Assessing the indoor air quality of natural-ventilated bedrooms in renovated Norwegian houses using detailed field measurements

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ABSTRACT

The objective of this work is to investigate the indoor environment in bedrooms ventilated by window opening during night-time. How window opening behaviour affects indoor air quality (IAQ), and how window opening behaviour and IAQ is influenced by external factors, are central questions. The context is renovation of detached wooden houses in Norway. To motivate building owners to renovate their ventilation system, it is important to know the typical indoor environment in bedrooms of existing buildings with natural ventilation. 37 bedrooms in 17 case houses were investigated by measuring temperature, relative humidity, CO2 and TVOC. The window opening and door opening was also logged. Each house was measured for a two-week period, during the winter of 2021. The dwellings were renovated single-family houses, situated in an area with unpolluted air and little outside noise, outside Trondheim. The bedrooms had natural ventilation, and the occupants stated they used to open bedroom windows at night. Participants answered a questionnaire about motivations and habits regarding window opening.

The most common motivation given for opening windows was to supply fresh air. The window opening behaviour was both predictable and persistent. Windows were open every night in most of the bedrooms, and most of the windows were opened to the same position every night. High CO2 levels during night were found in some bedrooms. In most of the bedrooms, the CO2 concentration was satisfying during night-time, although high concentrations were found in several bedrooms when occupied during daytime. Finally, indoor temperature measurements confirmed that many occupants prefer a low bedroom temperature.

INTRODUCTION

The scope of this research is renovation of detached wooden houses with a strong focus on user behaviour in Norway. Small wooden dwellings are responsible for more than half of the total energy use in the Norwegian building stock. A recent study found that 60% of the Norwegian detached households made no changes to the ventilation system when performing an energy renovation, while only 9% installed balanced mechanical ventilation. However, renovation usually includes a substantial improvement in airtightness of the building envelope. This reduces the air change due to infiltration, demanding specific ventilation measures to provide sufficient indoor air quality (IAQ). Opening bedroom windows at night is a common method to perform natural ventilation. Many people accept and prefer lower temperatures in bedrooms than in other parts of the home, see e.g. (Berge & Mathisen, 2016; Bjorvatn et al., 2017; Thomsen et al., 2016).

The objective of this study was to investigate IAQ in window-ventilated bedrooms in renovated houses. Important questions were whether a satisfying indoor environment can be achieved in bedrooms by opening the window during night-time, and whether people actually make the window opening area large enough for sufficient air change.

Bedroom are often small rooms where occupants spend many hours, often with the door closed. Although almost one third of people`s life is spent in bedrooms, there are not many field studies monitoring IAQ in bedrooms. Very few studies have measured diurnal and weekly fluctuations, and investigated the relationship between IAQ and window opening behaviour over these time scales (Andersen et al., 2013; Fernández-Agüera et al., 2019).

Installing balanced mechanical ventilation in an existing building may be challenging or expensive. Therefore, it is important to better understand the performance and limitations of natural ventilation in bedrooms. With good IAQ, these bedrooms could be left out of the balanced mechanical ventilation system and lead to simpler installations. With poor IAQ, the study may increase the motivation in investing in a (more expensive) balanced mechanical ventilation

Indoor air quality (IAQ)

Measured CO2 concentration is a common indicator of the air quality, but is not itself regarded as a hazardous component. In general, CO2 concentrations of 1000 ppm is used as a threshold value (Arbeidstilsynet, 2016). The standard NS-EN16798 operates with four different categories for IEQ, corresponding to different CO2 concentrations ("NS-EN 16798-1 Energy performance of buildings - Ventilation for buildings," 2019).

Several studies report low air change rates (ACH) and high levels of IAQ parameters. 344 residences in Oslo were investigated in fourteen-day periods (Øie et al., 1998). The total air change rate was measured with a passive tracer gas method, and showed that 36% of the residences had a lower air change rate than the national requirement (0.5/h). The studied dwellings included apartments and single-family houses with both mechanical exhaust and natural ventilation.

A similar investigation was done in 157 single-family houses and 148 apartments in Sweden during the heating season (Langer & Bekö, 2013). The mean air change rate was shown to be 0.37/h in the single-family houses, and 0.5/h in the apartments. This resulted in 85% of the single-family houses having an air change rate below 0.5/h, and 74% for the apartments. The results indicated that the buildings with natural ventilation had lower air change rates than those with mechanical ventilation.

The concentration of TVOC and formaldehyde was also investigated in the same study. The median concentrations found in this study were lower than the guideline values for formaldehyde suggested by WHO (WHO, 2010). Langer also found a negative correlation between the air change rate and the two pollutants.

Bedrooms, ACH and IAQ

Similar ACH were found investigating children's bedroom of 390 Swedish homes (Bornehag et al., 2005). The bedrooms in the single-family houses had a mean ventilation rate of 0.36/h, while the mean rate was measured to be 0.48/h in the apartments. Like Øie, Bornehag also found higher ventilation rates in the single-family houses with mechanical exhaust and supply ventilation, compared to those with natural ventilation. A passive tracer gas method was used, with a duration of one week.

The bedrooms of 500 Danish children were investigated in for periods of 2 days and 2 nights between March and May 2008 (Bekö et al., 2010). The CO2 concentration was measured during night-time and the ACH estimated by a single-zone mass balance model. The opening of windows and doors was logged by the parents. The results showed that 57% of the bedrooms had air change rates of less than 0.5/h. The study also indicated that the air change rate increased together with the occupant number, assuming more frequent window opening at higher occupancy. The windows were, however, closed both nights in 80% of the rooms. 33% of the bedrooms experienced a 20-minute period where the average CO2 level was above 2000 ppm and 6% where the concentration was above 3000 ppm.

Other studies have also found high CO2 levels in bedrooms during night-time. The indoor environment in 79 residences with natural ventilation in Greenland, was investigated for a period of seven days (Kotol et al., 2014) In 66% of the bedrooms the average night concentration exceeded 1000 ppm in winter. 46% of the bedrooms experienced 20-minute periods with CO2 concentration exceeding 2000 ppm.

Aubin et al. investigated 115 Canadian homes, using the Perfluorocarbon Tracer (PFT) technique (Aubin et al., 2012). In winter and fall, 85% of the homes did not achieve the nominal air change rate of 0.30/h. The 24-hour averaged CO2 concentrations in bedrooms were 1024 ppm. Formaldehyde and VOC was also measured using passive sampling, and showed more pollution when lower ACR.

Bedroom conditions were measured in 26 low-energy houses in Scotland, with both balanced and natural ventilation (Sharpe et al., 2014). CO2 levels in February were consistently above 1000 ppm in 62% of the bedrooms with natural ventilation. All but three of the bedrooms have some periods above 1000 ppm. CO2-levels were generally lower during summer.

A study across the whole season, of 26 Japanese bedrooms with natural or mechanical ventilation, used the PFT technique. (Shinohara et al., 2011). The mean ACH in the bedrooms was 1.3 in summer, 0.49 in autumn, 0.38 in winter, 0.84 in spring and 1.4 the following summer.

A Spanish study (Fernández-Agüera et al., 2019) measured indoor air quality in 3 case houses with natural ventilation. The typical median levels of CO2 in bedrooms ranged between 1199 and 2385 ppm. [5].

A study in Estonia involving 88 bedrooms with different ventilation strategies, used the night-time occupant generated CO2 to calculate ACH. Results showed a mean bedroom air change rate of 0.6/h, and mean air change rate of 0.32/h for the whole building, during winter (Ilomets et al., 2018).

Several studies on bedrooms have found seasonal variations of ACHs and some of the IAQ parameters, with higher concentrations in winter or fall (Aubin et al., 2012; Du et al., 2012; Fernández-Agüera et al., 2019; Hou et al., 2017; Sharpe et al., 2014; Shinohara et al., 2011). However, Bekø (Bekö et al., 2010) did not find any correlation between outdoor temperature and ventilation rate in Danish bedrooms. One study reported a correlation between low infiltration and high CO2 level (Fernández-Agüera et al., 2019). Some studies also reported higher ACH or lower CO2 concentrations in bedrooms than the living rooms or the rest of the apartment (Du et al., 2012; Fernández-Agüera et al., 2019; Hou et al., 2017; Ilomets et al., 2018), but others the opposite (Park et al., 2014).

Some studies show rather high CO2 levels also in bedrooms using balanced ventilation. One study found that 2 out of 7 measured bedrooms exceeded 1200 ppm, 5 and 6% of the night-time (Berge & Mathisen, 2016). Corresponding levels were reported in a Swedish study, where air quality was investigated in 20 new passive houses and 21 conventional new houses. The average CO2 level in the bedrooms exceeded 1000 ppm 6% of the time in the passive houses and 10% of the time in the conventional houses during the two-week measuring period (Langer et al., 2015).

In conclusion, although the number of studies is limited, they suggest that the IAQ is not sufficient in a large fraction of the bedrooms with natural ventilation.

Window opening behaviour

A Norwegian survey (Bjorvatn et al., 2017) reported that about 30% of the 1001 respondents always sleep with the bedroom window open. The percentage increases with increasing age. An investigation of the window opening behaviour in Danish dwellings (Andersen et al., 2013), found window openings most common in bedrooms, particularly the main bedroom. He also found that CO2 concentration and outdoor temperature correlates with the opening of windows. Closing behaviour relates to low indoor and outdoor temperature. RH seemed to correlate to both opening and closing. A study monitoring 10 dwellings in UK (Jones et al., 2017), found a correlation between window closing and both windspeed and rainfall. Bekø (Bekö et al., 2010) found that, for bedrooms, the driver to open windows, is to obtain fresh air and not to control the indoor temperature. However, a survey in highly-insulated buildings with balanced ventilation (Berge et al., 2016), showed that the main motivation to open windows was temperature regulation.

An investigation of window opening in Belgium (Verbruggen et al., 2020), found that many occupants follow habits regarding window openings, indicating that the window use is less related to the environmental variables. Most occupants have specific behaviours in the different rooms, especially in the bedroom (97%). Many open or close windows when going to bed, and getting up, while more than 10% leaves the bedroom windows always open in wintertime (also in houses with balanced ventilation). This increases to 37% in summer. Also a study in the UK (Sharpe et al., 2014) observed window opening being more prevalent in the summer.

A survey on ventilation behaviour during heating season was done (with 4534 responses) in Netherlands (Levie et al., 2014). They found clear differences in window opening behaviour in different rooms. For bedrooms, 90% of the respondents report to ventilate at least 1 h per week, 60% more than 7 h, 50% more than 14h and 30% more than 56 h per week. In general, bedrooms were ventilated considerably more than the living room during the heating season. Occupants of houses with better insulation, seemed to have windows or doors opened for a longer period.

In conclusion, the literature shows large differences of user behaviour regarding window openings. In many studies, the window openings appear to be more frequent in bedrooms than the other rooms. Window openings also seem to follow the culture and habits. In that respect, Norwegians use window openings extensively in bedrooms.

Bedroom temperature

Several studies have shown that many occupants accept or prefer low bedroom temperatures. A Norwegian survey (Bjorvatn et al., 2017) reported that about 32% of the 1001 respondents prefer a bedroom temperature below 12°C, and approximately 38% prefer a temperature between 13-17°C during the heating season. The desire for cool bedrooms is also shown in Denmark by measurements in bedrooms after renovation (Bjørneboe et al., 2017; Thomsen et al., 2016).

A study in China's hot summer and cold winter region (Liu et al., 2019) found that that occupants in have a very strong tolerance to low temperatures in bedrooms: 80% of occupants regarded the acceptable lower temperature to be as low as 4.7°C and the neutral temperature was found to be 10.7°C. However, one study (Sharpe et al., 2014) observed high temperature in UK bedrooms and concluded that "it would seem that the notion of a bedroom as a cooler space, used infrequently, is outdated". These studies show that preferences vary between countries, due to differences in culture, buildings and heating systems. Bedrooms used only for sleeping, equipped with highly insulating duvets may induce tolerance for lower temperatures and for draught from open windows.

Research questions

The literature review showed that the IAQ in naturally ventilated bedrooms was lower than the standard requirements in a significant fraction of the buildings. However, the literature showed variations in habits and culture regarding indoor environment and window openings in bedrooms. In particular, the use of window openings and preference for low bedroom temperatures are more pronounced in Norway. Consequently, it is important to investigate the IAQ of natural-ventilated bedrooms in the specific case of Norway.

The main research questions are to:

- Evaluate the indoor environmental quality in bedrooms with natural ventilation in renovated detached houses.
- Determine whether a satisfying IAQ can be ensured in bedrooms by window opening during night-time.

Complementary questions are:

- How does the window opening behaviour affect IAQ?
- How the window opening behaviour is influenced by external factors?
- Do people open the windows enough to achieve good IAQ? Including during the coldest part of winter?

METHOD

37 bedrooms in 17 different case houses were investigated by measuring temperature, RH, CO2, and total volatile organic compounds (TVOC). Outdoor temperature, occupant presence, bedroom door opening, and bedroom window opening was also logged. The window opening angle was also logged with an accelerometer on top-hinged and bottom-hinged windows. Each house was measured for a 2-week period, and the measurements logged every 5 minutes. Measurements were also done in the adjacent room (typically a corridor), in order to compare concentrations and diurnal cycles. The intention is to account for the airflow between bedroom and corridor, as well as outdoor infiltration. The measurements were conducted during the winter of 2021. Long-term measurements (from 2 to 6 months) are also being done in some houses, to investigate seasonal variation in window opening behaviour and IAQ.

In addition, participants answered a questionnaire about their motivation and habits regarding window opening. Most of the occupants stated that they used to open bedroom windows during night-time. Weather data is collected from a weather station located 1 to 5 kilometres away, using the Norwegian Metrological Institute database. This will be used for further analysis (Meteologogisk Institutt, 2021).

Description of the case houses

All the houses are detached, have 2 floors, and are constructed in wood. The houses are without mechanical ventilation, apart from extract fans in many bathrooms, mostly moisture-controlled, or controlled with the light-switch. Most of the houses also had kitchen hood fans. Two houses with balanced ventilation was also measured, as a reference. Most of the bedrooms had natural ventilation (house 5 and 15). The houses have been retrofitted with additional thermal insulation and improved air-tightening, leading to a lower infiltration rate. However, also a few non-renovated buildings were included as a reference (house 11). All buildings are located in Rissa, close to Trondheim. This is a small town and rural area, with a semi-coastal, cold climate. So, this is not an urban environment, the air is unpolluted, and outside noise is low. All but two of the houses are owned by the occupants.

Selection of buildings and occupants

To identify suitable renovated houses, building companies have been contacted, as well as the personal network of the authors. This study targets inhabitants using window ventilation in bedrooms. Consequently, occupants stating they often open the bedroom window when sleeping have been asked to participate. (However, this behaviour varies between different members of the households). Therefore, the case buildings may not be representative for Norwegian dwellings in general.

Logging instruments

For the measurements, the Wisensys Wireless Sensing System was used. This consists of a base station in each house, receiving data wireless from sensors distributed in different rooms. The sensors used were: WS-DLC (CO2, temp, RH), WSE-DLTa-p100 (outdoor temp), WSE-DLXcc-PIR (presence (infrared)), WSE-DLXct with magnet contact SensTech-Det-02 (window/door opening). These have the following accuracy:

- CO2: ±40 ppm + 3% of reading @ 22°C
- Humidity: ±1.8%RH from 10% to 90%RH
- Temperature: ±0.3°C @ 25°C; ±0.5°C from 0-25°C

In addition, Airthings Wave Plus sensors were used. These sensors measure temperature, RH, CO2 and TVOC every 5 minutes (as well as radon and atmospheric pressure). The motivation to install Airthings was mainly to measure TVOC. They are also a simple and robust possibility for non-invasive long-term measurements. This also secured back-up measurements of CO2, humidity and temperature. The accuracy for CO2 is ±30ppm ±3% within 15-35°C.

The Airthings Wave Plus uses the Sunrise CO2-sensor from Senseair, which is a Non-Dispersive Infra-Red Sensor (NDIR). The sensor self-calibrates versus outdoor air concentration, so called local background calibration. This is based on the assumption that the concentration is close to the outdoor concentration, at some time during a period of several days. In an environment with continuous high CO2 concentrations, the calibration will be inaccurate. There was good correlation between the Wisensys and Airthings measurements.

TVOC sensor

The Airthings Wave Plus is equipped with the Bosch BME680 sensor for the TVOC measurements. This is a tiny metal oxide (MOX) sensor based on the principle that the heated metal oxide changes resistance based on the VOCs in the air (Sensortec, 2021).

The sensor gives one resistance value with related to the total VOC content, but it cannot differentiate gases or alcohols. It is sensitive for almost all VOC components. Hence, it measures TVOC as a batch but does not specify which VOCs.

Like other sensors working on a similar MOX sensing technology, such devices cannot output an absolute TVOC level. These measurements are not reliable for comparing TVOC levels between different rooms and houses, but are useful for qualitative evaluation of the diurnal variations. The BME680 has local background calibration, relating to the local maximum and minimum values gradually over some days.

Window opening sensors

Previous studies on window opening behaviour have mostly recorded open or closed states, while the area of the opening has hardly been monitored. To be able to investigate the relation between the degree of window opening and IAQ, a sensor measuring the window opening angle was developed in the project. This is based on a BBC micro:bit, which is a small, lightweight codable computer that is used for educational purposes in schools (*BBC micro:bit*, 2021). Due to its small size and light weight, it can easily be mounted on the window frame with double-sided tape. It has a built-in accelerometer as well as a flash memory and can be programmed in Arduino. The micro:bit can also communicate with other devices via Bluetooth. In our case, the data was stored on a Raspberry Pi located in the same room. Hence, a code for the logging and data transfer was developed. Accuracy was tested to be 2 degrees. More details regarding the window angle sensor is described by Skyttern (Skyttern, 2020).

Figure 1. Sensor logging the window opening angle.

As the method is based on measuring the vertical angle, this unfortunately does not work on side-hinged windows. Magnetic contact sensors were used for the side-hinged windows, recording only open and closed states.

During the installation of the equipment, the size and shape of the windows as well as the thickness and extension of curtains were registered. Information about the curtain position and habits was also a part of the questionnaire

RESULTS

The measurements are still in process, and data is only partly analysed. Therefore, only preliminary results are presented, and some tendencies observed are illustrated. Five houses, with 13 bedrooms, are partly analysed so far. These have indications like H3B2; meaning house3, bedroom1. The master bedroom is generally given the number 1.

Questionnaire

So far, 40 questionnaires are analysed. All but 8 of the participants responded that they open the bedroom window at night. Fresh air was reported as the main motivation for opening. 16 respondents answered that lowering the bedroom temperature was also part of the motivations. However, low temperature was also the most common reason given for not opening windows, along with wind. People were in general satisfied with the IAQ and the bedroom temperature, although low temperatures were measured. Only 4 occupants answered they used a local heat source in the bedroom.

Table 1. Results of the questionnaire

Motivation for opening window at night	Habit	Lower temp		Fresh air	
	2	16		36	
Motivation for not opening window	Cold out	Cold in	Noise	Rain	Wind
	2	9	1	3	9
Usual window opening gap	5 cm	10 cm	20 cm	30 cm	
	10	9	6	3	
Satisfaction bedroom temperature	Too cold	Too hot	OK	Good	
	1	2	6	23	
Satisfaction IAQ	Bad	OK	Good	Very good	
	1	5	15	11	

Window opening behaviour

Results show that windows usually were open during the night, in the majority of the bedrooms. Most of the windows were opened to the same position each night. The window in H4B1 was open to the same position both day and night for the whole measuring period.

Bedroom temperatures

Table 2. Time-averaged bedroom temperatures

		Night-time bedroom temp			Whole period	
Case house	Bed-room	Average temp [°C]	Min. av. temp [°C]	Max. av. Temp [°C]	Av. Bedr temp [°C]	Av. outdoor temp [°C]
H2	B1	11.9	8.3	14.6	11.7	0.5
	B2	21.1	16.5	26.1	21.1	0.5
	B3	16.9	13.8	19.4	18.2	0.5
H3	B1	13.5	8.3	15.6	14.5	0.5
	B2	13.3	9.8	15.6	13	0.5
H4	B1	14.3	6.4	18.8	13	-6
	B2	17.3	14.2	19.0	17.5	-6
	B3	20.2	17.8	21.7	18.3	-6
H6	B1	11.6	10	12.8	10.2	-6
	B2	12.8	11	14.4	13.4	-6
H12	B1	10.9	-0.2	15.5	10.1	-7.1
	B2	17.6	13.6	21.4	18.1	-7.1
	B3	18.9	14.9	21.8	19.2	-7.1

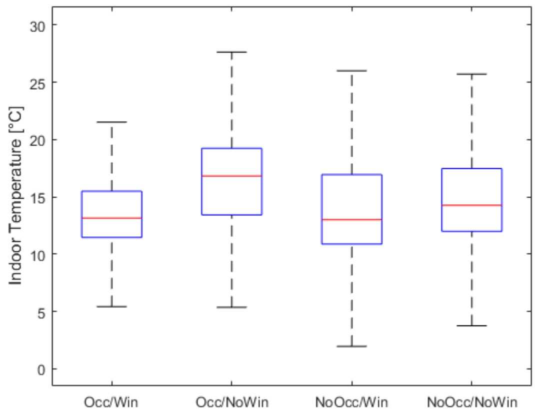

Figure 2. Temperature in bedrooms in houses 2, 3, 4, 6, 12 with and without occupancy. Win=open window. NoWin=closed window

Only the measurements when the rooms are occupied between 23:00 and 07:00, have been included in the nightly-averaged calculations. In addition, the nights with the lowest and highest average are reported, referred to as minimum and maximum averages.

In almost all the analysed houses the master bedroom has the lowest temperature. The temperatures are generally low. Large variations in the bedroom temperature is observed in almost all the rooms. This is not surprising, as very few rooms had a local heating source, thus relying on heat flow from other rooms. Temperatures related to occupancy and window opening is show in Figure 2. The lowest temperatures are actually found when the window is open, and the rooms are occupied.

CO2 levels

Table 3. Time-averaged night-time CO2 concentration.

Case house	Bed-room	Whole period average CO2 [ppm]	Night-time concentration Av. CO2 [ppm]	Min. av. CO2 [ppm]	Max. av. CO2 [ppm]
H2	B1	519	494	424	551
	B2	837	719	439	1618
	B3	698	521	457	687
H3	B1	1342	1475	471	2204
	B2	558	671	535	852
H4	B1	789	1045	663	1239
	B2	1087	1345	1071	1718
	B3	660	944	692	1185
H6	B1	729	862	416	1647
	B2	707	1053	526	1665
H12	B1	623	582	493	753
	B2	592	544	471	766
	B3	877	1049	563	1789

Like indoor temperature, only the measurements when the rooms are occupied between 23:00 and 07:00, have been included in the nightly averaged calculations. The time-averaged CO2 concentration during night-time exceeded 1000 ppm in 5 out of the 13 analysed rooms. The occupants in three of these 5 rooms (H4B2, H6B2, H12B3) informed that they usually did not keep the windows open during the night in wintertime, but usually aired out before going to bed.

The measurements did so far not show any clear tendency towards high concentrations when outdoor temperatures were low. This is illustrated in Fig. 3, during a very cold period.

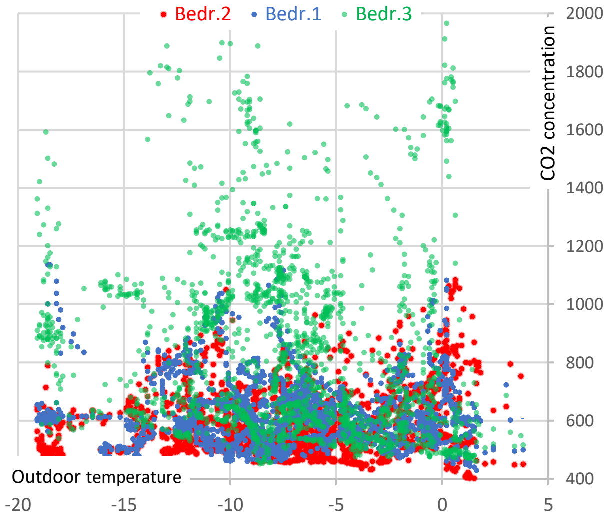

Figure 3. CO2 concentration versus outdoor temperature in 3 bedrooms in house 12.

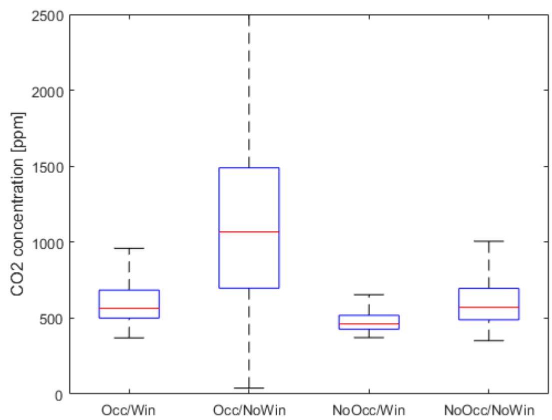

Figure 4. CO2 concentration in bedrooms in houses 2, 3, 4, 6, 12, with and without occupancy. Win=open window. NoWin=closed window

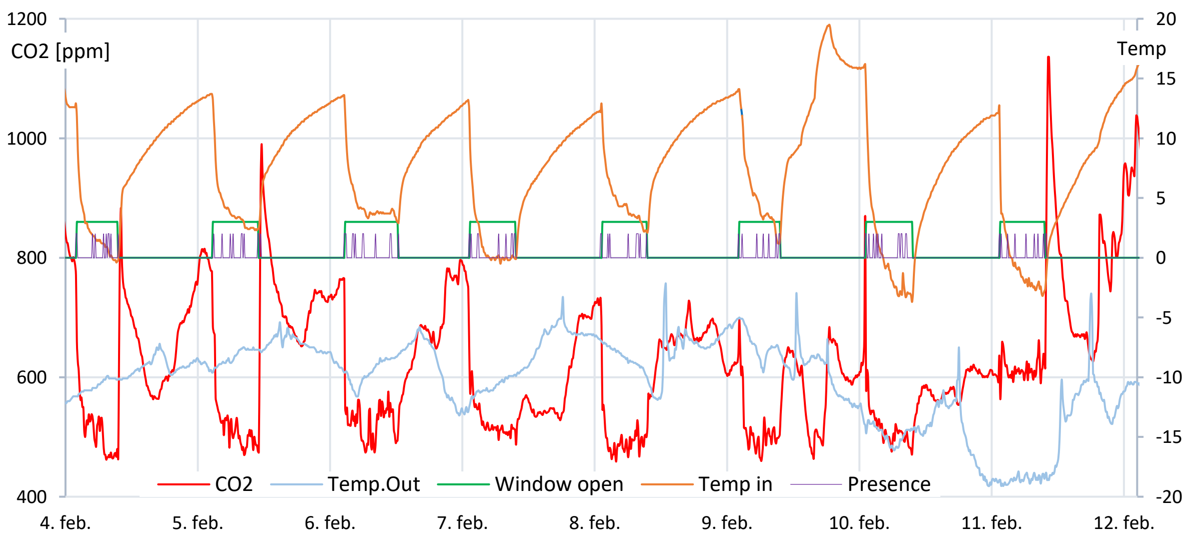

Figure 5. Variation in concentration of CO2, temperature and window opening of bedroom H12B1.

CO2 related to occupancy and window opening is show in Figure 4. The lowest concentrations are found when the window is open, and the rooms are not occupied. Occupied rooms with open window also have low CO2 levels, always lower than 1000 ppm. Occupied rooms with windows closed clearly show the highest levels, often exceeding 1000ppm.

In most of the bedrooms, a clear daily pattern in the CO2 levels could be seen. Examples are illustrated in Figures 5 and 6. The bedroom windows are opened when the occupants go to bed, leading to a low CO2 concentration during the night. The presence detector shows that these rooms hardly are occupied during daytime

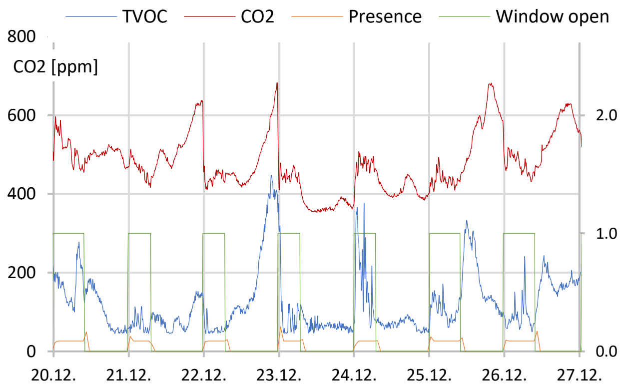

Figure 6. Variation in concentration of CO2 and TVOC, and window opening of bedroom H2B1.

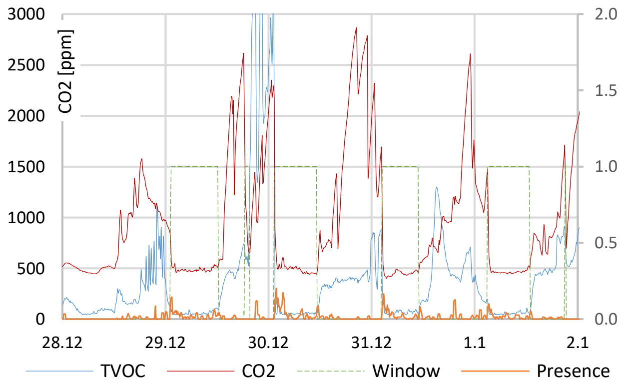

Figure 7. Variation in concentration of CO2 and TVOC, and window opening of bedroom H2B2.

Higher daytime CO2 concentrations

For some bedrooms, the highest levels were observed during the day (i.e., the afternoon or evening), with the windows closed during occupation. Several of these rooms were occupied by children or teenagers. Figure 7 illustrates how the concentration decreases rapidly when the window is opened at night. The occupants in these rooms seem to follow the regular habit of opening window when going to bed, and it seems like this opening is sufficient for good IAQ at night.

Total Volatile Organic Compounds

The highest values of TVOC were seen when rooms were occupied with the window closed. Some high values were found for short durations of time (Figures 6 and 7). Many of the peaks occur before window opening, and are most likely related to occupant behaviour. The tendency is that TVOC and CO_2 has some correlation, but also varies separately.

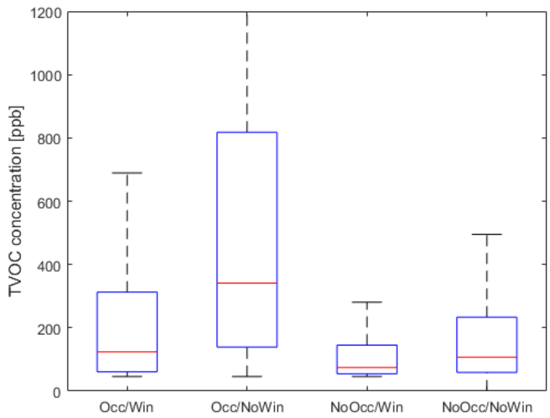

Figure 8. TVOC concentration in bedrooms in houses 2, 3, 4, 6, 12, with and without occupancy. Win=open window. NoWin=closed window

DISCUSSION

Selections of houses and occupants

This study targets inhabitants who state they usually open the bedroom window during night-time. In addition, the study considers building with a tight envelope. However, the real behaviour can differ from what people claim. Also, this behaviour varies between different members of the households. The houses are in a rural area, with a semi-coastal, cold climate. So, the air is unpolluted, and outside noise is low, not discouraging natural ventilation.

In sum, a selection bias may be present in the chosen buildings and inhabitants. The results may therefore not be transferable to dwellings or inhabitants, in general. Finally, the number of bedrooms analysed in this paper is too limited to generalize the conclusions.

Window opening area

During the tests and the field investigations, the accelerometer was found to be a good solution for measuring the opening angle of bottom- and top-hinged windows. Accuracy was estimated to be 2 degrees, clearly sufficient for a qualitative assessment of the window ventilation. Unfortunately, the method does not work on side-hinged windows.

Airflow through window openings are not only affected by the area, but also details of shape and construction. Other factors like wind speed and direction, temperature difference between indoor and outdoor, opening height and curtain configuration also determines the airflow through the window.

IAQ measurements

During the set-up of the equipment, it was not always possible to place sensors optimally in the bedroom. Some measurements may show local values close to the sensor and may not be representative for the IAQ in the entire room. The average IAQ during the night is calculated for the measurement between 23:00 and 06:00, when occupants are present. If peoples sleeping period deviates from this, inaccuracies may occur.

Five of the thirteen bedrooms analysed were found to have high CO2 concentrations during night-time. Three of these rooms (H4B2, H6B2, H12B3) did generally not have the window open during night-time, and reported they usually aired out before sleeping. In room H3B1 and H4B1, heavy curtains seemed to reduce the airflow. The latter rooms are also quite small, with 2 occupants.

In general, a quite large variation in the CO2 concentration from day to day, or night to night, is observed (see Table 3). Further analysis will seek to investigate reasons for this. Both occupant behaviour and weather variations may contribute to this variation.

Window opening behaviour

The window opening behaviour was shown to be both predictable and persistent. The bedroom windows were opened every night in most of the bedrooms. It seemed like many occupants had a habit of opening the window when going to bed.

The measurements in house 4, 6 and 12 were done in the coldest periods of the winter, with average period temperatures of -6°C and -7.1°C. Many occupants still opened the window every night (Figure 5). This behaviour may however differ strongly between the individuals.

Less extensive window opening during the coldest months may lead to more nights of lower IAQ. However, if the window is still opened during the colder months but with a smaller opening, the IAQ in the bedroom may not be lower (due to stronger driving forces caused by higher temperature difference between indoor and outdoor).

Bedroom door positions

Preliminary assessment of door opening data, indicate that bedroom doors are usually not open when the bedroom window is open. Thus, little cross ventilation is induced. We should keep in mind this is during winter, other seasons may be different. In the further work, door opening will be analysed together with IAQ measurements in the corridor outside the bedrooms.

IAQ values during daytime occupation

Some of the highest concentrations were found in the afternoon and evening, linked to occupancy with the window (and door) closed (Figure 7). This often seemed to be the case in bedrooms of children and teenagers. In most cases, the concentration decreases as the window is opened when going to sleep. This indicates how the use of the room during the day should be taken into consideration when natural ventilation is used in a bedroom.

Also some rooms without daytime occupation, showed the highest CO2 concentration during the day. An example is illustrated in Figure 5. Airflow from other rooms is assumed to cause the rise during the day.

The monitored rooms can be divided into two main groups: the “pure” bedrooms, and the multi-activity rooms (sleeping, homework, play, gaming etc.). The “pure” bedrooms often have the highest CO2 concentrations at night, simply because they are occupied only during the night. The multi-activity rooms often have the highest CO2 concentrations during daytime. These rooms are typically used by children or teenagers.

Temperature and RH

In 10 out of 13 analysed bedrooms, the nightly-averaged temperature was below 18°C, while only two had above 20°C. Seven rooms had averages below 15°C, and the lowest minimum nightly-average was below zero. These measurements confirmed that many occupants prefer a lower bedroom temperature. It indicates the importance of considering individual preferences when the indoor environment in bedrooms are evaluated.

Temperatures related to occupancy and window opening is show in Figure 2. The lowest temperatures were actually found when the window was open, and the rooms occupied. With open window and no occupancy, the temperatures were a bit higher. The explanation for this may be that people tend to have a larger opening size when they are present (sleeping), than if they leave the room with the window open.

The RH levels in the bedrooms were relatively high, mainly 30-55%. If such a high RH is combined with cold thermal bridges and interior surfaces (with low ability to transport moisture), this could cause mould problems. Our case houses are however renovated and well insulated.

CONCLUSIONS

The indoor temperature and IAQ was measured in 37 bedrooms with natural ventilation, mainly using window opening, in renovated houses. The window opening behaviour was shown to be both predictable and persistent. The bedroom windows were found to be open most nights, in the majority of the 13 bedrooms analysed. Occupied rooms with open window showed low CO2 levels, always lower than 1000 ppm. High CO2 levels at night were however found in five bedrooms, mainly due to inconsistent window opening. In the other bedrooms, CO2 concentration was at a satisfying level during the night-time. This suggests that it is possible to achieve a high IAQ with manual window ventilation when this is a deliberate strategy, also in energy-renovated houses. In some rooms used for activities during daytime (like for children and teenagers), the most unfavourable conditions were found during occupancy in daytime with the window closed.

The temperature measurements confirmed that many occupants may prefer a lower bedroom temperature and indicated the importance of considering individual preferences when the indoor environment in bedrooms are evaluated.

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REFERENCES

Andersen, R., Fabi, V., Toftum, J., Corgnati, S. P., & Olesen, B. W. (2013). "Window opening behaviour modelled from measurements in Danish dwellings". *Building and Environment*, *69*, 101-113. https://doi.org/10.1016/j.buildenv.2013.07.005

Aubin, D., Won, D., Schleibinger, H., Gauvin, D., Lajoie, P., Fugler, D., Ruest, K., & Gingras, V. (2012). "Effectiveness of ventilation interventions at improving indoor air quality in Canadian homes with asthmatic children". *Proceedings of Healthy Buildings*,

BBC micro:bit. (2021). https://tech.microbit.org/hardware/#hardware-description

Bekö, G., Lund, T., Nors, F., Toftum, J., & Clausen, G. (2010). "Ventilation rates in the bedrooms of 500 Danish children". *Building and Environment*, *45*(10), 2289-2295.

Berge, M., Georges, L., & Mathisen, H. M. (2016). "On the oversupply of heat to bedrooms during winter in highly insulated dwellings with heat recovery ventilation". *J Building Environment*, *106*, 389-401.

Berge, M., & Mathisen, H. M. (2016). "Perceived and measured indoor climate conditions in high-performance residential buildings". *Energy and Buildings*, *127*, 1057-1073.

Bjorvatn, B., Mrdalj, J., Saxvig, I. W., Aasnæs, T., Pallesen, S., & Waage, S. (2017). "Age and sex differences in bedroom habits and bedroom preferences". *Sleep medicine*, *32*, 157-161.

Bjørneboe, M. G., Svendsen, S., & Heller, A. (2017). "Evaluation of the renovation of a Danish single-family house based on measurements". *Energy and Buildings*, *150*, 189-199.

Bornehag, C.-G., Sundell, J., Hägerhed-Engman, L., & Sigsgaard, T. (2005). "Association between ventilation rates in 390 Swedish homes and allergic symptoms in children". *Indoor air*, *15*(4), 275-280.

Du, L., Batterman, S., Godwin, C., Chin, J.-Y., Parker, E., Breen, M., Brakefield, W., Robins, T., & Lewis, T. (2012). "Air change rates and interzonal flows in residences, and the need for multi-zone models for exposure and health analyses". *International journal of environmental research and public health*, *9*(12), 4639-4661.

Fernández-Agüera, J., Dominguez-Amarillo, S., Fornaciari, M., & Orlandi, F. (2019). "TVOCs and PM 2.5 in Naturally Ventilated Homes: Three Case Studies in a Mild Climate". *Sustainability*, *11*(22), 6225.

Hou, J., Zhang, Y., Sun, Y., Wang, P., Zhang, Q., Kong, X., & Sundell, J. (2017). "Air change rates in residential buildings in Tianjin, China". *Procedia Engineering*, *205*, 2254-2258.

Ilomets, S., Kalamees, T., & Vinha, J. (2018). "Indoor hygrothermal loads for the deterministic and stochastic design of the building envelope for dwellings in cold climates". *Journal of Building Physics*, *41*(6), 547-577.

Meteorologisk Institutt. (2021). *Norsk Klimaservicesenter*. https://seklima.met.no/observations/

Jones, R. V., Fuertes, A., Gregori, E., & Giretti, A. (2017). "Stochastic behavioural models of occupants' main bedroom window operation for UK residential buildings". *Building and Environment*, *118*, 144-158.

Kotol, M., Rode, C., Clausen, G., & Nielsen, T. R. (2014). "Indoor environment in bedrooms in 79 Greenlandic households". *Building and Environment*, *81*, 29-36.

Langer, S., & Bekö, G. (2013). "Indoor air quality in the Swedish housing stock and its dependence on building characteristics". *Building and Environment*, *69*, 44-54.

Langer, S., Bekö, G., Bloom, E., Widheden, A., & Ekberg, L. (2015). "Indoor air quality in passive and conventional new houses in Sweden". *Building and Environment*, *93*, 92-100.

Levie, D., Hoes-van Oeffelen, E., Hofstetter, H., Janssen, S., Spiekman, M., & Koene, F. (2014). "Determinants of ventilation behavior in naturally ventilated dwellings: Identification and quantification of relationships". *Building and environment*, *82*, 388-399.

Liu, D., Ren, Z., Wei, S., Song, Z., Li, P., & Chen, X. (2019). "Investigations on the Winter Thermal Environment of Bedrooms in Zhongxiang: A Case Study in Rural Areas in Hot Summer and Cold Winter Region of China". *Sustainability*, *11*(17), 4720.

Park, J., Jee, N. Y., & Jeong, J. W. (2014). "Effects of types of ventilation system on indoor particle concentrations in residential buildings". *Indoor Air*, *24*(6), 629-638.

Sensortec, B. (2021, January 2021). "BME680 LOw powergas, pressure, temperature and humidity sensor". https://www.bosch-sensortec.com/media/boschsensortec/downloads/datasheets/bst-bme680-ds001.pdf

Sharpe, T., Porteous, C., Foster, J., & Shearer, D. (2014). "An assessment of environmental conditions in bedrooms of contemporary low energy houses in Scotland". *Indoor and Built Environment*, *23*(3), 393-416.

Shinohara, N., Kataoka, T., Takamine, K., & Gamo, M. (2011). "Distribution and variability of the 24-h average air exchange rates and interzonal flow rates in 26 Japanese residences in 5 seasons". *Atmospheric environment*, *45*(21), 3548-3552.

Skyttern, S. (2020). "Assessment of the indoor environment in bedrooms of existing Norwegian dwellings" *Master thesis, NTNU.*

Thomsen, K. E., Rose, J., Mørck, O., Jensen, S. Ø., Østergaard, I., Knudsen, H. N., & Bergsøe, N. C. (2016). "Energy consumption and indoor climate in a residential building before and after comprehensive energy retrofitting". *Energy and Buildings*, *123*, 8-16.

Verbruggen, S., Delghust, M., Laverge, J., & Janssens, A. (2020). "Window use habits in Belgian households". *The 16th Conference of the International Society of Indoor Air Quality & Climate*

Øie, L., Stymne, H., Boman, C. A., & Hellstrand, V. (1998). "The ventilation rate of 344 Oslo residences". *Indoor Air*, *8*(3), 190-196.