Silje Skyttern

Assessment of the indoor environment in bedrooms of existing Norwegian dwellings

Master's thesis in Energy and Environmental Engineering
Supervisor: Laurent Georges, Vegard Heide
June 2020

Master's thesis

NTNU
Norwegian University of Science and Technology
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Assessment of the indoor environment in bedrooms of existing Norwegian single-family houses

Luftkvalitet på soverom I eksisterende norske eneboliger

Background and objective:

The master thesis is related to the research project OPPTRE (http://opptre.no/). OPPTRE aims to propose a nearly Zero Energy Building (nZEB) level for the renovation of wooden dwellings. The scope is small wooden dwellings, responsible for more than half of the total energy use in the Norwegian building stock. These can contribute significantly to the national target of 10 TWh/year energy saving by 2030 for existing buildings.

Many ambitious energy-efficiency measures are not cost-optimal when only considering investment and energy costs. However, renovation can serve other purposes, such as improving the indoor environment of the building (typically thermal comfort and indoor air quality). In Norway, many users would like cold bedroom with the window opened, even during wintertime. To motivate the building owner to renovate their ventilation system, it is important to know the typical indoor environment in bedrooms of existing buildings with natural ventilation. The master thesis aims at developing a methodology for assessing the indoor environment in bedrooms with extensive window opening, and then apply this methodology for a selection of buildings in Trondheim area.

The following tasks are to be considered:

- Continue and confirm the review of existing studies, especially in Scandinavia, regarding indoor environment in bedrooms from the specialization project.
- Improve the methodology for evaluating indoor environment in bedrooms from the specialization project, especially considering sensors for measuring window-opening, door opening and indoor air quality and logging of user behavior and perspectives.
- Investigate the indoor environment in window-ventilated bedrooms in existing single-family houses by applying the methodology. Hereunder, locating a selection of buildings that are fitted for the research project especially considering infiltration rate and user behavior.
- Further develop a model for analyzing air change rate in the bedrooms.
- Analyzing the results from the real cases.

Abstract

The objective of this work has been to investigate if a satisfying indoor environment can be ensured in bedrooms only by opening the window at nighttime. The superior goal was to investigate if natural ventilation in the bedroom, in combination with balanced ventilation in the rest of the house, can be a satisfying ventilation solution in buildings that are energy-upgraded. This work has been a continuation of a specialization project conducted during the fall of 2019.

A literature review of the indoor environment in Scandinavian buildings and bedrooms has been conducted. The reviewed studies indicated how the IAQ of naturally ventilated buildings are often characterized by low air change rates and occasionally high CO_2 levels. As a healthy indoor environment is becoming more important, the installation of balanced ventilation systems has also come to be more common - as it provides an easy way of controlling the IAQ. The reviewed literature illustrated how the transition from a natural ventilation system to a mechanical one, can lead to problems with noise, draught, and oversupply of heat to the bedroom. It was also shown how many occupants valued the opportunity of being able to control their indoor environment and how natural ventilation systems may, therefore, lead to a higher user satisfaction.

In the development of the methodology for evaluating the indoor environment in bedrooms, two different IAQ sensors were tested. A non-commercial sensor developed at NTNU was chosen to conduct the IAQ measurements. Two different window opening sensors were tested and developed; an accelerometer to measure the opening of top-and bottom-hinged windows, and an ultrasonic sound sensor to measure the opening of side-hinged windows. Ten bedrooms in six case houses were investigated through measurements of CO_2, temperature, RH, PM, formaldehyde and TVOC. The measurements were conducted over 2-3 weeks, during March and April, and weather data was collected from nearby weather stations. The participants were asked to answer a questionnaire about the building, their motivation for opening the bedroom window and reasons for why the window might be kept closed at night. On reasons for why the window would be closed, the most common answers were related to the outdoor temperature. The windows were open every night in most of the bedrooms.

High CO_2 levels were found in two out of ten bedrooms. These two bedrooms were also found to have a more extensive window opening behavior. In the other bedrooms, the CO_2 concentration was at a satisfying level during the nighttime. Although, higher levels were found during the days for some of the bedrooms. The average measurements of PM were found to be low, while high average levels were found for both formaldehyde and TVOC in most of the bedrooms. The high levels of formaldehyde and TVOC may be related to some inaccuracy of the IAQ sensors. Six bedrooms had an average nightly temperature below 18°C, whereas the value was higher than 21°C for the remaining four bedrooms. Higher bedroom temperatures were found in combination with a lower RH level. Some correlation between the RH level and the outdoor temperature was also indicated. No strong correlation was found between the IAQ and the size of the window opening area.

These investigations have shown that it is possible to ensure a high IAQ and a good indoor environment in bedrooms with only natural ventilation through occupant-controlled window openings. However, opening the window at night does not necessarily guarantee high IAQ, and this should be taken into account when this solution is considered.

Sammendrag

Hensikten med dette arbeidet har vært å undersøke om et tilfredsstillende inneklima kan oppnås i soverom kun gjennom å åpne vinduet på natten. Det overordnede målet var å se om bruk av naturlig ventilasjon, i kombinasjon med balansert ventilasjon i resten av huset, kan være en tilfredsstillende ventilasjonsløsning i bygninger som skal energioppgraderes. Dette arbeidet har vært en videreføring av et fordypningsprosjekt gjennomført høsten 2019.

Det har blitt gjennomført et litteratursøk relatert til inneklima i skandinaviske hus og soverom. De undersøkte studiene indikerte at luftkvaliteten i naturlig ventilerte bygg ofte karakteriseres av et lavt luftskifte og tidvis høye CO_2 nivåer. Med et økende søkelys på et sunt inneklima har også balansert ventilasjon blitt et vanlig ventilasjonssystem i norske boliger, ettersom det er en enkel måte å kontrollere luftkvaliteten på. De gjennomgåtte studiene har vist at overgangen fra et naturlig ventilasjonssystem til et mekanisk, kan bringe med seg noen utfordringer knyttet til støy, trekk og tilføring av overskuddsvarme til soverommet. Det ble også vist at mange verdsetter muligheten til å kontrollere omgivelsene sine, derav kan naturlig ventilasjon føre til mer fornøyde beboere.

I utviklingen av metoden for å evaluere inneklimaet i soverommene, ble to forskjellige inneklimasensorer testet. En ikke-kommersiell sensor utviklet ved NTNU ble valgt for å utføre inneklimamålingene. To forskjellige vindusåpningssensorer har også blitt testet og utviklet; et akselerometer for å måle åpningen av topp- og bunnhengslede vinduer, og en ultrasonisk lydsensor for å måle åpningen av sidehengslede vinduer. Ti soverom i seks case hus ble undersøkt gjennom målinger av CO_2, temperatur, RH, PM, formaldehyd og TVOC. Målingene i mars og april, og hadde en varighet på 2-3 uker. I tillegg til dette ble værdata samlet inn fra værstasjoner i nærheten. Deltakerne ble også bedt om å svare på et spørreskjema om huset, motivasjonen for å åpne vinduet om natten og årsaker til hvorfor vinduet eventuelt ikke ble åpnet. På spørsmålet om hvorfor de eventuelt ikke åpnet vinduet om kvelden, var de vanligste grunnene knyttet til lav utetemperatur. Vinduet ble åpnet hver natt i nesten alle soverommene.

Høye konsentrasjoner av CO_2 ble funnet i to av ti soverom. I begge disse soverommene var også vinduene mer åpne. På de andre soverommene var CO_2 konsentrasjonen på et tilfredsstillende nivå gjennom de fleste nettene. I noen soverom ble det funnet høyere nivåer på dagtid. Gjennomsnittskonsentrasjonen av PM var generelt lav, mens høye gjennomsnittlige nivåer ble funnet for både formaldehyd og TVOC i de fleste av soverommene. De høye nivåene av formaldehyd og TVOC kan ha en sammenheng med noe usikkerhet knyttet til inneklimamålerne. Seks soverom hadde en gjennomsnittlig temperatur under 18°C på natten, mens det samme tallet var over 21°C for de fire andre soverommene. Høyere soveromstemperaturer ble funnet i kombinasjon med lavere RH-nivåer. Det ble også sett en moderat sammenheng mellom RH-nivået og utetemperaturen. Ingen stor korrelasjon ble funnet mellom luftkvaliteten og størrelsen på vinduets åpningsområde.

Disse undersøkelsene har vist at det er mulig å oppnå høy luftkvalitet og et godt inneklima på soverom med kun naturlig brukerstyrt ventilasjon gjennom vinduet. Å åpne vinduet om natten garanterer ikke nødvendigvis et godt inneklima, og dette bør tas med i betraktningen når en slik løsning blir vurdert.

Preface

This master thesis has partly been written during a time where a pandemic treathened the world. I am therefore grateful for the kind people who still trusted me to enter their homes – prepared with antibac of course – and investigate their bedrooms during this strange time.

Single-family houses were at first targeted as investigation objects, but the search was expanded to include other types of dwellings as it was difficult to find a large and fitting selection of single-family houses. Several of the single-family houses also withdrew their partcipation in the project after the societal restrictions were introduced due to covid-19.

I would like to thank Laurent Georges and Vegard Heide. Laurent was my supervisor, and Vegard my co-supervisor. Vegard has helped me locate bedrooms to investigate and has helped me with some of the field investigations, in additon to offering his guidance when needed. I would also like to thank Amund Askeland at the Electro Department at NTNU for great help with developing the window opening sensors, and answering my many questions.

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1 Introduction

In 2015 Norway, along with 192 other countries worldwide, committed to United Nations seventeen Sustainable Development Goals. An important aim of these goals is to reduce the emission of greenhouse gases, along with responsible exploitation of resources worldwide. Along with this commitment the Norwegian government, together with the Norwegian Parliament, has also committed Norway to being carbon-neutral by 2050 [1].

The energy use in the building sector represents around 40 % of the total energy use in most developed countries [2]. Half of the energy use of the Norwegian building stock is linked to small wooden dwellings. Energy-upgrading of these dwellings is an important measure to reduce energy and resource consumption in the building sector, and the national target is to save 10 TWh/year by 2030 for existing buildings.

OPPTRE is a research project supported by the Research Council of Norway, where the aim is to propose a low-cost, low-carbon and high-quality architectural solution for upgrading small wooden dwellings to nZEB level [3]. One of the aims of OPPTRE is to realize energy-upgrading to nZEB level by optimizing the heating- and ventilation strategies, reduce energy use and secure a good and healthy indoor environment. This master thesis is linked to the research project OPPTRE.

Traditionally, Norwegian dwellings have been constructed without mechanical ventilation or with an extractor hood in the kitchen and a fan in the bathroom. Today, there are strict demands for the construction and design of new buildings to ensure energy-efficiency and a healthy indoor environment. For this reason, balanced ventilation is commonly installed in new buildings. This may in some cases come in conflict with the occupant’s habits and preferences – such as opening the bedroom window for fresh air supply at night.

The main objective of this master thesis is to investigate the indoor environment of bedrooms in existing Norwegian dwellings, where the occupant normally opens the window for fresh air supply during nighttime. The aim is to research if this use of natural ventilation can secure a good indoor environment and high air quality in the bedrooms. The main motivation is to examine the necessity of installing balanced ventilation in bedrooms when an existing building is energy-upgraded.

To investigate this, a combination of a literature review and field investigations are used. This work is a continuation of a specialization project, conducted during the fall of 2019. Through the specialization project, a literature review regarding the indoor environment in Scandinavian buildings and bedrooms was carried out. Based on this, a methodology for reviewing the indoor environment in bedrooms was developed. Both the methodology and the literature review has been further refined in this work.

2 Framework

The purpose of this chapter is to introduce the most important theoretical aspects regarding natural ventilation and indoor environment.

2.1 Indoor environmental quality (IEQ)

In 2010 Statistics Norway (SSB) reported that Norwegians spent on average 2 hours and 38 minutes outside per day [4], which is roughly 10 % of the day. Therefore, to avoid any risk of influencing the health or well-being of the occupants, it is important to consider the quality of the indoor environment.

When IEQ is discussed, both the terms indoor climate and indoor environment are frequently used. Indoor climate is by the World Health Organization (WHO) defined as the sum of the thermal, atmospheric, acoustic, actinic and mechanical environment. The term indoor environment also includes the aesthetic and the psychosocial environment [5]. As this work revolves around the IEQ in bedrooms, the thermal, the atmospheric and the acoustic environment has been considered as the three most relevant aspects. The next section aims to explain these three concepts.

2.1.1 Thermal environment

The most important term when describing the thermal environment is thermal comfort. Thermal comfort can be defined as "that condition of mind which expresses satisfaction with the thermal environment" [6]. The term can be used as an indicator of how satisfied someone feel with their surroundings. It is dependent on both environmental parameters, such as temperature and air velocity, but also physiological conditions and individual preferences affects how the thermal environment is perceived [5, 6].

2.1.2 Atmospheric environment

The atmospheric environment is related to the number of pollutants, gases, fibers and particles present in the air, and can be associated with the term indoor air quality (IAQ) [5]. IAQ is partly an expression for the chemical, physical and microbiological composition of the air, but also an expression for how the air is perceived by occupants [7]. The atmospheric environment is often considered the most important aspect of the indoor environment, as it can have direct effects on the health of the inhabitants [8]. To evaluate the atmospheric environment, some indicators of IAQ is discussed in section 2.3.1

2.1.3 Acoustic environment

The acoustic environment is related to how sounds are experienced in a room. Sounds that are experienced as disturbing, annoying, interrupting or too loud are categorized as noise. Whether something is perceived as noise, or not, is dependent on the person, the situation and the sound itself [5]. For example, a low humming sound from the ventilation system might not be perceived as noise, or even noticed, at a dinner party, yet, it might be very disturbing while trying to fall asleep.

2.2 Ventilation strategies

This section aims to give a brief introduction to the concepts of natural and mechanical ventilation.

2.2.1 Natural ventilation

Natural ventilation exploits natural forces, such as buoyancy and wind, to move fresh air into the building, and existing air around and out from the building. Wind forces create a pressure on the windward side of the building, where the airflow will either flow through open windows or vents, infiltrate through the construction, pass around the building or a mix of the above, as illustrated in Figure 1.

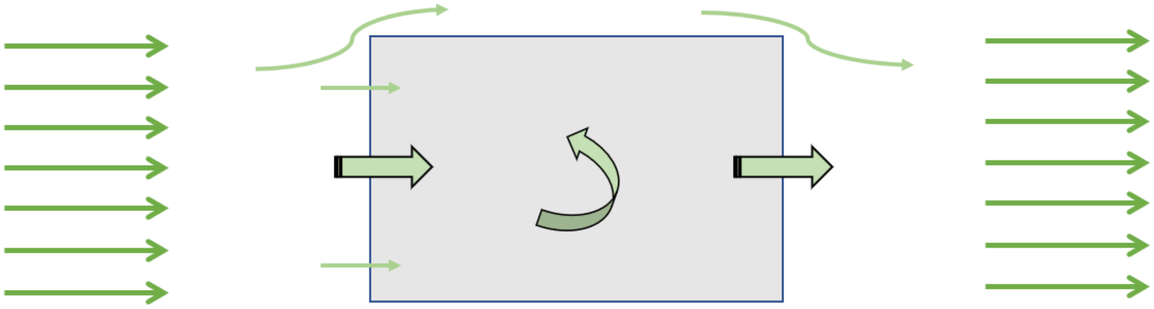


Figure 1: Natural ventilation with wind as driving force. The airflow is infiltrating through building construction, flowing through windows (larger arrows), and flowing around the building body. Inspiration for illustration collected from "ENØK i bygninger" figure 6.3.1 [5].

The exploitation of buoyancy forces is based on the principle of warm air having a lower density than cold air and will, therefore, raise towards higher levels in the building or in the room. This is called the stack effect. When this is exploited, fresh air will naturally be supplied in the lower levels of the building and extracted at the higher levels. These forces are strengthened with an increasing temperature difference between outdoor and indoor, such as in the heating season [5].

The complexity of a natural ventilation system can differ from opening a window to more complex systems. The common factor is the absence of energy-consuming installations such as fans and heat exchangers [5]. Therefore, the effect of a natural ventilation system will also vary considerably with outdoor and indoor temperature, number, size and duration of window openings, building structure, exposure and wind conditions. A study from 2008 concluded that the most important driving forces for single-sided natural ventilation were either wind speed or temperature difference, depending on the incidence angle of the wind [9]. By these reasons, controlling the air flows in a natural ventilation is often more demanding compared to mechanical ventilation.

2.2.2 Mechanical ventilation

The term mechanical ventilation comprises both balanced ventilation systems, with integrated fans for supply and exhaust, and more traditional systems, such as exhaust ventilation with e.g. an extractor hood in the kitchen or a fan in the bathroom [5]. The need for technical installations, such as fans, makes a mechanical ventilation system more energy-consuming, compared to a natural ventilation system.

Most of the buildings constructed after 2010 in Norway are designed with balanced ventilation systems. The main advantage of this system is the possibility to recover heat from the exhaust air and to control the supply air flow. The superior goal is to save energy and facilitate a good indoor environment with high IAQ [10]. Due to the need for ducts and technical installations, a balanced ventilation system is more resource demanding compared to an exhaust system, both materially and economically.

2.3 Demands, regulations and recommendations

Some of the most relevant recommendations and demands for IAQ is presented in this chapter, to form a basis for comparison later.

2.3.1 Indicators of IAQ

In the report published by the Norwegian Health Association (Folkehelseinstituttet) in 2015, temperature, relative humidity (RH), air velocity and CO_2 is mentioned as the most relevant IAQ parameters, when performing basic short-term measurements for indicating the state of the indoor environment [8].

CO_2

In the report from the Norwegian Health Association, CO_2 is stated as a good indicator of the air change rate [8]. Several studies have also used occupant-produced CO_2 as a tracer gas in order to calculate the air change rate and hereby the ventilation effectiveness of the room [11, 12]. The air change rate indicates the amount of supplied air in relation to the room volume. It should be noted that the air change rate does not imply directly how well the occupied zone is ventilated [13].

In general, CO_2 concentrations of 1000 ppm is used as a threshold value [14]. Wisconsin Department of Health Services states that for concentrations of CO_2 between 1000 – 2000 ppm, occupants often complain about the air quality and the feeling of drowsiness. Concentrations exceeding 2000 ppm can often be associated with headaches, sleepiness, increased heart rate and slight nausea [15]. High concentrations of CO_2 is often correlating with high concentrations of other indoor air pollutants, and the impacts are not necessarily causes by the CO_2 gas itself [8].

The standard EN16798, which considers energy performance and ventilation in buildings, operates with four different categories for IEQ [16]. The four categories are related to the different level of expectations the occupants may have to the IAQ, whereas category one corresponds to a high level, category two to a medium level, category three to a moderate level and category four to a low level of expectations. The standard considers category two as a normal level and states that a higher level would be chosen for occupants with special needs, such as asthmatics. It is important to notice that a lower level does not necessarily indicate any health risk but may result in a lower level of comfort for the user.

The four categories, together with the limit values for CO_2 design concentrations for bedrooms, are listed in Table 1. The standard operates with CO_2 concentrations in the unit "ppm above outdoors".

Table 1: IEQ categories as given in EN16798 [16].

IEQ category	Level of expectation	Design concentration of CO_2 [ppm above outdoors]
1	High	< 380
2	Medium	380 – 550
3	Moderate	550 – 950
4	Low	> 950

Temperature and RH

Thermal sensation is dependent on the temperature balance of the body, which is affected by activity level and clothing, as well as operative temperature, air velocity and RH [6]. It is therefore difficult to recommend a certain bedroom temperature, as it often is occupant dependent and a subjective matter [5].

At moderate temperatures, the humidity level in the air has limited influence on the thermal comfort [6]. However, dry air has been shown to have a negative effect on skin, eyes and airways [6]. High humidity levels can cause problems with mold or dust mites, which typically thrives at, respectively, levels of 75-80 % and 60-70 % [5]. To avoid condensation on cold surfaces it is important that a high humidity level is not combined with a low interior surface temperature.

2.3.2 Indoor air pollutants

As already mentioned, CO_2 is often used as an indicator of the IAQ but does not directly affect the health or well-being of the occupants [8]. However, as high levels of CO_2 are an indicator of a low air change rate, this can also indicate a risk of high concentration of other indoor air pollutants.

This section is based on three different reports regarding indoor air pollutants; "WHO Guidelines for indoor air quality: selected pollutants" [17], "WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide" [18] and Norwegian Health Association's (Folkehelseinstituttet) report from 2015 [8]. All three reports aim to provide recommendations or guidelines for a large amount of indoor air pollutants, to protect human health and well-being. The reports are based on published research reviewed by a group of experts.

As the field of indoor air pollutants is large and the types are many, only three types of indoor air pollutants have been researched during this thesis: formaldehyde, particulate matter (PM) and volatile organic compounds (VOC). A short description of these three pollutants is given in the sections below.

Volatile organic compounds (VOC)

Organic compounds in indoor air can be categorized after how volatile they are; very volatile (VVOC), volatile (VOC) and semi-volatile (SVOC). Sources of VOC can be both stationary, as from construction materials, or variable, as from cleaning products, smoking or cooking. Therefore, the total amount of VOC (TVOC) is expected to be higher in new or refurbished buildings. Some of the known health effects of exposure to a high amount of chemicals in indoor air are asthma, allergies and, in some cases, cancer. However, most

VOC’s are not directly associated with health problems, but may act as sensory irritants [19].

Airthings, a Norwegian-based tech company that develops sensors for surveillance of IAQ, has stated some limit values for TVOC used in their sensors. If the level is below 250 ppb it is considered low, levels between 250 and 2000 ppb suggests that it is time to ventilate and levels above 2000 ppm requires immediate ventilation of the room [20]. The limit values provided by Airthings are based on recommendations from health authorities.

It should be noted that there is no guideline value for TVOC today and the research on the effect of high levels of VOC’s is limited in Norway [8]. The limit levels provided by Airthings are included to give an impression of what levels of TVOC that can be considered as high.

Formaldehyde

Formaldehyde is categorized as a VVOC and indoor sources are the most common type of exposure. Sensory irritation is mostly the consequence of short-term exposure, but cancer has been revealed as one of the long-term health effects. Common sources of formaldehyde are glue, isolation materials, particle boards, textiles, smoking and cooking [8]. Therefore, use of e.g. low-emitting building materials and products can prevent long-term health effects. To avoid sensory irritation WHO recommends a guideline to short-term (30-minute mean) exposure of 0.1 mg/m^3 [17].

Particulate matter (PM)

Airborne particles have shown to have impact on respiratory and cardiovascular systems. PM is categorized after the size of the particles, whereas PM_{10} applies to both coarse particles with a size between 2.5-10 µm and finer particles smaller than 2.5 µm. Both PM_{10} and $PM_{2.5}$ can be present in urban areas as the main sources are, respectively, mechanical processes (construction, road dust) and combustion processes. The concentration of the different airborne particles may vary with geography. Burning candles, cooking, smoking and fireplaces is some of the most common indoor sources of PM [8]. WHO provides short- and long-term guidelines for both PM_{10} and $PM_{2.5}$ due to the known health effects [18]. The guideline values provided by WHO is showed in Table 2.

Table 2: Overview of the guideline values for PM provided WHO [18].

	$PM_{2.5}$ [µg/m^3]	**PM_{10} [µg/m^3]**
Short-term (24-hour mean)	25	50
Long-term (annual mean)	10	20

This section has illustrated that a high amount of indoor air pollutants can have serious long-term health effects for the occupants. As some of the consequences of exposure is not yet fully known, it is better to limit the time of exposure to a minimum by minimizing the source and ensure adequate ventilation rates [21].

2.3.3 Ventilation

The ventilation rates in residential building is regulated in the Norwegian regulations (TEK17). As the amount of pollutants present often is related to the air change rate, and hereby the ventilation effectiveness, this is an especially important measure.

The two most relevant demands are listed below.

1) Residential buildings need to have an average fresh air supply of minimum 1.2 m^3/h per m^2 floor area when the building is occupied.
2) Bedrooms must have an air supply of 26 m^3/h per person, when the bedroom is in use. [22]

The regulation also states that the easiest way to satisfy these demands is to have a mechanical ventilation system. To satisfy the maximum limit of energy consumption, a balanced ventilation with heat recovery is recommended [22]. These regulations are, however, mainly aimed at new buildings and are not much taken into consideration when a building is energy-upgraded.

3 Literature review: IEQ in bedrooms

A review on studies regarding indoor environment in bedrooms in Scandinavia is presented in this chapter. As was pointed out by Katsoyiannis and Cincinelli [23], the topic of air quality in bedrooms has not been addressed extensively in the past and the number of studies performed in Scandinavian dwellings is somewhat limited. Therefore, a few studies from outside of Scandinavia has also been included in the literature review.

3.1 IAQ in bedrooms

As discussed in section 2.1 and 2.3.1, the term IAQ is an extensive term with many possible indicators. Based on the objective of previous studies, this section is divided into two categories; one where the main objective has been to investigate air change rate and one where the main objective has been the presence of indoor air pollutants. Air change rate was earlier used as a national requirement for the ventilation rate in Scandinavian countries and is assumedly why many studies have targeted this topic.

3.1.1 Air change rate

In 1998 the ventilation rate of 344 residences in Oslo were investigated by Øie et.al [24]. The total air change rate was measured with a passive tracer gas method over a 14-day period for each residence. The goal was to determine the actual ventilation rate in existing Norwegian residences. The results showed that 36 % of the residences had a lower air change rate than the former national requirement (0.5 h^{-1}). When the results were compared to similar studies on air change rates in other Nordic countries, the rate of the Norwegian residences was shown to be slightly higher. The studied dwellings included apartments and single-family houses with both mechanical exhaust and natural ventilation. However, the air change rates did not vary significantly between the different building types or ventilation systems.

The results provided by Øie et.al is somewhat coinciding with the Swedish study from 2013 by Langer et.al [25], where 157 single-family houses and 148 apartments were investigated to research IAQ in Swedish residential buildings. As in the study located in Oslo, the air change rate was measured by a passive tracer gas method over a 14-day period during the heating season. The mean air change rate was shown to be 0.37 h^{-1} in the single-family houses, and 0.5 h^{-1} in the apartments. This resulted in 85 % of the single-family houses having an air change rate below 0.5 h^{-1}, the percentage was 74 for the apartments. The results of this study indicated that the buildings with natural ventilation had lower air change rates than those with mechanical ventilation.

Another Swedish study performed by Bornehag et.al also found similar air change rates as Øie when children's bedroom of 390 homes were investigated in 2005 [26]. The bedrooms in the single-family houses had a mean ventilation rate of 0.36 h^{-1}, while the mean rate was measured to be 0.48 h^{-1} 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. The duration of the measurements was one week, and a passive tracer gas method was used to measure the air change rate.

A similar study was performed by Bekö et.al in 2010, where the bedrooms of 500 Danish children was investigated [12]. The duration of these measurements was shorter, with a measuring period of only 2 days and 2 nights between March and May 2008. As opposed to Langer, Øie and Bornehag, Bekö estimated the air change rate by a single-zone mass balance model and measured the CO_2 concentration during nighttime. The opening of windows and doors was logged by the parents, and the window opening was registered as closed, open or ajar. The results of the calculations showed that 57 % of the bedrooms had air change rates of less than 0.5 h^{-1}. The study also indicated that the air change rate increased together with the occupant number, in which the author concludes might be a result of more frequent window opening at higher occupancy. The windows were, however, closed both nights in 80 % of the rooms.

It should be considered that the duration of the measurements was only two days and might therefore not be representable for some of the buildings or the occupant behavior. It should also be noted that the calculation method for the air change rate estimates the total amount of airflow into the bedroom, including those from adjacent rooms in addition to outdoors. The bedroom door was logged as open in most of the homes, which might be more usual in children's bedrooms compared to adults. However, this makes it difficult to predict if the air entered from outdoors or from adjacent rooms. In addition, the relative error of this calculation model for the air change rate was shown to be between 0 and 120 %, while the average error was in the range of 17 – 33 %.

3.1.2 CO_2 levels

As Bekö calculated the air change rate of the bedrooms from the CO_2 concentration in the room, the average concentrations of CO_2 during the nights were also analyzed. The results showed that 33 % of the bedrooms experienced a 20-minute period where the average CO_2 level was above 2000 ppm and 6 % where the concentration was above 3000 ppm.

Several other studies have also found high CO_2 level in bedrooms during nighttime. Kotol et.al investigated the indoor environment in 79 residences, for a period of seven days, located in Greenland in 2012 [27]. The average concentration of CO_2 in the bedrooms during winter was found to be above 1300 ppm and in 66 % of the bedrooms the average concentration exceeded 1000 ppm. Like Bekö the 20-minute moving average was also investigated by Kotol and CO_2 concentrations above 2000 ppm was found in 46 % the bedrooms, while 24 % of the bedrooms experienced concentrations above 3000 ppm. The author calls attention to the lack of ventilation equipment in Greenlandic households, which are often limited to an exhaust fan in the bathroom.

CO_2 levels have also been measured in newer buildings. The study by Berge and Mathisen investigated high-performance apartments with balanced ventilation located in Norway. High concentrations of CO_2 where the level exceeded 1200 ppm was found in 2 out of 7 measured bedrooms, 5 and 6 % of the nighttime period [28]. Corresponding levels was also reported in a Swedish study, where air quality was investigated in 20 new passive houses and 21 conventional new houses [29]. The average CO_2 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 14-days measuring period. It should be noted that the whole measuring period was analyzed, independent of periods of non-occupancy, and the occupants were refrained from opening the windows during the measurement period. The dwellings investigated in both these studies were equipped with a balanced ventilation system, and the time with CO_2 levels above 1000 ppm was shown to be significantly lower compared to the levels found by Bekö and Kotol.

The studies discussed in this chapter indicates that the air change rate of many Scandinavian bedrooms might be too low to satisfy the earlier recommendation of 0.5 air changes per hour, especially those with only natural ventilation. As noted in section 2.3.3, TEK17 has a fresh air supply-demand of 26 m^3/h per person in bedrooms, which might result in a higher demand than the one used for comparison in these studies. Some of the reviewed studies have also shown that the CO_2 concentration in the bedroom during nighttime can be very high in shorter time periods, where it can exceed both 2000 and 3000 ppm.

3.2 Indoor air pollutants in residential buildings

Some literature on the presence of indoor air pollutants, such as particles, formaldehyde and TVOC, in residential buildings is reviewed in this section. One study on indoor air pollutants correspondence with air change rate performed in Portugal has been included, due to its relevance.

3.2.1 Presence of TVOC, PM and formaldehyde

In the Swedish study conducted by Langer et.al, the concentration of TVOC and formaldehyde was also investigated [25]. The median concentrations found in this study for single-family houses and apartments were, respectively, 22 and 13 µg/m^3 for formaldehyde and 236 and 143 µg/m^3 for TVOC. This is lower than the guideline values suggested by WHO for formaldehyde [17]. No guideline value is provided for TVOC. Further, Langer et.al. mentions that these concentrations were similar to those found in other Scandinavian studies.

Langer also found a negative correlation between the air change rate and the two pollutants. As mentioned, the average air change rate in this study was below 0.5 h^{-1} for the single-family houses. This can indicate that concentrations of formaldehyde and TVOC in residential buildings can be below the limit values, even though the air change rate is not, or that the concentration of these pollutants are more dependent on other factors than the air change rate – such as indoor sources. In addition, the analysis indicated that concentration of TVOC was lower for newer dwellings, which may be explained by a higher air change rate - as most of the sources of TVOC are connected to building materials and therefore suspected to be higher in newer buildings.

In 2007 Kolarik et.al investigated 20 newly built single-family houses in Denmark for the levels of formaldehyde. The buildings were in normal use during the measurements, but all windows and doors were kept closed. The geometric mean of the concentrations of formaldehyde was shown to be 40 µg/m^3, but the WHO guideline value was exceeded in two of the buildings. Kolarik also measured the air change rate of these building, which was shown to be lower than 0.5 h^{-1} for 63 % of the houses. As opposed to Langer, no correlation between the air change rate and formaldehyde concentration was proven to be present.

The correlation between air change rate and indoor air pollutants was also investigated by Canha et.al in 2017, where the object was to research the impact of four different ventilation techniques on the IAQ at nighttime [30]. A third-floor apartment from 1999 located in an urban area in Portugal, was examined. The ventilation settings impact on the parameters CO, CO_2, formaldehyde, VOC, PM_{10}, $PM_{2.5}$ and PM_1 was studied. In addition, temperature and RH were measured and the air change rate was calculated based on the CO_2 measurements.

The four ventilation settings investigated in the study, each over a 3-day period:

- Closed door, closed window
- Closed door, open window
- Open door, closed window
- Open door, open window

As might be expected, the highest air change rate was found when both the door and the window was open (4.85 h^{-1}) and the lowest when both were closed (0.67 h^{-1}). It should be noted that these air change rates are quite high compared to the rates found in the

Scandinavian studies mentioned in section 3.1.1. The values of VOC, formaldehyde and $PM_{2.5}$ reached concentrations above the Portuguese recommendations in some of the scenarios which were, respectively, 600, 100 and 25 $\mu g/m^3$ at the time.

The results of this study can give an indication of how different indoor air pollutants are affected by different ventilation settings. The lowest concentration of both VOC and $PM_{2.5}$ was found when the door was open and the window was closed, but the lowest concentration of formaldehyde was found when the window was open, and the door was closed.

It should be noted that this study took place south in Europe, which represents a different climate than what is usually found in Scandinavian countries. The measurements were carried out in August, in which the outdoor temperature and humidity level varied respectively between 18-27°C and 60-80 %. The study has still been considered relevant, as it researches how natural ventilation affects the presence of different air pollutants and similar studies performed in Scandinavia are hard to obtain.

The studies reviewed in this section give an indication of the levels of TVOC, PM and formaldehyde present in residential buildings and bedrooms. The levels of formaldehyde were shown to be well below the WHO guideline in the Scandinavian studies. The reviewed literature has also shown some conflicting results on the pollutants' correlation with air change rate. The study by Langer et.al found pollutant concentrations well below the limit values, and that the concentrations had a negative correlation with air change rate. In the study performed by Canha et.al some scenarios showed higher levels than the recommended concentrations. This same study also showed significantly higher air change rate compared to the one by Langer et.al. In this study, the lowest pollutant concentration was not found when the air change rate was highest, meaning the correlation between the two was not clearly negative.

3.3 Considerations of user preferences and perceptions

As IEQ is also evaluated in terms of the occupant’s degree of satisfaction, some literature on this topic is presented in this section. Studies which have investigated the influence of mechanical and natural ventilation systems have been emphasized in this section.

3.3.1 Influencing factors on the user’s perception of the IEQ

Through an extensive questionnaire survey with over 5000 participants, different indoor environmental parameters, as to which might have the largest effect on the respondent’s perception of IEQ, was investigated by Zalejska-Jonsson and Wilhemsson in Sweden in 2013 [31]. The results indicated that although the most frequently experienced problems were related to dust, noise from outdoors and too low temperature inside the building, draught was reported as the most important factor to influence the general satisfaction with the IEQ. The study also illustrated that the influencing factors of IEQ may vary with the location and construction year of the building, in addition to individual factors and preferences.

A similar questionnaire survey was conducted in Denmark in 2012 by Frontczak et.al, where the object was to research new solutions for control of the indoor environment [32]. The researchers investigated which factors that might influence the occupant’s perception of comfort, and their preferred way of achieving it. The results showed that indoor environmental parameters such as light, temperature and noise level played an important part in the user’s feeling of comfort, in addition to the air quality.

3.3.2 User satisfaction in natural and mechanical ventilation systems

Fronczak et.al also investigated how the differences between a natural and mechanical ventilation system can impact the comfort level of the inhabitants [32]. The results of the survey indicated that the respondents valued the possibility of being able to open the window highly, which is often recommended to be restricted when a mechanical ventilation system is present. In addition, more than 40 % of the occupants who had mechanical ventilation installed replied that fresh air supply from a mechanical system was not important for them. From this, the author calls attention to the fact that the subjects in this study might not associate fresh air supply with mechanical ventilation. This perception may be related to traditions, habits or lack of knowledge.

The year before, one of the same co-authors performed a study based on a literature review and investigated how different indoor environmental factors influence the thermal comfort of the occupants [33]. The results indicated that occupants of naturally ventilated dwellings had a higher acceptance of the indoor thermal conditions compared to those of mechanically ventilated buildings. In addition, the literature study indicated that it might be difficult to develop universal solutions because of the high variation in individual preferences.

In an Austrian study from 2017 based on 575 interviewees, some contradicting results were found [12]. The study investigated how occupants who lived in highly energy efficient buildings rated their own health and well-being. The results indicated that inhabitants of naturally ventilated dwellings had more often a negative perception of the air quality, compared to those living in mechanically ventilated buildings. The inhabitants of the new and energy efficient buildings also rated their health and well-being higher than those living in houses with natural ventilation.

As these studies indicate, when natural and mechanical ventilation systems are compared the results can sometimes be conflicting whether what might be the best choice to satisfy the inhabitants. This may suggest that the ideal ventilation solution, regarding thermal comfort, will depend on the inhabitants' preference.

3.3.3 User satisfaction related to energy renovation of residential buildings

In 2008 Tommerup investigated the consequences of an energy renovation of a single-family house from 1972 in Denmark, regarding user satisfaction, indoor environment and energy conservation [34]. Typical energy saving measures were carried out, such as adding external insulation and changing the windows, in addition to installing a mechanical ventilation system with heat recovery for the whole building. This resulted in a decrease in infiltration rate, from 12 ach to 2.1 ach, measured by a blower door test. The average indoor temperature in January and February also increased with 2°C and the occupants experienced a reduction in disturbance from draught and temperature fluctuations. Tommerup suggests that especially the increase in temperature indicates a direct increase in indoor comfort.

The topic of user satisfaction during an energy-upgrading process was further researched by Thomsen et.al in 2016 [35], where the effects of a comprehensive energy renovation of an apartment building from the 1960s were investigated. The apartments were ventilated with a mechanical exhaust system before the renovation, with an extractor hood in the kitchen and a fan in the bathroom. During the renovation, a balanced mechanical ventilation system with heat recovery was installed, in which fresh air was supplied to the living room and extracted in the bathroom or by the manually controlled extractor hood in the kitchen. The ventilation conditions were measured in three of the apartments for a 7-day period, where temperature, RH and CO_2 were measured. The ventilation rate was measured using a passive tracer gas technique. In addition to measuring indoor conditions, a questionnaire was also sent out to the tenants to investigate how pleased they were with their indoor environment after the renovation. It should be noted that the response rate was quite low. The results from the survey indicated that problems related to temperature, draught and periods when it is too cold were improved, but noise problems from installations and periods when it is too hot had gotten worse after the renovation.

3.4 Energy renovation of residential buildings

In 1998 Øie et.al brought attention to a decreasing air change rate of the Norwegian building stock from 1945 until the 1980s. Øie identified this as a consequence of dwellings being built more airtight due to a growing focus on energy-saving measures, without a similar focus on indoor environmental issues. Indoor environment was not targeted in the building code before 1987 [24]. Today, the focus on energy-saving measures is becoming more and more important and Norwegian residential buildings are designed with a tighter and heavier building envelope to minimize heat loss. Sometimes energy-saving measures, especially related to ventilation techniques, might be in contradiction to the user's preferences and, by this, implemented at the expense of thermal comfort.

As can be seen by the studies discussed in the previous section, in the transition from a natural to a mechanical ventilation system during a retrofitting process there may be some trade-offs – either related to the air quality, the user satisfaction or the energy-use. Some of the main challenges will be discussed further in this section.

3.4.1 Challenge 1: Reduced user control

One challenge in the transition from a natural to a mechanical ventilation system, is the limitation in controlling indoor environmental parameters, such as temperature, air supply and noise level. In the report by the Norwegian Health Association it was also stated that when designing for a satisfying thermal environment, the possibility of individual regulation is often considered important [8]. This can in many cases be limited when installing a mechanical ventilation system, either due to the design of the system or due to lack of knowledge of the user.

Toftum investigated what effect the possibility to control the indoor environment could have on occupant satisfaction in Denmark. The results indicated that the type of ventilation system, here mechanical or natural, had a smaller impact on how the occupants perceived their indoor environment, than the possibility to adjust the parameters [36]. This may suggest that giving the user the opportunity to easily control their indoor environment should be valued highly in a retrofitting or design process. This study investigated office spaces and not residential buildings.

Sarran et.al found some of the same results at Toftum when Danish retrofitted dwellings were investigated by a questionnaire survey [37]. The general opinion of inhabitants of the retrofitted houses seemed to be more manual control, especially related to the heating system. The results also indicated that occupants who reported problems with the IAQ also expressed a wish for more manual control over their ventilation system, in addition to a correlation between the user's satisfaction and their perception of the usability of the building services.

The already mentioned literature survey by Frontczak et.al. also concluded that when designing a system for control of the thermal environment it is especially important to include the possibility for user control [33]. In this study the opportunity of following seasonal temperature variations was also reported as important for the user's satisfaction. This is normally a consequence in buildings with a natural ventilation system, due to the decrease in the air temperature during the heating season. However, it should be noted that decrease in temperature fluctuations is often reported as a positive experience in many studies of retrofitted buildings [34, 35, 38].

3.4.2 Challenge 2: Noise and draught

Several studies have also reported problems with noise and draught after the installation of a mechanical ventilation system. In one study it was discovered that some of the tenants had tried to close the air supply with tape and clothing, as a consequence of too high air rates [35]. About 20 % in this study also reported that noise problems from installations had worsened after the energy retrofitting. Noise from the mechanical ventilation system was also discovered as a problem in the study by Berge et.al [28]. The noise seemed to be of most disturbance in the bedroom during nighttime, whereas some of the users had reduced the level of the ventilation fan to try to reduce the noise. The author also suggests that this might have been a reason for a higher CO_2 concentration during nighttime in some of the apartments.

In the study of a Danish multi-family building, retrofitted to a nearly-zero energy building, problems with noise from the ventilation unit was also experienced in the bedroom [39]. In this study the noise level exceeded the recommendation of 30 dB when the fan was operated at the normal level of occupancy.

It should be noted that the installation of mechanical ventilation and insulation of the building envelope can reduce noise and draught from outside, especially in urban areas. This was reported as an important aspect when considering user comfort in the study by Frontzak et.al [32], but was also mentioned as one of the improvements after renovating a single-family house in the study by Tommerup [34]. The same result was also found by Liu et.al where a retrofitted multi-family building was compared to a similar non-retrofitted multi-family building in the same area [38]. The occupants of the retrofitted building experienced problems with noise from the air diffusers in the bedroom, while the occupants of the non-retrofitted building reported problems with outdoor noise.

3.4.3 Challenge 3: Oversupply of heat to bedrooms

As the main object of this project work revolves around the indoor environment in bedrooms, the aspect of user preference and some known challenges regarding mechanical ventilation in the bedroom are discussed in this section.

User preference regarding bedroom temperature

A study based on phone interviews from 2017 reported that about 32 % of the 1001 questioned subjects preferred a room temperature in the bedroom below 12°C, and approximately 38 % preferred a temperature between 13-17°C during the heating season. The same study also reported that about 30 % always slept with the bedroom window open. The percentage increased along with the age of the interviewed subjects [40]. Since this study only relied on phone interviews and did not perform any field investigation, the reliability of the answers can be questioned. However, the majority answered that they preferred a bedroom temperature below 17°C, which indicates that many prefer to sleep in a colder bedroom. The desire of having a lower bedroom temperature was also illustrated in the study by Thomsen et.al [35]. Where one of the three bedrooms had an average room temperature of 16°C.

Oversupply of heat to the bedroom

As mentioned in 2.3.3, to reach the demands of energy use, TEK17 recommends installing a balanced ventilation system with heat recovery. The possible consequences of this were addressed by Berge and Mathisen in 2016, where a high-performance multi-family building in Norway was investigated regarding indoor environment and user satisfaction [28]. They found that using a one-zone balanced ventilation system with heat recovery lead to a homogeneous temperature distribution in the apartment, where the temperatures were higher in the bedroom compared to what the occupants were satisfied with. This led to a more extensive window opening behavior, which again resulted in a higher energy use. The results also indicated that the user's motivation for window ventilation was, in most cases, lower temperatures in the bedroom – due to the correlation between these two parameters.

Another study, also performed by Berge et.al., further researched how heat is oversupplied to bedrooms during the heating season. They investigated a solution where the supply air to the bedroom is bypassed the heating coil in the ventilation system, but still passes through the heat exchanger [41]. The results from the simulations with the two-zone system showed that this could be a good solution if several bedrooms were at a lower temperature. This study investigated several scenarios for the supply of fresh air at a lower temperature. However, the possibility of not installing mechanical ventilation in the bedroom and only use natural ventilation in the bedrooms was not simulated.

3.4.4 Challenge 4:The energy aspect

The argumentation of installing balanced ventilation in residential buildings is primarily reduced energy-use and higher IAQ. However, some studies have indicated that installing balanced ventilation can result in the opposite and lead to a higher energy use.

The indication of the studies discussed in chapter 3.1 was that the air exchange rate of residential buildings in Scandinavia, in general, was low compared to the national recommendations. A study that in some way contradicted this is the study by Hesaraki et.al from 2015, where the influence of ventilation rate on IAQ and energy savings of a single-family house in Sweden was investigated [42]. The single-family house was a building from 1950, where some energy-upgrading measures, such as changing the windows and adding internal insulation, had been carried out. By testing the effect of four different ventilation levels, the result indicated that with a ventilation efficiency of 0.3 h^{-1} the CO_2 concentration never passed 1000 ppm. It should be noted that infiltration through the building envelope accounted for an additional ventilation rate of about 30 %. This study did not explore how the different ventilation levels affected the user's perception of the indoor environment but suggested that the Swedish ventilation rate demand might, in some cases, be high when considering the CO_2 level. The energy-saving was calculated to be 43 % when comparing a ventilation rate of 0.3 and 0.5 h^{-1}. As mentioned in section 3.4.3, the study by Berge and Mathisen also reported an increase in energy use due to high bedroom temperatures and an increase in the window opening with a balanced ventilation system [28].

It can also be discussed if the use of natural ventilation in bedrooms, and mechanical ventilation in the rest of the building, will increase the overall energy use in the building. This has not yet, to the author's knowledge been researched in Scandinavian buildings. However, how the energy use is impacted by the ventilation system may be dependent on user behavior and building structure.

The literature discussed in this section indicates that energy renovations in residential buildings should be carried out and designed with a greater focus on the user's habits and preferences –to minimize energy use and achieve a high IEQ. It has also been shown that there are some main challenges in the transition from a natural ventilation system to a mechanical one.

3.5 Window opening behavior in residential buildings

What affects the window opening behavior in residential buildings might be impacted by habits or traditions. Some studies have tried to establish models for window opening behavior in residential buildings, and, hereby, investigated which factors that may correlate with opening the window.

Among these is the study by Andersen et.al from 2013 [43], which investigated the opening behavior in Danish dwellings. The results indicated that the opening behavior seemed to be correlate the most with the CO_2 concentration in both the naturally and mechanically ventilated dwellings. Indoor temperature was also found to have correlation with the opening behavior for the owner-occupied, naturally ventilated buildings. The closing behavior was mostly affected by the outdoor temperature. The level of relative humidity seemed to influence both opening and closing behavior as opposed to wind speed, which did not seem to affect either. It should be noted that none of the windows were opened during the winter and the study only researched 15 dwellings, whereas 5 of these were single-family houses.

The opposite result was found by Berge and Mathisen, where the study showed no correlation between the CO_2 level and the window opening [28]. However, the results indicated that the window opening behavior was strongly influenced by the indoor temperature. The width of the window opening was not logged, only the duration.

4 Motivation and research questions

In this chapter the motivation behind the master thesis and some research questions are presented.

4.1 Motivation

As the master thesis is closely related to the research project OPPTRE, so is the main motivation. One of the goals of OPPTRE is to simplify the integration of ventilation systems in the retrofitting process by considering different solutions for heating- and ventilation systems. As was illustrated by the literature review, retrofitting of residential buildings by universal solutions can sometimes result in a decrease in user satisfaction. This difficulty is especially illustrated when a balanced ventilation system is installed in a bedroom where the inhabitant prefers to open the window at nighttime for fresh air supply.

This represents the motivation behind the master thesis; to investigate if a satisfying air quality can be reached without installing a balanced ventilation system in the bedroom. To ensure high IAQ and heat recovery of extract air, balanced ventilation is considered a good solution in the rest of the building, where there may be a higher amount of indoor air pollution sources and a higher activity level compared to the bedroom.

If this hybrid ventilation system can provide a satisfying IAQ, it may also be a more economic and energy-saving solution – as a reduction of the size of the ventilation system will reduce the needed fan power and the material use in the retrofitting process. It may also lead to a higher user satisfaction, as it can be developed to fit the inhabitant's need and established habits. On the other hand, if the results show that this is not an adequate ventilation technique, this can promote users to install balanced ventilation in the whole building in a retrofitting process.

4.2 Research questions

The aim of this master thesis is to investigate the indoor environment and the indoor air quality in existing Norwegian dwellings.

Main question:

Can natural ventilation, mainly through window opening, ensure a good indoor environment in bedrooms during the heating season?

Research questions:

1. How will the occupants' window opening behavior affect IAQ parameters such as CO_2 concentration, relative humidity and temperature in the bedroom?
2. How will the occupants' window opening behavior affect other relevant IAQ parameters such as particulate matter, formaldehyde and TVOC?
3. Can external factors, such as outdoor weather conditions, affect the IAQ parameters in the bedrooms?
4. Which factors may prevent the window opening behavior of the occupants?

5 Methodology

This chapter describes the methodology used in the investigations of the bedrooms, in addition to calibration and testing of the sensors used for surveying IAQ and size of window openings.

5.1 IAQ sensors

For the IAQ measurement, two types of sensor systems have been tested and compared: one commercial and one non-commercial. The commercial sensor measured CO_2, temperature, and RH, while the non-commercial sensor (Arduino sensor) also measured formaldehyde, TVOC and PM.

The Arduino sensor is developed at NTNU by Maria Justo-Alonso as part of her Ph. D. This sensor was also tested and described by Oda Kristine Gram in her master thesis "Use of low cost pollutant sensors for developing healthy demand controlled ventilation strategies"[44], and was also tested briefly during the specialization project.

A description of both sensor systems and calibration measurements are presented in this section, together with a comparison and a justification for the choice of IAQ sensor. In the choice of system, economy, availability, and possibility of communicating with additional devices have been considered important.

5.1.1 Method for calibration

To ensure the accuracy of the field measurements, both sensor systems were tested in a controlled environment and compared to a reference instrument. The two sensor systems were calibrated separately in a closed chamber.

The Pegasor AQ Indoor measuring instrument was used as a reference instrument for the measurements of CO_2, temperature, RH and PM. It measures PM with diameter in the range of 0.01 - 2.5 µm in diameter (PM2.5) [45]. The accuracy of the formaldehyde and TVOC sensors has not been confirmed, as there was no available calibration equipment.

To calibrate the sensors, CO_2 was supplied from a separate tank until a high concentration of 2500 - 3000 ppm was reached. Two small cups of hot water were placed inside the chamber to increase the RH level, and a small stirring fan was mounted in the ceiling to ensure a uniform concentration. The IAQ sensors were spread out in the chamber, as can be seen in Figure 2. The same set-up was used in the calibration of both the Arduino and the Wisensys sensor system.

The CO_2 concentration was increased rapidly over a few minutes and as this is considered an unrealistic scenario only the decay curve of the CO_2 measurements is analyzed. The degree of correlation, hereunder the linear relationship between the reference and the tested sensor, has been emphasized in the analysis of the measurements.

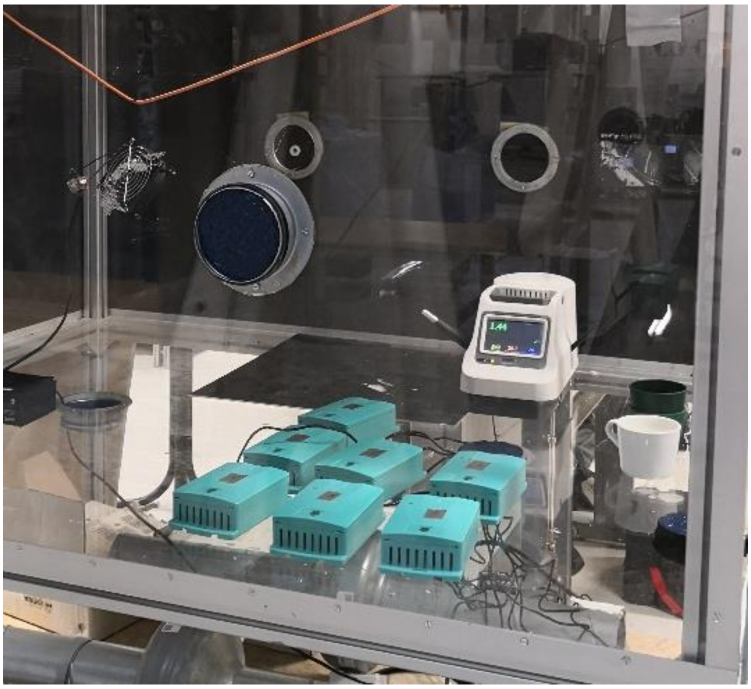


Figure 2: Calibration set-up of IAQ sensors. Here, represented by the Wisensys sensor system (commercial).

5.1.2 Description of Wisensys sensor system

The Wisensys sensor system consist of a base station, where several sensors can be connected wirelessly. Data received by the base station is either stored on a connected PC or locally with a SD card. The distance between the sensor and the base station can be up to 50-80 m inside of buildings. The measurement settings and the collection of data is adjusted in a program called SensorGraph.

Accuracy

For the CO_2, temperature, and RH measurements the WSE-DLC sensor was used [46], in combination with the Wisensys Base Station (WS-BU Ethernet 01) [47]. The CO_2 sensor uses NDIR technology with an accuracy of 75 ppm +10 % at 22 °C. The temperature and humidity sensor (SHT75) have an accuracy of ±2 % RH and ± 0.5°C.

5.1.3 Calibration results: Wisensys sensor system

Seven sensors were calibrated simultaneously, and the sample rate was set to 1 minute.

CO_2

The CO_2 calibration measurements are compared in Figure 3.

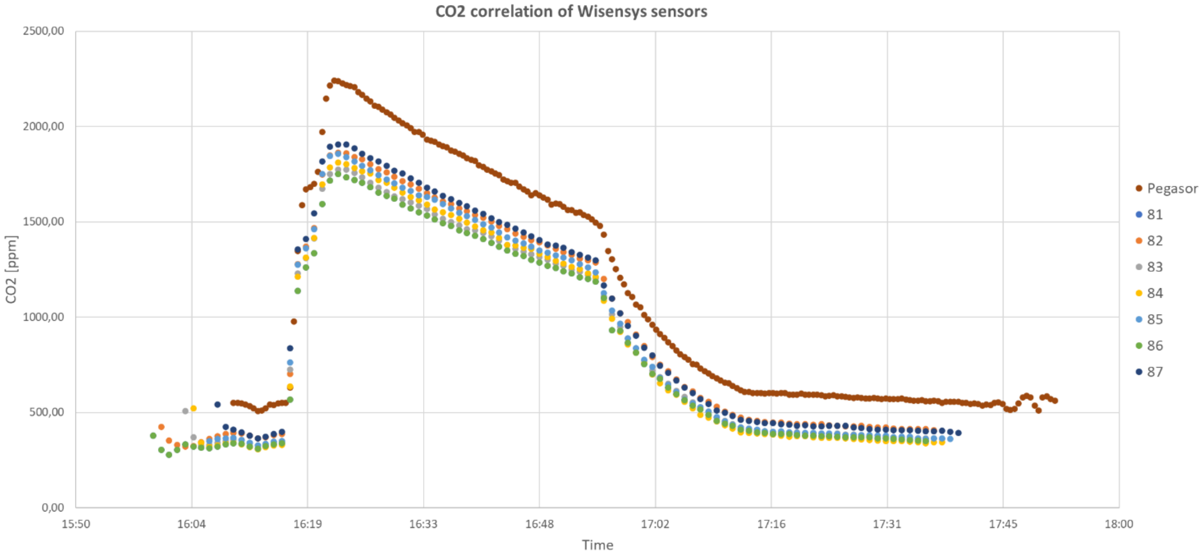


Figure 3: Comparison of CO_2 measurements performed by the Wisensys sensors and the reference.

The peak value of CO_2 measured by the reference is at approximately 2250 ppm, while the Wisensys sensors measures a peak value between 1750 and 1905 depending on the sensor. The CO_2 correlation factors varies between 0.9970 and 0.9985, which indicates a high correlation in the measured values. However, a large deviation from reference can be observed in the measurements. This is illustrated clearly in Figure 3, where the deviation seem to be increasing with higher CO_2 concentrations.

Temperature

A comparison of the temperature measurements is made in Figure 4.

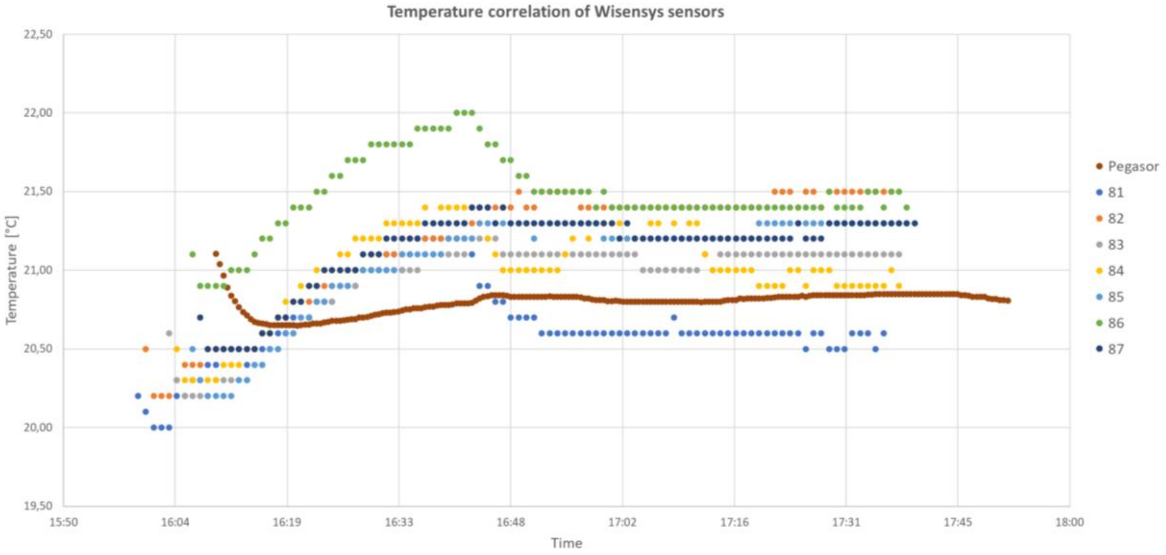


Figure 4: Temperature correlation of Wisensys sensors.

The temperature measurements are characterized by low correlations. The deviation from reference is, however, no more than 1-1.5 °C. As an example, two of the correlation curves are shown in Figure 5 and Figure 6.

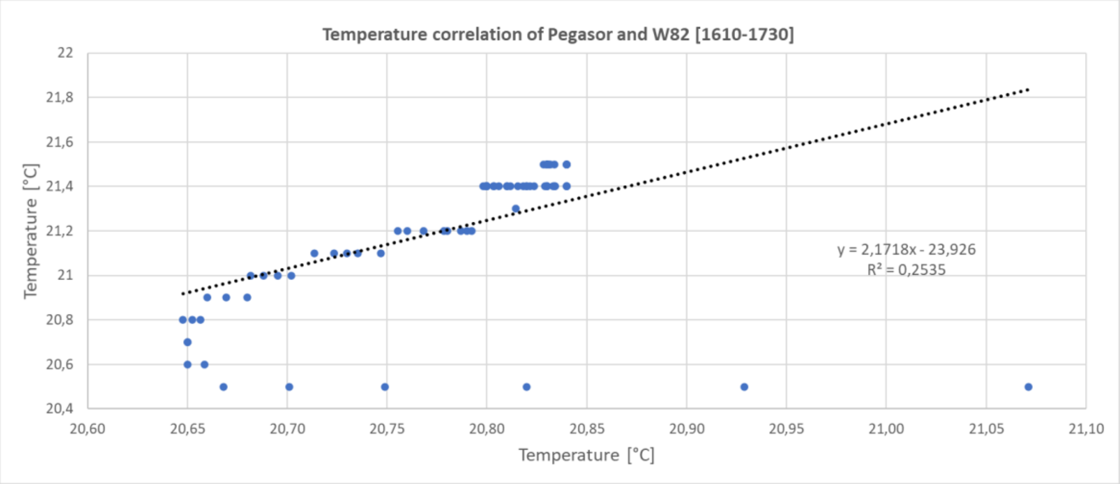


Figure 5: Temperature correlation of Wisensys sensor 82 and Pegasor.

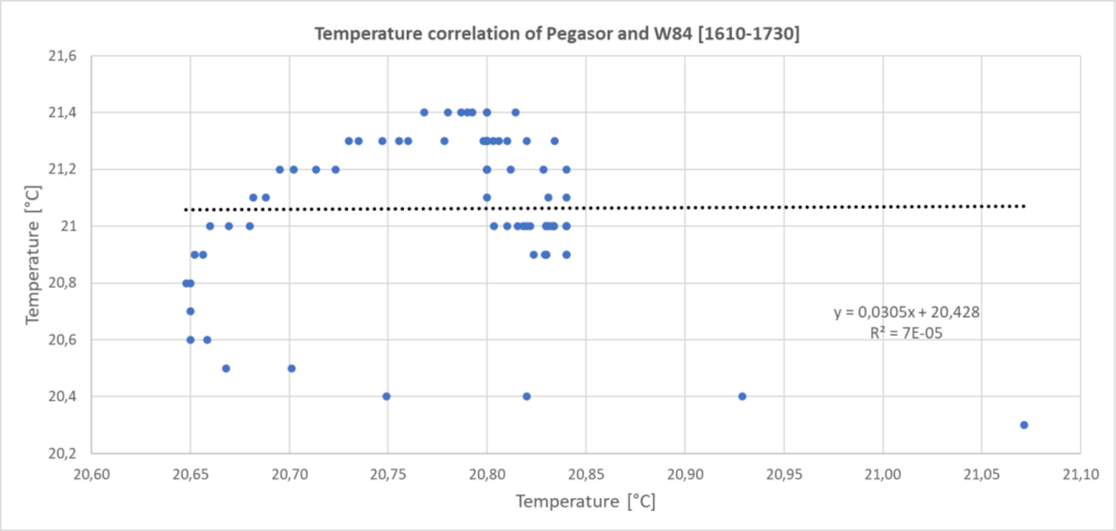


Figure 6: Temperature correlation of Wisensys sensor 84 and Pegasor.

The correlation factors vary from 0 to 0.2535, which indicates a very low correlation for these temperature sensors. These curves and coefficients are representable for all the sensors.

RH

A comparison of the RH measurements of the Wisensys sensor system is shown in Figure 7.

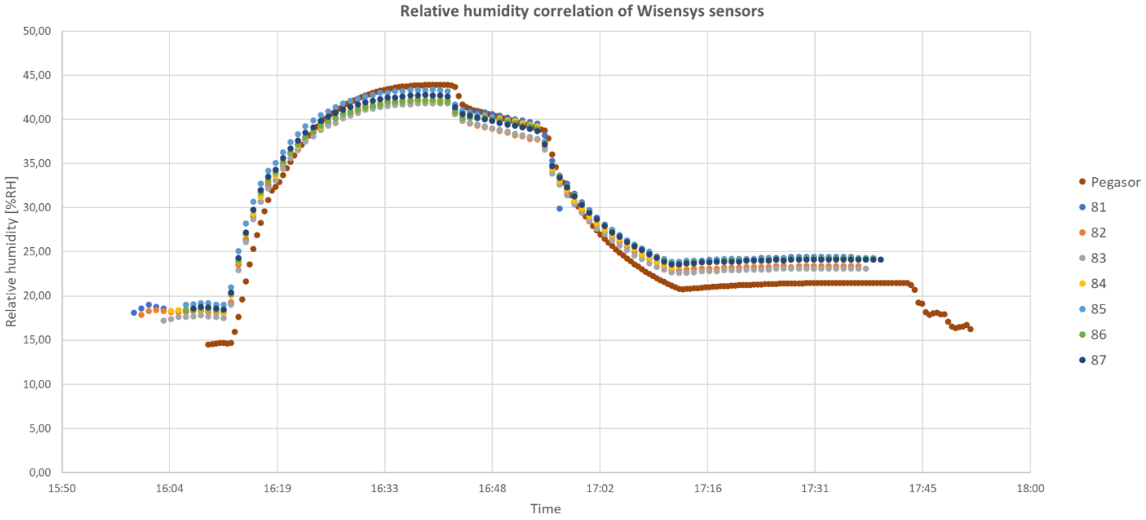


Figure 7: Relative humidity correlation of Wisensys sensors.

The RH measurements are characterized by lower variations between each sensor, compared to the temperature measurements. However, the graph illustrates how the deviation from reference seems to variating for the different RH levels. When the RH level exceeds approximately 40 % the Wisensys sensors measures a lower value than the reference, while for lower RH levels the sensors measures a higher value. The correlation factors are still high and in the interval of 0.9934-0.9973.

5.1.4 Description of Arduino sensor system

The Arduino sensor rig is built to measure IAQ through parameters such as temperature, RH, CO_2, formaldehyde, PM and TVOC. The sensor have been developed at NTNU and are a part of Maria Justo Alonso's ph. D.

An important aspect of Alonso's ph. D is to use low-cost sensors. The sensors used are SCD30 (CO_2, temperature, RH), WZ-S (formaldehyde), SPS30 (PM), SGP30 (TVOC) and SHTC1 (temperature, RH). Information about the sensors, except the SHTC1 sensor [48], can be found in Gram's master thesis [44]. The SHTC1 sensor was recently added to the sensor rig to increase the accuracy of the temperature and RH measurements. The SGP30 and the SHTC1 sensor are compared in the calibration of the Arduino sensor. The price of one sensor rig was around 2000 NOK at the time of acquisition, and five sensor rigs were built and calibrated to be used in the field investigations. The sensor is dependent on a power source connection. A picture of one of the rigs is given in Figure 8.

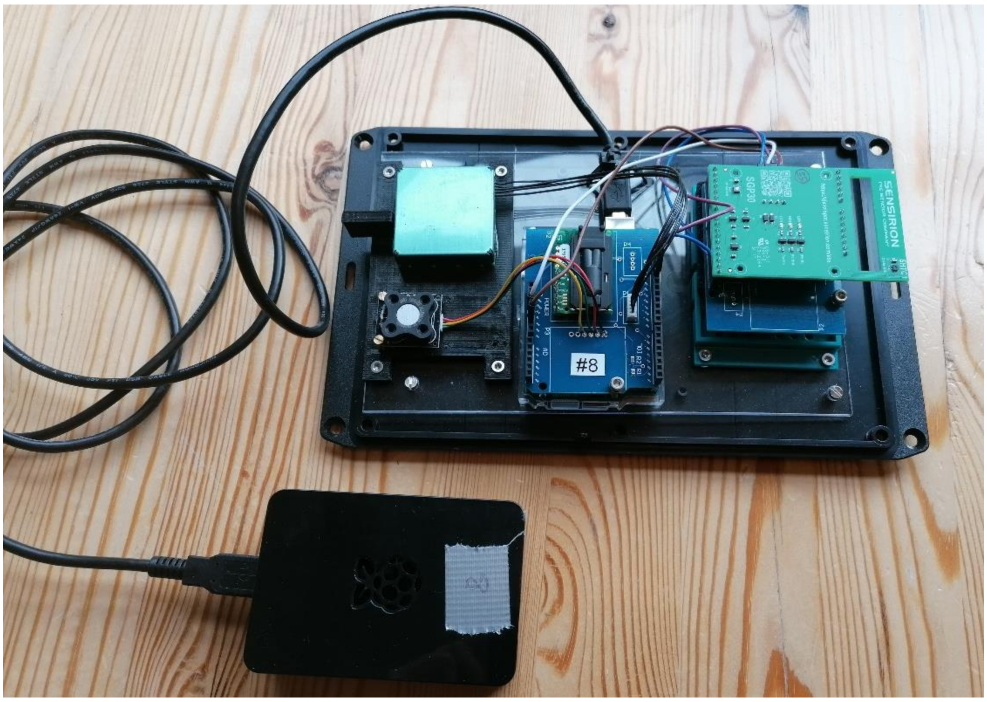


Figure 8: Arduino sensor rig together with a Raspberry Pi.

Accuracy

The SCD30 sensor uses self-calibration. Therefore, after it is activated for the first time it needs a period of seven days, where it is exposed to fresh air, to log a calibration file. In the data sheet it is also specified that temperature and RH offsets may occur when the sensor is operated in end-customer devices because of other heat emitting components. The accuracy of the CO_2 measurements is ± 30 ppm, ± 0.5 °C for the temperature measurements and ± 2 % for the RH measurements.

The SPS30 sensor can detect mass concentration of $PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$ and PM_{10}. The accuracy is said to be ± 10 $\mu g/m^3$ at levels between 0-100 $\mu g/m^3$ and ± 10 % at levels between 100-1000 $\mu g/m^3$.

The SGP30 sensor can detect small concentrations of TVOC. The sensor measures TVOC in ppb. The typical accuracy of this sensor is 15 % of the measured concentration.

The SHTC1 sensor has an estimated accuracy of ± 3 % and ± 0.3 °C for, respectively, the RH and temperature measurements.

5.1.5 Calibration results: Arduino sensor

As the CO_2 sensor had to be pre-calibrated in outdoor air for seven days, it was assumed that a room with a CO_2 level of around 400 ppm would be satisfactory for this, as nothing else was specified by the manufacturer. The sensor rigs were therefore stored in a calibration room for one week, where there was a minimum of human activity, before they were put through the calibration test described in section 5.1.1.

All five Arduino sensors were tested simultaneously.

CO_2

A comparison of the CO_2 measurements is shown in Figure 9.

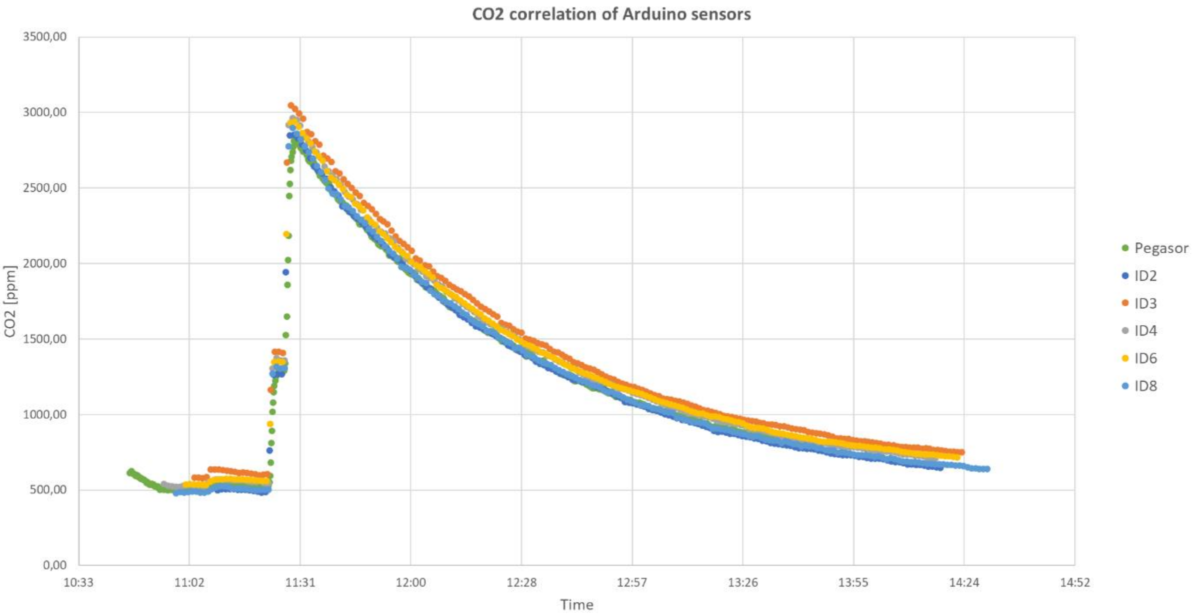


Figure 9: Comparison of CO_2 measurements of Arduino sensors and Pegasor sensor.

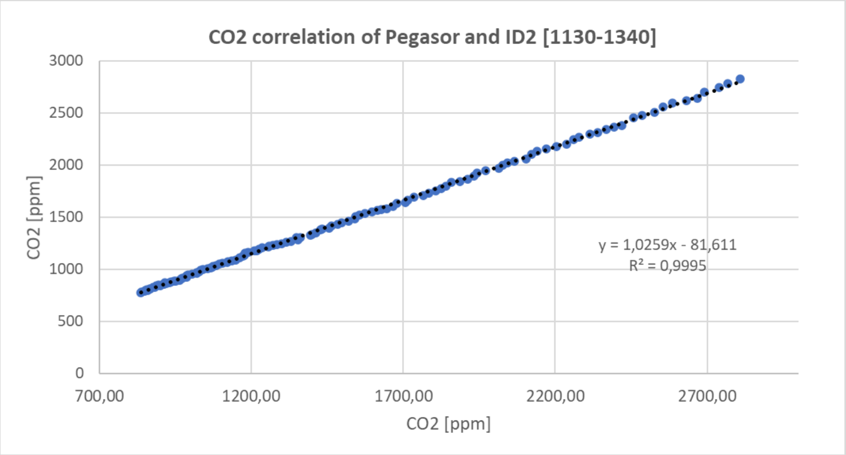


Figure 10: CO_2 correlation curve of Arduino sensor 2 and Pegasor sensor.

By plotting correlation curves for all five sensors the correlation values were found to be in the interval of 0.9994-0.9996. Figure 9 illustrates how sensor 2 and 8 are measuring similar values as the reference, while sensor 3, 4 and 6 seem to be measuring a higher value. Sensor 3 measured the highest deviation from reference, which was a percentage deviation of 5-7 % of the decay values. However, the high correlation factors make it easy to adjust for the deviation when the field measurements are analyzed.

Temperature and RH

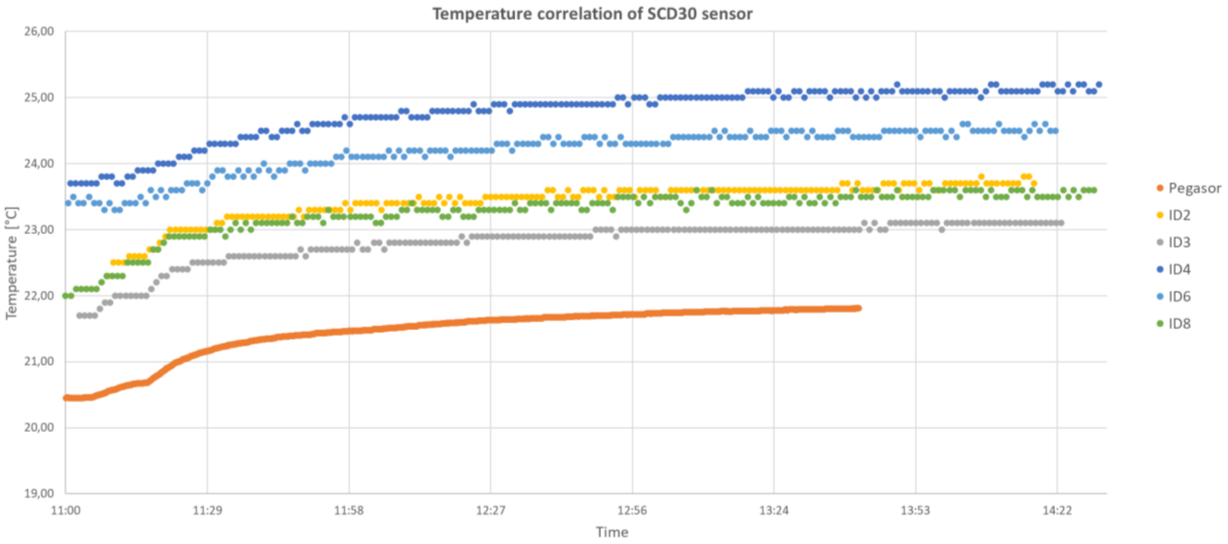


Figure 11: Temperature correlation of SCD30 sensor (Arduino).

The temperature correlation of the SCD30 sensor is shown in Figure 11. The measurements indicate that there is a systematic temperature deviation for each sensor, which varies between 1-3 degrees. Figure 12 illustrates the temperature correlation of the SHTC1 sensor, where the temperature deviation is less than 1 degree. Both sensors are measuring temperatures higher compared to the reference.

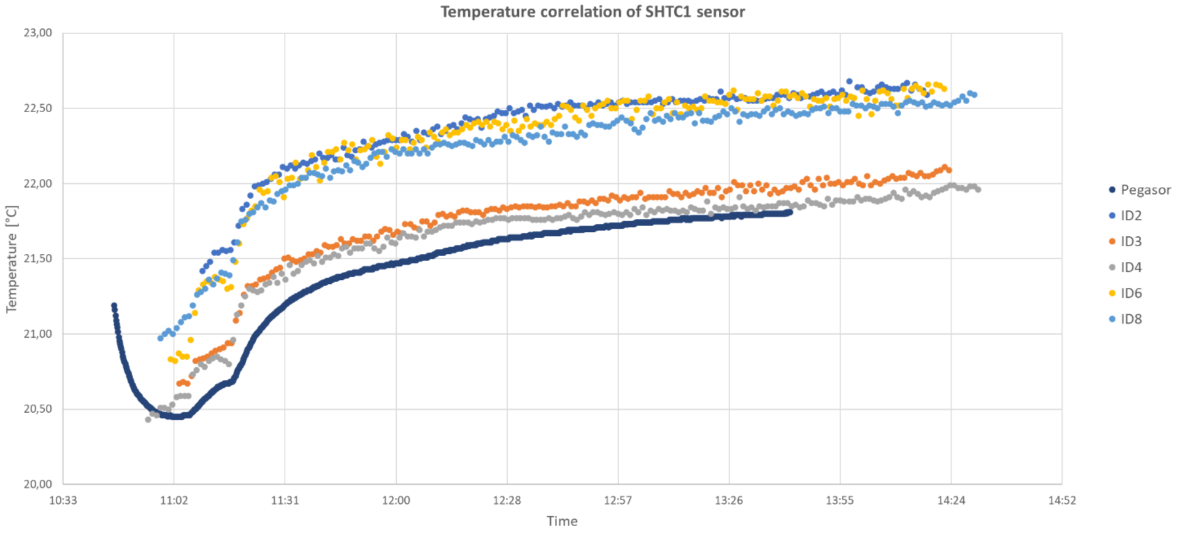


Figure 12: Temperature correlation of SHTC1 sensor (Arduino).

The corresponding correlation of RH are shown in Figure 13 and Figure 14.

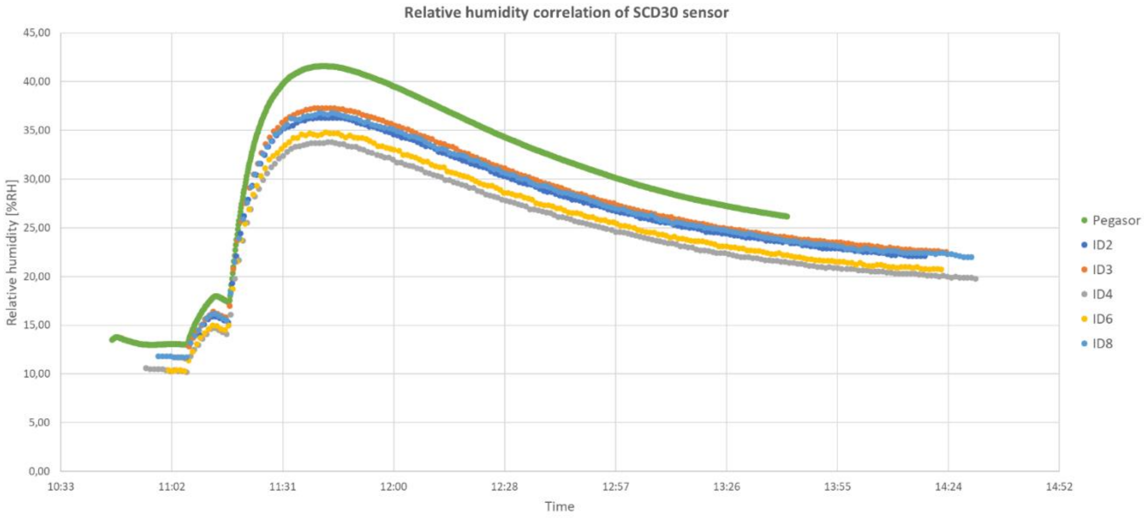


Figure 13: RH correlation of SCD30 (Arduino).

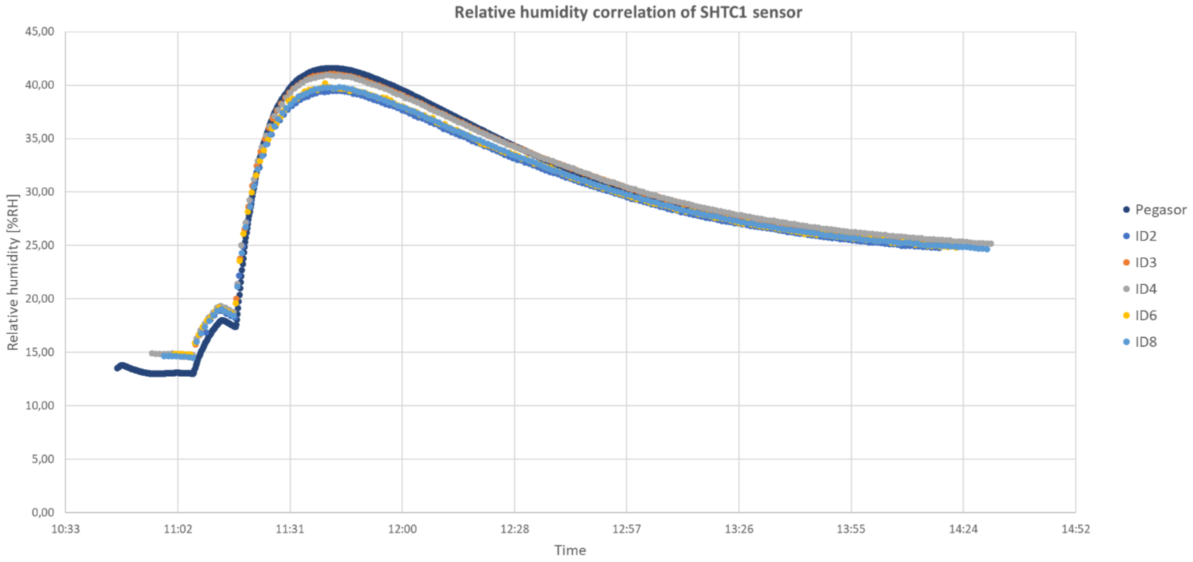


Figure 14: RH correlation of SHTC1 (Arduino).

As the RH level is dependent on the temperature measurement, there is also a systematic deviation present in these measurements and both sensors are measuring a RH level lower than the reference. The SCD30 sensor has a higher systematic deviation compared to the SHTC1 sensor.

The correlation factors are displayed in Table 3.

Table 3: Correlation factors of SCD30 and SHTC1 sensors for temperature andRH.

	R^2-value for temperature		R^2-value for relative humidity	
Sensor	**SCD30**	**SHTC1**	**SCD30**	**SHTC1**
ID2	0.9737	0.9825	0.9853	0.9842
ID3	0.9820	0.9856	0.9965	0.9954
ID4	0.9761	0.9686	0.9897	0.9908
ID6	0.9519	0.9276	0.9786	0.9748
ID8	0.9384	0.9623	0.9921	0.9908

There are small differences in the correlation factors and the high values indicate a strong correlation for both sensor types.

Particulate matter

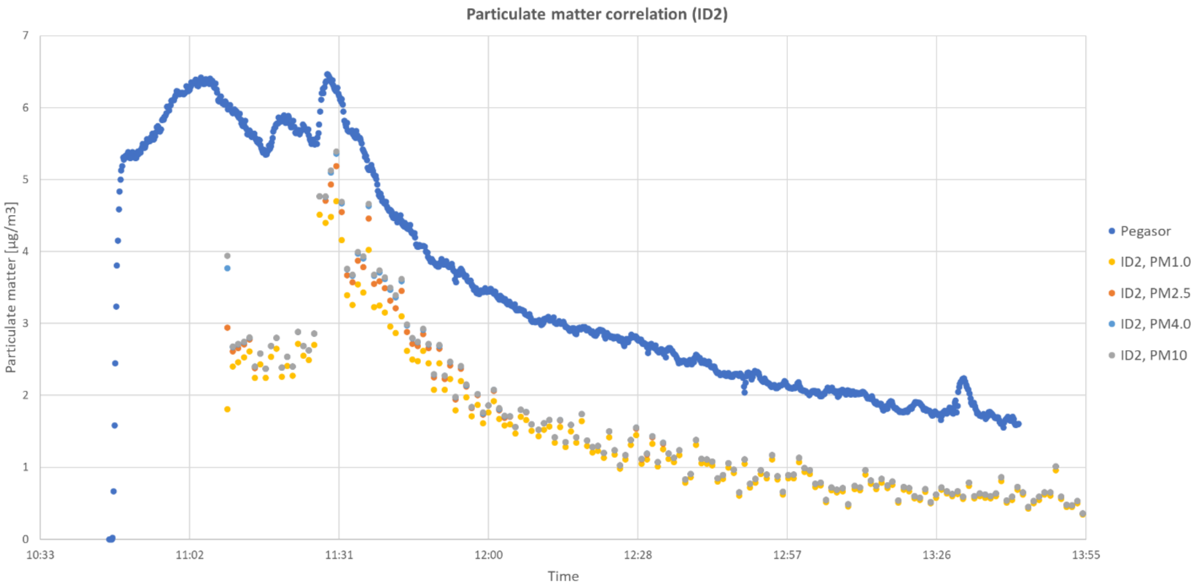


Figure 15: Measurements of PM1.0, PM2.5, PM4.0 and PM10 for Arduino sensor 2 compared to the reference.

A comparison of the measurements of $PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$ and PM_{10} performed by sensor 2 is presented in Figure 15. The figure illustrates a very low variation between the different sizes of PM, and for some datapoints the values are also overlapping. This result indicates a very high similarity in the concentration of the different sizes of PM.

The correlation factors between $PM_{1.0}$ and $PM_{2.5}$, $PM_{4.0}$ and PM_{10} is also high and between 0.9946 and 0.9805. Therefore, the sensors ability to separate the different particle sizes may be limited. This relationship between the PM measurements is representative for all the sensors.

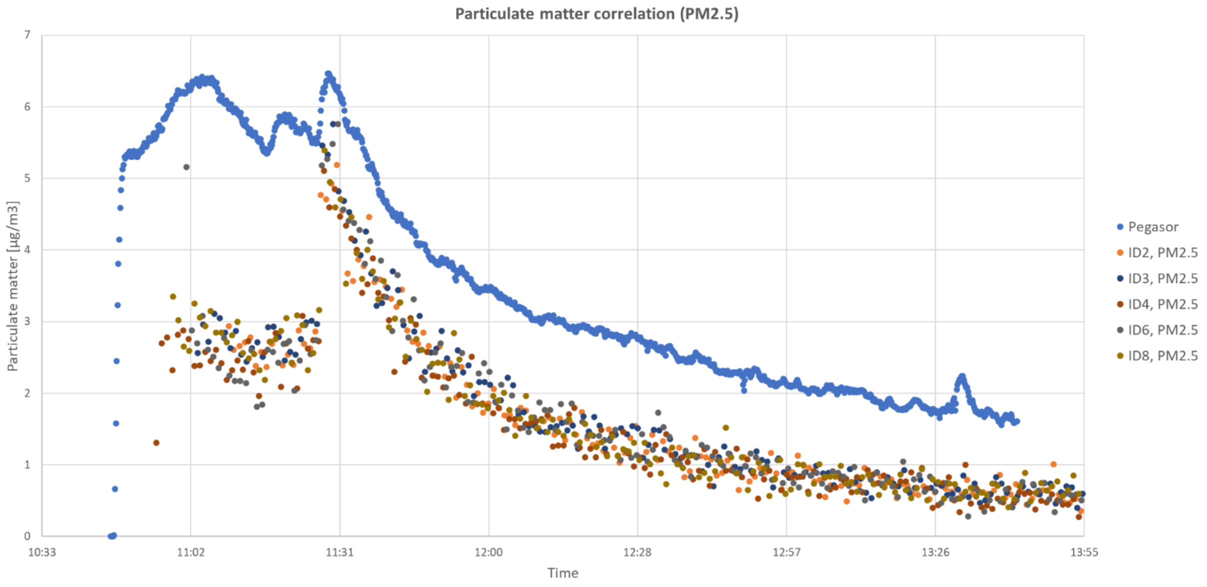


Figure 16: Comparison of $PM_{2.5}$ measurements between the Arduino sensors and the reference.

A comparison between the $PM_{2.5}$ measurements performed by each sensor are given in Figure 16 and illustrates the high similarity in the measurements. Compared to the reference, the measured values are slightly lower. However, the correlation factor between the reference and the $PM_{2.5}$ measurements vary between 0.9381 and 0.9618 which insinuates a high correlation.

Formaldehyde

A comparison between the formaldehyde measurements is presented in Figure 17. The lines are only an approximation to illustrate how the measurements vary with time.

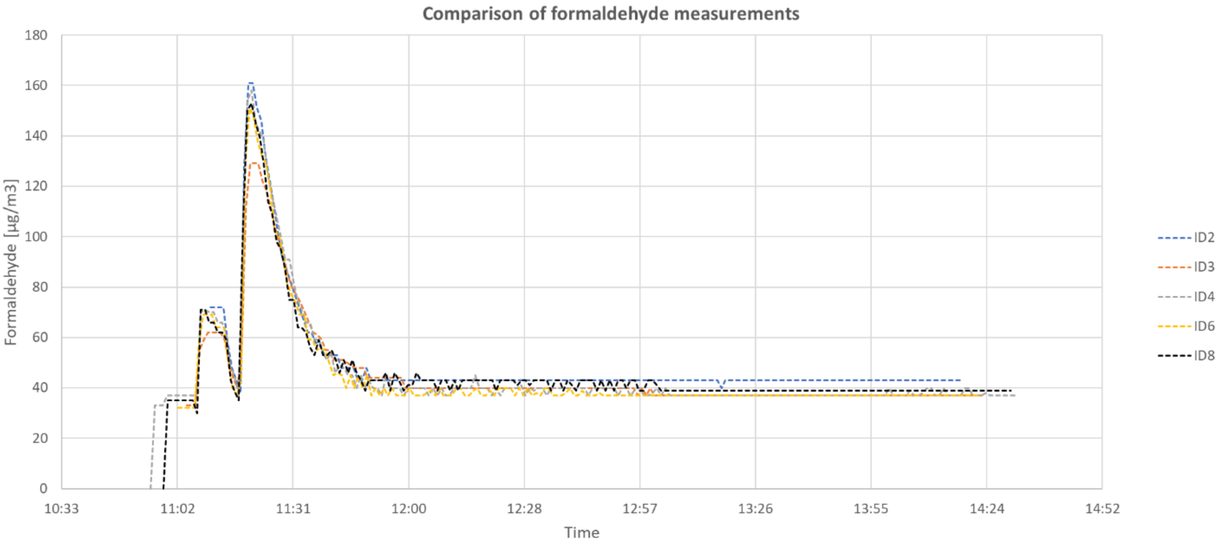


Figure 17: Comparison of formaldehyde measurements during calibration of sensors.

The correlation between the sensors seem to be quite high. Although sensor number 2 and 3 has a somewhat higher and lower peak, respectively, compared to the other sensors. As there is no reference to compare with in this case, it is difficult to say how exact these measurements are.

TVOC

A comparison of the TVOC measurements is presented in Figure 18. Sensor 2 measured a concentration of zero during the whole period, and sensor 3 only measured values above zero for approximately the first 15 minutes. The reason for this is not known.

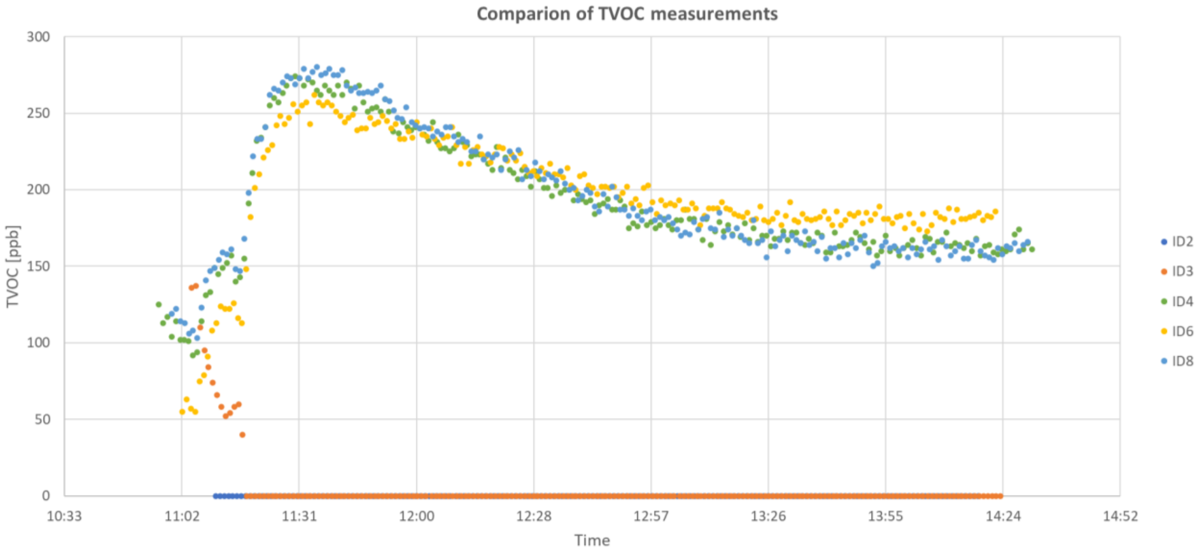


Figure 18: Comparison of TVOC measurements during calibration of Arduino sensors.

The measurements for the three other sensors seem to be following each other well, although there are some smaller variations especially for sensor number 6. As for the formaldehyde measurements, it is difficult to project the accuracy when there is no reference sensor for comparison.

5.1.6 Comparison and choice of IAQ sensor

Both IAQ sensor systems was tested using the same method of calibration. The CO_2 peak was somewhat higher during the calibration of the Arduino sensors, because the inlet of the CO_2 tank was difficult to control. The door was also opened midway through the calibration of the Wisensys sensors, and this is the explanation behind the more rapid drop in CO_2 and RH level, which can be seen in Figure 3 and Figure 7.

Although both systems had high CO_2 correlation factors, the Arduino sensors had a lower deviation from reference. For comparison, the maximum deviation from reference was approximately 200 ppm and 500 ppm for the Arduino and the Wisensys sensors, respectively.

When the temperature correlations are compared, higher deviations from reference can be found for the SCD30 sensor compared to the SHTC1 sensor and the Wisensys sensors. The SHTC1 showed the most promising results, with high correlation and a deviation from reference below 1°C. The temperature measurements of the Wisensys sensors had very low correlation coefficients and although the deviation from reference was low, this might make it difficult to trust the results by these sensors.

The RH measurement of the SCD30 and the SHTC1 are both dependent on the temperature, and the same results are found here as for the temperature measurements. The SHTC1 sensor measures a low deviation from reference, and the values are almost exact. The correlation coefficients are high for both sensors. This is also the case for the Wisensys sensors.

As there was not enough time to test the Wisensys sensors furthermore, it was decided not to use these in the field measurements mainly because of the large deviation in the CO_2 measurements and the low correlation of the temperature measurements. For temperature, only the result from the SHTC1 sensors are to be considered in the analysis of the field measurements, as this sensor had a higher accuracy than the SCD30 sensor.

5.1.7 Placement of IAQ sensors

According to the ASTM "Standard guide for using indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation" [49], the sensors for measuring CO_2 concentration should be placed such that the measurements may not be affected by people. This standard proposes a safe distance of 2 m. However, this may be difficult to achieve depending on the bedroom area and the placement of the bed in relation to the window. The placement of the IAQ sensors may therefore be a trade-off between practical placement, and representativity of the air quality in the room.

5.2 Window opening sensors

Motivation

Previous studies on window opening behavior and its correlation with ventilation rate have mostly looked at the window opening at different stages, such as open, closed or ajar [12, 28]. The size of the opening has not, to the author's knowledge, been analyzed in previous studies. The opportunity to investigate the relation between the degree of window opening and IAQ has been the main motivation behind developing the window opening sensors through the project and master thesis.

Background

To better understand the challenges with finding one fitting sensor for all types of windows, an overview of the most common window models is presented in this section. The typology is listed below and illustrated in Figure 19.

Window typology:

1. Opening outwards and top-hinged
    a. Small opening, where the window is connected to the upper sill.
    b. Large opening, where the window is no longer connected to the upper sill. Here, there will be an opening at both the bottom and the top.
2. Opening inwards and bottom-hinged
3. Opening outwards or and side-hinged

Figure 19: Window typology [50]. The upper row shows window type 1a and 1b (from left to right), and the lower row shows window type 2 and 3 (from left to right).

It is important to consider that the window type may have a strong effect on the ventilation efficiency of the room. This can be illustrated by taking a closer look at the window of type 1b. In theory, explained by buoyancy forces, the air can here enter efficiently through the lower opening and exit through the upper opening. This principle is illustrated in Figure 20. This may lead to a more effective air change rate compared to a window with only one opening.

Figure 20: Illustration of how window opening can affect the effectivity of natural ventilation. The green arrows illustrate the fresh air that enters the room from outdoors, the blue arrows illustrate the mixed air which exits the room.

5.2.1 Choice of sensor technology

Sensor criteria

The choice of sensor technology has been based on a set of criteria. An overview of the most important sensor criteria is given by the list below.

- Possibility of measuring independently for 2-3 weeks
- The ability of local storage
- High accuracy
- Easy mounting
- Possibility of communicating with IAQ sensor
- Universal solution
- Economy

To be able to carry out measurements over a 2-3-week period in occupied residential buildings, it was considered important that the technology was able to measure independently, over a certain amount of time, with no need for human interference. Therefore, the possibility of storing the data locally was considered important. During the process, a cloud-solution with continuous uploading of measurement data was discussed. As this solution is dependent on either a wireless router or using the internet connection in the investigated building, it was decided that local storage would be a safer, cheaper, and simpler solution.

Precision and accuracy were also considered important. It was discussed that deviation of the window opening should ideally not be more than approximately one degree, as an ordinary top-hinged window opens around six degrees before the child safety lock is triggered. It was also considered valuable that mounting of the sensor would not require any large intervention of the windowsill or similar. For easier interpretation of the data, the possibility of communicating with the IAQ sensor was considered an advantage.

Ideally, the chosen sensor technology should be a universal solution applicable for a set of different window typologies – to have as few limitations as possible for the choice of bedrooms. Through the specialization project, this was shown to be more difficult than expected. Economy was also considered as one of the more important factors, due to a limited budget.

Based on these criteria, four different types of sensors for measuring the width of the window opening was reviewed in the specialization project: an accelerometer, a magnetometer, an ultrasonic sound sensor and an infrared sensor. Practical testing was only carried out for the accelerometer and the magnetometer due to limited amount of time. The ultrasonic sound sensor has been tested and developed during the master thesis, along with some further testing of the accelerometer.

5.2.2 Accelerometer

A brief description of the accelerometer is given in this section. Testing and calibration are described in section 5.2.6.

Background

An accelerometer is a well-known technology and is normally used in navigation and control of vehicles or to measure vibrations in constructions. It is an electromechanical device, which can measure acceleration along one, two or three axes [51]. Therefore, it can measure if a window is being tilted due to changes in the gravitational acceleration vector and the displacement angle can be displayed as output [52]. The angle can be used to give an indication of the degree of window opening or be used to approximate the width of the opening. Andersen et.al used this technology for the study of window opening behavior in Danish dwellings [43]. In this case, the accelerometer was only used to see if the window was open or not.

Working principle

When the accelerometer is held still it measures the acceleration of gravity. This can be used as a reference position in the measurements, hereafter a vector $\overrightarrow{v_1}$. After the reference vector is sampled and stored, the accelerometer samples a new vector, $\overrightarrow{v_2}$, at a certain time step e.g. every minute. The angle between these two vectors can then be calculated by Equation 1.

$$\theta = \frac{180^\circ}{\pi} \cos^{-1}\left(\frac{(\overrightarrow{v_1} \cdot \overrightarrow{v_2})}{|\overrightarrow{v_1}||\overrightarrow{v_1}|}\right) \text{ [degrees]} \qquad (1)$$

The output will then be the angle between the two vectors, which will represent the angle of the window opening. The accelerometer can only measure differences in the gravitational acceleration vector and will therefore not detect side-ways movement. This means that this sensor will only work for top- and bottom-hinged windows.

Type and price

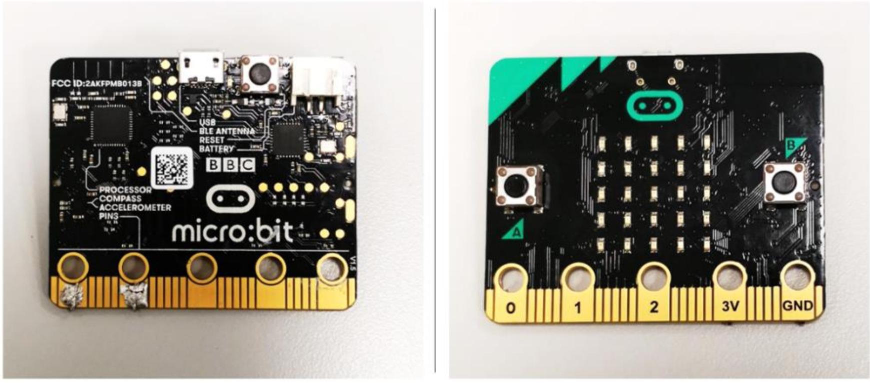


Figure 21: BBC Micro:bit

A BBC micro:bit was used to test the accelerometer. This is a small, lightweight codable computer that is used for educational purposes in children's schools [53]. Due to its small size and light weight, it can easily be mounted on the windowpane without the need of any additional interference. It has programmable buttons, LED lights and a built-in accelerometer and magnetometer. It can be powered by a battery package or a power cable, has flash memory and is easily programmed in Arduino. The micro:bit also has a Bluetooth connection, which makes it possible to communicate with other devices e.g. IAQ sensor. The price was around 200 NOK at the time of acquisition.

Mounting

To avoid leaving marks on the window frame, the accelerometer can be mounted using Pritt Multi Tack [54]. This solution is shown in Figure 22.

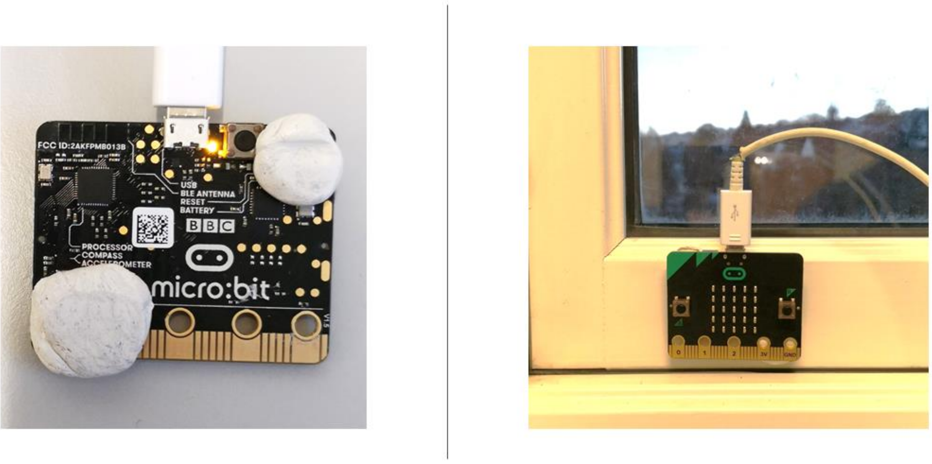


Figure 22: Mounting of accelerometer on windowsill by using Pritt Multi Tack [54].

5.2.3 Magnetometer

There are many different types of magnetometers, and they are commonly used for measuring magnetic fields on the ground and in space. A vector magnetometer can measure the strength and direction of a magnetic field [55]. Measuring an angle with a magnetometer is not a common solution, and there is little literature on this field.

The BBC micro:bit was also used to test the magnetometer in the specialization project to see if the magnetometer could be used to measure the opening of side-hinged windows.

Working principle

The principle behind the magnetometer is the same as for the accelerometer. Only here the reference vector is based on the strength and direction of a magnetic field and therefore works similar to a compass [55]. In this case the magnetometer detects the strength of the earth's magnetic field as the reference position. The deviation from reference is calculated in the same way as for the accelerometer measurements, and the output is the opening angle of the side-hinged window.

Calibration test

The magnetometer was tested during the specialization project, and it was found that the magnetometer of the micro:bit was unable to detect the differences in the magnetic field. No further testing was done during the master thesis, as other sensor technologies were explored for measuring the opening of side-hinged windows.

5.2.4 Ultrasonic sound sensor

An ultrasonic sound sensor is based on the principle of soundwaves being reflected in the opposite direction when they encounter an object. It can be used for many purposes, such as measuring liquid levels, detecting objects and distance measurements [56].

Working principle

The sensor consists of a Transmitter, which sends out a very short ultrasonic soundwave, and a Receiver, which registers the reflected soundwave. By registering the time interval from the soundwave is transmitted until it reaches back to the sensor, the distance can be calculated by knowing the speed of sound in air [56].

The idea is that the sensor can measure the distance from the window frame to the window and indicate the width of the opening. As it is based on the reflectance of soundwaves it is not affected by different light conditions. However, some articles [56, 57] has suggested that the ultrasonic sensor might have problems with measuring the distance to angled objects due to the reflectance of the soundwaves in dispersed directions. This is illustrated in Figure 23, where the sensor and the object of detection are presented respectively as the blue and orange box.

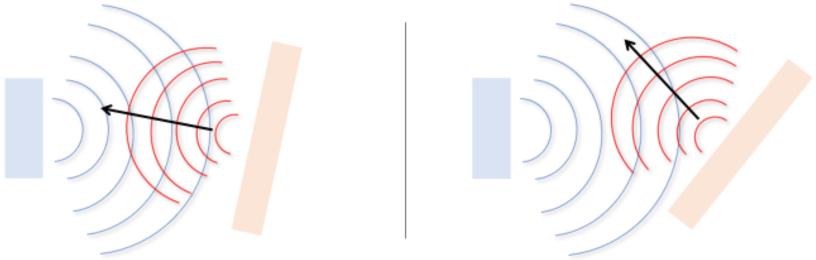


Figure 23: Reflectance of soundwaves from the ultrasonic sensor, depending on the orientation of the object, where the blue lines represents the transmitted waves and the red lines represents the reflected waves.

If the object is placed perpendicular to the sensor, the principal part of the reflected waves will most likely be directed straight back to the sensor. If the object is angled, as shown in Figure 23, the reflected waves might be directed in another direction than back to the sensor. This could affect the distance measurement for side-hinged windows. The reflectance of the waves can also be affected, positively or negatively, by the roughness of the surface [56].

Type and price

The type of sensor that has been used is a RCWL-1601 sensor, as shown in Figure 24, produced by Adafruit Industries [58]. The price was around 50 NOK/piece at the time of acquisition.

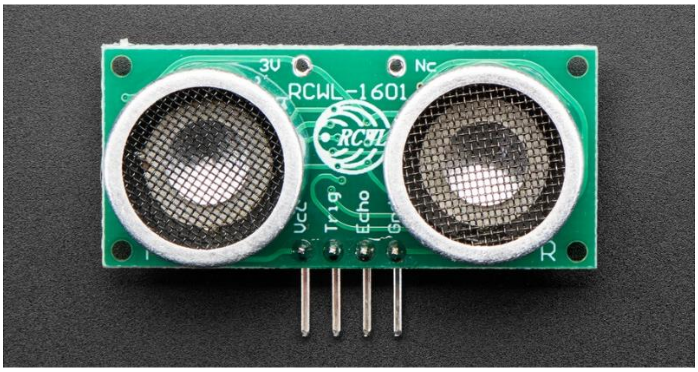


Figure 24: Ultrasonic sound sensor (RCWL-1601) [58].

It is said to have a high range and accuracy, with a measuring range of 2 – 450 cm.

The ultrasonic sound sensor can be run through the BBC micro:bit, and the measurements are transmitted and stored in the exact same way as for the accelerometer. This solution is shown in Figure 25.

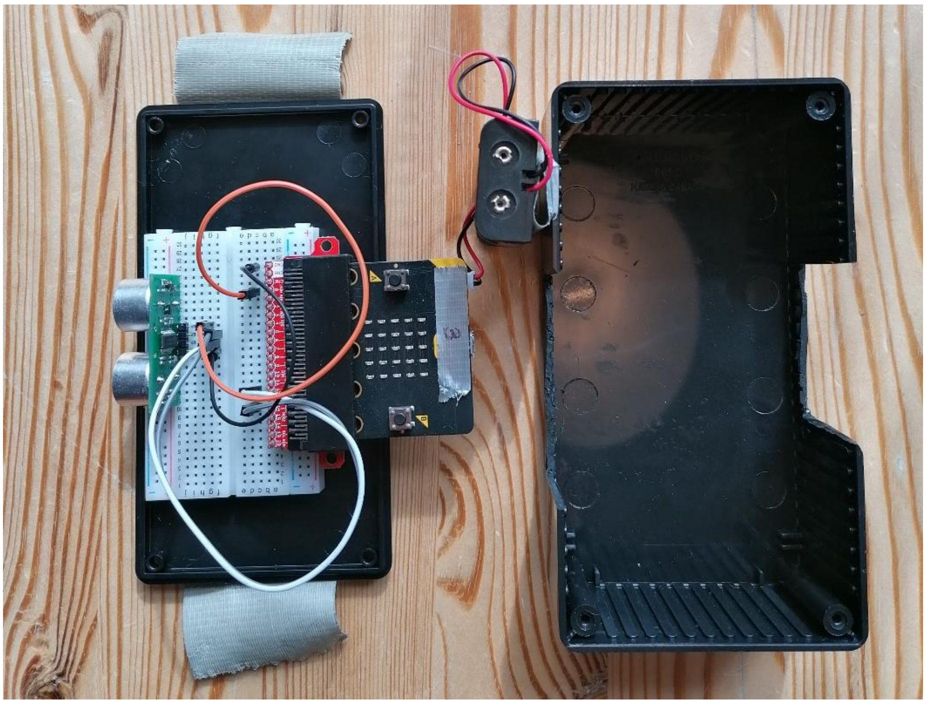


Figure 25: Ultrasonic sound sensor connected to the BBC micro:bit.

Mounting

The sensor can be placed both vertically and horizontally, a picture of the vertical mounting is shown in Figure 26.

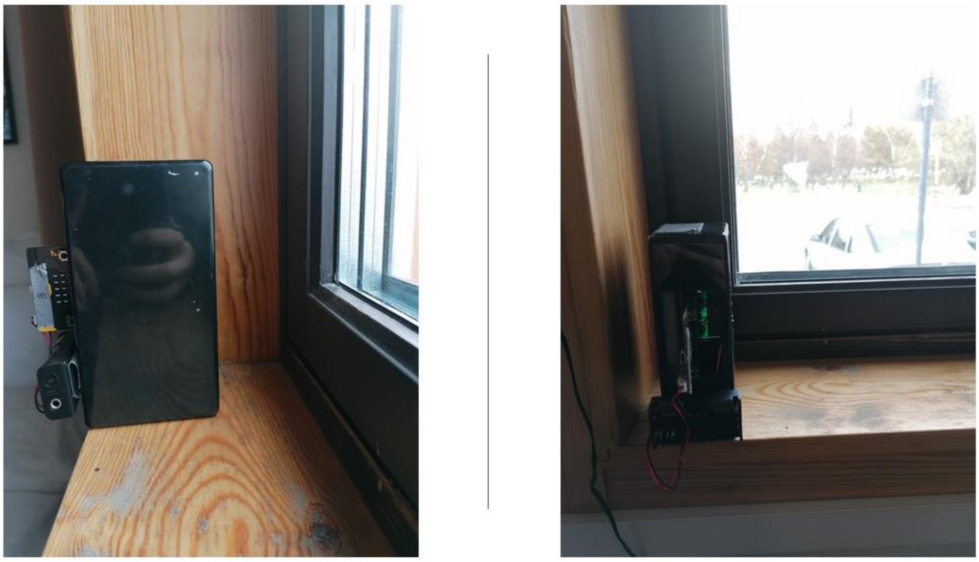


Figure 26: Mounting of ultrasonic sound sensor.

It should be noted that the distance between the sensor and the window must be registerd, when the sensor is set-up.

5.2.5 Infrared (IR) Sensors

In the process of finding a sensor technology that could fulfill the sensor criteria, infrared distance sensors were considered as a possible solution. These sensors are based on the same principle as the ultrasonic sensor, only they measure the reflectance of light waves instead of soundwaves [59]. They are typically more expensive and have a higher minimum range than the ultrasonic sensor, when it comes to distance measuring. Due to a limited amount of time this sensor technology was decided not to be investigated further.

5.2.6 Calibration and testing of accelerometer

Important findings from the specialization project

The accelerometer was first tested during the specialization project as a stand-alone sensor, where the measurements were stored locally on the micro:bit. This showed promising results, but the angle measurements had some variation and the inaccuracy could be up to 2 degrees.

As a stand-alone sensor the micro:bit has limited battery capacity and limited storage. Therefore, to increase the accuracy of the measurements, implementation of average and moving average in the code was explored. The latter one was shown to behave somewhat unreliably with the sensor and due to this only the average measurements were tested in an 8h test. When implementing the average measurement, the inaccuracy of the accelerometer was around ± 1 degree. An offset of around 0.5 degrees was also shown to be present in this test. As the test period was only 8h (one night) it was decided that a full-scale test should be performed during the master thesis to confirm or disprove the results.

Further testing

During this work several full-scale tests of the accelerometer have been carried out. An example of one of these tests can be found in Figure 27.

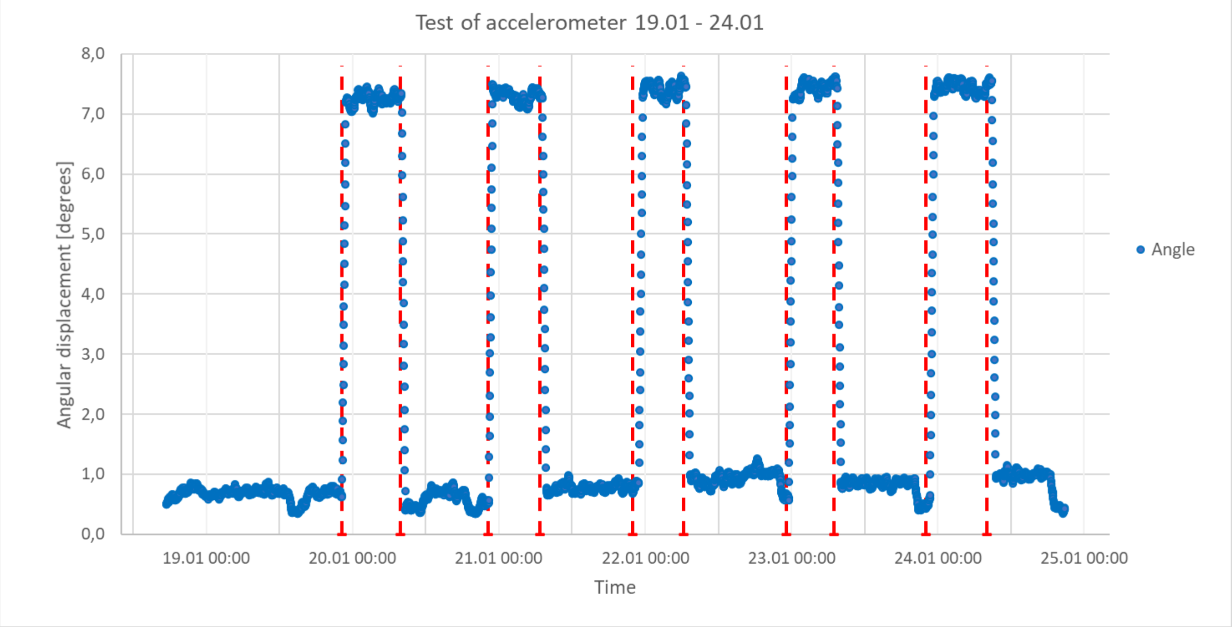


Figure 27: Test of accelerometer 19.01-24.01. Delay set to 2 minutes and an average of 20 data points were used.

During the first full-scale test an inaccuracy connected to the time stamps of the data stored by the micro:bit was discovered. It was found that when the delay between the measurements was set to e.g. 120 seconds, the micro:bit measured a new sample approximately every 113th second. As this makes the measurements inaccurate over a long time period, it was decided that the micro:bit should not be used as a stand-alone sensor. Therefore, the code was refined to send the measurements, via Bluetooth, to a Raspberry Pi, which is already used in the IAQ Arduino sensors. The measurements are then timestamped by the clock on the Raspberry Pi.

This also made the data saving process safer, as the measurements does not have to be intermediately stored in flash memory. Some data is, however, lost in the transfer process but if the data is sampled and transmitted often enough this is not considered a problem. The sample rate can be increased when Bluetooth transfer is used, because of a lower power consumption of the micro:bit and a higher storage capacity of the Raspberry Pi.

Due to the integration of Raspberry Pi, it was decided to discard the average measurements and store raw data instead – as the sample frequency could be increased. The accelerometer occasionally measures highly deviating angles, which can easily be accounted for when analyzing the raw data. This may lead to a more demanding data analyzing process afterwards but may also lead to fewer sources of errors in the field investigations.

Assumed accuracy of accelerometer

A test of the accelerometer through two nights with no filration of data and Bluetooth transfer is displayed in Figure 28. The opening angle of the window was approximated to be between 6.5 and 7 degrees, estimated by measuring width and height of the window. The moving average of 10 samples is plotted by the black line.

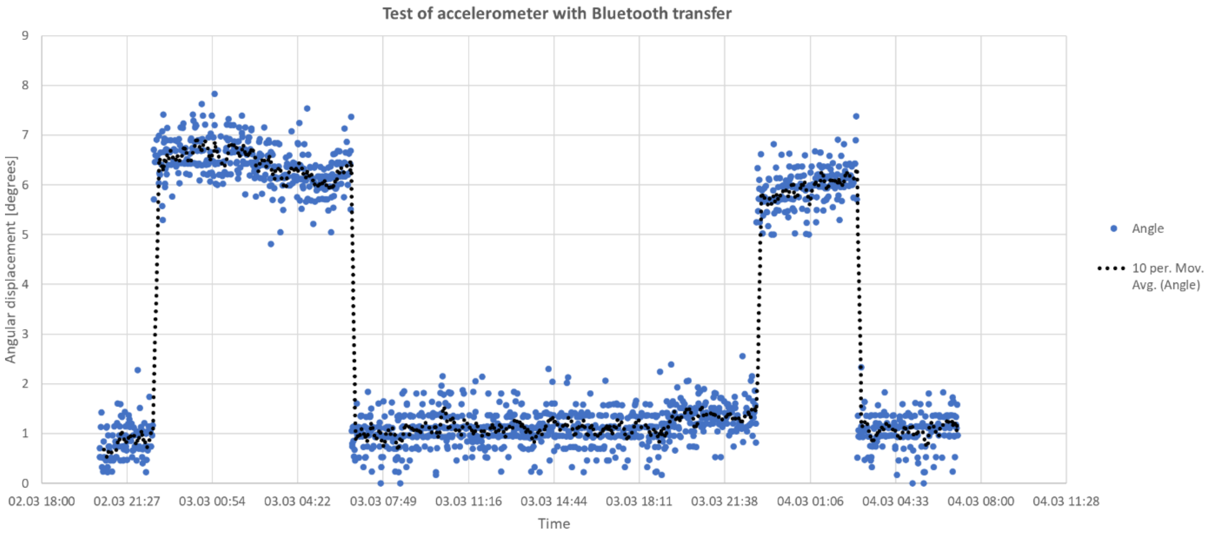


Figure 28: Test of accelerometer with raw data, Bluetooth transfer and a sampling time of 1 minute. The black line is the moving average of 10 measurements.

As the figure illustrates, the accelerometer measurements have a high spread and the variation in the measurements can be up to three degrees. However, when the moving average is plotted the opening trend is clear.

There is also an offset of the accelerometer, which here seems to be around one degree. As the offset may vary between sensors and can easily be considered when the measurements are analyzed, it has been chosen not to adjust for this in the code.

When considering the offset, the angle measurements seem to alternate between six and seven degrees the first night, and between 5 and 6 degrees the second night. By similar tests, the accuracy of the accelerometer has been estimated to be approximately ± 2 degrees.

5.2.7 Calibration and testing of ultrasonic sound sensor

To test the functionality and accuracy of the measurements, the sensor was first tested by measuring the increasing distance to a perpendicular surface. The results from the test is illustrated in Figure 29.

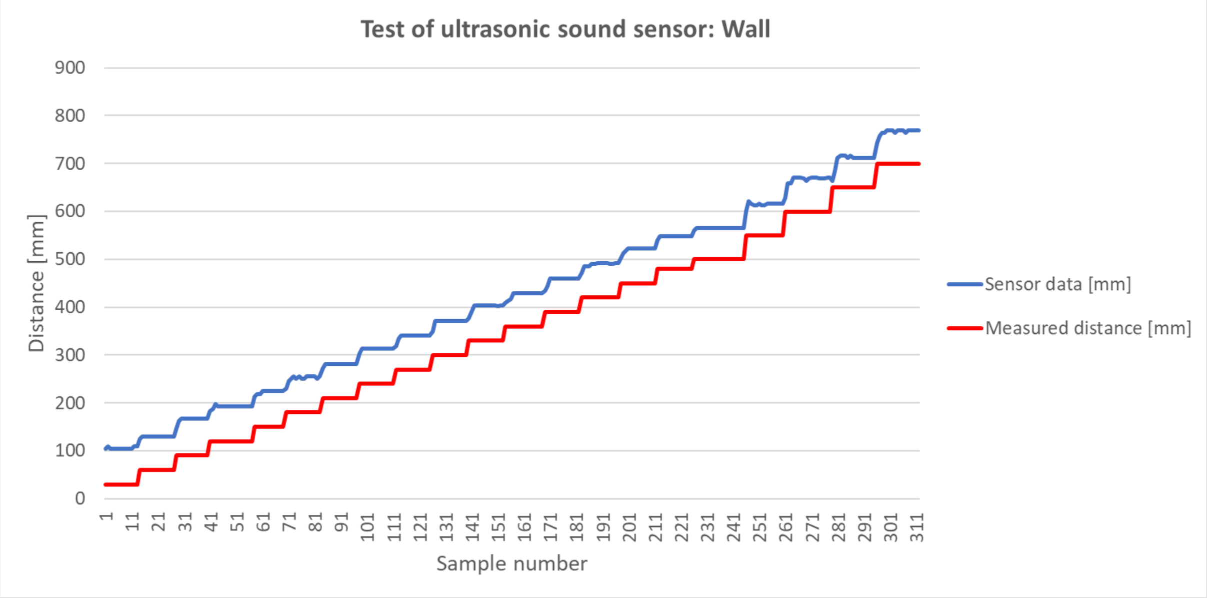


Figure 29: Test of ultrasonic sound sensor by measuring the increasing distance to a wall.

It was shown that the ultrasonic sound sensor measures a systematic error of around seven cm. However, the measurements are characterized by a high correlation and the correlation coefficient is 0.995.

To see how well the soundwaves were reflected when the surface was not perpendicular to the sensor, a doorway was used. The sensor was placed on the opposite side of where the door was hinged and the minimum distance from the sensor to the door was 3 cm. The door was moved approximately 10 cm every time, measured from the doorway to the tip of the door. The results from the test is illustrated in Figure 30.

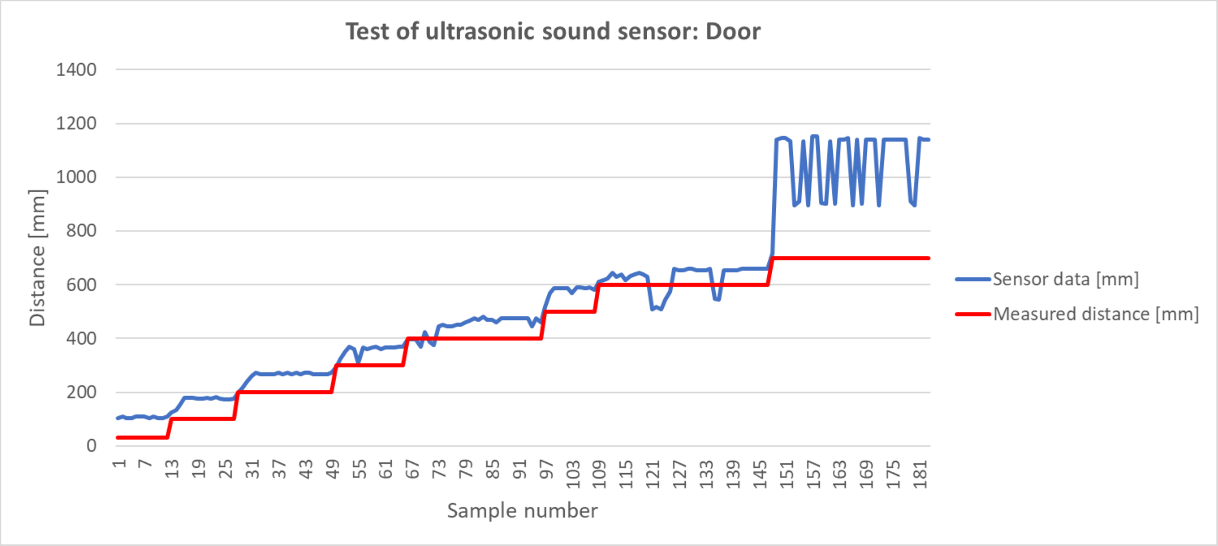


Figure 30: Test of ultrasonic sound sensor by measuring the distance to a door. The sensor was placed in the doorway, at the opposite side of the hinge.

As can be seen from the figure, the measurements are characterized by some more variation with the non-perpendicular surface and the variation seem to be increasing with the opening angle. When the door was opened more than 60 cm, which corresponds to a door opening of approximately 40 degrees, the soundwaves were no longer reflected by the tip of the door. This was expected and explained in section 5.2.4. If the correlation curve is plotted from 0 cm to 60 cm, the correlation factor is 0.9672.

The ultrasonic sound sensor was only full-scale tested with a doorway as there was no side-hinged window available. However, the results of this test were promising as the opening was measured by a high approximation for up to 40 degrees. It was considered a reasonable assumption that bedroom windows would not be open more than this during the heating season. Due to limited time the sensor was not tested further before the field measurements took place.

5.2.8 Window opening area

As the accelerometer measures the opening angle of the measurements and the ultrasonic sound sensor measures the opening distance, window opening area can be used as a general parameter for comparing the different window typologies.

For top-hinged windows, the opening distance can be found by using the opening angle and then the opening area can be calculated by Equation 2,

$$A_{top-hinged} = W * H * \tan\theta \qquad (2)$$

where W and H is the width and height of the window and θ is the opening angle of the window.

The same calculation can be done for side-hinged windows, only here the sensor measures the opening distance to the window. The opening area of windows that are middle-hinged can also be approximated by Equation 2, as the height is halved, and the opening distance is doubled. The opening area of a top-hinged and a side-hinged window is illustrated in Figure 31.

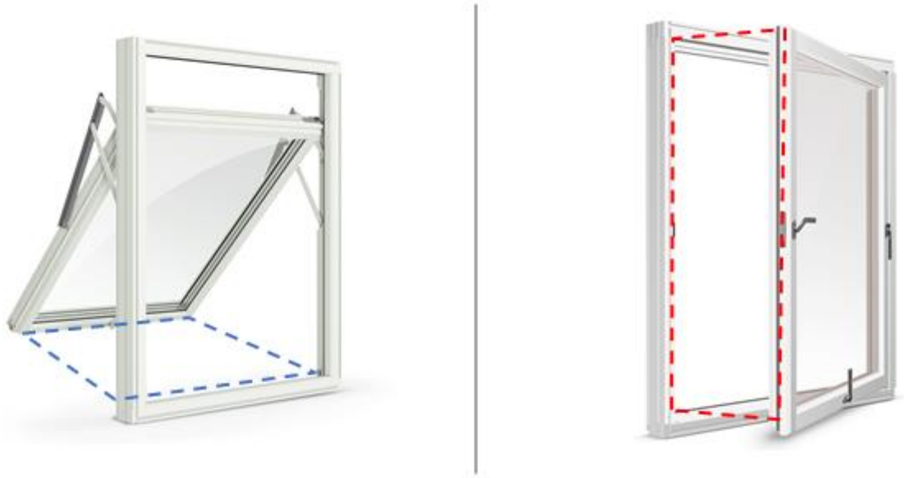


Figure 31: Illustration of how window opening area is calculated for top-hinged (left) and side-hinged (right) windows.

It is important to consider that this window opening area is only a simplified parameter to form a basis for comparison for different types of windows. It does not reflect the total opening area of the windows, where the air can flow through the window. For small opening angles the opening area is also less accurate, as the frame is not fully clear of the sill. It should also be noticed that if top-hinged windows are higher or side-hinged windows are wider, this would result in a larger total opening area which is not reflected in the calculated window opening area. By the same reason, rectangular top-hinged windows where the width is larger than the height will have a smaller total opening area, compared to top-hinged quadratic windows, with the same opening area. The opening area of a rectangular top-hinged window is illustrated in Figure 32.

Figure 32: Illustration of window opening area of a rectangular top-hinged window.

These differences should be considered when the window opening areas are compared.

5.3 Questionnaire and occupant log

To project and get an overview of factors that might be of influence on the field measurements, the occupants are asked to fill out a questionnaire. The questionnaire is sent through the secure web service *Nettskjema.no*. An overview of the questions is given in Table 4.

Table 4: Overview of questionnaire content.

General information about building and bedroom	Information about occupant and occupant behavior
• Year of construction • Renovations carried out • Number and type of windows in the bedroom being measured • Volume of bedroom and size of windows • Type of ventilation and heating system • Window valves and their usual position day and night • Type of curtains and their usual position in the nighttime	• Sex, age, height and weight • Number of people in the room at night under normal circumstances • Bedroom door open or closed (day and night) • Motivation and habits related to opening bedroom window • Habits related to heating system in the bedroom at night • How the occupants normally perceive the IAQ (“fresh air”)

Some information about the bedroom is also collected during the set-up of the sensors, such as room volume, window type, window and door area, bedroom location and type of heating system. If several bedrooms are participating in the field investigation, the name of the occupant sleeping in the bedroom is also collected.

The use of an occupant log through the measurement period was discussed. However, as this might be an incentive for the occupants to subconsciously deviate from their usual habits, this was idea discarded. The participants were only asked to log necessary information, such as nights where the bedroom window was closed, nights of non-occupancy or nights in which the number of occupants deviated from normal.

5.3.1 Curtain typology

As different types of curtains may have a variating effect on the airflow through the window, the occupants are asked to answer what type of curtains they have in their bedroom. Therefore, an overview of the main types of curtains is given in Figure 33. This figure was also displayed in the survey.

Figure 33: Typology of the most common types of curtains. From left: dropdown curtain, heavy curtain, light curtain, plissé curtain [60].

5.4 Privacy policy

The project has been approved by the Norwegian Centre for Research Data (NSD) for the treatment and storage of personal information. The participants are given information about the project and how their personal data are treated before the field investigations are begun. They are also asked to give their written consent to their participation in the field measurements, including the following questionnaire, and to how their data and the measurements are treated and stored throughout the project.

5.5 Weather data

As the IAQ measurements may be affected by outdoor conditions, the possibility of collecting information about the local weather has been considered important.

Information about the past weather can be collected from the website seklima.met.no, which is provided by the Norwegian Center for Climate Services (Norsk klimaservicesenter). Several outdoor conditions can be collected from this portal, such as temperature, RH, wind and precipitation for the previous days, weeks or years. The use of this presupposes that the building of investigation is located close to a weather station in the register. The measured parameters and the sampling rate also vary between the stations.

An example of where the weather stations in Trondheim is located is given in Figure 34. The figure illustrates that the relevance of the weather data may differ strongly from case to case.

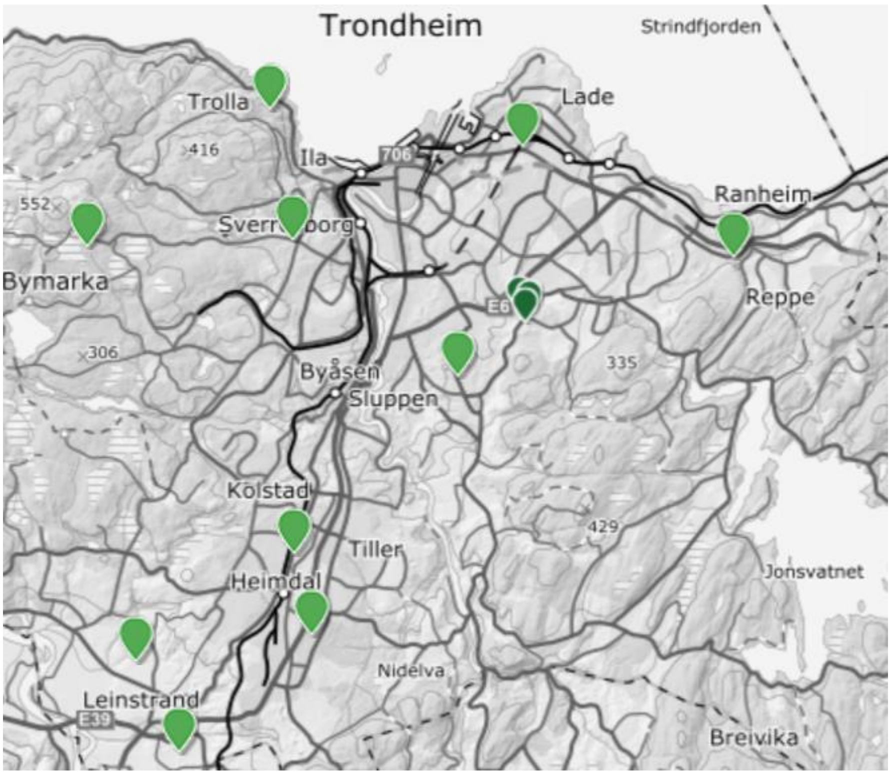


Figure 34: Location of the weather stations in Trondheim, here represented by the green dots [61].

The parameters that are expected to be have most influence on the IAQ measurements are outdoor temperature, RH, precipitation, wind velocity and wind direction. In the spring- or summertime, the amount of sunshine may also be of importance. The relevance of wind data may vary strongly from case to case, as it depends on both location of weather station and the degree of exposure of the building.

5.6 Selection of building objects and inhabitants

The main objective of the thesis is to investigate if natural ventilation, through opening the bedroom window, can be used as the only ventilation solution in bedrooms when older houses are renovated. Hereby, the ideal case house has recently been renovated without installing a balanced ventilation system in the bedroom. The infiltration rate through the building envelope of renovated houses is usually lower, compared to older buildings, and it is important to ensure that fresh air enters through the window opening and not the outer wall.

As was discussed in the literature review, the user's habits and wishes is an important aspect when planning for a good IEQ. For this reason, only inhabitants who normally opens the bedroom window during nighttime have been asked to participate.

To achieve a uniform selection of houses, building type has been limited to single-family, multi-family and terraced houses. Apartment buildings have been avoided, as the buoyancy and wind pressure forces are dependent on the height from ground.

To identify houses that fits within these criteria, building societies (TOBB) have been contacted, in addition to utilizing personal network and acquaintances. TOBB provided a list of building cooperatives that had recently been insulated, without installing a ventilation system. The suggested building cooperatives were contacted, but only a few chose to forward the information to their members.

In addition to this, dwellings that are chosen to participate in the OPPTRE project, located in Trondheim, have been invited to take part in the field measurements. These buildings may have a higher infiltration rate since they are not yet renovated, but the results from investigating these buildings and the occupant's habits may be used for comparison later in a ph. D thesis related to OPPTRE. The inhabitants of these buildings may be more motivated to participate in the investigation of the IEQ, and results that depend on occupant observations can be of higher quality in these dwellings.

This process resulted in 6 different houses, with a total of 10 bedrooms. The participants were both children and grown-ups.

5.6.1 Description of case houses

Below follows a short description of each case house. The information has been provided by the occupants. An overview of the characterization of each bedroom can be found in Table 5 and Table 6.

Case house 1

Case house 1 is a terraced house and was built in 1978. The house was upgraded in 2010, where the building envelope was additionally insulated and the windows were changed. Three bedrooms took part in the investigations, whereas one main bedroom with two adults and two children's room. All the bedrooms were located on the second floor of the house.

Case house 2

Case house 2 is a detached house, built in 1961. The house was energy-upgraded in 2007 to the same level as a new building. In addition, a mechanical balanced ventilation system was installed in the house with exception of the two bedrooms included in the field measurements. Both bedrooms were occupied by two teenagers during the measurements and both were located on the ground floor. This case house is the closest one to the ideal case house.

Case house 3

Case house 3 is a semi-detached house, built in 1925. The house has been upgraded, with additional insulation and new windows. Two bedrooms were included in the measurements: one main bedroom at the ground floor and one bedroom at the attic with a pitched roof and a skylight, occupied by an adult and a teenager, respectively.

Case house 4

Case house 4 is a terraced, self-assembled house and was built in 2018. The occupant living here is especially interested in the re-use of materials, and the materials used inside has therefore been treated with non-synthetic materials. The wall panel of the bedroom is re-used with original paint from the 1960s, and the wooden floor is from the 1890s. The bedroom has connected original windows from 1950. A synthetic wind barrier is only used around the windows, and the building envelope is well insulated.

Case house 5

Case house 5 is an apartment building with only two floors, built in 2000. One bedroom inhabited by a student, located on the second floor, was included in the field measurements.

Case house 6

Case house 6 is the home of two of the participants in the OPPTRE project, but not one of the OPPTRE houses. It was built in 1980 and included in the field measurement to observe occupant behavior.

Table 5: Overview of the building and bedroom characteristics of the case houses.

Case house	Bedroom	Type of house	Floor area (Height)	Floor	Number of people	Heating system
1	1	Terraced	7.4 (2.4)	2nd	2	-
	2		8.1 (2.4)	2nd	1	On
	3		9.1 (2.4)	2nd	1	On
2	1	Single-family	10.9 (2.3)	1st	1	Off
	2		10.9 (2.3)	1st	1	Off
3	1	Semi-detached	10.0 (3.4)	1st	1	-
	2		14 (~2.1) (pitched roof)	3rd	1	-
4	-	Terraced	6.5 (~2) (pitched roof)	2nd	1	Off
5	-	Multi-family	12.0 (2.4)	2nd	1	On
6	-	Single-family	9.4 (2.2)	1st	2	-

Table 6: Overview of window characteristics of the bedrooms.

Case house	Bedroom	Type of window	Window area [m^2] (H x W)	Window valve	Type of curtains
1	1	Top-hinged	0.4 (0.34 x 1.25)	-	Heavy (Closed)
	2	Top-hinged	1.1 (1.06 x 1)	Open	Dropdown (Undrawn)
	3	Top-hinged	1.1 (1.06 x 1)	Open	Dropdown (Closed)
2	1	Top-hinged	1.0 (1 x 0.95)	Closed	Plissé (Closed)
	2	Top-hinged	1.0 (1 x 0.95)	Closed	Light (Closed)
3	1	Side-hinged	0.7 (1.43 x 0.47)	-	Heavy (Closed)
	2	Middle-hinged (Skylight)	0.3 (0.6 x 0.45)	-	-
4	-	Side-hinged	0.5 (1.1 x 0.45)	-	-
5	-	Side-hinged	0.3 (1.18 x 0.28)	Open (indoor/outdoor)	Light (Semi-closed)
6	-	Top-hinged	0.4 (0.45 x 0.77)	Open	?

5.6.2 Selection bias

As this study targets inhabitants who has a habit of opening the bedroom window during nighttime, in addition to living in a building with a tight envelope, there is a selection bias present in the chosen building objects and inhabitants. The results can be affected by this and may therefore not be transferable to other types of houses or inhabitants.

Many of the previous studies have been extensive ones, where more than 100 buildings have been researched over several years. The selection of bedrooms in this thesis is limited by both time and resources.

The results of this master thesis may therefore not reflect a general opinion or trend, but give an indication if natural ventilation by window openings can be a satisfactory ventilation solution in the bedrooms of users who would prefer this above installing a ventilation system in the bedroom.

5.7 Calculations of air change rate

To compare the results of this study to earlier studies, an estimation of the air change rate can be conducted. To continuously investigate the air change rate of a room a tracer gas method is best suited.

5.7.1 Tracer gas method with occupant generated CO_2

The basis for these calculations is collected from the books by Sturla Ingebritsen "Ventilasjonsteknikk del I og del II" (2019) [13], but is also explained in the ASHRAE Handbook: fundamentals from 2001 [62] and in the ASTM standard [49].

The calculation of the air change rate is based on a single-zone mass balance model, where occupant-produced CO_2 is used as tracer gas. The CO_2 measurements can be used to give an estimate of the air change rate of the room, by estimating the CO_2 production of the occupants and knowing, or estimating, the CO_2 level in the supply air.

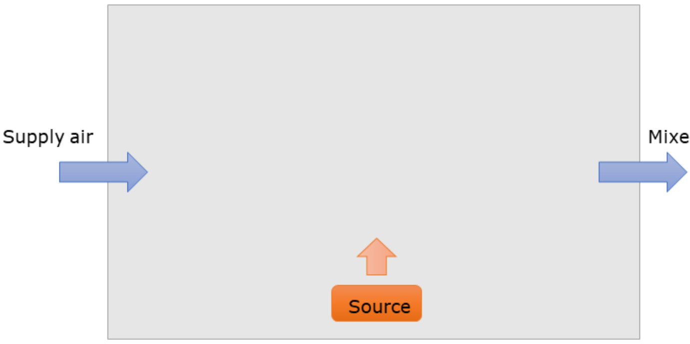


Figure 35: Illustration of a single-zone mass balance model.

Based on Figure 35 a mass balance can be drawn up, and the change in concentration is presented by Equation 3,

$$F + Q_s * c_o = V * \frac{dc}{dt} + Q_m * c_i \ [mg/h] \tag{3}$$

where F is the generation rate of CO_2 from the source, c_o is the concentration of CO_2 in outdoor air, c_i is the concentration of CO_2 in indoor air at time i, and Q_s and Q_m is the airflow rate of supply and mixed air, respectively. V is the volume of the room.

To apply Equation 3 in the air change rate calculation, the in- and outflow is assumed to be equal and the CO_2 production of the source is assumed to be constant. It is also assumed that air is only supplied from outdoors, or with the same concentration as outdoor air. This model therefore requires a closed room, where no airflow from adjacent rooms enters.

The equation will have two different solutions; one when there is no one occupying the room and one when there is source present in the room. Only the build-up method is presented here, for when there is a CO_2 source in the room.

Build-up method:

As explained by Jung Hou et al. the measured data can be fitted into a theoretical model by an exponential curve using the least square method. This can be done by Equation 4, where Δc is the change in indoor concentration for the time Δt.

$$\Delta \mathrm{c} = \frac{\Delta \mathrm{t}}{\mathrm{V}} * [\mathrm{F} - \mathrm{N} * \mathrm{V} * (\mathrm{c}_1 - \mathrm{c}_\mathrm{o})] \; [\mathrm{mg/h}] \tag{4}$$

The CO_2 concentration at the end of the interval can be calculated as a sum of c_1 and the change in concentration, and a theoretical exponential curve can be fitted to the measured data [11].

An approximation of the air change rate based on the CO_2 measurements during nighttime can be made by Equation 5.

$$\mathrm{N} = \frac{\mathrm{F} - \frac{\Delta \mathrm{c} * \mathrm{V}}{\Delta \mathrm{t}}}{\mathrm{V} * (\mathrm{c}_\mathrm{i} - \mathrm{c}_\mathrm{o})} \; [\mathrm{h}^{-1}] \tag{5}$$

Generation rate:

The generation rate of CO_2 for a person can be approximated by Equation 6,

$$\mathrm{F} = \mathrm{RQ} * \mathrm{BMR} * \mathrm{M} * \frac{\mathrm{T}}{\mathrm{p}} * 0.000211 \; [\mathrm{L/s}] \tag{6}$$

where RQ is the respiratory quotient, dependent on a person's diet and usually approximately 0.85. BMR is the basal metabolic rate and is dependent on sex, age and body mass. It is calculated based on the procedure given in ASTM D6245. M is the metabolic rate, approximated to 1.0 during sleeping. T and p is the air temperature and pressure [49].

5.7.2 Simplifications and uncertainties

Estimation of air change rate by occupant-generated CO_2 is a well-known method and several studies have used this to measure the air change rate of residential buildings [12, 30, 63]. It should, however, be mentioned that this method has sometimes shown to be associated with large uncertainties, and average errors can be up to 40 % as was discussed in section 3.1.1. However, when the assumptions of this analysis are valid the calculations can be a good representation of the air change rate [49].

Simplification of generation rate

As seen by Equation 6, the generation rate of CO_2 is dependent on many factors such as person characterizations, temperature and BMR. ASTM D6245 provides an overview of the generation rate of a person as a function of age, mass, BMR and level of physical activity [49]. This is also elaborated in this article [64].

With an air temperature of 273 K and a pressure of 101 kPa, 1 L/s of CO_2 equals 1.965 g/s. The CO_2 generation rate at these conditions and with an activity level of 1 met, varies between 0.0037 – 0.0038 L/s and 0.0029 – 0.0030 L/s for, respectively, for males and females between 16 and 60 years. This corresponds to a generation rate of 0.0262 – 0.0269 mg/h for the males, and 0.0205- 0.0212 mg/h for the females.

To see if it is possible to simplify the generation rate, an example is provided.

A nightly period of 7 h is assumed, where the concentration decreases from 1200 to 1000 ppm during the night, with one male and one female present in the room. The room volume is 20 m^3 and the outdoor air concentration is assumed to be 400 ppm. These conditions can be inserted into Equation 5, as shown below in Equation 7.

$$N = \frac{F - \frac{200\ (mg/m^3)*20m^3}{7h}}{20\ m^3*(800\ mg/m^3)}\ [h^{-1}] \qquad (7)$$

With a CO_2 generation rate of 0.0467 mg/h (0.0262 + 0.0205 mg/h), this would result in an air change rate of 0.03571. With a generation rate of 0.0481 mg/h (0.0269 + 0.0212 mg/h), this would also result in an air change rate of 0.03571 h^{-1}.

As the differences in generation rate results in very small changes of the air change rate, these are approximated in the calculations, but differentiated between children, male and female adults. The generation rates are estimated to be 0.027 mg/h for adult males, 0.021 mg/h for adult females and 0.017 mg/h for children. An outdoor air concentration of 400 ppm is assumed.

6 Results

The nightly average of CO_2, temperature, RH, PM, formaldehyde and TVOC, in addition to the average opening area of the window have been calculated. Only the measurements between 23:00 and 06:00 have been included in the nightly average calculations, and nights of non-occupancy have been disregarded. In addition, the night with the lowest and highest average concentrations are also presented for each parameter, referred to as minimum and maximum averages. In addition to this, some bedrooms are studied more closely for each parameter. To make the illustrations clearer many of the parameters are plotted by the moving average of 30 minutes.

The window sensor of bedroom 1 in case house 2 only measured until around 03:00 of the first night. The occupant of this room did not report the window as closed any nights, and it is therefore assumed that the average of these hours can be used to approximate the window opening area for the remaining nights. The window sensor installed in case house 5 was not able to store any of the measurements, and therefore no data on the window opening behavior is available for this bedroom. The occupant reported the window as being closed two days, and the window is assumed open remaining nights.

Wind data are included in the appendix but has not been revised during the analysis of the results. Variations of IAQ parameters that are not included in this section, can also be found in the appendix.

6.1 Questionnaire

All the participants, except those of case house 6 and one participant in case house 3 (bedroom 2), answered the questionnaire. In the houses where children or young adults participated, parents answered on the children’s behalf. This was the case for bedroom 2 and 3 in case house 1 and both bedrooms in case house 2. In bedrooms where two adults were sleeping, both answered the questionnaire. Thereby, a total of 9 out of 12 questionnaires were sent out and collected after the measurements were conducted. The most important results of the questionnaire are presented in Table 7.

Table 7: Results of the questionnaire.

Case house	Bed-room	Motivation for opening window at night			Reasons for why the window is not opened at night			
		Fresh air	Lowering the bedroom temp.	Habit	Outdoor temp.	Outside noise	Will get too cold in the bedroom	Forgetful-ness
1	1	x	x		x			
	2	x	x					x
	3	x	x	x				x
2	1	x	x		x		x	
	2	x					x	
3	1	x	x					
4	-	x					x	
5	-	x				x		

All the participants in the questionnaire answered fresh air as being a motivation for opening the bedroom window at night. In addition, three out of six houses answered that a lower bedroom temperature was also a part of the motivation.

On reasons for why the window might be closed during the nighttime, one participant reported noise from outside, two reported outdoor temperature, three reported that it would get too cold in the room and two of the participants reported forgetfulness as ordinary causes.

All the participants answered that high IAQ (fresh air) in the bedroom was in a large or very large extent important to them. Only one participant wished to install ventilation in the bedroom, whereas the rest answered that they preferred fresh air supply through the window in the bedroom.

On the question about IAQ during the measurement period, one parent answered that she had noticed what she described as “bad air” in the morning after the window was closed one night. The occupant, however, did not notice anything. This occurred in the second bedroom of case house 2.

6.2 Window opening behavior

To give an indication of how the window opening behavior varied between the bedrooms, the window opening duration for the whole measurement period is illustrated in Figure 36. For the rooms where the percentage is above 40 %, the window opening data showed that the window was open at least every night.

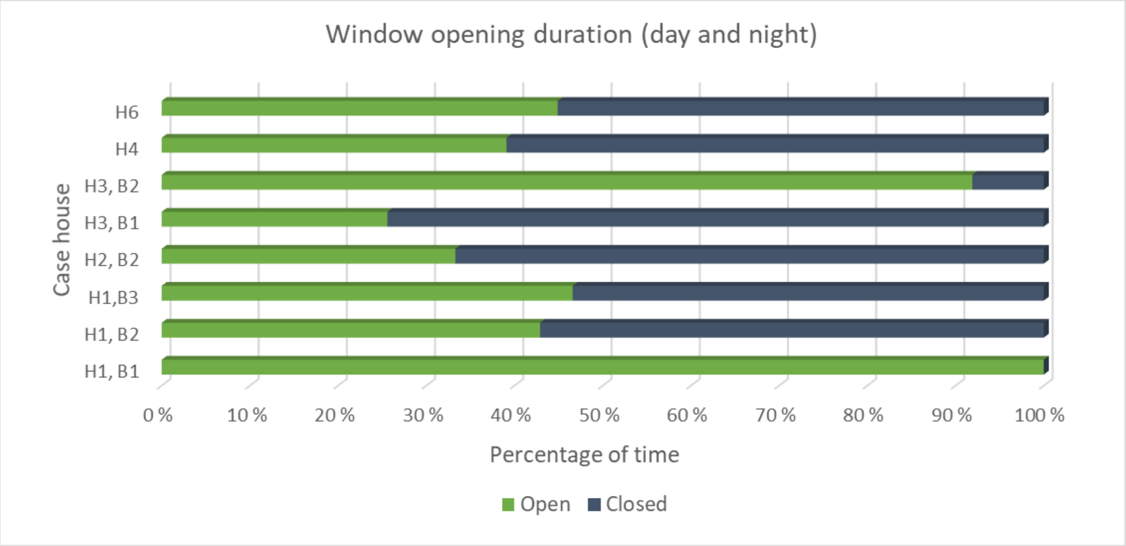


Figure 36: Window opening duration during the whole period for each bedroom. Bedroom 2 in case house 2 and case house 5 not included.

The figure illustrates how bedroom 1 in case house 1 and bedroom 2 in case house 3 has a more extensive window opening behavior, compared to the other bedrooms. The window in these rooms were normally open both days and nights.

An overview of the nightly average of the window opening area and the standard deviation (SD) is given in Table 8, together with the type of window and the area.

Table 8: Nightly average of window opening area, together with window characteristics.

Case house	Bedroom	Type of window	Av. window opening area [m^2] (SD)	Window area [m^2] (H x W)
1	1	Top-hinged	0.15 (0.00)	0.4 (0.34 x 1.25)
	2	Top-hinged	0.13 (0.01)	1.1 (1.06 x 1)
	3	Top-hinged	0.10 (0.01)	1.1 (1.06 x 1)
2	1	Top-hinged	0.09 (0.01)	1.0 (1 x 0.95)
	2	Top-hinged	0.08 (0.01)	1.0 (1 x 0.95)
3	1	Side-hinged	0.15 (0.06)	0.7 (1.43 x 0.47)
	2	Middle-hinged (Skylight)	0.01 (0.00)	0.3 (0.6 x 0.45)
4	-	Side-hinged	0.11 (0.06)	0.5 (1.1 x 0.45)
5	-	Side-hinged	-	0.3 (1.18 x 0.28)
6	-	Top-hinged	0.06 (0.01)	0.4 (0.45 x 0.77)

The largest average window opening area were found in bedroom 1 of case house 1 and in bedroom 1 of case house 3. The smallest average was found in bedroom 2 of case house 3 and was significantly smaller compared to the other bedrooms. A low standard deviation of the window opening area indicate that the window is opened to the same position each night. It should also be noticed how the windows in bedroom 2 and 3 in case house 1 and both bedrooms of case house 2 have almost twice the area as some of the other rooms.

Large differences were also found in the average window opening areas of the bedrooms as they ranged from 0.01 to 0.15 m^2. However, as discussed in section 5.2.8, this does not necessarily reflect the total opening area of the window. The average opening areas of bedroom 1 and 2 in case house 1 are close to equal, but the height of the window in bedroom 1 is around 30 % of the height of the window in bedroom 2. A picture of these two windows are displayed in Figure 37.

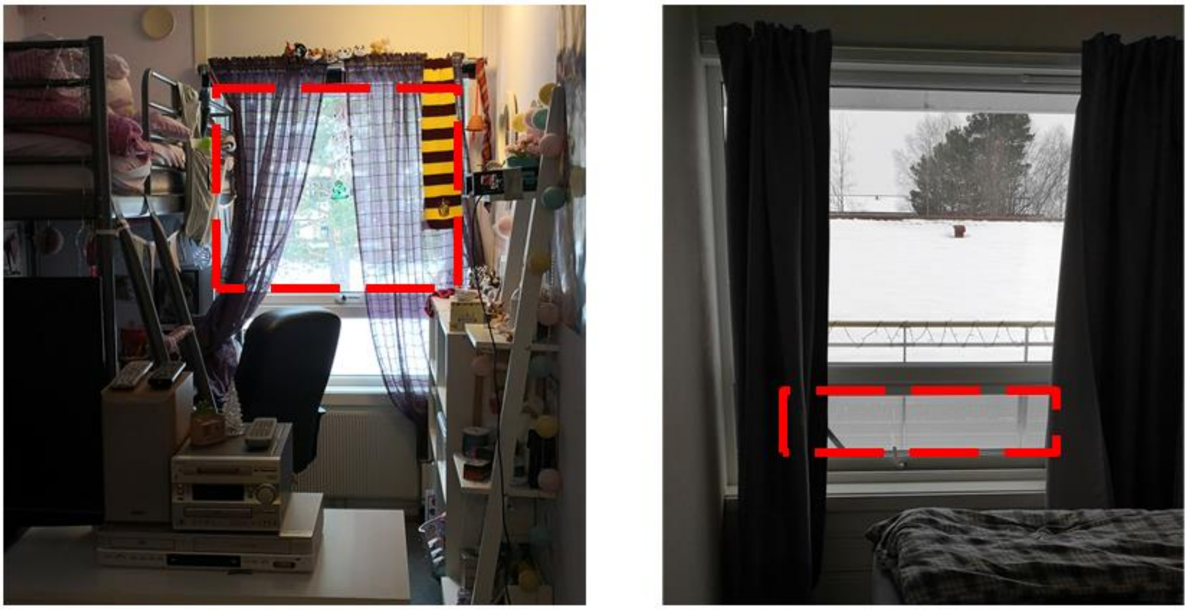


Figure 37: Bedroom 2 (left) and bedroom 1 (right) in case house 1. The red dotted line indicates the size of the window that is opened during the night.

As the pictures illustrate, the window in bedroom 1 is much smaller compared to bedroom 2 and therefore also has a smaller total window opening area.

6.3 CO_2 levels

6.3.1 Average concentrations

The average nighttime characteristics of the CO_2 concentration are displayed in Table 9.

Table 9: Nightly average characteristics of CO_2 in the bedrooms.

Case house	Bedroom	Av. CO_2 [ppm] (SD)	Min. av. CO_2 [ppm]	Max. av. CO_2 [ppm]	Av. window opening area [m^2] (SD)	Window area [m^2]
1	1	1097 (232)	901	1303	0.15 (0.00)	0.4
	2	532 (89)	439	657	0.13 (0.01)	1.1
	3	733 (130)	470	1118	0.10 (0.01)	1.1
2	1	516 (58)	431	671	0.09 (0.01)	1.0
	2	657 (110)	480	1848	0.08 (0.01)	1.0
3	1	719 (176)	513	1715	0.15 (0.06)	0.7
	2	1409 (255)	657	2272	0.01 (0.00)	0.3
4	-	593 (57)	447	800	0.11 (0.06)	0.5
5	-	658 (35)	547	749	-	0.3
6	-	705 (88)	565	905	0.06 (0.01)	0.4

The average CO_2 concentration exceeded 1000 ppm in bedroom 1 of case house 1 and in bedroom 2 of case house 3. The latter one was also where the highest nightly average was measured of approximately 1850 ppm, which was almost 350 ppm higher than the second highest average. The standard deviation of these two rooms were both above 200 ppm, which can indicate a higher variation in the CO_2 level during nighttime.

When the minimum nightly averages are compared, the highest one was also found in bedroom 1 of case house 1 and was approximately 250 ppm higher than the second highest. This suggests that the nightly CO_2 concentrations of this room were evenly high. High maximum nightly averages of concentrations around 2000 ppm are found in both bedrooms in case house 3 and the second bedroom in case house 2.

The average CO_2 concentrations were well below 1000 ppm in the majority of the bedrooms. An unambiguous correlation between window opening area and CO_2 correlation, or window area and CO_2 concentration, is not indicated in these measurements.

6.3.2 Time duration of high CO_2 levels

To give a better understanding of how the CO_2 levels vary through the period, the time duration of the CO_2 measurements have been sorted into the four IEQ categories presented in section 2.3.1. From the number of measurements per hour, the time duration of each IEQ category has been calculated for both the nighttime measurement and the whole measurement period. This is shown in, respectively, Figure 38 and Figure 39. An outdoor concentration of 400 ppm has been used for all the case houses. Days and nights where the occupant reported to be away has not been included.

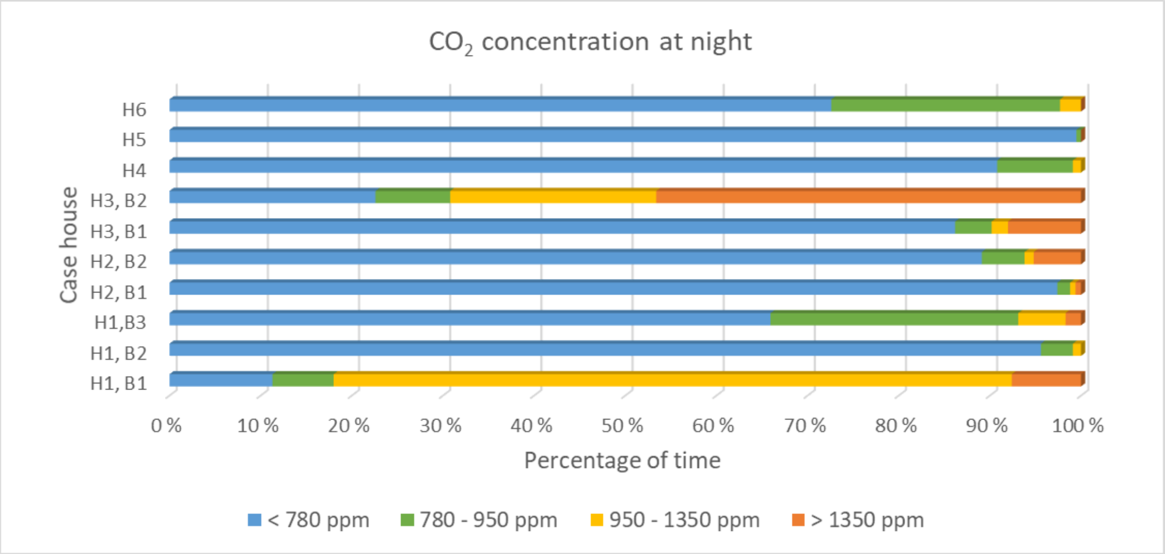


Figure 38: Time duration of CO$_2$ concentration at night distributed in the four IEQ categories.

In bedroom 1 in case house 1 and in bedroom 2 in case house 3, the CO$_2$ concentration exceeded 950 ppm, respectively, 80 and 70 % of the time during the nights. The duration where the level was above 1350 ppm was, however, much higher for bedroom 2 in case house 3 and close to 50 %. This confirms what was indicated by the average measurements; the CO$_2$ concentration is generally higher in bedroom 1 of case house 1 and in bedroom 2 of case house 3.

In the other bedrooms the concentration exceeded 950 ppm for smaller durations of the time and the percentage was around 10 or lower.

The same categorization of the CO$_2$ measurements for the whole measurement period is shown in Figure 39.

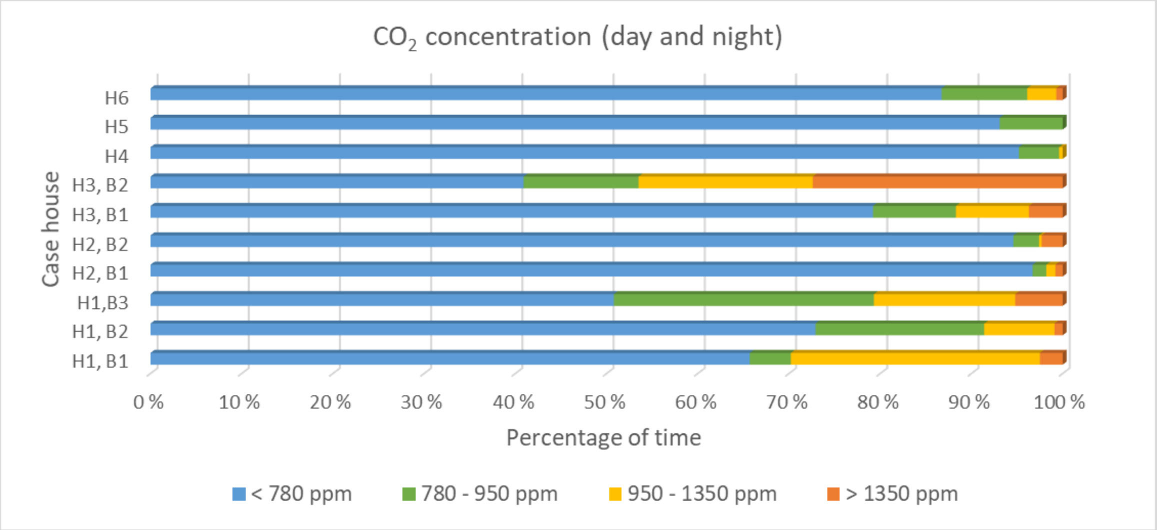


Figure 39: Time duration of the CO$_2$ concentration for the whole measurement period distributed in the four IEQ categories.

When comparing the nighttime measurements with the levels for the whole period, it can be seen how the time duration of levels above 950 ppm is significantly lower for bedroom

1 in case house 1. Implying that the concentrations are low during daytime in this room. In bedroom 2 of case house 3 the percentage only decreased 20 percentage points.

It can also be seen how the CO_2 concentration were higher for some bedrooms when the whole period is evaluated. The CO_2 level exceeded 950 ppm a bit over 20 % of the time in bedroom 3 in case house 1, and a bit over 10 % in bedroom 1 of case house 3. The percentage is also higher for bedroom 2 in case house 1. This can indicate that the rooms were also occupied during the daytime. For the other bedrooms, the concentration exceeded 950 ppm less than 10 % of the time, as for when only nights were evaluated.

6.3.3 Estimations of air change rates

Air change rates were estimated by analyzing some presentable nights of the period when the window was open. The time from when the CO_2 concentration peaks, until the concentration reaches steady-state is used to estimate the air change rate by the build-up method, as described in section 5.7. The bedrooms that did not have data on the window opening behavior were not included in these calculations.

The CO_2 level in bedroom 1 of case house 3 varied a lot through the period and presentable nights were hard to find. The occupant was away for several nights and two people were also sleeping in the room on occasions. The window opening data of this sensor were also characterized by some noise. Estimated air change rates were for these reasons not calculated. The concentration of CO_2 in bedroom 3 of the same house increased during the nights when the occupant was present, and an air change rate is therefore not estimated.

In bedroom 1 of case house 1, the concentration only decayed slightly a few nights. In case house 6 when two people were sleeping in the room the concentration did not decrease during the nights, and only nights when one person was sleeping in the room have been included.

The estimated air change rates are displayed in Table 10. It should be noted that these calculations are based on large assumptions, and only gives an estimate of the air change rate of the bedrooms.

Table 10: Estimated air change rates.

Case house	Bedroom	Estimated air change rate interval [h^{-1}]
1	1	~ 0.01
	2	0.2 - 0.5
	3	0.2 - 0.3
2	1	-
	2	~ 0.5
3	1	-
	2	-
4	-	~ 0.3
5	-	-
6	-	0.03 - 0.05

Very low air change rates were found in bedroom 1 of case house 1 and in case house 6. In bedroom 2 of case house 3 the concentration increased during the nighttime. Higher air change rates were found in bedroom 2 and 3 in case house 1, in bedroom 2 in case house 2 and in case house 4.

6.4 Variation in CO_2 levels through the measurement period

In this section the variation in the CO_2 concentrations of some chosen bedrooms are presented, either for the whole measurement period or for an extract of it. Bedrooms where the concentration have been significantly high or low through the period have been prioritized. In addition to bedrooms where the window opening behavior has varied through the period.

6.4.1 High nighttime CO_2 concentrations

As was shown in section 6.3.2, bedroom 1 in case house 1 and bedroom 2 in case house 3 had significantly higher average CO_2 levels during the nights compared to the other bedrooms.

The variation in CO_2 concentration and window opening area in bedroom 1 of case house 1 for an extract of the measurement period is illustrated in Figure 40. The nightly variations were close to the same every night, and the figure is representable for the whole period.

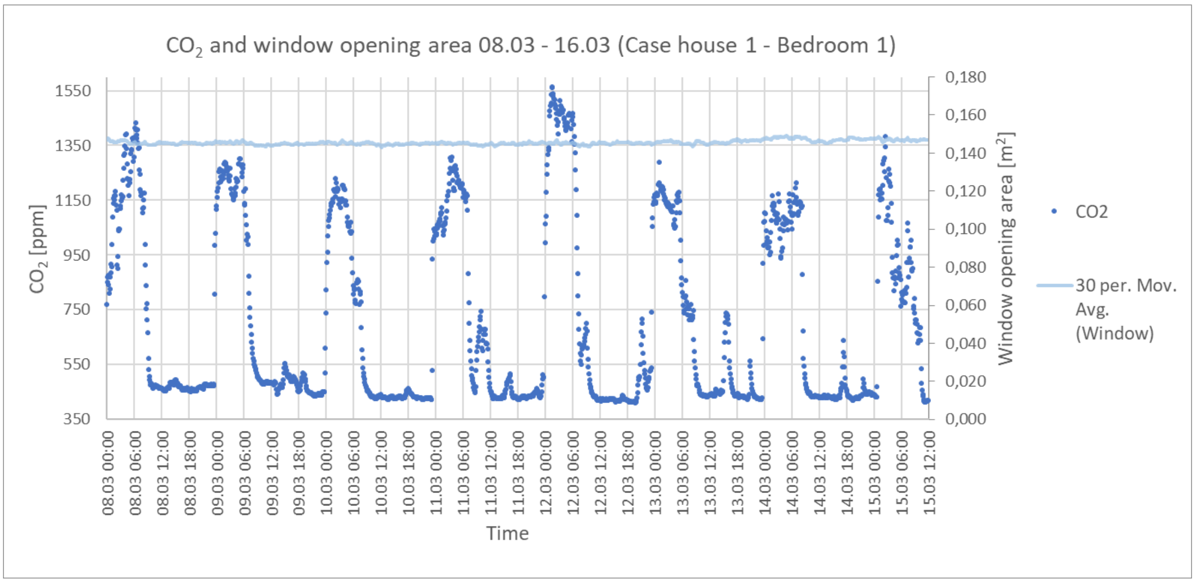


Figure 40: Variation in CO_2 concentration and window opening area of bedroom 1 in case house 1 (08.03 – 16.03).

The figure illustrates how the CO_2 concentration increases during the night, when the bedroom is occupied by the two adults. The average nightly concentrations varied between 901 and 1303 ppm, and the concentration is also close to constant through the night. The figure also illustrates how the concentration decreases rapidly in the morning and decreases to almost outdoor level during the day. Heavy curtains were in use during the nighttime of this bedroom, a picture of these are given in Figure 37.

The highest nightly average of CO_2 was found in bedroom 2 in case house 3. A comparison of the window opening area and the CO_2 level is shown in Figure 41. The occupant was away the night to 04.04, 05.04, 11.04 and 13.04, indicated by the orange circles in the figure.

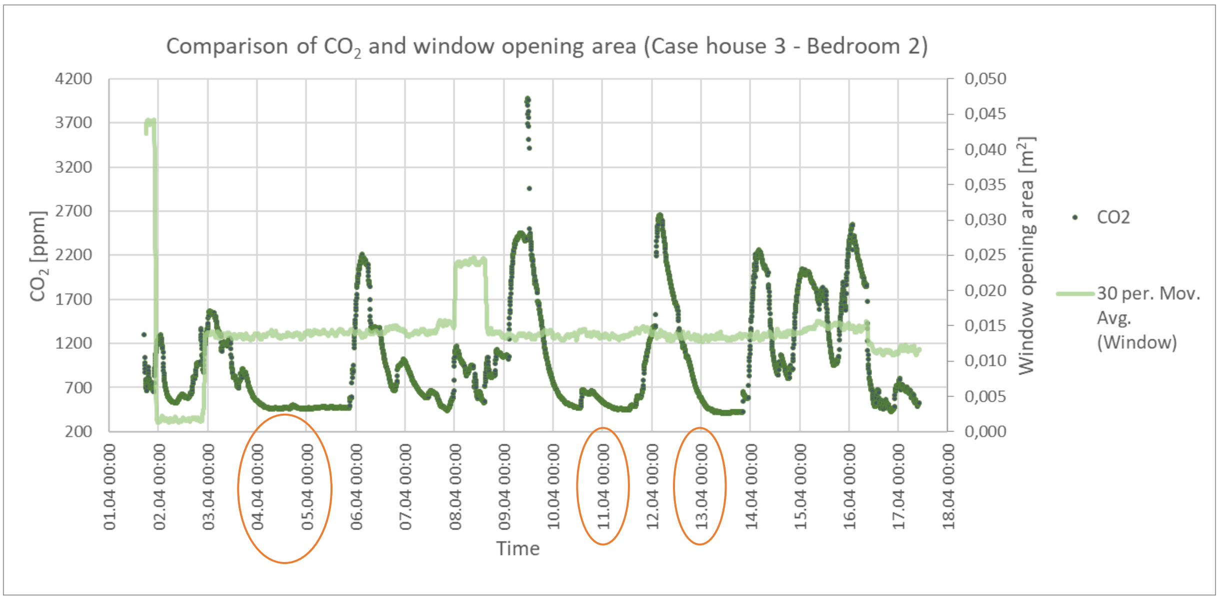


Figure 41: CO_2 levels and window opening area in bedroom 2 of case house 3.

The average nightly CO_2 concentration were less predictable compared to bedroom 1 in case house 1. The average concentrations varied between 657 and 2272 ppm.

When the occupant reported to be away the CO_2 concentration is considerably lower during the night. The same low concentration is also found other nights, such as night to 10.4. Therefore, it may be reasons to believe that the occupant was away more nights than what was reported. If this were the case, the average CO_2 concentration would have been higher than the calculated average of 1409 ppm. The figure also indicates a possible measuring error occurring on 09.04, as a high concentration was measured during a small amount of time.

During the night to 08.04, the window was open approximately 2 degrees more than normal, a resulting increase in the window opening area of around 0.01 m^2. The CO_2 concentration during this night was also considerably lower compared to other nights in the period. This can be seen in Figure 42.

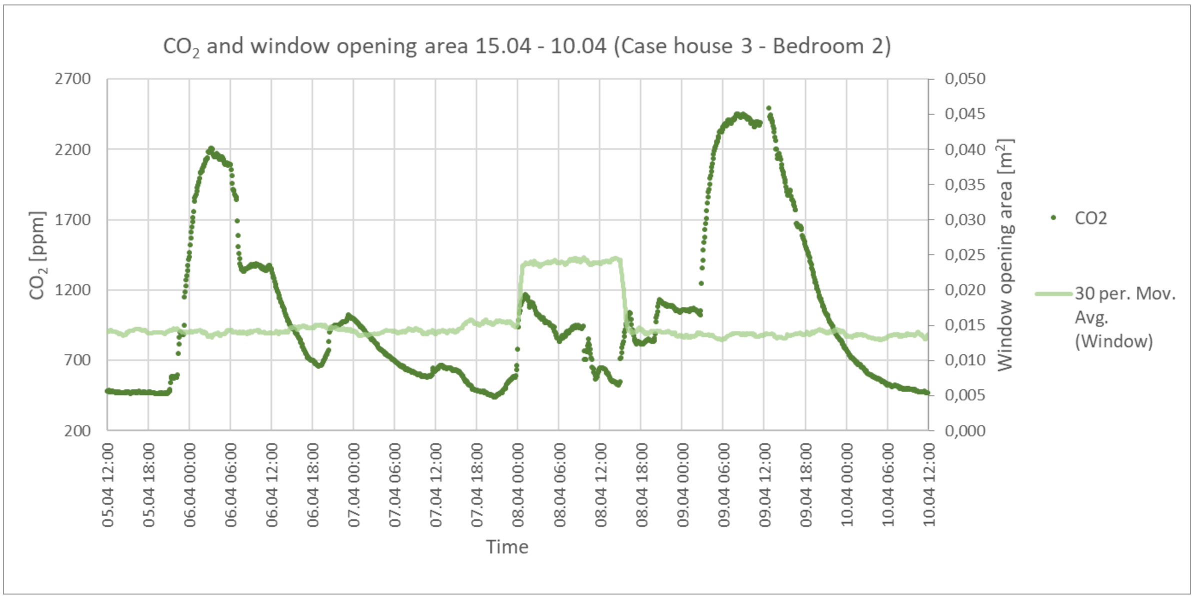


Figure 42: Impact of an increase in window opening area on CO₂ level in bedroom 2, case house 3.

The figure illustrates how there is an increase in the CO₂ level when the window is opened more, and how the concentration did not exceed 1200 ppm this night. The same low CO₂ level also occurred the night before, when the window was opened to the same degree as most of the nights in the period.

Figure 43 illustrates how the periods with a high CO₂ concentration are longer for this room, compared to the one in case house 1. This can indicate a higher occupancy of this room.

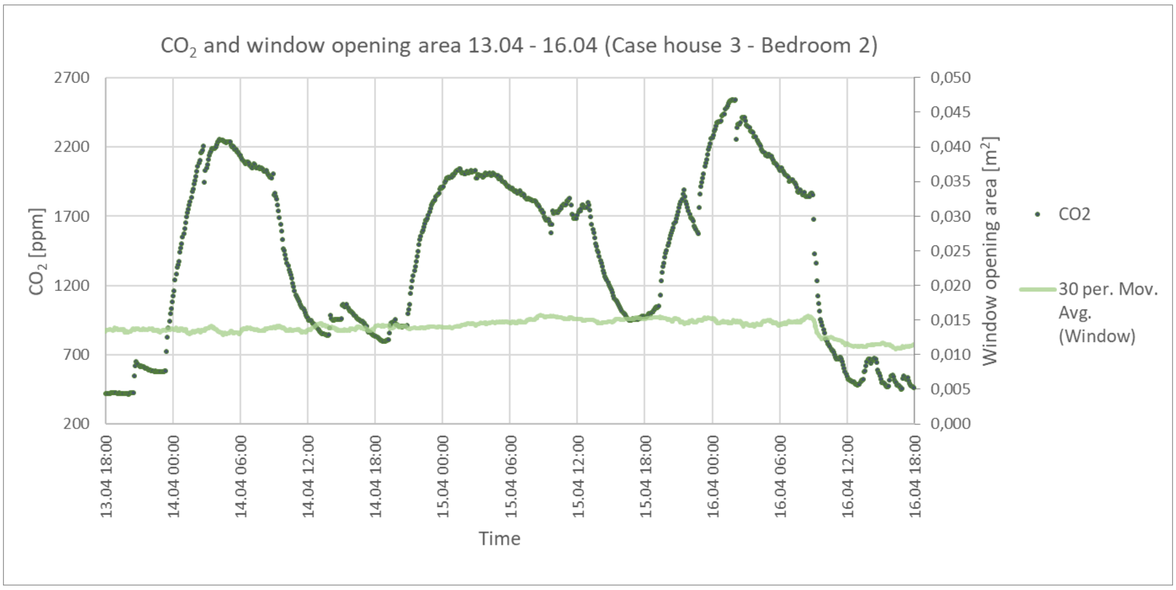


Figure 43: Variation in CO₂ concentration of bedroom 2 in case house 3 (13.04 – 16.04).

The figure also shows how the CO₂ increases during nighttime, as it also did in bedroom 1 of case house 1. However, the concentration in this room reaches a much higher peak. The window opening area was, however, significantly smaller for this room compared to the other bedrooms.

6.4.2 Higher daytime CO_2 concentrations

Low nightly average concentrations were found in bedroom 2 and 3 of case house 1, where two children were sleeping, and Figure 44 illustrates how the concentration decreases when the window is opened at night in bedroom 3.

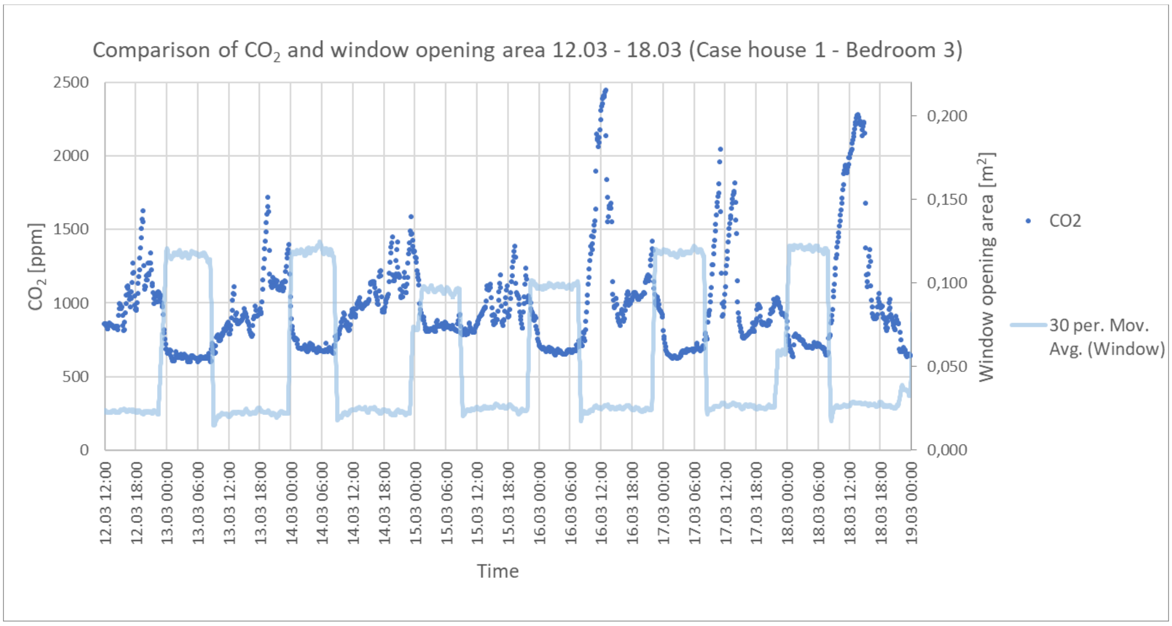


Figure 44: Variation in CO_2 concentration of bedroom 3 in case house 1 (12.03 – 19.03).

The figure illustrates how the concentration is occasionally very high during the day. It should also be noted how the concentration also decreases during the day, when the window is closed. Some days have higher peaks, which can imply that the room was more occupied in the daytime. The concentration during the presented period was a bit higher, compared to the rest of the period.

The same decrease in the concentration when the window was opened was also found in the bedroom 2 of this house. Although, the concentration in this room reached a lower minimum during the nights. This is illustrated in Figure 45, where the CO_2 level and window opening area of both bedrooms are shown.

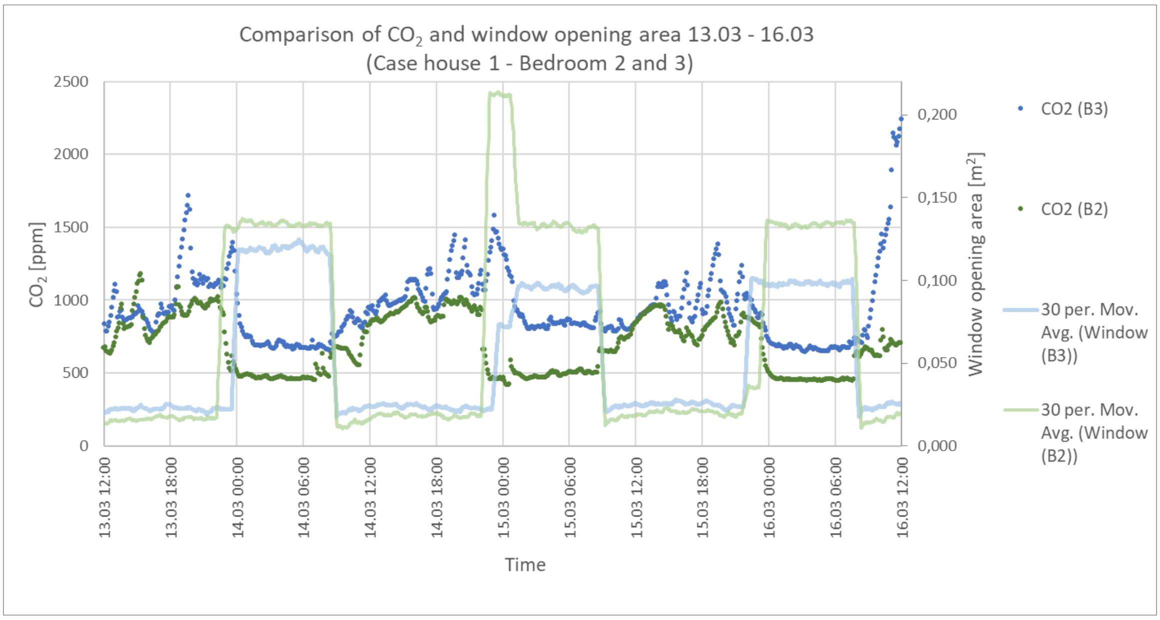


Figure 45: CO$_2$ concentration and window opening area of bedroom 2 (green lines) and bedroom 3 (blue lines) in case house 1 (13.03 – 16.03).

The figure indicates a slightly smaller window opening for bedroom 2, compared to bedroom 3, which also had higher CO$_2$ levels. The occupant in bedroom 2 was sleeping in a high bunk bed. The sensor was placed lower than this and can be an explanation for the lower average measurements in this room. The difference in window opening area is small and may also be explained by inaccuracies in the measurements by the window opening sensors.

6.4.3 Flow from adjacent rooms

Both bedrooms of case house 2 had in general low and similar levels of CO$_2$. The variation in CO$_2$ for a representative part of the measurement period for the second bedroom, together with the window opening area, is illustrated in Figure 46.

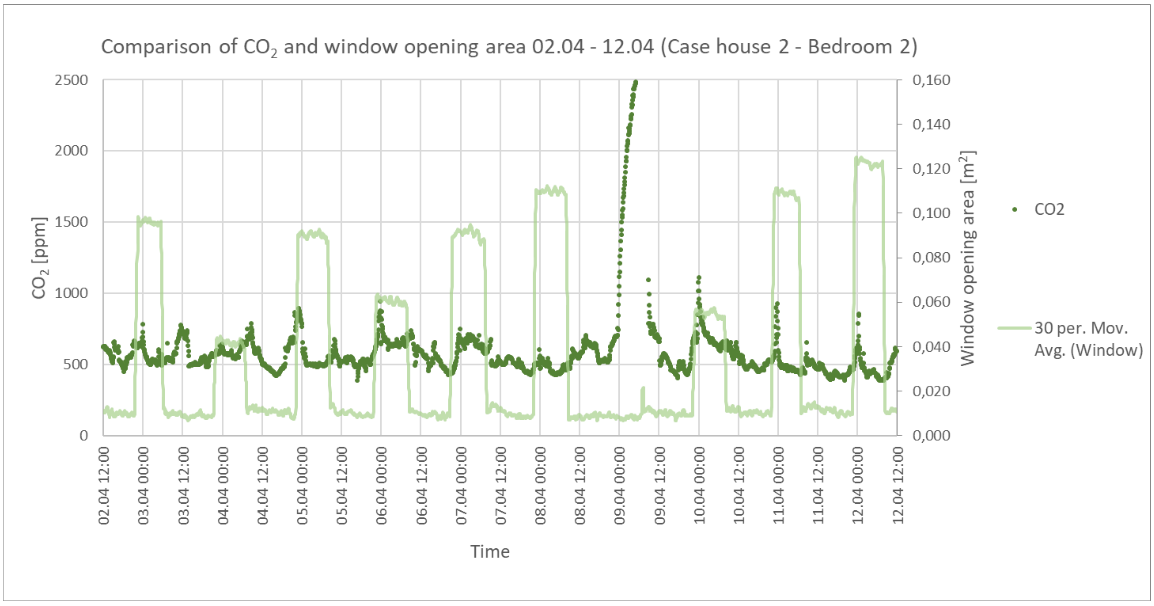


Figure 46: Variation in CO$_2$ concentration and window opening area for bedroom 2, case house 2 (02.04 – 12.04).

The nightly average concentration varied between 480 and 1848 ppm. The reason for the large variation is explained by night to 09.04, where the average concentration was almost twice as high compared to the other nights. This was also the only night where the window was closed during nighttime. The CO_2 concentration increases continuously from midnight to around nine in the morning, where it decreases rapidly from around 3000 ppm to around 1100 ppm in 10 minutes. This is illustrated more closely in Figure 47.

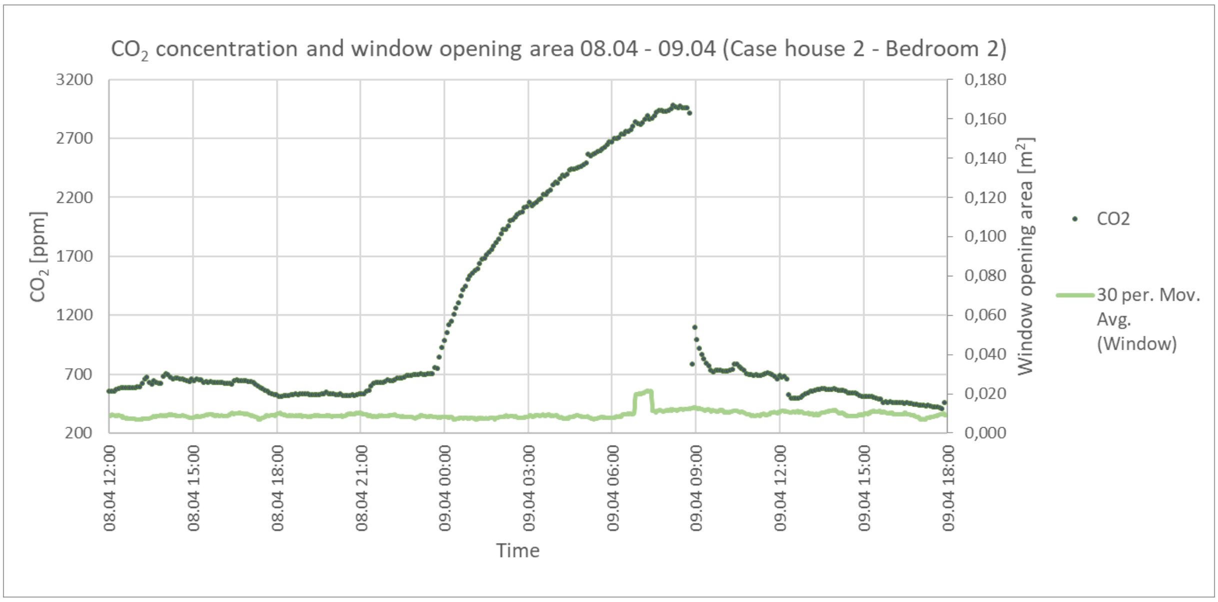


Figure 47: CO_2 concentration and window opening area in bedroom 2, case house 2 of 08.04-09.04.

As can be seen by the figure, the window is not opened during the decrease in concentration. The parent in this house reported stuffy air when she entered the room in the morning of this night. The occupant, however, did not report anything. This, together with the general low average CO_2 concentrations of both bedrooms in case house 2, may indicate how the CO_2 levels are affected by airflow from adjacent rooms. Case house 2 was the only room with installed balanced ventilation in the rest of the house, except these two bedrooms. However, the sudden decrease in concentration may also be due to some error in the measurement.

Impact of flows from adjacent rooms were also observed in case house 5, where the occupant was away two nights of the measurement period. The window, and assumedly the bedroom door, was closed during this period. The variation in CO_2 concentration of case house 5 is shown in Figure 48.

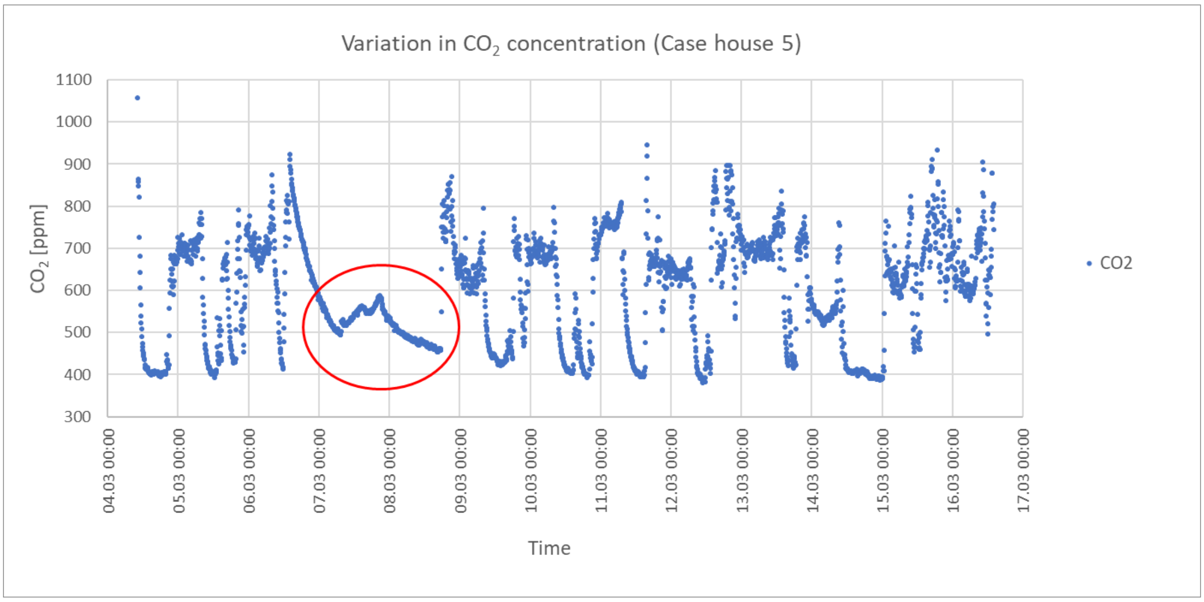


Figure 48: CO_2 levels of case house 5.

It can be observed how the concentration increased while the occupant was away (07.03-08.03), indicated by the red circle, and the window was closed. In this room there were installed air valves between the kitchen area and the bedroom, and flow through the air valve may explain the increase in the concentration during the non-occupied period. The concentration during these days also seems to be higher compared to the other days, when the window assumedly is open during daytime. However, as there were no available measurements for the window opening of this room, this is difficult to confirm and based on statements by the occupant during the set-up of the equipment.

6.4.4 Bedrooms with variating window opening behavior

In some of the case houses, the window was occasionally also open during the day. This was observed in case house 4 and in case house 6. The occupant of case house 4 reported that the window was closed due to too low temperature in the bedroom during the nights and, therefore, opened the window in the morning instead. No reasons were provided by the occupants in case house 6.

The variation in CO_2 concentration and window opening area of the bedroom in case house 4 is presented in Figure 49. Nights where the window was closed is indicated by the orange circle, and it can be seen how the CO2 concentration of these nights were somewhat higher, compared to the other nights.

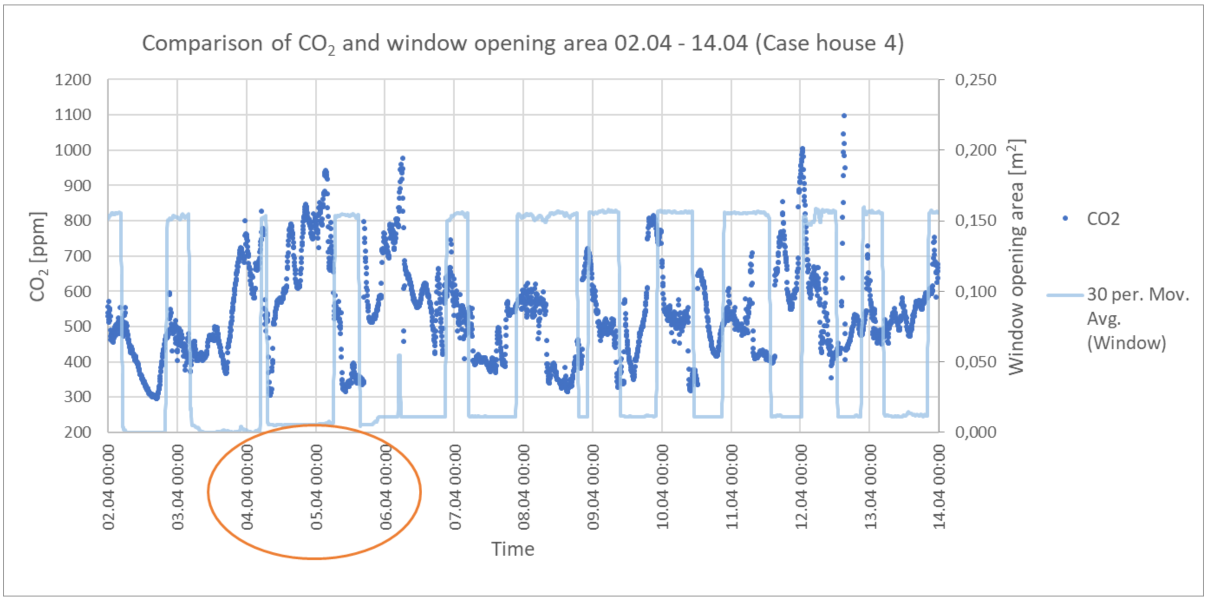


Figure 49: CO₂ levels and window opening area of case house 4, with side-hinged window.

The calculated average of these three nights where the window was closed was 753 ppm, compared to an average of 552 ppm for the other nights. The concentration also increased during these nights. It should be noted that the minimum concentration measured by this sensor was very low (300 ppm), which may indicate some faulty calibration as the usual outdoor level is normally around 400 ppm.

Case house 6 also had the window open during the daytime for some days during the measurement period. The variation in the CO₂ level and the window opening area for the whole period is shown in Figure 50.

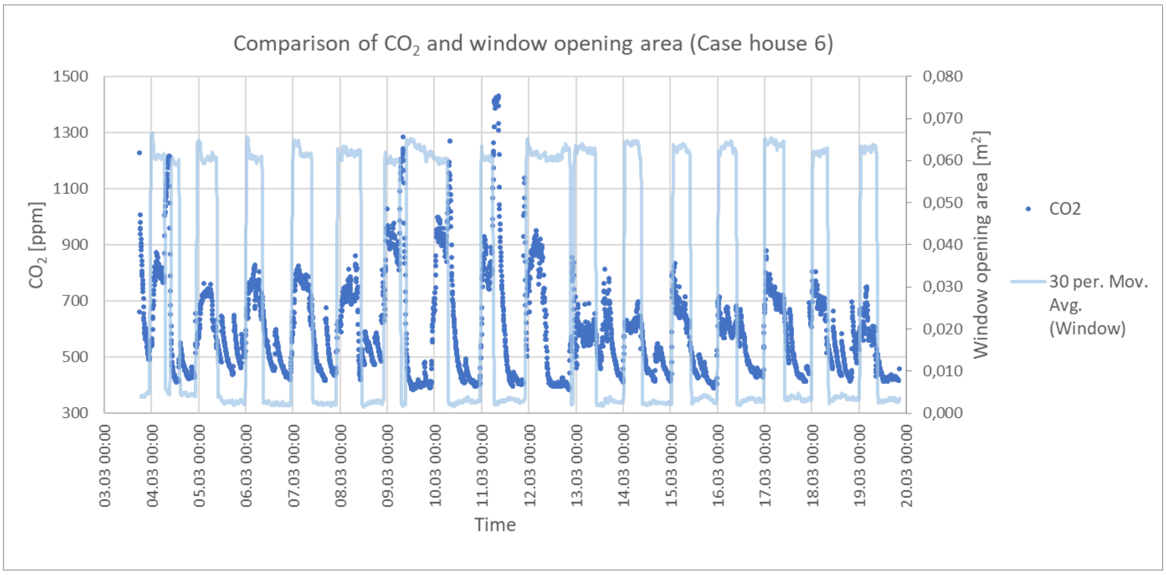


Figure 50: CO₂ levels and window opening area of case house 6. Two occupants sleeping in the bedroom until 12.03.

The figure illustrates how the window opening behavior is quite predictable through the period, and how the CO₂ level is higher for the nights between 09.03 – 12.03. The occupants of this house reported that only one person was sleeping in the room from 12.03 and did not inform that they were less than two people any of the other nights. However, as they did not answer the questionnaire this is not confirmed in writing.

Figure 51 illustrates closer how the window is opened more extensively after the first night of a higher average CO₂ concentration.

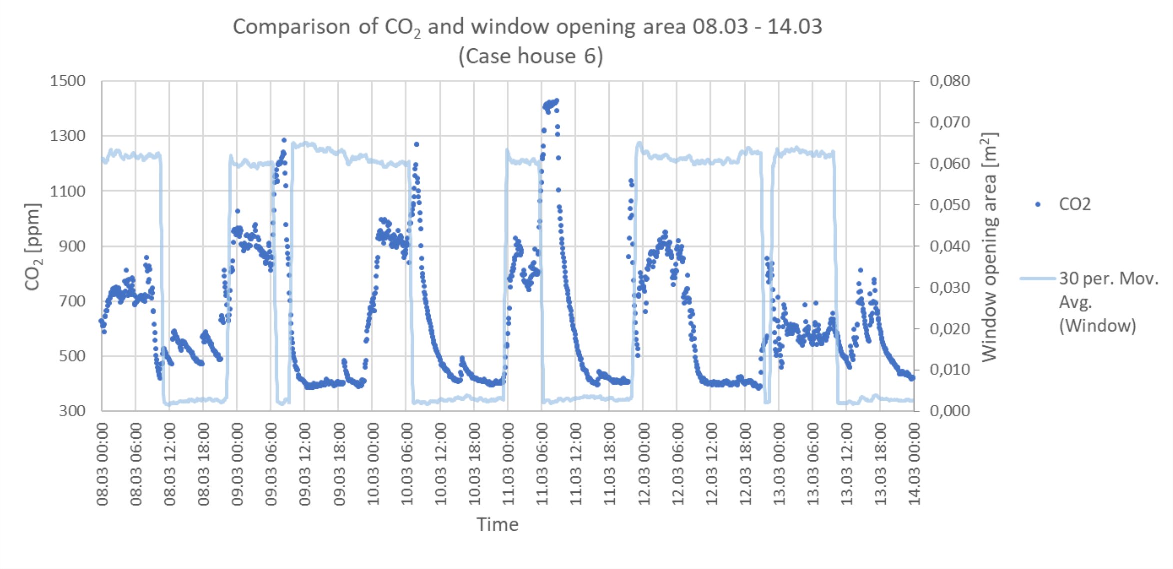


Figure 51: CO₂ levels and window opening area of case house 6 between 08.03 – 14.03.

Higher peaks during the day also seems to be occurring during this period. The more extensive window opening behavior can be related to a higher occupancy in the room, or directly related to the increase in CO₂ concentration.

6.5 Temperature and RH measurements

6.5.1 Nightly averages

As for the CO_2 concentration the nightly average temperature and RH characteristics have also been calculated for all the bedrooms and are displayed in Table 11 and Table 12.

Table 11: Nightly average characteristics of temperature and RH for all bedrooms.

Case house	Bedroom (IAQ sensor)	Av. temperature [°C] (SD)	Av. RH [%] (SD)	Av. window opening area [m^2]	IAQ sensor
1	1	22.3 (0.4)	27.0 (2.6)	0.15 (0.00)	6
	2	22.8 (0.6)	22.5 (1.0)	0.13 (0.01)	4
	3	23.3 (0.4)	24.9 (2.0)	0.10 (0.01)	3
2	1	17.5 (0.8)	34.3 (1.7)	0.09 (0.01)	2
	2	15.8 (1.4)	41.6 (1.9)	0.08 (0.01)	4
3	1	15.4 (0.6)	40.5 (2.4)	0.15 (0.06)	6
	2	17.5 (0.4)	48.8 (1.4)	0.01 (0.00)	8
4	-	14.6 (0.9)	43.3 (1.8)	0.11 (0.06)	3
5	-	21.9 (0.5)	23.9 (1.0)	-	2
6	-	16.3 0(0.5)	32.6 (1.0)	0.06 (0.01)	8

Table 12: Nightly min. and max. average characteristics of temperature and RH for all bedrooms.

Case house	Bedroom	Min. av. temperature [°C]	Max. av. temperature [°C]	Min. av. RH [%]	Max. av. RH [%]
1	1	20.9	23.2	21.9	31.1
	2	21.5	23.6	18.1	27.5
	3	22.1	24.2	19.9	28.7
2	1	15.5	20.0	29.7	39.2
	2	14.3	17.7	34.0	50.3
3	1	13.5	18.3	33.0	46.5
	2	14.9	21.1	40.1	56.6
4	-	10.8	17.9	35.7	46.7
5	-	20.3	23.5	16.8	32.0
6	-	14.3	18.8	28.8	38.0

In 6 out of 10 bedrooms the nightly average temperature was below 18°C. In the 4 others it was above 21°C. Higher average room temperatures are found in all the bedrooms of case house 1, in addition to case house 5. Lower average RH levels are also found in these bedrooms. In some of the bedrooms the average RH level was quite low and almost down to 20 %.

The highest maximum nightly RH level is found in bedroom 2 in case house 3 and is close to 60 %. Both bedroom 2 and 3 in case house 1 and the bedroom in case house 5 had minimum average RH levels below 20 %.

6.5.2 High temperature and low RH level

The variation of temperature and RH level of the main bedroom of case house 1 is illustrated in Figure 52, together with the outdoor temperature and precipitation through the period.

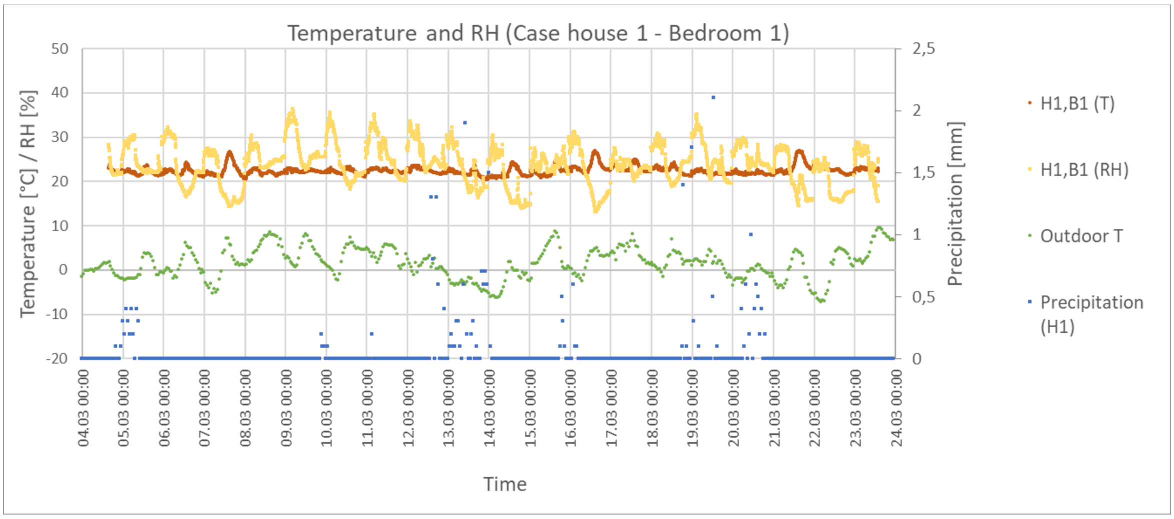


Figure 52: Temperature and RH level of bedroom 1 in case house 1, compared to outdoor temperature and precipitation.

The window in this bedroom was open both days and nights during the measurement period and no heating source was installed in the room. The differences in the temperature is, therefore, either caused by the occupants or related to indoor or outdoor airflows. However, the temperature seems to be quite steady during the period and some the peaks seem to be partly corresponding with peaks in outdoor temperature.

The figure also shows how the RH level falls below 20 % several times during the period, although minimum levels seems to be occurring during the daytime. This may indicate that the occupancy of the room increases the humidity level, or how outdoor airflow into the room is reduced during nighttime.

For the two other bedrooms of case house 1, where the windows are open only during the night, the RH level seem to be decreasing when the window is opened – especially when the outdoor temperature is below 0°C. This is illustrated for bedroom 2 in Figure 53.

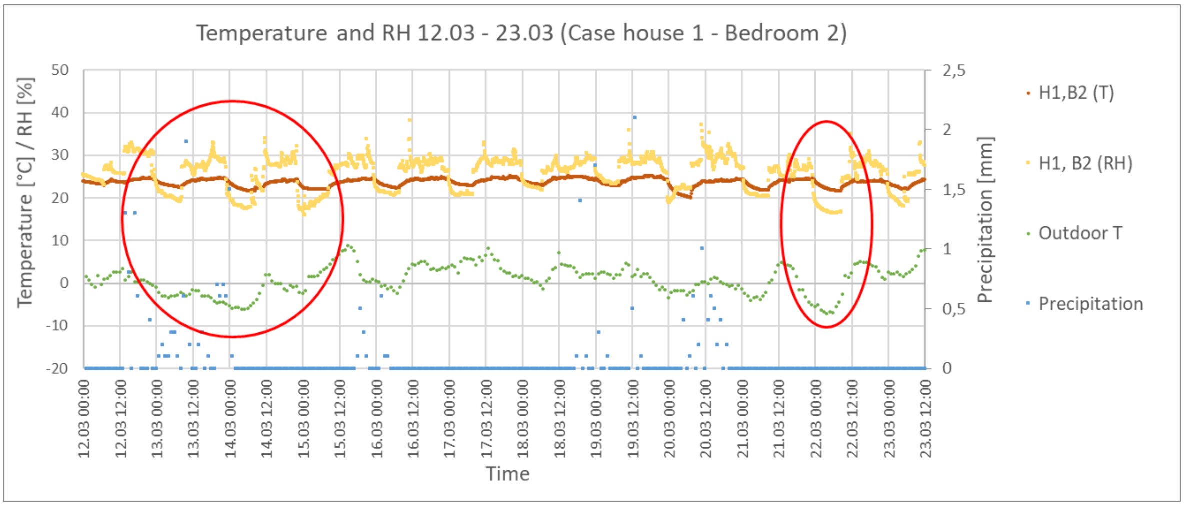


Figure 53: Temperature and RH level of bedroom 2 in case house 1, compared to outdoor temperature and precipitation.

The humidity level is below 20 % several nights in bedroom 2. The figure also shows how the temperature is decreasing slightly during the nighttime when the window is open. The temperature seems to be less affected by the outdoor temperature, than the RH level.

The temperature and RH variation in bedroom 2 and 3 of case house 1 were similar, although the RH level during nighttime decreased below 20 % more frequently in the second bedroom. Both these rooms had the heat source turned on during the nighttime, which may explain why the temperature does not fall below 20°C.

Low levels of RH were also found in case house 5. Figure 54 illustrates how the temperature and RH varies thorough the whole measurement period.

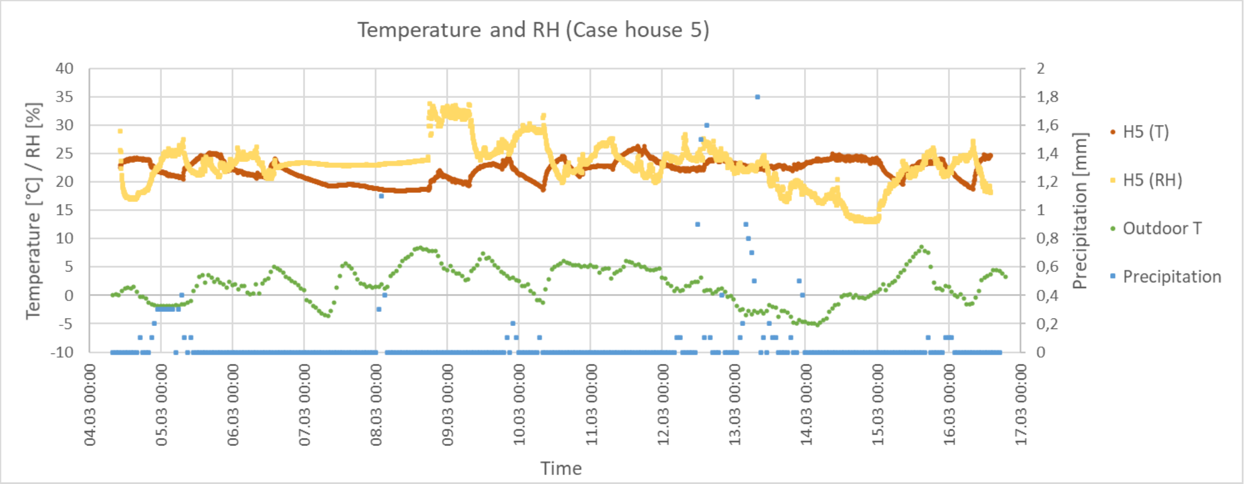


Figure 54: Temperature and RH levels for case house 5, compared to outdoor temperature and precipitation.

The RH level reaches below 20 % a few times during the measurement period and is also below 20 % over a longer time between 13.03 and 15.03. However, both the temperature and the RH level of this room is less periodic – compared to those in case house 1. The RH level seem to follow the variation in outdoor temperature. The period of non-occupancy can also be observed by the steady temperature and RH measurements between 07.03 and 08.03.

6.5.3 Low temperature during nighttime

The lowest nightly average temperature was found in case house 4, and the variation in temperature and RH level through the period is illustrated in Figure 55.

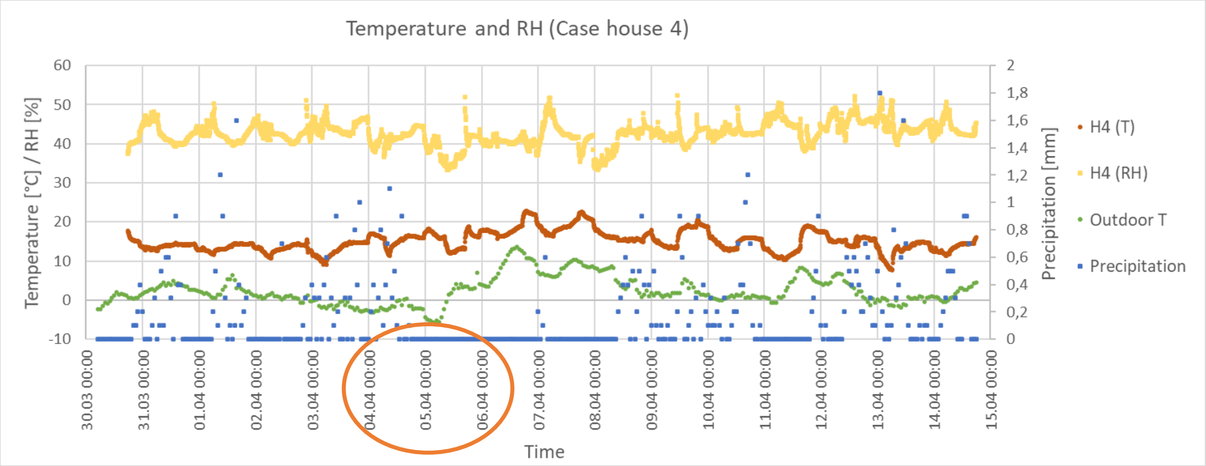


Figure 55: Temperature and RH levels for case house 4, compared to outdoor temperature and precipitation.

The occupant in this house was also the only one who reported that the window was closed due to too cold temperature in the bedroom during the night. These nights are indicated by the orange circle. The average temperature during nighttime of the first five nights was 12.4°C and the average when the window was closed was 17°C. The nightly average of this room showed high fluctuations and varied between 17.9°C and 10.8°C, both maximum and minimum average occurred when the window was open during nighttime.

Low bedroom temperatures were also found in the two bedrooms of case house 2. The variation in temperature and RH level of the two bedrooms are illustrated in Figure 56. Both bedrooms were located on the ground floor and were similar in design and size. The heating system of both rooms were also turned off during the night and the bedroom door was normally kept close.

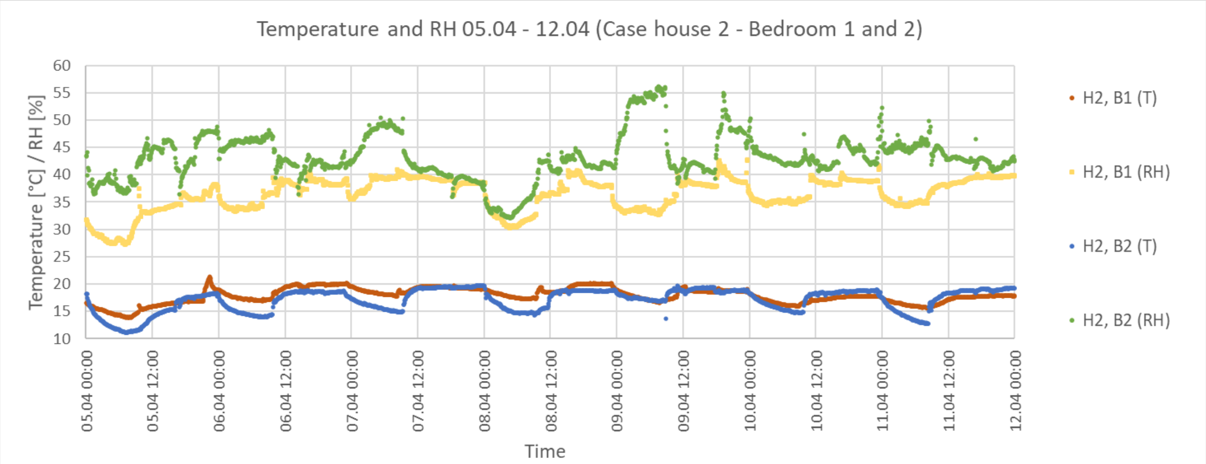


Figure 56: Variation in RH and temperature of bedroom 1 and 2 (case house 2), 5.4-12.4.

The figure illustrates how bedroom 2 seems to be more affected by the window opening during nighttime, compared to bedroom 1. This is confirmed by the temperature curve on the night to 09.04, where there is no significant decrease in the temperature.

The average window opening area of these two rooms were also approximately the same during the period. The higher temperature fluctuation of bedroom 2 may be due to the placement of the IAQ sensor or the sensor itself.

6.5.4 High levels of RH

The highest average level of RH was found in bedroom 2 in case house 3, where the nightly average varied between 40 and 57 %. The variation of temperature and RH, together with outdoor temperature and precipitation, is illustrated in Figure 57.

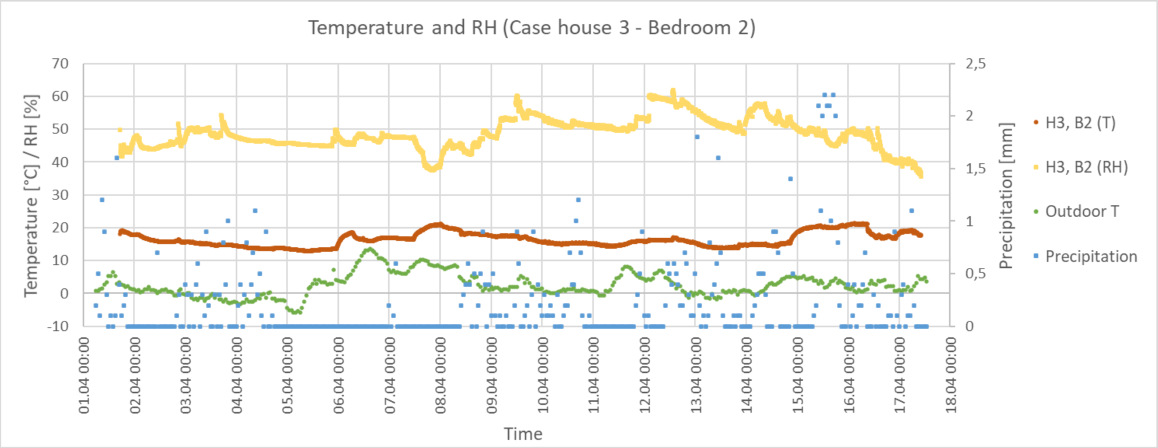


Figure 57: Temperature and RH level for bedroom 2 in case house 3, compared to outdoor temperature and precipitation.

It should be noted that the nights of non-occupancy had an average temperature of 14.3°C, which was approximately 3°C lower compared to the other nights. This indicates that the occupant behavior has some effect on the temperature level of the room as the window opening was close to constant during the measurement period. The outdoor temperature and precipitation seem to have low impact on the temperature and RH level of the bedroom. To see how the occupant behavior may affect the temperature and RH level, CO_2 is plotted together with both these parameters in Figure 58.

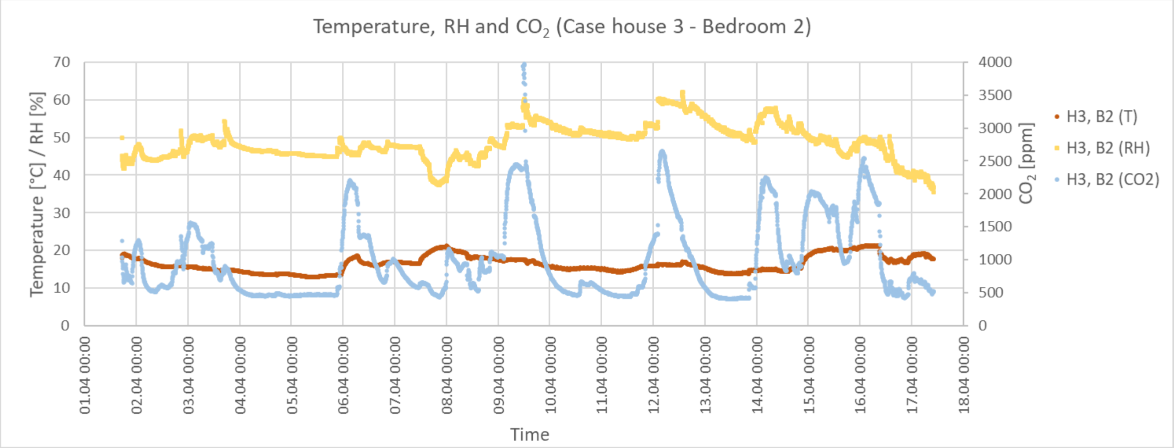


Figure 58: Comparison of temperature, RH and CO_2 measurements of bedroom 2 in case house 3.

The figure illustrates how the peaks in the RH level seem to be somewhat coinciding with peaks in the CO_2 concentration. The same correlation does not seem to be present for the temperature.

6.6 PM

As was shown in section 5.1.5, the Arduino sensor showed a large correlation between the different PM measurements. Therefore, only PM is evaluated in this section. The numbers used are the measured values of PM2.5.

The correlation coefficients between PM and CO_2 are displayed in the appendix. A weak correlation was found in bedroom 1 of case house 3, with a correlation coefficient of 0.2. Otherwise the correlations coefficients were close to zero.

6.6.1 Nightly averages

The nightly average characteristics of PM are presented in Table 13.

Table 13: Nightly average characteristics of PM.

Case house	Bedroom	Av. PM [µg/m^3] (SD)	Min av. PM [µg/m^3]	Max. av. PM [µg/m^3]	Av. window opening area [m^2]	IAQ sensor
1	1	1.04 (0.43)	0.18	2.75	0.15 (0.00)	6
	2	1.01 (0.44)	0.30	3.33	0.13 (0.01)	4
	3	0.96 (0.44)	0.19	3.52	0.10 (0.01)	3
2	1	2.12 (0.94)	0.47	5.79	0.09 (0.01)	2
	2	2.73 (1.31)	1.15	6.91	0.08 (0.01)	4
3	1	3.49 (2.03)	1.18	7.51	0.15 (0.06)	6
	2	4.28 (1.66)	0.83	10.82	0.01 (0.00)	8
4	-	14.14 (14.34)	1.37	168.98	0.11 (0.06)	3
5	-	1.05 (0.48)	0.15	2.38	-	2
6	-	1.17 (0.79)	0.60	2.62	0.06 (0.01)	8

In general, the average PM measurements are quite low compared to the guideline limits provided by WHO, which is 10 µg/m^3 for long-term concentrations of PM2.5. The average measurement of case house 4 is considerably higher, compared to the other houses and the guideline value. This is explained by one night with very high concentrations, with an average of 169 µg/m^3 and a peak concentration of 500 µg/m^3. If this night is disregarded, the average PM measurement of case house 4 would have been 3.1 µg/m^3 and the maximum average night concentration would have been 8.8 µg/m^3.

The bedrooms who showed higher average concentrations of PM, such as case house 4 and case house 3 are further discussed in this section.

6.6.2 High peaks in PM concentration

The variation in the PM concentration throughout the measuring period in case house 4 is presented in Figure 59.

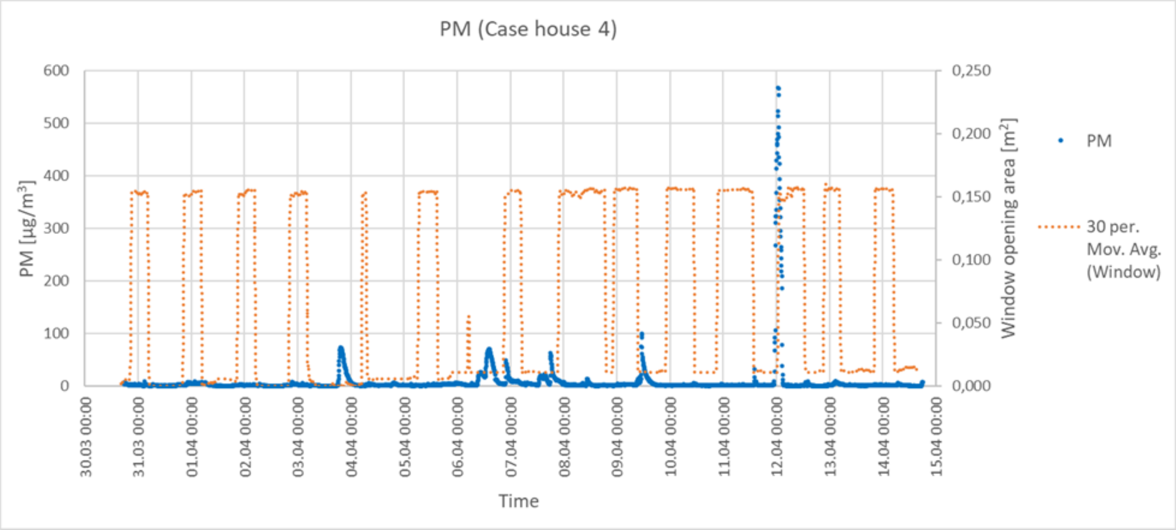


Figure 59: Concentration of PM of case house 4, together with window opening area.

The figure illustrates how the high peak measurement stands out, compared to the rest of the period. The peak occurred at around 23:00 of 11.04, where the PM level increased from a normal level of 2.63 µg/m^3 to a peak concentration of 566.7 µg/m^3 at 00:53 and then again decreased and reached normal levels around 03:00. This peak was several hundred times larger than the normal level and can be explained by the occupant being too close to the sensor. The CO_2 level and the PM concentration are compared in Figure 60.

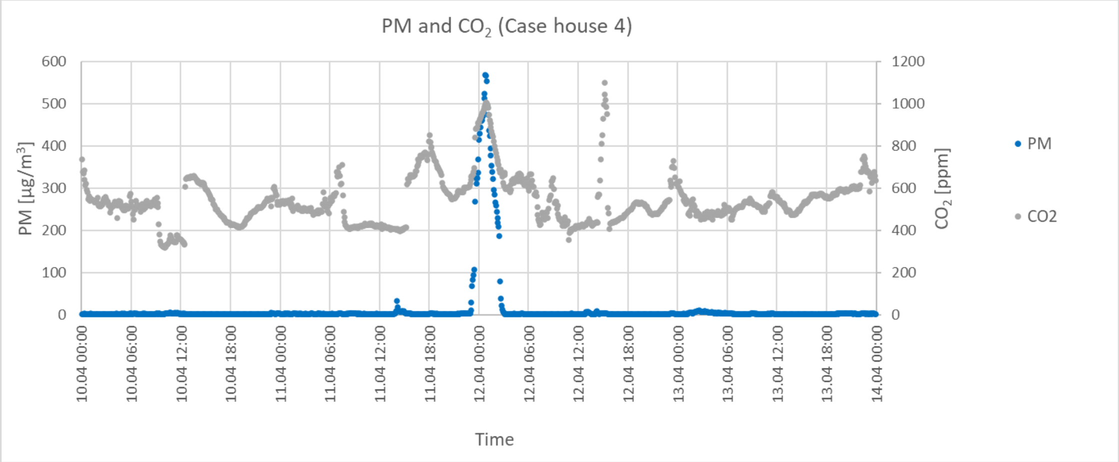


Figure 60: Comparison of PM and CO_2 concentration of 12.04.

The figure shows how the peak PM concentration seems to be coinciding with an increase in the CO_2 concentration. This shows that the occupant was present in the room during the peak measurement but may not necessarily indicate an error as the peak concentration of CO_2 only reaches 1000 ppm. If the axis is adjusted, as in Figure 61, other occasional high measurements are uncovered.

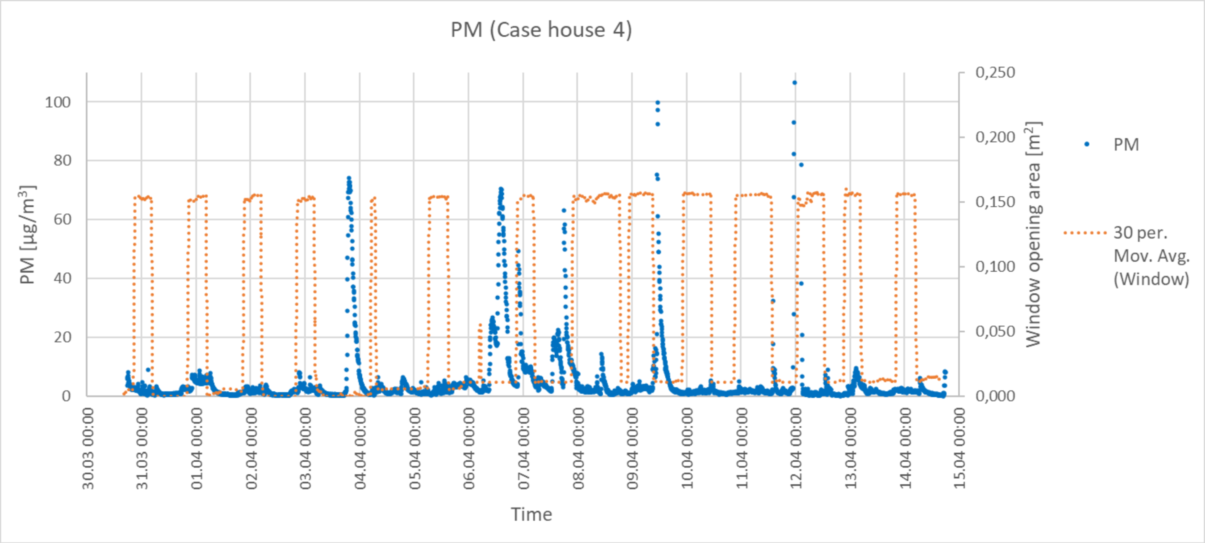


Figure 61: PM level in case house 4, with adjusted y-axis.

As the figure illustrates the window is closed at the time when the PM peaks occurs, and it is reasonable to believe that the peak is caused by the occupant behavior. A comparison of the variation in the CO_2 and PM levels is shown in Figure 62.

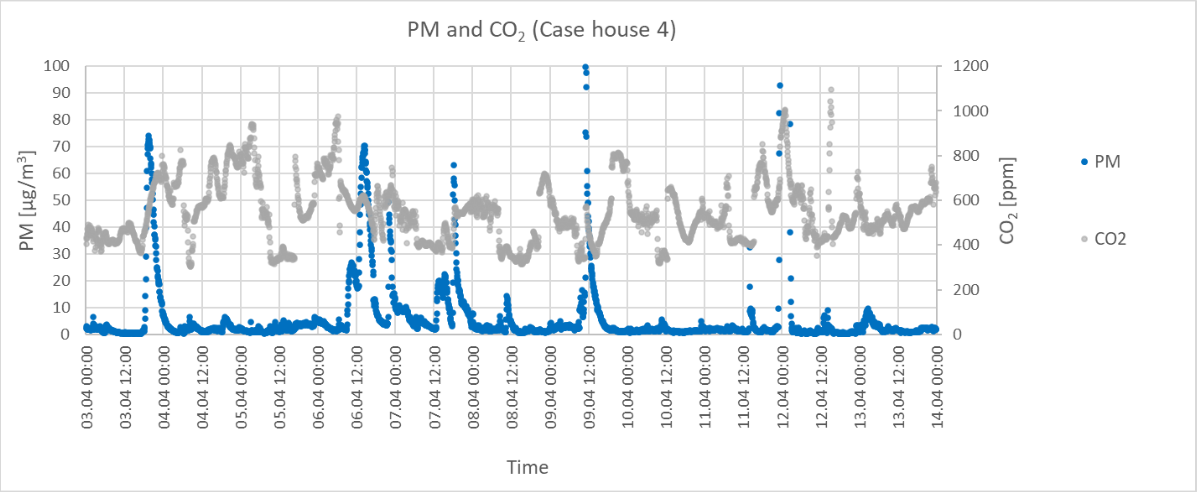


Figure 62: Comparison of PM measurements and variation in CO_2 level for case house 4.

From the figure it can be seen how the peaks of PM are somewhat coinciding with increasing CO_2 levels. However, the low correlation between CO_2 and PM is also observed in the figure.

Higher peaks were also found in both bedrooms of case house 2. The variation of PM in bedroom 2, compared to window opening area, for the whole period is shown in Figure 63.

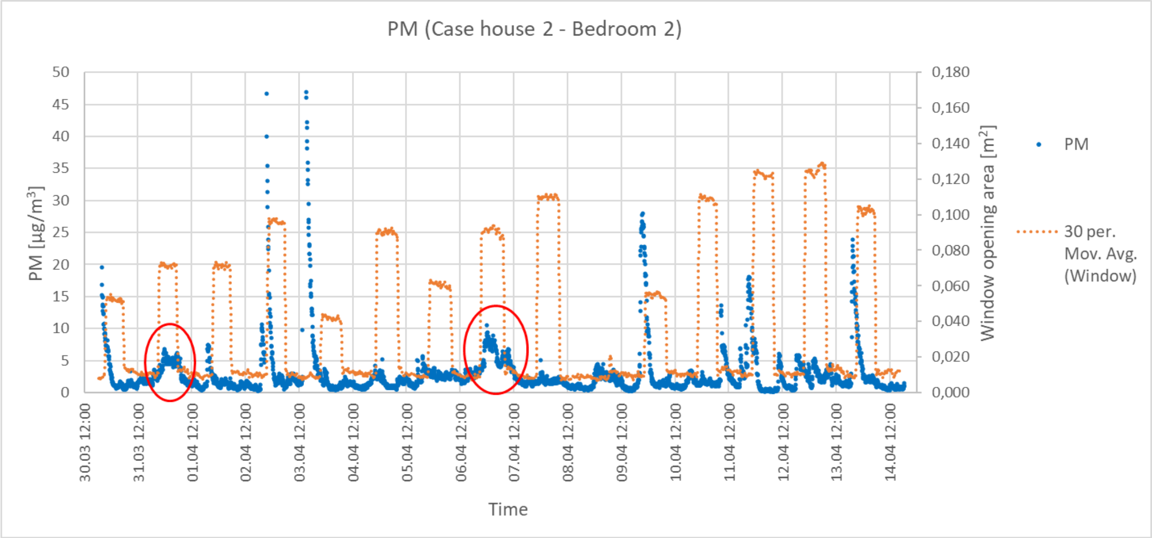


Figure 63: Variation of PM and window opening area of bedroom 2 in case house 2.

The figure illustrates how the concentration of PM is sometimes higher during nighttime, indicated by the red circles. Some of the peaks are also occurring straight before the window is opened. This is illustrated in Figure 64.

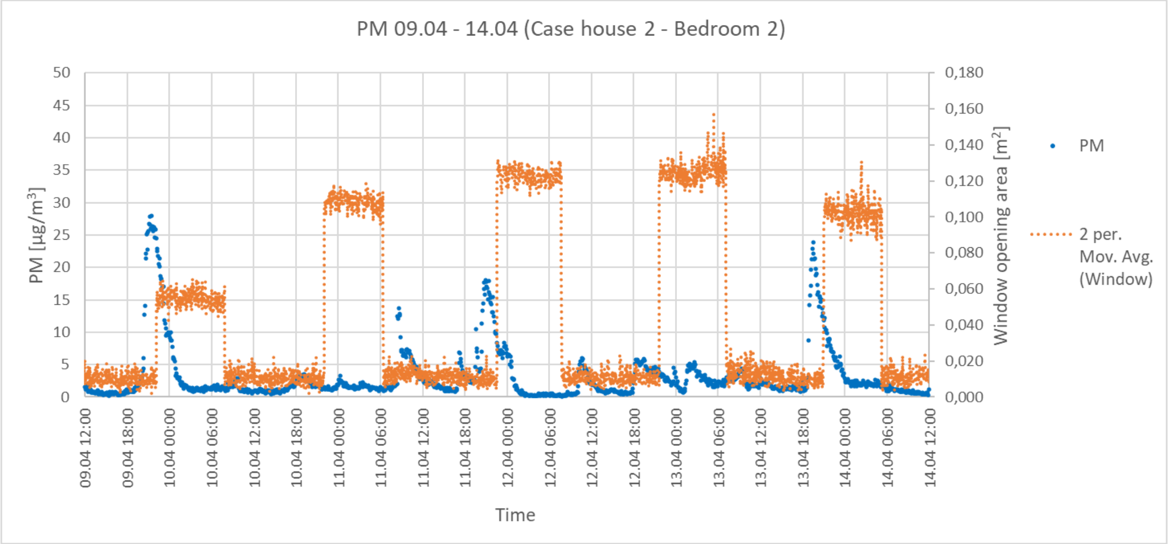


Figure 64: PM and window opening area of bedroom 2 in case house 2, 09.04 – 14.04.

As the peaks occurs before the window is opened, they are most likely related to the occupant behavior. A comparison of the PM and CO_2 level is shown in Figure 65.

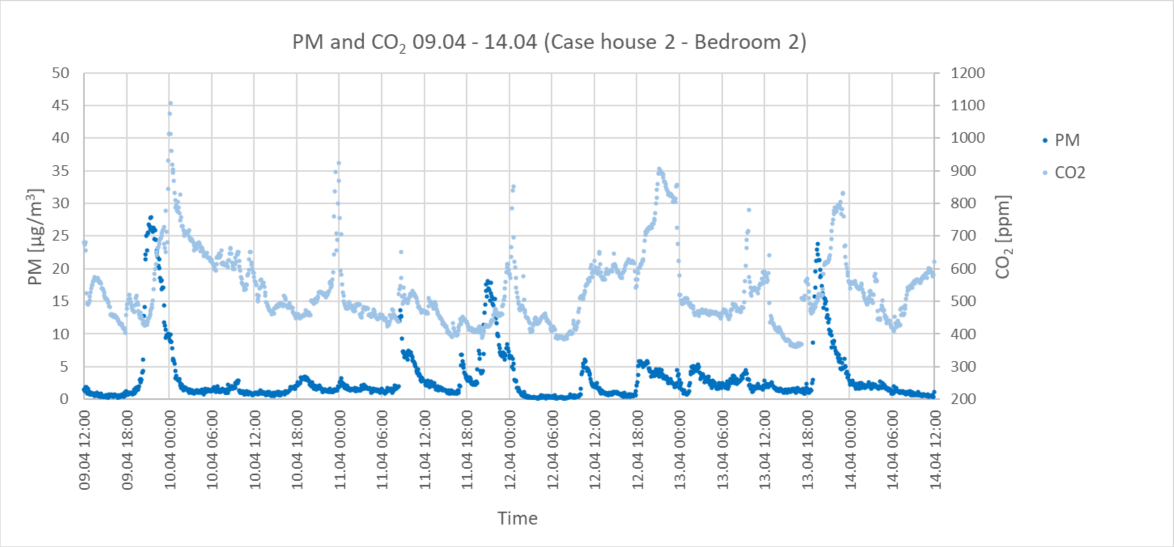


Figure 65: PM and CO_2 level of bedroom 2 in case house 2, 09.04 – 14.04.

The figure illustrates how the peaks in the PM concentration occurs before the similar peaks of CO_2. This can be explained by a possible delay in the increase in CO_2 concentration or for the CO_2 sensor. Occasional high peaks in the PM measurements are also found in the other bedrooms. As no strong correlation was observed between CO_2 and PM, activities in other rooms may also affect the PM level in the bedrooms.

6.7 Formaldehyde

6.7.1 Nightly average

The nightly average characteristics of formaldehyde is shown in Table 14.

Table 14: Nightly average characteristics of formaldehyde.

Case house	Bed-room	Av. formaldehyde [µg/m^3] (SD)	Min. av. formaldehyde [µg/m^3]	Max. av. formaldehyde [µg/m^3]	Av. window opening area [m^2]	IAQ sensor
1	1	50.7 (53.3)	5.3	315.5	0.15 (0.00)	6
	2	112.0 (94.7)	14.9	348.2	0.13 (0.01)	4
	3	183.8 (113.0)	70.8	509.9	0.10 (0.01)	3
2	1	55.9 (83.5)	5.3	315.5	0.09 (0.01)	2
	2	131.7 (137.9)	36.3	286.1	0.08 (0.01)	4
3	1	379.8 (293.0)	5.3	3513.7	0.15 (0.06)	6
	2	645.4 (158.4)	181.4	2759.2	0.01 (0.00)	8
4	-	124.4 (51.5)	12.3	444.1	0.11 (0.06)	3
5	-	7.5 (3.0)	0.16	15.6	-	2
6	-	101.3 (79.9)	14.9	949.5	0.06 (0.01)	8

The WHO short-term guideline limit of formaldehyde is 100 µg/m^3 per 30-minutes. The table shows how the nightly average concentrations in the majority of the bedrooms exceeds this limit.

The lowest nightly average was found in case house 5, which was also considerably lower compared to the other bedrooms. The highest nightly average concentrations were found in bedroom 2 in case house 3, and the second highest in bedroom 1 of the same house. The maximum nightly averages of the whole period were also found in these two bedrooms and were significantly higher than the other bedrooms.

Higher average measurement when the window was closed was also observed in some of the case houses. In case house 5 the two nights where the occupant was away, and the window closed, were shown to have the highest concentrations of 51.1 and 62.6 µg/m^3. The average of the remaining nights was 7.5 µg/m^3.

6.7.2 High peak concentrations

The formaldehyde measurements were characterized by high variations in most of the bedrooms, which is also indicated in the high average measurements. In many of the bedrooms there were also measured very high peak concentrations. This is illustrated in Figure 66.

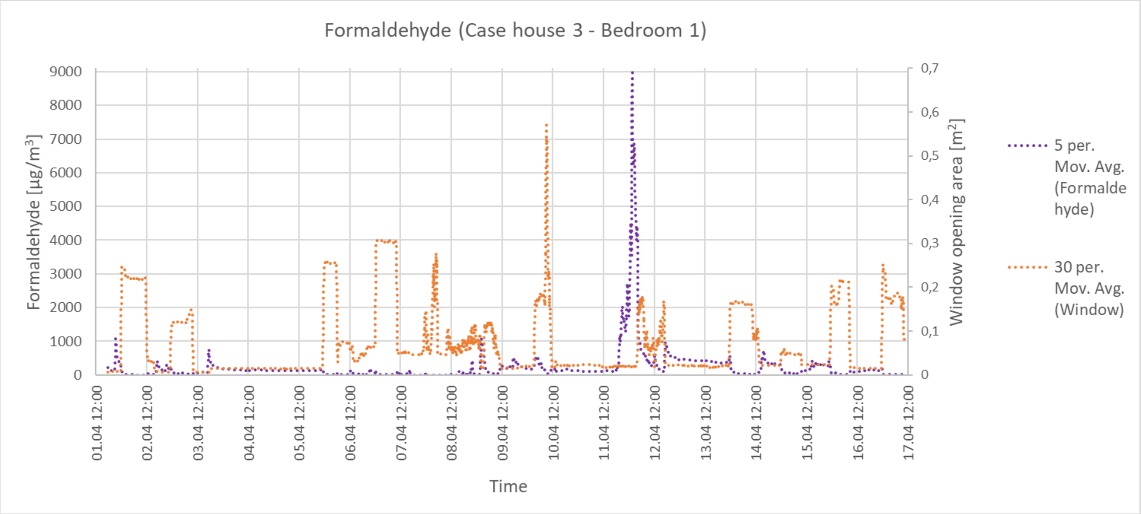


Figure 66: Peak concentration of formaldehyde level in bedroom 1, case house 3.

As the figure illustrates, the peak in the formaldehyde concentration is exceptionally high and reaches a concentration of almost 9000 µg/m^3. If this night is disregarded the overall nightly average concentration would have been 94.9 µg/m^3 for this bedroom. This would also have reduced the standard deviation with approximately 30 %. This high peak was also found to correlate with a high peak in the PM, TVOC and CO_2 level.

Bedroom 1 in case house 2 also experienced one night with a higher average than usual, where the average was 315.5 µg/m^3. If this night is disregarded the average for the whole period would have been 37.4 µg/m^3 and below the guideline limit. This was also seen in case house 6 where the average was 949.5 µg/m^3, and if this night is disregarded the overall average would have been 44.8 µg/m^3.

6.7.3 Correlation with window opening

The variation of formaldehyde in bedroom 3 of case house 1 throughout the measurement period is shown in Figure 67.

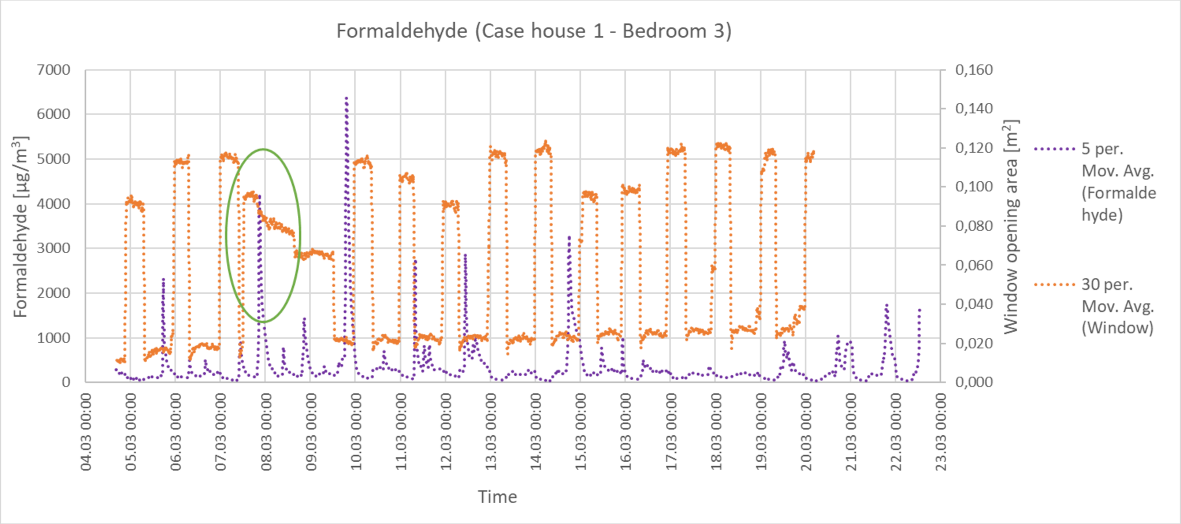


Figure 67: Formaldehyde concentration of bedroom 3 in case house 1.

The figure illustrates how the concentration of formaldehyde occasionally reaches very high peaks. Even though the window was open for a longer period between 07.03 and 09.03 a high peak in the formaldehyde concentration occurred, indicated by the green circle in the figure. If very high peaks are ignored the nightly variations can be observed, as illustrated in Figure 68.

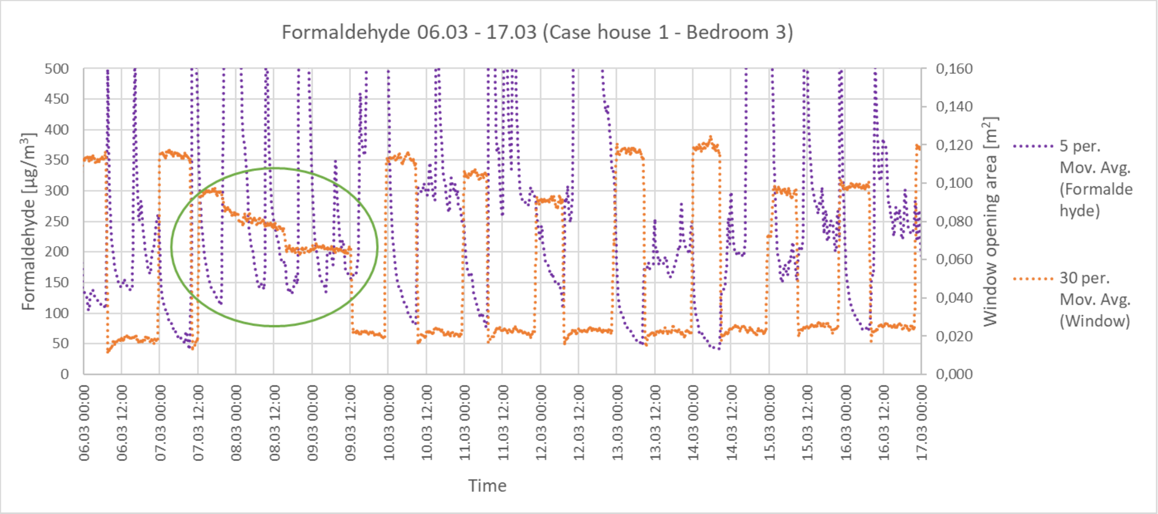


Figure 68: Formaldehyde concentration of bedroom 3 in case house 1, 06.03 – 17.03, with adjusted y-axis.

From the figure it can observed how the formaldehyde level fluctuates between 07.03 and 09.03, when the window was open for a longer period. This indicates how the occupant behavior may affect the formaldehyde level.

The figure also shows how the formaldehyde level decreases during the nights, when the window is open. However, the level rarely falls below 50 µg/m^3. This clear decrease during nighttime, when the window is open, were also observed in the other children's room of case house 1, in both bedrooms of case house 2 and in case house 4.

6.7.4 Correlation with CO$_2$

The correlation coefficients of formaldehyde and CO$_2$ are shown in Table 15.

Table 15: Correlations coefficients of formaldehyde and CO$_2$.

Case house	Bedroom	R^2-value for CO$_2$ and formaldehyde	IAQ sensor
1	1	0.010	6
	2	0.066	4
	3	0.015	3
2	1	0.467	2
	2	0.009	4
3	1	0.524	6
	2	0.198	8
4	-	0.244	3
5	-	0.004	2
6	-	0.006	8

It can be observed how the degree of correlation of formaldehyde and CO_2 differed strongly between the bedrooms, as the correlation coefficients were in the range of 0 to 0.5. Stronger correlations were observed in bedroom 1 of both case house 2 and 3.

Although, strong correlations were not found between CO_2 and formaldehyde, many larger peaks were observed to coincide with peaks in the CO_2 concentration. This is illustrated in Figure 69 by bedroom 2 in case house 3.

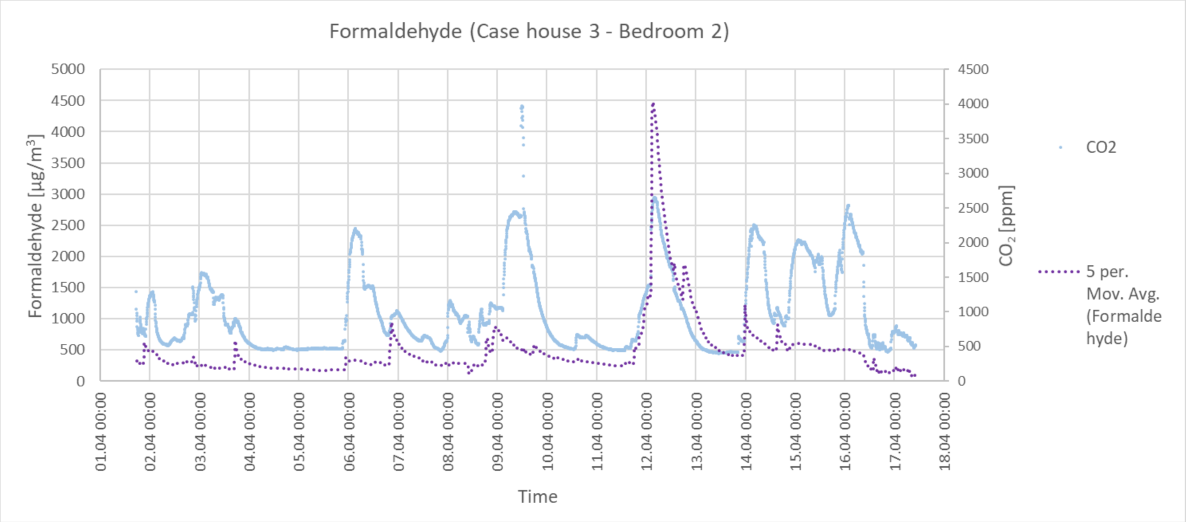


Figure 69: Variation of formaldehyde and CO_2 in bedroom 2, case house 3.

The figure shows how the high peak in the formaldehyde concentration is coinciding with a peak in the CO_2 concentration on the night to 13.04. If the axis is adjusted for lower concentrations of formaldehyde, this can also be partly observed for lower peak concentrations. This is illustrated in Figure 70.

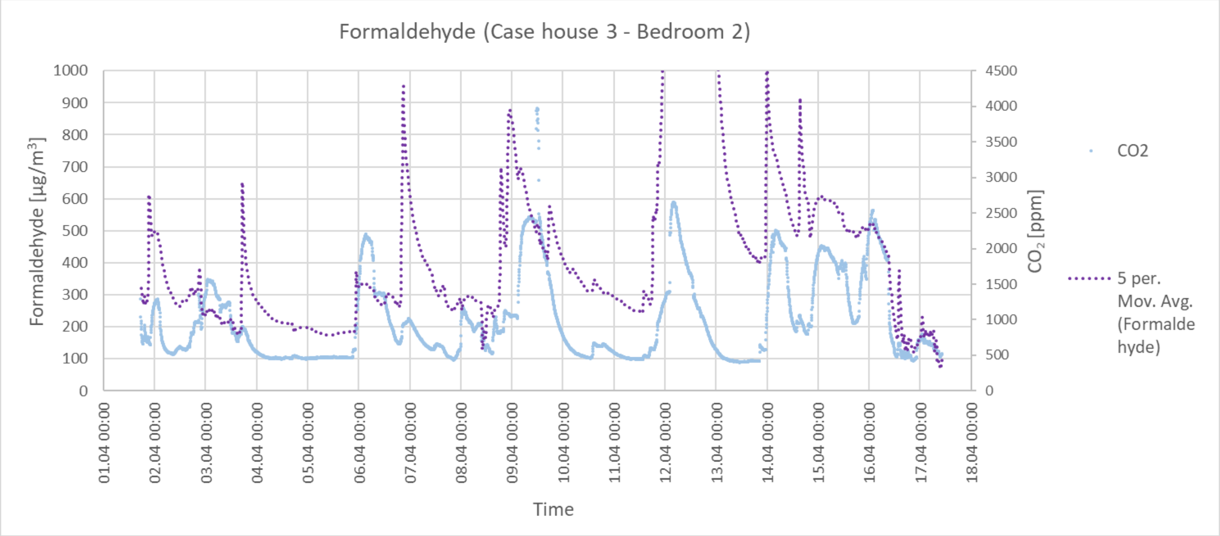


Figure 70: Concentration of formaldehyde and CO_2 in bedroom 2, case house 3, with adjusted axis for formaldehyde.

6.8 TVOC

6.8.1 Nightly average

The nightly average characteristics of TVOC are presented in Table 16.

It should be noted that very low concentrations of TVOC are found in bedroom 1 of case house 1 and in case house 4, where IAQ sensor 3 was used. This sensor also measured concentrations of 0 during the calibration of the sensors, described in section 5.1.5.

Table 16: Nightly characteristics of TVOC.

Case house	Bedroom	Av. TVOC [ppb] (SD)	Min. av. TVOC [ppb]	Max. av. TVOC [ppb]	Av. window opening area [m^2]	IAQ sensor
1	1	1626 (814)	431	3496	0.15 (0.00)	6
	2	620 (313)	284	1299	0.13 (0.01)	4
	3	101 (29)	54	168	0.10 (0.01)	3
2	1	238 (188)	2	560	0.09 (0.01)	2
	2	417 (180)	175	793	0.08 (0.01)	4
3	1	725 (461)	190	4289	0.15 (0.06)	6
	2	1905 (385)	573	5219	0.01 (0.00)	8
4	-	92 (16)	28	144	0.11 (0.06)	3
5	-	247 (64)	143	371	-	2
6	-	400 (133)	236	1357	0.06 (0.01)	8

As discussed in section 2.3.2, Airthings suggests that TVOC concentrations below 250 ppb are considered low and levels above 2000 ppb suggests that the room should be ventilated immediately.

When evaluating the nights of highest average concentrations through the period, both bedrooms of case house 3 and bedroom 1 in case house 1 have very high concentrations. In bedroom 1 of case house 3, this is explained by one very high nightly average of 4289 ppb. If this night is disregarded, the overall average would have been 415 ppb. This one high nightly average was also coinciding with, peak measurements in concentrations of CO_2, PM and formaldehyde.

The second bedroom of case house 3 had an overall average concentration close to 2000 ppb. The overall average of bedroom 1 in case house 1 was slightly lower, but also high.

6.8.2 Correlation with CO_2 and formaldehyde

The correlation coefficients of TVOC and CO_2, and TVOC and formaldehyde are shown in Table 17. The letter N indicates a negative correlation.

Table 17: Correlation coefficients of CO_2/TVOC and formaldehyde/TVOC. N indicates a negative correlation.

Case house	Bedroom	R^2-value for CO_2 and TVOC	R^2-value for formaldehyde and TVOC	IAQ sensor
1	1	0.497	0.076	6
	2	0.144	0.823	4
	3	0.223 (N)	0.227 (N)	3
2	1	0.537	0.470	2
	2	0.054	0.845	4
3	1	0.614	0.908	6
	2	0.538	0.780	8
4	-	0.206 (N)	0.349 (N)	3
5	-	0.215	0.132	2
6	-	0.018	0.436	8

Compared to PM and formaldehyde, the correlation coefficients for TVOC and CO_2 are higher. The range of the coefficients is, however, high as they vary between 0.02 and 0.6. Higher correlations between formaldehyde and TVOC are observed in some of the bedrooms, but the variation is also high.

In both rooms where IAQ sensor 3 was used, there was found a negative correlation between formaldehyde and TVOC. This, together with the low average measurements, strengthens the assumption that there was something wrong with this sensor.

The variation of TVOC, formaldehyde and CO_2 for bedroom 3 in case house 3 is illustrated in Figure 71.

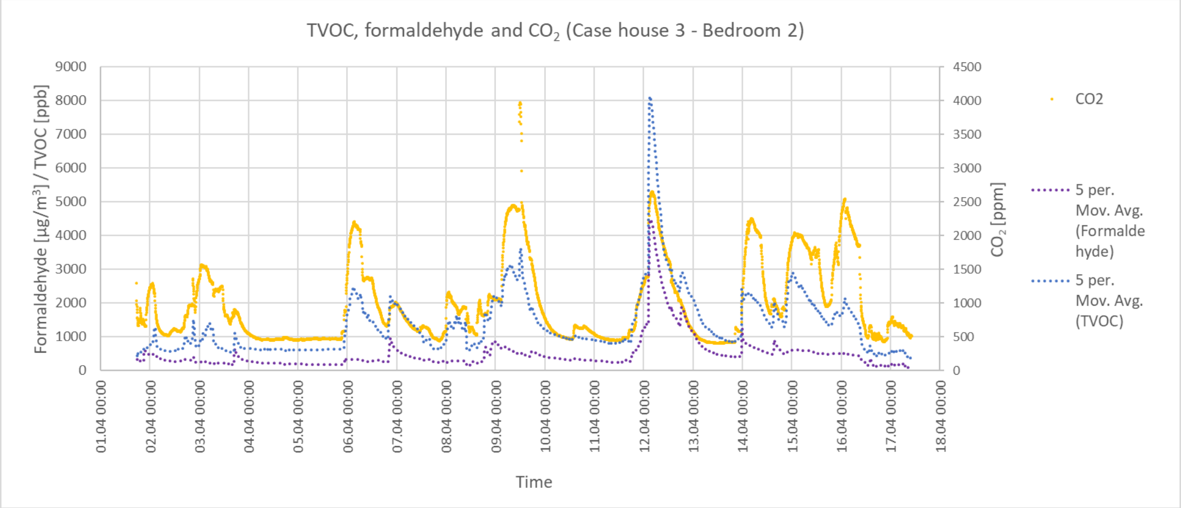


Figure 71: Concentrations of TVOC, formaldehyde and CO_2 in bedroom 2 of case house 3.

The concentrations of TVOC in this room clearly correlated with the concentrations of formaldehyde and CO_2. If large peaks are ignored, it can be observed how the level of TVOC is high even when the occupant is not in the room. This is illustrated in Figure 72, where periods of non-occupancy are indicated by the red circles.

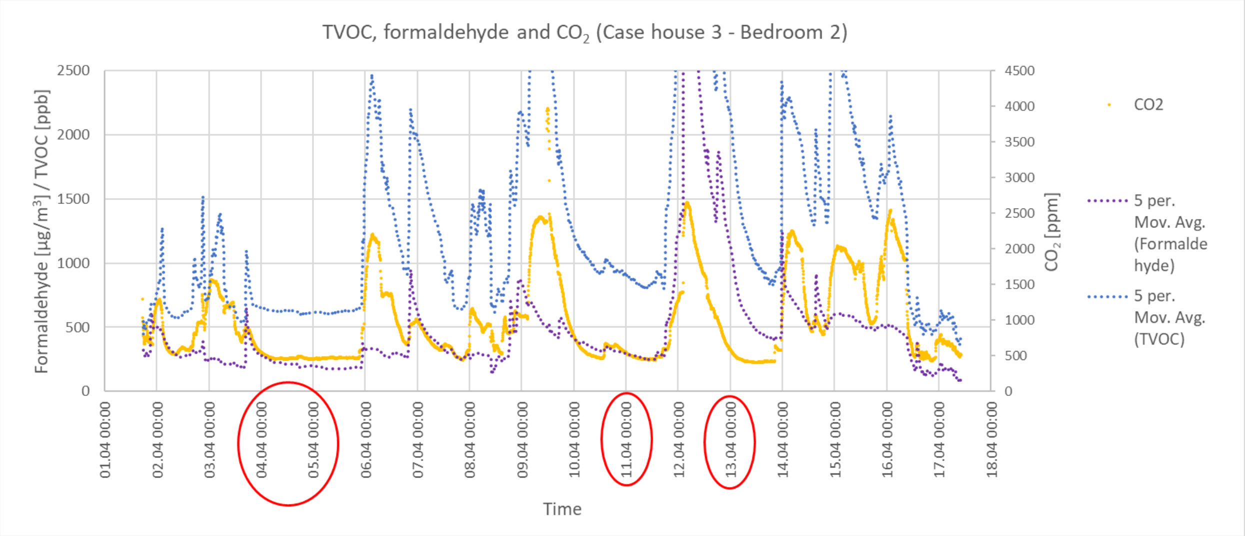


Figure 72: Concentration of TVOC, formaldehyde and CO₂ in bedroom 2 of case house 3, with adjusted y-axis (left).

A correlation of TVOC and CO₂ was also observed in bedroom 1 of case house 1 This is illustrated in Figure 73.

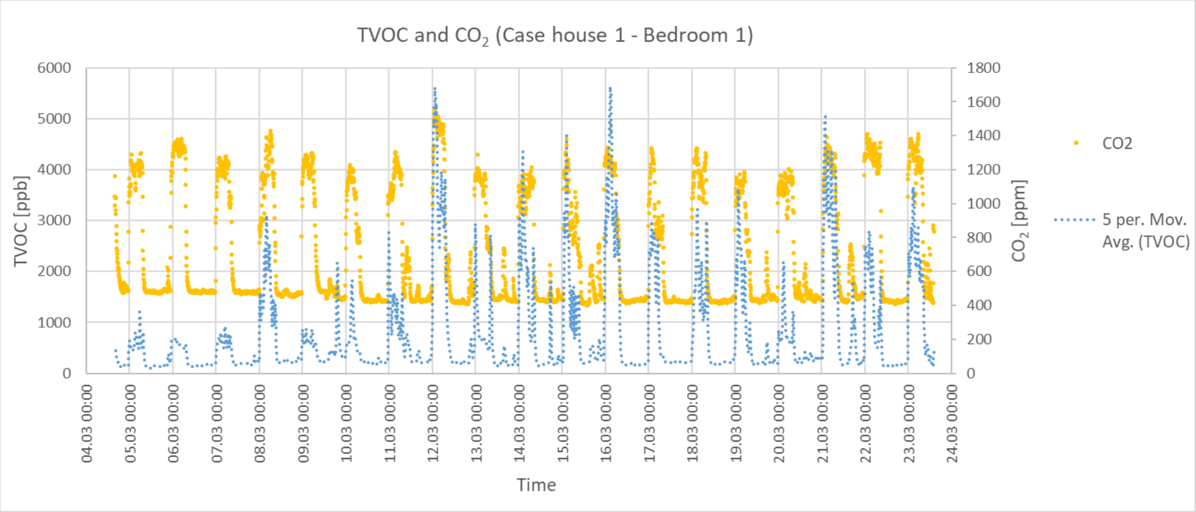


Figure 73: Concentration of TVOC and CO₂ in bedroom 1 of case house 1.

The figure illustrates how the peak in TVOC concentrations seems to be affected by the occupancy of the room. The concentration of TVOC is higher during the nights compared to the days for this room. This is illustrated clearer in Figure 74.

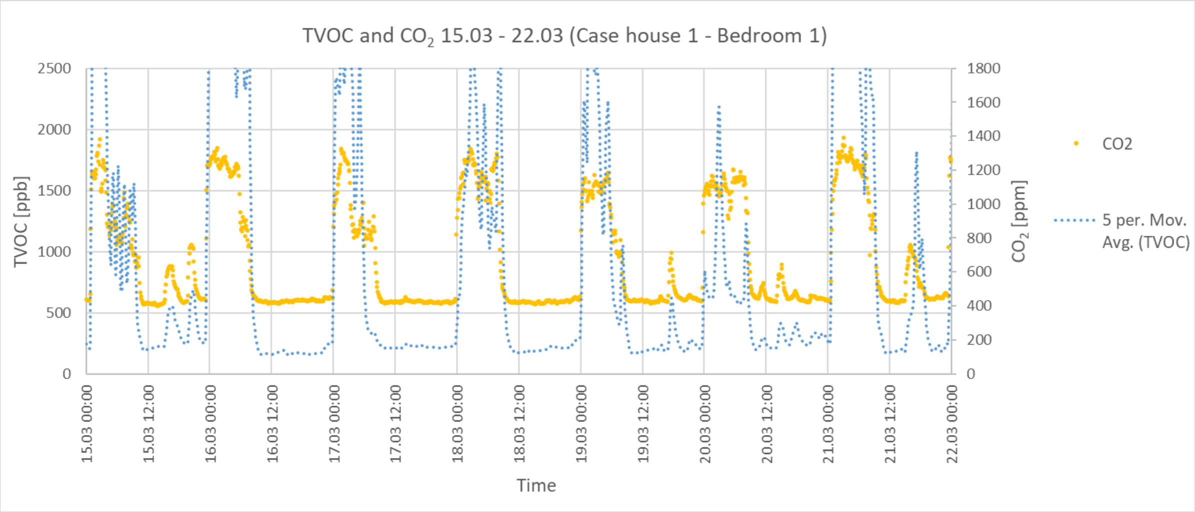


Figure 74: Concentration of TVOC and CO$_2$ in bedroom 1 of case house 1, 15.03 – 22.03, with adjusted y-axis for TVOC.

The correlation coefficient of TVOC and CO$_2$ for the whole measurement period was 0.5, which indicates a moderate correlation between the two parameters in this bedroom. It can also be observed how the level decreases during the day, when the window is open, and the room is unoccupied.

In bedroom 2 of the same house, the correlation between TVOC and CO$_2$ was weaker, with a correlation factor of 0.14. Formaldehyde and TVOC showed a strong correlation in this bedroom, and the correlation factor was 0.82. While the concentration of formaldehyde showed a clear decrease during the nighttime, when the window was open, the TVOC concentration fluctuated significantly more during some of the nights. This is illustrated in Figure 75.

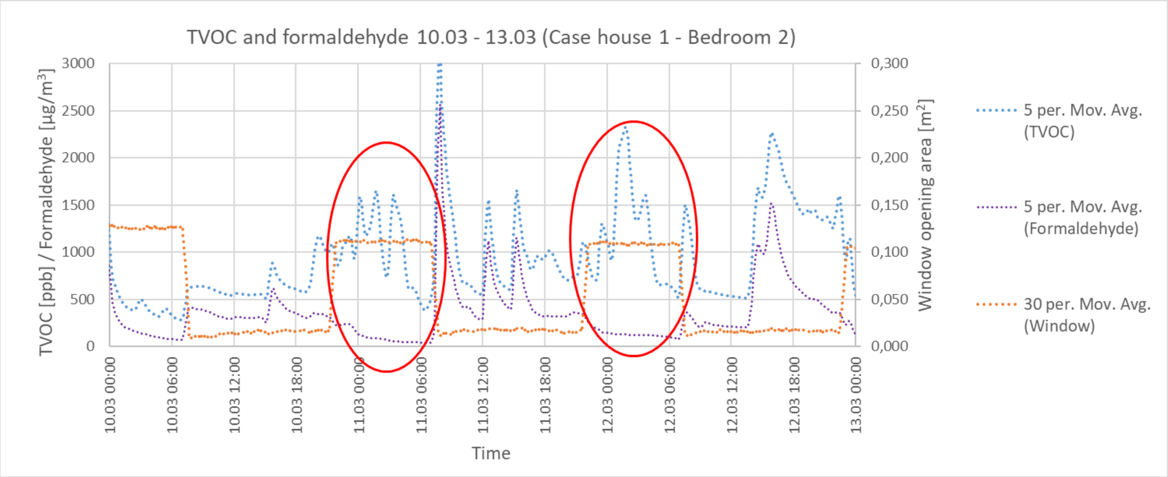


Figure 75: Concentrations of TVOC and formaldehyde in bedroom 2 (case house 1), 10.03 – 13.03.

Higher fluctuations of TVOC can also be observed through the whole period, illustrated in Figure 76.

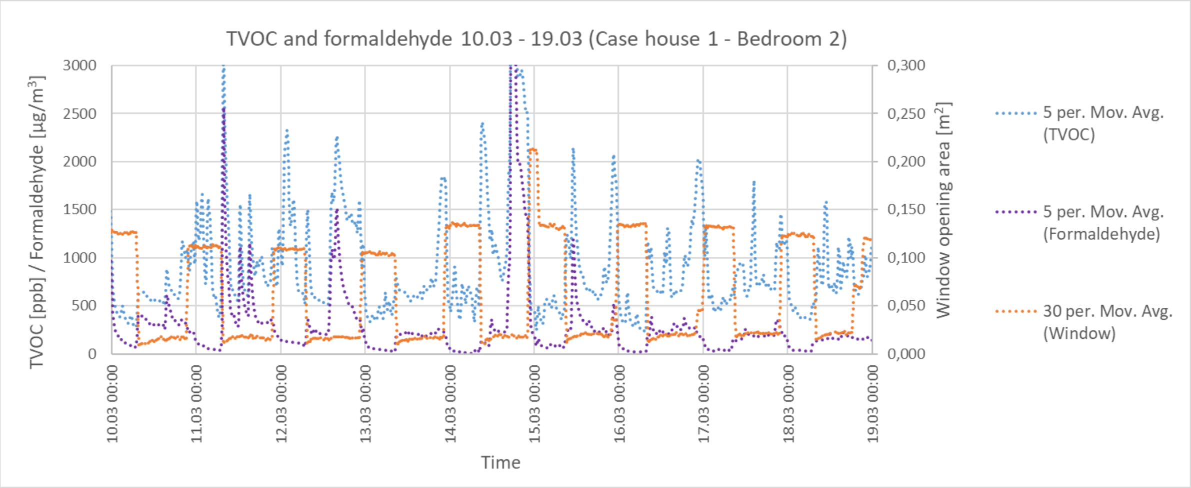


Figure 76: Concentrations of TVOC and formaldehyde in bedroom 2 (case house 1), 10.03 – 19.03.

7 Discussion

In this section the results from the field investigations are discussed in relation to the research questions in 4.2. The measurements of the size of the window opening and the IAQ and window opening sensors are also evaluated in this section.

7.1 Evaluation of measurements and calculations

7.1.1 Window opening sensors

Through both the tests and the field investigations, the accelerometer was found to be a good solution for measuring the opening size of bottom- and top-hinged windows, especially when it was integrated into the IAQ sensor system. There was, however, shown to be some inaccuracies related to these measurements.

The ultrasonic sound sensor, on the other hand, was shown to have more noise in its measurements and some of the measurements were therefore difficult to interpret. The degree of noise varied between the bedrooms. This indicates how the performance of the sensor is dependent on the size of the window opening and the window opening behavior.

Initially, the ultrasonic sound sensor was also used to log door openings of the bedroom door. However, in the first measurement period the sensor only measured through approximately the five first nights. The faulty measurement was explained by an error in the sensor that drained the battery. This was also why no measurements of the window opening area were available for case house 5. In the second measurement period, the ultrasonic sound sensor was connected to a power source. This was, however, not possible to do for the door openings and these measurements were therefore excluded from further analysis.

7.1.2 Window opening area

Window opening area has been used as a basis of comparison for the windows. However, clear correlations between the opening area and the air quality were not found in the analysis of the field investigations. This can reflect how the airflow through the window opening is also dependent on several other factors than the size of the opening, such as type of window, orientation, degree of exposure and the use of curtains, in addition to wind and buoyancy forces. Therefore, window opening area may not be the ideal parameter to compare the different windows.

Through the testing of the accelerometer there was shown to be some noise present in the measurements, and the measured angle of the accelerometer varied in a range of 2 degrees when the window was open. In addition to this, an offset of around 0.5 – 1 degree was present when the window was closed. The window opening area is also dependent on the area of the window. This was measured during the set-up of the equipment, and there may also be some inaccuracy related to these measurements.

To exemplify this, a window with height and width of 1 m and an opening angle of 6 degrees, are overestimated by 1 cm in both height and width. This would result in a window opening area of 0.107 m^2, instead of an opening area of 0.105 m^2. On the other hand, if the opening angle of the same window is measured to be 1 degree larger than it is, this would result in an opening area of 0.123 m^2. As the window opening areas calculated in this work varied in the range of 0.01 – 0.15 m^2, overestimation of the angle can have large impacts on the opening area of the windows.

In some of the houses the size of the window opening also seemed to have smaller and larger variations throughout the period. However, this can be a result of inaccuracies caused by the window opening sensor itself and, by this, not a result of user behavior. This is also the reason why possible correlations between size of the window opening and IAQ parameters have not been investigated further in this thesis.

7.1.3 IAQ measurements

In the calibration of the IAQ sensor, the measurements of temperature, RH, CO_2 and particulate matter were validated. As no available calibration equipment for formaldehyde and TVOC were available, the accuracy of these measurements could not be confirmed. The accuracy of these sensors was more thoroughly investigated in another master thesis in 2019, where the manufacturer of the formaldehyde sensor reported that these low-cost sensors might have some cross-sensitivities [44]. The measured formaldehyde concentrations may therefore be impacted by other volatile compounds. The high correlation of TVOC and formaldehyde is also an indication of this.

During the set-up of the equipment it was strived to place the IAQ sensors as described in section 5.1.7. This was, however, shown to be difficult as many of the bedrooms were small in size. The sensors were also difficult to mount on the walls without leaving marks and similar. Therefore, the IAQ sensors were often placed on top of dressers or available furniture in the room, which may have led to the occupant's movements affecting the IAQ measurements. Therefore, some measurements may not have been representable for the air quality in the room, but local values close to the sensor.

7.1.4 Average measurements

The average measurements were presented to give an indication of the general air quality in the investigated bedrooms. The average measurements were calculated between 23:00 and 06:00 each night, without taking individual differences into account. The nightly occupancy time of the bedroom may not necessarily be within this interval, which can have had some effect on the average measurements. If one of the occupants went to bed at 00:00, then one hour of possible lower concentrations would have been included in the average measurements.

The duration of the measurement period also varied between the case houses, where it for some houses were closer to three weeks due to some delay in collecting the measurement equipment. All measured days were, however, included in the average measurement. A longer measurement period can contribute to even out the effect of higher and lower peaks and make the average more representable. For this reason, some averages may be more representable than others and a comparison of these may not be fair.

7.1.5 Calculation of air change rates

A part of this thesis was originally to investigate the possibility of developing a more thorough model for calculating air change rates. In the research of this it was discovered how large errors have previously been shown to be present when a single-zone mass balance model is used to evaluate air change rates by occupant-generated CO_2, as was discussed in 3.1.1. Thereby, the need for a more thorough model was also indicated. This work was not prioritized in this thesis.

The calculation of air change rates carried out in this thesis have therefore been largely simplified and only give an indication of the air change rate of the bedrooms. Large estimations have been carried out, both in relation to the generation of CO_2 in the room and for the decrease of the CO_2 level at nighttime. Some of the bedrooms had very high variations in the CO_2 measurements and the air change rate was therefore difficult to estimate. Two of the bedrooms did also not have available data for the window opening behavior and were excluded from these calculations. In addition, only a few nights were analyzed per bedroom.

If air change rates are to give a satisfying indication of the IAQ of the bedrooms they need to be calculated more extensively than what they have been during this thesis, and by the use of a proper model to analyze all nights through the period.

7.2 Research question 1

How will the occupants' window opening behavior affect IAQ parameters such as CO_2 concentration, relative humidity and temperature in the bedroom?

7.2.1 CO_2 concentrations during the night

Through the analysis of the field investigations it was found how two of the bedrooms had high average CO_2 concentrations during the nights. The levels exceeded 950 ppm 80 and 70 % of the time during the nights, respectively, for bedroom 1 in case house 1 and bedroom 2 in case house 3. The same number was close to 10 and 50 % for concentrations above 1350 ppm. It should also be noted how both the area of the windows in these bedrooms were small. The window opening area in case house 1 was large, compared to the other bedrooms, but the window was covered with heavy curtains at night. The window opening area of the window in bedroom 2 of case house 3 was very small compared to the other bedrooms. These two factors may have reduced the airflow through these windows at night.

The window opening behavior of these two bedrooms were also shown to be more extensive, where the window was open both day and nights through the measurement period. This is discussed further in section 7.5.

A small indication of a correlation between a more extensive window opening behavior and higher CO_2 levels was also seen in case house 6. Here the duration of the window openings increased in a period of higher average CO_2 concentrations during the night. In case house 6, this correlation may have been explained by a higher occupancy of the bedroom.

Although two bedrooms were found to have very high CO_2 concentration during the night, the percentage of levels above 1200 ppm was around 10 or lower for the other bedrooms. This is similar to what Mathisen and Berge found when they investigated high-performance apartments with balanced ventilation, where levels above 1200 ppm were found in two of the seven apartments, 5 and 6 % of the time [28]. This indicates how the CO_2 levels of naturally ventilated bedrooms can reach the same CO_2 concentrations as bedrooms with balanced ventilation systems.

No clear correlation was found between the window opening area and the CO_2 concentrations through these investigations. Several different windows with different window opening areas, seemed to provide enough fresh air to keep the CO_2 level below 1000 ppm during the night.

7.2.2 CO_2 concentrations during the day

When the duration of high CO_2 concentrations at nighttime were compared to the whole period, the time duration of levels above 950 ppm decreased from 80 to 30 % in case house 1 (bedroom 1). In bedroom 2 of case house 3 the percentage only decreased with 20 percentage points. This is also an indication of the effect of curtains in the bedroom, which heavy and drawn during the night in bedroom 1 of case house 1.

In some of the bedrooms there was also found higher concentrations of CO_2 during the day, compared to the nights. This seemed to be related to a higher occupancy of the room at daytime and was mainly found in bedrooms of children or young adults. This indicates how the occupancy of the room during the day should be taken into consideration, when natural ventilation in the bedroom is considered.

7.2.3 Impact of flows from adjacent rooms

The CO_2 concentrations also seemed to be impacted by airflow from adjacent rooms. This was especially illustrated in the second bedroom of case house 2, where the CO_2 level was high during the one night when the window was closed. A rapid decrease in the CO_2 concentration was observed in the morning and can be an illustration of how the airflow from the remaining building entered the room and diluted the concentration. The parent also described the air as stuffy when she entered in the morning, which may indicate how the door was opened when she entered. Case house 2 was also the only house with a balanced ventilation system installed in the rest of the building. The concentration of CO_2 in the airflow from adjacent rooms in this house may also naturally be lower, compared to the other houses.

It is difficult to confirm this assumption, as no data was available for the door openings in the bedroom. If this assumption is right, it is a good illustration of how a hybrid ventilation system can contribute to a low concentration of CO_2 during the daytime – if the bedroom door is opened. It should also be noted how the CO_2 levels of the bedrooms in case house 2 was generally low.

7.2.4 Temperature and RH levels

A differentiation of the bedrooms was shown to be present when the temperature measurements were analyzed. In 6 out of 10 bedrooms the overall average temperature was below 18°C, and in the remaining 4 bedrooms the average was above 21°C.

In the bedrooms with higher temperatures the average RH level was also found to be lower, and the level dropped below 20 % several times during the period. In three of these bedrooms the night of lowest average RH level was below 20 %. 3 of these 4 bedrooms had normally the heat turned on during the night, except for bedroom 1 in case house 1.

The RH level also seemed to be affected by the outdoor airflow. The level clearly decreased in bedroom 2 and 3 of case house 1, when the window was opened. In bedroom 1, on the other hand, the RH level increased during the nights and decreased during the day. This can be an indication of how the outdoor airflow through the window may have been reduced by the heavy curtains during nighttime, or how the occupancy contributed to raising the RH level of the room.

Fluctuations in both RH and temperature were observed, and the RH level was shown to have higher fluctuations than the temperature. This can indicate how the RH level was more easily affected by outdoor temperature and occupant behavior.

In some bedrooms the temperature had a clear correlation with the window opening behavior, where the temperature decreased when the window was opened and increased when it was closed. This was shown to be the case for bedroom 2 and 3 case house 1 and the bedrooms in case house 2. These bedrooms also had a larger window area. However, there are many other parameters that could have caused this correlation, such as placement of the IAQ sensors, door openings during the day and insulation of the building.

In the bedrooms with lower temperatures, all the occupants reported how they did not have heating installed in the bedroom, or that they had turned it off. This confirms how many may prefer a lower bedroom temperature, which was also seen in the literature review. These observed differences in bedroom temperatures is also an indication of how it is important to consider individual preferences, when the indoor environment is evaluated.

7.3 Research question 2

How will the occupants' window opening behavior affect other relevant IAQ parameters such as particulate matter, formaldehyde and TVOC?

7.3.1 Particulate matter

In general, the nightly average measurements of PM were low and well below the long-term guideline value provided by WHO. The correlation between CO_2 and PM was low or not present in most of the bedrooms. Although the nightly average concentration of PM was low, higher peaks were observed in most of the bedrooms. In some cases, the peaks seemed to correlate with an increase in the CO_2 concentration, and in other cases smaller increases could be partly coinciding with when the window was opened. For some of the nights, the concentration of PM could also be observed to be higher during nighttime. Whether this is related to the PM concentration in outdoor air affecting the indoor concentration or related to the occupancy of the room is difficult to conclude based on these observations. It was also shown how the IAQ sensors seemed to be easily affected by occupant behavior, and some of the average measurements may therefore be overestimated.

7.3.2 Formaldehyde and TVOC

As opposed to the PM measurements, high nightly average concentrations were found for formaldehyde and the short-term guideline limit was exceeded in most of the bedrooms. However, the possible cross-sensitivities of the formaldehyde sensor should be taken into consideration when these levels are evaluated. The large nightly averages may, therefore, not necessarily be due to high levels of formaldehyde. This is also indicated by the correlation between formaldehyde and TVOC, which was present in many of the bedrooms.

When the TVOC measurements were analyzed, very large variations and high peak concentrations were found. A higher correlation between CO_2 and TVOC was also found in many of the bedrooms. This may indicate how the TVOC measurements are more impacted by the occupant behavior than formaldehyde and PM.

Occasionally very large peak concentrations were found for all these parameters. This can indicate how the IAQ sensors were easily impacted or placed too near the occupants. The use of low-cost sensors may also be a reason for the high measurements of TVOC and formaldehyde. As these sensors have not been calibrated, their accuracy is difficult to confirm. It is, therefore, difficult to conclude if the airflow through the window opening is enough to dilute the air pollution in the bedroom by these measurements.

7.4 Research question 3

Can external factors, such as outdoor weather conditions, affect the IAQ parameters in the bedrooms?

A correlation between the indoor and outdoor temperature was indicated in some of the bedrooms. In addition, the RH level also seemed to be affected by the outdoor temperature in some of the bedrooms. Only a graphic comparison was made, and the correlation between outdoor temperature and RH, and outdoor and indoor temperature, can be investigated further. Precipitation seemed to have no significant effect, either on window opening behavior or indoor temperature and RH.

As the outdoor temperature and precipitation was collected from near-by weather stations, their relevance may be variating. Wind data could only be collected from one weather station in the Trondheim area, and was thereby not investigated in this work.

When the occupants were asked why they would normally not open the window at night, the most common answers were related to temperature in the bedroom or outdoors. As only one person avoided opening the window due to too cold temperatures, when the outdoor temperature was just below 0°C, the closing behavior during colder months may be more extensive than what was observed during these measurements.

A less extensive window opening behavior during the colder months may lead to more nights of lower IAQ, if the window is not opened. However, it is not known at which outdoor temperature the occupants will choose to not open the window at night, and this may also differ strongly between the individuals. If the window is opened during the colder month but with a smaller opening, the IAQ in the bedroom may not be lower - due to a higher difference between indoor and outdoor temperature in the colder months.

7.5 Research question 4

Which factors may prevent the window opening behavior of the occupants?

All the participants who answered the questionnaire, stated that air quality in the bedroom was important to them. This was also expected, as participants who preferred to open the window was targeted when case houses were chosen. It should be considered that some of the questionnaires were answered by the parents on the children’s behalf, and the answers may therefore be affected by this.

A tendency of low IAQ and more extensive window opening behavior was found in bedroom 1 of case house 1 and in bedroom 2 of case house 3. Based on observations during the set-up of the equipment, the occupants of case house 1 seemed very concerned with the IAQ in the bedrooms. This same awareness was not observed for the occupant in bedroom 2 of case house 3, but rather by the parent in this case house. If the occupant of bedroom 2 was not concerned with the IAQ in the room, this may be an explanation for the small window opening area and the constant opening behavior through the period. If this room had been occupied by someone else, the opening behavior may also have been different.

This can indicate how the motivation of the occupant plays an important role for the resulting IAQ of the bedroom, when only window openings are used to ventilate the room. It can also indicate how the preferences of different occupants in the same house, may have consequences for the IAQ in some bedrooms. It should be noted that these assumptions are based on observations and is difficult to confirm as the questionnaire was not answered by the occupant in bedroom 2 of house 3.

Outdoor temperature was also indicated as a factor that could prevent window opening at night.

8 Conclusion

The objective of this thesis was to investigate if natural ventilation, mainly through occupant-controlled window opening, could ensure a good environment in bedrooms during the heating season.

This was done through the measurements of CO_2, temperature, relative humidity, particulate matter, formaldehyde and TVOC in ten bedrooms of six case houses. To investigate the influence of the window opening behavior of the occupants, the size of the window openings in the bedrooms was also measured. As windows of different type, area, orientation, and exposure were included in the investigations, it was difficult to find a definite correlation between the window opening area and the IAQ parameters. However, the window opening behavior was shown to be both predictable and continuous and the bedroom windows were found to open every night in almost all the bedrooms.

Two of the ten investigated bedrooms were found to have high levels of CO_2 during the nighttime. These bedrooms were also shown to have a more extensive window opening behavior, where the window was open both days and nights. In the other eight bedrooms the window opening seemed to be adequate to keep the CO_2 concentration low during nighttime. Although higher concentrations were found during the daytime in some of the bedrooms, most likely caused by a higher occupancy.

The average concentrations of PM were found to be low and well-below the WHO guideline limit for most of the bedrooms. For the measurements of formaldehyde and TVOC, higher average concentrations were found in most of the bedrooms. As there were some uncertainties related to the measurements of these pollutants, these high levels cannot be confirmed. There was, however, found a small correlation between the decrease in CO_2 concentration and the levels of formaldehyde and TVOC in some of the bedrooms. This can indicate how dilution of indoor air pollutants is possible only by the use opening the window in the bedroom.

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

These investigations have shown how it is possible to ensure a high IAQ and a good indoor environment in bedrooms, with only natural ventilation through occupant-controlled window openings. However, this does not mean that an open window guarantees adequate IAQ. It is important to consider the risk of high CO_2 levels and low RH levels when this solution is chosen, in addition to the preferences of the occupants. The conducted investigations also gave an indication of how the combination of a hybrid ventilation system, with natural ventilation in the bedroom and balanced ventilation in the rest of the home, can be a good solution – with lower risk of an unsatisfying indoor environment and IAQ.

Further work

If these measurements are to be further investigated, more detailed analysis could be conducted. A more thorough correlation analysis of outdoor temperature and IAQ parameters could be studied, to see if new correlations could be found - or to confirm or disprove the correlations indicated in this work. The possible impacts of the stack effect should be further investigated, to see if this can be exploited during the colder months of the year. In addition, the correlation between wind data and the IAQ parameters can also be investigated.

If air change rates are to be used further, as a parameter of IAQ, a more exact model should be developed. By this, more detailed analysis of the whole measurement period could be studied to get a better understanding of the variations between the nights and the bedrooms.

If similar measurements are to be conducted using the same methodology, new methods of comparing size of window opening should be investigated. A solution for collecting information about door openings should also be included in the methodology, as was attempted in this work. In addition, a new sensor for evaluating the opening of side-hinged windows may also be considered – as the measurements by the ultrasonic sound sensor were not ideal. A gyroscope is an example of a possible solution. The formaldehyde sensors should be calibrated before further tests are conducted, and an additional re-calibration should be performed for the TVOC sensors that were found to measure very low concentrations during the field investigations.

References

1. *Klimaforliket*. 2014 16.12.19]; Available from: https://www.regjeringen.no/no/tema/klima-og-miljo/klima/innsiktsartikler-klima/klimaforliket/id2076645/.
2. Bygg21, *Bygg- og eiendomssektorens betydning for klimagassutslipp.* 2018.
3. *OPPTRE: Energioppgradering av småhus i tre til nesten nullenerginivå*. 16.12.19]; Available from: opptre.no.
4. Vaage, O.F., *Utendørs 2,5 time - menn mer enn kvinner* Tidsbruk 2010, Statistisk sentralbyrå 2012.
5. SINTEF, *ENØK i bygninger: Effektiv energibruk* 2016: p. 99-135.
6. *NS-EN ISO 7730 Ergonomi i termisk miljø.* 2006.
7. Cao, G., *Indoor environment - Indoor air quality.* Lecture slides from NTNU, 2019.
8. Folkehelseinstituttet, *Anbefalte faglige normer for inneklima. Revisjon av kunnskapsgrunnlag og normer* 2015.
9. Larsen, T.S. and P. Heiselberg, *Single-sided natural ventilation driven by wind pressure and temperature difference.* Energy and Buildings, 2008. 40(6): p. 1031-1040.
10. Østerbø, S., *Balansert ventilasjon.* Energismart, Naturvernforbundet, 2017.
11. Hou, J., et al., *Single and Multiple Zone Methods to Calculate Air Change Rate in Apartments.* Procedia Engineering, 2015. 121: p. 567-572.
12. Bekö, G., et al., *Ventilation rates in the bedrooms of 500 Danish children.* Building and Environment, 2010. 45(10): p. 2289-2295.
13. Ingebrigtsen, S., *Ventilasjonsteknikk (Del 1 og Del 2).* 2019.
14. Arbeidstilsynet, *Veiledning om Klima og luftkvalitet på arbeidsplassen* 2016.
15. *Carbon Dioxide*. Available from: https://www.dhs.wisconsin.gov/chemical/carbondioxide.htm.
16. *NS-EN 16798-1 Energy performance of buildings - Ventilation for buildings.* 2019.
17. WHO, *WHO Guidelines for indoor air quality: selected pollutants.* 2010.
18. WHO, *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Global update 2005.* 2005.
19. Wolkoff, P. and G.D. Nielsen, *Organic compounds in indoor air—their relevance for perceived indoor air quality?* Atmospheric Environment, 2001. 35(26): p. 4407-4417.
20. Airthings. *Total VOC*. 2019 01.06.20]; Available from: https://www.airthings.com/resources/voc-software-update.
21. *Indoor Air Quality* Available from: https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality.
22. *Byggteknisk forskrift (TEK17), Kapittel 13-2. Ventilasjon i boligbygning*. 2017 08.10.2019]; Available from: https://dibk.no/byggereglene/byggteknisk-forskrift-tek17/13/i/13-2/.
23. Katsoyiannis, A. and A. Cincinelli, *'Cocktails and dreams': the indoor air quality that people are exposed to while sleeping.* Current Opinion in Environmental Science & Health, 2019. 8: p. 6-9.
24. Leif Øie, H.S., Carl-Axel Boman, Vidar Hellstrand, *The Ventilation Rate of 344 Oslo Residences.* 1998.
25. Langer, S. and G. Bekö, *Indoor air quality in the Swedish housing stock and its dependence on building characteristics.* Building and Environment, 2013. 69: p. 44-54.
26. Bornehag, C.G., et al., *Association between ventilation rates in 390 Swedish homes and allergic symptoms in children.* Indoor Air, 2005. 15(4): p. 275-80.
27. Kotol, M., et al., *Indoor environment in bedrooms in 79 Greenlandic households.* Building and Environment, 2014. 81: p. 29-36.

28. Berge, M. and H.M. Mathisen, *Perceived and measured indoor climate conditions in high-performance residential buildings.* Energy and Buildings, 2016. 127: p. 1057-1073.
29. Langer, S., et al., *Indoor air quality in passive and conventional new houses in Sweden.* Building and Environment, 2015. 93: p. 92-100.
30. Canha, N., et al., *Indoor air quality during sleep under different ventilation patterns.* Atmospheric Pollution Research, 2017. 8(6): p. 1132-1142.
31. Zalejska-Jonsson, A. and M. Wilhelmsson, *Impact of perceived indoor environment quality on overall satisfaction in Swedish dwellings.* Building and Environment, 2013. 63: p. 134-144.
32. Frontczak, M., R.V. Andersen, and P. Wargocki, *Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing.* Building and Environment, 2012. 50: p. 56-64.
33. Frontczak, M. and P. Wargocki, *Literature survey on how different factors influence human comfort in indoor environments.* Building and Environment, 2011. 46(4): p. 922-937.
34. Tommerup, H.M., *Measurement results and experiences from an energy renovation of a typical Danish single-family house*. 2008, Danish Society of Engineers, IDA: Copenhagen, Denmark. p. 1111-1118.
35. Thomsen, K.E., et al., *Energy consumption and indoor climate in a residential building before and after comprehensive energy retrofitting.* Energy and Buildings, 2016. 123: p. 8-16.
36. Toftum, J., *Central automatic control or distributed occupant control for better indoor environment quality in the future.* Building and Environment, 2010. 45(1): p. 23-28.
37. Sarran, L., C.A. Hviid, and C. Rode, *Correlation between perceived usability of building services and indoor environmental satisfaction in retrofitted low-energy homes.* Building and Environment, 2020: p. 106946.
38. Liu, L., P. Rohdin, and B. Moshfegh, *Evaluating indoor environment of a retrofitted multi-family building with improved energy performance in Sweden.* Energy and Buildings, 2015. 102: p. 32-44.
39. Morelli, M., et al., *Energy retrofitting of a typical old Danish multi-family building to a "nearly-zero" energy building based on experiences from a test apartment.* Energy and Buildings, 2012. 54: p. 395-406.
40. Bjorvatn, B., et al., *Age and sex differences in bedroom habits and bedroom preferences.* Sleep Medicine, 2017. 32: p. 157-161.
41. Berge, M., L. Georges, and H.M. Mathisen, *On the oversupply of heat to bedrooms during winter in highly insulated dwellings with heat recovery ventilation.* Building and Environment, 2016. 106: p. 389-401.
42. Hesaraki, A., J.A. Myhren, and S. Holmberg, *Influence of different ventilation levels on indoor air quality and energy savings: A case study of a single-family house.* Sustainable Cities and Society, 2015. 19: p. 165-172.
43. Andersen, R., et al., *Window opening behaviour modelled from measurements in Danish dwellings.* Building and Environment, 2013. 69: p. 101-113.
44. Gram, O.K., *Use of low cost pollutant sensors for developing healthy demand controlled ventilation strategies* 2019.
45. *Pegasor AQ Indoor (Datasheet)*. 01.06.20]; Available from: https://www.etserv.be/wp-content/uploads/2017/05/pegasor_indoor_brochure_2015_web.pdf.
46. *Wisensys WSE-DLC* 01.06.20]; Available from: https://wisensys.com/products/indoor-air-quality-sensor/.
47. *Wisensys Base Station WS-BU (Datasheet)*. 01.06.20]; Available from: https://wisensys.com/products/indoor-air-quality-sensor/.
48. *SHTC1 (Datasheet)*. 01.06.20]; Available from: https://www.mouser.com/datasheet/2/682/Sensirion_Humidity_Sensors_SHTC1_Datasheet_V4-1109411.pdf.

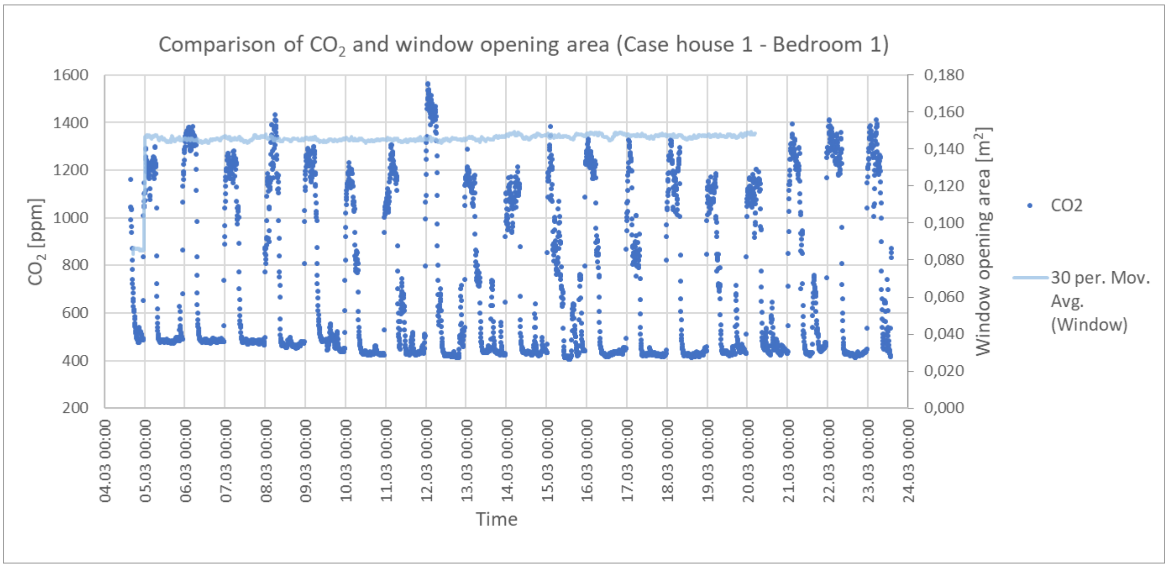
49. *Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation*.
50. *NorDan Vinduer*. Available from: https://www.nordan.no/vinduer/vinduer.
51. Andresen, G., *Akselerometer.* Store norske leksikon, 2018.
52. I, B. and R. Rajesh, *Tilt Angle Detector Using 3-Axis Accelerometer.* 2018. 4.
53. *BBC micro:bit*. 2015; Available from: https://www.bbc.co.uk/mediacentre/mediapacks/microbit.
54. *Pritt Multi Tack*
55. Holtet, J.A., *Magnetometer.* Store norske leksikon, 2018.
56. *Ultrasonic Sensor FAQs*. Available from: https://www.senix.com/ultrasonic-sensor-faqs/.
57. *Influencing Factors on Ultrasonic Sensors*. Available from: https://www.levelsensorsolutions.com/influencing-factors-on-ultrasonic-sensors-i-61.html.
58. *Ultrasonic distance sensor RCWL-1601 (Datasheet)*. 01.06.20]; Available from: https://media.digikey.com/pdf/Data%20Sheets/Adafruit%20PDFs/4007_Web.pdf.
59. *SparkFun Distance Sensor Breakout - RFD77402 (Qwiic)*. Available from: https://www.sparkfun.com/products/14539.
60. *Gardiner*. 16.12.19]; Available from: uniggardin.no.
61. *Weather observations and statistics.*
62. *2001 ASHRAE Handbook: fundamentals.* 2001.
63. Strøm-Tejsen, P., et al., *The effects of bedroom air quality on sleep and next-day performance.* Indoor Air, 2016. 26(5): p. 679-686.
64. Persily, A. and L. De Jonge, *Carbon Dioxide Generation Rates from Building Occupants.* Indoor Air, 2017. 27.

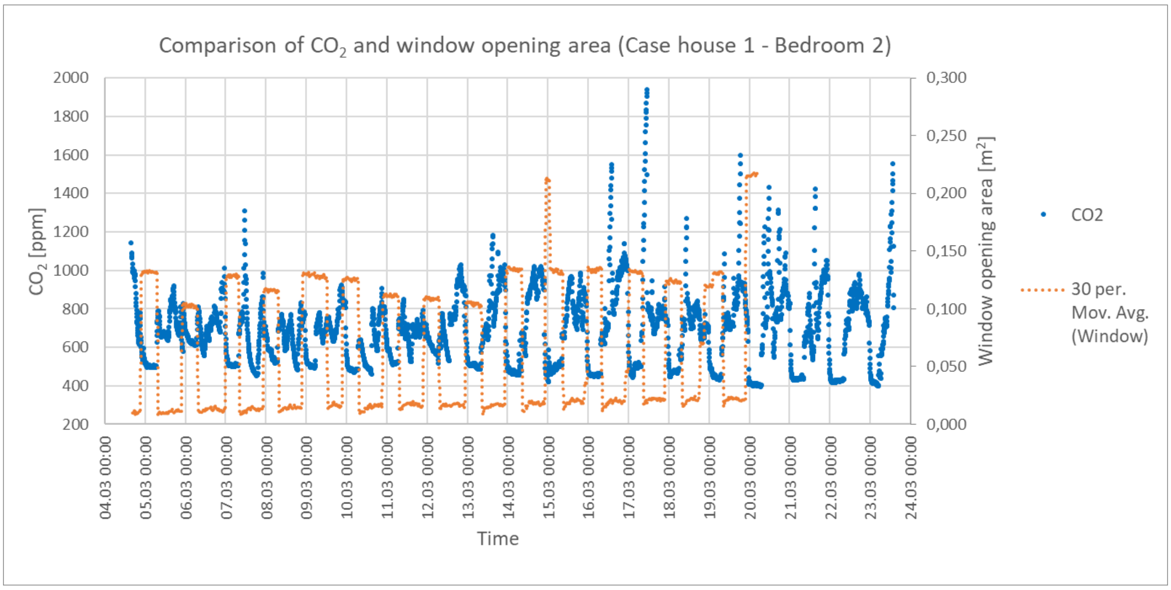
Appendix A

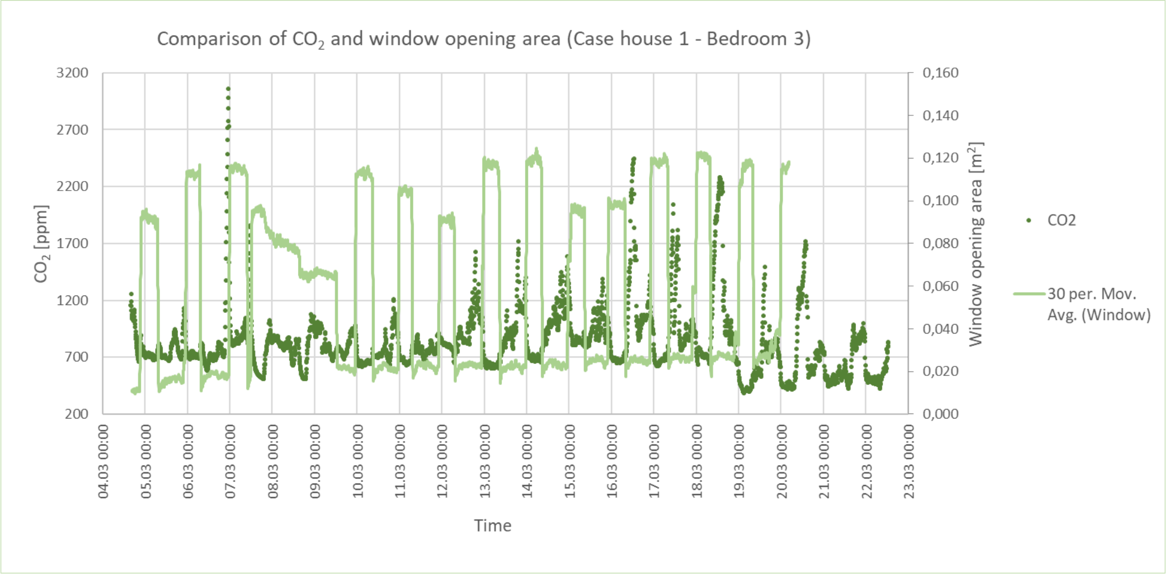
A.1: IAQ parameters

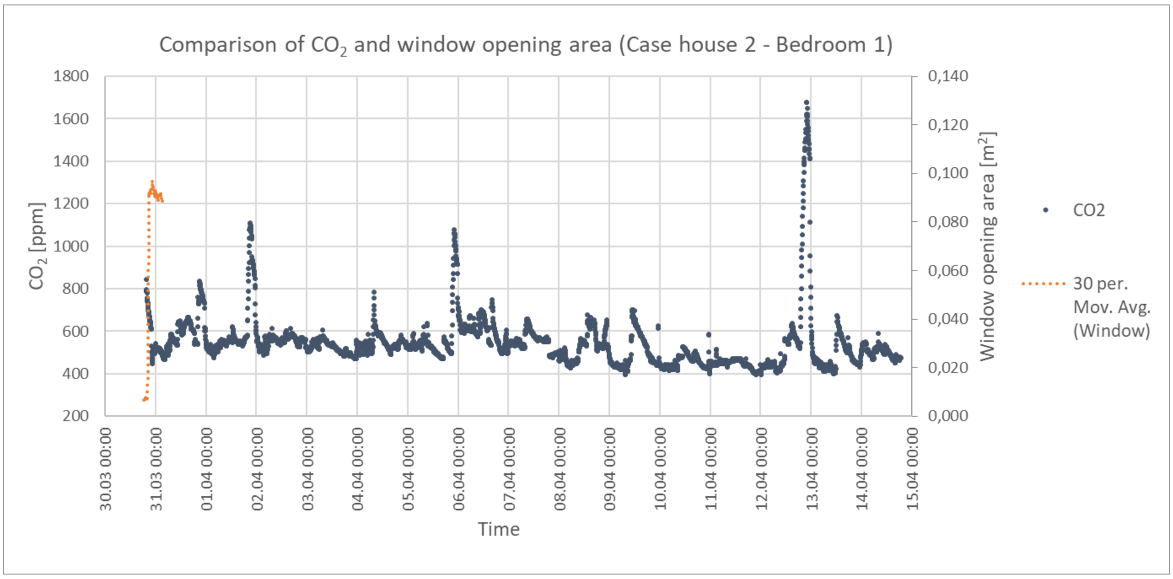
The variations of IAQ parameters that was not displayed in the result section, are displayed in this section.

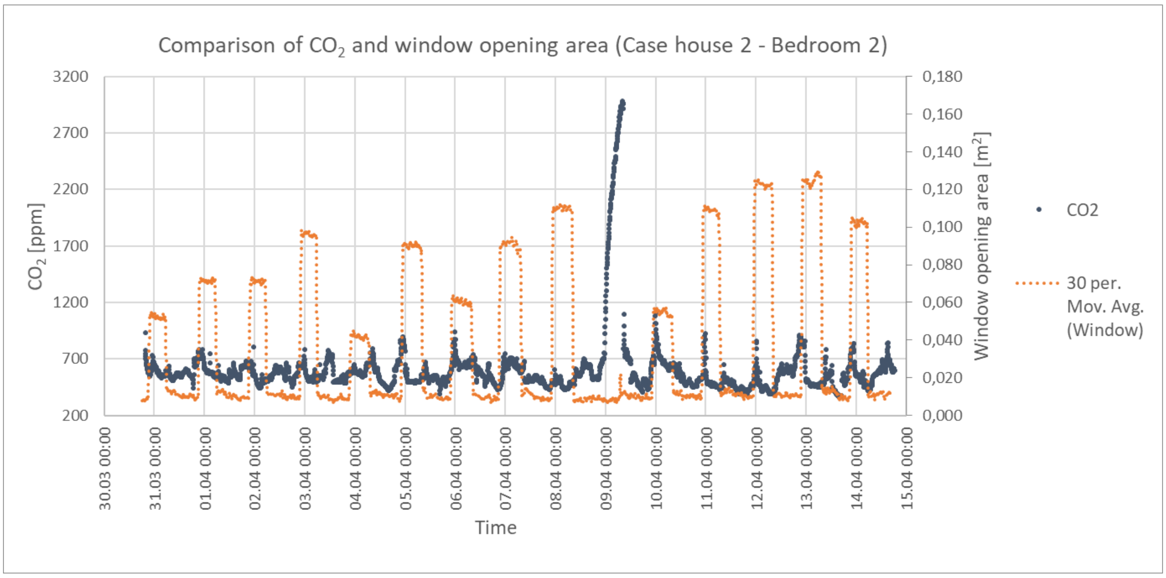
A.1.1: CO_2

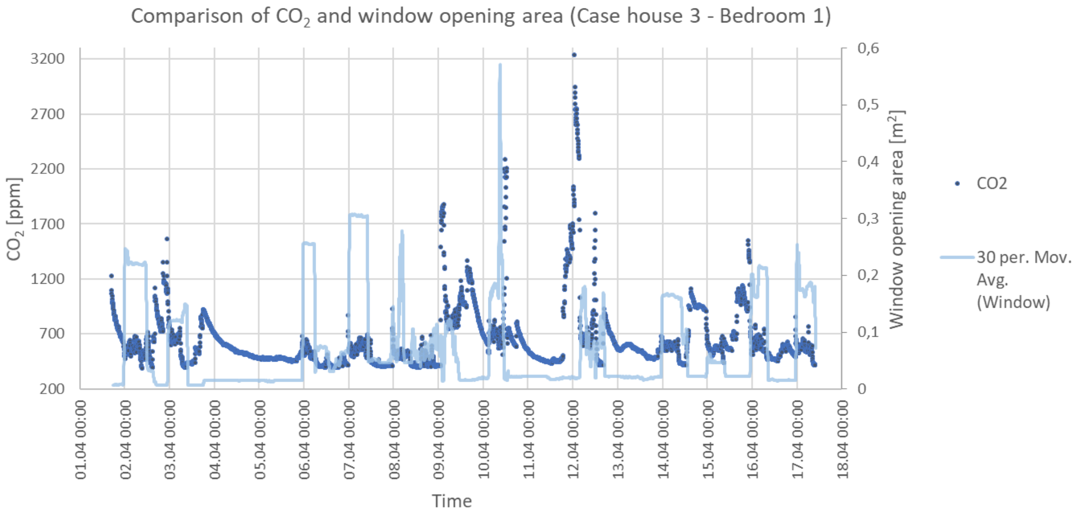




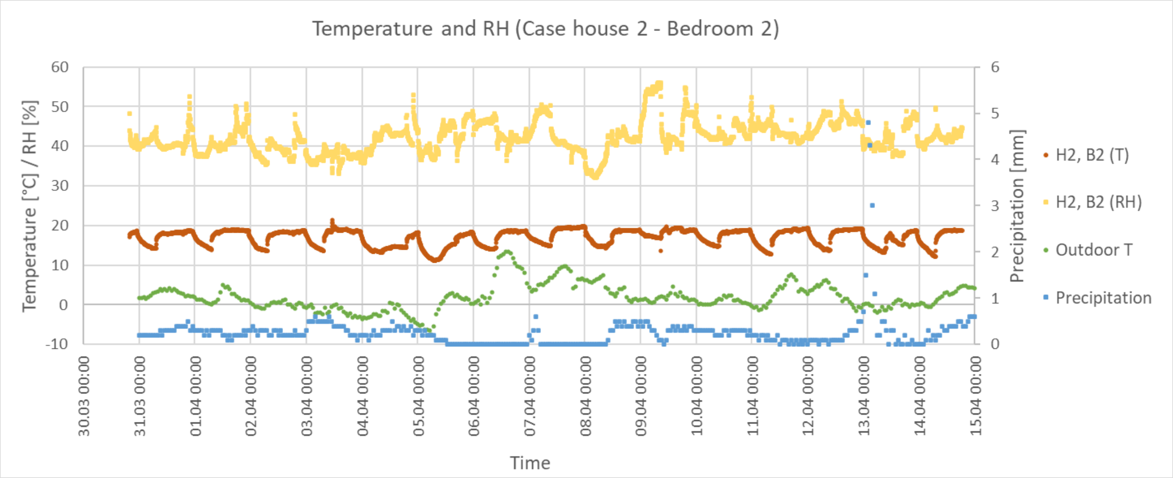

Comparison of CO_2 and window opening area (Case house 1 - Bedroom 3)
CO_2 [ppm]
3200
2700
2200
1700
1200
700
200
Window opening area [m^2]
0,160
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
21.03 00:00
22.03 00:00
23.03 00:00
Time
CO2
30 per. Mov. Avg. (Window)

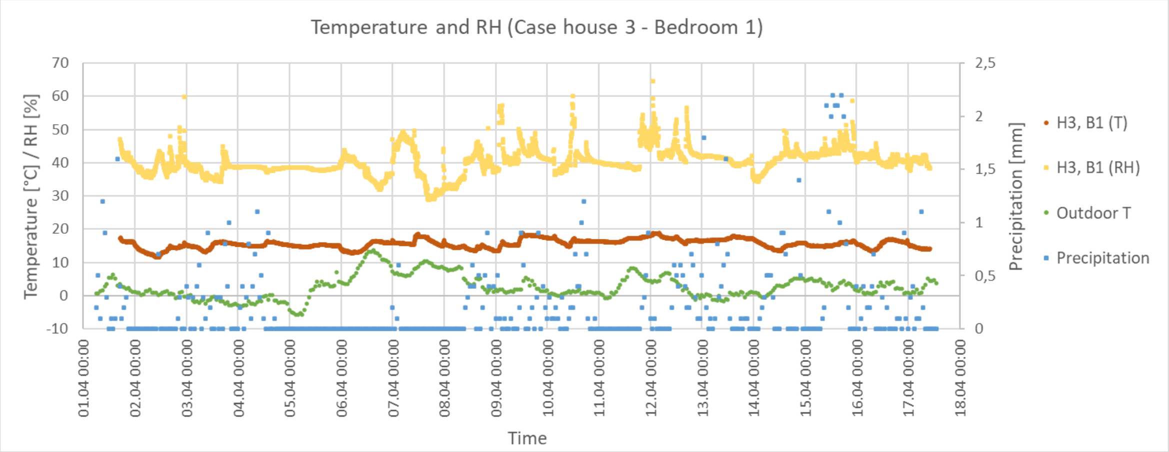

Comparison of CO_2 and window opening area (Case house 2 - Bedroom 1)
CO_2 [ppm]
1800
1600
1400
1200
1000
800
600
400
200
Window opening area [m^2]
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
CO2
30 per. Mov. Avg. (Window)

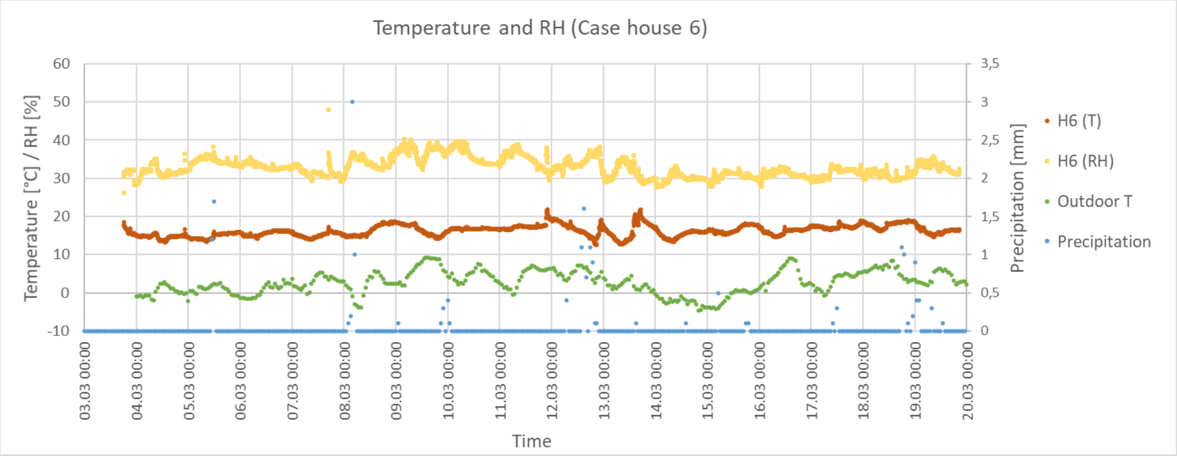

Comparison of CO_2 and window opening area (Case house 2 - Bedroom 2)
CO_2 [ppm]
3200
2700
2200
1700
1200
700
200
Window opening area [m^2]
0,180
0,160
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
CO2
30 per. Mov. Avg. (Window)

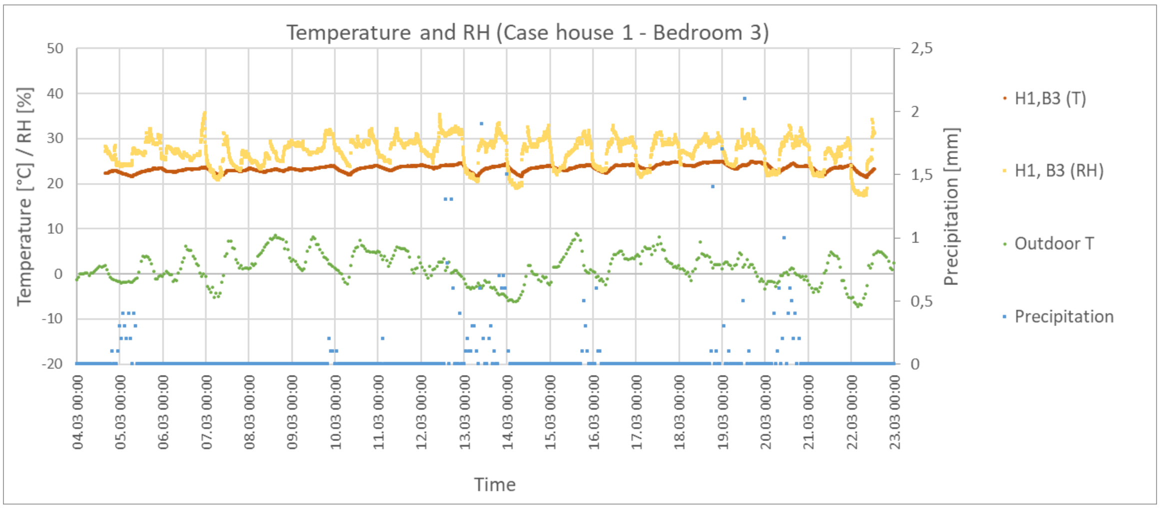

Comparison of CO$_2$ and window opening area (Case house 3 - Bedroom 1)
CO$_2$ [ppm]
3200
2700
2200
1700
1200
700
200
Window opening area [m^2]
0,6
0,5
0,4
0,3
0,2
0,1
0
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
16.04 00:00
17.04 00:00
18.04 00:00
Time
CO2
30 per. Mov. Avg. (Window)

A.1.2: Temperature and RH

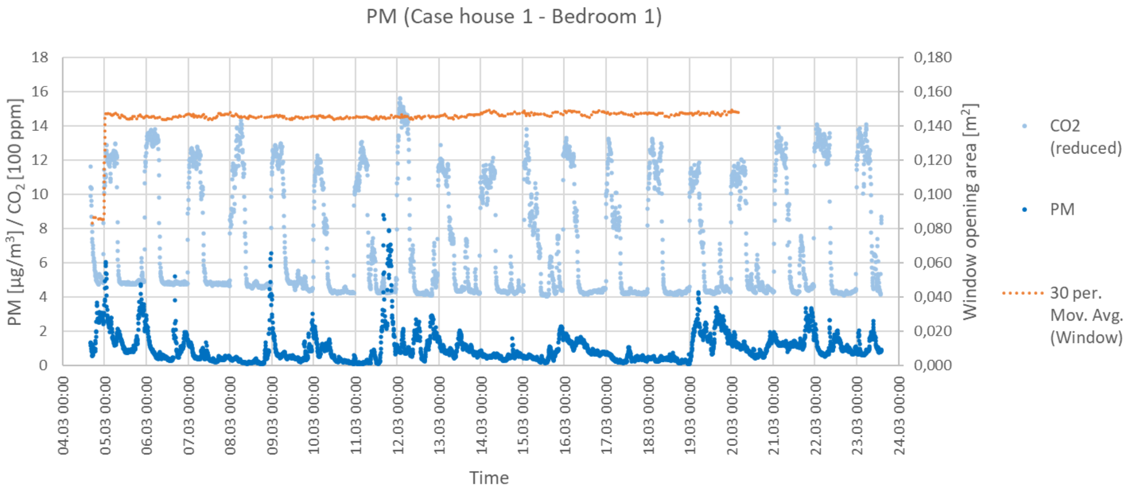


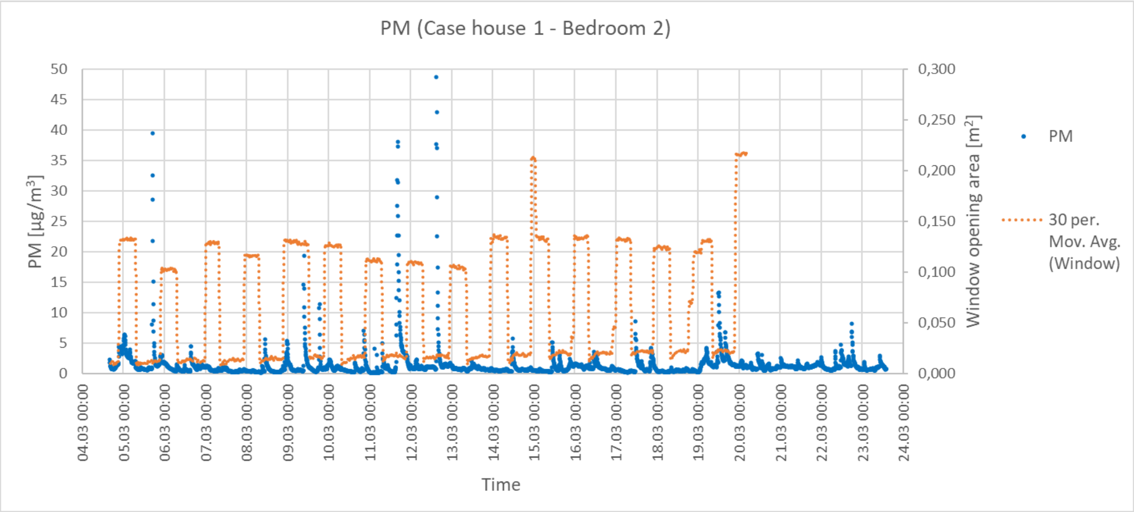


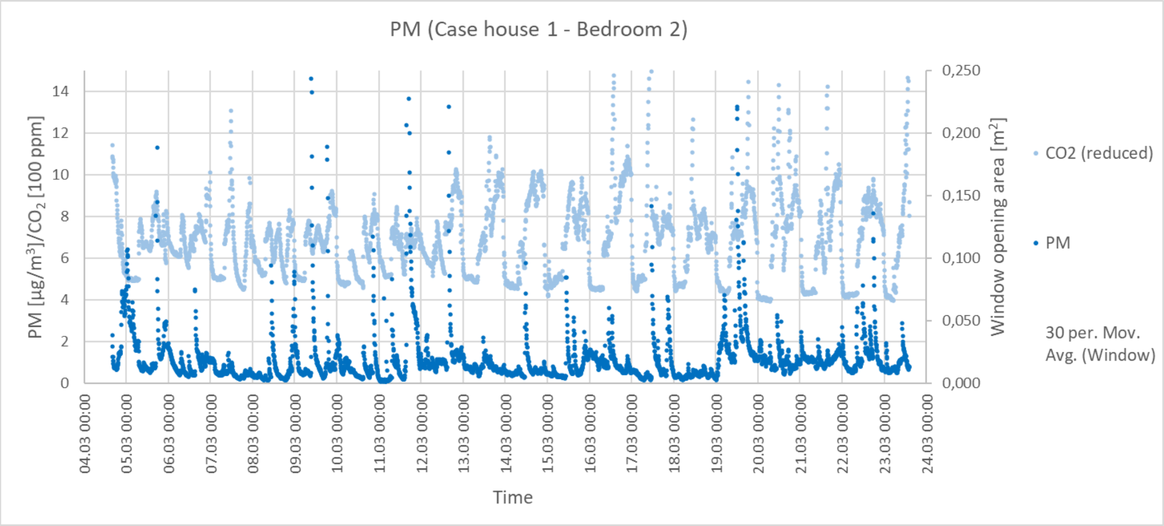


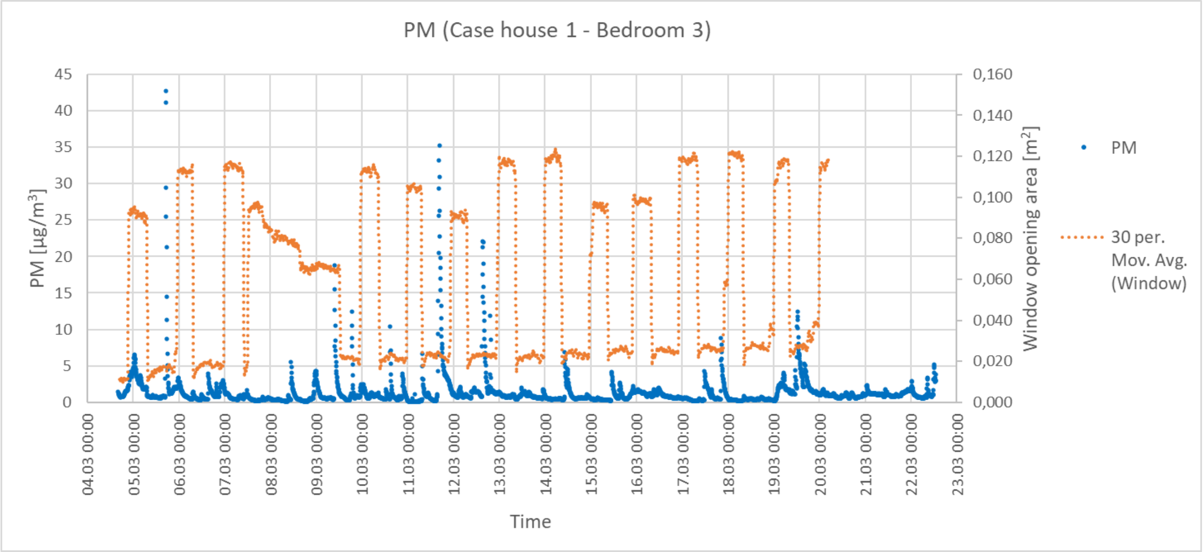

Temperature and RH (Case house 1 - Bedroom 3)
Temperature [°C] / RH [%]
50
40
30
20
10
0
-10
-20
Precipitation [mm]
2,5
2
1,5
1
0,5
0
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
21.03 00:00
22.03 00:00
23.03 00:00
Time
H1,B3 (T)
H1, B3 (RH)
Outdoor T
Precipitation

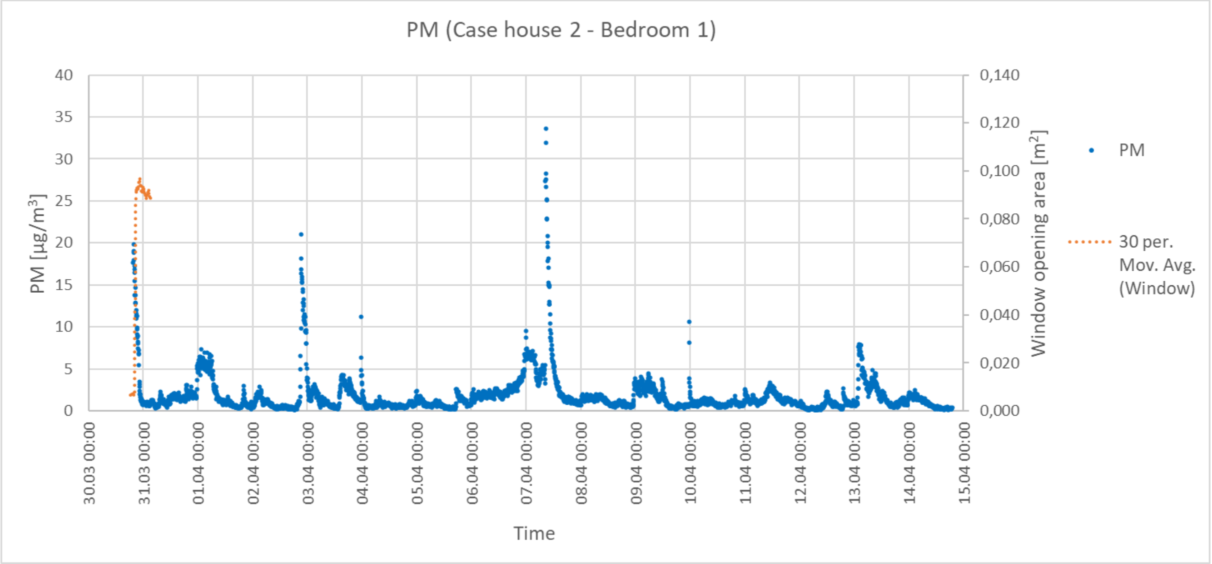
A.1.3: PM

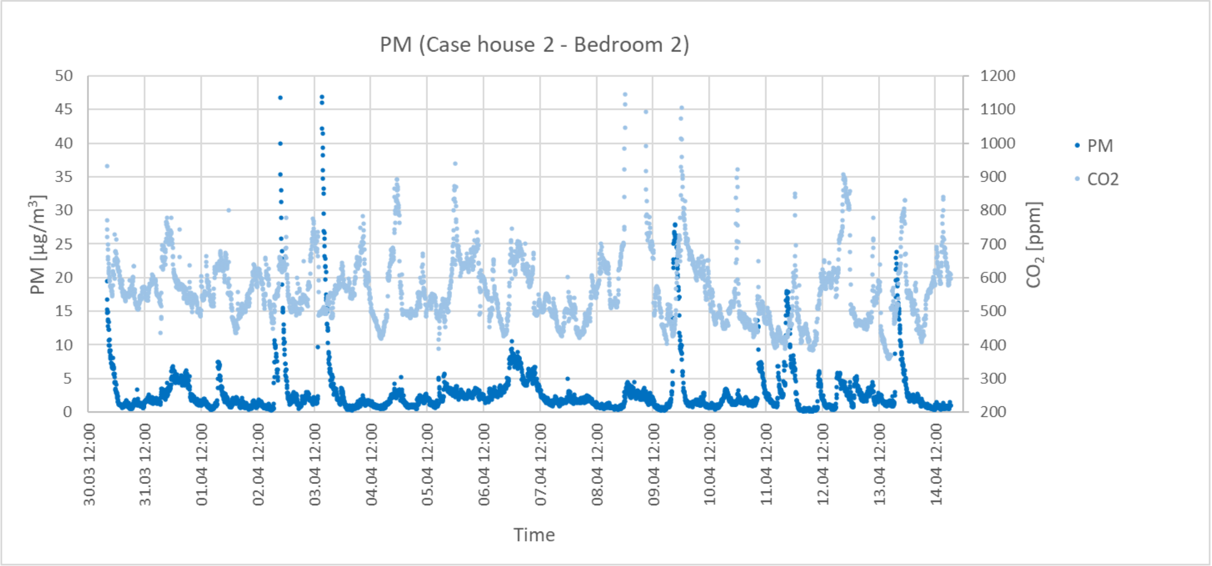

PM (Case house 1 - Bedroom 1)
PM [µg/m³] / CO₂ [100 ppm]
18
16
14
12
10
8
6
4
2
0
Window opening area [m²]
0,180
0,160
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
21.03 00:00
22.03 00:00
23.03 00:00
24.03 00:00
Time
CO2 (reduced)
PM
30 per. Mov. Avg. (Window)

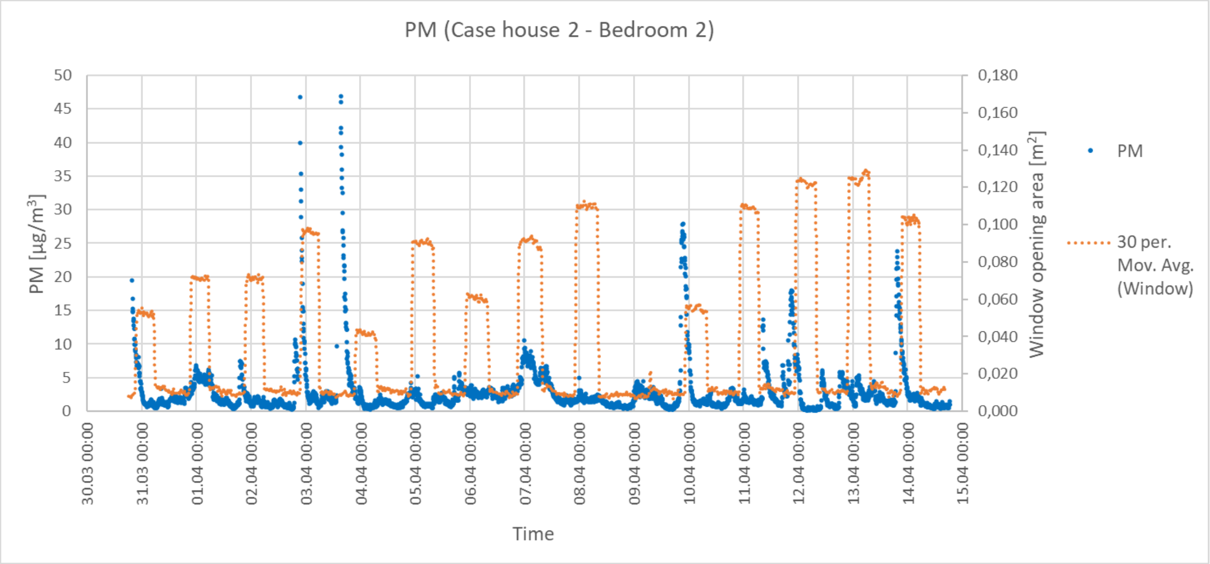

PM (Case house 1 - Bedroom 2)
PM [µg/m³]
50
45
40
35
30
25
20
15
10
5
0
Window opening area [m²]
0,300
0,250
0,200
0,150
0,100
0,050
0,000
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
21.03 00:00
22.03 00:00
23.03 00:00
24.03 00:00
Time
PM
30 per. Mov. Avg. (Window)

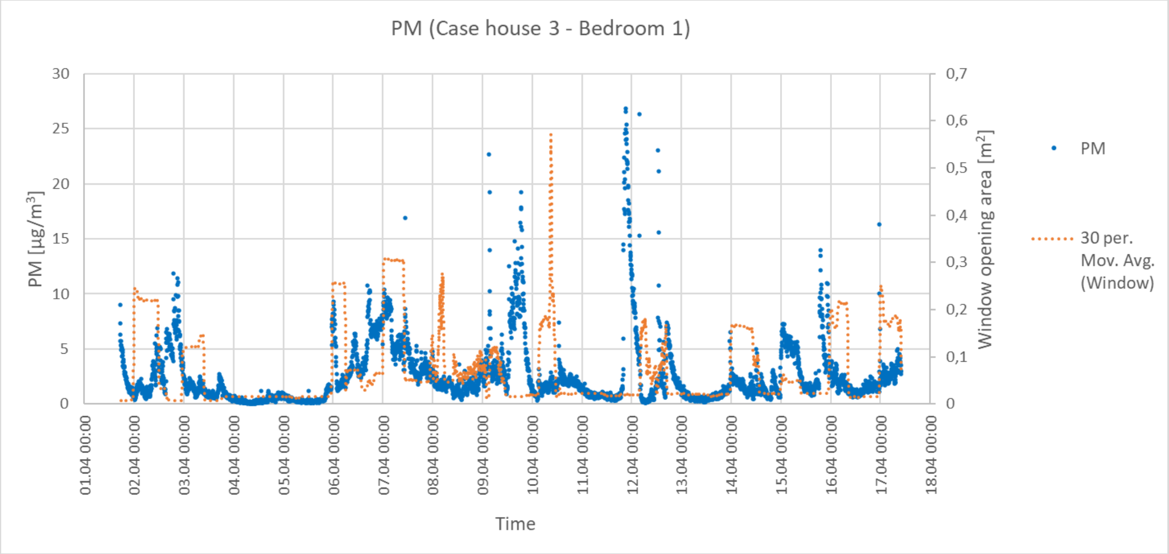

PM (Case house 1 - Bedroom 2)
PM [µg/m³]/CO₂ [100 ppm]
14
12
10
8
6
4
2
0
Window opening area [m²]
0,250
0,200
0,150
0,100
0,050
0,000
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
21.03 00:00
22.03 00:00
23.03 00:00
24.03 00:00
Time
CO2 (reduced)
PM
30 per. Mov. Avg. (Window)

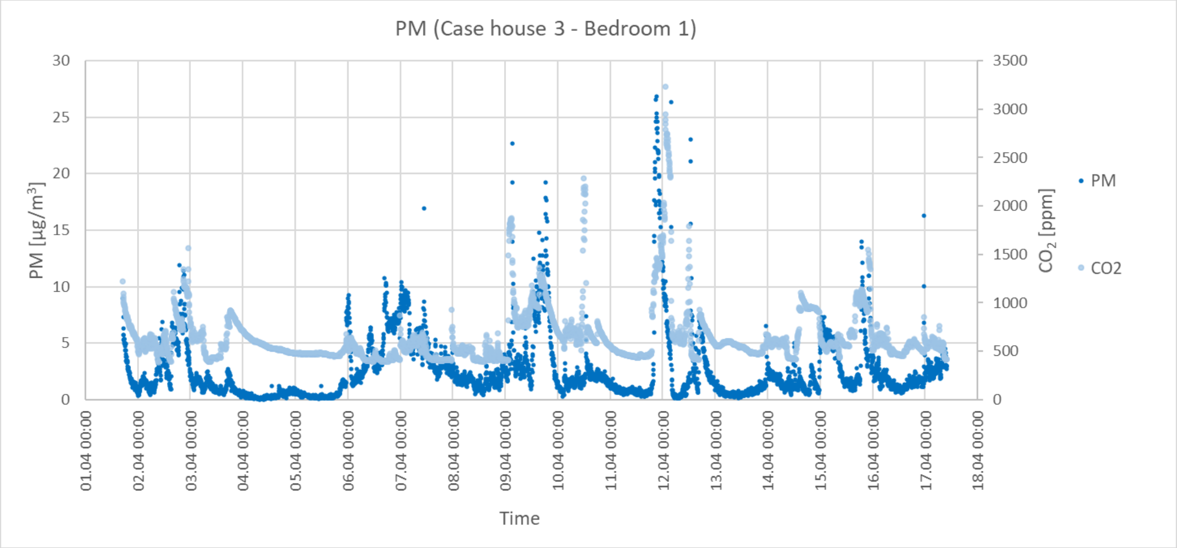

PM (Case house 1 - Bedroom 3)
PM [µg/m³]
45
40
35
30
25
20
15
10
5
0
Window opening area [m²]
0,160
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
21.03 00:00
22.03 00:00
23.03 00:00
Time
PM
30 per. Mov. Avg. (Window)

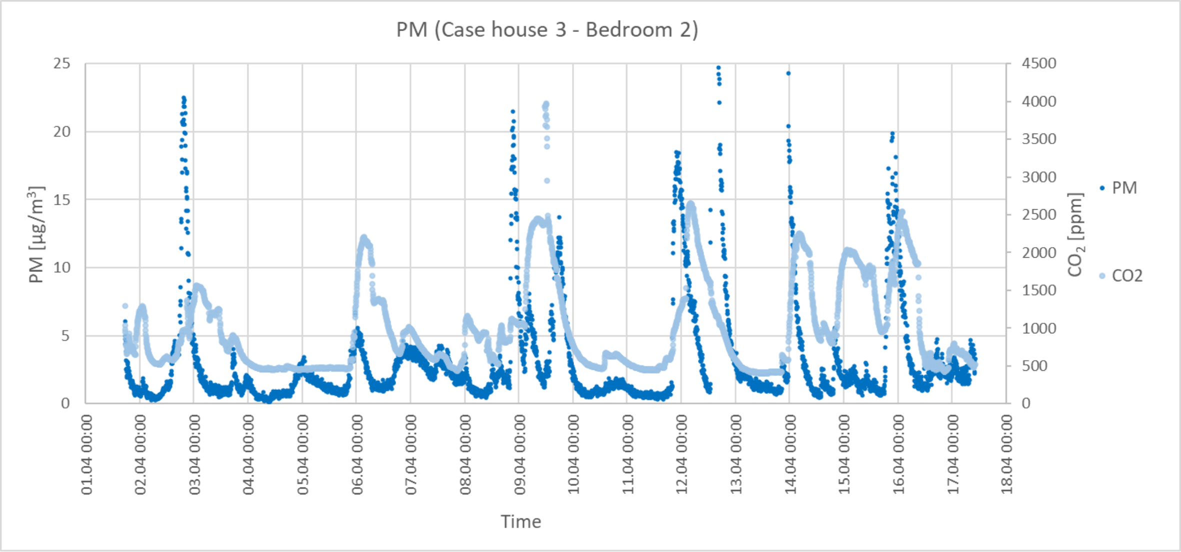

PM (Case house 2 - Bedroom 1)
PM [µg/m³]
40
35
30
25
20
15
10
5
0
Window opening area [m²]
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
PM
30 per. Mov. Avg. (Window)

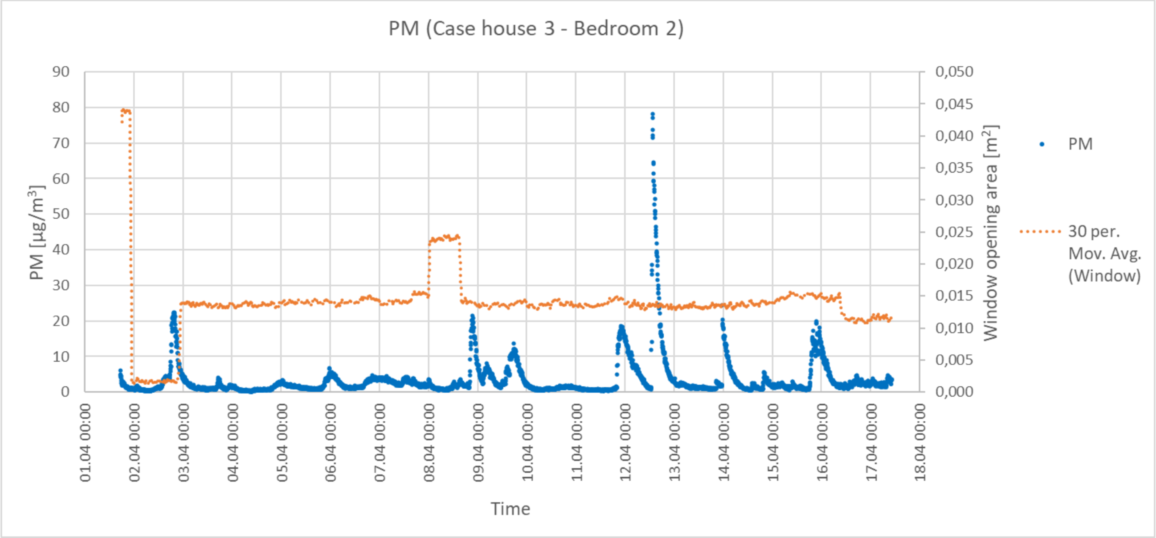

PM (Case house 2 - Bedroom 2)
PM [µg/m³]
50
45
40
35
30
25
20
15
10
5
0
CO₂ [ppm]
1200
1100
1000
900
800
700
600
500
400
300
200
30.03 12:00
31.03 12:00
01.04 12:00
02.04 12:00
03.04 12:00
04.04 12:00
05.04 12:00
06.04 12:00
07.04 12:00
08.04 12:00
09.04 12:00
10.04 12:00
11.04 12:00
12.04 12:00
13.04 12:00
14.04 12:00
Time
PM
CO2

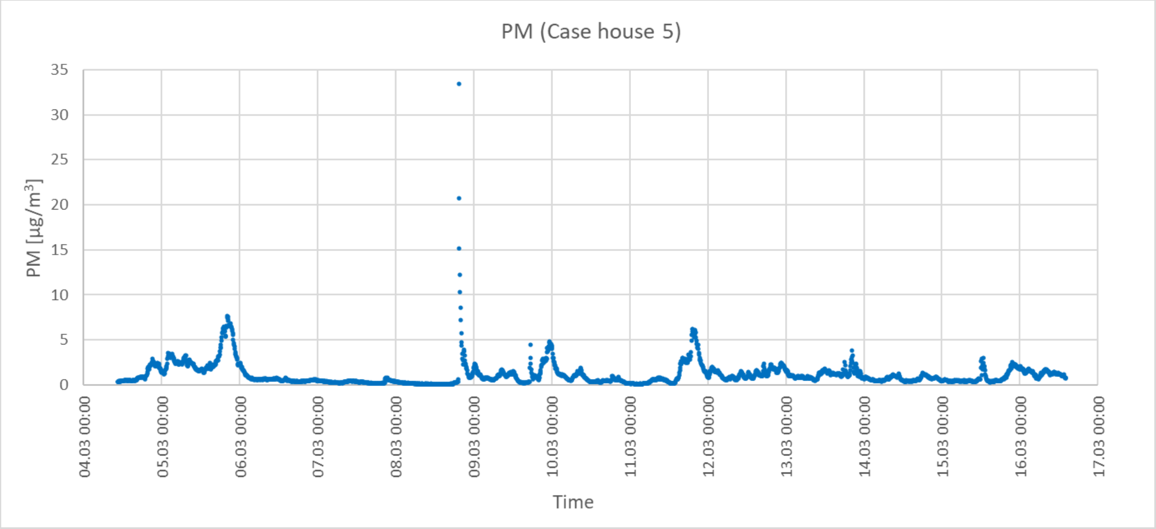

PM (Case house 2 - Bedroom 2)
PM [µg/m³]
50
45
40
35
30
25
20
15
10
5
0
0,180
0,160
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
Window opening area [m²]
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
PM
30 per. Mov. Avg. (Window)

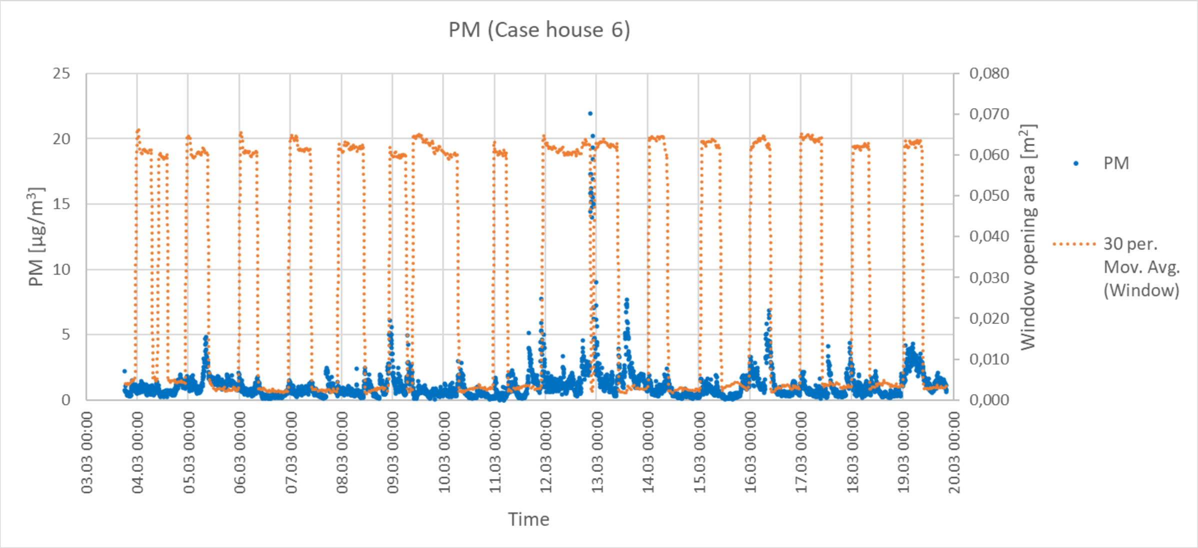

PM (Case house 3 - Bedroom 1)
PM [µg/m³]
30
25
20
15
10
5
0
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
Window opening area [m²]
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
16.04 00:00
17.04 00:00
18.04 00:00
Time
PM
30 per. Mov. Avg. (Window)


PM (Case house 3 - Bedroom 1)
PM [µg/m³]
30
25
20
15
10
5
0
3500
3000
2500
2000
1500
1000
500
0
CO₂ [ppm]
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
16.04 00:00
17.04 00:00
18.04 00:00
Time
PM
CO2

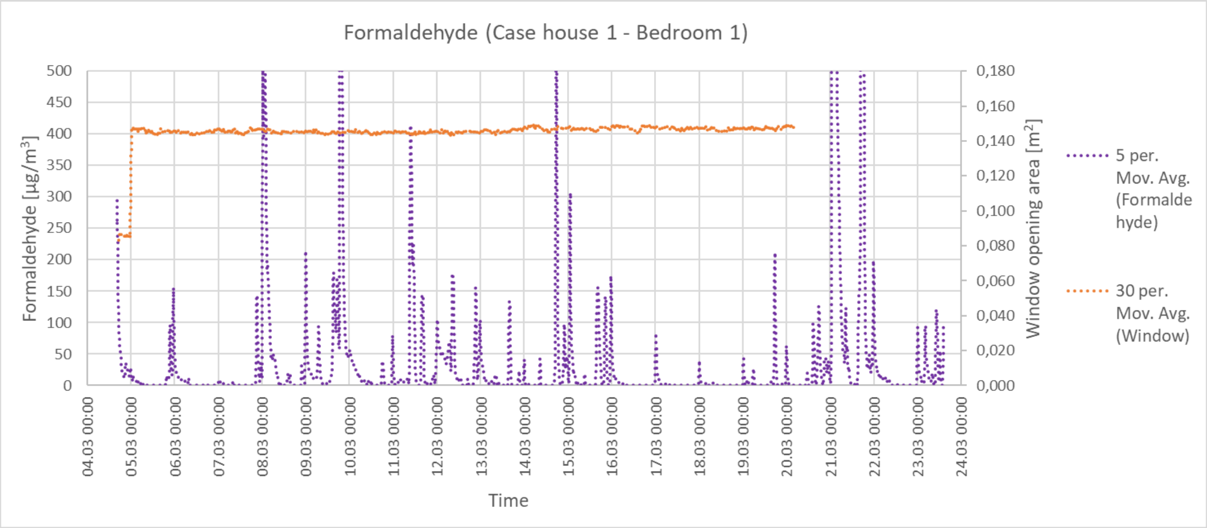

PM (Case house 3 - Bedroom 2)
PM [µg/m³]
25
20
15
10
5
0
CO₂ [ppm]
4500
4000
3500
3000
2500
2000
1500
1000
500
0
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
16.04 00:00
17.04 00:00
18.04 00:00
Time
PM
CO2

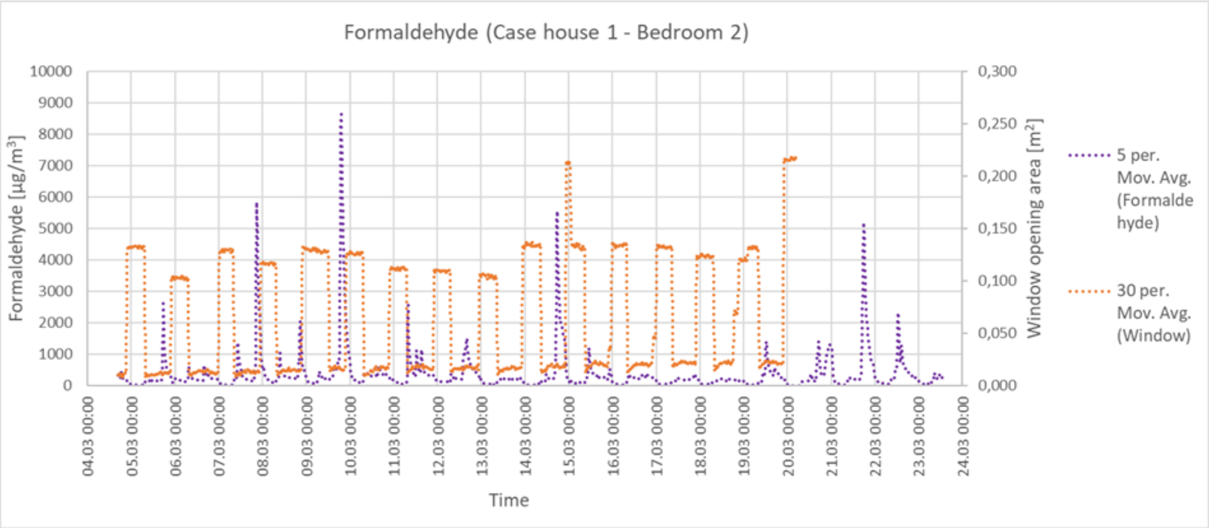

PM (Case house 3 - Bedroom 2)
PM [µg/m³]
90
80
70
60
50
40
30
20
10
0
Window opening area [m²]
0,050
0,045
0,040
0,035
0,030
0,025
0,020
0,015
0,010
0,005
0,000
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
16.04 00:00
17.04 00:00
18.04 00:00
Time
PM
30 per. Mov. Avg. (Window)

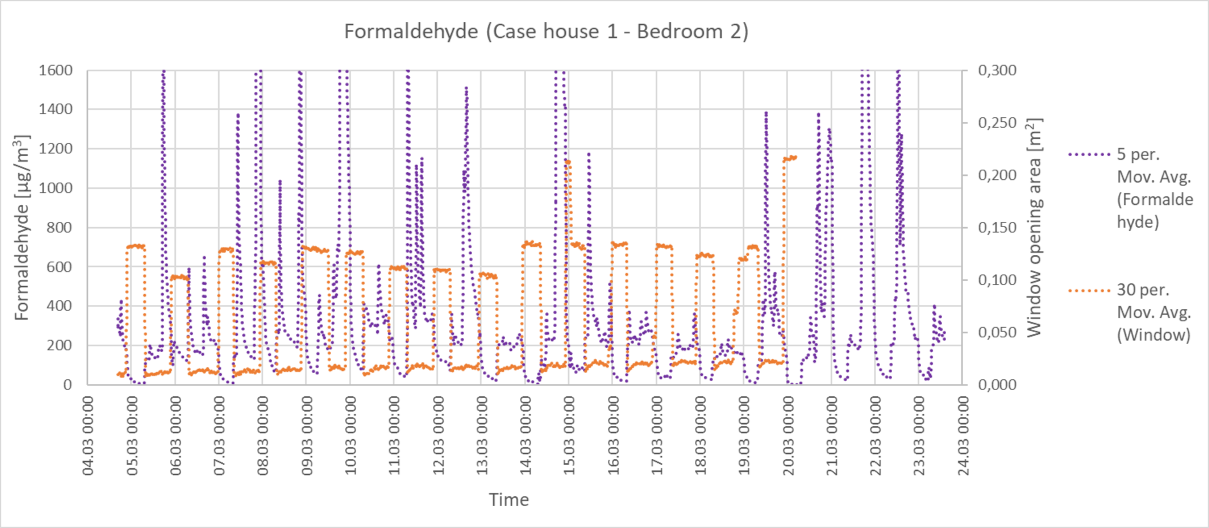

PM (Case house 5)
PM [µg/m³]
35
30
25
20
15
10
5
0
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
Time

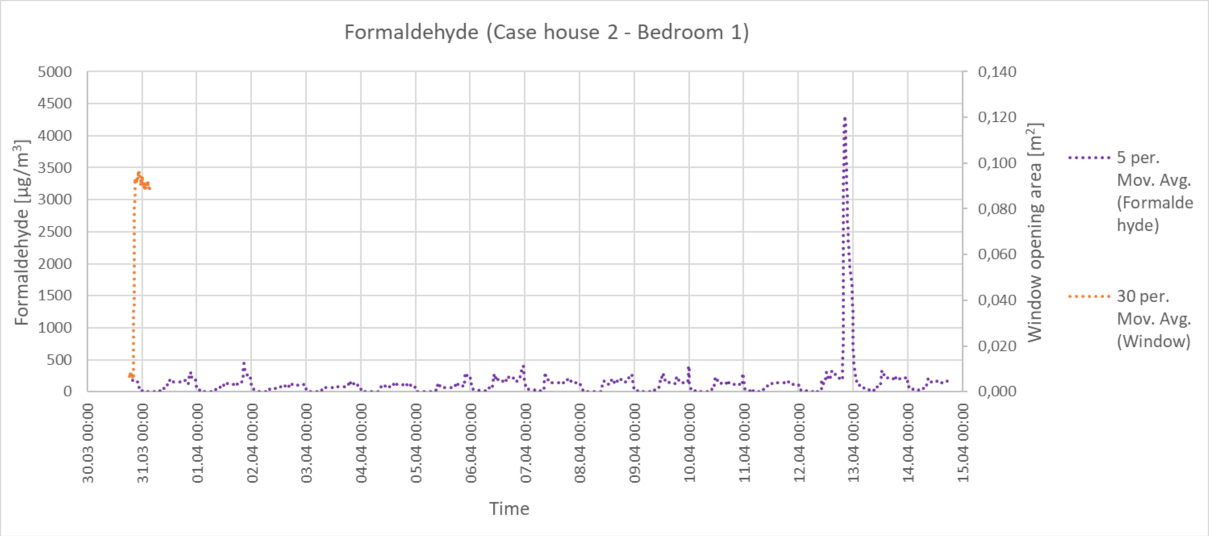

PM (Case house 6)
PM [µg/m3]
25
20
15
10
5
0
Window opening area [m2]
0,080
0,070
0,060
0,050
0,040
0,030
0,020
0,010
0,000
03.03 00:00
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
Time
PM
30 per. Mov. Avg. (Window)

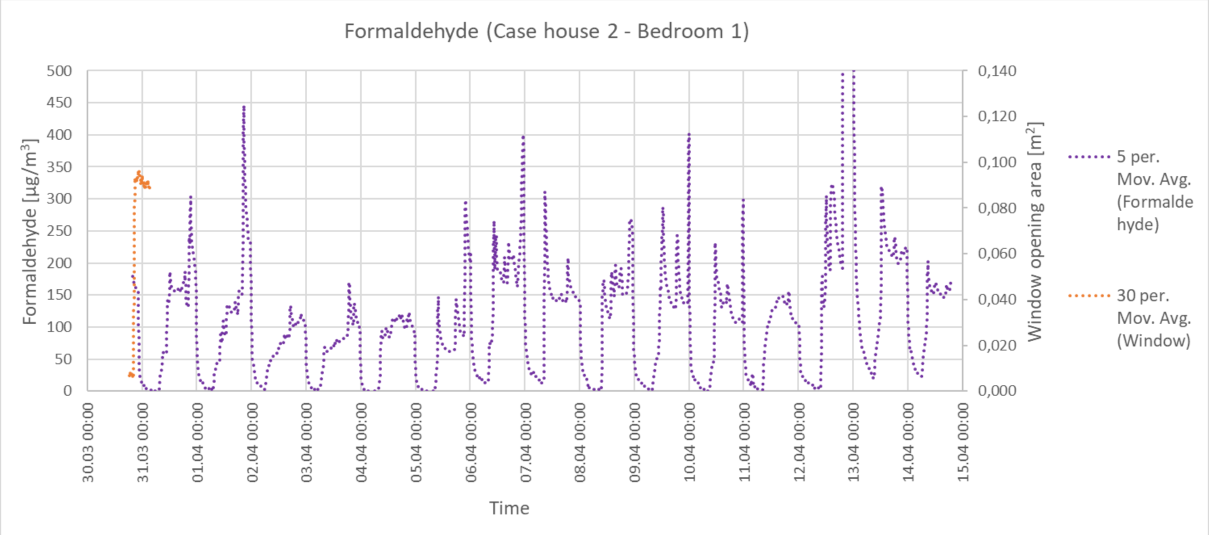
A.1.4: Formaldehyde

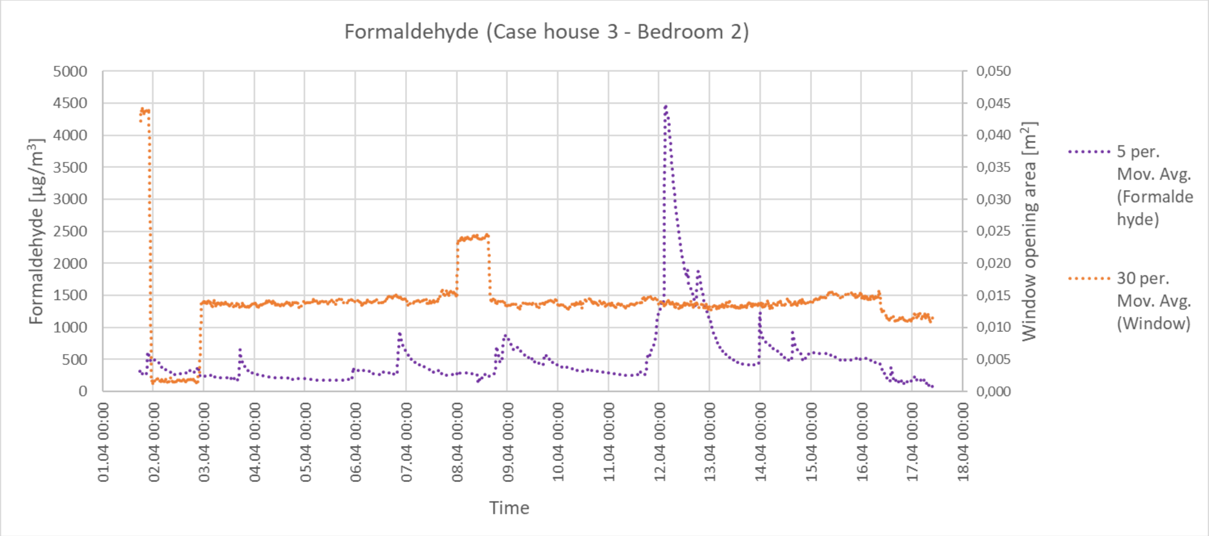


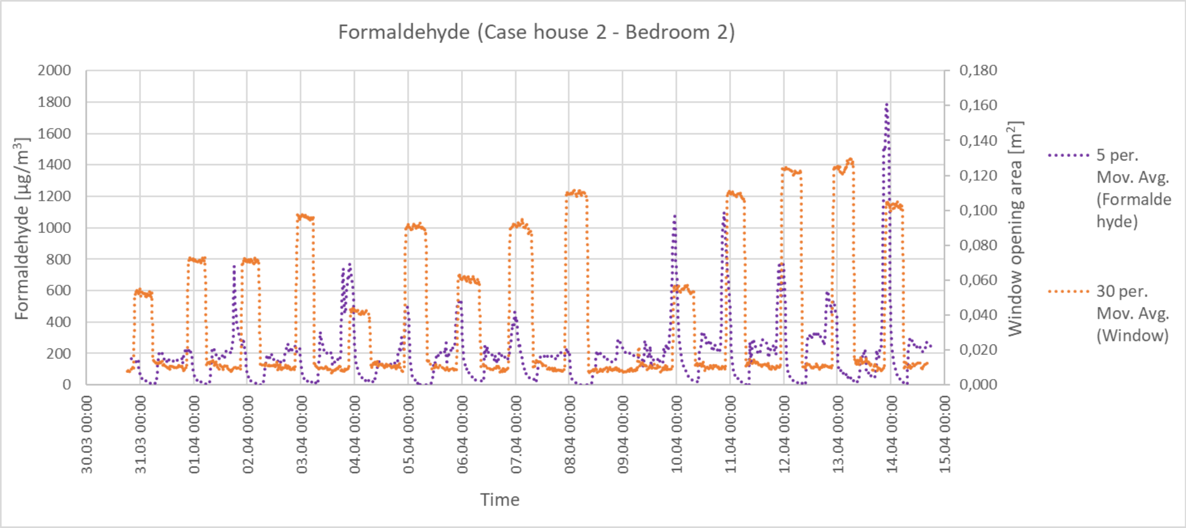


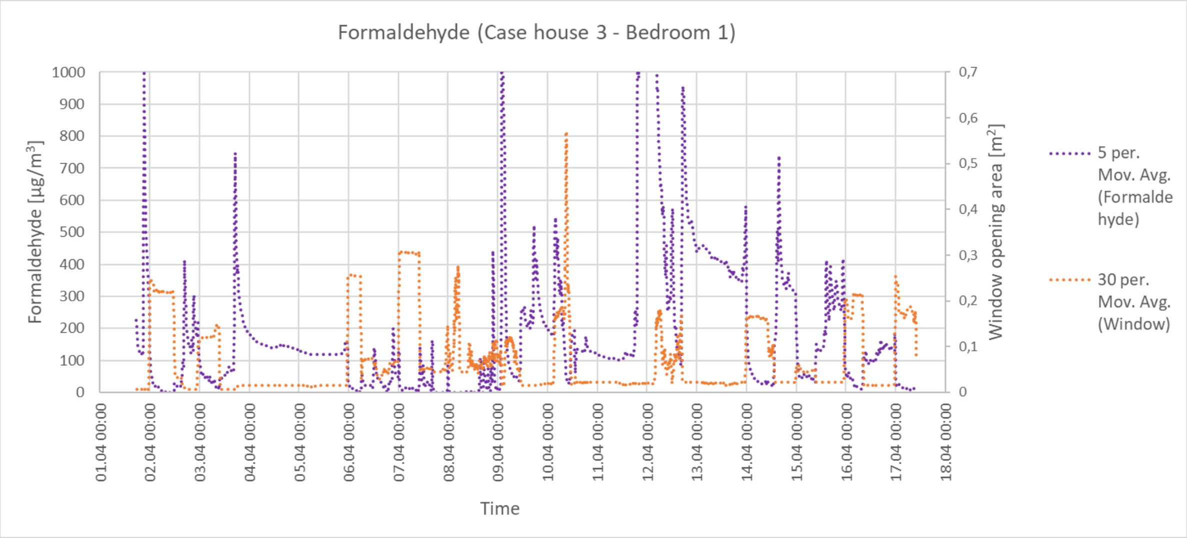


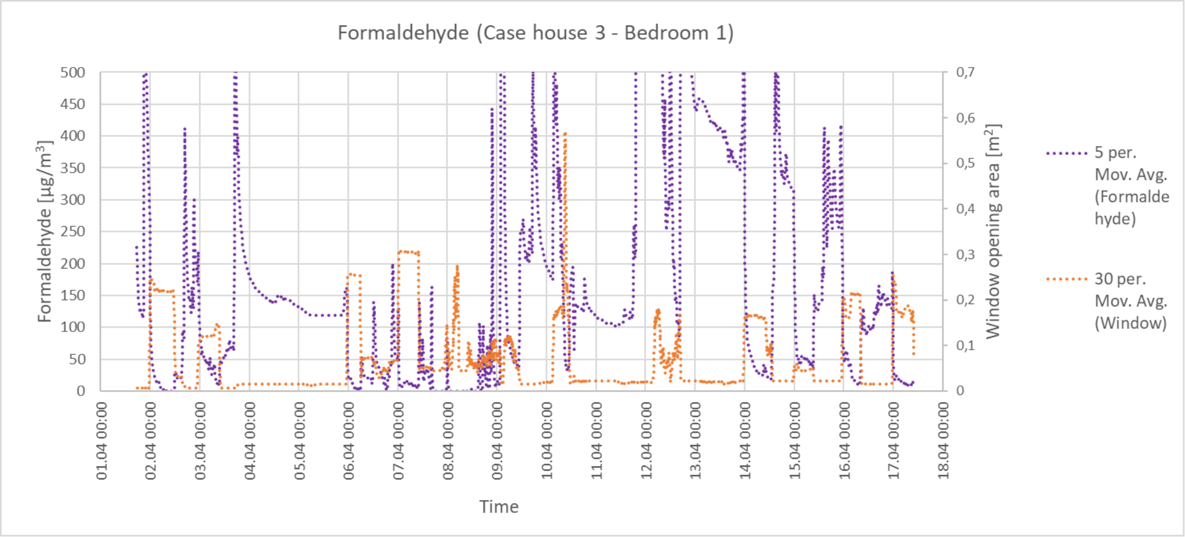

Formaldehyde (Case house 2 - Bedroom 1)
Formaldehyde [µg/m³]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Window opening area [m²]
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
5 per. Mov. Avg. (Formaldehyde)
30 per. Mov. Avg. (Window)

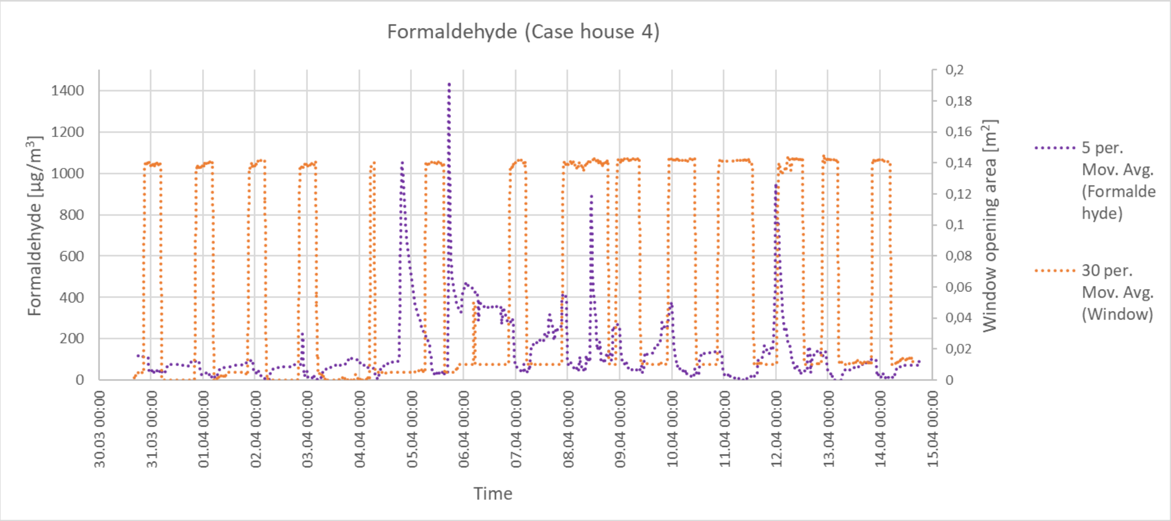

Formaldehyde (Case house 2 - Bedroom 1)
Formaldehyde [µg/m³]
500
450
400
350
300
250
200
150
100
50
0
Window opening area [m²]
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
5 per. Mov. Avg. (Formaldehyde)
30 per. Mov. Avg. (Window)

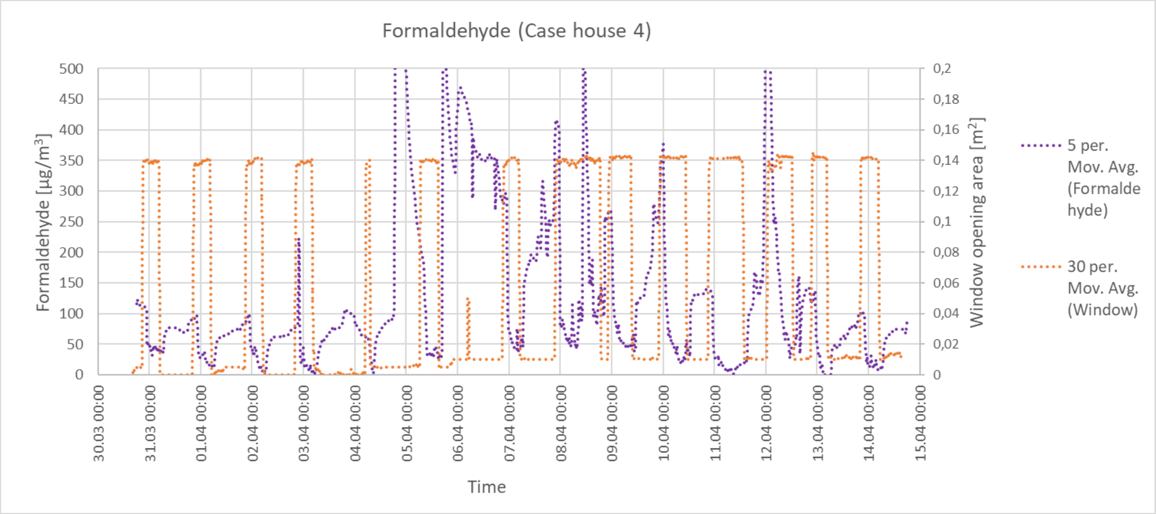

Formaldehyde (Case house 3 - Bedroom 2)
Formaldehyde [µg/m³]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Window opening area [m²]
0,050
0,045
0,040
0,035
0,030
0,025
0,020
0,015
0,010
0,005
0,000
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
16.04 00:00
17.04 00:00
18.04 00:00
Time
5 per. Mov. Avg. (Formaldehyde)
30 per. Mov. Avg. (Window)

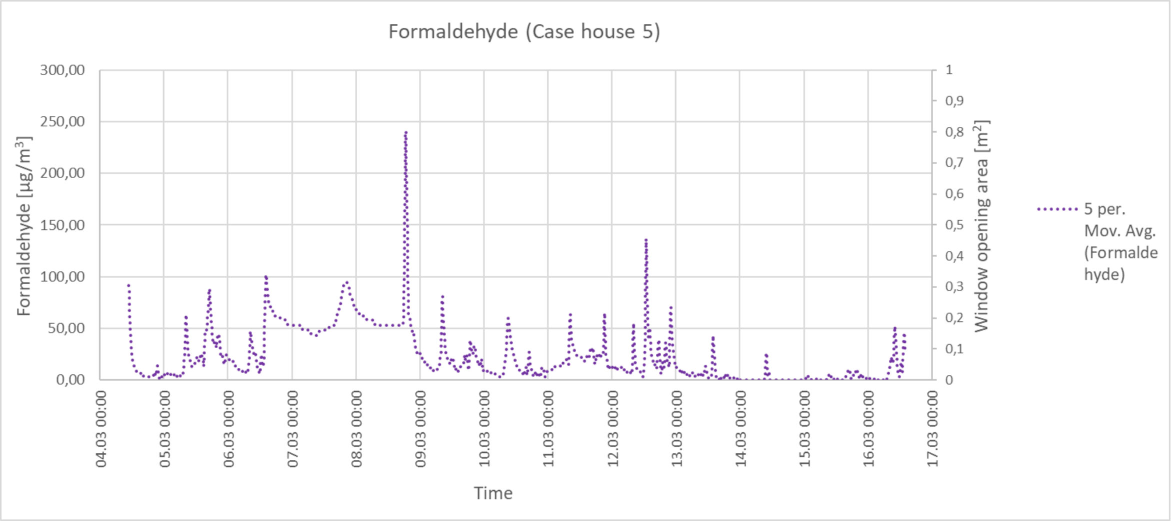

Formaldehyde (Case house 2 - Bedroom 2)

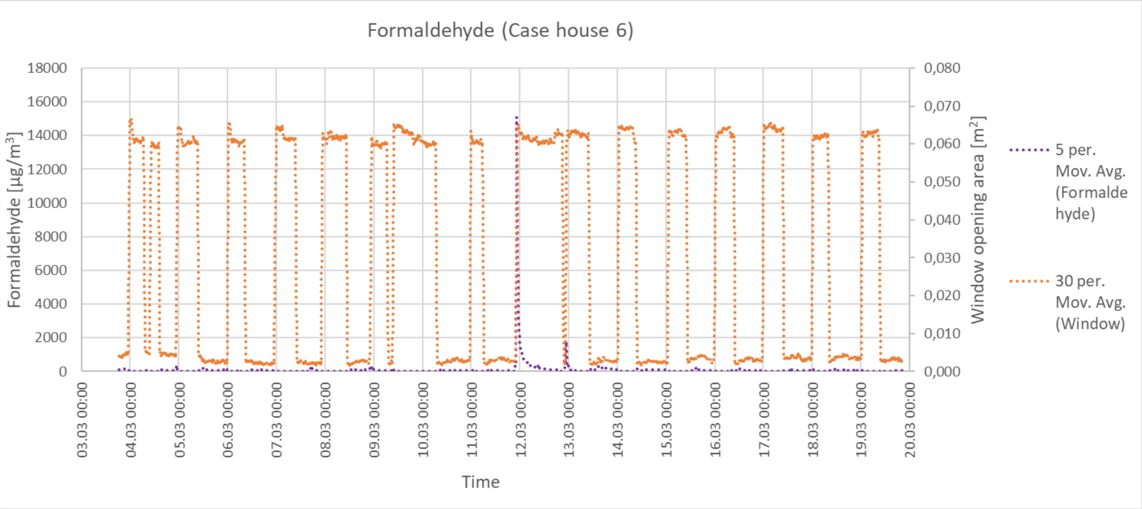

Formaldehyde (Case house 3 - Bedroom 1)

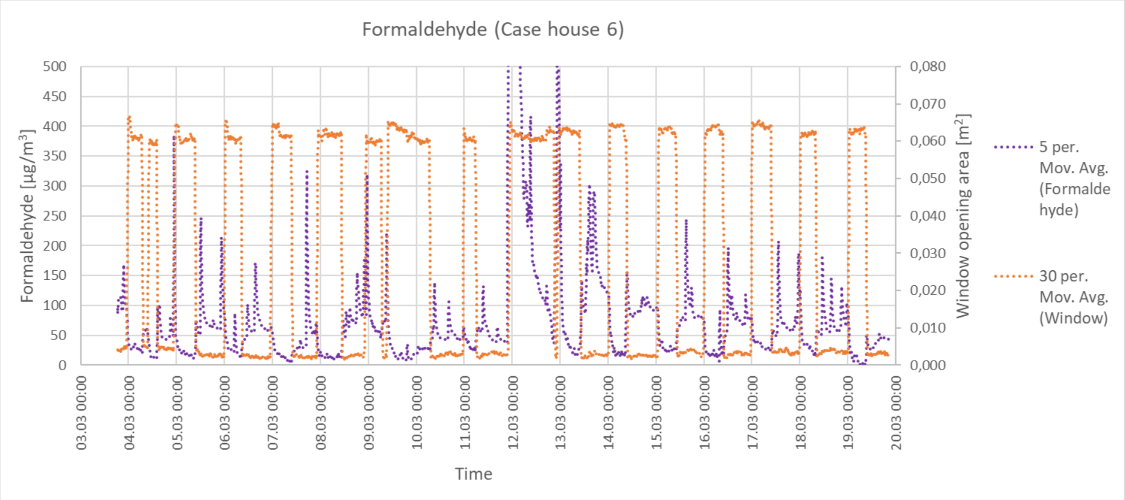

Formaldehyde (Case house 3 - Bedroom 1)


Formaldehyde (Case house 4)
Formaldehyde [µg/m³]
1400
1200
1000
800
600
400
200
0
Window opening area [m²]
0,2
0,18
0,16
0,14
0,12
0,1
0,08
0,06
0,04
0,02
0
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
5 per. Mov. Avg. (Formaldehyde)
30 per. Mov. Avg. (Window)

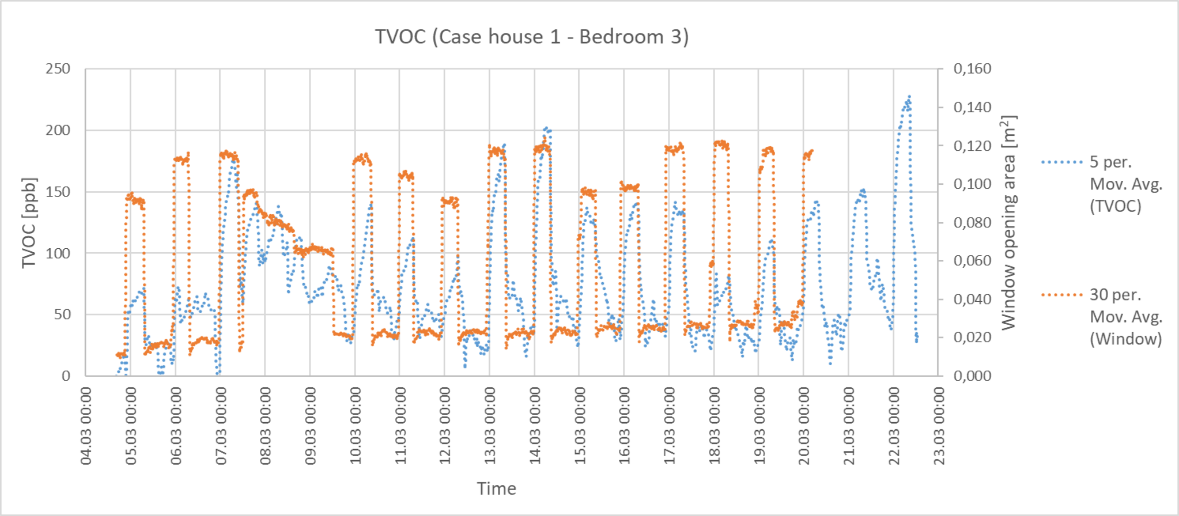

Formaldehyde (Case house 4)
Formaldehyde [µg/m³]
500
450
400
350
300
250
200
150
100
50
0
Window opening area [m²]
0,2
0,18
0,16
0,14
0,12
0,1
0,08
0,06
0,04
0,02
0
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
5 per. Mov. Avg. (Formaldehyde)
30 per. Mov. Avg. (Window)

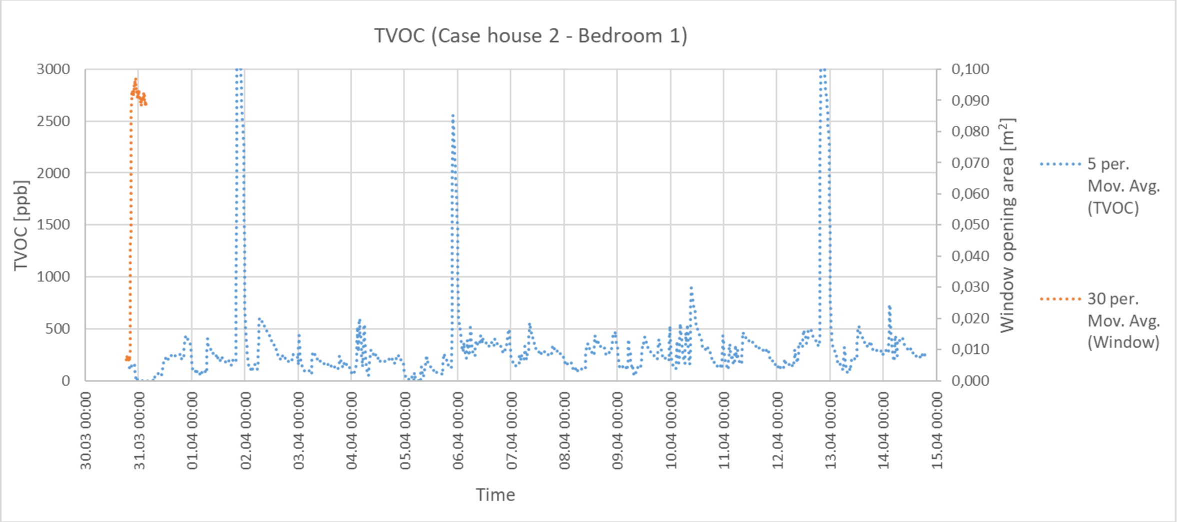

Formaldehyde (Case house 5)
Formaldehyde [µg/m³]
300,00
250,00
200,00
150,00
100,00
50,00
0,00
Window opening area [m²]
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
Time
5 per. Mov. Avg. (Formaldehyde)

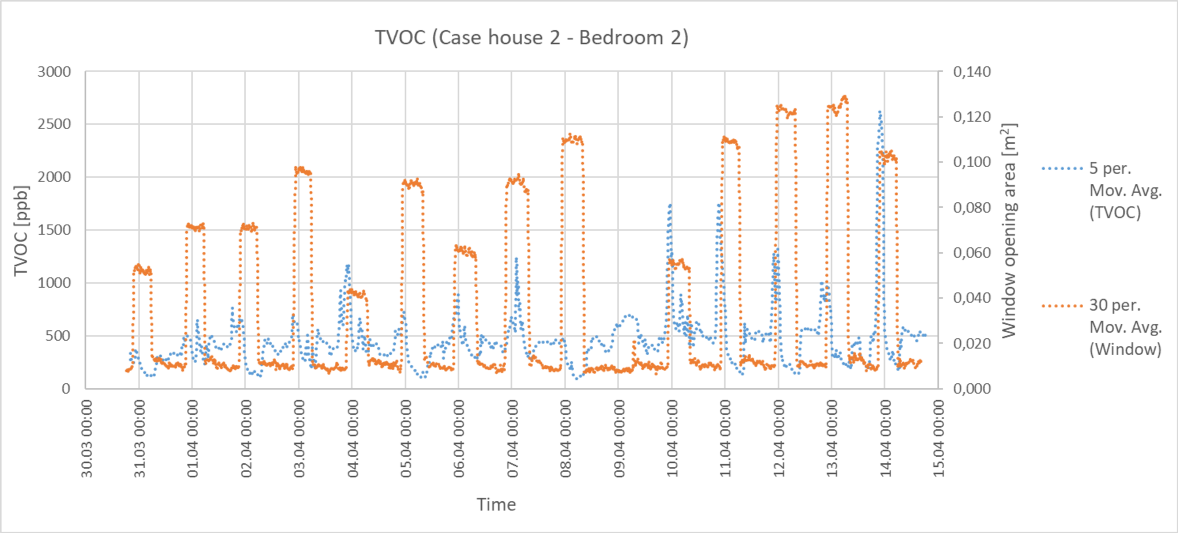

Formaldehyde (Case house 6)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Formaldehyde [µg/m³]
0,080
0,070
0,060
0,050
0,040
0,030
0,020
0,010
0,000
Window opening area [m²]
03.03 00:00
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
Time
5 per. Mov. Avg. (Formaldehyde)
30 per. Mov. Avg. (Window)

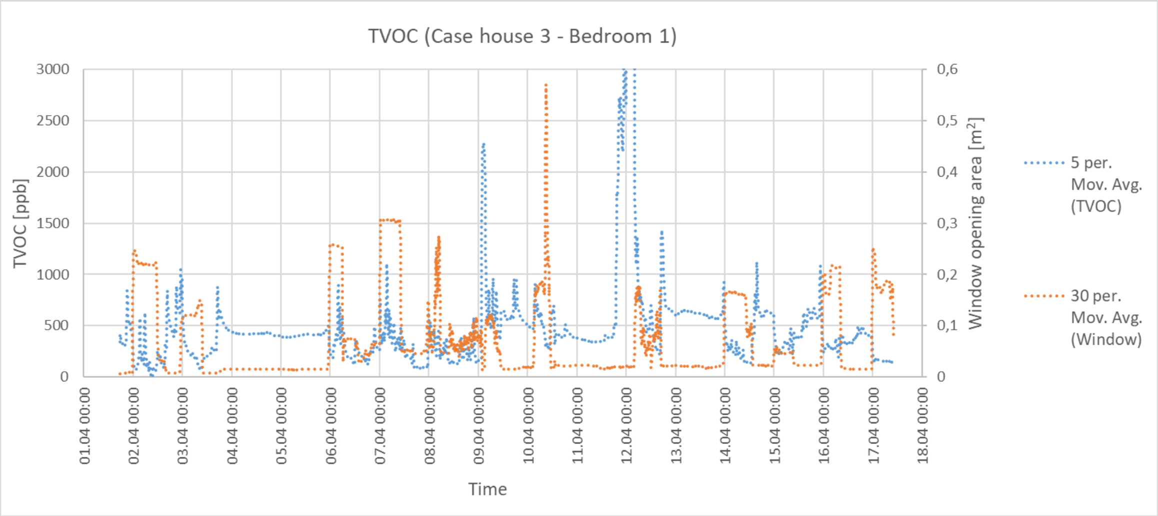

Formaldehyde (Case house 6)
500
450
400
350
300
250
200
150
100
50
0
Formaldehyde [µg/m³]
0,080
0,070
0,060
0,050
0,040
0,030
0,020
0,010
0,000
Window opening area [m²]
03.03 00:00
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
Time
5 per. Mov. Avg. (Formaldehyde)
30 per. Mov. Avg. (Window)

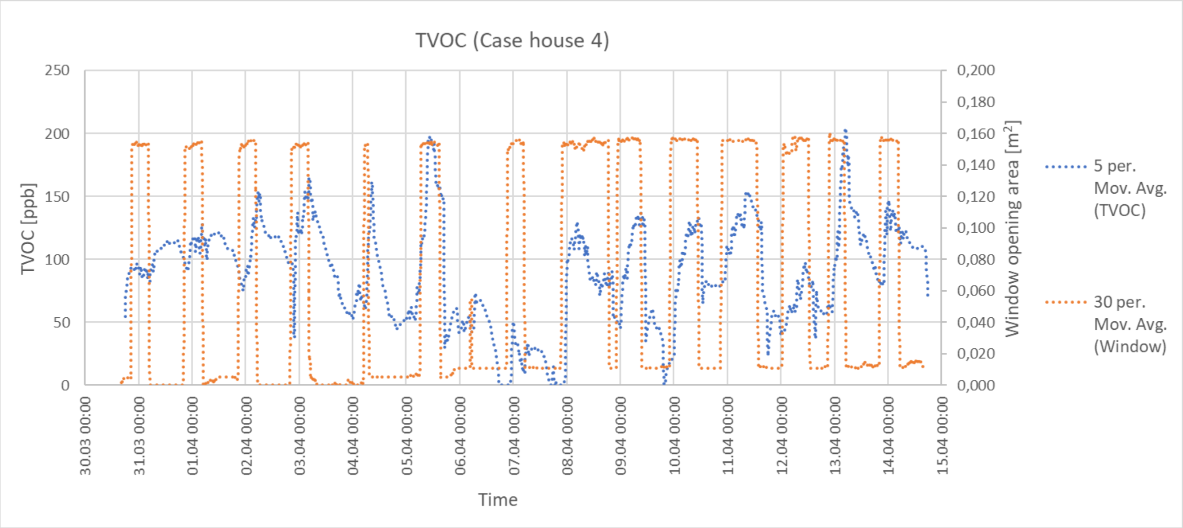
A.1.5 TVOC

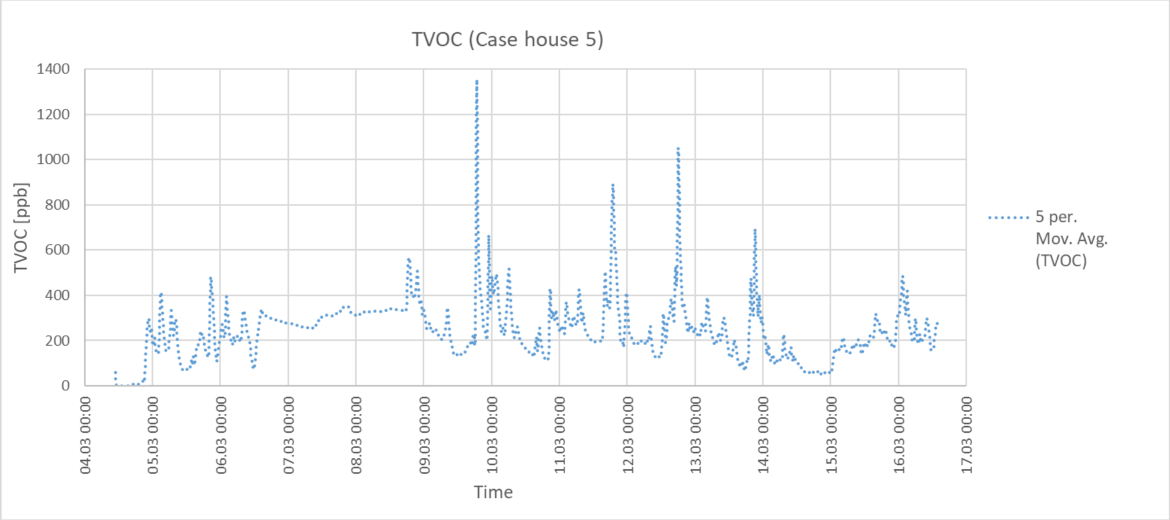

TVOC (Case house 1 - Bedroom 3)
TVOC [ppb]
0
50
100
150
200
250
Window opening area [m²]
0,000
0,020
0,040
0,060
0,080
0,100
0,120
0,140
0,160
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
21.03 00:00
22.03 00:00
23.03 00:00
Time
5 per. Mov. Avg. (TVOC)
30 per. Mov. Avg. (Window)

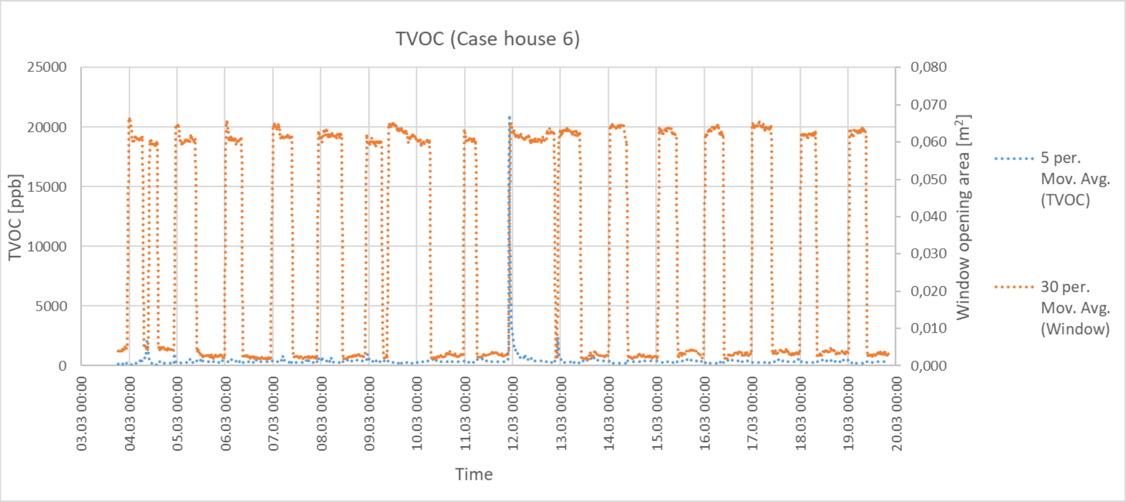

TVOC (Case house 2 - Bedroom 1)
TVOC [ppb]
0
500
1000
1500
2000
2500
3000
Window opening area [m²]
0,000
0,010
0,020
0,030
0,040
0,050
0,060
0,070
0,080
0,090
0,100
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
5 per. Mov. Avg. (TVOC)
30 per. Mov. Avg. (Window)

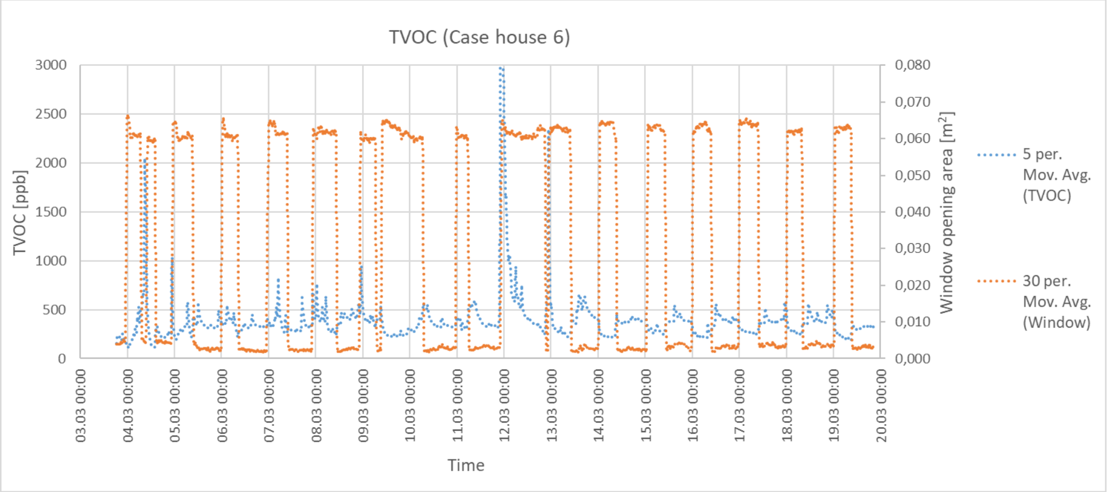

TVOC (Case house 2 - Bedroom 2)
TVOC [ppb]
0
500
1000
1500
2000
2500
3000
Window opening area [m²]
0,000
0,020
0,040
0,060
0,080
0,100
0,120
0,140
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
5 per. Mov. Avg. (TVOC)
30 per. Mov. Avg. (Window)


TVOC (Case house 3 - Bedroom 1)
TVOC [ppb]
3000
2500
2000
1500
1000
500
0
Window opening area [m^2]
0,6
0,5
0,4
0,3
0,2
0,1
0
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
16.04 00:00
17.04 00:00
18.04 00:00
Time
5 per. Mov. Avg. (TVOC)
30 per. Mov. Avg. (Window)


TVOC (Case house 4)
TVOC [ppb]
250
200
150
100
50
0
Window opening area [m^2]
0,200
0,180
0,160
0,140
0,120
0,100
0,080
0,060
0,040
0,020
0,000
30.03 00:00
31.03 00:00
01.04 00:00
02.04 00:00
03.04 00:00
04.04 00:00
05.04 00:00
06.04 00:00
07.04 00:00
08.04 00:00
09.04 00:00
10.04 00:00
11.04 00:00
12.04 00:00
13.04 00:00
14.04 00:00
15.04 00:00
Time
5 per. Mov. Avg. (TVOC)
30 per. Mov. Avg. (Window)


TVOC (Case house 5)
TVOC [ppb]
1400
1200
1000
800
600
400
200
0
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
Time
5 per. Mov. Avg. (TVOC)


TVOC (Case house 6)
TVOC [ppb]
25000
20000
15000
10000
5000
0
Window opening area [m²]
0,080
0,070
0,060
0,050
0,040
0,030
0,020
0,010
0,000
03.03 00:00
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
Time
5 per. Mov. Avg. (TVOC)
30 per. Mov. Avg. (Window)


TVOC (Case house 6)
TVOC [ppb]
3000
2500
2000
1500
1000
500
0
Window opening area [m²]
0,080
0,070
0,060
0,050
0,040
0,030
0,020
0,010
0,000
03.03 00:00
04.03 00:00
05.03 00:00
06.03 00:00
07.03 00:00
08.03 00:00
09.03 00:00
10.03 00:00
11.03 00:00
12.03 00:00
13.03 00:00
14.03 00:00
15.03 00:00
16.03 00:00
17.03 00:00
18.03 00:00
19.03 00:00
20.03 00:00
Time
5 per. Mov. Avg. (TVOC)
30 per. Mov. Avg. (Window)

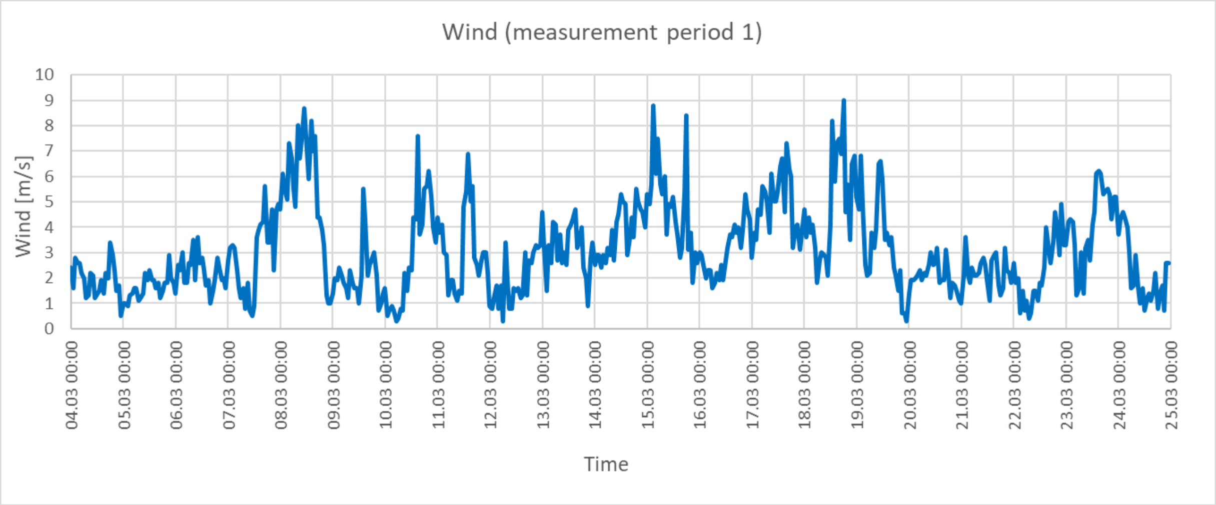
A.2: Correlation coefficients

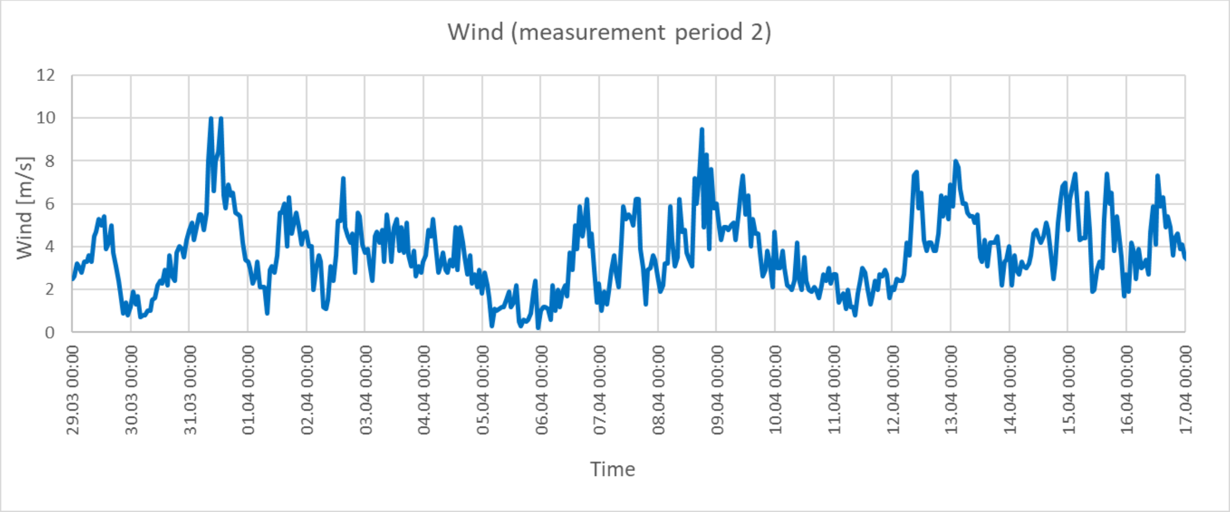
Correlation coefficient for CO_2 are displayed in the table below.

Case house	Bedroom	CO_2 and PM	IAQ sensor
1	1	0.000	6
	2	0.004	4
	3	0.000	3
2	1	0.003	2
	2	0.000	4
3	1	0.196	6
	2	0.058	8
4	-	0.077	3
5	-	0.029	2
6	-	0.013	8

A.3: Wind measurements

Mean wind for measurement period 1 and 2 are displayed below.





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Kunnskap for en bedre verden