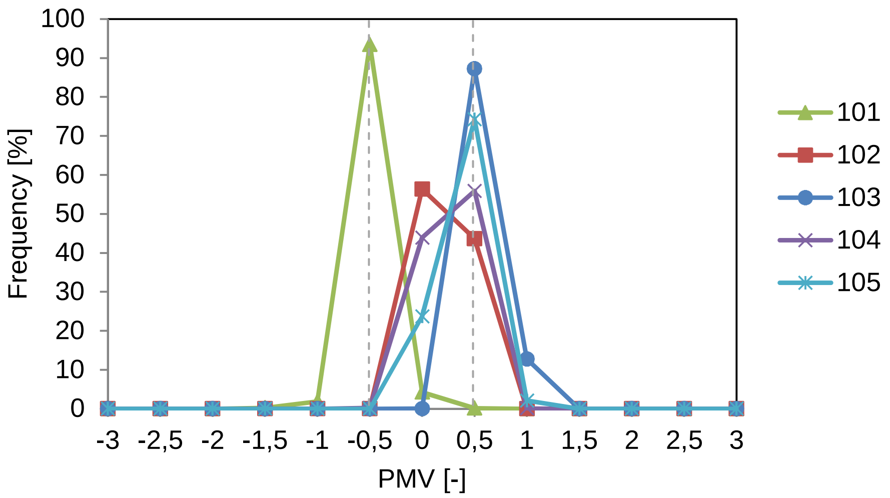

Figure 52: Frequency distribution of the PMVs in the apartments at the ground floor (living room)

The figure above (Figure 52) reveals that all living rooms in the apartments in the ground floor perform quite well. Nearly all of the measured data points lie within the values of -0.5 and 0.5.

The following histogram (Figure 53) shows the results of the PMV calculation for the apartments in the remaining three floors of the building.

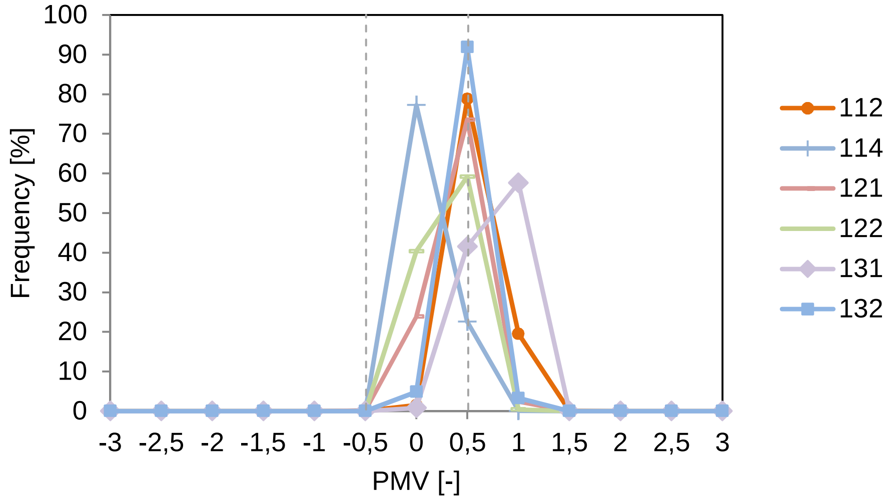

Figure 53: Frequency distribution of the PMVs in the apartments at the upper floors (living room)

Figure 53 shows the results of the PMV in the living rooms of the remaining apartments. Like in the ground floor the PMVs lie inside the area that is perceived from most of the people as comfortable.

In apartment 131 the results reveal that there are rather warm temperatures.

In apartment 112 the indoor air is predicted as sometimes also slightly too warm. The inhabitants in this apartment mentioned in the questionnaire that they usually dress during the winter months indoor like they do in summer and therefore the predicted too warm temperatures may not be a problem.

Figure 54 and 55 display the PMVs of the bedrooms of the apartments. First again the results of the maisonettes (101 and 105) and the apartments in the ground floor are shown, in the second histogram (Figure 55) the results of the remaining ones.

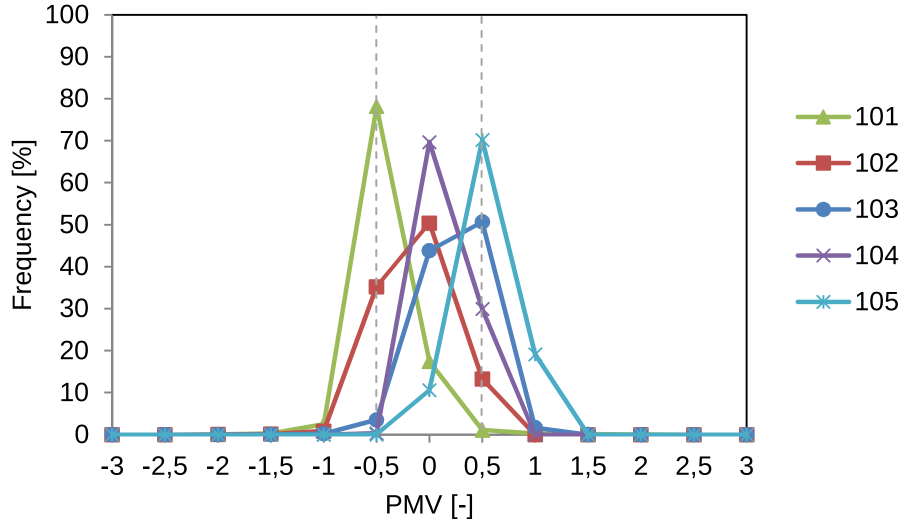

Figure 54: Frequency distribution of the PMVs in the apartments at the ground floor (bedroom)

The PMV values presented in the above figure (Figure 54) reveal that most of the calculated PMVs lie within the range of -0.5 to 0.5.

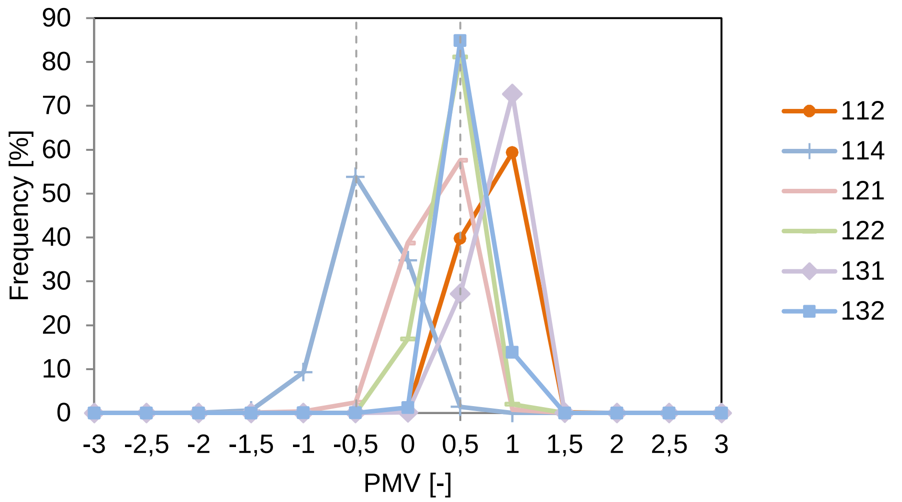

Figure 55: Frequency distribution of the PMVs in the apartments at the upper floors (bedroom)

Again in apartment 131 the temperature is predicted as slightly warmer than in the other apartments. In apartment 112 temperatures are rather warm too.

The frequency distribution in apartment 131 of the PMV results for each month in the living room (Figure 56) and the bedroom (Figure 57) is displayed in the following histograms.

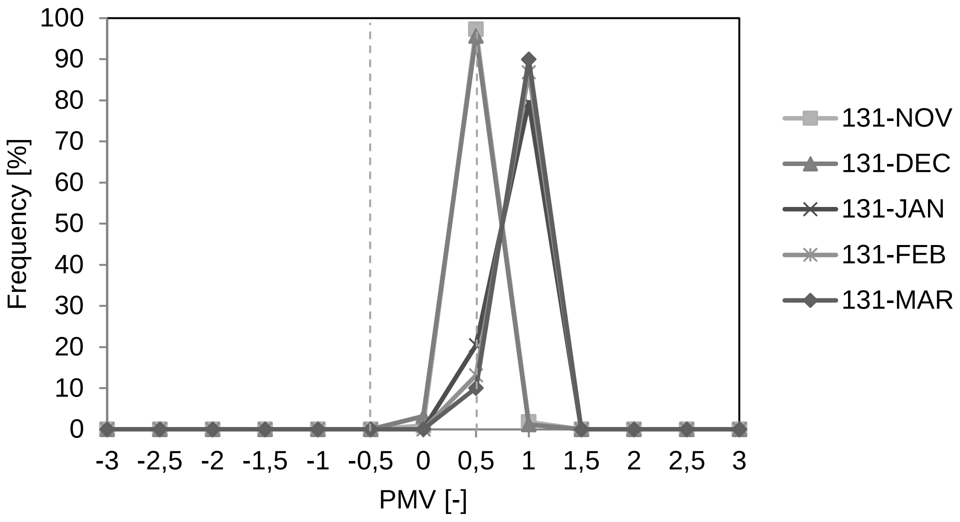

Figure 56: Frequency distribution of the PMVs per month in one apartment (living room)

Figure 56 and Figure 57 display that the higher PMV values occur in the living room and the bedroom in January, February and March and in the bedroom also in November.

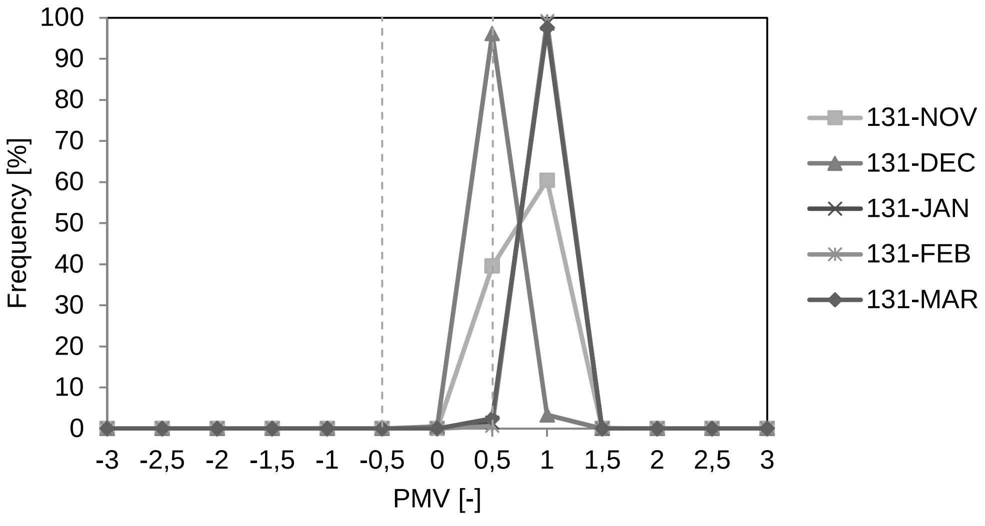

Figure 57: Frequency distribution of the PMVs per month in one apartment (bedroom)

3.3.2 PPD

In this section the predicted percentage of dissatisfied (PPD) for each apartment, room and month is evaluated. The following table (Table 17) presents the results of the PPD evaluation.

Table 17: All apartments_PPD [%]

		Month						
Apartment	Room	NOV	DEC	JAN	FEB	MAR	Average	Both rooms
101	LR	11.4	16.3	16.0	16.1	15.9	15.9	15.2
	BR	11.3	17.4	15	14.7	11.4	14.6	
102	LR	5.4	5.8	5.5	5.4	5.3	5.5	7.6
	BR	6.7	11	9.7	11.7	8.3	9.8	
103	LR	6.0	6.9	8.4	9.5	8.4	8	7.3
	BR	6.8	7.6	6	6.4	6.3	6.6	
104	LR	5.6	5.8	5.9	5.6	5.6	5.7	5.7
	BR	5.4	5.5	5.9	5.8	5.9	5.7	
105	LR	6.6	6.2	6.1	6	5.8	6.1	7
	BR	10.1	6.2	8.5	8	8.1	7.9	
112	LR	11.3	8.4	8.2	8.0	8.5	8.6	10.3
	BR	18	15.2	8.5	12.3	8.3	9.5	
114	LR	5.3	6.0	5.6	6.1	6.1	5.9	10.3
	BR	8.5	18	14	18.8	11.4	14.8	
121	LR	-	6.3	6	5.9	5.9	6.0	6.1
	BR	-	5.9	6	6.3	6.3	6.1	
122	LR	5.3	5.7	6.5	5.6	5.6	5.8	6.0
	BR	6.2	5.5	6.6	6.0	6.6	6.2	
131	LR	7.3	6.3	12.4	12.8	12.6	10.7	12.2
	BR	13.4	7.0	16	15.9	16.5	13.8	
132	LR	6.9	5.9	7.1	6.5	7.2	6.7	7.4
	BR	7.4	6.6	9	8.8	8.5	8.1	

3.4 Subjective evaluation by the inhabitants

Due to the fact that before this study was conducted some of the inhabitants complained about bad indoor climatic conditions in winter, questionnaires were designed to quantify the problems. It was also necessary to declare which area they address.

As a first step a questionnaire at the beginning was handed out to get an overview of the inhabitants. Table 18 shows a summary of the evaluation.

Table 18: Summary of the relevant influencing factors of the indoor climatic conditions

	Air humidifier		Eat-in kitchen	Aquarium	
Apartment	LR	BR		LR	BR
101	-	-	-	-	-
102	-	-	x	-	-
103	-	-	x	-	-
104	-	-	x	1	-
105	-	-	-	1	-
112	-	-	x	2	-
114	-	-	x	-	-
121	-	-	x	-	-
122	-	-	-	-	-
131	x	x	-	-	-
132	-	-	-	-	-

The inhabitants had the possibility to rate the indoor climatic conditions by a paper based questionnaire that was handed out weekly.

Following questions were generated:

- Do you have the need to open your windows more often than usual?
- Do you need to switch on the increased ventilation in the bathroom?
- How do you perceive the current temperature in the living room/bedroom?
- How do you perceive the current humidity in the living room/bedroom?
- How do you evaluate the indoor climate in general in the last week? Why?

Furthermore they were able to insert handwritten additional comments at the end of the questionnaire.

The before mentioned questions (except the first one) had five possible answers and were structured in a scale from -2 to +2. Regarding the different categories this means:

Bathroom ventilation increased: from -2 (never) to +2 (every time when needed)
Current temperature: from -2 (too cold) to +2 (too hot)
Current humidity: from -2 (too dry) to +2 (too humid)
Indoor climate in general: from -2 (very bad) to +2 (very good)

The first question concerning the necessity of opening windows had only three possible answers and was evaluated by -1 (less often than usual) to +1 (more often than usual) to highlight the tendency.

The following diagram (Figure 58) displays the mean values of the answers in all the apartments during the entire period to the question:

- Do you have the need to open your windows more often than usual?

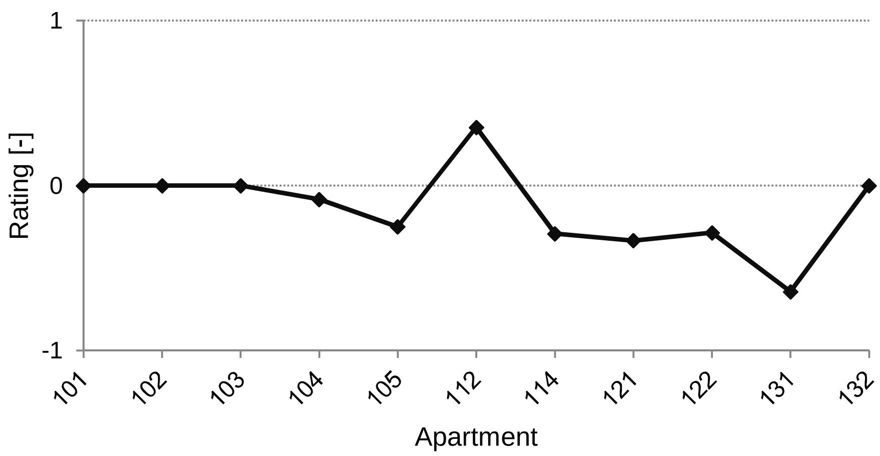

Figure 58: Rating of the need to open the window due to thermal discomfort of all apartments

In Figure 58 it is visible that over the entire measuring period in apartment 112 the inhabitants get the impression to have to open their windows more often than usual.

The result of the same question monthly evaluated in apartment 112 is shown in Figure 59.

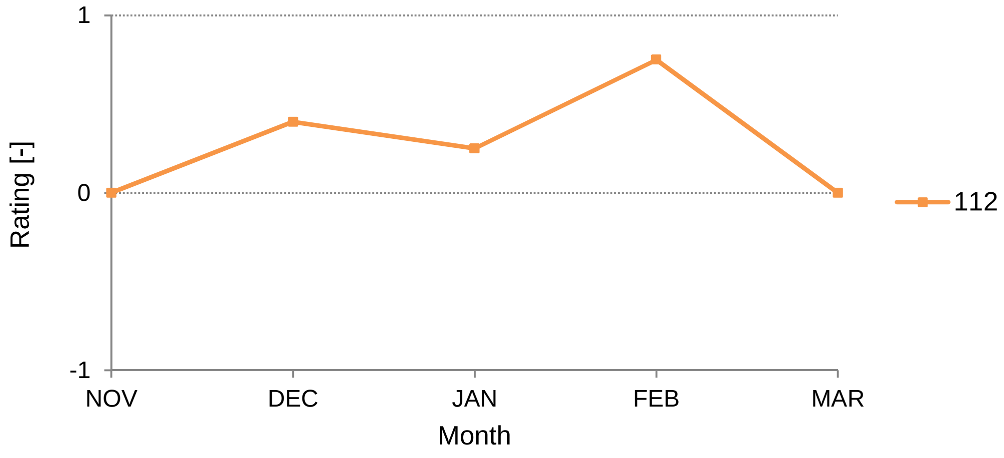

Figure 59: Rating of the need to open the window due to thermal discomfort in one apartment

The evaluation of the need to increase the ventilation in the bathroom is shown in the following diagram (Figure 60).

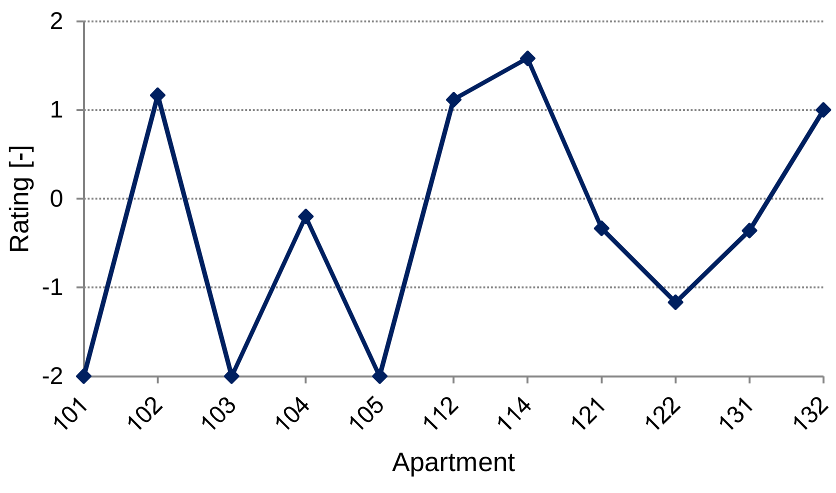

Figure 60: Rating of the need to increase the ventilation due to thermal discomfort in all apartments

Figure 60 gives information about the tendency how often the ventilation was increased by the inhabitants. The fan in the bathroom was switched on most often in apartment 114.

The rating of the next question is displayed in the below presented diagram (Figure 61).

- How do you perceive the current temperature in the living room/bedroom?

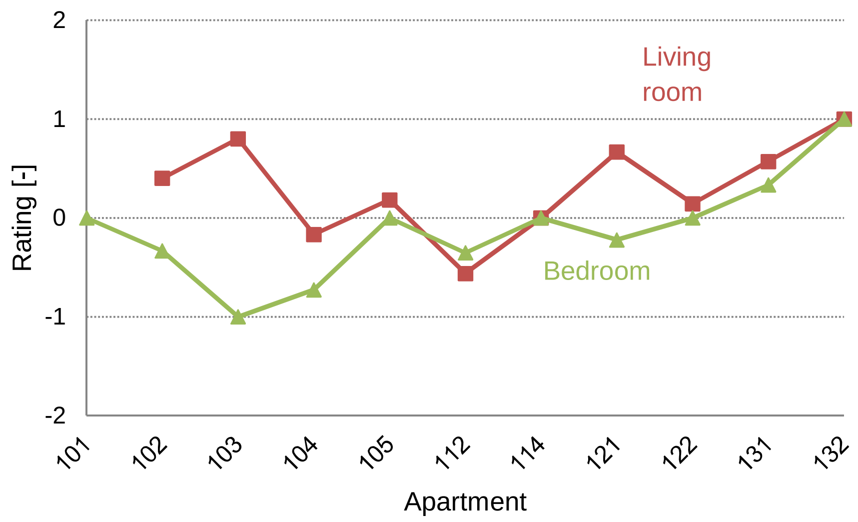

Figure 61: Rating of the temperature in all apartments

Regarding the following question the results are displayed in Figure 62.

- How do you perceive the current humidity in the living room/bedroom?

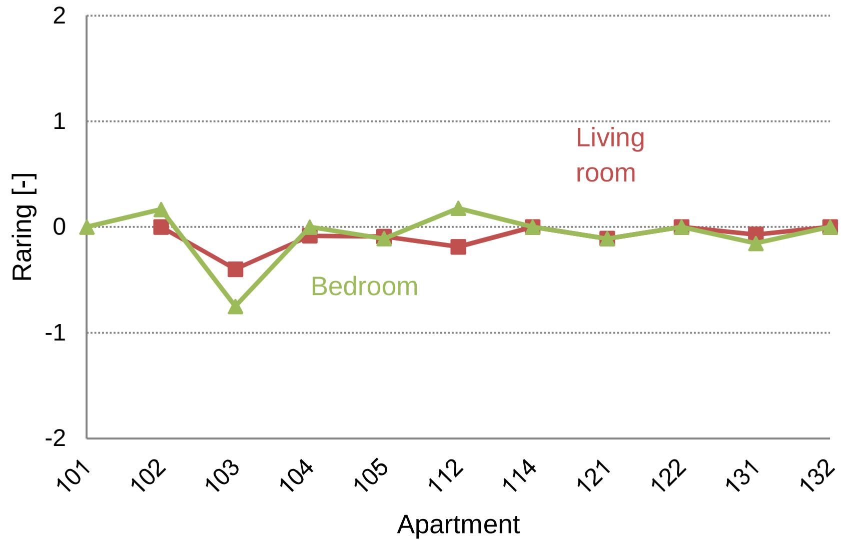

Figure 62: Rating of the relative humidity in all apartments

The inhabitant in apartment 103 suffers from rather low humidity in the bedroom as well as in the living room.

Figure 63 displays that the overall satisfaction with the indoor climatic conditions is rather good.

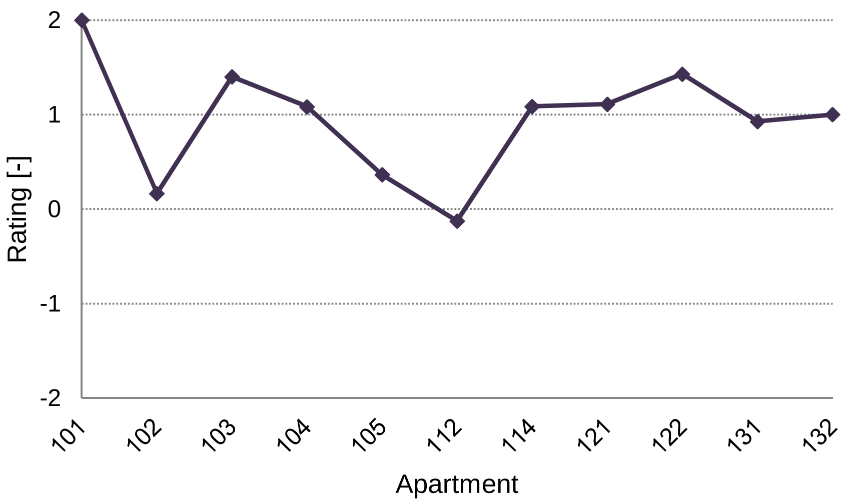

Figure 63: Rating of the overall satisfaction with the indoor climatic conditions in all apartments

4 Discussion

In this chapter central findings based on the collected data are discussed.

4.1 Air quality

The evaluation of the CO_2 concentration in the bedroom of five apartments reveals that the mean concentration of the apartments is very poor as displayed in Figure 29 (62% > 1000 ppm).

Especially during the night the CO_2 concentrations are significantly higher than during the day (89% > 1000 ppm) (see Figure 30). Generally the CO_2 concentrations rise significantly in the evening and during the night (see box plot in Figure 31).

At night even in the best performing apartment (apartment 101) the CO_2 concentrations are only about 20% of the time below 800 ppm (see Figure 36). Values below 800 ppm represent according to DIN EN 15251 (DIN 2007) acceptable levels.

The increasing CO_2 concentration at night can be explained by:

- The increasing presence of the inhabitants and/or
- Insufficient ventilation

According to the questionnaire all of the inhabitants are in the bedroom during the night, so the increasing CO_2 due to the increased presence of the inhabitants is established. There are always two persons sleeping at night in the bedroom in all apartments.

The humidity-responsive ventilation reacts to the indoor relative humidity. Till a relative humidity of 35% it has a minimum airflow of 5 m³/h. From 35% - 65% relative humidity it increases the airflow and reaches the maximum opening position at 65% indoor relative humidity with an airflow of 35 m³/h.

As displayed in Figure 32, there is almost no correlation between the indoor relative humidity and the CO_2 concentration. Hence, the ventilation must be regarded as insufficient to maintain acceptable CO_2 concentrations.

Regarding the relative humidity values in the observed apartments, the humidity-responsive ventilation works properly, because the measured relative humidity lies within reasonable ranges (see Figure 45).

4.2 Thermal comfort

The temperature distribution in the living room differs from the one in the bedroom most of the time by one degree.

According to the questionnaire the inhabitants stated that they prefer colder temperatures in the bedroom.

The evaluation of the PMV also reveals that the temperatures are predicted to be comfortable in the bedrooms of all apartments except in apartment 112 and 131 (see Figure 55). According to the PMV results the inhabitants of apartment 131 also evaluate the temperature in the bedroom as rather warm (see Figure 61).

In the bedroom of apartment 101 the highest as well as the lowest measured temperatures of all apartments could be detected (see Figure 44). The inhabitants of this apartment stated that they are most of the time outdoor and are very sportive, so they prefer cooler temperatures in their apartment. Looking at the relative humidity values in this apartment the highest values were measured. Nevertheless the inhabitants of this apartment did not complain about too humid air (see Figure 62). This may be because the absolute humidity compared to the others is rather low (see Figure 51).

Relative humidity values in apartments with either a humidifier or an aquarium (104, 105, 112 and 131) do not differ much between the other apartments.

The inhabitant of apartment 103 complains about too dry indoor air especially in the bedroom of his apartment (see Figure 62). Although in this apartment there is an eat-in kitchen, the frequency distribution of the relative humidity values tend to be rather low. The measured relative humidity values in the bedroom of this apartment are 13% of the time below 30% (see Figure 48). Also the absolute humidity (see Figure 51) in the bedroom of this apartment is lower than in the other ones.

Apartment 103 is the smallest apartment of the observed ones. According to the questionnaire the inhabitant of this apartment dresses in winter indoor not different than in summer.

5 Conclusion

Although the observed building is equipped with a demand controlled ventilation system the indoor air quality in the bedrooms of the apartments is generally very poor regarding the measured amount of CO_2.

The evaluation reveals that the humidity-responsive ventilation works properly in terms of reducing relative humidity, but insufficient to maintain reasonable CO_2 concentrations. Especially during the night, the CO_2 concentrations are too high.

There is almost no correlation between the indoor relative humidity and the CO_2 concentration.

Evidently, the maintained fresh air supply (rather dry in winter) is sufficient in view of indoor humidity control, but not enough to reduce the CO_2 concentration effectively.

The relative humidity values in the apartments with additional humidity sources do not differ significantly from the other apartments.

This may also partially explain the negative evaluations by some inhabitants.

6 Further research

Due to the fact that previous research in the area of controlled ventilation inside residential buildings reveals that main problems occur during the winter months, this thesis was also conducted during the colder months of the year.

In further research it would be interesting to investigate the indoor air quality in residential buildings with humidity-responsive ventilation also in summer.

Further research can also continue with case studies where the supply with fresh air is driven by the CO_2 concentration in a room.

At least it would be interesting to do also some studies about the acceptance of demand controlled ventilation systems in residential buildings.

Acknowledgement

I would like to thank my supervisor Univ. Prof. DI Dr. Ardeshir Mahdavi, who constantly supports this work and encouraged me.

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I also would like to express my special thank to the inhabitants of the observed building.

Above all I would like to use this possibility to thank my parents and my friend, Matthias. They encouraged and motivated me during my studies and my Master's thesis.

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7.2 Tables

7.3 Figures

8 Appendix

In the following the weekly paper based questionnaire is presented.

Name: …. TOP: ……. Datum: …………….. Uhrzeit: ……….

<u>In der letzten Woche öffnete ich die Fenster im Wohn- und Schlafzimmer …?</u>

○ seltener ○ wie immer ○ öfter

<u>Wurde bei Ihnen der Bad-Ventilator in der letzten Woche zugeschaltet?</u>

	○ nie	○ selten	○ manchmal	○ häufig	○ immer
Badfenster geöffnet (nur wenn vorhanden)	○ nie	○ selten	○ manchmal	○ häufig	○ immer

<u>Wie empfinden sie derzeit die Raumtemperatur im …?</u>

Wohnzimmer	○ kalt	○ eher kühl	○ neutral	○ eher warm	○ heiß
Schlafzimmer	○ kalt	○ eher kühl	○ neutral	○ eher warm	○ heiß

<u>Wie empfinden Sie derzeit die Luftfeuchtigkeit im …?</u>

Wohnzimmer	○ zu trocken	○ trocken	○ passt so	○ feucht	○ zu feucht
Schlafzimmer	○ zu trocken	○ trocken	○ passt so	○ feucht	○ zu feucht

<u>Wie beurteilen Sie das Raumklima bei Ihnen in der letzten Woche generell?</u>

○ sehr gut ○ eher schon gut ○ geht so ○ weniger gut ○ gar nicht gut

Falls „weniger gut“ oder „gar nicht gut“ geben Sie bitte an warum:

Sonstige Anmerkungen (Besonderheiten der letzten Woche, …)