The resulting CO_2 levels and the heating/cooling consumption of apartments with balanced ventilation versus window ventilation

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ABSTRACT

Four apartments have been monitored for an entire year. Two apartments were ventilated with a balanced ventilation system, and two apartments were ventilated by manual opening of windows. CO_2 values have been registered as indication of indoor air quality in each living room and the available bedrooms. The opening of windows and doors was registered, from which an airing factor was calculated. The heating and cooling consumptions was also registered for each apartment.

The CO_2 levels in all rooms of the apartments with balanced ventilation was lower than the manually ventilated apartments, with less variation between hours and seasons. The percentage of hours exceeding 1000 ppm is below 1% of the year for the apartments with balanced ventilation and 30-60% of the year for window ventilated apartments.

Space heating and cooling use are investigated by energy signatures of the four apartments. The balanced ventilation - including recovery - not only brings a higher indoor air quality, but also a lower heating (-24%) and cooling use (-50%) as follows from the specific heating slope and specific cooling slope in the energy signatures.

INTRODUCTION

Renovation of houses always incorporates measures for improved insulation and improved air tightness. In order to keep the indoor air quality at a healthy level, the indoor air needs to be refreshed in a sufficient way. The refreshment is usually done by introducing a mechanical ventilation system. In Switzerland, however, it is also allowed to refresh the indoor air only by opening windows and doors regularly, hereafter called window ventilation.

Monitoring of the situations before and after renovation is difficult due to many factors changing during the renovation. Therefore, the comparison between window ventilation and mechanical ventilation is done in this project in a newly built multi-family house in Switzerland. Two apartments have balanced ventilation, and two other apartments have window ventilation. Because the whole building is insulated and airtight, the comparison entirely focuses on the type of ventilation, the resulting indoor air quality and the necessary energy consumption to heat and cool the apartments in the building.

Examples of comparison of window ventilation with balanced ventilation are given in the studies “Holsteijn & Li (2014)” and “Burgholz & Müller (2021)”.

PROJECT DESCRIPTION

The building

A multi-family apartment is built in 2017 in the village Büren in Switzerland. The building has a wooden construction with up-to-date insulation and airtightness measures.

The building consists of four layers: two floors, an attic and a basement (Figure 1). The first and second floor each have two apartments, of which the left apartments have 80 m² surface area and the right apartments have 113 m² surface area. On the attic there is a penthouse. In the underground basement on the left there is a nursery school and, on the right, there are cellars for the technical installations and for storage rooms.

Figure 1. The building with the conditioned areas that can be heated and cooled (green) and unconditioned areas (grey).

Figure 1 also indicates which rooms are conditioned (heated and cooled). The apartments themselves and the nursery school are conditioned spaces, whilst the staircase and the cellar are unconditioned spaces. The apartments of interest in this study are only four apartments, which are the apartments on the first floor and the second floor. The penthouse and the nursery space are not analysed. For easy reference, the first-floor apartments will therefore be named bottom apartments and the second-floor apartments will be named top apartments.

Figure 2 shows that the four monitored apartments are occupied by different family sizes. Only the top left apartment is occupied by a single person, the rest is occupied by two persons. Moreover, there is one dog living in the bottom right apartment and two cats in the top right apartment.

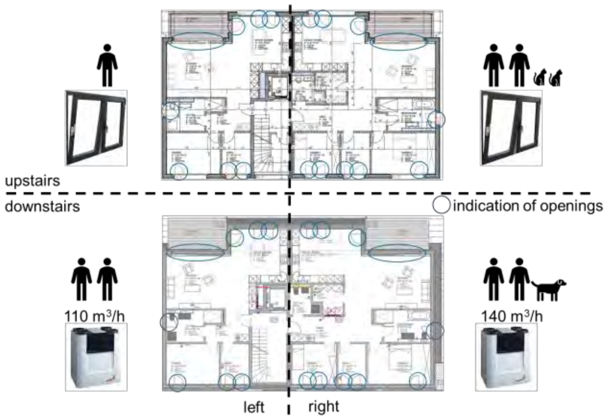

Figure 2. Plan view of the four monitored apartments, with indicated family size, ventilation type and airing possibilities.

The two bottom apartments are mechanically ventilated with a balanced ventilation system. The two top apartments have no mechanical ventilation system, apart from a small toilet fan in the top right apartment. All four apartments have the possibility to open doors and windows leading to the outdoor environment, indicated in Figure 2 by blue circles. These openings are used for airing (natural ventilation). The different types of airing openings are sliding doors, kitchen doors, and windows that can be opened either by turning and some of them also by tilting.

The installations

The four apartments are conditioned by one Zehnder heat pump with a capacity of 25 kW. The heat pump has a free-cooling possibility as the heat pump is ground-sourced. The heat and cold are transported and released via a floor distribution system. Controlling of the indoor temperature can be done via separate thermostats in each room of the apartment.

The bottom apartments are constantly ventilated, each with a Zehnder balanced ventilation unit, type ComfoAir Q350 ERV. Outdoor air is transported to and supplied in each of the living rooms and bedrooms by individual round (supply) air ducts (type ComfoFresh). Indoor air is extracted from the kitchen and bathroom and via individual round (extract) ducts (type ComfoFresh) is led to the ComfoAir Q unit.

The ComfoAir Q units are each equipped with an enthalpy exchanger, meaning that not only heat, but also moisture is transferred between the incoming and the outgoing air stream. The air flow rate in this project is set to a constant value: 110 m^3/h for the bottom left apartment and 140 m^3/h for the bottom right apartment.

The top apartments are ventilated only when a door or window to the outdoor environment is opened.

The monitoring system

The mechanical ventilation data is monitored via a KNX system connected to the ComfoAir Q units. This makes it possible to analyse air flow rates, temperatures and humidities of all four air streams (outdoor ODA, supply SUP, extract ETA and exhaust EHA) and electricity consumption, for each ComfoAir Q unit dedicated for the bottom apartments.

The indoor air quality is indicated by air quality sensors for analysing CO_2 values and VOC values per sensor (AVELON Wisely CarbonSense). Sensors are positioned in each apartment in the living and the master bedroom and for the larger apartments (bottom right and top right) in a second bedroom. Moreover, the natural ventilation by airing is monitored with the position of the windows and doors at the envelope of the building. Every window and door is equipped with contact sensors that can discriminate between a tilted window (top part open) and a turned window (sideways open). These sensors cannot detect how far the window is opened.

The sliding door in each apartment is monitored in a special way, with a distance sensor. This makes it possible to know how far the sliding door has been opened.

The energy use for each apartment is determined with data from the heat pump. This makes it possible to analyse the heating use and the cooling use for space conditioning, excluding the domestic hot water part.

The mechanical ventilation data are measured and stored with an interval of 5 minutes. The CO_2 and VOC data are measured and stored with an interval of 1 minute. Both these types of data have been averaged to hourly averaged values for long term analysis. However, the VOC values have not been averaged as they are "incident driven" rather than "occupation driven" and was beyond the scope of this study. Therefore, hourly averages do not give a clear representation of the phenomena in the house. The energy use data are measured by recorded meter values on an hourly basis. However, the resolution of the meters is such that only daily meter values give meaningful data. So, the energy consumption is further analysed on a daily basis.

All the data have been analysed for a full year. The mechanical ventilation data and the CO_2 data have been analysed for the period from the 8th of July 2019 until the 30th of June 2020. The energy use data was monitored later in time, therefore the energy use has been analysed for the period from the 11th of October 2019 until the 30th of September 2020.

PERFORMANCE OF THE BALANCED VENTILATION

The ComfoAir Q units provide a constant air flow rate, 110 m^3/h for the bottom left apartment and 140 m^3/h

for the bottom right apartment. Therefore, the efficiencies of heat recovery and humidity recovery are clearly observed and shown in Figure 3. Thanks to a balance correction algorithm, the extract and supply air flow rates are equal, so thermal (humidity) efficiency is calculated by the temperature (humidity) difference supply-outdoor divided by extract-outdoor.

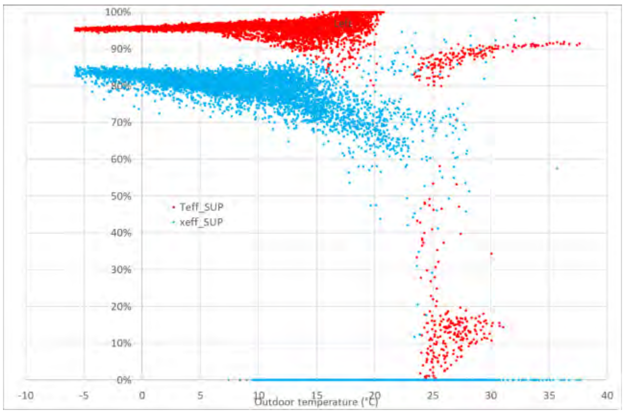

Figure 3. Temperature recovery efficiency (red) and humidity recovery efficiency (blue) based on the supply as a function of outdoor air temperature for the bottom left apartment.

The temperature recovery efficiency shows three modes of the ComfoAir Q unit. For low outdoor temperatures, the indoor heat is recovered with 95-96%. The consequence is a comfortably warm supply of fresh air and savings on the heating load of the apartment. For high outdoor temperatures, the outdoor heat is kept outside for 80-90%. The consequence is a comfortably cool supply of fresh air and savings on the cooling load of the apartment.

For outdoor temperatures between 25 and 30°C, there are also points which appear below 15%. These are conditions where the bypass was activated to let in warm air when the house was not warm enough (passive heating). This happened too often because the settings of the ComfoAir Q were not aligned with the heat pump. At the end of the monitoring year, the settings of the heat pump and the settings of the balanced ventilation unit have been improved.

The humidity recovery efficiency shows that during the cold season 70–85% of the humidity is recovered. The consequence is that in winter the indoor humidity does not fall below a comfortable level despite the constant refreshment with (dry) winter outdoor air.

The last result from the monitoring of the ventilation unit is the electrical consumption. The constant air flow rate results in a constant electrical consumption for the fans. Table 1 shows that the fans of the units take 17.1 W for the bottom left apartment and 21.9 W for the bottom right apartment.

Table 1. Electricity consumption of the ComfoAir Q ventilation unit in both apartments

Apartment	Ventilation flow rate	Electricity consumption	Electricity power
Bottom left	110 m³/h	149 kWh/yr	17.1 W
Bottom right	140 m³/h	191 kWh/yr	21.9 W

COMPARISON OF CO_2 VALUES

The CO_2 values are a result of the occupation of the rooms, the mechanical ventilation rate (for the bottom apartments) and the natural ventilation rate (for all apartments) by opening windows and doors in the envelope of the building. In this chapter, the explanation and the results for the airing of the apartments are given first. After that, the CO_2 values are compared in various ways.

Airing factor

Airing of the apartments is done by the occupants by opening windows and doors in the envelope of the building. To investigate the use of airing, an airing factor was defined.

Each individual window could be in a state "open" or "closed" as measured by the window contacts. A window that could also be tilted has also a "half open" state when tilted. The sliding door of each apartment could have a stepless open factor ranging from "fully closed" to "fully open" and anything in between, according to the opening distance as measured by the laser distance meter. Then, all the open states were divided by the maximum open states to come to an instantaneous airing factor. This instantaneous airing factor ranges from 0% (none of the openings are open) to 100% (all of the openings are open, with the sliding door fully open). The airing factor can be averaged over a longer period.

Table 2 summarizes the use of the windows and doors in all four apartments. Numbers are given for each season, for the entire heating season and for the entire year. The results show that in every apartment (regardless of the ventilation type), windows and doors tend to be used less in colder periods and more in warmer periods. This is also expected from the natural behaviour of people for comfort reasons.

Table 2. Airing factor during the seasons of the year and the entire year for all apartments.

						
	Period	Out-door	Bottom left	Bottom right	Top left	Top right
	1-7-19 30-9-19	18.3°C	9%	7%	6%	17%
	1-10-19 31-12-19	6.9°C	6%	5%	6%	6%
	1-1-20 31-3-20	4.8°C	4%	6%	1%	3%
	1-4-20 30-6-20	13.9°C	4%	9%	7%	5%
	heating season	5.8°C	5.3%	5.5%	3.6%	4.6%
	entire year	10.9°C	6%	7%	5%	8%

During the heating season, the bottom apartments have similar airing factor, a bit higher than 5%. According to the amount of openable windows, one could say that this means that (on average) one window is tilted continuously. During the heating season the top apartments use a bit less airing, probably as the effects of the airing are more noticeable in comfort.

Over the entire year, the top left apartment is the least aired, the top right apartment is most aired, and the bottom apartments are ranked in between.

Detail of CO_2 values during one day

Figure 4 shows examples of one day in terms of airing factor and CO_2 value. The CO_2 value is averaged over all monitored CO_2 sensors in the apartment.

The bottom right apartment with balanced ventilation shows a CO_2 value between 400 and 600 ppm. During the night there is a small increase of CO_2 with the occupants sleeping. In the morning, some windows are opened for about an hour and resultingly the CO_2 value decreases a bit. During the day, the occupants are not at home, but the balanced ventilation still refreshes the air and the result is that the average CO_2 value in the apartment drops from nearly 600 ppm to 400 ppm (outdoor value). When the occupants return home at 17:00 they open a window or door for about three hours, the CO_2 stays close to the outdoor CO_2 value.

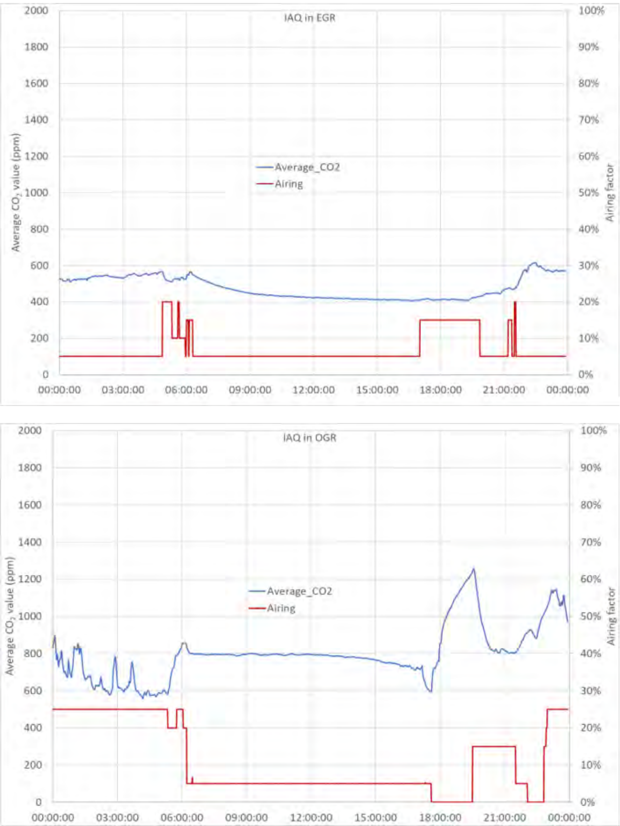

Figure 4. Example day in summer of airing factor (red line) and CO_2 values (blue line) for bottom right apartment (a) and top right apartment (b).

The exact reason for opening the windows is not known. It could be that opening the windows while coming home is a habit from the past, but it is surely not necessary for a comfortable indoor climate. In the evening, with most windows closed, there is again a slight rise in CO_2 value. Throughout the day, the CO_2 level stays low (<800 ppm). The regularity of the CO_2 line shows that the refreshment of indoor air is very constant.

The top right apartment with window ventilation has quite a few windows open in the night. Because the refreshment of indoor air is dependent on wind effects around the building, the average CO_2 value is irregular and slowly decreasing from 800 to 600 ppm. At 9:00 the occupants leave the house with only one window in the tilted position. With one tilted window, there is hardly any refreshment of the indoor air, the CO_2 value stays at the level of 800 ppm during the day. At 17:30, the occupants return home, all windows and doors are closed, and the result is a sharp increase of CO_2 up to 1200 ppm. At 19:30 a window is opened, making the CO_2 decrease again to 800 ppm. When occupants presumably go to sleep, there is an increase of CO_2 value again. Throughout the day, the CO_2 value does not fall below 600 ppm, despite opening of windows.

Regularity of CO_2 week profiles

The (ir)regularity of the CO_2 values is also shown in Figure 5, where the hourly averaged CO_2 values in the master bedroom are displayed for all Tuesdays in a year. Tuesdays are displayed in the assumption that this day is very regular weekly in occupation profile.

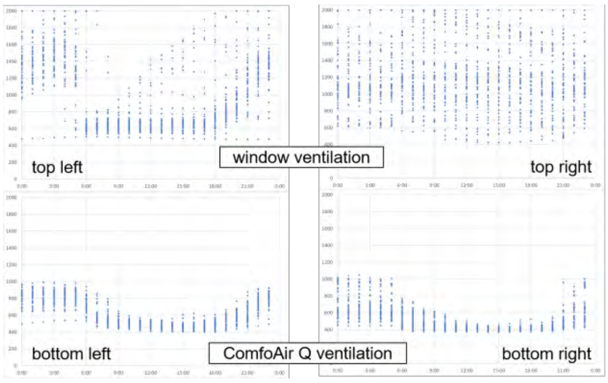

Figure 5. CO_2 values in master bedroom on all Tuesdays.

The apartments with balanced ventilation show a regular profile with CO_2 level below 1000 ppm when there are people in the master bedroom and decreasing values when the bedroom is unoccupied. The mechanical, balanced ventilation has a constant refreshment effect. This results in low CO_2 values (below 1000 ppm) when occupied, and decreasing values to outdoor values when unoccupied.

The apartments with window ventilation are very different. The top left apartment has an occupant with a very regular airing profile, always opening the sliding door in the living room in the morning to refresh the indoor air. Depending on the hours of occupation during the day, the CO_2 value increases again to values typically ranging between 1200 and 1600 ppm. The occupants in the top right apartment do not have a regular airing profile. As a result, the CO_2 value in the master bedroom can take any value between 400 ppm and 2000 ppm (or even higher, because the maximum sensor value was 2000 ppm) over the whole day. The indoor air is not refreshed, except for the occasional opening of a window to shortly refresh the air.

CO_2 values over the whole monitored year

First, carpet plots in all monitored rooms are shown to express CO_2 values during each hour of the day and during each season.

The overview of CO_2 levels in all rooms is shown in Figure 6 (last page). Immediately it is clear that the CO_2 with balanced ventilation is at a much lower level than for the apartments with window ventilation. The analysis of these results is given per apartment.

The bottom left apartment has low CO_2 levels in the living room, apart from some evenings during the colder season. Most of the time, the balanced ventilation ensures a good refreshment of the room for the occupants. Presumably, sometimes there are visitors, especially during the Christmas holidays. Keep in mind that for this monitoring year, the occupants were instructed to keep the ventilation flow setting at a constant, medium level. When there are visitors or a party, the general recommendation however, is to increase the ventilation flow setting to a high level. In the master bedroom, with two occupants, the night CO_2 level reaches values between 800 and 1000 ppm.

The bottom right apartment also has low CO_2 level in the living room, apart from some evenings in the colder season. The master bedroom had some nights in 2019 with higher levels of CO_2 but in 2020 the master bedroom CO_2 level was good. This could be the result of a changing occupation of the master bedroom, dependent on the total number of people sleeping.

The top left apartment shows very similar CO_2 profiles when living room is compared with bedroom. This is an indication that the internal door between living room and bedroom is mostly open. Night CO_2 levels are mostly high, indicating that the occupation of one person, and the absence of constant refreshment is resulting in a lasting high CO_2 level. Every morning, short opening of the sliding door in the living room refreshes the apartment. During weekdays, without occupation, the CO_2 level stays low, but during the weekends the CO_2 level increases when the occupant stays home all day. The airing of the apartment is absolutely necessary to keep the CO_2 level at an acceptable value. Around the Christmas holidays, the CO_2 level remained high, probably from a holiday where the house was occupied for three full weeks.

The top right apartment only has acceptable CO_2 levels in the summer of 2019. In this period, the airing was used in a sufficient way to keep the CO_2 level low. The rest of the year, the CO_2 level was high, with the master bedroom showing the largest values of CO_2. Probably, the internal door to the master bedroom was closed at night, and with insufficient airing the CO_2 level quickly increases to high values.

Another way to compare the resulting CO_2 levels is with box plots. The comparison of box plots for all rooms in all apartments is shown in Figure 7. The CO_2 levels for the bottom apartments (with balanced ventilation) are much lower than CO_2 values for the top apartments (with window ventilation). Also, the spread of the CO_2 levels is much smaller in the bottom apartments than in the top apartments resulting from the constant refreshment of the ventilation system.

Median CO_2 values for the rooms in the bottom apartments are between 420 and 640 ppm whereas they are between 850 and 1100 ppm for the top apartments. Average CO_2 values for the rooms in the bottom apartments are between 450 and 640 ppm whereas they are between 900 and 1120 ppm for the top apartments.

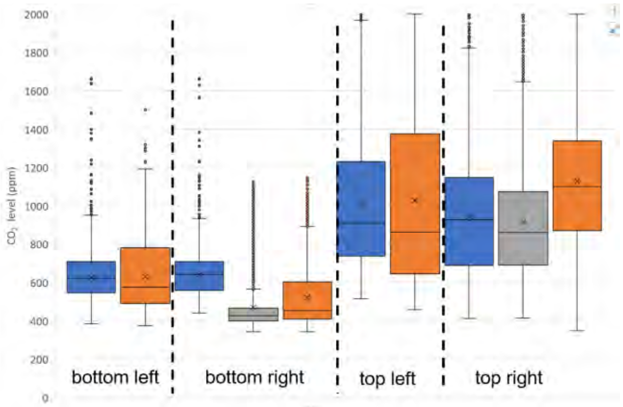

Figure 7. Box plots of CO_2 levels in all monitored rooms. Bottom apartments have balanced ventilation and top apartments have window ventilation. Living rooms in blue, master bedrooms in orange, and second bedrooms in grey.

The third and last comparison method is by the number of hours exceeding 1000 ppm and the amount at which the CO_2 level exceeds 1000 ppm. Above the level of 1000 ppm, refreshment of the indoor air is insufficient and therefore adverse effects can occur like fatigue, headaches, or hindered decision making.

Table 3 shows the number of hours above 1000 ppm for all rooms in all apartments. Again, there is a huge difference between rooms with continuous balanced ventilation and rooms with occasional window ventilation. The typical value is below 100 hours for balanced ventilation and 3000 to 5000 hours with window ventilation. So, you could say that in the window ventilated rooms the CO_2 level is a factor 30-50 times more often unacceptable than the rooms with balanced ventilation.

The percentage of unhealthy hours in a year is below 1% for the apartments with balanced ventilation and 30–60% in the apartments with window ventilation. Overall, the master bedroom has the most hours with high CO_2 values of all the rooms in an apartment. The difference with the hours with high CO_2 levels in the living room is larger when the internal doors between bedroom and living room are closed.

Table 3. Number of hours with CO_2 above 1000 ppm and CO_2 overdose above 1000 ppm during the whole monitored year (total 8616 hours) for all rooms in all apartments.

Apartment/ ventilation	Room	Nr hours	Overdose (kppmh)
Bottom left; Balanced; airing 6%	living room	28	5
	1st bedroom	33	4
Bottom right; Balanced; airing 7%	living room	21	5
	2nd bedroom	105	5
	1st bedroom	113	4
Top left; window; airing 5%	living room	3588	1195
	1st bedroom	3674	1671
Top right; window; airing 8%	living room	3367	850
	2nd bedroom	2665	687
	1st bedroom	5153	1806

Not only the number of hours can be evaluated, but also the amount how much higher than 1000 ppm the CO_2 value has been. For this, a CO_2 overdose is defined and presented in Table 3.

The values can be compared with the Belgian standard which states that the CO_2 overdose above 1000 ppm in the heating season should not exceed 100 kppmh. The overdose from Table 3 is for the entire year, so let us make the prudent assumption that the overdose for the heating season is half of the value in the table. Then we can conclude that with balanced ventilation all the rooms meet the standard, but for window ventilation none of the rooms meet the Belgian standard.

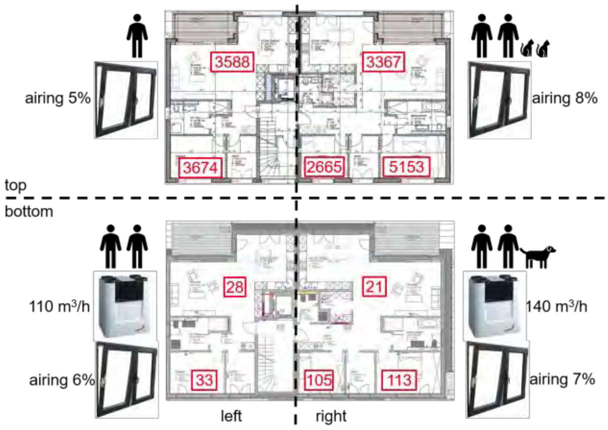

Figure 8. Infographic of plan view of the building with family size, airing factor, ventilation possibilities, and monitored number of hours with CO_2 above 1000 ppm.

For a better view of the number of hours with CO_2 values higher than 1000 ppm in all rooms of all apartments, Figure 8 shows an infographic that gives a plan view of the whole building with the apartments. Also, it shows the family size, including pets. The pictures show that airing can be used in all apartments (with the year averaged airing factor given), but only the bottom apartments each have a balanced ventilation unit. The red numbers show the number of hours with a CO_2 value in a room above 1000 ppm for the whole monitored year (8616 hours in total).

Conclusions from monitored CO_2 levels

Looking at the monitored CO_2 levels, it is proven that a balanced ventilation system provides a constant refreshment of the rooms in the apartment. The use of windows and doors for airing can be used normally and are proven to be used whenever it is desired by the occupants.

For monitoring purposes, the ventilation unit was set to a constant position. If the air flow rate was controlled by CO_2 sensors, higher CO_2 levels would have led to higher air flow, and therefore even further reduced number of hours with high CO_2.

The apartments with window ventilation have higher CO_2 levels. The occupants have the (only) possibility to refresh the air when they open the window, but the monitoring shows that the occupants do not air significantly more than the occupants from the bottom apartments. This means that the perceived indoor air quality is not a sufficient incentive to open window and doors in time to keep the air exchange at a good level.

Airing brings some amount of refreshment only if a window is open, but averaged over a longer period it cannot bring the refreshment that a mechanical ventilation unit can guarantee.

COMPARISON OF HEATING AND COOLING USE

The comparison of the CO_2 levels has shown that the bottom apartments with balanced ventilation have a much better air exchange than the top apartments with window ventilation. The question to be addressed in this chapter is whether this higher air exchange has an impact on the heating and cooling use.

All of the apartments need to be heated and cooled to overcome transmission losses via walls and floors.

With balanced ventilation, the indoor spaces are continuously ventilated. Usually, all balanced ventilation systems are equipped with an exchanger of heat (and here also humidity). The incoming, fresh outdoor air is heated or cooled by the recovery in the exchanger, so that the supply air temperature is near to the indoor air temperature. But this amount of fresh air needs to be heated in the winter and cooled in the summer by the central heating/cooling system.

With window ventilation, the indoor air is only refreshed when the occupant opens a window or door in the envelope of the building. During this period, outdoor air is directly flowing into the rooms, and consequently needs to be heated in winter and cooled in summer, from outdoor to indoor temperature.

Figure 9 shows the total energy used for heating and cooling an apartment. The total energy use is expressed as the sum of the heating use and the cooling use, and divided by the floor area of the apartment. This makes it possible to compare apartments of 80 m^2 and 113 m^2.

Figure 9. Total energy use in one year for heating and cooling the apartments. Also shown are the airing factors averaged over the whole year. Conditioned spaces are coloured green and unconditioned spaces are coloured blue.

The results show that the two left apartments have similar energy use. The use of windows and doors for natural ventilation was also used in a comparable way. That means that the addition of a mechanical supply of fresh air has no effect on the energy use of the apartment. Comparing the top apartments, the energy use seems to be dependent on the airing factor. The more the windows and doors are used, the higher the energy needed for conditioning the rooms.

The bottom right apartment needs much more energy than the others, almost twice as much as the bottom left apartment, with the same ventilation principle. This is most probably due to a higher thermostat setting and/or due to the unconditioned (cold) cellar below the bottom right apartment. In order to support this hypothesis, the energy analysis is investigated by analysing heating and cooling use separately.

Total heating use

The total heating use of the heat pump to heat the apartments is given in Figure 10. Comparing the top right apartment with the bottom left apartment (apartments that have the same airing factor), it can be concluded that the addition of a balanced ventilation system with recovery saves 24% of the total heating use of the apartment.

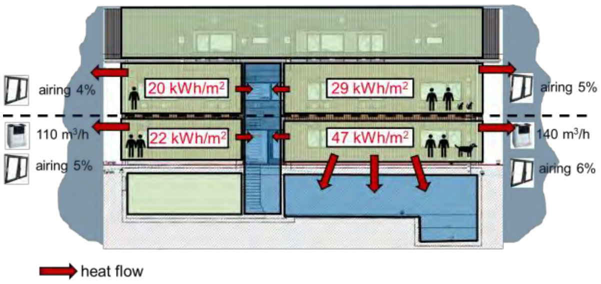

Figure 10. Total heating use in one year. Also shown are airing factors averaged over the months October 2019 until March 2020. Conditioned spaces are coloured green, unconditioned spaces are coloured blue. The winter outdoor environment is indicated in blue. Expected heat flows by transmission are indicated by red arrows.

The highest heating use over the year is for the bottom right apartment. The bottom right apartment is situated above an unconditioned cellar, which is cold in the winter. Therefore, the expected heat flow by transmission is much higher in this apartment. There is a constant flow of heat from the bottom right apartment to the cold cellar, something which the other apartments do not experience. The other apartments all have warm indoor spaces above them and below them. This is the so-called 'neighbour effect': the amount of energy use depends on the average indoor temperature of the surrounding spaces.

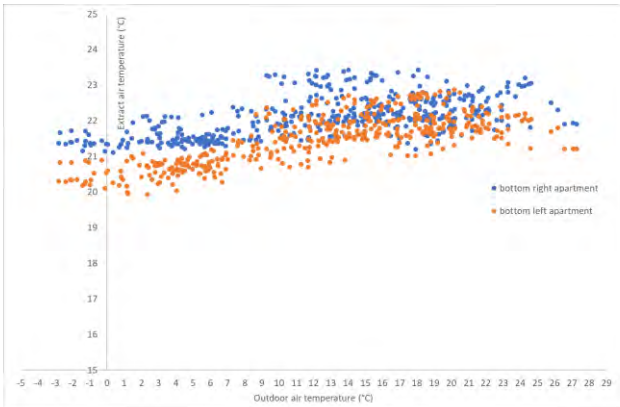

Figure 11. Daily averaged values of extract air temperature as a function of outdoor air temperature in bottom left apartment (orange) and bottom right apartment (blue).

Another interesting difference is that the indoor temperature of the bottom right apartment was always approximately 1.5°C higher than the indoor temperature of the bottom left apartment (Figure 11). This can be concluded from the daily average values of the extract air temperature, which is a measure for the indoor air temperature over all the rooms where the stale air is extracted by the ventilation system. The bottom right apartment was always 1 to 1.5°C warmer than the bottom left apartment, apparently because the occupants have a higher thermostat setting for conditioning their indoor spaces.

Total cooling use

Figure 12 shows the total cooling use of the heat pump to cool the apartments. Comparing the two left apartments (apartments that have the same airing factor), it can be concluded that the addition of a balanced ventilation system with recovery saves 35% of the total cooling use of the apartment. The top right apartment has a lower cooling use than the top left apartment, despite the higher airing factor. It might be explained by other thermostat settings or a higher number of occupied hours (larger family size). Unfortunately there is no data of the average indoor temperature of the top apartments to give proof to this.

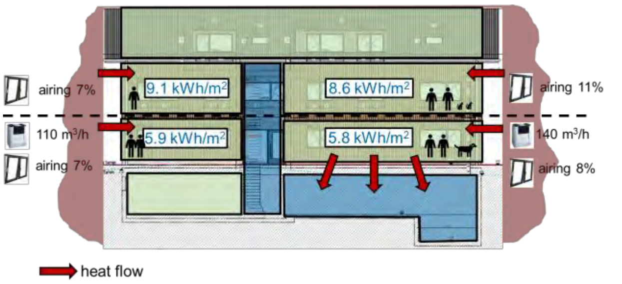

Figure 12. Total cooling use in one year. Also shown are the airing factors averaged over the months April until September 2020. Conditioned spaces are coloured green and unconditioned spaces are coloured blue. The summer outdoor environment is indicated in red. Expected heat flows by transmission are indicated by red arrows.

The lowest cooling use over the year is for the bottom right apartment. The bottom right apartment is situated above a cellar, which is still relatively cool in the summer. The so-called 'neighbour effect' now leads to a lower cooling use of the bottom right apartment.

Moreover, the higher indoor air temperatures in the bottom right apartment (Figure 11) indicate a higher thermostat setting and therefore a lower cooling use.

Energy signatures for heating and cooling

The energy use for heating and cooling apartments are also studied by using energy signatures. Energy signatures are a graphical representation of the daily energy use as a function of the daily averaged outdoor temperature. Figure 13 shows the energy signatures of the four apartments.

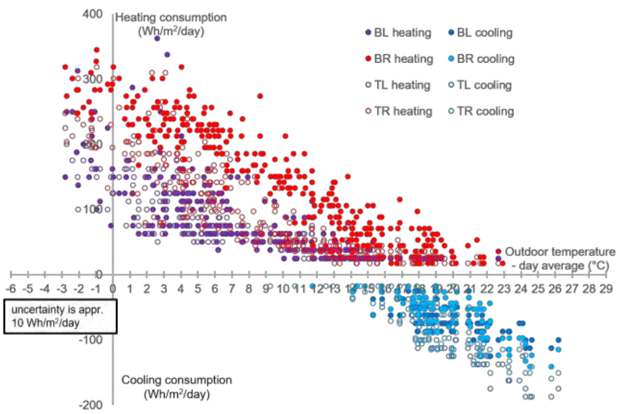

Figure 13. Energy signatures (heating and cooling) for all apartments. Daily heating use is shown above the horizontal axis and daily cooling use is shown below the horizontal axis.

The general outcome of the energy signatures is a downward sloping line. In winter, the colder it gets outdoors, the more heating is used to keep the indoor spaces at the setpoint temperature. In summer, the warmer it gets outdoors, the more cooling is used to keep the indoor spaces at the setpoint temperature.

The uncertainty resulting from the resolution of the energy meter values is approximately 10 Wh/m²/day. The typical spread of the energy values for one specific apartment is more than the measurement uncertainty. This spread is caused by occupation hour profiles, changes in thermostat settings, and specific temperature profile over the day.

When the average outdoor temperature over a day is between approximately 14 and 21°C, there is heating and cooling taking place during the same day. This is because during the night heating is used and during the consecutive day cooling is used. Although this strategy is beneficial from a comfort point of view (the setpoint is always tried to be reached), it takes more energy than a temperature range in which the apartment is neither heated nor cooled (free-running apartment).

For the analysed building, after the monitoring year, settings have been changed to reduce the number of occasions with heating and cooling within 24 hours.

Energy signatures for heating

The heating part of the energy signatures has been approximated with linear trendlines. Figure 14 shows all heating trendlines. All apartments except bottom right are heated for outdoor temperatures below 17°C (the heating balance temperature T_h). Only the bottom right apartment is different because it is heated for outdoor temperatures below 21°C. Such a translation in energy signature is the result of a systematic higher heating use. Hence, the heating balance temperature T_h depends on the thermostat setting and the neighbour effect, resulting in a high value at the bottom right apartment.

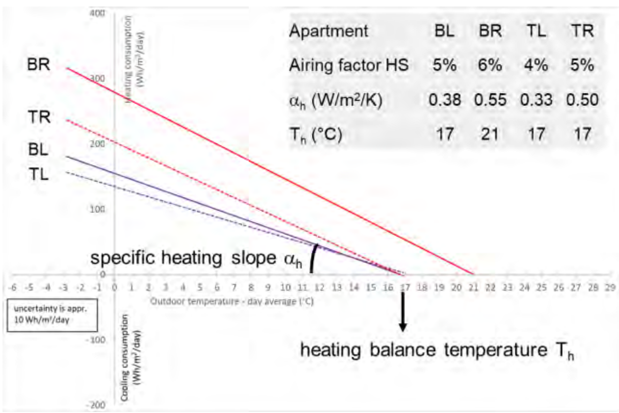

Figure 14. Trendlines for energy signatures (heating part) with specific heating slopes α_h and heating balance temperatures T_h. BL and BR stand for bottom left and right apartment, respectively. TL and TR are for top left and top right apartments, respectively.

For the specific heating slope α_h, a ranking can be established from the lowest to the highest value:

1. Top left: because of the lowest airing factor (4%)
2. Bottom left: because of higher airing factor (5%), but with heat recovery
3. Top right: same airing factor as bottom left (5%), but without heat recovery
4. Bottom right: because of highest airing factor (6%)

Bottom left and top right apartment have the same airing factor. The conclusion follows that for the same airing factor, the specific heating slope for the apartment with balanced ventilation is 24% lower than the apartment with window ventilation.

Energy signatures for cooling

The cooling part of the energy signatures has been approximated with linear trendlines. Figure 15 shows all cooling trendlines. All apartments are cooled for outdoor temperatures above 10 to 13°C. This cooling balance temperature T_c depends on the thermostat setting and the neighbour effect. That is why the value for T_c is high for the bottom right apartment.

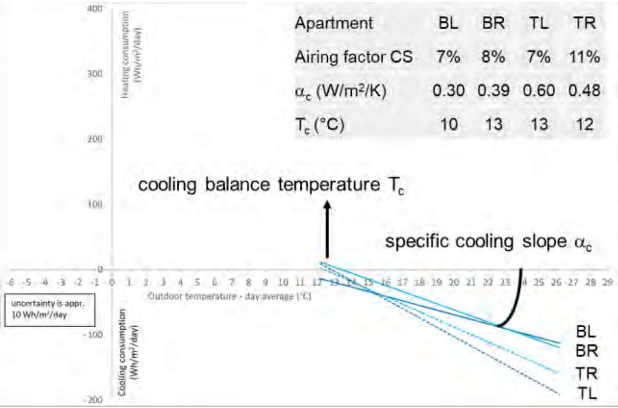

Figure 15. Trendlines for energy signatures (cooling part) with specific cooling slopes α_h and cooling balance temperatures T_c. BL and BR stand for bottom left and right apartment, respectively. TL and TR are for top left and top right apartments, respectively.

For the specific cooling slope α_c, a ranking can be established from the lowest to the highest value:

1. Bottom left: because of the lowest airing factor (7%), AND with cold recovery
2. Bottom right: because of slightly higher airing factor (8%), AND with cold recovery
3. Top right: because of highest airing factor (11%), without cold recovery
4. Top left: same airing factor as bottom left (7%), but without cold recovery.

Bottom left and top left apartment have the same airing factor. The conclusion follows that for the same airing factor, the specific cooling slope for the apartment with balanced ventilation is 50% lower than the apartment with window ventilation.

Conclusion from heating and cooling use

The monitored heating and cooling use for an apartment seems to have a dependency with the airing factor, that is the amount and duration of windows that are opened by the occupants. That is logical, because the outdoor air coming in via the window has to be conditioned to the desired indoor temperature.

For the same airing factor, however, the energy use for conditioning the apartments is less for an apartment with balanced ventilation. The difference is 24% (heating) and 50% (cooling) less than for the apartment with window ventilation, based on the slopes of the trendlines in the energy signatures.

As proven, the overall heating and cooling use is not only the result of the use of windows, and the use of recovery in a balanced ventilation system. It is also dependent on the thermostat setting (desired room temperature) and on the position relative to conditioned and unconditioned neighbouring spaces.

CONCLUSIONS

For a healthy indoor climate, the indoor air needs to be refreshed to take away the pollutants that people bring into the houses. In this document, a comparison is made between two apartments with ventilation with windows only, and two apartments with ventilation with a mechanical, balanced ventilation unit. The comparison is made with respect to the obtained CO_2 values and the heating and cooling use to bring the apartments to the desired temperature.

The CO_2 values with window ventilation shows that the apartments are refreshed when windows or doors in the envelope of the building are opened. But of course, the windows are not always open. As soon as the windows are closed, and the house is still occupied, the pollutants start rising again. The result is that 30-60% of the time in a year, the air exchange is insufficient (CO_2 value above 1000 ppm).

The monitored CO_2 values with a balanced ventilation system show that the apartment is constantly and sufficiently refreshed. The occupants are still using their windows for airing a room temporarily. But opening windows is not a necessary action for maintaining a good air exchange. The result is a good air exchange, with CO_2 values exceeding 1000 ppm less than 1% of the time in a year.

Opening windows and doors means that more energy is used to keep the rooms at the desired temperature. Heating is used during colder periods and cooling is used during warmer periods. The overall energy use for conditioning the rooms seems to be dependent on the amount that windows are opened over the year. The addition of the balanced ventilation does not lead to a higher energy use. Reason for this is that balanced ventilation uses recovery between extract and supply air and therefore keeps the energy load for ventilation low.

There is one apartment with mechanical ventilation that has twice the energy use for heating and cooling than expected on the basis of the other apartments. It has been proven that this is the effect of a higher thermostat setting in this apartment, and because this apartment is situated above an unconditioned cellar. The position above this cool cellar takes extra heating use in winter, but saves cooling use in summer.

The heating use is 24% lower and the cooling use is 50% lower for a mechanically ventilated apartment, relative to an apartment with window ventilation.

These numbers apply for apartments with the same amount of window openings, the same thermostat setting and the same position in the multifamily house relative to conditioned spaces.

Overall conclusion is that mechanical, balanced ventilation brings a better and healthier indoor climate, with a lower energy load, for the same amount of opening windows. It is expected that people in a mechanically ventilated apartment get accustomed to the fact that they do not have to open windows for a good air exchange. As soon as that happens, they rely on the ventilation system to maintain a fresh indoor climate, and the resulting energy use for heating and cooling is expected to be much lower than for apartments that are ventilated by window opening only.

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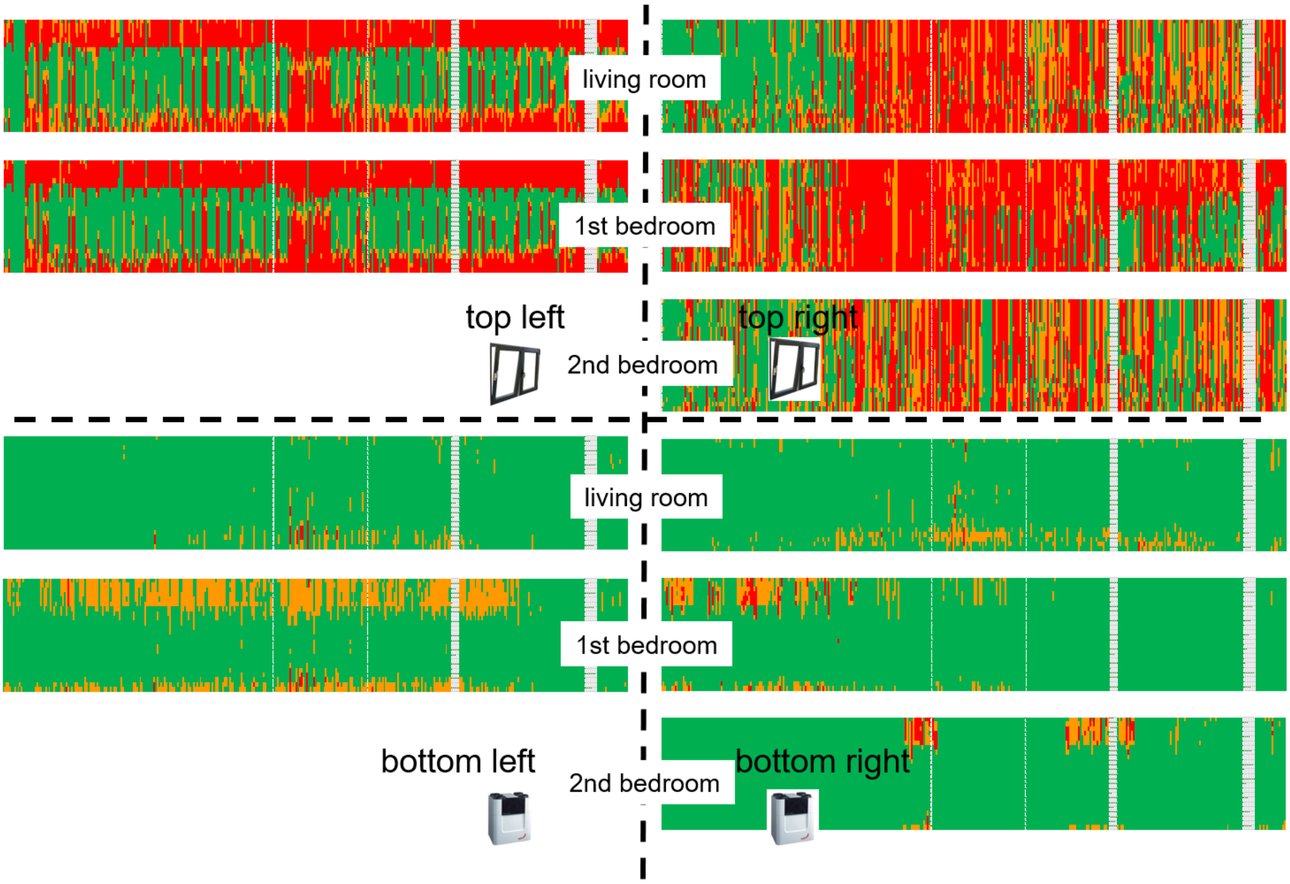

Figure 6. Carpet plots of CO_2 values in all rooms of all apartments. Individual carpet plots range horizontally from July 2019 until June 2020 and vertically downwards from 0:00 to 23:00. Green for low CO_2 values (<800 ppm), orange for medium CO_2 levels (between 800 and 1000 ppm) and red for high CO_2 values (>1000 ppm).