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Utilizing IoT technology for healthy and energy efficient improvement of existing ventilation systems

Case study of indoor air quality in a primary school classroom using Arduino sensors and CONTAM simulations

June 2020

Master's thesis

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2020

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Case study of indoor air quality in a primary school classroom using Arduino sensors and CONTAM simulations

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Submission date: June 2020
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Master Thesis

For

Student Thomas Berg Jørgensen

Spring 2020

IOT for ventilation of zero emission buildings (ZEB)

IOT for ventilasjon av nullutslippsbygninger

Background and objective

To obtain zero emission buildings (ZEB) it is essential to reduce the energy use to a minimum. Demand controlled ventilation is a widespread method to control the supply of fresh air and reduce energy use. CO_2 is normally used as the control proxy as it is directly proportional to the number of occupants. Thus, when used to control Demand controlled ventilation, the supply of fresh air is regulated proportionally to the number of people and down to the minimum airflow rates when the concentration of CO_2 drops below the threshold that means vacant room.

However, there are other parameters that may not be proportional to occupancy and are more dangerous regarding health. In this master thesis, the student is expected to improve an Arduino based sensor previously developed and use it to measure the air quality in realistic environments. The thesis should assess how the measurements can be used to improve an existing ventilation strategy regarding both indoor air quality and energy use. The reliability of the Arduino technology should be tested and assessed. The final goal is to obtain or improve indoor air quality with minimum use of energy.

Due to the extraordinary measures following the Covid-19 outbreak, planned measurements in schools could not be done. The tasks for this master thesis have therefore been revised in March 2020.

The student will add to the work being developed on the Ph.D. work of the student Maria Justo Alonso. This Ph.D. is part of the Research Centre on Zero Emission Neighbourhoods in Smart Cities.

The following tasks are to be considered:

1. What type of pollutants can be found in a normal indoor climate, and which of these have adverse effects on a healthy indoor environment? Which of these are most relevant for controlling a ventilation system?
2. Do the developed low-cost sensor systems perform as intended, or do they require adjustments? If needed, are the calibrations generalizable?
3. Is the sensitivity, stability, and selectivity of the Arduino sensor system acceptable for use in a ventilation control system? Which limitations apply?
4. Can the developed Arduino system be used to assess the IAQ and ventilation control in a real classroom?
5. Is it possible to make an IAQ simulation model using CONTAM, that imitate a real classroom? Can this model be used to predict how changes in ventilation rate affect IAQ?
6. How big energy savings can be acquired by reducing the ventilation rate in a classroom using DCV, without reducing IAQ?

Some of the tasks have already been done in the project work.

Abstract

The residential and commercial building sector is responsible for a substantial amount of the worlds energy use and greenhouse gas emissions but is also one of the sectors that are best rigged to cut energy and emissions cost-effectively. Demand-controlled ventilation (DCV) is one way of doing so, and involves controlling the ventilation system based on the actual demand rather than constantly running at a given ventilation rate. However, given that most people spend a considerable amount of time indoors, the indoor air quality (IAQ) must not be reduced when using DCV, as this can cause a variety of adverse health effects.

This thesis aims at providing a health-based assessment of IAQ in a real building using a low-cost Arduino based sensor system. Further, a CONTAM simulation model is made to assess whether it is possible to increase IAQ while reducing energy use for ventilation.

Most DCV systems only apply CO_2 as a control proxy as it is considered a general IAQ indicator. When doing so, occupants may suffer from bad IAQ caused by other pollutants that are not correlated with CO_2. The literature review in chapter 2 shows that CO_2, temperature, relative humidity, $PM_{2.5}$, and volatile organic compounds are important to monitor in indoor environments, as these pollutants have adverse health effects for the occupants at concentrations often occurring indoors. Calibrations of the sensors show that temperature, RH, and CO_2 only are reliable enough to provide conclusive measurements. Formaldehyde, TVOC, and $PM_{2.5}$ require further calibrations before they should be used for IAQ assessment.

For the measurements made for this thesis, the Arduino sensor is placed in a primary school classroom already using DCV, in Trondheim during winter 2019. The measurements show that the CO_2 levels are generally around 850 ppm during occupancy, which is lower than the maximum limit of 1000 ppm. However, during winter, the RH is below the proposed minimum limit of 30 % most of the time, which can cause a series of adverse health effects. An earlier thesis using the same sensors found that formaldehyde should be included as a controlling parameter in the DCV system. The measurements and calibrations in this thesis conclude that this is not the case, but further research to strengthen this is advised.

The simulation model uses a simplified VAV schedule to imitate the DCV ventilation in the classroom, and can reproduce the real measurements realistically. The model includes simulation of CO_2, specific humidity, and ventilation rates. The simulation model is further used to test alternative ventilation rates, to investigate how it affects IAQ. Three scenarios for reduced ventilation rates are tested, and all show that it is possible to increase IAQ while reducing energy consumption for ventilation. The most realistic scenario controls the CO_2 at approximately 1000 ppm and has an annual energy reduction of 22.4 % compared to the current ventilation setpoints. The most optimistic scenario uses ventilation rates of 4 L/s per person during occupancy and reduces the annual energy for ventilation by 43 %. This solution requires strict control of RH and removal of all primary pollution sources present in the ventilated zone.

Findings in this thesis strongly advise a broader perspective regarding IAQ, health, and ventilation than what is common today, and indicate that technical standards regarding the design of ventilation systems overestimate the ventilation rate requirement. By reducing the primary pollution sources in the ventilated zones, adding sensors, and increase knowledge regarding IAQ and pollutants, it may be possible to increase IAQ while saving energy in many existing ventilation systems.

Sammendrag

Byggebransjen er ansvarlige for betydelige deler av verdens energibruk og utslipp av klimagasser, men er også en av bransjene som er best rigget til å kutte energiforbruk og utslipp mest kostnadseffektivt. Behovsstyrt ventilasjon (DCV) er en av måtene å gjøre nettopp dette og innebærer å styre ventilasjonen etter et faktisk behov, heller enn å la det gå hele tiden. Gitt at de fleste mennesker bruker vesentlige deler at tiden innendørs, er det viktig at luftkvaliteten innendørs (IAQ) ikke reduseres av å bruke DCV, da dette kan føre til en mengde negative helseeffekter.

Denne oppgaven prøver å gi en helsebasert vurdering av luftkvaliteten i et faktisk bygg ved bruk av rimelige Arduino-baserte sensorer. Videre er CONTAM simuleringsmodell utviklet for å vurdere om det er mulig å øke luftkvaliteten samtidig som energiforbruket til ventilasjonen senkes.

De fleste behovsstyrte ventilasjonsanlegg bruker i dag CO2 som styrende parameter fordi det er ansett som en generell indikasjon på innendørs luftkvalitet. Når dette er tilfelle kan beboerne bli utsatt for dårlig luftkvalitet, ettersom ikke alle forurensinger korrelerer med CO2. Litteraturstudien viser at CO2, temperatur, relativ fuktighet (RF), $PM_{2.5}$, og flyktige organiske forbindelser (TVOC) er viktig å følge med på ettersom skadelige konsentrasjoner av disse kan oppstå i vanlig inneluft. Kalibrering av sensorene viser at kun sensorer for temperatur, RH, og CO2 er pålitelige nok til å gi troverdige målinger. Bruk av sensorer for formaldehyd, TVOC, og $PM_{2.5}$ krever videre kalibreringer før de kan brukes til vurdering av innendørs luftkvalitet.

Arduino-sensorer er plassert i et klasserom som bruker DCV, på en barneskole i Trondheim vinteren 2019. Målingene viser at CO2-nivåene stort sett ligger rundt 850 ppm, som er lavere enn maksimumsgrensen på 1000 ppm. Samtidig ligger RF stort sett lavere enn den foreslåtte minimumsgrensen på 30 % på vinteren, hvilket kan forårsake en rekke uheldige helseeffekter. En tidligere oppgave som bruker de samme sensorene konkluderte med at formaldehyd burde brukes som en kontrollerende parameter i CO_2 i behovsstyrte ventilasjonsanlegg. Målingene og kalibreringene i denne oppgaven viser at dette ikke er tilfelle, men at videre forskning for å undersøke dette anbefales.

Simuleringsmodellen bruker en forenklet og tilpasset variabel luftmengde-kontroller for å imitere et behovsstyrt ventilasjonsanlegg, men gjenskaper de ekte målingene fra klasserommet på en god måte, og inkluderer simulering av CO2, spesifikk fuktighet (SH), og ventilasjonsrate. Modellen brukes videre til å teste alternative ventilasjonsrater for å se hvordan endring av disse påvirker luftkvaliteten. Tre scenarioer for reduserte ventilasjonsrater er testet, og alle viser at det er mulig å øke luftkvaliteten samtidig som energibruket til ventilasjonen senkes. Det mest realistiske scenarioet styrer anlegget etter et settpunkt på rundt 1000 ppm CO_2, og har en årlig energibesparelse på 22.4 % sammenlignet med dagens ventilasjonsstyring. Det mest optimistiske scenarioet bruker ventilasjonsrater på 4 L/s per person som er tilstede, og reduserer det årlige energiforbruket til ventilasjon med 43 %. Dette scenarioet krever streng kontroll av relativ fuktighet og fjerning av alle primære forurensningskilder som er til stede i det ventilerte rommet.

Denne oppgaven viser til flere anbefalinger om å utvide perspektivet rundt luftkvalitet, helse, og ventilasjon, og resultater indikerer at de tekniske standardene for utforming av ventilasjonsanlegg overvurderer luftmengdebehovet. For mange ventilerte områder vil en ved å redusere de primære forurensningskildene, sette opp flere målinger, og øke den generelle kunnskapen om luftkvalitet, kunne øke luftkvaliteten samtidig som energiforbruket til ventilasjon senkes.

Acknowledgement

This master’s thesis is the final result from the work on the subject "TEP4935 - Energy Planning and Environmental Analysis Master's Thesis" at the Department of Energy and Process Engineering. The thesis is written as the final assignment of the five years MSc program "Energy and Environmental Engineering", at the Norwegian University of Science and Technology, NTNU, in Trondheim. This thesis is a continuation of the Project Thesis, "Health-based DCV using low-cost sensors" during the fall of 2019.

I would like to express massive gratitude to the supervisors of this thesis, Prof. Hans Martin Mathisen and Maria Justo Alonso, for knowledge, enthusiasm, and insight into the fields of indoor air quality, ventilation systems and sensor technology.

A special thanks to Trondheim Municipality and school personnel for being helpful during the measurements in the classrooms. I would further like to thank the professional system developers from the Department of Electronic Systems at NTNU for production and support regarding the Arduino sensors.

The author gratefully acknowledges the support from the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN), 286183.

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Abbreviations

AHU	Air Handling Unit
BMS	Building Management system
CAV	Constant Air Volume
CO_2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
DCV	Demand-Controlled Ventilation
EC	Electrochemical Cell
EPA	Environmental Protection Agency
FET	Field Effect Transistors
FHI	Norwegian Institute of Public Health
HCHO	Formaldehyde
IAQ	Indoor Air Quality
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IPCC	International Panel on Climate Change
MOx/MOS	Metal Oxide Semiconductor
NDIR	Non-Dispersive Infrared Absorption
NIST	National Institute of Standards and Technology
PID	Photo-Ionization Detector
PM	Particulate Matter
POM	Particulate Organic Material
RH	Relative Humidity
SBS	Sick Building Syndrome
SH	Specific Humidity
TVOC	Total Volatile Organic Compounds
VAV	Variable Air Volume
VOC	Volatile Organic Compounds
VR	Ventilation Rate
WHO	World Health Organization
µGC	Micro-Gas Chromatograph

1 Introduction

1.1 Background and motivation

Most people spend considerable amounts of time indoors, either at home, school, work, or similar. The indoor air quality where this time is spent is a prerequisite for well-being, productivity and health (WHO, 2010). Children are more vulnerable than adults to health effects from bad indoor air quality, which makes it extra important to provide a good indoor environment in for example schools and kindergartens (Branco, Alvim-Ferraz, Martins, & Sousa, 2019).

The Residential and commercial building sector is responsible for a substantial part of the worlds greenhouse gas emissions and is one of the sectors that is best rigged to cut emissions cost-effectively using already available technology (WHO, 2011). Therefore, international building regulations have gradually increased the technical standards regarding energy use in buildings, making new and refurbished building more airtight, more resistant to cold weather, and more energy-efficient by using technical equipment like heat pumps and ventilation systems (EU, 2019).

The International Panel on Climate Change (IPCC) has released several reports stating that climate changes in the future will bring more extreme weather (M. Mendell, Mirer, Cheung, Tong, & Douwes, 2011). At the same time, densification and industrialization have made outdoor air more hazardous in big cities. This might feel distant to many, but it is important to remember that most buildings today are erected with an intended lifespan of 50-100 years, and their surrounding climate for sure will change over time.

Ventilation is one of the strategies that are used for controlling indoor air quality (IAQ) (Carrer et al., 2018). Historically, ventilation was driven by natural forces like weather and buoyancy and was meant to control odour and thermal comfort (J. Sundell, 2004). Modern ventilation plants are often driven by mechanical forces (fans), either to control pollutants from industrial processes or to provide "fresh air" to buildings. To reduce energy consumption from ventilation systems, demand-controlled ventilation (DCV) was developed, controlling the airflow based on indoor air quality and/or a thermal comfort (Merema, Delwati, Sourbron, & Breesch, 2018).

Over the last decades, knowledge on the effects of indoor air pollution on people has been developed, and the importance of a holistic approach to IAQ has been urged. The indoor environment is complex, influenced by emissions from e.g. materials, occupants, outdoor air, equipment, and processes. The impact the IAQ has on human health is well documented and includes, among others, respiratory effects, allergies, skin and mucous membrane irritation and cancer (Tham, 2016). In the years to come, climate-related illnesses caused by indoor air quality is expected to increase because of the changing climate (M. Mendell et al., 2011). To compensate for the worsened outdoor air, indoor climate control and good ventilation systems are needed.

To ensure that the indoor climate in energy-efficient buildings is healthy for its occupants, it is important to monitor and control the indoor climate based on all pollutants relevant for human health, not only energy use, CO_2, and thermal comfort. Most of the houses that will provide shelter for the coming generations are already built, and it is therefore important that the sensors and control system is easy to use, cheap, and adaptable to future needs.

1.2 Problem description and research questions

CO_2 is often used as a control proxy for demand-controlled ventilation systems because it is proven to correlate with other pollutants, hence being a general marker for indoor air quality (Salthammer et al., 2016). During the last years, sensor technology has improved, and commercialized low-cost sensors can measure formaldehyde, TVOC, ozone, and similar pollutants that can be harmful if present indoor (Castell et al., 2017). If these sensors work as intended, it might be able to regulate and assess demand-controlled ventilation plants based on several relevant parameters, not only CO_2.

The objective of this thesis is to use a specially developed Arduino sensor system to measure and assess the air quality in a realistic environment. The reliability of the sensor technology must be tested. The goal is to use the sensor for assessment of IAQ and propose changes to the ventilation system, that improve IAQ with minimum use of energy. Further, a simulation model that can test how changes in the ventilation system affect IAQ should be made. Real measurements shall be used to verify the sensor performance and simulation model validity.

To assess these problems, the following research questions will form the basis for the research and conclusion for this thesis:

- What type of pollutants can be found in a normal indoor climate, and which of these have adverse effects on a healthy indoor environment? Which of these are most relevant for controlling a ventilation system?
- Do the developed low-cost sensor systems perform as intended, or do they require adjustments? If needed, are the calibrations generalizable?
- Is the sensitivity, stability, and selectivity of the Arduino sensor system acceptable for use in a ventilation control system? Which limitations apply?
- Can the developed Arduino system be used to assess the IAQ and ventilation control in a real classroom?
- Is it possible to make an IAQ simulation model using CONTAM, that imitate a real classroom? Can this model be used to predict how changes in ventilation rate affect IAQ?
- How big energy savings can be acquired by reducing the ventilation rate in a classroom using DCV, without reducing IAQ?

1.3 Scope and limitations

This thesis was originally defined in January 2020. Due to the COVID-19 pandemic and the restrictions following this, the focus and objectives of the thesis had to be redefined in March 2020. The original thesis was a practical project based on actual measurements and sensors, while the redefined thesis is a theoretical project based on laboratory measurements, earlier conducted measurements and simulations.

To narrow down the scope of the thesis, some limitations are applied to the focus of the research. Because the results are based on measurements done in Trondheim, the literature review regarding indoor air quality and ventilation principles are mainly based on a Nordic climate, and Norwegian ventilation systems. The measurements are done in a classroom that use DCV. Classrooms have a relatively high occupant density, which narrow the validity of the results down to rooms or buildings with similar use patterns and occupant density. The results regarding ventilation rates may not be valid for buildings that use other ventilation systems than mixing ventilation, because the pollutants distribution is inequal. However, the method for assessing IAQ will be equal, given that the sensors are placed correctly compared to the pollutant distribution.

Because of the COVID-19 pandemic, it was not possible to do measurements at the school during the work on this thesis, and the measurements from the preparatory project work is therefore used as basis for the conclusions.

1.4 Earlier work

This report is a continuation of an earlier master thesis written by Oda Kristine Gram and will to some extent be based on the findings from this thesis (Gram, 2019). Gram performed a literature review to find the relevant indoor pollutants in Norwegian primary schools. Based on these findings, an Arduino-based sensor system was made and installed in four different schools. These sensors measured for two months and found that the formaldehyde levels in some of the schools exceeded the maximum limits at several points of time. Based on these results, modifications on the control schedule was proposed to keep the formaldehyde levels below the limit values.

As preparation for this thesis, the author has written a project work, entitled "Health-based DCV using low-cost sensors". Since this thesis is a continuation of the preparatory project, parts of the project have been re-used from this project. This includes parts of chapters 1, 2, 3, and 4. The parts of the method descriptions that is common for the project work and master thesis is re-used in chapter 5.

As for the project work and Gram (2019), this report focuses on IAQ in Norwegian schools and continues the cooperation with Trondheim Municipality, via Trondheim Eiendom. This assures concrete and realistic results are applicable to existing ventilation systems. All measurements are done at a primary school in Trondheim.

1.5 Structure of this master thesis

The thesis will firstly present important background knowledge for setting up the measurements and evaluating the results. Chapter 2 introduces the concept of IAQ, and the most relevant pollutants, and will form an understanding of how the different pollutants are assessed. Chapter 3 introduces the basics of sensor technology to provide a basis for assessing the performance of the different Arduino sensors. Chapter 4 present the basics of different ventilation systems, which will give understanding of how the IAQ is connected and controlled with ventilation system.

Further, the methods and assumptions for setting up the laboratory experiments, classroom measurements, and simulation model is presented in chapter 5. The results from the laboratory calibrations, classroom measurements, and simulation model is presented in chapter 6 and discussed in chapter 7. Lastly, the conclusions from the thesis and its research is presented in chapter 8.

2 Indoor air quality

2.1 Introduction

Indoor air was thought to be the most dominant source of pollution for humans from the hygienic revolution around 1850. Humans was thought to be the main pollution source, while thermal comfort and odours were thought to be the marker for indoor air quality (IAQ) (J. Sundell, 2004). From around 1960 outdoor air was thought to be the dominant source of exposure of pollution to humans, and industrial emissions the source of pollutants. IAQ was therefore given lower priority during this period (J. Sundell, 2004).

Over the last decades, following the enlightenment around e.g. radon, formaldehyde, house dust mites and sick building syndrome (SBS), IAQ has entered the scientific agenda once again (J. Sundell, 2004). Despite the extensive knowledge of indoor air pollutants, most demand-controlled ventilation systems today only use CO_2 and temperature as a marker for control (Guyot, Sherman, & Walker, 2018; Ramalho et al., 2015). Buildings in the Nordic countries have become more airtight to reduce energy losses, which has called for a holistic and multi-disciplinary solution regarding IAQ. To assure that the ventilation and climatization systems are both energy efficient and healthy, knowledge about the buildings local conditions, building methods and usage are needed (Carrer et al., 2018).

IAQ is a complex issue regarding the composition of air pollutants. The total indoor environmental composition is determined by chemical, biological and physiological contaminants (Tham, 2016). Some of these contaminants exist independently, while some, like ozone, can interact with other chemicals to create byproducts that can be worse for IAQ than its origin (Weschler, 2000). Pollution sources can be outdoor particulate that infiltrates indoors, gases emitted by either human processes (e.g. cooking, cleaning, use of technical equipment) or indoor materials (e.g. furniture, construction materials) (Rivas, Fussell, Kelly, & Querol, 2019).

The effect of the IAQ on humans is a challenging problem because most people spend varying amounts of time in different microclimates like school, work, home, outdoors, and similar. When analysing the health impact of a pollutant in indoor air, it is also important to remember that people will react differently to pollutants, with different maximum limits of exposure (Tham, 2016). Some people can react to pollutants long before the general lower limit of exposure, while others do not perceive the same pollutants before the concentration is significantly higher. The effect of pollutants also varies on the time of exposure and the pollutions' potency. Formaldehyde, for instance, is barely noticeable for humans and often appear in combination with other more annoying pollutants, but might be carcinogenic over time (FHI, 2015). Some of the pollutants will cause discomfort and reduced performance if exposed over short periods, or sickness and allergies if exposed for a longer period of time (Salthammer et al., 2016). Consequently, conclusions regarding IAQ and health must be drawn critically.

Chapter 2 is written to give an introduction and understanding of the complexity of indoor air, to provide an understanding of what is important and what is not when assessing IAQ. Chapter 2.2 gives a brief introduction to which factors impact IAQ, before chapter 2.3 presents the most common diseases and symptoms related to bad IAQ. Chapter 2.4 gives an overview and introduction to the pollutants that cause the various effects mentioned in chapter 2.3. This is done to differentiate the potency and importance of each of the pollutions and will act as a fundament for discussion of the sensor setup and measurement results presented later. Finally, chapter 2.5 summarizes the main findings about IAQ, and the limit values for the most important pollutants.

2.2 Indoor air composition

The air inside a room or a building is the sum of the originating outdoor air, the treatment of the air in the ventilation systems, and the pollutants added from the indoor environment and processes. The indoor air is consequently dependent on many factors, some of which are illustrated in

Figure 2.1 below.

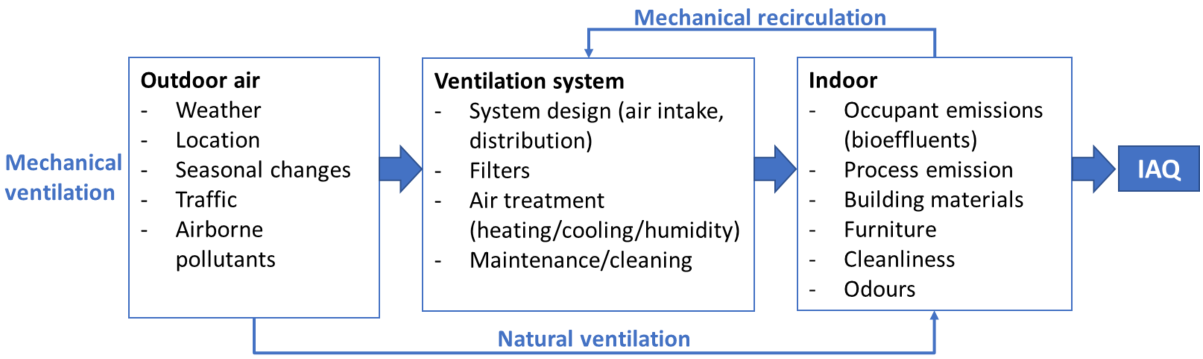

Figure 2.1 Factors affecting IAQ

The result of the processes in Figure 2.1 in sum makes up the IAQ. The quality of the indoor air is assessed on a set of sensible or measurable parameters. These parameters are not necessarily equal for all. For example, the IAQ in a hospital and a storage will be assessed based on different parameters. The following chapters try to form a set of parameters that can be used to assess the indoor air quality in school classrooms, or other environments similar to this.

2.3 Common diseases, symtpoms and health effects caused by bad IAQ

This chapter discusses symptoms and diseases that may be caused by IAQ. The chapter is not a complete list but mentions some of the most usual symptoms and health effects.

Cancer, heart- and vascular diseases are not included in this list as there is no general understanding that IAQ contributes to cause or worsen these in a large extent (FHI, 2015).

2.3.1 Skin and mucous membrane irritation, headaches and odour

The perception of bad air quality is often connected to discomfort identified by a feeling of dry air, tiredness, headaches, runny eyes and nose or itchy skin (EPA, 2019). These symptoms can be caused by dry or irritated mucous membranes in eyes or throat, sensitivity to specific odours, lack of ventilation, draft, or unfavourable temperatures. Pollutants such as particulate matter (PM), volatile organic compounds (VOC), and biocontaminants from moisture damages can cause or accelerate these symptoms (EPA, 2019; FHI, 2015).

Symptoms from odours can potentially result from either the odour itself or the subjective psychological response (Wolkoff, 2013). Compounds releasing odour will mainly cause psychological effects until they exceed a threshold, where sensory irritation occurs. Sensory irritation from odorous compounds may cause redness, irritation, burning, itching, pain, scratching and stinging in eyes and nose. Relative humidity (RH) can cause dry mucous membranes which can exacerbate the effects of sensory irritants (Wolkoff, 2013).

General for many of the symptoms is that they often lack medical proof and might be confused or mixed with symptoms of sick building syndrome. This is further discussed in chapter 2.3.3.

2.3.2 Respiratory diseases and allergies

Many people suffer from chronic respiratory diseases or allergies, whose strength varies with time and exposure to some pollutions. The most common respiratory nuisances are allergic rhinitis (inflammations in the upper respiratory tract due to allergic reactions), non-allergic rhinitis (irritations caused by specific pollutants) and asthma (chronic inflammations whose intensity can vary over time) (FHI, 2015).

Asthma is a chronic disease and can vary in degree from day to day but can also be triggered and worsened by rhinitis. Respiratory diseases and asthma are mainly hereditary, and research has shown that exposure to pollutions such as tobacco smoke, diesel exhaust, polyaromatic hydrocarbons (from incomplete combustion), phthalates (substance in some plastic products), particulate matter (PM), and ozone can worsen or accelerate the development of Asthma, but probably not be the lone cause for it to develop (FHI, 2015; Peden, 2000).

A cross sectional study from M. Mendell et al. (2011) regarding health effects from moisture damages and mould fungi in indoor climate has shown that exposure can develop asthma and allergies, and not only worsen them as thought earlier. These connections have not been proved in longitudinal studies, but has shown that measures to improve moisture damages and ventilation has drastically improved symptoms from rhinitis (FHI, 2015; WHO, 2011).

Chronic obstructive pulmonary disease (COPD) is a permanent degrading of lung capacity and is considered a worse disease than the ones mentioned above. COPD is often correlated to smoking and passive smoking, but long exposures to traffic pollution might contribute to develop COPD in sensitive patients (Andersen et al., 2011). The only clear correlation to IAQ and COPD is that asthmatics have a higher possibility to develop COPD (FHI, 2015). Therefore, reducing the asthma-related pollutants in the indoor environment is the most effective measure to reduce COPD.

2.3.3 Building related illnesses and effects on health

People that suffer from a defined illness caused by a known pollutant is called building related illness (BRI), and are caused by viruses or bacteria (EPA, 2019; FHI, 2015). Building related illnesses can be put into two categories: 1) illness directly caused by the building or its technical equipment, e.g. legionnaire's disease, pneumonia, humidifier fever, all of which are linked to moisture or mould and 2) illness or disease caused by bacterial infections or viruses that are spread by the indoor climate or its technical equipment (FHI, 2015).

Studies have shown that air temperature and relative humidity (RH) are important factors for survival of viruses in the indoor environment, while ventilation rate and the number of people in a room are important factors for spread (Ciencewicki & Jaspers, 2007; Steel, Palese, & Lowen, 2011). Studies have proven that passive smoking, NO_2, ozone and PM can weaken the immune system, increasing the chance of contamination (Ciencewicki & Jaspers, 2007).

Opposite to building related illnesses, which is caused by a known pollutant, there are many symptoms and reactions that cannot be explained medically. These symptoms are often similar to the ones described in the chapters above and occur in similar conditions, but it is no known cause for the symptoms. The collective term for these symptoms is called sick building syndrome (SBS). Even though there is no medical known causality between pollutant and symptom, there are proven correlations between ventilation rate (VR) and SBS symptoms (William J. Fisk, Mirer, & Mendell, 2009). As the symptoms related SBS are often common symptoms in the population, they can have a number of other reasons not related to IAQ (FHI, 2015).

2.4 Indoor air quality markers and pollutants

Chapter 2.3 presents the most common diseases and health effects related to IAQ. It shows that in some cases there is a causality between a sickness and IAQ parameters, whereas most sicknesses only show a correlation. In both cases, it is important to reduce or exclude the parameters that are known to cause or trigger specific health effects. This chapter examines the triggers mentioned in chapter 2.3 and other relevant pollutants, to examine how they enter the indoor air, how to reduce them, and if there exist any upper limits of exposure. All obtained limit values are summarized in Table 2.1 in chapter 2.5.

The information given in the following chapters is derived from FHI (2015) and WHO (2010) which are considered as important and serious legislators in the field of indoor environment. Other sources are also used and are cited where need be.

2.4.1 CO_2

CO_2 in the indoor environment is primarily a product of its occupants but can also be a by-product from combustion. Where there are no processes where CO_2 is an expected emission, it is expected to come from human exhalation. CO_2 is odourless and colourless. CO_2 is a common marker for control of DCV systems today because it has a linear relation to the number of people present in a room. High concentrations of CO_2 in a room also correlates with the perception of bad odours and bad indoor climate and is therefore convenient to use as a general hygienic marker.

CO_2 has no known negative health effects for the concentrations that can be expected in normal indoor environments and is shown not to have any physiological effects for concentrations under 10.000 ppm. However, recent tests have shown that concentrations down to 1000 ppm can reduce the ability to take decisions (Allen Joseph et al., 2016; Liu, Zhong, & Wargocki, 2017). High concentrations of CO_2 are often an indicator of low ventilation rates, followed by elevated levels of indoor air pollutants, and is therefore considered a good indicator of IAQ (Salthammer et al., 2016). Therefore, the Norwegian institute of public health recommends a maximum CO_2 level of 1000 ppm. The German Federal Environment Agency recommends maximum CO_2 levels dependent on RH and temperature, and divides between "hygienically acceptable" (<1000 ppm), "hygienically noticeable" (<2000 ppm) and "hygienically unacceptable" (>2000 ppm) (Salthammer et al., 2016).

The CO_2 level based on the number of occupants and room size can be derived from the following formula:

$$C_{CO_2}(t) = C_{CO_2(ambient)} + 1000\frac{N * Q_{CO_2}}{n * V}(1 - e^{-n*t})$$

Where

$$C_{CO_2}(t): CO_2\ concentration\ as\ a\ function\ of\ time\ t\ [ppm]$$

$$C_{CO_2(ambient)}: CO_2 concentration\ in\ outoor\ air\ [ppm]$$

$$N: number\ of\ persons\ in\ room$$

$$Q_{CO_2}: CO_2\ emission\ rate\ [l/h]$$

$$n: air\ exchange\ rate\ [1/h\ ]$$

$$V: room\ volume\ [m^3]$$

When $t \to \infty$ in the formula above, one can decide the minimum air exchange rate n required to stay below a certain CO_2 level in steady state:

$$n = \frac{1000 * N * Q_{CO_2}}{\left(C_{CO_2}(t) - C_{CO_2(ambient)}\right) * V}$$

2.4.2 Relative humidity (RH)

Relative humidity (RH) is the amount of water vapour present in air expressed as a percentage of the amount needed for saturation at the same temperature. There are many misconceptions regarding RH in indoor environments, like the feeling of "dry air", which in reality is irritations caused by air pollutants and dust (Wiik, 2011; Wolkoff, 2018). Wolkoff (2018) divides the effects of humidity indoors into different categories: elevated moisture in construction materials, elevated RH resulting in condensation on surfaces, and RH in the breathing air.

Low humidity in indoor environments (<30 %) can cause increased resuspension of coarse particles and dry eyes (even after short exposures of low RH) causing sensory irritation and extra sensitivity to pollutants or bacteria (Wolkoff, 2018). Eye irritation can also cause reduced visual data acquisition, which in turn reduces efficiency for office and schoolwork (Wyon, Fang, Lagercrantz, & Fanger, 2006). The eye irritation symptoms seem to be better at levels around 40 % RH than 30 % RH (Wolkoff & Kjaergaard, 2007). A study by Lowen, Mubareka, Steel, and Palese (2007) implicates that transmission of the influenza virus spread most effectively at RH between 20 and 35 % and at lower temperatures (around 5 °C). Lowen et al. (2007) also showed that the spread reduced at higher temperatures (around 30 °C) and RH around 50 %. Noti et al. (2013) have shown a significantly reduced infectivity of aerosolized viruses above 40 % RH. In sum, low humidity can cause both discomfort, increased virus/bacterial infection rates, and several physical reactions. Low RH should therefore be considered an important factor of IAQ.

When considering high relative humidity indoors it is important to separate effects from high RH, and effects from water/moisture damages caused by too high RH and condensation. High RH (> 70 %) indoors can cause condensation on surfaces and in the construction, especially during winter when indoor surface temperatures and outdoor temperatures are low. This can cause and increase mould and bacteria growth, which is considered as moisture damages. Such damages may be hard to notice, but can be very harmful over time both for sensitive groups and healthy people (FHI, 2015). Indoor dampness and dampness-related agents are clearly associated with a number of serious respiratory and allergic effects (M. Mendell et al., 2011). Salthammer et al. (2016) recommend keeping RH between 40-60 % to avoid mould growth, and the Swedish government recommends keeping a steady RH below 45 % during winter (FHI, 2015). Problems with condensation in constructions is expected to reduce for newer buildings that are built more airtight, which will reduce exfiltration of hot humid indoor air to the construction. Under normal conditions, RH between 20-60 % has little effect on the human perception of the indoor climate (FHI, 2015)

The indoor air humidity is highly dependent on the humidity outdoors, and the outdoor climate is therefore of importance for the climate indoors. As shown in the middle panel in Figure 2.2, during winter the specific humidity (SH) in the outdoor air is lower, making the total water amount transported indoors via ventilation air lower.. This means that the supply air during winter will have a lower relative humidity, because it is usually heated without adding water. Despite the seasonal changes in SH, the outdoor RH correlates with temperature, and remains stable year-round, as shown in the top and bottom panel in Figure 2.2.

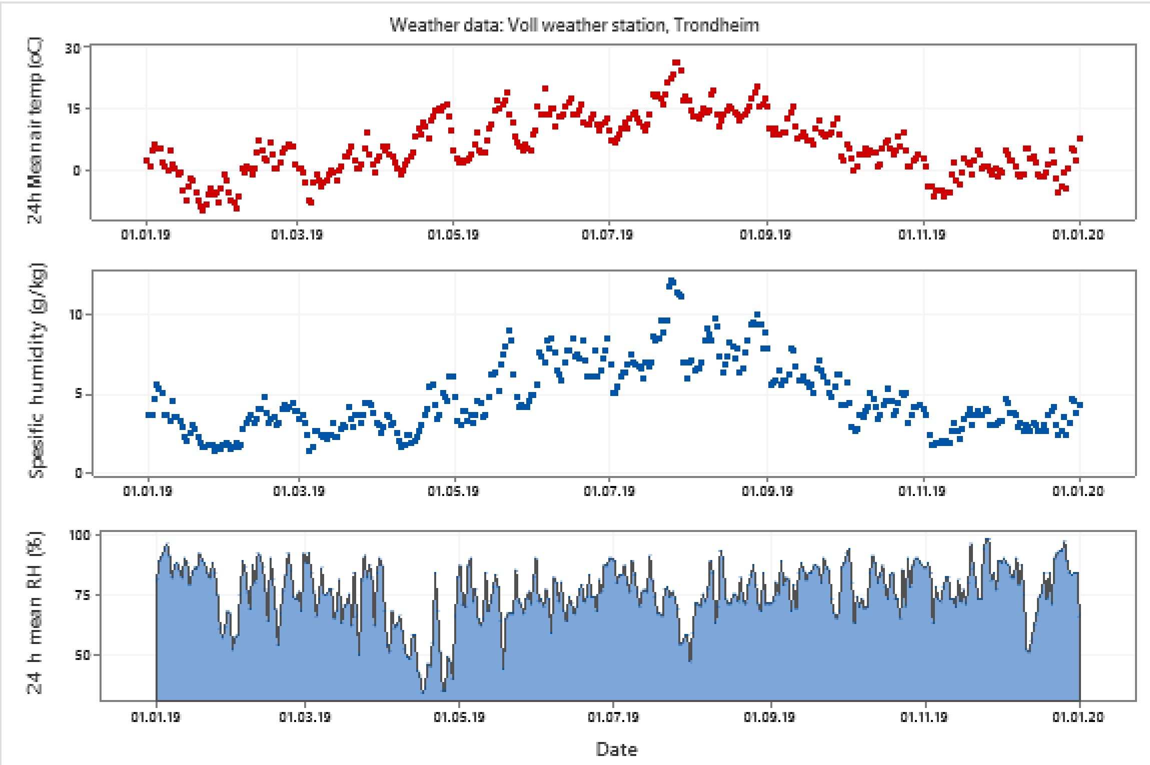

Figure 2.2 Climate data for Trondheim, Voll, 2019

Source: (Norwegian Centre for Climate Services, 2020)

Other sources of moisture inside a normal indoor climate are human perspiration and activities (cooking, showering, breathing, sweating), infiltration from outdoors (through clothes, open windows, cracks, vents) or other things like flowers, aquariums, pets, etc. All these processes add to the total amount of water in the air, which will increase unless the water is removed by natural or mechanical forces, for example ventilation, exfiltration, dehumidification, or condensation.

2.4.3 Air temperature

Air temperature is often mixed with thermal comfort, which is the sum of air temperature, RH, air movement, radiant temperature, activity level and clothing. Temperature is therefore not directly relevant for indoor air quality, but several studies have shown that air temperature exceeding 22 °C may have negative health impacts related to the perceived indoor air quality. Temperatures exceeding 24 °C is shown to cause reduced mental capacity and productivity.

High temperatures during the heating season can cause low RH, which in turn can have negative health impacts, as mentioned in chapter 2.4.2. Arbeidstilsynet (2016) therefore recommends, for light activities, to keep the air temperature below 22 °C during the heating season, and above 19 °C.

2.4.4 Particulate matter (PM)

The general term of particulate matter refers to particles of different shapes and sizes, which can be organic or non-organic, and contain or carry e.g. bacteria, VOC, fungi, or pollen. The particles are divided into subgroups based on their aerodynamic size: PM_{10} (coarse particles) have a diameter between 10 μm and 2.5 μm, $PM_{2.5}$ (fine particles) have a diameter less than 2.5 μm, $PM_{0.1}$ (ultrafine particles) have a diameter less than 100 nm (FHI, 2015). Coarse particles can come from construction work, traffic, sand and dust from nature, pollen, chalkboards, etc. Fine and ultrafine particles can come from human processes, hair, skin, combustion processes like wood stoves, open fireplaces, candles, or cooking. Even though there are different indoor and outdoor sources of PM, infiltration through building envelope and ventilation system is normal, making the indoor and outdoor concentrations connected.

Both $PM_{2.5}$ and PM_{10} can cause respiratory illness as they enter the upper airways. Coarse particles are often stopped in the upper airways, but fine and ultrafine particles can go deeper in the body, causing more serious illnesses (Brunekreef & Forsberg, 2005). The damage potential is partly dependant on whether the particles carry bacteria, viruses, allergens, or similar, but "clean" particles can also be harmful. Research on outdoor PM concentrations has been on the scientific agenda for a while and has proven a linear correlation between increasing outdoor PM concentrations and mortality in the population. Health effects from indoor PM have not had the same focus, but WHO has recently classified indoor incineration of coal and wood in open fireplaces in developing countries as a critical problem to public health. In western countries, particles from furnaces are the main source of pollution indoor. Coarse particles, like dust that swirls up during human activities, will generally not enter lungs or tissue but can cause irritation of mucous membranes in eyes and nose which can cause discomfort.

The daytime concentration of coarse particles in classrooms is connected to the number of people per hour per day, due to the resuspension of particles from clothing fibre and biological emissions (Rivas et al., 2019). Research from schools in Barcelona, presented in the same report, has shown that the main contributors to $PM_{2.5}$ were organic carbons (from skin flakes, cotton fibres and other organic particulates from ozone reaction with skin oil and personal care products) and particles from chalkboards.

Because of limited research on particles in indoor environments, there are no separate maximum limits of exposure, and the maximum values for outside particles therefore applies. The Norwegian institute of public health has introduced the following maximum limits in outdoor air:

$$PM_{10}\ (24hr\ average) < 30\ \mu g/m^3$$

$$PM_{10}\ (One\ year\ average) < 20\ \mu g/m^3$$

$$PM_{2,5}\ (24hr\ average) < 15\ \mu g/m^3$$

$$PM_{2,5}\ (One\ year\ average) < 8\ \mu g/m^3$$

WHO has proposed the following guidelines:

$$PM_{10}\ (One\ year\ average) < 20\ \mu g/m^3$$

$$PM_{2,5}\ (One\ year\ average) < 10\ \mu g/m^3$$

It is mainly fine particles that enter the indoor environment infiltration, therefore the $PM_{2.5}$ maximum limits are proposed as maximum limits for the indoor environment (WHO, 2010).

2.4.5 Volatile organic compounds (VOC)

Volatile organic compounds are a collection of numerous gaseous compounds that can be found in the breathing air, many of which are still unidentified. More than 300 different VOCs have been measured in indoor air, therefore the total VOC (TVOC) is often used as a measuring parameter, as they are hard to separate from each other. Volatile compounds can also bind to PM, which is called particulate organic material (POM). Most VOCs are found in higher concentrations indoors than outdoors and can be split into two categories: stationary emissions (building materials and furniture) and variable sources (human activities like smoking, cleaning products, cosmetics, alcohol or cooking).

An extensive research project performed by the EU assessed 40 different VOCs in different indoor environments and proposed benzene, formaldehyde and naphthalene as the most important VOCs to regulate, based on their actual concentrations and known health effects. Formaldehyde (from stationary sources) were found to be important in northern Europe, while benzene and naphthalene (from traffic and use of moth balls) were most important in southern Europe.

Single compounds rarely (except for formaldehyde, which will be discussed in chapter 2.4.6) exceed levels that can have a negative health impact, but when combined, the TVOC concentration can cause sensory irritation. Based on a meta-analysis of formaldehyde and asthmatic symptoms, the American Environmental Protection Agency (EPA) has set a maximum limit of exposure on 7 ppb (8.7 $\mu g/m^3$) in California. VOCs released from cleaning products have also proved to increase asthmatic symptoms. As many of these VOCs are aromatic, these results must be used with caution, as odours alone can cause asthmatic symptoms.

Several VOCs, mainly from solvents, are considered carcinogenic, like trichloroethylene and tetrachloroethylene, but these are generally not found outside industrial processes in Norway and is therefore not considered as a risk by FHI. Benzene is also carcinogenic and can be emitted to indoor environments from fireplaces and smoking, but if smoking is reduced and fireplaces and stoves have adequate draft it is not considered a risk (FHI, 2015).

Because of the complexity of VOC FHI sees no basis for an upper limit of exposure in indoor climates, but recommends reducing the known sources, and keep the exposure at a low level as a precaution. In contrast to the recommendations from WHO, there are some sources that provide limit values for TVOC, but these must be considered together with other contaminants, to get a nuanced picture of its health effects (Schieweck et al., 2018).

2.4.6 Formaldehyde

As discussed in chapter 2.4.5, formaldehyde is a carcinogenic gaseous pollution that is considered a VOC. The major formaldehyde sources in indoor environments are smoking, combustion (heating, cooking), consumer- and cleaning products (cosmetics, disinfectants, shoe products, soaps, etc.) and some types of building materials and furniture (wood-based products, paints, adhesives, etc.). The emission from building materials and furniture decreases noticeably within a year, but modern production methods have reduced the emission. Environments with increased temperature and humidity will increase the emission rate. Analysis done on 96 homes in Canada in 2005 showed a negative correlation between increased ventilation rate and formaldehyde. The same study showed a significant increase in homes that used electrical heaters and had refurbished during the last 12 months (WHO, 2010). Formaldehyde from food is also considered to be a general pathway of exposure, but as most of the negative impacts come from inhalation, the formaldehyde bound in foods are evaluated separately and is not considered an IAQ problem.

Formaldehyde is highly soluble in water and is therefore absorbed in the nose and upper respiratory tract, causing sensory irritation in eyes and nose. Uncomfortable odours and health effects can develop from short-term concentrations below 50-500 $\mu g/m^3$, including sensory irritation in eyes, throat and nose, tears, sneezing, coughing, respiration problems and nausea. Longue capacity is normally not reduced for healthy persons or asthmatics at concentrations below 2500 $\mu g/m^3$.

Long-term exposure to a concentration of 20 $\mu g/m^3$ has been connected with respiratory symptoms, while concentrations above 60 $\mu g/m^3$ are connected to asthma (M. J. Mendell, 2007). Formaldehyde concentrations above 7500 $\mu g/m^3$ have been proven to cause cancer during animal tests, while other studies have found that high occupational exposure to formaldehyde may cause leukaemia. Formaldehyde is therefore considered a carcinogen by the International Agency for Research on Cancer (IARC). Animal tests have shown an exceedingly low risk for cancer development for concentrations below 100 $\mu g/m^3$ (80ppb, 30 min average), which is WHOs recommended upper limit of exposure. This limit will prevent or reduce short-term sensory irritation and lung function, as well as eliminate long-term effects like cancer.

2.4.7 Phthalates

Consumer products often contain numerous chemical substances, some of which might be harmful if emitted to the indoor air or directly by skin contact. Such substances are found in plastic products, building materials, furniture, cosmetics, cleaning products, medicines, among others. The most usual path of exposure in indoor environments is via house dust and similar particles. Phthalates are mainly used as a softener in PVC-plastic products like food containers, floor covering, plastic toys, medical equipment, etc. As the phthalates are not chemically bound to the plastic, it can leak from the products, into air, water, food or physically through contact. There are different types of phthalates, some of which are more harmful than others. However, the most harmful phthalates have been removed or replaced through national and international product regulations.

Generally, phthalates have low toxicity, making the short-term health effects minimal, but have severe long-term effects like cancer, reproductive harm, and hormone imbalance. None of these effects are proven to occur within normal limits of exposure. Over the last decades, research investigating the correlation between phthalates and asthma and allergies has found some correlations for homes with high concentrations, but correlations for homes within the normal boundary of concentration are not found. As for VOCs, humans are exposed to several types of phthalates at the same time, but the accumulative effect needs more research to provide accurate recommendations. Because of the lack of knowledge regarding both health effects and path of exposure, no maximum limit of exposure is provided. As a precaution, the known harmful types of phthalates are banned from being used in consumer products.

2.4.8 Ozone (O3)

Ozone is a well-known key part of the atmosphere, but it also occurs in the breathing air close to the ground. Most of the ozone found outdoor in Norway is transported from other climatic zones, with more direct sunlight. Ozone in indoor environments mainly comes from the infiltration of outdoor air, hence making the indoor concentration lower than the outdoor concentration. Indoor sources are specific types of processes like some types of printers and air cleaners, but modern production techniques have reduced the emission noticeably. Ozone is highly reactive with other emissions and increased ozone levels are only for a short period of time in proximity to the ozone source, which also makes it difficult to measure the ozone concentration in indoor air.

The health effects from ozone are most relevant for some exposed groups, which include children, seniors, persons with respiratory diseases, persons performing physical activities and persons with a hereditary weak immune system. Short-term exposure to ozone can cause respiratory inflammations of irritations for concentrations above 160 $\mu g/m^3$ (8-hour average) and 250 $\mu g/m^3$ (1-hour average). Exposure to other pollutants may reduce this limit, making people more sensitive to ozone exposure. The upper limit of exposure in outdoor air is set to 80 $\mu g/m^3$ (8-hour average) and 100 $\mu g/m^3$ (1-hour average) by FHI. Because the indoor ozone concentration is most often lower than outdoor, no upper limit for indoor air is set.

2.4.9 Mould and other biocontaminants

Dampness and mould in buildings are common, and might become more common for older buildings and buildings with construction deficiencies, because extreme weather is expected to increase (M. Mendell et al., 2011). In normal indoor environments, there are many types of biocontaminants present, most of whom are not harmful. When dampness or water is introduced regularly indoors, either via building shell damages or condensation, mould has good conditions for growth, which is proven to be harmful in many ways (FHI, 2015).

Research over the last years has pointed out dampness and mould as a risk factor for respiratory diseases or allergies (W. J. Fisk, Lei-Gomez, & Mendell, 2007). Numerous studies have proved a correlation, but common for this research is the fact that it is not proven which biological mechanisms causes the health effects. There can be several different biocontaminants, including dust mites, bacteria and viruses, and mould fungi. As mentioned earlier, other pollutant sources (PM, bacteria, and viruses) can also increase or intensify with increased humidity indoor. Since biocontaminants appear in a wide variety, it is hard to measure and identify them, especially in real-time.

Some types of mould emit Microbial Volatile Organic Compounds (MVOC) which are related to "mould odours". Laboratory tests have shown over 200 different types of MVOC, none of which are considered a clear marker for harmful microbiological species and is therefore unfit for identifying type or concentration of mould. MVOC is correlated with negative health effects, but it is unclear whether this is caused by its potency or odour.

Based on the complexity of biocontaminants and mould, there exists no easily measurable parameter to reduce the risk of negative health effects in indoor environments. The only advice given by FHI is to reduce dampness and condensation on surfaces and take care of leaks and water damages as soon as possible.

2.4.10 Other pollutants

There are many pollutions that are found in outdoor air, which origin from industrial processes or traffic, and can be harmful if present in high concentrations indoors. Common for these are that if they are found indoors, the outdoor concentrations are higher, and that they are removed by ventilation or infiltration. The pollutants that may be considered under this category are:

- Nitrogen dioxide (NO_2): Houses close to highly trafficked roads and houses with gas stoves should take extra care to reduce NO_2 concentrations.
- Diesel exhaust, benzene and polyaromatic hydrocarbons: All these pollutants are mainly caused by traffic and indoor concentrations will be lower than outdoor concentrations

2.5 Obtained limit values and summary

Finds from chapter 2.4.1-2.4.10 are summarized in the table Table 2.1:

Table 2.1 Obtained limit values

Pollutant	Upper limit of exposure	References
CO_2	<1000 ppm	(FHI, 2015)
	>2000 ppm: Hygienically unacceptable <2000 ppm: Hygienically noticeable <1000 ppm: Hygienically acceptable	(Salthammer et al., 2016)
Relative humidity (RH)	40-60 %	(Salthammer et al., 2016)
	Winter: Below 45 % (reduce condensation risk)	(FHI, 2015)
Air temperature	<22 °C >19 °C	(Arbeidstilsynet, 2016)
Particulate matter (PM)	No IAQ limit, outdoor limits apply: $PM_{10}\ (24hr\ average) < 30\ \mu g/m^3$ $PM_{10}\ (One\ year\ average) < 20\ \mu g/m^3$ $PM_{2,5}\ (24hr\ average) < 15\ \mu g/m^3$ $PM_{2,5}\ (One\ year\ average) < 8\ \mu g/m^3$	(FHI, 2015)
	$PM_{10}\ (One\ year\ average) < 20\ \mu g/m^3$ $PM_{2,5}\ (One\ year\ average) < 10\ \mu g/m^3$	(WHO, 2010)
Volatile organic compounds (VOC)	No upper limit. Reduce exposure and be aware of typical sources	(FHI, 2015)
Formaldehyde (HCHO)	100 $\mu g/m^3$ (30 min average)	(WHO, 2010)
Phthalates	No measurable limit value	
Ozone (O_3)	Outdoor max level, no indoor level: $80\ \mu g/m^3$ $\mu g/m^3$ (8-hour average) $100\ \mu g/m^3$ $\mu g/m^3$ (1-hour average)	(WHO, 2010)
Mould/biocontaminants	No measurable limit value	(FHI, 2015)
Other	NO_2, diesel exhaust, polyaromatic hydrocarbons, benzene: $C_{indoor} < C_{outdoor}$ – precaution needed if living in highly trafficked areas	(FHI, 2015; WHO, 2010)

It is clear from the findings in this chapter that IAQ and health is closely correlated, but that very few causal relations are known. Therefore, it is hard to provide general recommendations for all climates and building types. The indoor air quality is dynamic and is influenced by a number of pollutants from different sources. When considering IAQ, it is therefore important to also assess which pollution sources are present and reduce the emissions from these. This implies that the ventilation should be considered a secondary tool for controlling IAQ, while primary source control, surveillance of IAQ and occupant satisfaction should be prioritized to take necessary actions. Some pollutants have acute effects while others have long-term effects. The IAQ should therefore be monitored both to control acute effects and follow up on changes over time.

Based on the findings in this chapter, the following conclusions are made for further use in this report:

- Mould/biocontaminants, phthalates and ozone are hard or impossible to measure correctly using low cost sensors. Spot samples can be taken to assess the presence of for example mould. Regular or annual campaigns to document changes for the mentioned pollutants should be evaluated.
- NO_2, polyaromatic hydrocarbons, benzene, PM, and other foreign pollutants most often have higher concentration outdoors than indoors and are therefore not prioritized to measure indoors. Outdoor measurements are often provided from governmental sources and should be checked regularly if the building in question is close to highly trafficked roads. Pay close attention to seasonal changes.
- The rest of the pollutants should be evaluated in indoor environments, using the limit values in Table 2.1: CO_2, relative humidity (RH), air temperature, particulate matter (PM), volatile organic compounds (VOC), and formaldehyde (HCHO).

3 Air quality sensors

The general definition of a sensor or a detector is a device that translates a physical or chemical property to an electrical signal (Bastuck, 2019). There are many different types of sensors commercially available today, and sensors seemingly measuring the same thing have a variety of builds and prices. This chapter highlights some of the different technologies used in sensors relevant for this report, and provides a basis for the evaluation of the results from the measurements in chapter 6, and discussion in chapter 7.

One of the premises for this report is that the developed methods and solutions should be easy to install and use for building owners. Therefore, the focus of this report is microsensors and low-cost sensors that are commercially available. Specialized and costly air analysers may be used as a reference or for comparison.

Chapter 3.1 introduces three important sensor features, followed by chapters 3.2.1 and 3.2.2 giving a brief overview of chemical and physical sensors. Chapter 3.3 emphasizes important limitations to low-cost sensors, before chapter 3.4 summarizes the main finds.

3.1 Sensor definitions

This chapter introduces three important sensor definitions that are often used to assess the performance of sensors.

Sensitivity

Defined as the change of the output signal due to change in the input signal at a specific working point (Fraden, 1996; Tränkler & Reindl, 1998). An ideal sensor should have a high and linear response to any input signal so that a small change in the input creates a large and proportionate change in the output.

Selectivity

A measure of how strongly a sensor is influenced by non-target analytes in a mixture (Vessman, 1996). As selectivity for mixtures is very time-consuming to determine, values for sensitivity are often tested for specific substances and concentrations only, and must be reported accordingly (Persson & Vessman, 2001).

Stability

A sensors ability to maintain an identical response to identical stimuli, as well as a stable baseline over time. Sensor drift can cause changes to both baseline and response. A related parameter is reversibility, which determines if and how quickly the sensor reaches baseline again once the stimulus is removed (Göpel, Hesse, & Zemel, 2008).

3.2 Sensor types

3.2.1 Chemical sensors

Chemical sensors are sensors that translate chemical quantities into electric signals. Gas- or air analysers have originally been unmanageable and costly to operate, which have made it hard to assess indoor air quality in real-time, or in several zones of a building at the same time. Over the last years, chemical micro-sensors have developed rapidly, making it easier to get a more detailed picture of indoor air quality in buildings (Caron, Redon, Coddeville, & Hanoune, 2019).

To choose an appropriate sensor it is important to know exactly what to measure, and which environment the sensor will be operating in. Some sensors do not necessarily measure the exact concentration of the gas in question, but chemical correlations that indicate the presence of the measured quantity (Caron et al., 2019). These sensors are called *intrinsically non-selective sensors*. Sensors that measure a specific gas are called *selective or nearly selective* sensors and are sometimes referred to as detectors rather than sensors.

Non-selective sensors react to multiple compounds in the analysed air while selective electrochemical sensors target single compounds like carbon, ozone, etc. (Caron et al., 2019). This means that measurements from chemical sensors must be reviewed carefully to decide whether the results are caused by the analysed gas or other similar gases that can trigger the output, so-called cross sensitivities.

In addition to cross-sensitivities, chemical sensors are prone to drifts, which weakens or changes the sensor response over time (Haugen, Tomic, & Kvaal, 2000). Sensor drifts may be reversible or irreversible and can be caused by ageing or degrading of the sensor surface (irreversible) or condensation on the sensor surface (reversible). Unless treated, measurements will be inaccurate or wrong. Irreversible drifts are not necessarily fatal to a sensor and can be treated by applying a mathematical correction to the output signals. Some combinations of metal oxide sensors (MOX/MOx) sensors do not need calibration if the output data is treated with pattern recognition algorithms (Caron et al., 2019).

The availability of low-cost chemical sensors has made it possible to get real-time measurements from several parts of a room or a building. The most common sensor principles used in these sensors are metal oxide sensors (MOx/MOS), photo-ionization detector (PID), electrochemical sensors (EC; amperometric and potentiometric), field effect transistors (FET), optical sensors, optical/non-dispersive infrared (NDIR). and micro-gas chromatograph (μGC) (Bastuck, 2019; Salthammer et al., 2016; Schieweck et al., 2018; Spinelle, Gerboles, Kok, Persijn, & Sauerwald, 2017; Szulczyński & Gębicki, 2017)

Metal oxide sensors (MOS)

In metal oxide sensors, the analyte particles diffuse towards a heated receptor surface made of metal oxides, changing the resistance of the receptor element. This principle depends on several co-existing reactions: diffusion, chemisorption and desorption of gases, catalysed chemical reactions, the electric conductivity of semiconductors and electron surface phenomena (Szulczyński & Gębicki, 2017). The sensitivity of the sensor varies with e.g. the thickness of the receptor layer and the catalytic particles placed on it and the temperature of the receptor layer. In addition to semiconducting materials, dielectrics are also used for gas detection by measuring their impedance.

Because of the sensing principle, sensor selectivity is hard to achieve. However, it has a great sensitivity down to parts per billion range (Bastuck, 2019).

Electrochemical sensors (EC)

In electrochemical sensors, analyte particles in a gas mix diffuse through a membrane, which separates the gas from internal electrolytes. Redox reactions create an electrical current (amperometric) or a potential difference (potentiometric) between the electrodes in the electrolyte (Bastuck, 2019; Szulczyński & Gębicki, 2017). This reaction increases linearly with the amount of analyte gas passing the membrane. Due to electrolyte depletion, the sensor has to be replaced regularly.

Nondispersive infrared sensors (NDIR)

Nondispersive infrared sensors have a chamber with an optical line where infrared light is emitted. When the analysed gas passes, it absorbs a specific part of the infrared light, based on the wave number of a functional group of VOCs (Szulczyński & Gębicki, 2017). This reduction of light intensity is proportional to the concentration of the analysed gas or vapor subject to detection. An optical filter passes light of a defined wavelength, providing selectivity for a particular set of gases.

Photoionization sensor (PID)

The operation of photoionization sensors is through the ionization of neutral molecules of chemical compounds by lighting them with a UV lamp (Szulczyński & Gębicki, 2017). Then, the gas molecules are directed between two polarized electrodes, making a current flow and a voltage signal that depends proportionally to the concentration of the analyte gas. Variation in the filling gas in the UV lamp can vary the characteristics of the sensor. PID sensors are mainly used for measurements of the summary concentration of VOC.

Gas-sensitive field effect transistor (GasFET)

Field effect transistors describe stacks of materials instead of the material itself. One of the simplest field-effect devices is a metal-insulator-oxide (MIS) capacitor (Bastuck, 2019). A *metal-oxide-semiconductor field-effect transistor* (MISFET) is a combination of the mentioned technologies. These sensors have a variety of builds, depending on their intended use. The common denomination for gas-sensitive field effect transistors is GasFET (Bastuck, 2019).

Sensor arrays

Sensor arrays are grouped sensors that measure simultaneously and interpreting the output for special patterns. The different sensor elements in these arrays should have different sensitivities and responses and can be made from different technologies. By doing this the sensor array can benefit from the different sensors' benefits (Bastuck, 2019). For these arrays, caution must be made for the individual strengths and weaknesses, when interpreting the sensor output.

Table 3.1 shows examples of the normal applications for some of the sensor types mentioned above

Table 3.1 Sensor types and applications

Sensor type	Applications	Compounds/gases
MOS	- Indoor air quality - Internet of things modules - Fire detection - Ventilation control	Alcohols, aldehydes, carbon oxides, CH_4, organic acids
NDIR	- Indoor air quality - Combustion process monitoring - Biogas production	Infrared absorbing VOC's

EC	- Breathanalyzer - Environmental protection - Urban and industrial area monitoring - Mobile monitoring applications	Ethanol, formaldehyde, mecaptanes

Source: (Szulczyński & Gębicki, 2017)

3.2.2 Physical sensors

Physical sensors are to some extent based on straightforward and well-known physical relationships. Temperature sensors measure the electrical resistance in a temperature probe, which changes when the metal in the probe changes temperature. Other examples of quantities measured by physical sensors are pressure, magnetic field, acceleration or lightning intensity (Bastuck, 2019).

Particle sensors

Particle sensors may function by analysing an air sample qualitatively if checking for bacteria or other biochemical or particulate pollutions. One of the well-known physical pollutions in both indoor and outdoor air is particulate matter (PM). The particles vary in size but are often measured in PM_1 - PM_{10}. The harmfulness of the particles depends on their size, as mentioned chapter 2.4.4

Traditional ways of measuring particulate matter concentration in the air include chemical analysis of an air sample (Federal Reference Method) (Chee F. P., 2018). Equivalent methods with higher sampling rate have been developed, such as the beta attenuation monitor (BAM) which uses radioactive decay to measure at an hourly resolution, or tapered element oscillation which measures the change in vibration of a sensor glass tube caused by the particles (Chee F. P., 2018; Kelly et al., 2017).

Low-cost sensors offer more flexible and high-resolution air quality data at a lower cost. One of the most used low-cost PM sensor principles lately is laser scattering, which sends a controlled airflow through a sensor, which then passes a laser light source before a photosensor registers the reflections from the PM (Lattanzio, 2019).

3.3 Low-cost sensor limitations

Price and quality often correlate. Therefore, the output from the chosen low-cost sensors must be assessed with care. This chapter summarizes a brief literature review for some of the known limitations regarding low-cost sensors.

Castell et al. (2017) compared "AQMesh" units, that measure four gaseous pollutants and total particle count, with a known reference. The test compared 24 units for six months, and found that the main challenges robustness and measurement repeatability (Castell et al., 2017). The tests showed that laboratory calibrations cannot correct totally for real-world conditions, and that each sensor changes differently over time causing uncertainties whether the sensors are over- or underestimating the results. Meteorological conditions, season and surrounding environment might also affect the sensors differently. Castell et al. (2017)points out that many low-cost sensors show good correlations to the reference detectors even though the exact concentrations are deficient, which can be acceptable for sensors that do not require exact measurement of concentration. Application of field calibrations based on machine learning can reduce the uncertainties noticeably (Castell et al., 2017)

Field tests and literature review from Castell et al. (2017), Snyder et al. (2013), and White et al. (2012) provided the following general concerns regarding low-cost sensors:

- Lack of information and tests from manufacturers regarding the performance of sensor (e.g. error characteristics, data quality, long-term stability in field with varying conditions)
- Have low selectivity and cross-sensitivities
- Are prone to sensor drifts
- Sensitive to weather changes (temperature, RH, pressure)
- Require filter changes, or are too fragile

These negative effects do not necessarily ruin the measurements but require extra care when assessing the results and measurement setup. The table below summarizes some known strengths and concerns with commercialized gas and PM sensors:

Table 3.2 Sensor characteristics

Gases	Strengths	Concerns		
Electrochemical cell (EC)				
CO, O_3, NOx	- Low cost - Low power - Small - Real-time - More sensitive than MOX sensors	- Interferences: CO, VOC, NO_2	- Drift - Frequent recalibration needed - 1 year lifetime	
Metal oxide semiconductor (MOS)				
CO, O_3, NOx	- Small size - Inexpensive - Stable	- Sensitive to change of RH, T, P - Cross sensitivity	- Power consumption - Fragile materials	- Typically less sensitive than EC
Non-dispersive infrared absorption (NDIR) (4.26 μm)				
CO_2	- Compact - Stable to changing RH and T	- Sensitivity depends on path length	- Calibration may be misinterpreted or inaccurate	- Some singe-beam devices auto-calibrate as if background CO_2 is 400 ppb
Ultraviolet absorption (254 nm)				
O_3	- Accuracy - Stable to change in P	- Size (not yet miniaturized)	- Sensitive to changes in RH	- Cost
Particle properties				
Light scattering	- Small - Inexpensive - Commercially available	- Not a direct mass measurement	- Does not measure ultrafine particles	
Light absorption	- Handheld - Well established - Stable - Continuous	- Still relatively large and costly	- Requires changing a filter	

Direct particle mass	- Small - Inexpensive - Direct mass concentration	- In development stage	- Likely sensitive to changes in T and RH

Source: (Snyder et al., 2013; White et al., 2012)

3.4 Summary and recommnedations

The discussions in this chapter underline the importance of knowing sensors and their intended use to avoid errors and misinterpretations of results when using low-cost sensors. It is important to bear in mind that many sensors do not measure the analyte gas directly, but provide an estimate based on known correlating factors. This is the reason many sensors are subject to faulty measurements due to cross-sensitivities. Hence, different sensor fabricates measuring the same pollutant can produce different results.

Even though general strengths and weaknesses exist for different sensor types, it is important to remember that identical sensors can give different results, and each sensor should be calibrated before and during experiments. It is advised to evaluate sensor performance using basic concepts of sensitivity, stability, and selectivity.

Before constructing an experiment or project using low-cost sensors, their known limitations should be assessed before the acquisition and when evaluating the results to ensure that the setup is working as intended. Calibration of the final sensor system on-site is recommended, to reduce the impact of external factors.

4 Ventilation principles and control

The main principle of a ventilation system is to supply fresh air and extract polluted air from the building. There are different principles for doing this, each with different strengths and weaknesses. The main differences are discussed in this chapter, in addition to any relevant specifics for the physical measurements presented in chapter 6. The differences between some of these principles will reduce the scope of the results.

The focus of this report is the supplied airflow to a room and the pollutants that are used as control parameters. Ventilation system efficiency, losses, pressure control, and similar, is not emphasized. Therefore, the proposed ventilation rates in this thesis must be adapted to the system efficiency for different locations.

Chapter 4.1 presents the basic ventilation driving forces and air distribution principles, which are important for understanding how air and pollutants distribute in the ventilation system, and each zone. Chapter 4.2 describes the main differences between common ventilation rate regulating methods, while chapter 4.3 briefly describes how the most important components work and why limitations regarding ventilation rates apply. The simplified method for estimating energy use for ventilation is introduced in chapter 4.4 before chapter 4.5 briefly discuss how ventilation rates are dimensioned. Chapter 4.6 presents a literature review of the priorities between ventilation rates, energy, and health.

Chapters 4.1 to 4.6 are to some extent produced with support from the books "Ventilasjonsteknikk" part I and II written by Ingebrigtsen and Stensaas (2016), which are the source of information unless other is stated.

4.1 Basic ventilation principles

Ventilation systems are a form of influencing or controlling the indoor air quality and thermal environment. As a consequence of the green shift, energy use from ventilation systems have become more important, which has resulted in new types of ventilation systems or modifications to the traditional systems. The most relevant principles for this report are presented in chapter 4.1.

4.1.1 Ventilation driving forces

4.1.1.1 Natural ventilation

Natural ventilation is based on natural driving forces, like buoyancy, wind power and infiltration. The pressure caused by these forces will push the used air out of the building, resulting in an underpressure indoor that causes outdoor air to enter the building. This ventilation principle is good for rooms and buildings that are less airtight. The natural driving forces are small compared to mechanical ventilation and requires more attention during design and operation to get a well-functioning ventilation system. If the building is refurbished or the pattern of usage is changed, this might reduce the ventilation efficiency.

Natural ventilation principles are less fit for new buildings that are built more airtight to reduce heat losses. Some new buildings use natural driving forces for ventilation, but this requires extra attention to the design of the building to avoid large pressure drops in the system.

4.1.1.2 Mechanical ventilation

Mechanical ventilation is driven by mechanical fans and have a more complex technical system than natural ventilation systems, and include filters, heat recovery, heaters, coolers, de-humidifiers, etc. If designed and built properly, mechanical ventilation systems can be as energy efficient as hybrid ventilation (chapter 4.1.1.3). Mechanical ventilation systems are often balanced, which means that they mechanically extract approximately the same amount of air that is supplied.

4.1.1.3 Hybrid ventilation

Hybrid ventilation is based on the same principles as natural ventilation systems, but the driving forces are supported by mechanical fans. Such ventilation systems are often less complex than mechanical ventilation systems but are more flexible than natural ventilation systems as they can include heaters, filters, and heat recovery. Some hybrid ventilation systems only have extract fans for extraction of used air, while fresh air enters the building through valves, cracks, and infiltration. If the ambient temperature is lower than the indoor air temperature, energy use for heating inside will increase. Some other systems use two or more fans to create an airflow through the building without using ducts. Such systems can use heat exchangers or thermal elements in the fans.

4.1.2 Air distribution principles

In short, the air distribution principles describe how to supply fresh air and how to extract used air in a ventilated zone or building. The distribution principle for a zone is chosen based on factors such as occupancy, intended use, geometry, climate, etc. This chapter will discuss the most usual air distribution principles, how they are designed, and to which type of use they are most fit.

4.1.2.1 Displacement ventilation

For displacement ventilation, fresh air is supplied near the floor with a lower temperature than the room air and at low velocity, so it does not mix with the room air. The fresh air spread over the floor, providing fresh air to most of the room area. When the air around the internal loads in the room (persons, technical equipment) heats, it rises due to convection, creating an upward flow. The used air is then extracted at ceiling level. Common faults or inaccuracies in displacement ventilation are disturbances of the airflow, stagnant zones or short-circuit of the airflow. Rooms with displacement ventilation are less flexible because of the low-velocity supply air. This means that the placement of furniture, technical equipment, and pollution sources should be placed according to the room design.

The displacement ventilation principle removes contaminants efficiently and normally provides good air quality in the occupied zone. Figure 4.1 illustrates the contaminant concentration in the room, occupied zone (white area), and the contaminant zone (red area). The contaminant concentration for each zone is in the brackets.

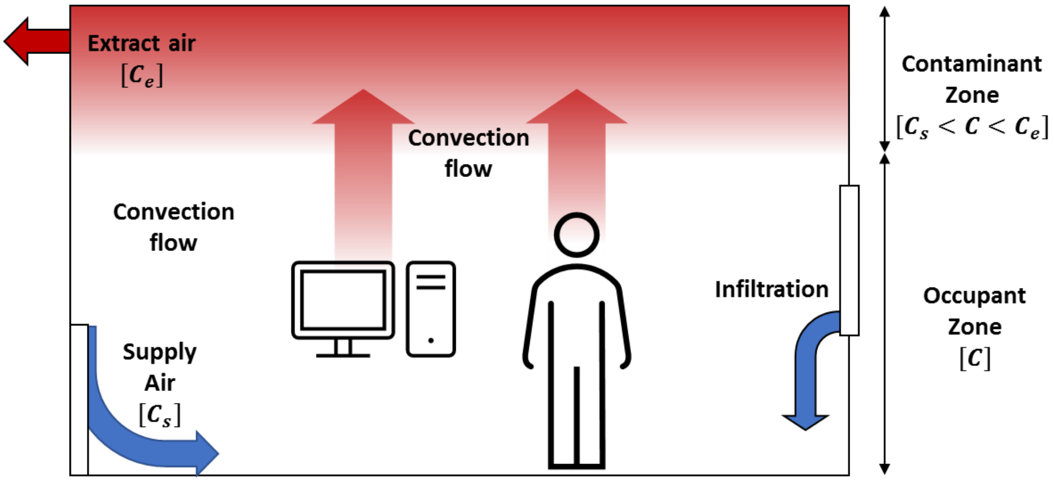

Figure 4.1 Displacement ventilation contamination distribution

Made with inspiration from: (Mundt, Mathisen, Nielsen, & Moser, 2004)

The red area in Figure 4.1 indicates the emissions from the occupant and computer. $[C]$ indicates the mean pollution concentration in the room, $[C_e]$ the pollution concentration in the extract, and $[C_s]$ the concentration in the supply. If operated correctly, there should be a clear difference between the occupied and contaminant zone. The boundary between the two zones is dependent on the supply airflow. The height of the boundary should be placed above the height of the occupants in the room.

The contaminant removal efficiency is best for displacement ventilation when the pollution sources produce heat, since the pollutants faster rise above the occupied zone without mixing with the breathing air. Human bioeffluents and technical equipment are examples of pollution sources with heat. Garbage cans, chemicals and particles are examples of pollutants that do not necessarily rise to the contaminant zone.

4.1.2.2 Mixing ventilation

Supply air in mixing ventilation is supplied via air jets or diffusers placed close to roof height. The momentum of the supply air mixes the fresh air with the used air and dilutes the contaminants present in the room air. In theory, the air in mixing ventilation zones is fully mixed ($C = C_e$), making the room air homogenous (pollutant concentration is uniform over the room volume). Figure 4.2 illustrates the spread of contaminants in a fully mixed room (ideal mixing ventilation).

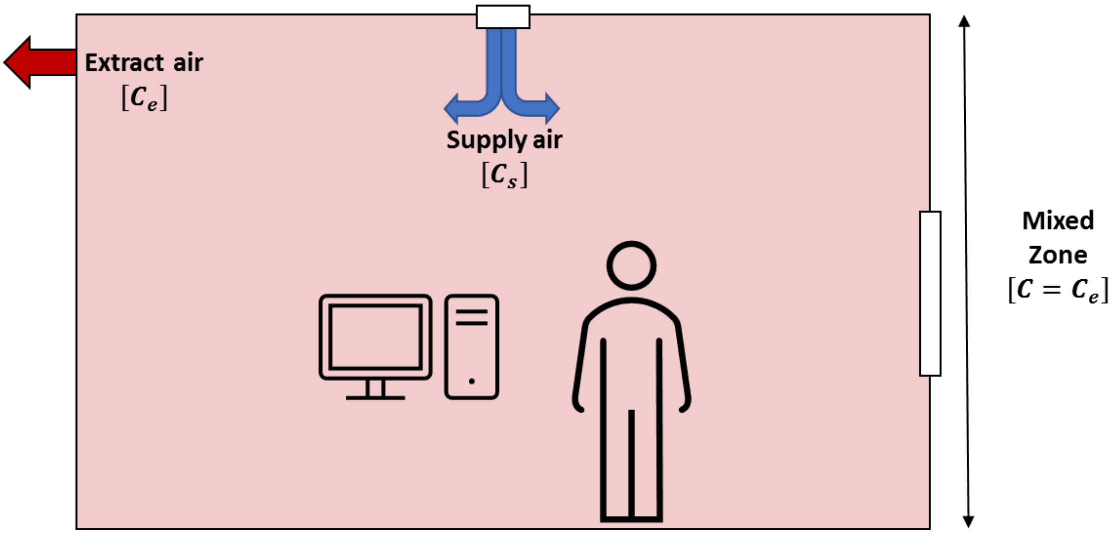

Figure 4.2 Contaminant distribution mixing ventilation

Made with inspiration from: (Mundt et al., 2004)

The pink area in Figure 4.2 indicates that the pollutants from the person and computer are diluted by the supply air and mixed with the contaminated air already present. [C] indicates the mean pollution concentration in the room and C_e the pollution concentration in the extract. If designed and operated correctly, the pollution concentration in the room should homogenous (fully mixed).

Mixing ventilation is more flexible than displacement ventilation, as its airflow and efficiency are less dependent on use patterns and furniture. Mixing ventilation is better to use for room heating and cooling than displacement ventilation because it spreads better in the room. Mixing ventilation is the most common air supply method in Norwegian schools, daycare centres and office buildings (Ingebrigtsen & Stensaas, 2016).

In theory, the supply airflow needed to control human emissions is lower for displacement ventilation as it only extracts contaminated air, while mixing ventilation extracts contaminated air mixed with fresh air.

4.2 Ventilation control principles

Ventilation systems have different control schedules, depending on how the system is built. Some systems are built to supply a constant air volume (CAV) while others can vary the airflow based on some sort of control variable (variable air volume, VAV). CAV systems may have on/off control, while VAV systems have more advanced control of the airflow. Some VAV systems are controlled based on the measured occupancy in the ventilated room and is called demand-controlled ventilation (DCV).

4.2.1 Constant air volume

Ventilation systems with constant air volume are applicable where the occupancy of a room is known and has little variations. Some CAV systems operate 24/7, and some are only operating during working hours to save energy. In CAV systems, most of the components are static and have little room for variations, which means that the airflow ratios for each of the ventilated rooms and zones are somewhat constant. The ventilation components are designed for a specific volume flow, which is the operating point.

When designing CAV plants, technical standards are often used to calculate the needed airflow rate, based on occupancy, room size and/or specific industrial processes. As these calculations are for static operation, zones with varying occupancy or processes might have too high or too low ventilation rates at times. This can result in e.g. increased pollutant levels, draft, and decreased thermal satisfaction.

4.2.2 Demand-controlled ventilation

Demand-controlled ventilation (DCV) is a type of variable air volume (VAV) ventilation system. To reduce energy use while maintaining a high comfort level, DCV is normal in modern buildings and ventilation systems. DCV provides the necessary amount of air when there are people present in a room and reduces or shuts off the ventilation when there is less, or no people present. DCV is optimal in rooms where the contaminant load is variable and when it is possible to measure how and when the load varies. DCV is also appropriate when there are industrial processes in a room that has variable production of heat or pollutants. The variable airflow can both be used for control of the thermal environment (heating and cooling via supply air) and control of pollutants in the indoor environment.

When designing the ventilation system components (ducts, dampers, valves), there are several factors to consider making sure that the air is distributed as planned. This includes pressure losses in components, control of airflow, noise in ducts, airflow requirements, etc. The result of this is a maximum and a minimum flow to obtain high enough air velocity in the pipes to distribute the air, and low enough air velocity to prevent noise from ducts. When different zones change the airflow demand during operation, the pressure ratio changes in the system and the dampers should act accordingly to balance the system. This is discussed further in chapter 4.3. In the CAV system, this is not a problem as the ratio between the branches is constant, but in DCV systems, these ratios change. To ensure that the operation of the DCV system is optimal, it should be self-balancing based on the variations in demand. This can be done using dynamic valves and room units, frequency-controlled fans, or other types of control.

Regardless of how the air is moved between the air handling unit (AHU) and the room unit, the measurable parameter that is important is the amount of air that is supplied to the room. The supplied amount of air can vary between the maximum airflow rate ($\dot{V}_{max}$) and minimum airflow rate ($\dot{V}_{min}$). Between these two amounts, the airflow can be varied either linearly or stepwise based on a controlling parameter. This controlling parameter is often CO_2 as it has a linear correlation to the number of people in the room and their activity level, but might also be temperature, VOC, relative humidity, etc. (Ramalho et al., 2015; Salthammer et al., 2016).

4.3 Ventilation system components and limitations

Ventilation systems are built from a basic set of components. A list of the most common components is shown below:

- Air handling unit: The driving force for air in the ventilation system. Includes for example fans, filters, heaters, coolers, or heat recovery.
- Ducts: Pathway for transport and distribution of air to and from the ventilated zones
- Dampers (valves): Regulates airflow to the different zones. Valves can be both static and dynamic, depending on the type of regulation.
- Room air diffusor: Distributes air from supply duct to room
- Extract air valve: Extract air from the room to exhaust ducts

All the components mentioned above must be dimensioned according to the main purpose of the ventilation system. Different regulation principles (CAV or VAV) or other special cases must also be considered when designing the system. Most components have a maximum flow limit, which should not be exceeded. Some components also have a minimum flow limit that needs to be obtained for the system to work properly. Examples of such components are room air diffusers, AHU, and VAV-dampers. If the airflow is too low or too high, the system will be unstable, and components can break or run inefficiently. This is important to consider when planning VAV-systems, as the difference between minimum airflow and normal airflow can be significant.

While some of the components have an impact on the whole ventilation system, others mostly influence specific rooms or zones. This implies that the whole system should be considered as one during the planning and final testing, and the whole system should be tested both for minimum and maximum ventilation rate, and all regulation scenarios. Overloading is known to cause damages to equipment or noise in ducts and fans, but underloading can have more vague effects. Underloading of equipment is a relevant scenario for VAV-systems, and some examples of consequences are discussed in the paragraphs below.

Air handling units

The following section is supported by information from Byggforskserien (2002) 552.308.

Air handling units (AHU) are often a centralized driving force for the ventilation system in a building. The main rule is that a large AHU is more efficient than several small AHUs, both regarding energy and area use in a building. The optimal AHU for a system is chosen based on the system airflow demands. The chosen AHU provides a working point based on system characteristics. Figure 4.3 illustrates an example of a fan system diagram.

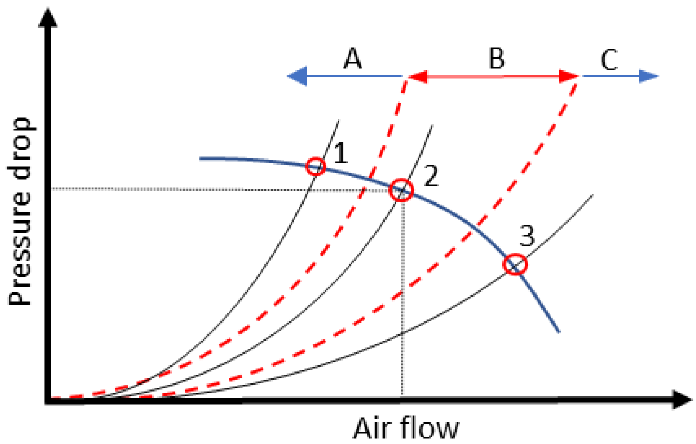

Figure 4.3 AHU working point (red circle) for scenario 1-3

Made with inspiration from (Byggforskserien, 2002)

Figure 4.3 has three areas: the optimal operating area (B), the reduced efficiency area (C), and the unstable area (A). The Y-axis is the total pressure drop in the ventilation system, and the X-axis is the ventilation rate from the AHU. The three operating scenarios are described below:

1) The working point is in the unstable region and must be avoided. The scenario is typical for VAV-systems that runs at too low ventilation rates have too large

pressure drop. There are several ways of regulating a VAV system to avoid this, but this means that the airflow rate cannot change from 0-100% without limitations.

2) The working point is in the optimal area and the fan efficiency is at maximum. The system should regulate the airflow along the system curve, or else the system might reduce efficiency or become unstable.
3) Reduced efficiency region. This will probably work but components will be less efficient and produce more noise and heat.

Room air diffuser

The room air diffuser is the component that connects the ventilation system and the room air. The diffuser in mixing ventilation is placed near roof height and introduces supply air at high velocity, while displacement ventilation is placed near the floor, and introduces supply air at low velocity. This chapter focuses on mixing air diffusers, as it is of higher relevance for the real measurements.

The diffuser or diffusers should ensure that room air is mixed, without creating stagnant zones. To ensure that the supplied air spreads properly in the room, it is important to know the throw length from the diffuser. The throw length is the length from the diffuser to where the supplied air velocity hits a given limit, often 0,2 m/s. If the throw length is too short, the room air is not mixed properly, while too long throw length can cause uncomfortable draft in the occupied zone. Unless the ventilated room is quite small, it is often better to have several smaller diffusers than one large.

There are both static/passive room air diffusers and active/dynamic room air diffusers. Passive diffusers work as described above and operate optimally for a given interval. Active diffusers change their opening when the airflow rate is changed to maintain the throw length. This means that the operating range for the diffuser increase and is more fit for VAV ventilation systems.

4.4 Ventilation system energy use

The ventilation system is, as discussed earlier, a complex composition of different components. The total energy used to move the air in the system is often referred to as specific fan power (SFP) and is a measure of the energy efficiency of the ventilation system. A system with high SFP uses more energy to transport one unit of air than a system with low SFP. Increased SFP can be caused by ineffective fan operation, increased friction in ducts or equipment, and similar. Some automation systems estimate a real-time SFP value, but many systems only estimate an SFP as part of the system documentation.

The Norwegian building codes (TEK17) provided by Norwegian Building Authority (2017) have provided several demands regarding energy efficiency for buildings, where the upper boundary for SFP in residential buildings is 1.5 kW/(m^3/s). The passive house standard for commercial buildings (NS3701) is 1.5 kW/(m^3/s) for passive houses and 2.0 kW/(m^3/s) for low energy buildings (Standards Norway, 2012). Older ventilation systems are expected to have higher SFP. A standardized method of calculating SFP is given in NS3031 from Standards Norway (2016):

$$SFP = \frac{\Sigma P_f}{\dot{V}_{net}}$$

Where

$$\Sigma P_f = Total\ fan\ power\ in\ ventilation\ system\ (supply\ and\ extract\ fans)$$

$$\dot{V}_{net} = Net\ air\ flow\ rate\ (largest\ of\ supply\ or\ extract\ air\ flow\ rate)$$

There are also other ways of measuring SFP:

SFPv

The letter "v" stands for validation. This is a known SFP value for a specific air flow rate and pressure loss in the system. The value is used to validate the SFP when doing control measurements after installation, or during service. This can be the same point as the AHU working point.

SFPe

The letter "e" stands for energy, and SFPe is a theoretical value that is used to calculate the average energy use for fans and is derived from the average airflow rate during a year (all seasons). For demand-controlled systems, this value is derived from different operation scenarios. If the operation scenarios are too many, SFP for different percentages of the dimensioned air flow rate ($\dot{V}_{dim}$), $0.8 * \dot{V}_{dim}$, $0.6 * \dot{V}_{dim}$, etc. can be given as documentation (Standards Norway, 2016)

4.5 Ventilation rate dimensioning

A key point for the design of a ventilation system is determining the required ventilation rate to the ventilated zones. The most important pollution sources are human emissions (bioeffluents), static emissions (furniture, building materials, etc.), and process emissions (showering, cooking, cleaning, hobbies, etc.). This is discussed in detail in chapter 2.4.

The actual emission rate for each room can be hard to quantify, and the resulting ventilation rate equally difficult. Therefore, different international and standards provide standardized requirements for ventilation rates. Examples of such standards are TEK17 (Norway), NS-EN 16798 (Europe, formerly NS 15251) and ASHRAE 62.1 (USA) (Carrer et al., 2018). These proposed ventilation rates aim to remove pollutants produced by building materials and occupants but also aims at reducing sensory irritation like bad odours.

TEK17, written by Norwegian Building Authority (2017), provides a functional demand description and presents pre-accepted ventilation rates. The given requirements in TEK17 § 13-1 states, among others, that the ventilation should provide acceptable air quality regarding odours, dampness and pollutants that can cause irritation or be unhealthy. Some of these demands are connected to the pre-accepted performances given in § 13-3, which provides ventilation rates to help design a ventilation system. The proposed ventilation rates provided by TEK17 for different situations and types of rooms are summarized below:

- Fresh air supply to a room for pollution from persons in light activity should be 26 m^3/h per person
- Fresh air supply to a room for pollution from materials, products and installations should be 2.5 m^3/h per person when in use and 0.7 m^3/h per person when not in use
- Rooms with polluting activities should have sufficient air extraction:
    - Bathroom/shower: 54 m^3/h per shower
    - Toilet: 36 m^3/h per toilet/urinal
    - Elevator shaft: 30 m^3/h per m^2 floor area in shaft
    - Basement: 2.5 m^3/h per m^2

The top two points in the list above are the same ventilation rates given in NS-EN 16798, for category 2 air quality (20 % dissatisfied occupants) when using low-emission materials in the building (Standards Norway, 2019). This, in turn, is heavily based on ASHRAE 62.1 (Carrer et al., 2018).

It is well documented that there are correlations between IAQ and health, as discussed in chapter 2. There have been several studies to find which ventilation rate different health risks are likely to occur, but results vary from around 20-140 m^3/h per person (Carrer et al., 2015; Jan Sundell et al., 2010). Despite the proven correlation between ventilation-IAQ-health, the ventilation rates suggested by standards and building codes are made based on subjective factors, resulting in increased ventilation rates (Carrer et al., 2018). However, the proven correlations have minimal focus on pollution sources and source strengths in the assessed buildings but focus mainly on the ventilation-health coherence. This can explain the wide range of ventilation rate for which no health effects can be observed. The method and quality of ventilation rate measurements are also considered to be of low quality, and are for some reviews only estimates, meaning that the exact ventilation rates are not necessarily exact numbers (Carrer et al., 2015). This proves that it is hard to generalize ventilation rate requirements and that a more systematic and holistic approach is needed.

Based on the challenges described above, the European HelathVent project as summarized in Carrer et al. (2018), proposes new guidelines for establishing ventilation rates in buildings. Carrer et al. (2018) underline that ventilation is a supplement to controlling IAQ and that pollution source control must be considered before ventilation if IAQ is not satisfactory. The proposed base ventilation to remove occupant emissions is 15 m^3/h, but additional criteria should be met before increasing the ventilation, in case of bad IAQ. The base ventilation should, under several assumptions, be enough to control the bio-effluents produced by occupants. In case of other processes or activities with noticeable emissions, the ventilation rate should be adapted to remove these emissions.

4.6 Ventilation vs. health vs. energy use – one or all?

The main motivation for using DCV is that it has the potential for saving energy. The DCV system runs at reduced airflow rates for a large amount of the time, reducing the energy needed operating fans, heating, or cooling. By comparing seven bigger studies, Merema et al. (2018) found that it is possible to reduce the total energy need from 30-50 % by using DCV compared to an equivalent CAV system. One of the studies considered by Merema et al. (2018) compares 157 classrooms in 81 buildings in Oslo, Norway. They found that infrared and CO_2 sensor based DCV reduced energy use due to ventilation by 38% and 51% respectively, compared to a CAV system running from 07:00 to 17:00 (Mysen, Berntsen, Nafstad, & Schild, 2005).

Indoor air quality is considered in Merema et al. (2018) but only includes CO_2 as IAQ parameter. This method for assessing IAQ is based on standard EN 13779, which only include CO_2 as a measuring parameter. Guyot et al. (2018) compared several studies of residential smart ventilation systems, which showed that most of the houses studied used a combination of CO_2, temperature, and RH (in extra wet and humid rooms) for controlling the ventilation rate. This indicates that conventional DCV systems generally use a limited set of indicators for demand control and that there is a potential to increase the health-awareness in DCV.

CO_2 is assumed to be a general hygiene marker for indoor environments, but several studies have shown weak correlations with CO_2 and other pollutants such as the ones described in chapter 2.4, which emphasizes the importance of a wider understanding and holistic approach to IAQ (Ramalho et al., 2015; Tham, 2016). Statistical correlations imply that higher ventilation rates will reduce negative health impact, but there are no clear causalities or universal ventilation-health relationship is established (Carrer et al., 2015).

DCV is proven to save considerable amounts of energy only by changing the control schedule, as mentioned before. However, the research mentioned above mainly focuses on how to control ventilation rate from occupancy, and less on factors like outdoor air quality, thermal comfort, productivity, and health. Therefore, it is reasonable to believe that there is further potential both for reducing energy use and increasing IAQ.

The standards and regulations that support design and evaluation of indoor environments have been reviewed by Khovalyg et al. (2020). This is relevant to Norway because the internationally proposed ventilation rates are close to the Norwegian standards, which is presented in chapter 4.5. The reviewed standards mainly focus on thermal comfort as measured by PPD (thermal comfort model) and IAQ as measured by CO_2. The review demonstrated that climate, building typology, demographics, and culture are not considered, which reduce the feasibility of the standards. The review concludes, among others, that future standards should include health and performance in standards higher, take more consideration of local differences, and control indoor environment using more relevant control parameters.

The question of how to reduce energy use from ventilation while increasing health has proven to be a complex problem. Health has proven not to be a simple question of which contaminants are present in the air, but also a question of thermal comfort, visual comfort (Dong, Prakash, Feng, & O'Neill, 2019). These factors can be gathered as indoor environmental quality (IEQ), which is a more holistic approach to occupant satisfaction and energy use. Some of these factors are a mix of both subjective and objective parameters, that all can influence health, wellness and productivity (Dong et al., 2019; Khovalyg et al., 2020).

According to Dong et al. (2019), sensors are important both to understand occupants' reaction and perception of IEQ and to map their behaviour pattern. This is important regarding IEQ and energy use, as it provides a better understanding of which measures are important and where they should be applied. Not only are sensors needed to provide quality data of the physical environment but data analysis tools are essential to turn the data into appropriate actions by the technical systems to avoid sub-optimized systems (Han et al., 2019). This means that IEQ issues require knowledge of sensor systems, data management, communication, health, technical equipment, cyber-security, and building designers.

Smart ventilation is introduced as a concept for reducing ventilation energy use and cost while maintaining or improving IAQ relative to a CAV system (Guyot et al., 2018). Provided this definition, DCV controls using only CO_2 to control airflow must, therefore, be considered a limited type of smart ventilation. One of the ventilation principles under the smart ventilation umbrella is "residential integrated ventilation-energy controller" (RIVEC). RIVEC aims at cutting electrical power peaks from ventilation, avoid ventilating when outdoor air is more polluted than indoor air, and reduce ventilation when other appliances influencing air movement are running (kitchen/bathroom exhaust fan, heaters, heat pumps, etc.) (Sherman & Walker, 2011).

4.7 Summary

Chapter 4.1 and 4.2 present the basic principles that most ventilation systems are based on and provides a general understanding of how air and pollutants are transported in the ventilated zones. It is, for example, important to keep in mind that the required supply ventilation rates have different effect with mixing and displacement ventilation, and that the pollutants in a room are not distributed equally for all ventilation principles. The design of a ventilation system also depends on its intended use, as some of the principles are more fit than others for different types of rooms. To improve DCV systems, it is also important to understand why and how they are used, and how the different operation modes are defined.

When dimensioning ventilation systems, it is important to find a proper balance between the required ventilation rates during occupancy and the base ventilation when there are no occupants. These ventilation rates must also fit the ventilation rate boundaries on the ventilation system equipment. Therefore, there are limits to how far the ventilation rates can be adjusted before the efficiency, energy use, and functionality of the system change noticeably. These boundaries and requirements are discussed in chapter 4.3, 4.4 and 4.5.

The literature review in 4.6 shows that the standards for dimensioning ventilation rates, as discussed in 4.5, not necessarily are based on strong scientific evidence, rather than experience and statistics. Therefore, the standards should be developed to include more parameters than the current standards. Such development may have effects on both energy use and IAQ. Smart ventilation is introduced as a holistic approach to ventilation and increases the importance of health, energy use, and economy for control of ventilation systems. Regarding health, other pollutants are considered in addition to CO_2 when assessing IAQ, including static pollutant sources like building materials. It is also stressed that ventilation systems must be considered as a supplement to pollution source control. This is well in line with the findings in chapter 2 where it is stated that the indoor environment is dynamic, and both have daily variations and long-term changes.

5 Methods

This thesis is a continuation of the master thesis by Gram (2019), who initially picked each of the sensor parts for the sensor that is used in this thesis. Chapter 5.1 presents the work done by Gram (2019) to build and calibrate the sensors, while chapter 5.2 describes the changes done to the sensors for this thesis. Chapter 5.3 describes the laboratory calibration experiments, that are conducted to assess the sensor performance. The physical measurements are conducted in a classroom at a primary school in Trondheim during winter 2019. The field measurement setup and relevant information regarding the classroom ventilation system are described in 5.4. Chapter 5.5 introduce the CONTAM simulation model and the setup of the classroom simulation model. Finally, the methods regarding measurement and data retrieval are described in chapter 5.6.

5.1 Initial sensor setup

5.1.1 Sensor choices

One of the premises for this thesis is that the chosen sensor technology needs to be cheap, in order to be a realistic alternative for building owners to install in already existing ventilation systems. The Arduino system was therefore chosen, as it is an acknowledged open-source system that is cheap and relatively easy to use. The following criteria was set for picking sensors:

- Cheap, small and easy to install and use – to increase the usability
- Factory precalibrated and maintenance free
- Measure relevant pollutants for relevant intervals, in indoor air

Based on the identified pollutants for control of DCV in Gram (2019) the following sensors were chosen for the project:

Table 5.1 Initial sensor setup

Sensor name	Measurand
Sensirion SCD30	CO_2, temperature (T) and relative humidity (RH)
Sensirion SPS30	Particulate matter ($PM_{0.5}$-PM_{10})
Sensirion SGP30	Total volatile organic compounds (TVOC)
Dart Sensors WZ-S	Formaldehyde

Detailed characteristics for the sensors in Table 5.1 are listed in Appendix A: Sensor datasheets. Figure 5.1 shows the mounted sensor and its components. In addition, a plastic cover with openings on the sides is added for physical protection of the sensor system.

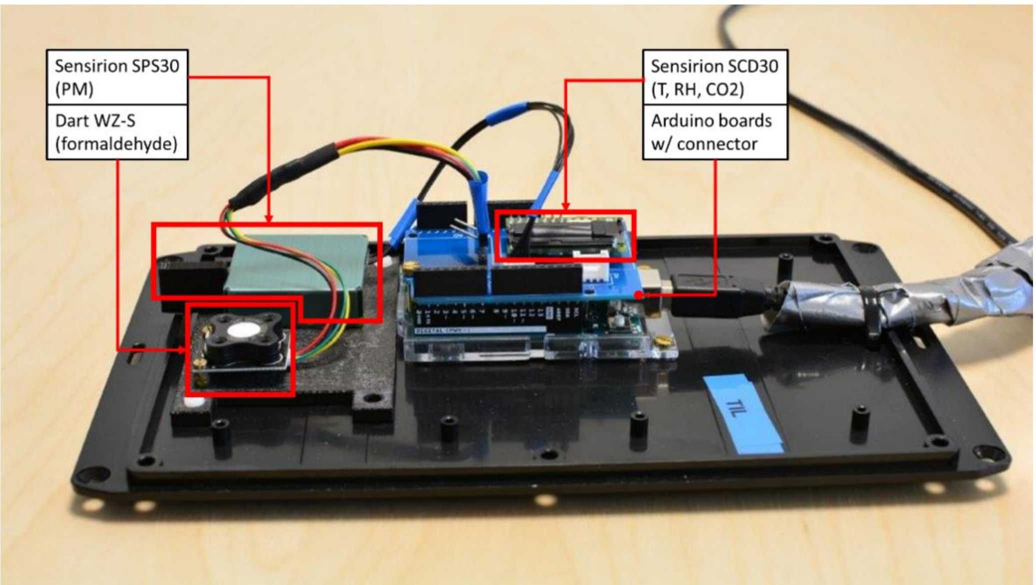

Figure 5.1 Sensor system

To utilize and make use of the sensor for actual operation of a ventilation system, or to gather IAQ data, it is important that the sensor is able to communicate its results real-time (or close to). This is possible with the current setup but was not installed to protect the pupils' privacy.

5.1.2 Sensor assembly

To ensure the quality and reproducibility of the sensors, the assembly and programming of the sensors and Arduino board were done by professional system developers from the Department of Electronic Systems at NTNU. A total of eight Arduino sensors were produced, all equal to the sensor shown in figure Figure 5.1. Each sensor setup use two sensors – one to monitor breathing air, and one for supply air. The two sensors are linked to one Raspberry Pi computer that logs the measured data. Because of practical issued regarding the Sensirion SGP30 sensor, this was excluded from the initial sensor system.

5.1.3 Initial sensor calibration

All Arduino sensors were calibrated using high-performance sensors as reference, to check for offsets or errors on the measurements done by the Arduino sensors. These calibrations are used to correct the raw data provided by the Arduino sensors. This is important because low-cost sensors have several known cross-sensitivities, or offsets caused by sensor drifts.

Method and main findings from earlier calibration are summarized below, while more detailed results from the calibrations are presented in Gram (2019).

Table 5.2 Initial sensor calibrations

Calibrated sensor	Reference sensor	Mean value	R^2	Comment (method and result)
SCD30 (CO_2)	Vaisala GM70	0.9911		- Individually calibrated in small semi-enclosed box - Acceptable performance.
SCD30 (T/RH)	Pegasor AQ	0.9570		- Calibrated together in small room without ventilation. Varied by window opening - Temperature/RH offset, otherwise good

SPS30 ($PM_{2.5}$)	Pegasor AQ	0.7393	- Same as above, 6 candles lit to produce PM - Did not track reference
WZ-S (HCHO)	N/A	N/A	- No reference sensor or HCHO source available

Source: (Gram, 2019)

5.2 Further development of sensor

Even though the initial sensor setup worked acceptably, further improvements were made for this thesis to ensure that the sensors give a realistic and more detailed representation of the actual indoor climate. This includes updating some of the sensor hardware and calibrating the sensor output using high-performance sensors. The improvements and calibrations of the sensor setup are presented in this chapter.

Based on the preparatory project work, the following hardware improvements were done on the sensor systems in January 2020. The improvements are described in more detail below.

- Installation of TVOC sensor
- Move temperature sensor away from Arduino board to avoid temperature disturbance from the circuit board
- Unique sensor ID

The new sensor hardware is shown in Figure 5.2 below.

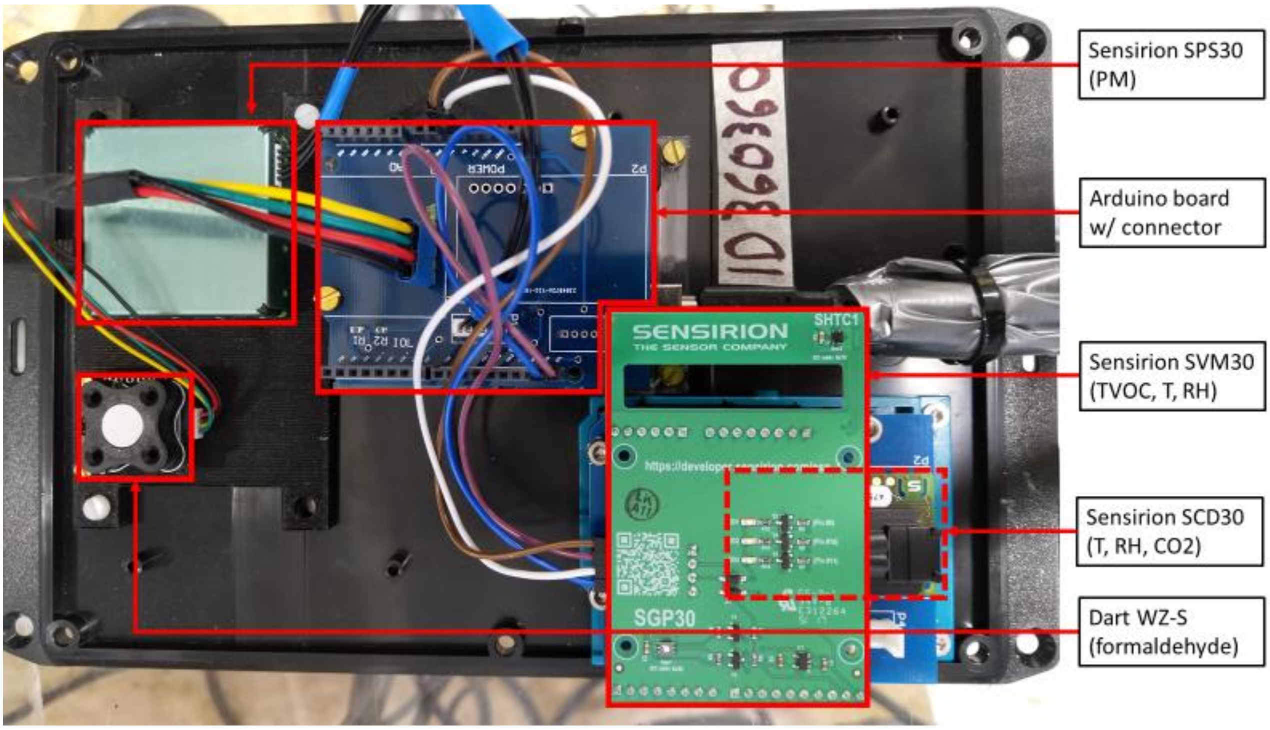

Figure 5.2 Revised sensor system

5.2.1 Installation of a new sensor module – Sensirion SVM30

As described in chapter 5.1.3, the temperature measurements are disturbed by the heat from the Arduino circuit board. Both Gram (2019) and the authors' preparatory work have shown that the temperature measurements from the SCD30 sensor have an offset compared to reference sensors, and the sensor hardware should be updated to provide accurate temperature measurements. Sensirion launched a new sensor called SVM30 in March 2019, that measures TVOC, RH and temperature. The SVM30 sensor was installed in February 2020 and is expected to reduce the T/RH offset in addition to measuring TVOC. This is tested during the calibrations in February and March 2020, whose results are presented in chapter 6.1. The SVM30 sensor was installed by professional system developers from the Department of Electronic Systems at NTNU.

The Sensirion SVM30 sensor combines a SHTC1 T/RH sensor and a SGP30 TVOC gas sensor. This also solves the initial problem with the SGP30 being too small to install for the system developers, as mentioned in chapter 5.1.2 and Gram (2019). A summary of key data for the SVM30 sensor is given in table below. Sensor data for all the used sensors is provided in Appendix A: Sensor datasheets.

Table 5.3 Sensirion SVM30 sensor data

General information	
Price	~220 NOK/unit (ex. taxes and shipping)
Output	Total VOC in ppb H_2 based CO_2-eq in ppm Relative humidity Temperature
Size	39x15x6,5 mm^3
Sensor types	Relative humidity/temperature: CMOS capacitor VOC + CO_2-eq: multi-pixel MOX gas sensor
Indoor air quality	
Typ accuracy	15 % of measured value
Output range	TVOC: 0-60.000 ppb CO_2-eq: 0-60.000 ppm
Sampling rate	1 s
Long-term stability	MOXSens: siloxane resistance: Typ 1,3 % accuracy drift per year in siloxane accelerated lifetime test
Humidity compensation	Yes
Temperature	
Measurement range	-20 °C – 85 °C
Typ accuracy	± 1 °C
Humidity	
Measurement range	0 % - 100 % RH
Typ accuracy	± 5 % RH

Source: (Sensirion, 2019a)

5.2.2 Unique sensor ID

As part of the development of the sensors, each of the eight Arduino sensors are now marked with a six-digit identification number, that connects the physical sensor with the measurement data provided by the sensor systems. The physical identification tag for sensor ID360360 is visible in Figure 5.2. The data from the sensors may, in this thesis, be presented as "A360360" which is measurements from Arduino sensor 360360. This system is set up to divide between different data sources, such as the central control system, weather data, Arduino data, etc.

5.2.3 Sensor system characteristics

The characteristics of the sensor is presented in Table 5.4.

Table 5.4 Sensor characteristics

Parameter	Sensor type	Sensor name	Accuracy	Range
Relative humidity	Capacitive (CMOS)	Sensirion SCD30	± 3 % RH (25 °C)	0-100 %
CO_2	NDIR	Sensirion SCD30	≤ ± 3 % (500-1500 ppm)	400-10000 ppm
Temperature	10K NTC thermistor	Sensirion SCD30	± (0.4 °C + 0.023 (T-25)°C)	-40 °C - 70 °C
Particulate matter	Optical sensor	Sensirion SPS30	± 10 μg/m^3 @ <100 μg/m^3 ± 10 % @ > 100 μg/m^3	0-1000 μg/m^3
Formaldehyde	Electrochemical (MOS)	DART WZ-S	≤ 0.02 ppm (~25 μg/m^3) formaldehyde eq. < ± 2 % repeatability	0.03-2 ppm
TVOC	Metal-oxide (MOx)	Sensirion SGP30 (SVM30)	± 15 % of measured value	0-60000 ppb
Relative humidity	Capacative (CMOS)	Sensirion SHTC1 (SVM30)	± 5 % RH (25 °C)	0 -100 %
Temperature	Bandgap	Sensirion SHTC1 (SVM30)	± 1 °C	(-20) °C – 85 °C

Source: (ProSense Technologies Co.; Sensirion, 2018, 2019a, 2019b)

5.3 Sensor calibrations

The sensor calibration is conducted by measuring air quality during an experiment in a controlled environment, using a high-performance sensor for reference measurements. The reference measurements are assumed to provide correct concentrations of the measured pollutant. All eight Arduino sensors are calibrated to check for measurement offsets or errors, which is especially important as these sensors are low-cost sensors and have several known cross sensitivities and potential weaknesses. The calibrations are used to correct the raw data provided by the Arduino sensors. Results from all calibrations are presented in 6.1.

Different tests are conducted to determine the performance of the different sensor parameters, but not all are tested, since reliable reference sensors are hard to come by. The following sensors have been used for reference measurements:

- Graywolf FM-801 – Formaldehyde, temperature and RH
- Pegasor AQ – $PM_{2.5}$, CO_2, temperature and RH

Different laboratory experiments are conducted to test the sensors under different conditions, and the results from these experiments are used to make calibrations for each of the eight Arduino sensors. All tests are conducted in a test chamber measuring approximately 1.5x1x1 m^3, using a small fan to mix the air in the chamber.

The following chapters describe the lab experiments that are set up to calibrate the sensor output. The results from the calibrations are presented in chapter 6.1, and discussed further in chapter 7.

5.3.1 Experiment 1: CO_2 injection

For this experiment, the Pegasor AQ is used as reference sensor. The experiment setup is shown in figure Figure 5.3. All Arduino sensors and the Pegasor are put in the test chamber at the same time, and a small fan is active to ensure that the air in the test chamber is well mixed and the CO_2 concentration is close to equal for all sensors. Before the experiment is started, all openings in the test chamber are closed. CO_2 is injected to the test chamber via the tube to the right, as shown in Figure 5.3. The CO_2 concentration quickly increases and stop at around 2000 ppm. The experiment setup is shown in Figure 5.3.

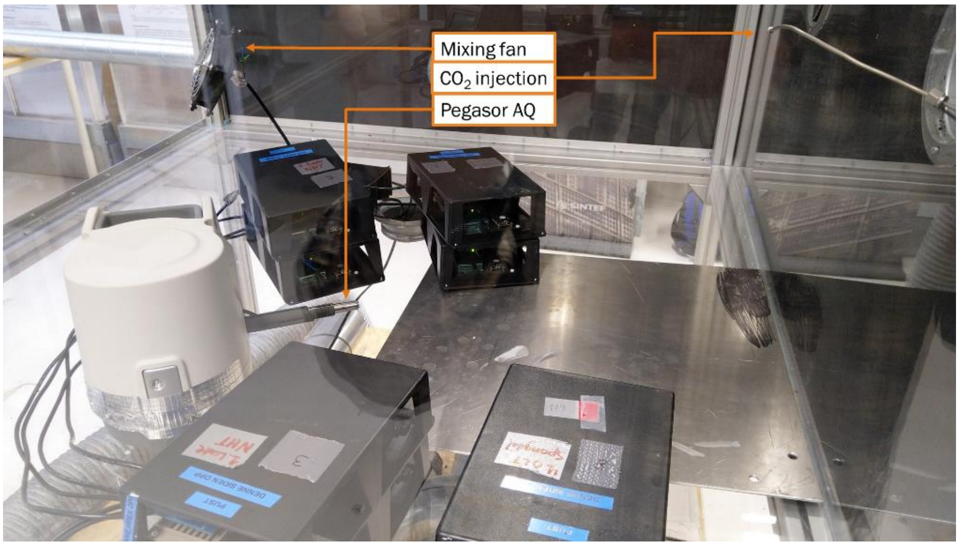

Figure 5.3 CO_2 injection setup

After some time, the openings in the test chamber are opened slightly, to increase the infiltration of fresh air. The concentration in the test chamber is logged for a few hours, until the CO_2 concentration is reduced to approximately ambient concentration. The logged concentrations are compared to determine how well the Arduino measurement matches the Pegasor measurement. The results from this experiment determines a calibration equation for the Arduino sensor, based on its correlation to the Pegasor measurement.

Temperature and RH are not regulated in the test chamber during the experiment.

5.3.2 Experiment 2: Formalin formaldehyde measurement

One of the challenges when measuring formaldehyde with low-cost sensors is that it also reacts to other volatile gases. To reduce the disturbances from other volatile gases, thinned formalin, which is a concentrated formaldehyde source, is used during this experiment. A Graywolf FM-801 is used for reference measurements. The test setup is shown in Figure 5.4.

Figure 5.4 Formalin experiment setup

The formalin container is placed in the test chamber with a perforated plastic cover to control the emission rate. The formalin container is removed after some time, and the formaldehyde concentration in the test chamber reduces slowly. To ensure equal conditions for all sensors, they are placed in a circle around the formaldehyde source, and a mixing fan is active during the whole experiment. The Graywolf sensor logs the concentration one per 30 minutes, while the Arduino sensor use logs more frequently, bug use 30-minute average values for calibration.

As this experiment use a concentrated formaldehyde source, the concentrations are higher than under normal conditions. Therefore, the results from this experiment are combined with results from other experiments to provide a correction curve working for both high and low formaldehyde concentrations. The formaldehyde calibration results are presented in chapter 6.1.2.

5.3.3 Experiment 3: Chipboard with and without heat source

For this experiment, three wetted chipboard plates are placed in the test chamber using Graywolf FM-801 for reference measurements. Chipboards are used to imitate emissions from new building materials. By wetting the plates, the gas inside the chipboard is "pushed out" by the water and mixed with the air in the test chamber. The test chamber is closed, and the mixing fan is on during the experiment. Two different setups are used for this experiment: one with an external heating source, and one without. Both setups are shown in Figure 5.5 and Figure 5.6.

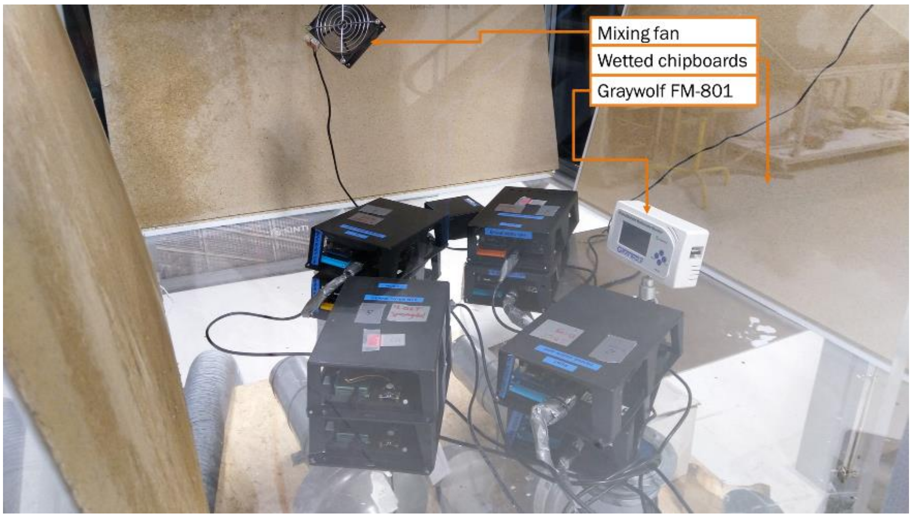

Figure 5.5 Chipboard without heating

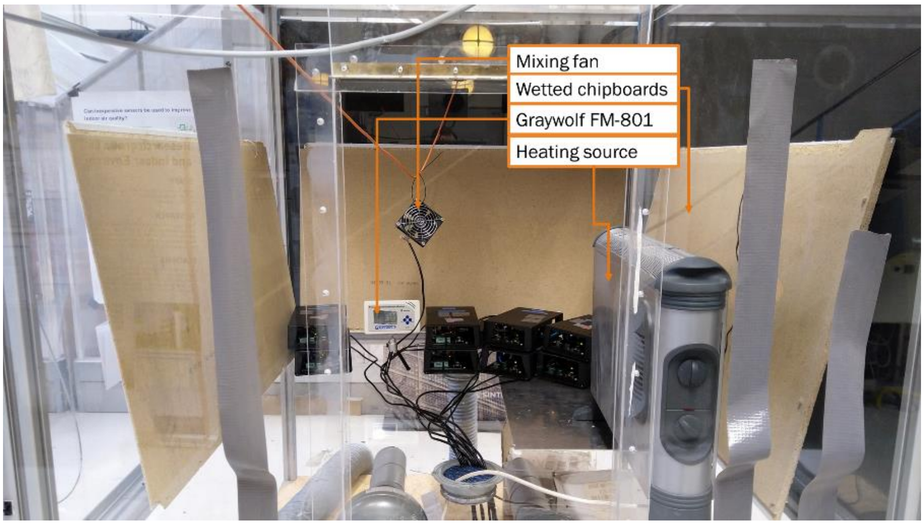

Figure 5.6 Chipboard with heating source

For the experiment with the heating source, a circulation fan in the heater is also turned on. A heat source is used to test how the emission from the chipboards change by increased temperatures. The formaldehyde emission from the chipboards is low compared to the formalin experiment, and the correlation between the Arduino and Graywolf measurements may be different compared to the formalin experiment.

5.3.4 Experiment 4: Candles

The Arduino PM sensor have previously given variable results, as shown in Gram (2019) and the preparatory work. This experiment is set up to test how the Arduino PM sensor performs compared to the Pegasor PM sensor. Fine particles mainly origin from combustion processes, and candles are therefore used during this experiment. Seven candles are lit inside the test chamber before it is closed. The mixing fan is turned off to prevent the candles from extinguishing, but the thermal plume is expected to provide sufficient mixing of the air in the test chamber. Candles are removed from the test chamber gradually, to reduce the PM production, and to check how the PM concentration changes. The candles are removed when the PM concentration is stabilized. The initial setup is shown in Figure 5.7.

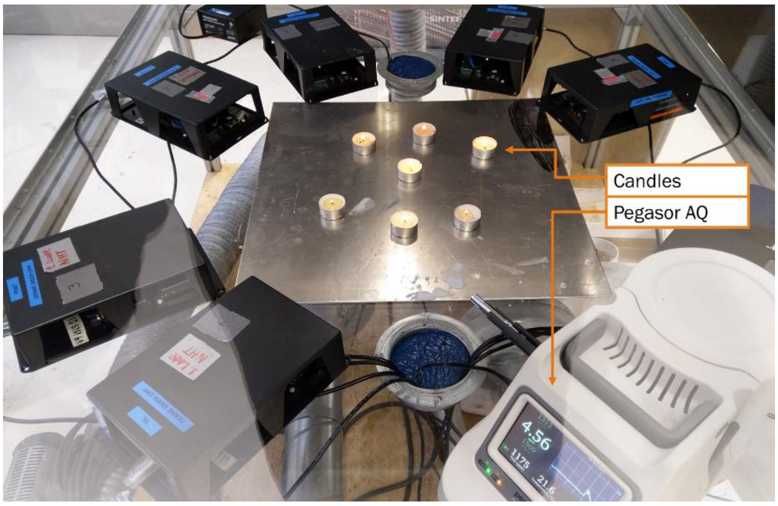

Figure 5.7 Candle experiment setup

The logged concentrations from the Arduino sensors and the Pegasor sensor is compared, and the results are presented and discussed in chapter 6.1.5 and 7.3.1. The Pegasor measure $PM_{2.5}$, as described in Pegasor (2016), while the Arduino sensor measures several PM types. Only $PM_{2.5}$ is compared to each other, but other particle sizes may be highlighted to check the validity of the Arduino measurements if need be.

During experiment 4 the Pegasor AQ sensor should have been turned 90 degrees counter-clockwise, since the PM sensor is placed on the opposite side of the sensor display, and not in the sensor arm that is facing the candles as seen in Figure 5.7. However, this is not thought to have any severe effects on the results of the experiment.

5.4 Field measurement setup

Field measurements are carried out in a classroom in a primary school in Trondheim. This specific school is chosen, in cooperation with Trondheim Eiendom, partly random and partly because the classrooms are using DCV. To prevent misinterpretations of the measurement results, the identity of the school is anonymized. The school was originally built more than 50 years ago but has been upgraded and extended in several steps after that. The most recent were in 2017, when the school was renovated and expanded with a new wing. The classroom where the measurements are done are in the new wing. The school is located approximately 90 meters above the ocean and is located more than 2 km from Trondheimsfjorden. The area has low traffic (more than 1 km to the closest highway, E6) and the neighbourhood is mainly detached houses. The sensors was installed in the from October 2019 to January 2020.

The ventilation in the classroom has variable air volume controlled by a building management system (BMS) using CO_2 concentration, and is heated by waterborne radiators using temperature as controlling parameter. The classroom is used Monday-Friday by approximately 26 6^{th} grade students. The area of the classroom is 62 m^2 and the ceiling height is 3.2 m. Figure 5.8 and Figure 5.9 shows the setup of the classroom, and placement of technical equipment. There are no trash cans or sinks inside the classroom. The room is cleaned several times per week without any use of soaps or detergents.

The breathing air sensor is placed 1.2 m above the floor, taped on a cabinet door facing the windows, and is marked with orange arrows in Figure 5.9. The supply air sensor is placed inside the supply air duct just after the T-junction to the textile diffusor and is marked with green arrows in Figure 5.9. The BMS-sensors are placed on the wall not far from the breathing air sensor, as shown with the blue arrow in Figure 5.9.

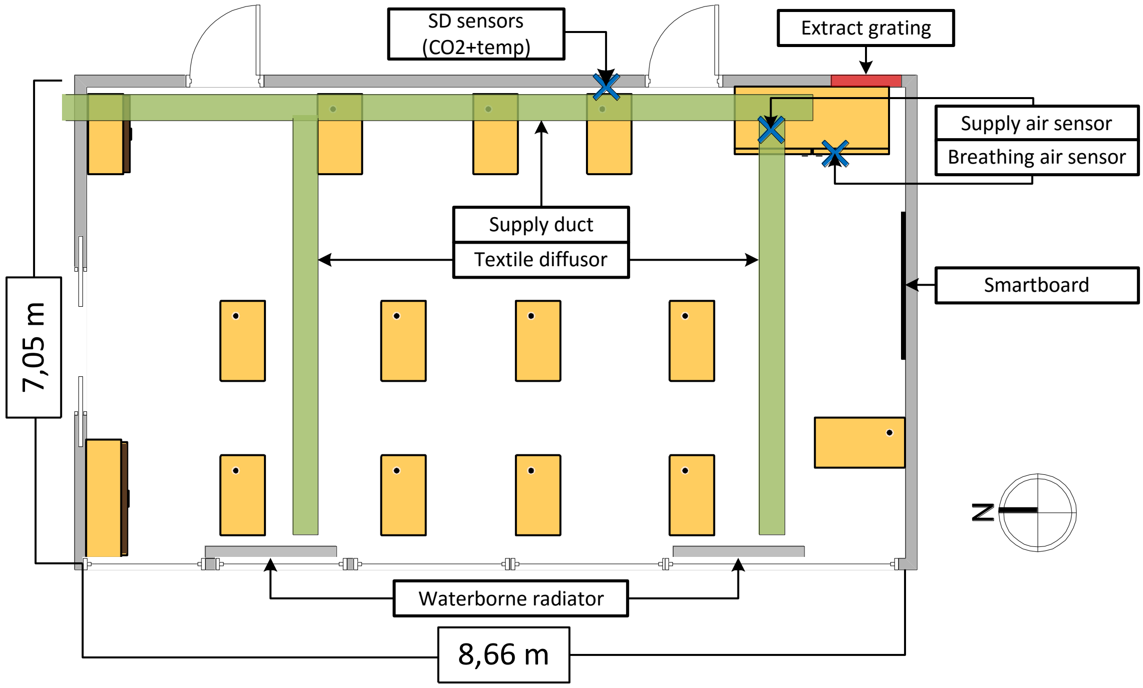

Figure 5.8 Classroom measurement setup

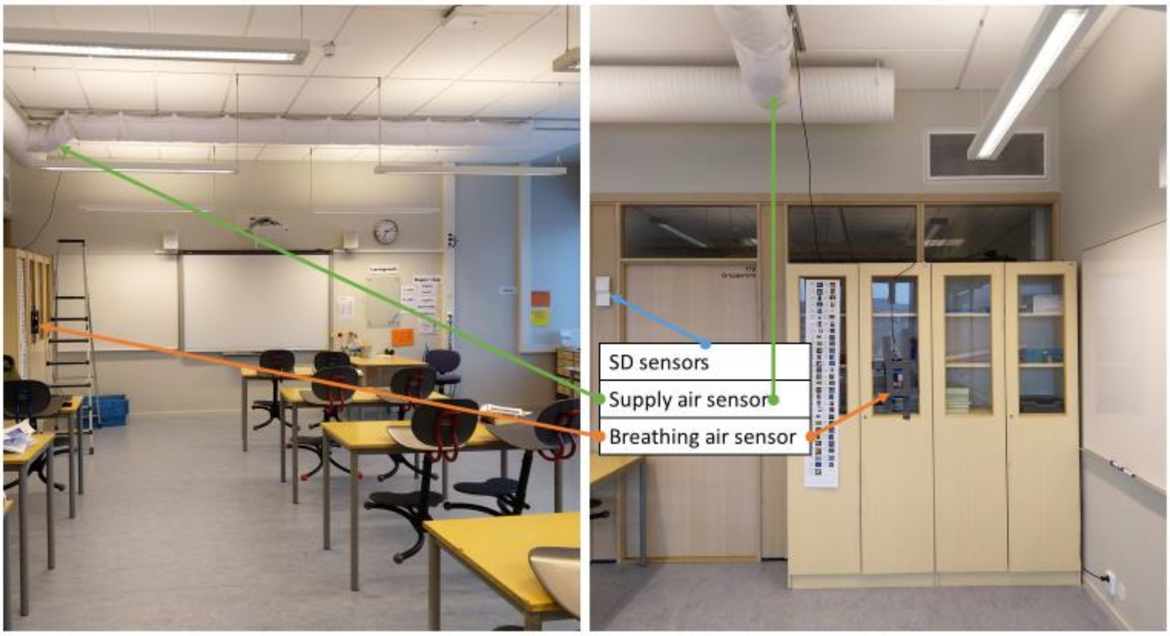

Figure 5.9 Classroom with sensors

The classroom is supplied and extracted by a DCV system, and the DCV damper controlling the airflow is not shared with any other rooms. When the DCV damper is 100 % open the airflow to the classroom is 1750 m^3/h, and when it is 0 % open the airflow is 0 m^3/h. The maximum and minimum setpoints for the airflow to the classroom is 1300 m^3/h (75 %) and 250 m^3/h (15 %). The ventilation system is active between 06:30-16:00. The DCV control schedule is illustrated in Figure 5.10, where the X-axis is the measured CO_2

concentration in ppm, and the Y-axis is the resulting ventilation rate for both supply and extract ventilation, in % of maximum setpoint.

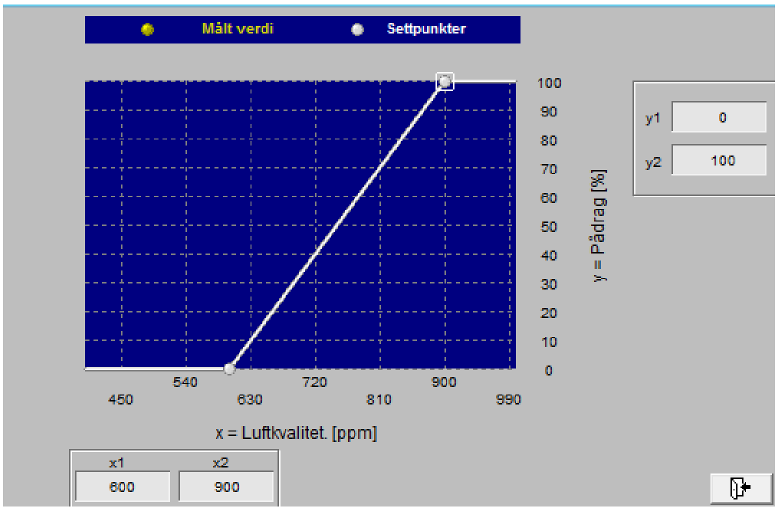

Figure 5.10 CO_2 control schedule for DCV

As shown in the figure above, the ventilation rate is at minimum rate (15 % of 1750 m^3/h) at CO_2 concentrations below 600 ppm and reaches the maximum setpoint at 900 ppm (75 % of 1750 m^3/h).

5.5 CONTAM simulation model

One of the objectives of this thesis is to test whether it is possible to create a simulation program that can be used to see how changes in ventilation rate changes the indoor air quality. This chapter presents the chosen simulation tool and how the model is constructed. Further, the input data is presented, which forms a basis for discussion of the model validity. The simulation model aims at creating a realistic representation of the classroom used for measurements, and earlier measurements from this room are used as reference to assess the model. The focus of the simulation model will be the relationship between occupancy and indoor air quality.

5.5.1 Simulation tool choice

The main goal of this thesis is to investigate how some specific IAQ parameters are affected by changes in ventilation rate and occupancy. A secondary goal is to check whether it is possible to use this information, either for improving IAQ and/or saving energy. With these objectives in mind, several different simulation tools are considered plausible to use.

However, the objectives of this thesis have been adjusted due to the COVID-19 pandemic. As there is limited time to fully comprehend new software, simulation tools that require complicated codes and experience for basic use, has been excluded. With this in mind, CONTAM is chosen to build the simulation model, based on the following criteria:

- Easy to build a basic model
- Possible to develop further using other software
- Specialized software tool for simulation of numerous contaminant concentrations and IAQ in a multizone building
- Available experience in-house for support with development of simulation model

CONTAM is developed by National Institute of Standards and Technology (NIST) that can be used to determine airflows, contaminant concentrations and personal exposure in a multizone model of a building (NIST, 2012). The software allows input of transient weather files, occupants with specified pollutant generation, static pollution sources, interaction with other zones and the ambience, simulation of ventilation systems, and more. CONTAM is used in several earlier research projects and is therefore assumed to be of sufficient quality to use for the objectives of this thesis.

5.5.2 Simulation model structure

As part of this thesis and its preparatory project work, reference measurements are done using Arduino-based sensors in a primary school classroom in Trondheim. This model is built with the intent of recreating the reference classroom, both regarding geometry, technical systems, and occupancy. This chapter illustrates how the model was made, while the results from the simulation model is presented in chapter 6.

Geometry and model overview

CONTAM use a sketching tool called SketchPad, which is a basic geometric tool to create different zones and levels with internal openings and walls to connect them. Sketchpad only allows straight corners, and the geometry of the real building is not an exact recreation of the real building. Despite this, important data like room area and volume is included in the model.

The simplified model geometry includes the adjacent rooms and ambient conditions. The model geometry is shown in Figure 5.11, with numbered elements that are explained in the relevant paragraphs below.

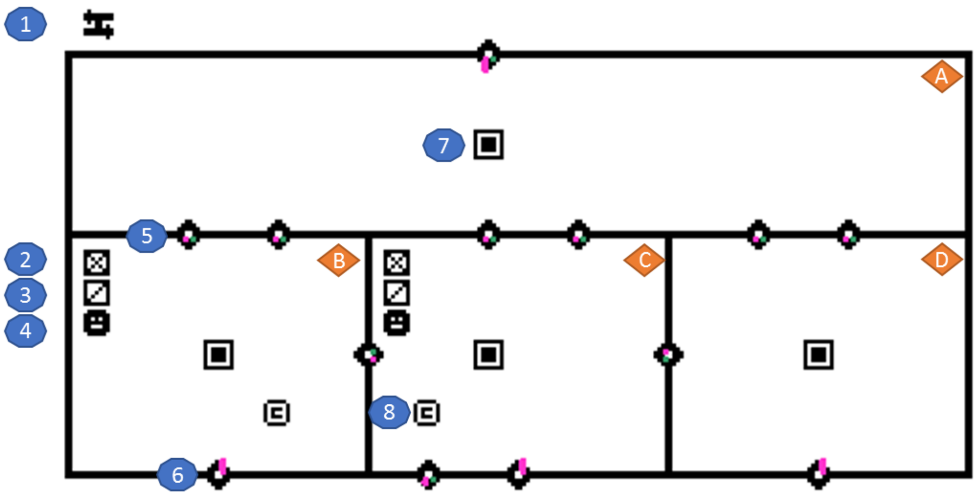

Figure 5.11 CONTAM model overview with numbered elements

The black lines in Figure 5.11 represent the inner and outer walls. Each room is numbered with an orange letter. The bottom classroom (C) will be assessed during this thesis. Each of the lettered rooms represent an independent zone. The zone properties (7) is given for each zone and includes zone area, zone volume, zone temperature, and initial contaminant concentrations. The remaining parameters are kept as default.

The room sizes and volumes are found in drawings collected from Trondheim Eiendom. The roof height is assumed to be 3.5 m for the whole floor. The area of classroom B and C are

62 m^2, group room D is 75 m^2, and the corridor is 180 m^2. The zone temperatures are 21 °C for room B, C, and D and 19 °C for the corridor (A).

Internal and external openings

The internal and external openings (5 and 6) includes interior doors, exterior windows, internal leakages, and external leakages. These are illustrated equally in Figure 5.11 but have different values. The leakage numbers for doors and openings are gathered from a standardized set of elements provided by NIST. As no detailed information about the building envelope is available, it is considered sufficient to use standardized values for these elements. There is only one window in classroom C, and an interior door to classroom B, but this is expected to be closed most of the time.

The internal and external leakages simulate the constant infiltration between the zones, while interior doors and exterior windows can be opened and closed according to a schedule. The exterior window is always closed, while the interior doors are open 15 minutes per hour to simulate class breaks.

Technical systems

The technical system in the model includes the ventilation system AHU (1), air supply (2) and extract (3) to each zone. The air handling unit is set up as an ideal AHU without any capacity restrictions, filters, or schedules. This is necessary to get the simulation model working. The supply- and return units are also set up as ideal units, but the design flow rate is set to 0.595 kg/s for supply flow rate and 0.590 kg/s for return. The value is set based on information from Trondheim Eiendom. The difference is set to create a slight overpressure in the ventilated room, according to normal design procedures.

This model does not use ducts and diffusers and assumes that the air flow provided to the room is mixed ideally with the existing room air. The results from using this simulation model is therefore only valid for ventilation systems using mixing ventilation or similar principles. There are no added heaters to the zones or ventilation systems, and energy use for heating and thermal comfort is not considered in the simulations.

Occupancy and dynamic pollutants

The classroom was used by approximately 26 pupils during the reference measurements from the preliminary project work. The classroom seems to be designed for around 30 people, as it is normally 2 m^2 per person in a classroom. The simulations are done using 26 pupils plus one teacher, to recreate the actual conditions. The occupants (4) are placed in the zone they occupy, but their location in the zone does not impact the result as full mixing is assumed for all simulations.

Each occupant in the zone has a multiplier, which is set to the number of occupants. Each occupant is assigned with a contaminant generation, which is set to a desired value for the relevant pollutants. The generation rate for each pollutant is set independent of each other. The generation rate can also be controlled by a schedule.

For this model, the pupils are expected to be in light or medium activity (1.2 met), and between age 11-16. According to Persily and de Jonge (2017), this group has a CO_2 emission rate of 0.0041 L/s for males and 0.0035 L/s for females. The generation rate used in the simulation is 0.0040 L/s, which is an average that is rounded slightly up because of the teacher.

The H_2O emission rate during light activity varies from 0.03 to 0.12 kg/h/person according to Johansson, Pallin, and Shahriari (2010). These numbers are based on results from three different studies, of which two suggest 0.04 to 0.065 kg/h/person, and an emission rate of 0.05 kg/h/person is therefore assumed to be realistic.

Contaminants and pollution sources

Each pollution source (8) is defined for a single pollutant (CO_2, formaldehyde, etc.) and the pollution source strength is defined by a contaminant model, generation rate, multiplier, and schedule. The contaminant model is a mathematical representation of the emission pattern, and the model can be constant, pressure driven, cutoff, decaying source, among others.

Pollution sources represent the static pollutants, that are not directly emitted from the occupants. For the classroom assessed in this thesis, the goal is to recreate the formaldehyde emissions using a pollution model and estimating a formaldehyde source strength from the reference measurements.

The chemical properties of each pollutant must be defined manually, but most of this input is relevant for more complex CFD analysis only, according to Dols and Polidoro (2015). The chemical properties used for the simulations in this thesis is presented in Table 5.5.

Table 5.5 Contaminant species properties in CONTAM

Species	Molecular weight $\left[\frac{kg}{kmol}\right]$
CO_2	44
Formaldehyde	30
H_2O	18

Source: (PubChem, 2020)

This is a simplified list of contaminants that are simulated to assess the IAQ. More contaminants can be added, but this requires extensive information about their emission rates and chemical properties. One example of this is VOC, which is a set of hundreds of compounds with different properties and emission rates. This means that CONTAM is better to track one specific pollutant with one specific source.

The simulated classroom has no major pollutant sources in the classroom. There are no sinks, the wardrobe and thrash are placed in the corridor, and a whiteboard is used instead of a chalkboard. The remaining main pollutant is therefore formaldehyde from building materials and furniture. The pollution model that is found fit the reference measurements best was is the cutoff model. Model tests have found that this model is not optimal to determine the peak of the pollution but recreates the relation between ventilation rate and pollution rate better than the others. The generation strength is estimated to be 15 μg/m^3 based on the slope from the reference measurements, which is presented in 6.3.1. The cutoff concentration is set to 150 μg/m^3 but is expected to be lower in reality.

Ambient conditions

The ambient conditions include outdoor temperature, wind, humidity, among others. These parameters can be either static or dynamic. The ambient conditions for this simulation are controlled by a dynamic weather file, which is recorded in Trondheim, and therefore provides realistic environmental data. The weather file used in the simulation model is provided from earlier research on a similar model by the CO-supervisor of this thesis.

Occupancy schedule

The ventilation system in the simulation model is a scheduled CAV system. The schedule is made according to the occupancy in the classroom, and the desired min/max points for the ventilation rate. It is only the ventilation rate in classroom C that is controlled, while the others are held constant.

A random reference week is chosen from the reference measurements, Monday November 18 to Sunday November 25, 2019. The occupancy schedule is retrieved from the actual weekly schedule of the class that uses the classroom. The occupancy schedule for the reference week is presented in Table 5.6.

Table 5.6 Classroom occupancy schedule.

Day	Classroom occupancy period
Monday	08:15 – 10:00 11:00 – 12:00 12:30 – 14:00
Tuesday	08:15 – 09:30 10:00 – 10:50 11:50 – 13:00
Wednesday	08:15 – 10:00 11:00 – 12:00 12:30 – 13:50
Thursday	08:15 – 10:00 10:40 – 12:00 12:30 – 14:00
Friday	08:15 – 09:30 10:00 – 11:30

During the occupancy periods in the classroom, the emission rate is 100 % of the occupant emission rate for CO_2 and H_2O. The periods that are not mentioned in Table 5.6 has zero occupancy, including weekends.

Ventilation schedule

The ventilation schedule for the simulations is based on information on the real ventilation system, provided by Trondheim Eiendom. The key data of the classroom ventilation system is described in chapter 5.4, and summarized in Table 5.7.

Table 5.7 Ventilation system setpoints

Setpoint	VAV damper opening (%)	Air flow rate (27 persons in classroom)	
		$\left[\frac{m^3}{h}\right]$ / $\left[\frac{kg}{s}\right]$	$\left[\frac{m^3}{h * person}\right]$
Off	0	0	0
V_{min}	15	250 / 0.0851	9.3
V_{max}	75	1300 / 0.442	48.1
$V_{nominal}$	100	1750 / 0.595	64.8

The ventilation schedule in CONTAM is given in %-value of the nominal ventilation rate, as defined in the supply (3) and return (4) units in each ventilated zone in CONTAM. To imitate a DCV ventilation system, a CAV system based on the occupancy schedule from Table 5.6 is implemented. The results from changing the ventilation rates are presented and discussed in chapter 6.4, but an illustration of a ventilation schedule is presented in Figure 5.12.

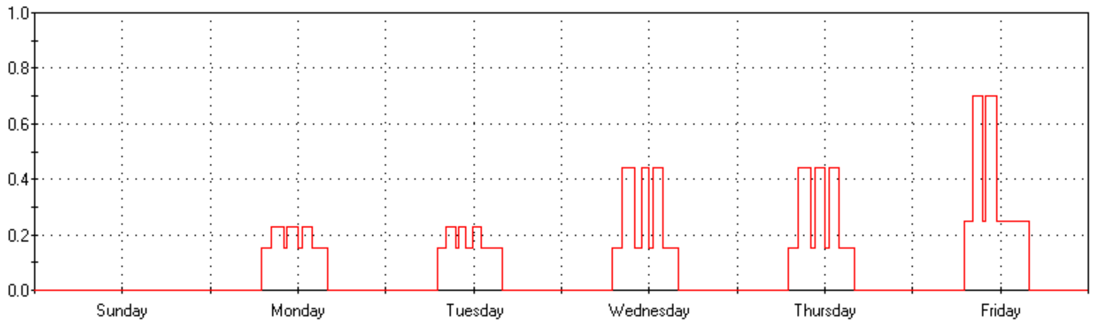

Figure 5.12 Ventilation rate schedule in CONTAM

Several different ventilation rates are illustrated in Figure 5.12. The base ventilation (V_{min}, 15 %) is active from 07:00 to 16:00, and the ventilation is increased during occupancy periods.

5.6 Measurements and data retrieval

Arduino sensor data

The measurements are out from October 23, 2019 to January 8, 2020. During this period, the sensors are checked upon regularly to prevent the sensor from shutting down unexpectedly. As the sensors are not connected to the internet, sensor data is retrieved manually when checking the sensors.

Building management system (BMS)

Data from the BMS-system (building management system) is retrieved from technicians working for Trondheim Eiendom, who owns and operate the school building. This data includes VAV damper opening for supply and exhaust air, CO_2 concentration in the indoor air, and temperature.

Outdoor air quality data

Outdoor weather and air quality data are collected to see how these factors correlate with the indoor climate, for example particles, humidity, temperature, etc. PM levels, temperature, humidity and rainfall are collected from Trondheim Municipality (TrondheimKommune, 2019) and Norwegian Service for Climate Services (Norwegian Centre for Climate Services, 2020).

6 Results

6.1 Laboratory calibrations

6.1.1 Calibration of SCD30 CO_2 sensor

The calibration of the SCD30 CO_2 sensors are based on experiment 1, as described in chapter 5.3.1. All eight Arduino sensors are tested at the same time, and the step-response is logged by all eight sensors and the reference sensor. As the sensors have different sampling times for the experiments, the data for these tests show average data per minute. Each sensor has 4-5 samples per minute. The step-response and correlation between SCD30 and Pegasor reference sensor is presented in the figures below.

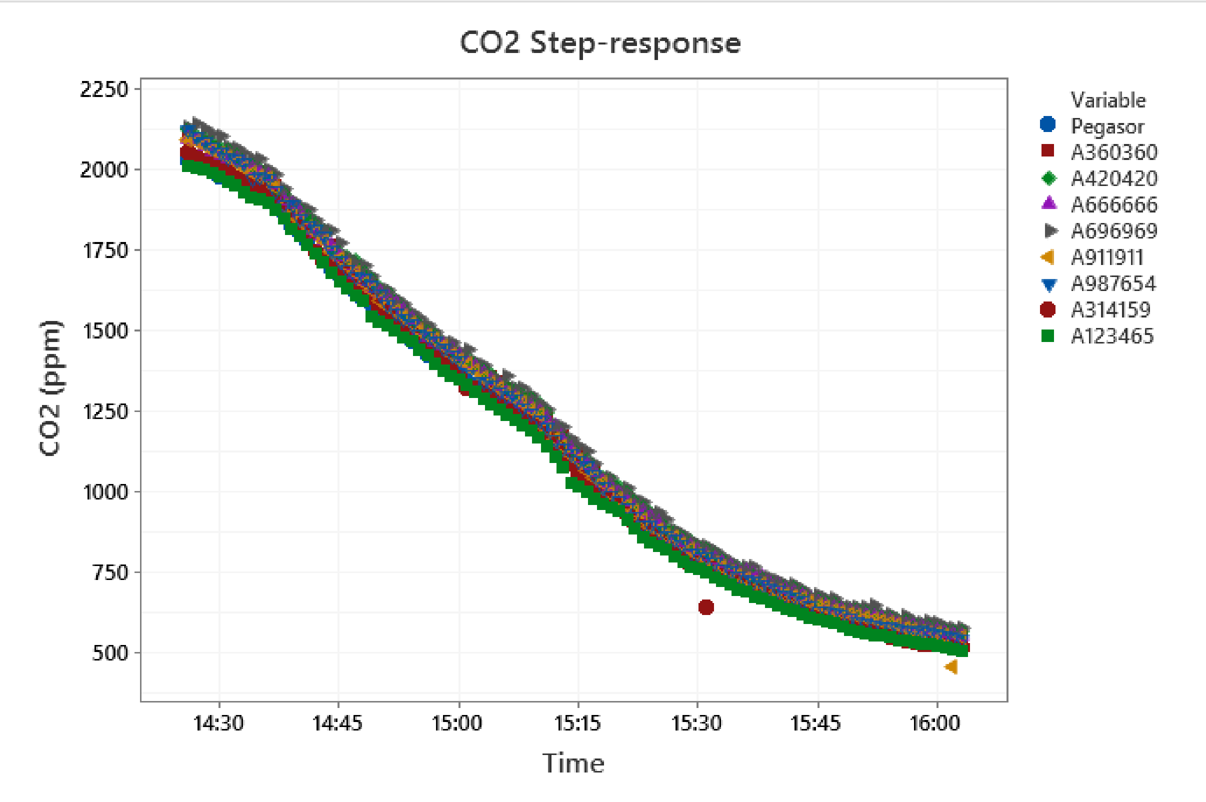

Figure 6.1 Step response for CO_2 experiment

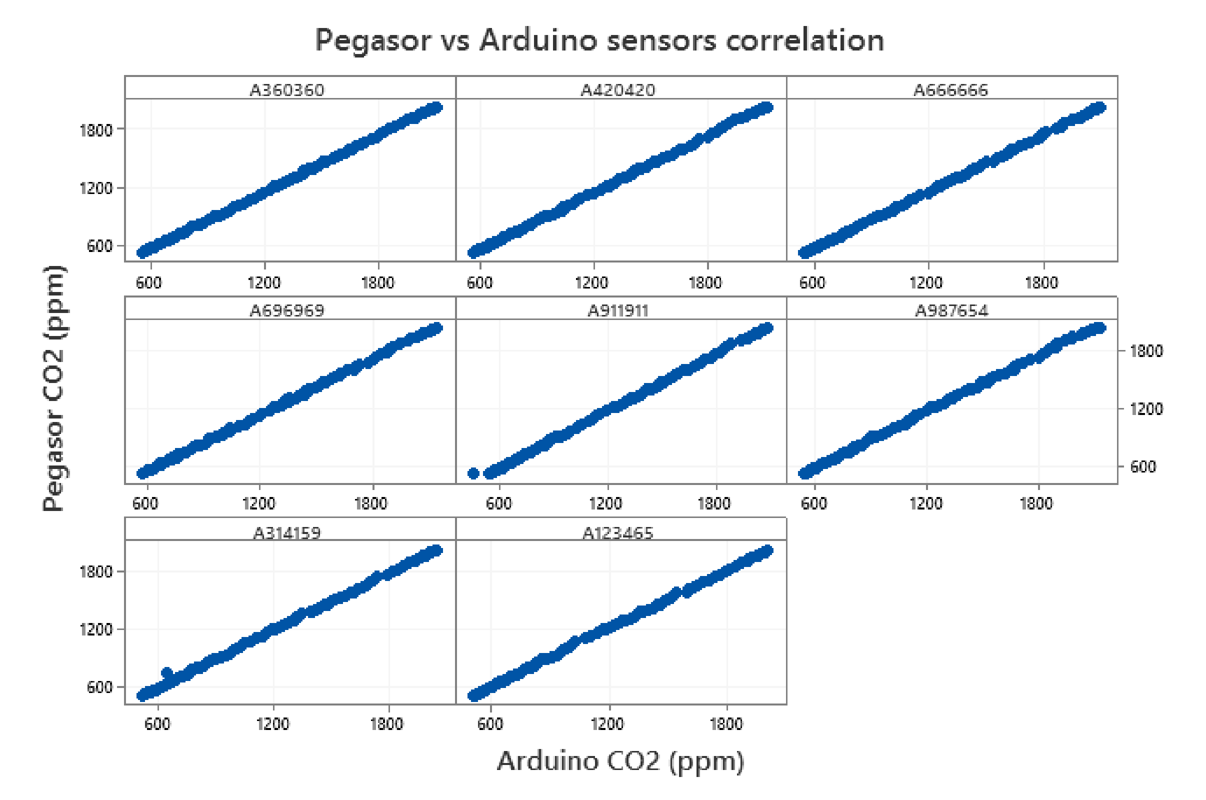

Figure 6.2 Pegasor vs Arduino correlation

The step-response for all eight sensors and reference sensor is plotted in Figure 6.1. It is obvious that the CO_2 concentration measured by the Arduino sensor is close to the reference sensor. For each of the correlations shown in Figure 6.2, a linear regression equation is made to correct the output from the CO_2 sensor. This regression equation is called the calibration equation and is presented for all sensors in Table 6.1.

Table 6.1 SCD30 CO_2 calibration summary

Sensor	CO_2 calibration equation	R-squared
A360360	$-19.2 + 0.97 * C_{meas}$	100 %
A420420	$-29.8 + 0.97 * C_{meas}$	100 %
A666666	$-21.2 + 0.98 * C_{meas}$	100 %
A696969	$-34.4 + 0.97 * C_{meas}$	100 %
A911911	$-5.2 + 0.97 * C_{meas}$	100 %
A987654	$1.8 + 0.97 * C_{meas}$	100 %
A314159	$18.83 + 0.98 * C_{meas}$	100 %
A123465	$-5.2 + 0.97 * C_{meas}$	100 %

Table 6.1 shows that the Arduino sensors track the reference sensor well and has little offset. The R-squared value describes the goodness-of-fit between the regression line and the actual concentration. Even though the calibration equation and R-value are good, the residual plot for the calibration equation should be considered. The residual plot for one of the sensors is presented in Figure 6.3, and show that the difference between the measured and estimated value (Y-axis) is ± 10 ppm, which is low compared to the normal measured values. The X-axis show that the calibration equation is tested for values between 500 and 2000 ppm.

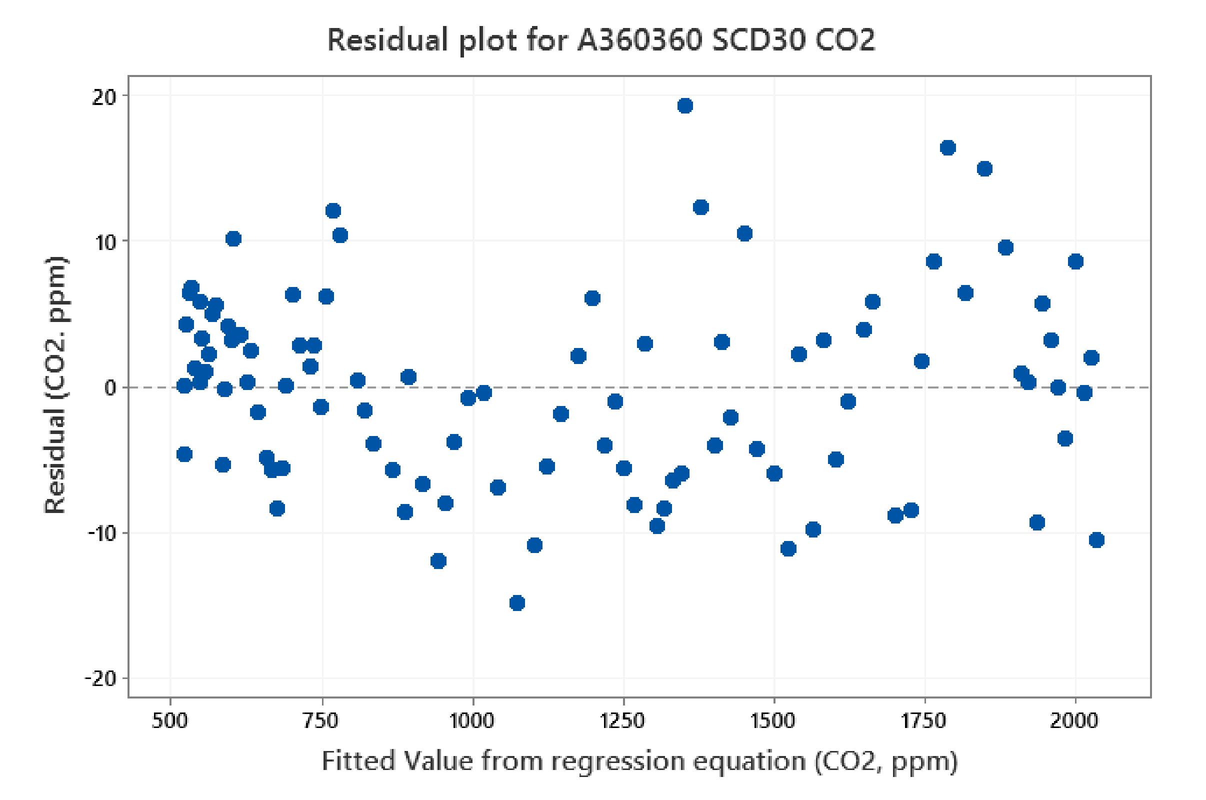

Figure 6.3 Example residual plot for CO_2 regression equation

6.1.2 Calibration of WZ-S formaldehyde sensor

The data used to calibrate the WZ-S formaldehyde sensor comes from experiment 2 and 3, which is described in chapter 5.3. The Graywolf reference sensor measure 30-min average values, while the Arduino sensors measure once per 5 or 10 minutes during the experiments. For the calibration curves, 30-minute average values have been calculated for each Arduino sensor. A summary for all sensors and experiments is shown in Figure 6.4, where the bottom blue line is the reference measurements for all experiments.

Between the two experiments sessions in experiment 2, sensor A666666 crashed, and had to be withdrawn from the experiment. The system developers could not fix the problem on-site, and it is unclear if the error has impacted earlier measurements.

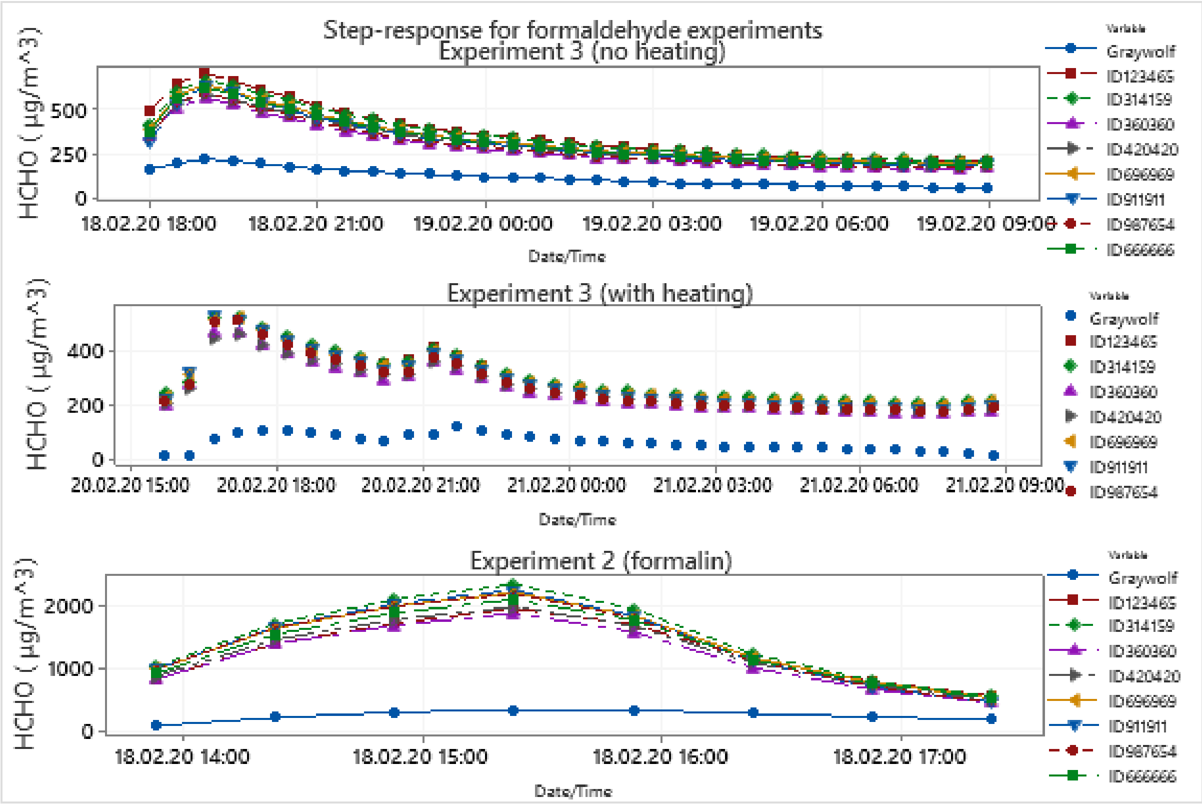

Figure 6.4 Formaldehyde experiment summary

Figure 6.4 shows that the WZ-S formaldehyde sensors track each other nicely but have a large offset from the reference sensor (bottom graph), that increase for higher concentrations. It should be noted that the formaldehyde concentrations for experiment 2 are several times higher than for experiment 3 and is close to the nominal measurement range of 2 ppm (approximately 2500 µg/m^3).

To see how the Arduino sensors perform compared to the reference sensor, a regression line for one of the sensors is shown in Figure 6.5.

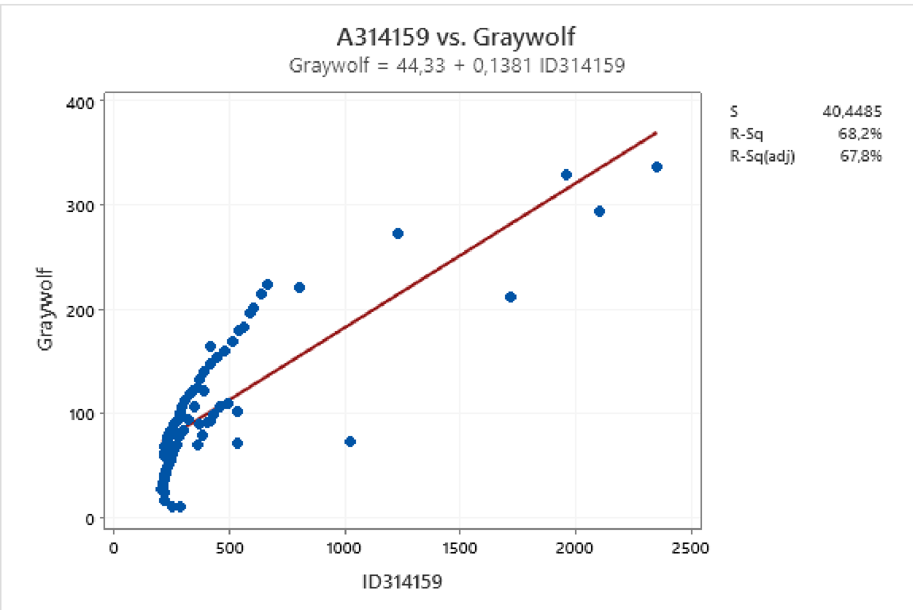

Figure 6.5 A314159/Graywolf correlation

The data points in Figure 6.5 seems to be gathered for lower concentrations, but spread more for the points above 700 μg/m^3 on the x-axis. A closer look shows that these points come from the formalin experiment, which recorded very high formaldehyde concentrations. Based on earlier measurements, it is assumed that the formaldehyde concentrations in the classroom rarely will exceed 200 μg/m^3, and that the data from experiment 2 therefore can be neglected when making the calibration curve for the WZ-S formaldehyde sensor. This implies that the calibration only is valid for formaldehyde concentrations below ~700 μg/m^3. The regression line, excluding data from experiment 2, is shown in Figure 6.6.

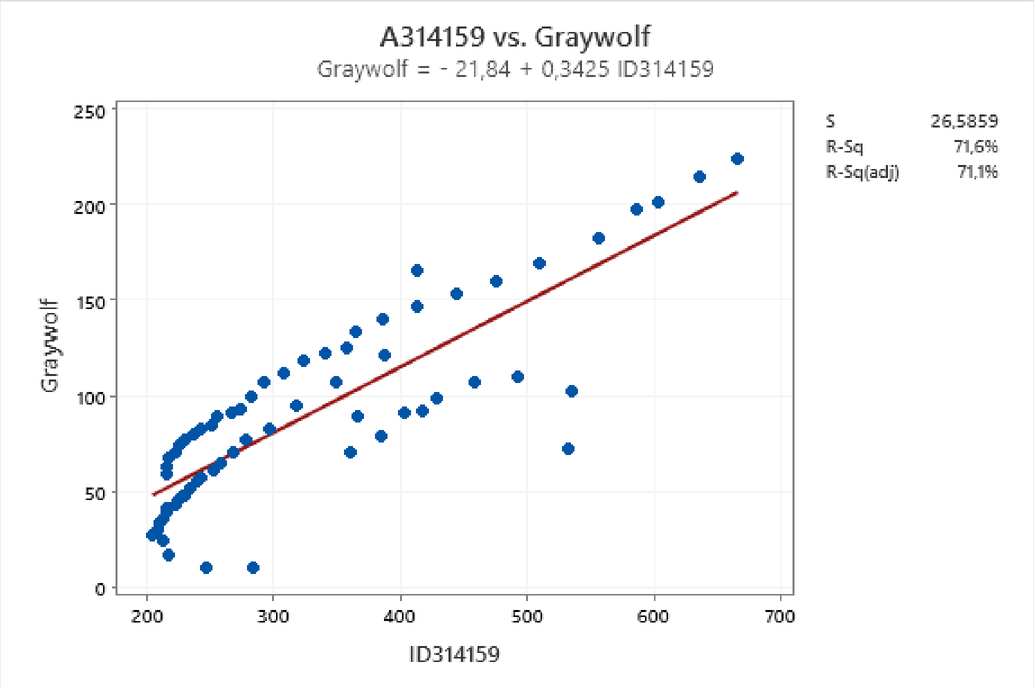

Figure 6.6 A314159/Graywolf ex. Experiment 2

Figure 6.6 clearly shows that the correlation between the Arduino sensor and reference sensor is higher when only considering experiment 3. The R-squared has increased from 68 % to 72 %, and the residual plots shown in Figure 6.7 show that the expected error between the actual concentration and estimated concentration has reduced noticeably.

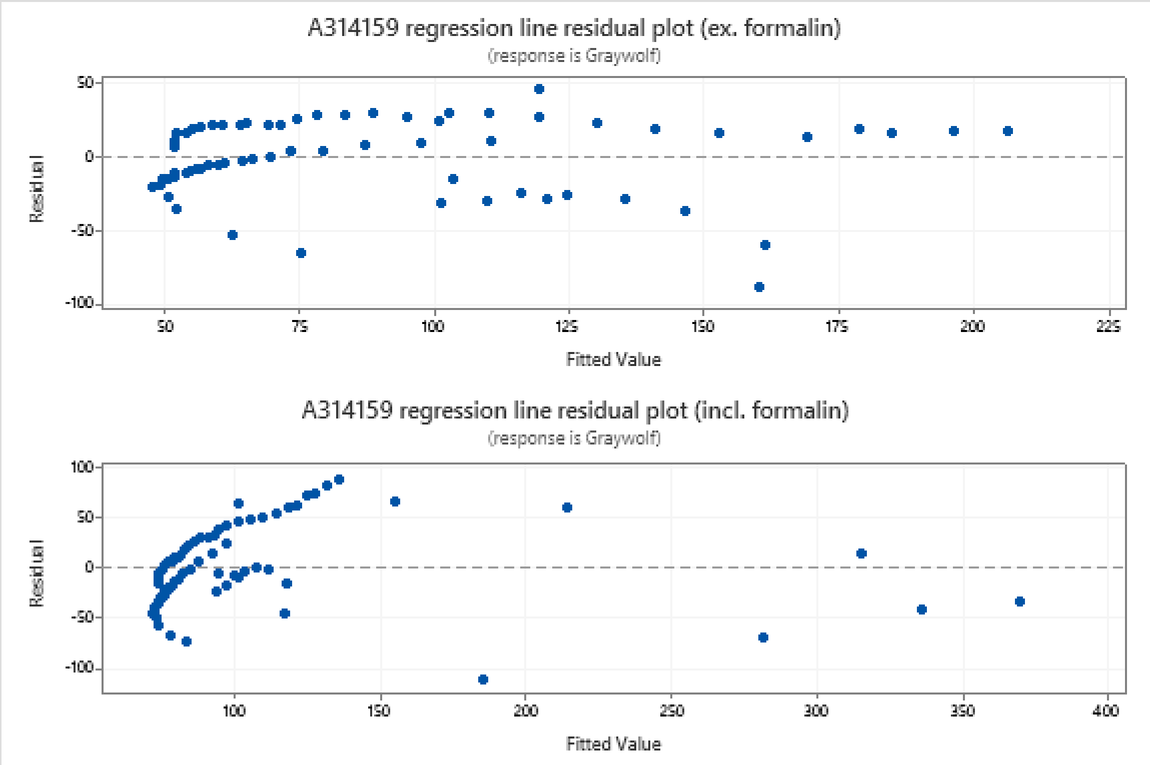

Figure 6.7 Residual plots

The top graph of Figure 6.7 shows that the actual value mostly is ± 50 µg/m^3 from the actual value when using the regression line that does not use the data from experiment 2. The same expected error is up to 100 µg/m^3 when including experiment 2, as shown in the bottom part of Figure 6.7. The calibrated curve should not be used if the calibrated measurements reports higher values than 150-200 µg/m^3.

The calibration curves and R-squared values for all sensors are summarized in Table 5.3.

Table 6.2 WZ-S Formaldehyde calibration summary

Sensor	Formaldehyde calibration equation	R-squared
A360360	$-11.0 + 0.3733 * C_{meas}$	64 %
A420420	$-22.4 + 0.3916 * C_{meas}$	72 %
A666666*	$3.4 + 0.3639 * C_{meas}$	97 %
A696969	$-16.4 + 0.3415 * C_{meas}$	65 %
A911911	$-7.7 + 0.3262 * C_{meas}$	60 %
A987654	$-7.3 + 0.3416 * C_{meas}$	61 %
A314159	$-21.8 + 0.3425 * C_{meas}$	72 %
A123465	$-17.7 + 0.3302 * C_{meas}$	78 %

* The table above shows that the R-squared and calibration equation is similar for all sensors. As mentioned for A666666, only one test was done, and results are based on approximately half as many datapoints.

6.1.3 Calibration of SHTC1 temperature sensor

As described in chapter 5.2, the Arduino sensor system now has two temperature sensors. Both sensors are checked to see how they perform, but the SCD30 temperature sensors still have a noticeable offset when in operation. Therefore, only data from the SHTC1 T/RH sensor are calibrated.

Data from experiment 1 and experiment 4 are used for the calibrations. These experiments are chosen because they use the Pegasor temperature sensor, which gives measurements per 60 seconds. Experiment 1 have stable temperature and RH during the whole experiment, while experiment 4 varies both in temperature and RH. Combining these experiments for the calibrations will increase the robustness and validity of the calibration.

The step-response for both experiments are shown in Figure 6.8. The leftmost graph is form experiment 4 and the right part of the graph is from experiment 1.

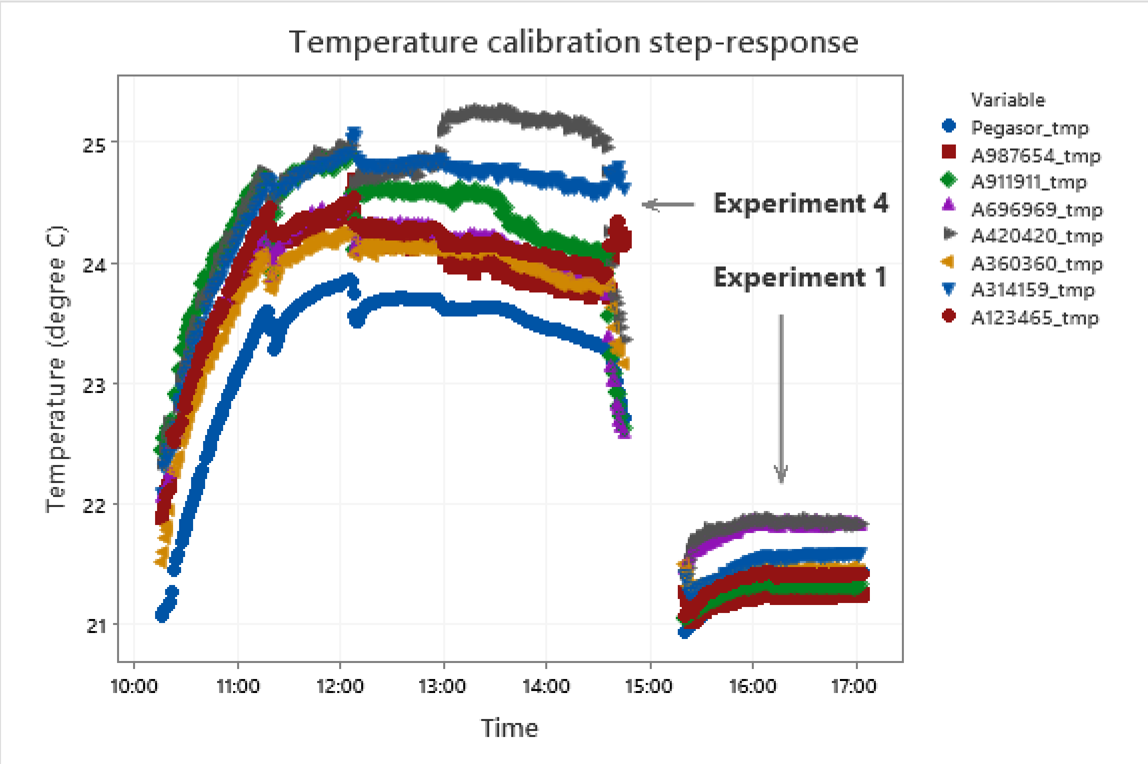

Figure 6.8 Step response for temperature calibrations

There is still some offset, but the SHTC1 measurements track the reference measurements nicely, even with variations in temperature as seen from experiment 4. The correlation and residual plot for one of the sensors is shown in Figure 6.9.

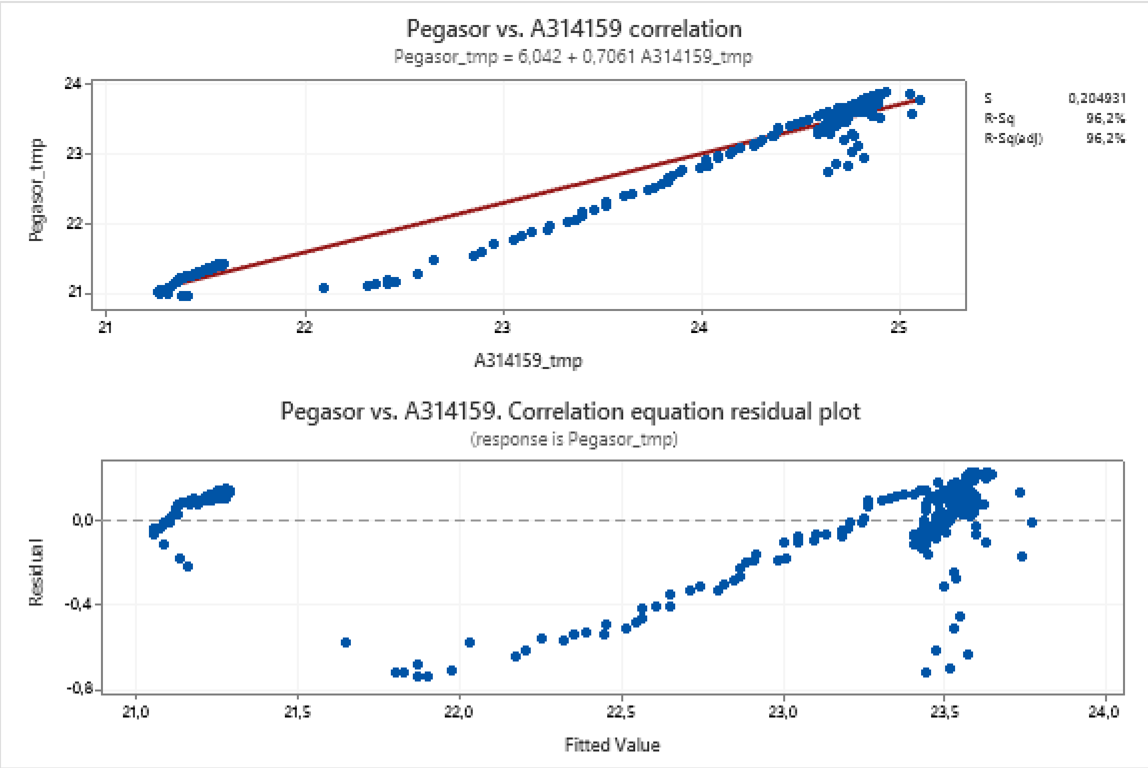

Figure 6.9 A314159 temperature calibration curves

Figure 6.9 clearly shows the importance of having calibration data based on several tests under different conditions. The leftmost datapoints are from experiment 1, where the temperature is stable around 21 °C during the whole test. The datapoints to the right is from experiment 4, where the temperature was fluctuating, and varied from 21 °C to 25 °C. The residual plot shows that the calibration equation must be expected to have errors up to ±0.8 °C. The calibration equation for all sensors is summarized in Table 6.3.

Table 6.3 Temperature calibration summary

Sensor	Temperature calibration equation	R-squared
A360360	$2.4 + 0.88 * T_{meas}$	98 %
A420420	$5.5 + 0.72 * T_{meas}$	95 %
A666666	NA	NA
A696969	$0.7 + 0.94 * T_{meas}$	97 %
A911911	$6.4 + 0.70 * T_{meas}$	92%
A987654	$4.5 + 0.79 * T_{meas}$	94 %
A314159	$6.0 + 0.71 * T_{meas}$	96 %
A123465	$4.1 + 0.8 * T_{meas}$	96 %

6.1.4 Calibration of SHTC1 relative humidity sensor

As the RH is derived from the temperature measurements, the SHTC1 RH sensor is assumed to give the most correct RH measurements. To calibrate the RH sensor, the same experiments and reference sensor used for temperature calibrations are used. The step-response for all sensors for both experiments is shown in Figure 6.10.

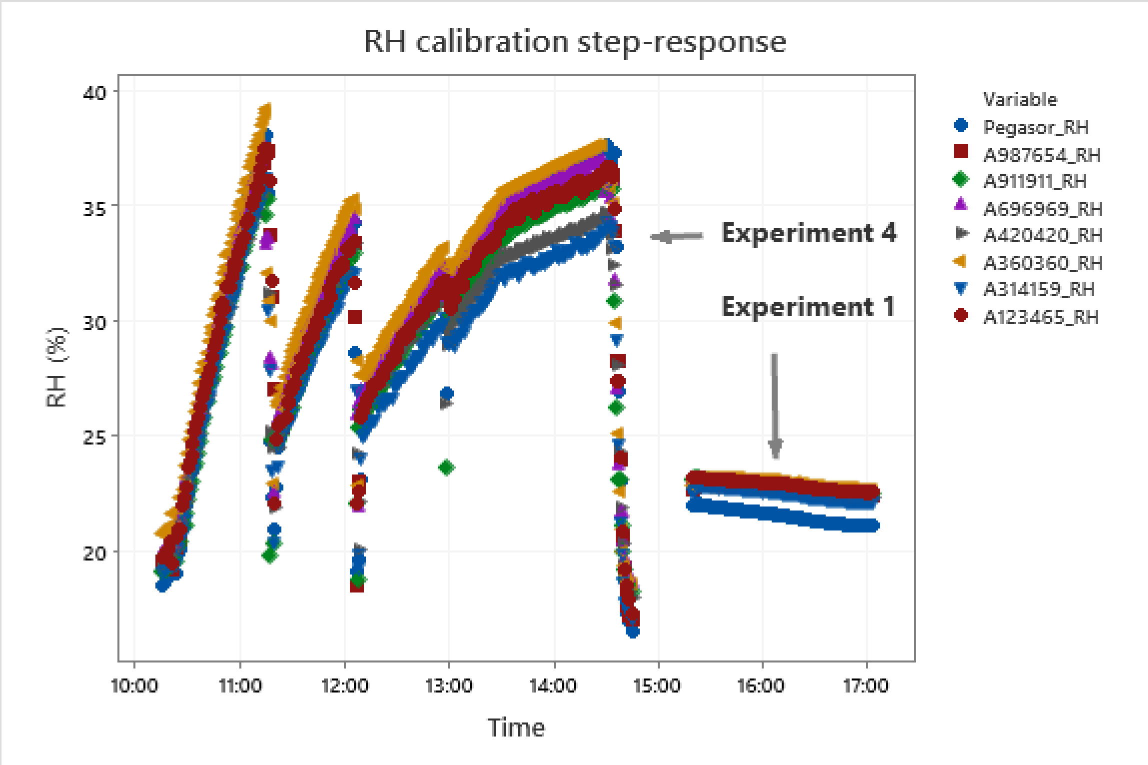

Figure 6.10 RH calibration step-response

The humidity measurements from the SHTC1 sensors clearly tracks the Pegasor reference sensor nicely, even when subjected to abrupt changes. The correlation equation and residual plot for A314159 is shown in Figure 6.11.

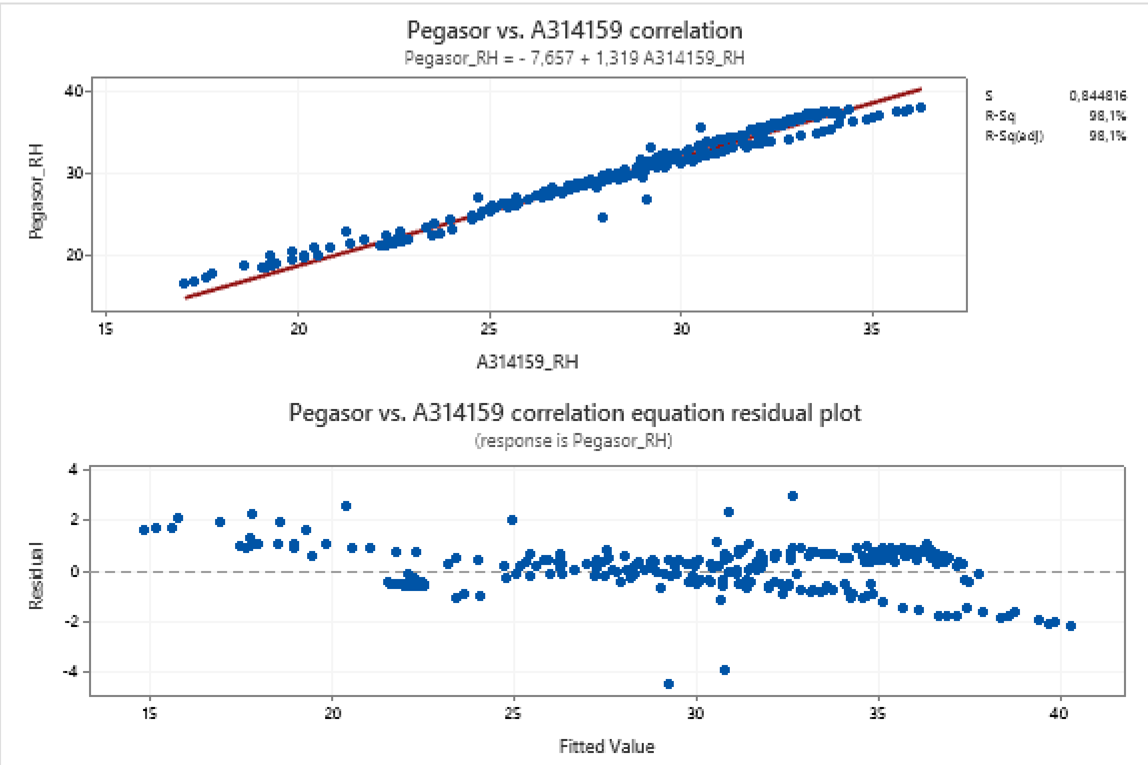

Figure 6.11 A314159 RH calibration curves

Even though the calibration equation for A314159 has the largest offset, the R-squared and residual show that the accuracy of the calibration curves is good, with an expected error of just ±2 % RH. It must be mentioned that these tests are done during Norwegian winter, which means the humidity during the tests is low. Consequently, the calibration curve has its highest datapoints around 40 % RH, which is lower than what can be expected in a normal indoor climate. This is not optimal, but no tests with sufficient data are run as part of this master thesis, and the calibration is, therefore, assumed to be adequate also for higher RH levels. Calibration curves for all sensors are summarized in Table 6.4.

Table 6.4 RH calibration summary

Sensor	RH calibration equation	R-squared
A360360	$-3.1 + 1.06 * C_{meas}$	98 %
A420420	$-7.1 + 1.27 * C_{meas}$	98 %
A666666	NA	NA
A696969	$-3.8 + 1.11 * C_{meas}$	98 %
A911911	$-5.1 + 1.19 * C_{meas}$	97 %
A987654	$-4.2 + 1.14 * C_{meas}$	97 %
A314159	$-7.7 + 1.32 * C_{meas}$	98 %
A123465	$-4.6 + 1.15 * C_{meas}$	97 %

6.1.5 Calibration of Sensirion SPS30 particle sensor

For calibration of the Sensirion SPS30 PM sensor, data from experiment 1 and experiment 4 are used. While experiment 4 is designed to test fine particle fractions, experiment 1 also use the Pegasor reference sensor, and is therefore eligible for PM calibration.

The difference between the two tests is, in theory, that the candles in experiment 4 should produce fine particles from the candle combustion, while the only PM source in experiment 1 is dust and particles from the test chamber. The test chamber was not cleaned before starting the experiments, and the dust in the box is assumed to have been swirled up by the mixing fan and pressure from the CO_2 injection. The mixing fan is used in experiment 1, but not in experiment 4.

The SPS30 sensor claims to measure both $PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$, and PM_{10}. The same sensor is used for measurements in both Gram (2019) and Jørgensen (2019), and the correlation between the measured particle fractions have been very high. Figure 6.12 shows the correlation between the measured particle sizes for two of the sensors.

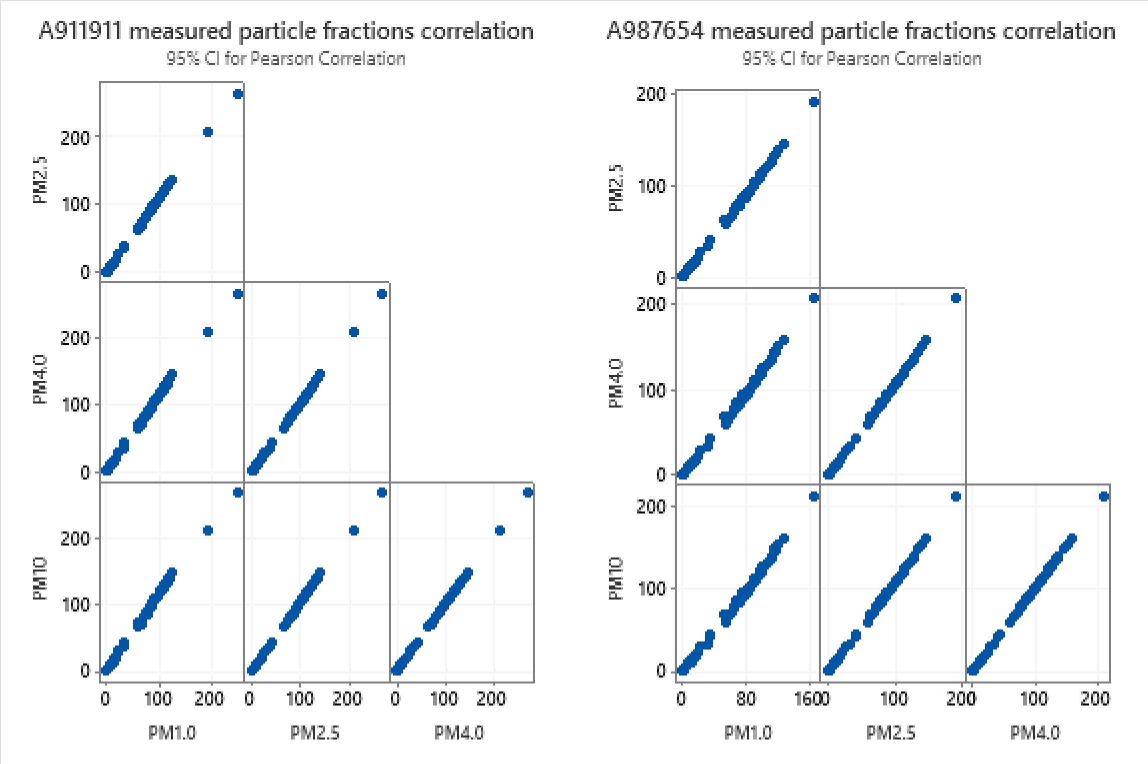

Figure 6.12 Particle size correlation

It is clear from the correlations shown in Figure 6.12 that the measured particle concentrations are close to equal for all particle sizes. The data in Figure 6.12 is based on 400 measurements with 1-minute intervals, from two different experiments. Because the measured concentrations for the particle sizes is close to equal, data for one of the particle sizes is used in the following graphs.

The step-response for experiment 4 is shown in Figure 6.13 and experiment 1 in Figure 6.14. The timeline for the experiment is:

- 10:20-10:25: Seven candles lit; test chamber closed
- 11:15-11:20: Test chamber opened; 3 candles removed. Test chamber ventilated before closing, 4 candles left
- 12:05-12:10: Test chamber opened; 2 candles removed. Test chamber ventilated before closing, 2 candles left
- 13:30: One of the two remaining candles self-extinguished, causing visible smoke
- 14:30: Opened ventilation holes in test chamber. Mechanical fan started to change air in test chamber

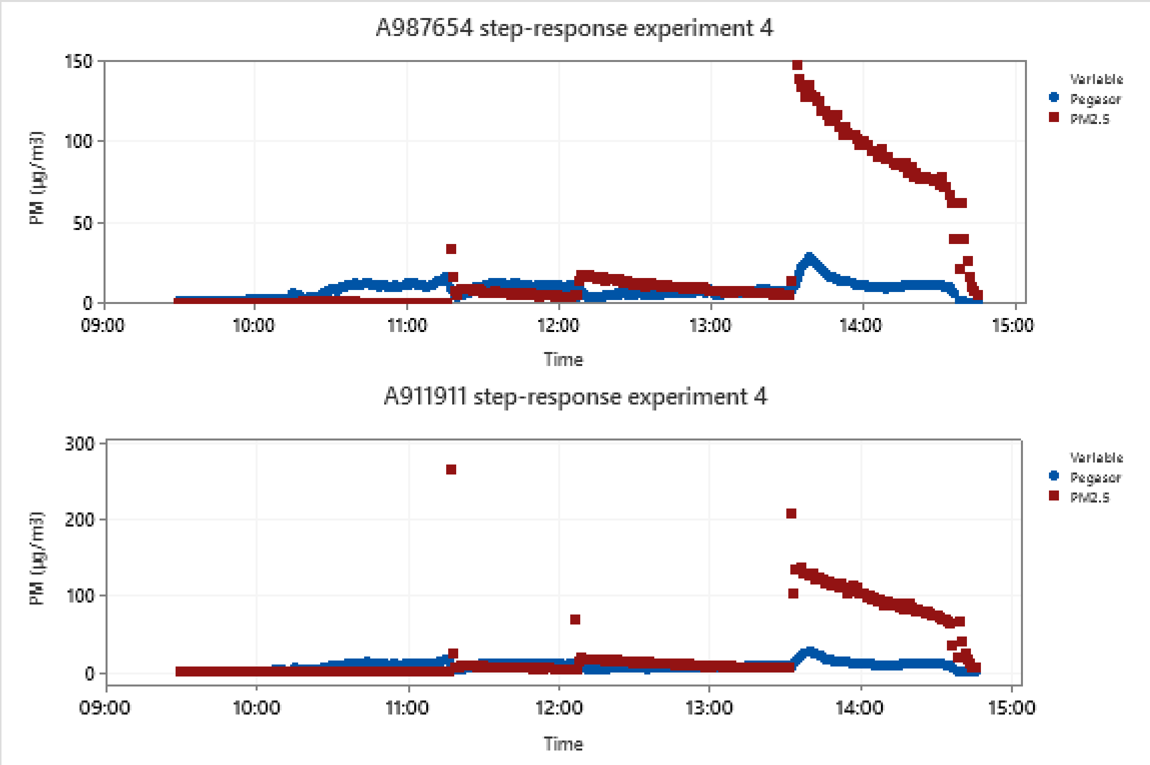

Figure 6.13 Experiment 4 step-response for A987654 and A911911

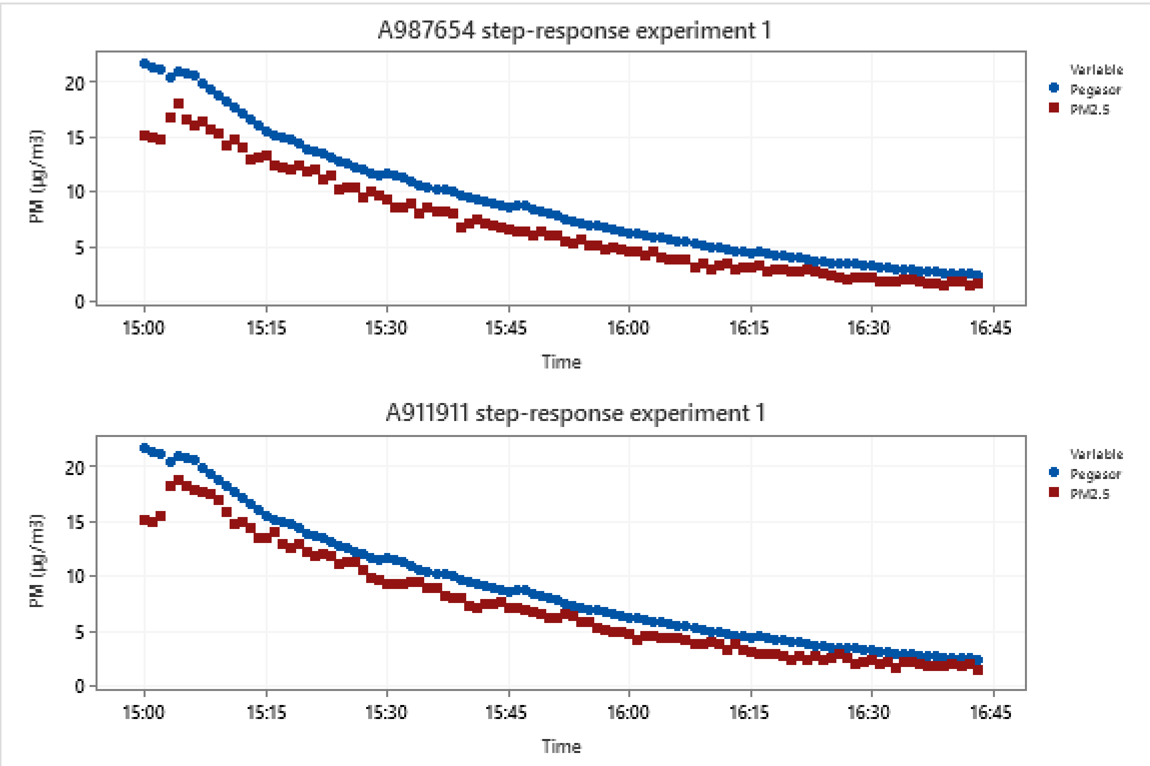

Figure 6.14 Experiment 1 step-response for A987654 and A911911

It seems that the PM sensor tracks the reference sensor nicely in experiment 1, but it is hard to see from experiment 4 because of the large peak at ~13:30. Therefore, Figure 6.15 shows a zoomed view of Figure 6.13.

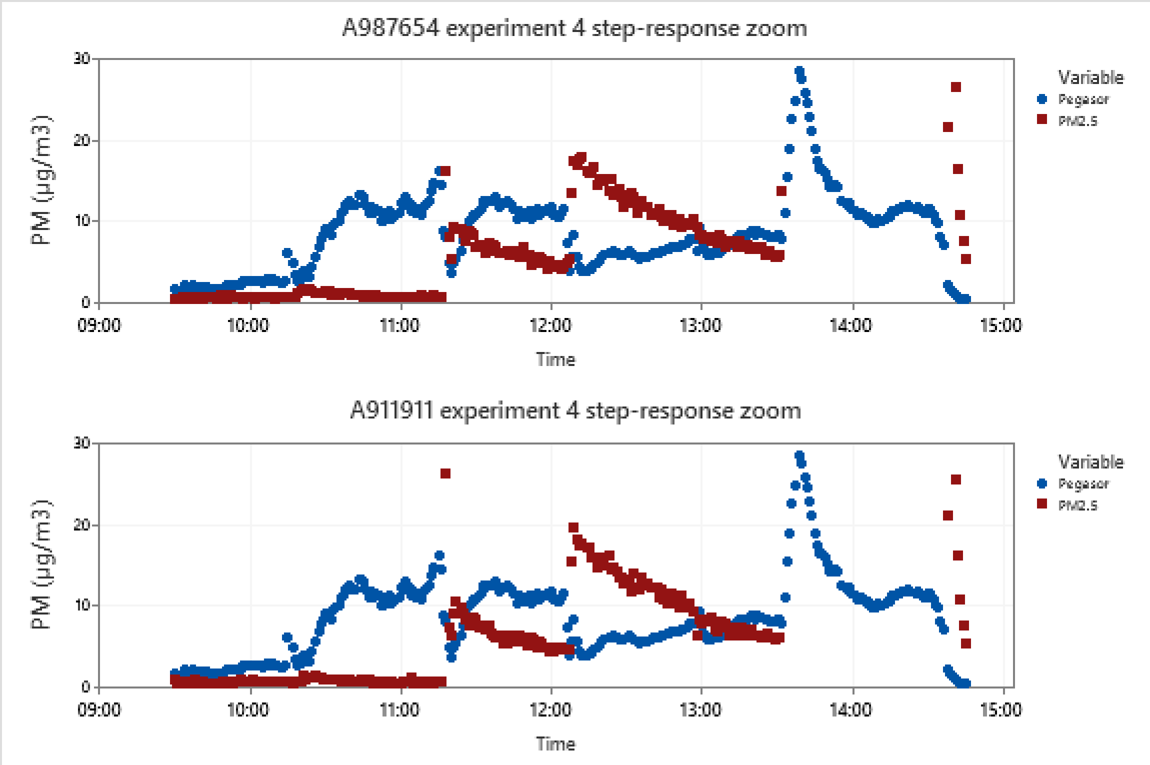

Figure 6.15 Experiment 4 step-response zoom

As seen from the difference between Figure 6.14 and Figure 6.15, there are substantial differences between the Pegasor and SPS30 sensors for experiment 4. The SPS30 increases when the door to the test chamber open, while the Pegasor sinks. The SPS3 does not seem to react noticeably on the particles from the burning candles, but more on the dust that is swirled around when the door is opened. However, both the SPS30 and Pegasor measurement increases noticeably when one of the candles self-extinguished at 13:30.

In the tests above, the SPS30 seem to react noticeably to two things: the candle that self-extinguishes and the door to the test chamber opening. These are both processes that is believed to produce coarse particle. The burning candles should emit fine particles, as measured by the Pegasor during experiment 4, but the SPS30 does not seem to react much to this.

Based on the tests and results from this chapter, the SPS30 sensor should not be used for continuous assessment of the indoor air quality without using other sources of information together with the SPS30 measurements. Such sources can be outdoor air quality measurements, knowledge of pollution sources, or other reference sensors. It is still possible that other calibrations with a more detailed setup over a longer period may conclude otherwise.

6.2 Corrections by using earlier measurements

Because no real measurements could be done after the laboratory calibration of the SHTC1 T/RH sensor, older measurements using the SCD30 are used instead. These measurements are taken in the same classroom, and therefore acts as a good substitute given the current circumstances. The Arduino measurements are calibrated using the BMS sensor data. The temperature is only corrected to get correct the RH measurements, but both sensors must be calibrated because RH is temperature dependent. This method was chosen over laboratory calibrations to better account for the actual conditions in the classroom.

6.2.1 Corrected temperature for reference week

This setup is not optimal as the BMS temperature sensor is not calibrated either, but the results are assumed to be of acceptable quality for the comparisons of this thesis. The temperature calibration will further be used to correct the measured RH data from the SCD30 sensor.

The calibration curve for the SCD30, shown in Figure 6.16, is made using measurement data from the reference week, and is logged every 10 minutes over 7 days.

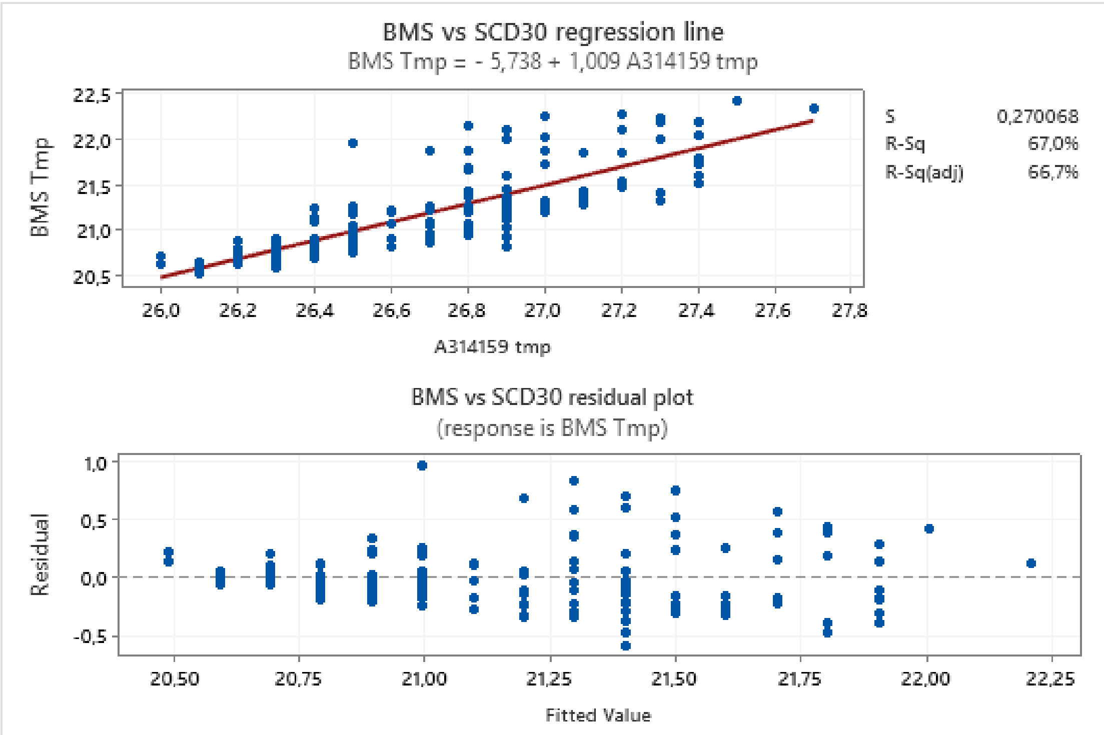

Figure 6.16 SCD30 calibration curve

The calibration in Figure 6.16 tells that the offset is close to constant at -5,7 °C. The R-squared value is only 67 %, but the residual plot shows that most fitted values are well inside ± 0,5 °C from the actual value, which is acceptable. The resulting calibration equation for the SCD30 sensor is $T_{actual} - 5.738 + 1.009 * T_{Arduino}$. This is assumed to be equal for both supply and breathing air sensors.

6.2.2 Corrected RH measurements from reference week

Further, the relative humidity must be corrected, using the new temperatures. The new RH is calculated by assuming that the amount of water and ambient pressure is constant for the room air. The equations used below are found in Ingebrigtsen and Stensaas (2016). First the water amount in the air, based on the uncalibrated temperature, is found from:

$$X = 0{,}622 * \frac{p_d}{p - p_d}\ [kg\ water/kg\ dry\ air]$$

Where

$$p = atmospheric\ pressure = 101325\ [Pa]\ (at\ sea\ level)$$

$$p_d = water\ vapor\ partial\ pressure = \phi * p_{dm}\ [Pa]$$

$$p_{dm} = water\ vapor\ saturation\ pressure = \exp\left(23{,}5771 - \frac{4042{,}9}{T + 235{,}42}\right)\ [Pa]$$

$$T = dry\ buld\ temperature\ [°C]$$

Combined, these give:

$$X = \frac{\phi * p_{dm}}{p - \phi * p_{dm}}\ [kg\ water/kg\ dry\ air]$$

With the corrected temperature, new saturation pressures can be calculated, which gives a new RH using the same water amount (X) as before. The new RH is given by:

$$RH_{new} = \phi_{new} = \frac{p_d}{p_{dm,new}}$$

Where

$$p_{d,new} = \frac{X}{0{,}622 + X} * p$$

$$p_{dm,new} = \exp\left(23{,}5771 - \frac{4042{,}9}{T_{corrected} + 235{,}42}\right)$$

X and p unchanged due to static conditions.

RH can either be transformed as described, or by a RH calibration curve, as presented in Figure 6.17.

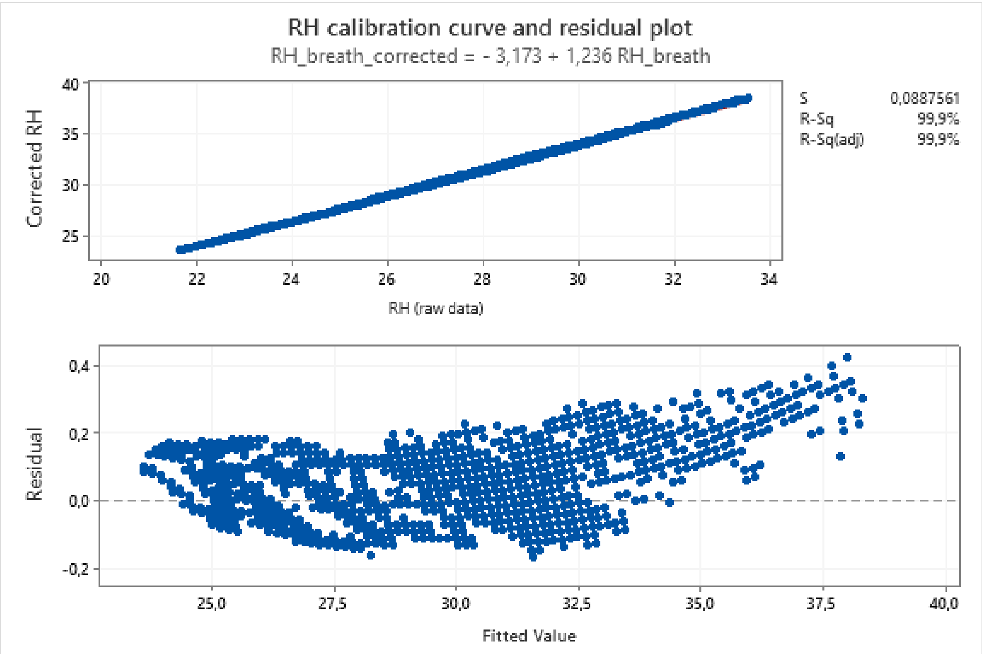

Figure 6.17 RH calibration curve

The supply air sensor have been shown to drastically reduce the measured temperature when the air velocity is increased (Jørgensen, 2019). Therefore, these calibrations are only valid when the air velocity around the sensor is low, as for the breathing air and the supply air when there is no supply air flow.

6.3 Arduino classroom measurements

Because of restrictions due to COVID-19, new measurements could not be taken after the laboratory calibrations from chapter 6.1. Therefore, the results in this chapter is based on measurements done during winter 2019, as part of the preparatory project. The formaldehyde, CO_2, and PM sensors are the same as in chapter 6.1, but the temperature and RH sensors are changed, and a different calibration routine, discussed in chapter 6.2, is used to correct these measurements. Despite the measurements being from an older hardware setup, the new calibrations made as part of this master thesis may put the measurements in a new perspective.

6.3.1 Formaldehyde

The measurements taken during fall and winter 2019 as part of Jørgensen (2019) can now be corrected, using the calibration curves made in chapter 6.1.2. Calibration curves for A420420 (supply) and A314159 (breath) is used. The measured 30-minute average concentrations for breathing zone and supply air is presented in Figure 6.18.

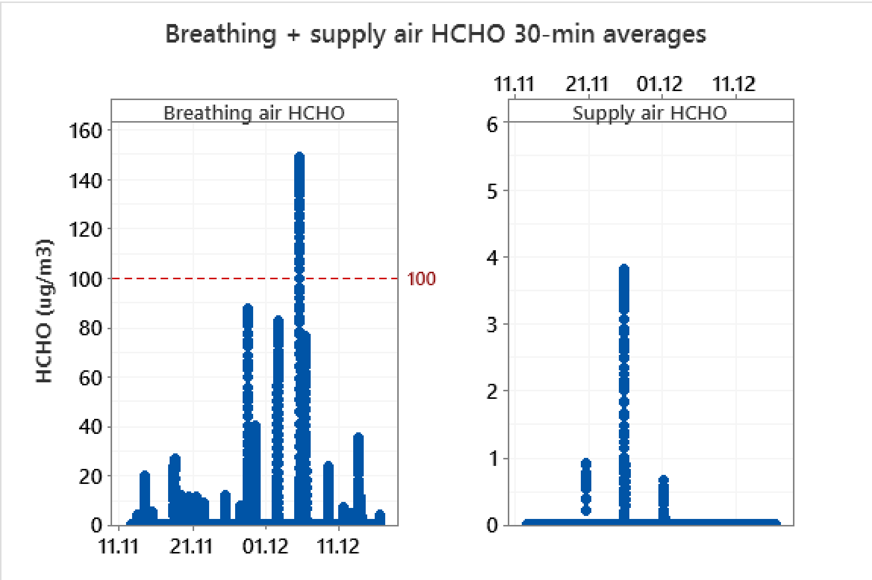

Figure 6.18 Breathing/supply air 30 minute average HCHO concentration

It is clear from the measurements that the calibration has radically reduce the formaldehyde concentration in the classroom. Because the concentration is so low in the supply air, the measured formaldehyde is assumed to come from sources inside the classroom. The formaldehyde concentration seems to exceed the maximum limit during the school day, but the peaks are short lived. Figure 6.19 shows how many minutes the maximum limit 30-min average is exceeded.

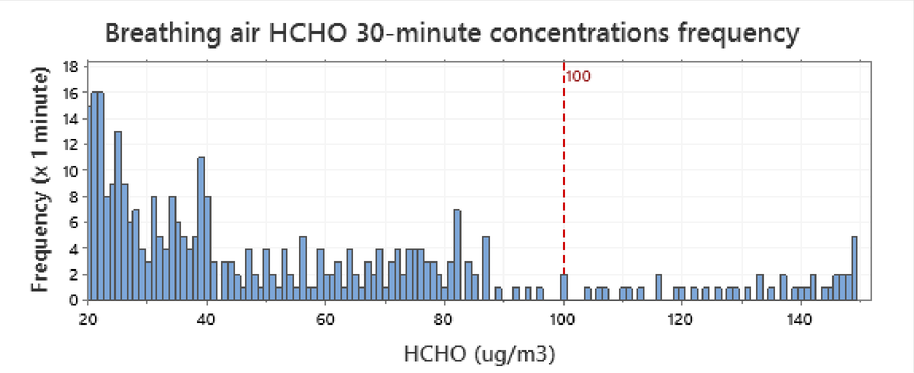

Figure 6.19 Duration of HCHO concentrations over 100 µg/m³

It is clear from Figure 6.19 that the 30-minute average concentration have exceeded the 100 µg/m³ maximum limit only for short periods. These periods are probably caused by sudden peaks caused by cross-sensitivities. Bear in mind that Figure 6.19 shows all recorded concentrations above 20 µg/m³ which is less than 500, while there are over 45,000 datapoints in total.

The large reduction from the calibration on the measured values, causes most of the measured value to be less than zero. Therefore, all values < 0 µg/m³ are assumed to be equal to zero. The uncalibrated values, shown in Figure 6.20, shows that the formaldehyde measurement seems to provide reasonable data. However, since the calibration have reduced the amplitude of the measurements, the measured concentrations are assumed not to be harmful.

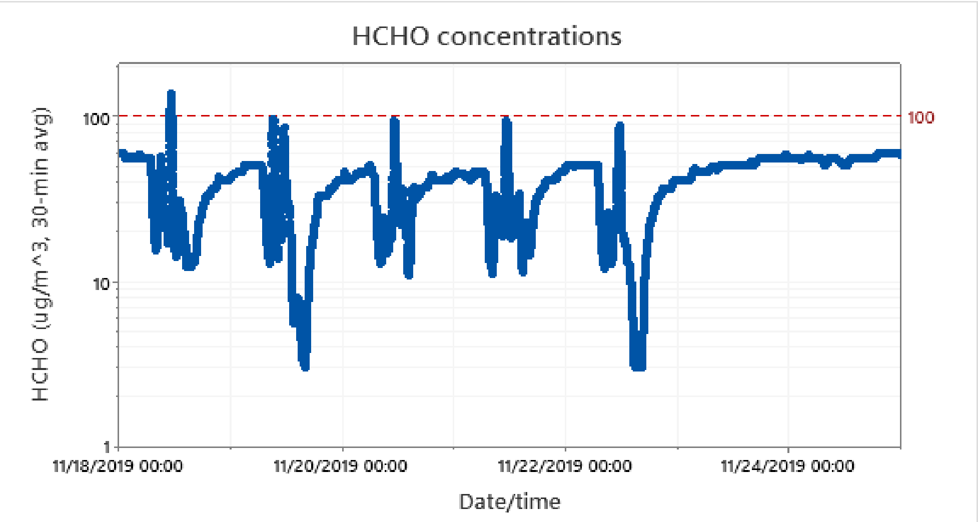

Figure 6.20 Non-calibrated formaldehyde measurements (log x-axis)

6.3.2 Relative humidity

The relative humidity measured in the classroom, from 13.11.2019 to 13.12.2019, is presented in Figure 6.21. The values are calibrated according to the results from chapter 6.2.2.

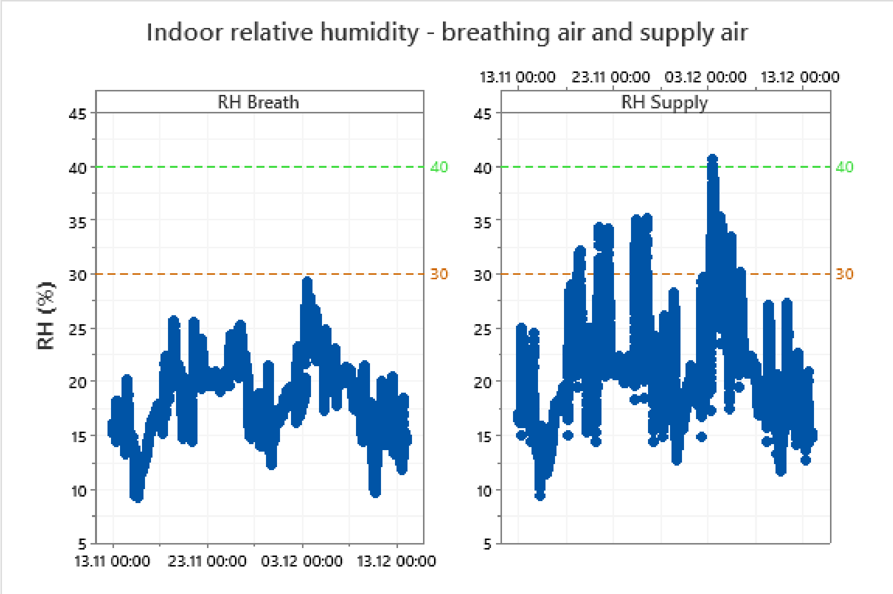

Figure 6.21 Breathing air and supply air RH

According to the findings in chapter 2.4.2 the RH indoor during winter should not drop below 30 % and preferably be stable around 40 % to avoid negative health effects and reduce the spread of viruses and influenza. The recorded levels for the breathing air are well below 30% most of the time. The measured RH for the supply air clearly rises when the ventilation is turned on every morning. This is assumed to be a result from the lowered temperature measurements caused by the increased air flow. Because of this, the RH results from the supply air is not useful for assessing the IAQ. Instead, the SH for the outdoor air is calculated based on temperature and RH measurements, using the same method as for the RH corrections in 6.2.2. The resulting humidity levels are presented in Figure 6.22, including outdoor SH, which is retrieved from an external source of information.

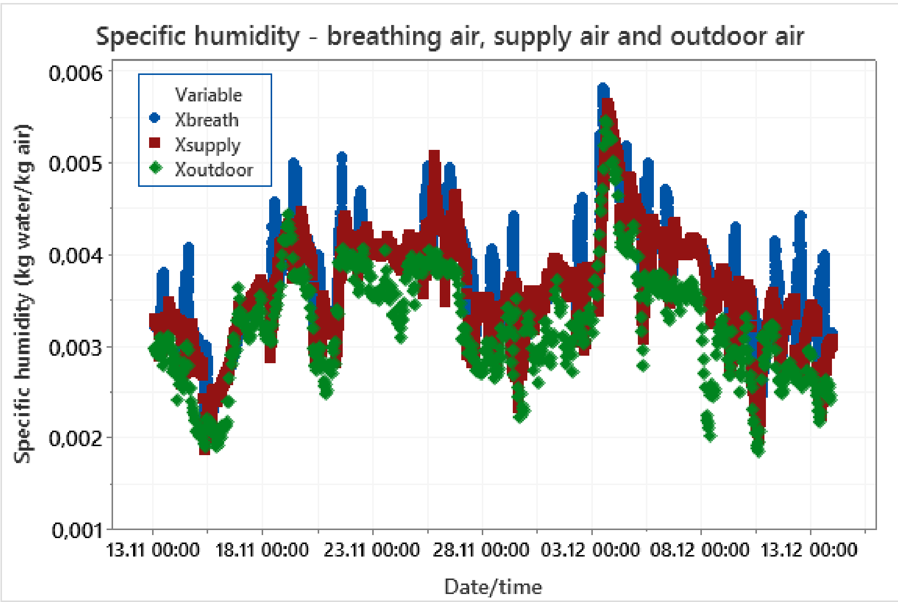

Figure 6.22 Indoor and outdoor specific humidity

Source "Xoutdoor": (Norwegian Centre for Climate Services, 2020)

The indoor humidity levels clearly follow the outdoor humidity level. This makes sense since it is the same air, but it also strengthens the model used to calculate the SH. The breathing zone humidity also rises above the supply air regularly, which is probably the result of the emitted humidity from the occupants. These results imply that when comparing two different measurement points, SH should be used rather than RH. RH should still be used to assess the IAQ in the breathing zone.

6.3.3 CO_2 concentration

The CO_2 concentrations measured in the classroom breathing air and supply air, from 13.11-13.12, is presented in Figure 6.23. The measured values are calibrated according to results from chapter 6.1.1.

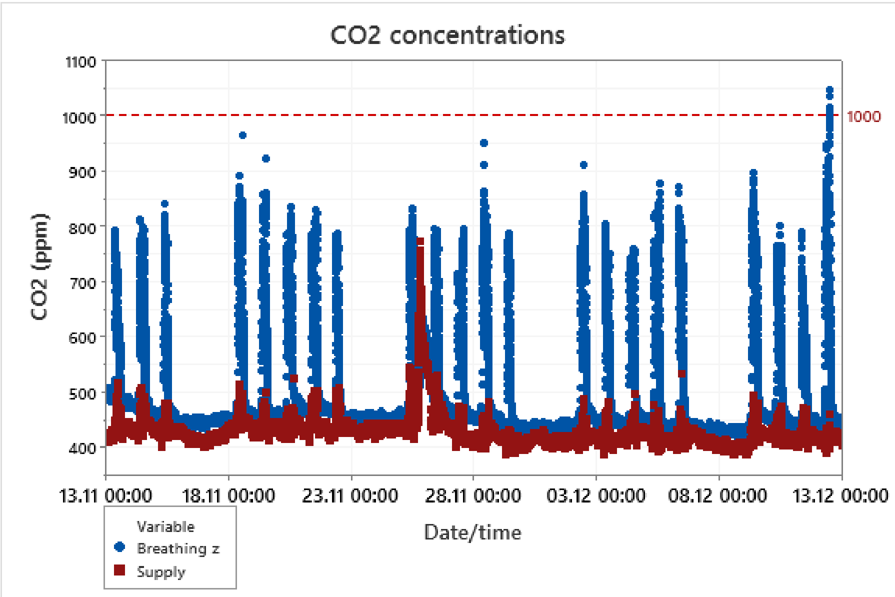

Figure 6.23 Classroom CO_2 concentrations

The measured concentrations show that there are peaks every school day caused by the occupants in the classroom. The ventilation system effectively controls the CO_2 levels in the classroom, which rarely exceeds the proposed maximum limit of 1000 ppm. The supply CO_2 concentration reacts as expected, and has no major increases, except for a peak at November 25, which is caused by occupancy after the ventilation system is shut off. This peak is measured both by the breathing air and supply air sensors. Figure Figure 6.24 show the duration of each measured concentration during the working days (08:00-15:59), since these are the most relevant data regarding IAQ.

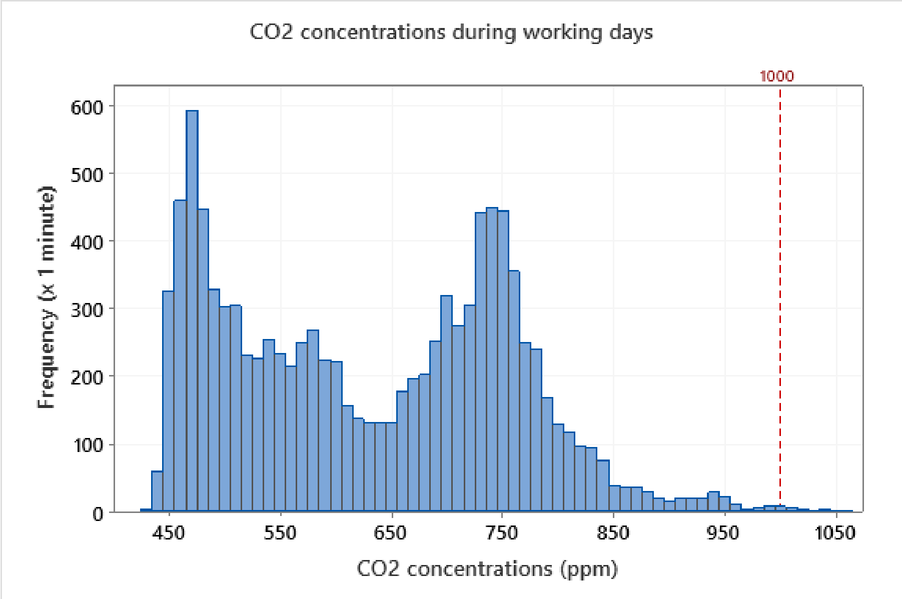

Figure 6.24 Duration of measured CO2 concentrations

The histogram in show the duration of the concentrations exceeding the 1000 ppm limit. The measurements are taken every minute, and there are around 20 measurements recorded above the limit of 1000 ppm. The concentrations during the working days are mainly below 850 ppm.

6.3.4 Particulate matter

As described in chapter 6.1.5 the SPS30 particle sensor is not yet proven to produce reliable results, and have not been calibrated. The results presented in this chapter must therefore be seen in relation with other, more reliable, sources of information. The $PM_{2.5}$ concentration from November 13 to December 13 is presented in Figure 6.25.

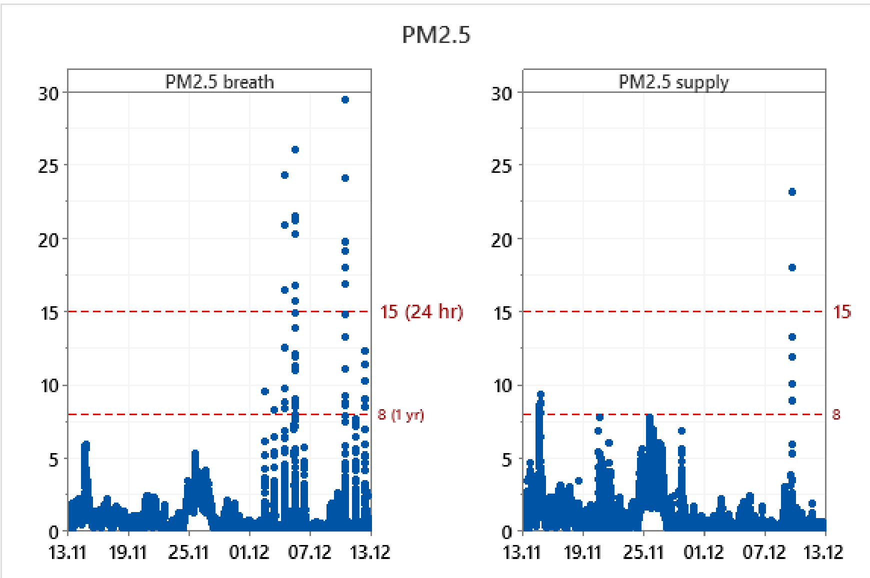

Figure 6.25 Measured $PM_{2.5}$ concentrations in breathing and supply air

The measured values, except for some short term peaks, seem to be well below both the short term limit (24 hr average, 15 µg/m^3) and long term limit (1 year average, 8 µg/m^3) as described in chapter 2.5. There seems to be an increase in $PM_{2.5}$ in the breathing air from December 2. The $PM_{2.5}$ concentrations at different measuring stations in Trondheim is presented in Figure 6.26. The colours are different severity classifications of the pollution strength (green = low, red = high).

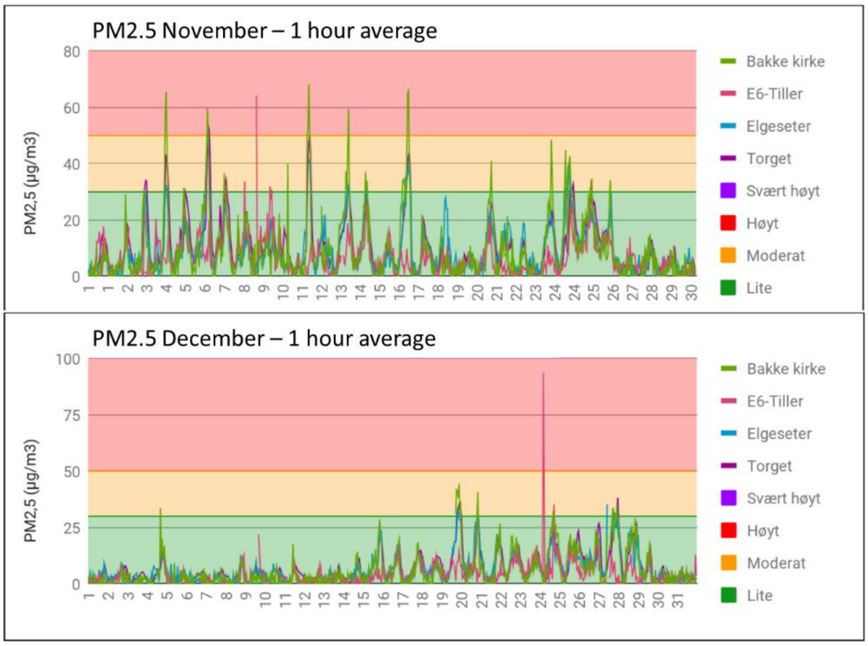

Figure 6.26 $PM_{2.5}$ concentrations in Trondheim

Source: (TrondheimKommune, 2020)

Figure 6.26 does not show drastically elevated PM concentrations after December 1. This and the fact that the supply air does not record increased levels, implies that the PM source may be inside the classroom. For comparison, it is evident on both breathing air and supply air measurements that the PM concentration around November 25 increases. This is also the case for the outdoor PM levels, which may have caused the indoor increase.

When the sensors were checked and restarted at December 16, a tray with knives and used sandpaper was found next to the Raspberry pi, on top of the cabinet where the breathing air sensor is placed. Since the equipment was stored in the classroom, this is probably the source of the increased PM levels after December 1, which is illustrated for one of the days in Figure 6.27.

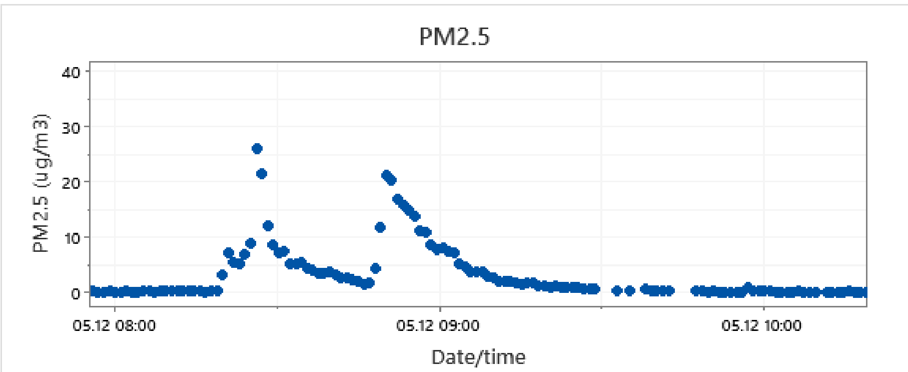

Figure 6.27 PM increase December 5

The measured increase after December 1 occurs from around 8:15 when the pupils start their day, until around 10. The peaks only occur during school days and not during weekends, as shown in Figure 6.25. This implies that the measured increase is caused by resuspension of surface particles, either from human activity or from the ventilation air flow.

6.4 Simulation model results

The simulation model of the classroom is made using CONTAM, and the method for creating the model is described in chapter 5.5.

The goal for making the model is to predict how IAQ reacts to changes in the ventilation system control and see if it possible to reduce energy consumption while maintaining or improving IAQ. In chapter 6.4.1, a base case is established, where the simulation model replicates the real system. Chapter 6.4.2 simulates how the IAQ is affected by changing the ventilation rate.

To compare the model and the real measurements, a reference week is chosen from the measurements as part of Jørgensen (2019), and the same week will simulated in CONTAM. The reference week is from Monday November 18 through Sunday November 24, 2019.

6.4.1 Adapting model to real life measurements

The emission rates and ventilation rates referred to in chapter 2 and 4 are theoretical numbers. CO_2 and H_2O emissions from humans can differ between individuals, activity level, and time of year. The measured ventilation rate from the BMS is an estimate based on the DCV damper opening, which can cause overestimation of the ventilation rates. Since CONTAM uses the actual ventilation rate, and assumes perfectly mixed air, which is not the case for the real systems, the ventilation rates in the simulation model should be reduced to fit the real-life system. To establish a base case model, the ventilation rates, CO_2 emission rates, and H_2O emission rates are adjusted until they all fit the real-life measurements simultaneously. This model can be used further to study how changes in ventilation affects IAQ. The initial data for the mentioned parameters was:

- Ventilation rate setpoints: from 15 % and up to 75 % during occupancy
- Occupant CO_2 generation rate per person: 0.004 L/s
- Occupant H_2O generation rate per person: 0.05 kg/h

When adjusting these parameters, they are kept as close to original as possible, to avoid unrealistic values.

First the average real ventilation rate in the classroom during occupancy is found. Data from the BMS is used to find the average DCV damper opening when present, which varies from 50-65 %. The variance can be caused by classes with reduced occupancy, varying activities, etc. The ventilation rate when occupied is therefore expected to be somewhere in that interval.

The CO_2 and H_2O generation rates are then adjusted to fit the concentrations from the real measurements. The final values used in the CONTAM base case are:

- Ventilation rate during occupancy: 58 %
- Occupant CO_2 generation rate per person: 0.0045 L/s
- Occupant H_2O generation rate per person: 0.04 kg/h

The simulated contaminant concentrations are compared with the real measurements and is presented in the following paragraphs for each of the parameters (CO_2, H_2O, and formaldehyde). The real measurements are logged every minute while the simulation is every 10 minutes. The measurements from the real classroom is only from the breathing air because this is the equivalent to the simulated results.

CO2

The CO_2 concentration is the controlling parameter for the real system, while the ventilation rate and occupancy control the CONTAM model. Therefore, the simulated, and simplified, system is more static than the real measurements. This is evident in Figure 6.28, where the CO_2 concentration varies more form day to day, probably because of the variation in occupant load and/or activity. The mean concentration in the simulations is close to the real measurements when the classroom is occupied.

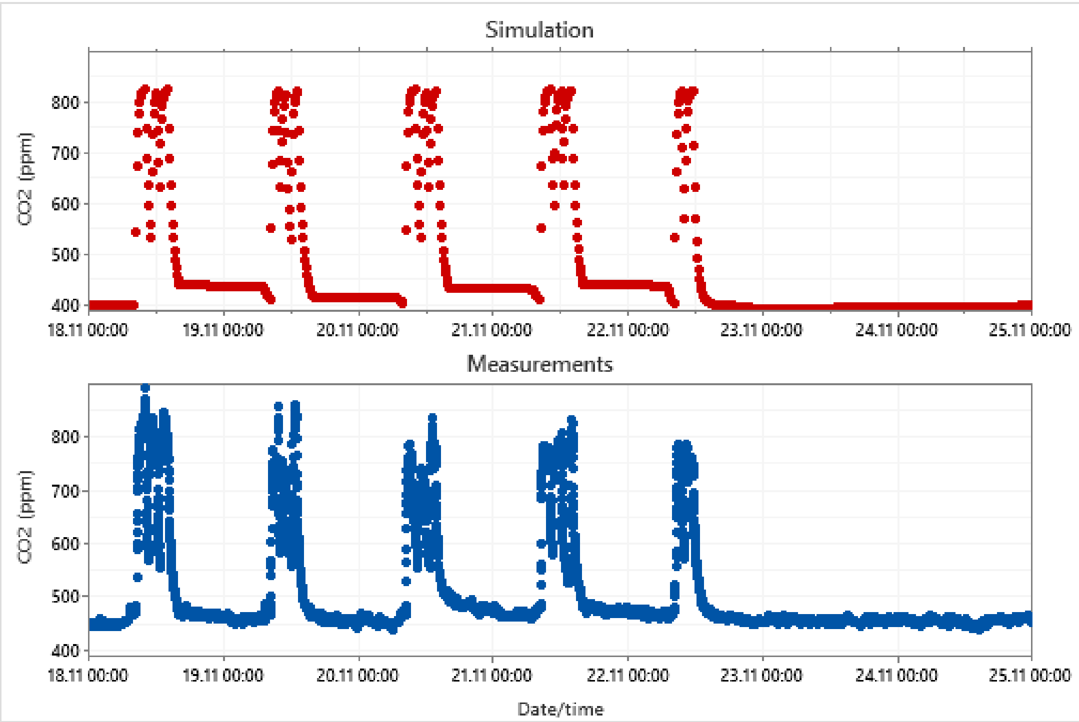

Figure 6.28 CO_2 reference week comparison

Figure 6.29 zooms in on one of the days, where it is evident both for simulations and measurements that there are three separate periods of occupancy. Both the peak and the stable CO_2 concentration are close, and the thinning after the occupied period is a good fit.

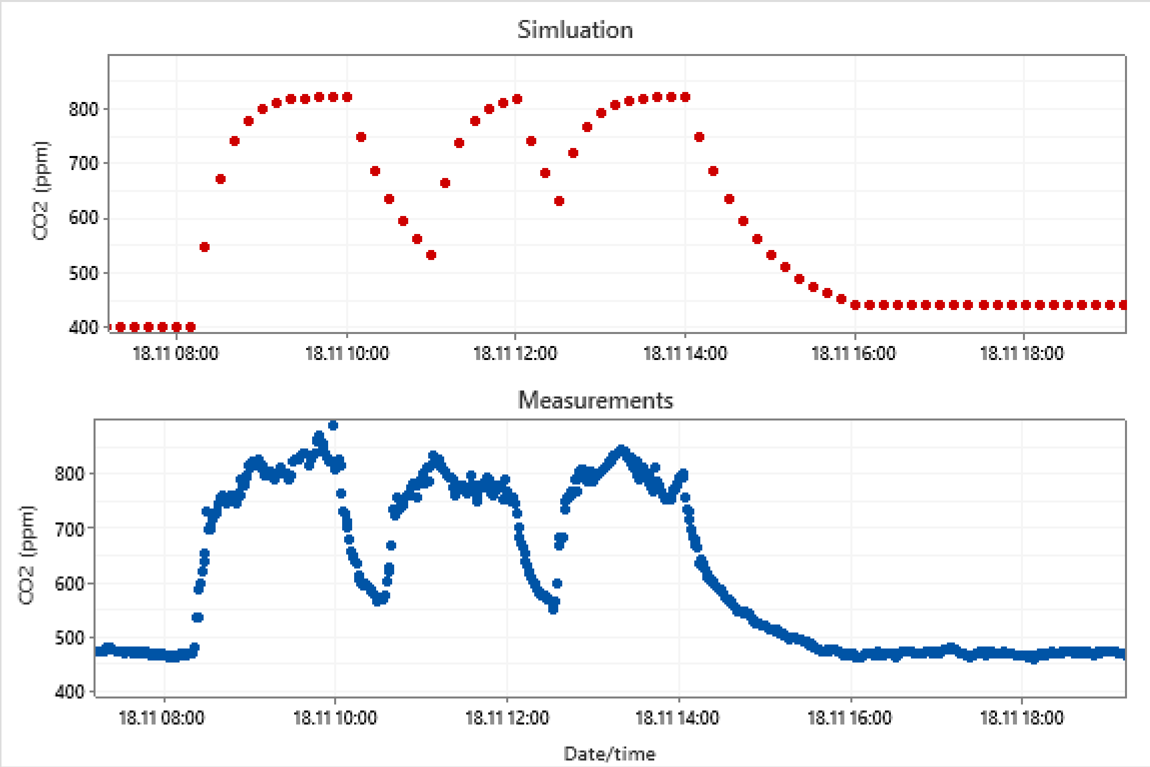

Figure 6.29 CO_2 one-day comparison

H_2O/humidity

It is important to mention that the simulation model does not simulate indoor air temperature and is therefore not able to simulate RH directly, only the SH. By using the method in 6.2.2, and assuming that the temperature in the classroom is 21 °C constantly, the resulting RH in the classroom will be 27 %, 31 %, and 38 % for a SH of 0.003, 0.004, and 0.005 kg/kg, respectively.

The weather file provided for these simulations do not use outdoor H_2O concentrations from 2019, but average data from Trondheim instead. Despite this, the excess humidity (difference between indoor and outdoor SH) is equal for the real measurement and the simulations. The indoor SH is closely connected to the outdoor SH when the ventilation is active, but not as much when the ventilation system is turned off, as shown in Figure 6.30.

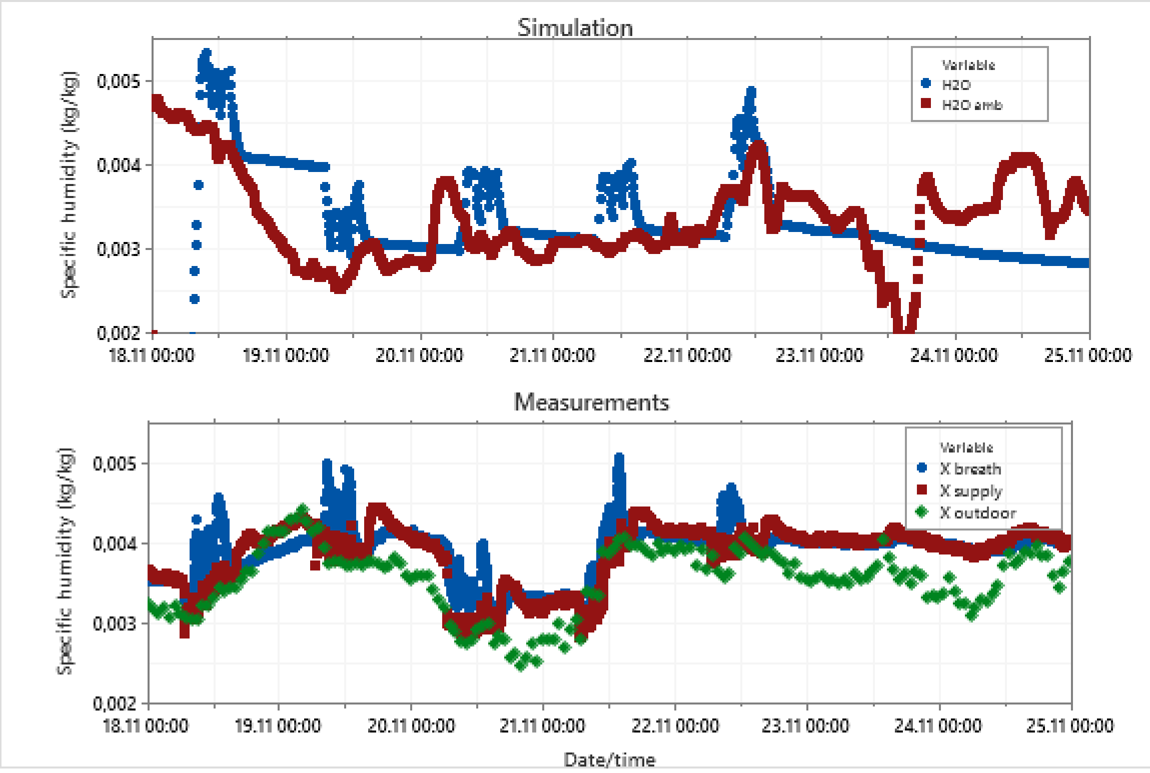

Figure 6.30 Indoor and outdoor specific humidity for simulation model and real measurements during the reference week

More detailed measurements, as presented in Figure 6.31, shows that the excess humidity when occupants are present is approximately the same for both the simulations and real measurements. The plotted days are not the same but are chosen because the outdoor humidity is stable during the day, which was not the case for most days during the reference week. These days are not the same date, but as the outdoor humidity is from a random year this does not matter. The total excess humidity during occupancy ranges between 0,0005 and 0,001 kg water/kg dry air for both plots.

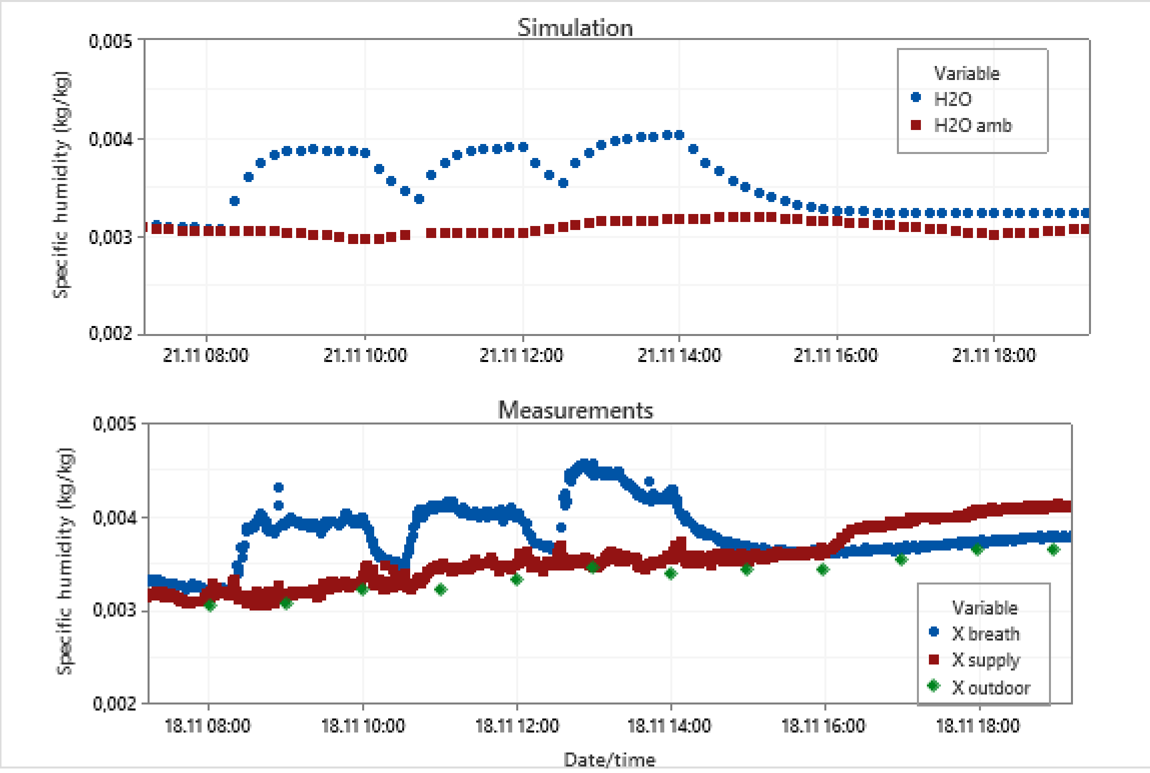

Figure 6.31 Zoomed specific humidity for simulation model and real measurements

Formaldehyde

Even though formaldehyde pollution is hard to implement properly in the CONTAM model, it is discussed here to illustrate how it is affected by the ventilation rate, compared to the real measurements. As discussed in chapter 6.3.1 the calibrated formaldehyde measurements reduce the measured concentrations of formaldehyde close to zero. In Figure 6.32 the calibration equation found in chapter 6.1.2 is used on both simulation and real measurements. For practical reasons, values below zero are assumed to be of no harm, but they are included in the figure to show that the sensors are providing realistic data, and that the simulation step response is equal to the real measurements.

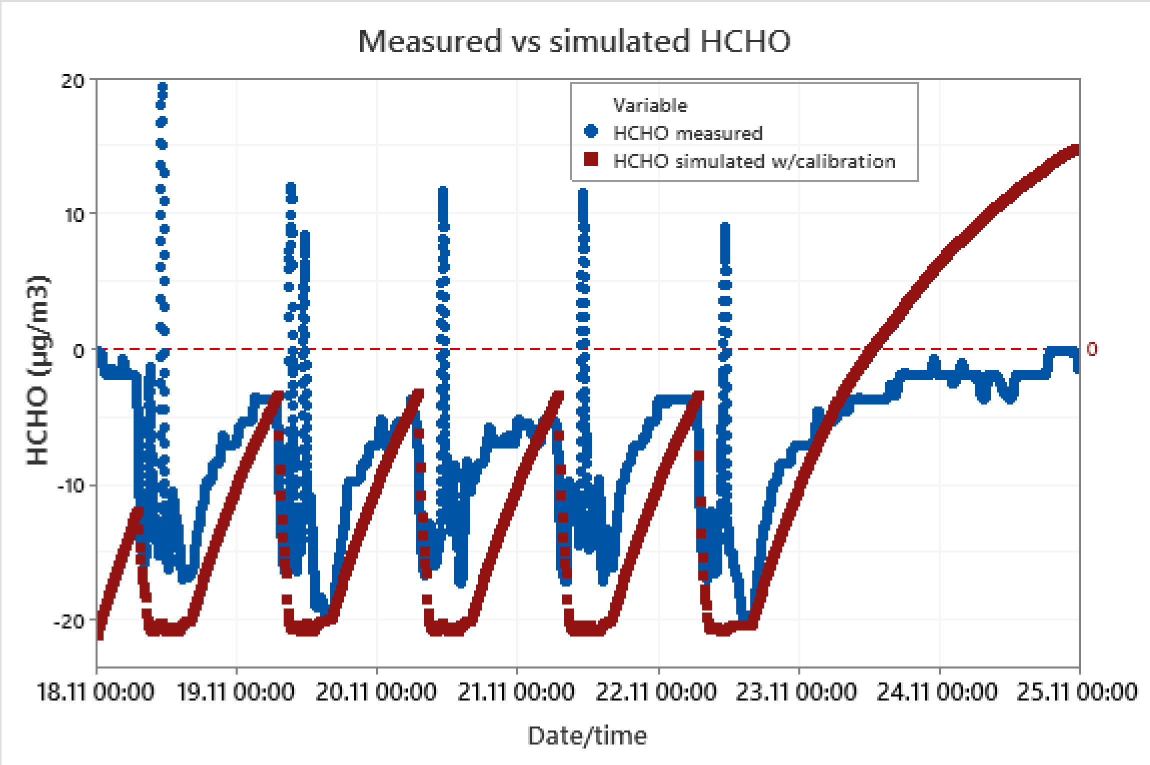

Figure 6.32 Calibrated formaldehyde concentrations during the reference week

The most important equality between the real measurements and simulation model, as shown in Figure 6.32, is that the formaldehyde is quickly removed when the ventilation system is active. This implies that the ventilation schedule used today does not require further adjustment to reduce the formaldehyde concentrations that occupants are exposed to.

The simulated values are calibrated using the same calibration equation to fit the measured concentrations. Even though the models give realistic results, the real concentrations rise quicker, and reach equilibrium at a lower concentration. It is hard to make the models fit without introducing more complex simulation tools, but as the measured formaldehyde concentrations in the classroom does not cause any health effects, this is not pursued any further.

6.4.2 Adapted ventilation rates

There are several different measures to reduce the energy use from the ventilation system and reducing the ventilation rate is one of these. When doing this, it is important to make sure that the IAQ parameters, as summarized in chapter 2.5, is still at acceptable levels. For this chapter, this involves making sure that CO_2 and RH in the classroom is within acceptable limits. Formaldehyde concentrations are assumed to reduce quickly after the ventilation system is started and is therefore not considered an IAQ risk for the classroom. The CONTAM model will be used to simulate how far the ventilation rate can be reduced without the IAQ parameters exceed their maximum limits. The base-case established in chapter 6.4.1 form the basis for comparison.

Three different cases are presented in the chapters below, each presenting an alternative VAV schedule. Case 1 and 2 does not reduce the base ventilation of 15 % as this limit is assumed to be the lower limit of operation for the classroom ventilation. Case 3 is a more theoretical case, and the base case is therefore reduced.

Case 1 – CO_2-adapted ventilation rates

First, the ventilation rate is adjusted until the CO_2 concentration reaches a stable level around 1000 ppm during occupancy, which is the proposed maximum limit. The resulting CO_2 concentration for ventilation rates at 40 % of nominal rate during full occupancy is presented in Figure 6.33.

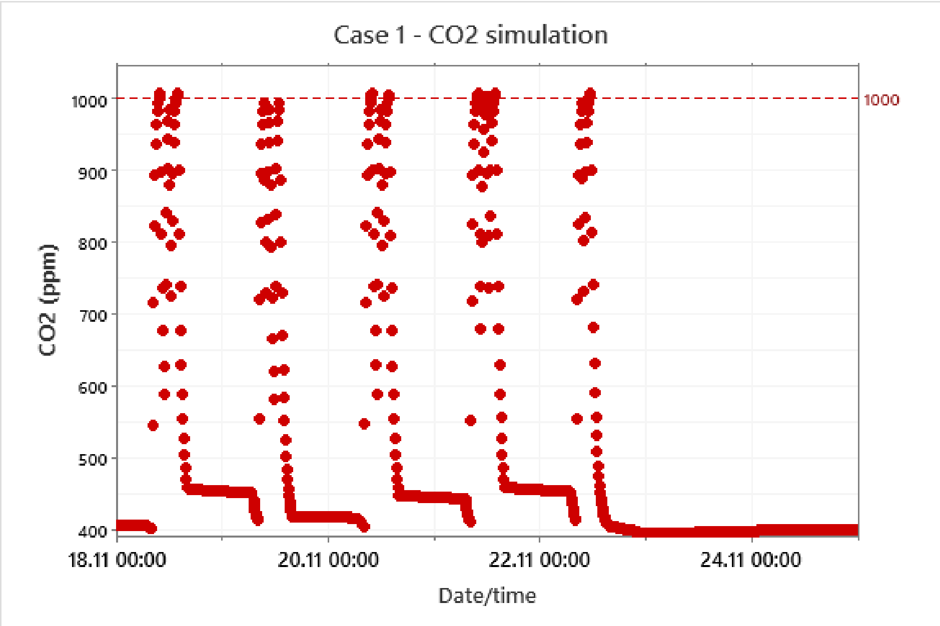

Figure 6.33 Simulated CO_2 concentrations for 40 % vent. rate

The simulations show that the CO_2 concentration slightly exceed the maximum limit, but not by far. It is important to consider that the limit of 1000 ppm is not a strict limit, and can be increased up to 2000 ppm before the IAQ is unacceptable, as described in chapter 2. The RH for the proposed ventilation rate is presented in Figure 6.34. The RH is presented for a longer period to include the outdoor humidity fluctuations.

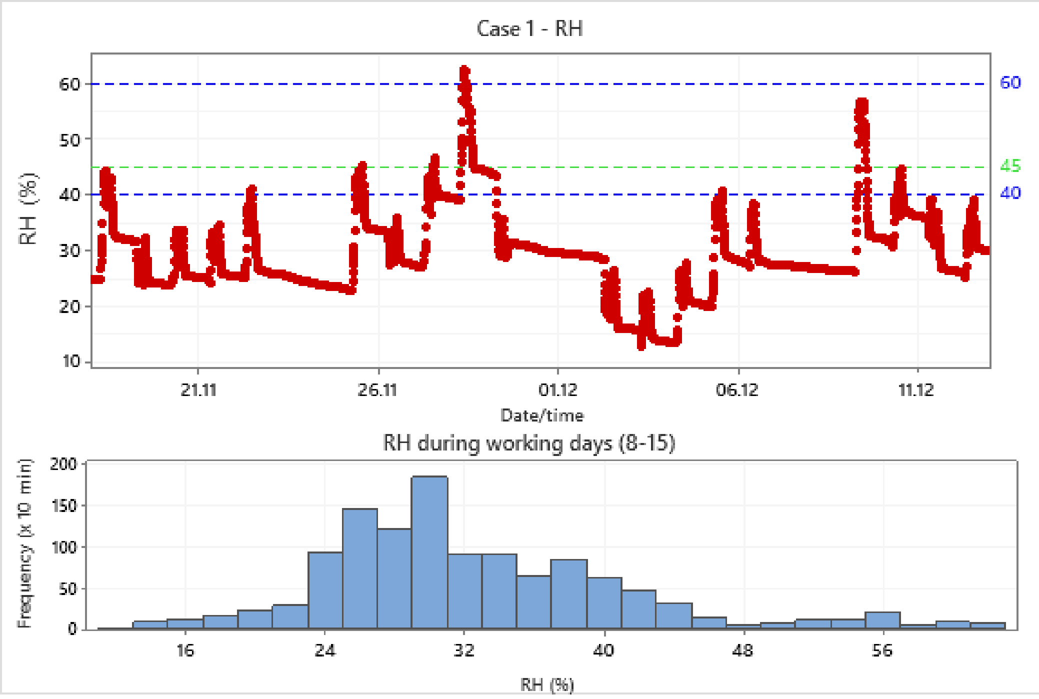

Figure 6.34 Simulated classroom RH for case 1

Each peak on the timeline of Figure 6.34 is the maximum peak during occupancy. The day with highest RH (28.11) has RH around 60% during occupancy. The excess humidity is the same for all days, but the outdoor humidity level fluctuates, causing elevated indoor RH some days. Despite this, many of the days are under the proposed limit of 40%, which implies that the ventilation rate is too high when the outdoor humidity is low. A ventilation rate of 40 % is therefore assumed adequate to keep the average IAQ at an acceptable level.

Case 2 – RH-adapted ventilation rates

As illustrated for case 1, the indoor RH is highly dependent on outdoor humidity. This means that it is hard to find one ventilation rate that can hold the indoor RH below a given point during winter. To assess how effectively the ventilation system removes humidity from the classroom, eight different ventilation rates are tested (20-55 % of nominal rate) to see how much excess humidity is in the classroom. Excess humidity is here defined as the difference between indoor and outdoor humidity.

Assuming that the indoor temperature is 21 °C, 45 % RH occurs at specific humidity 0.0058 kg/kg. This assumption is based on the formulas in chapter 6.2.2. When the excess humidity and outdoor humidity is known, it is possible to choose a ventilation rate that keep the indoor RH below 45 %. This method assumes that the only source of humidity is the occupants, and that little humidity is lost or removed in the air handling system.

Figure 6.35 and Figure 6.36 presents a summary of the simulations from CONTAM, testing how the ventilation rate affects the indoor excess humidity for two different operating days (Monday and Tuesday). Each panel represent the different ventilation rates, e.g. 0.20 = 20% during occupancy. The base ventilation during non-occupancy is 15 % for all tests.

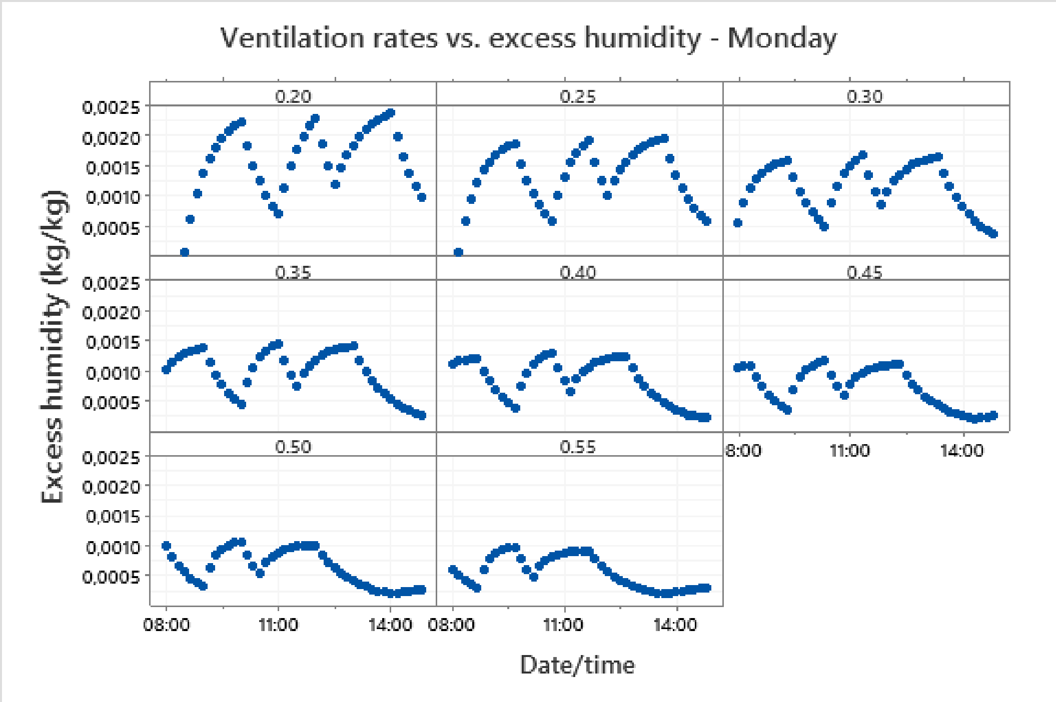

Figure 6.35 Excess humidity vs. ventilation rate. Simulated Monday schedule

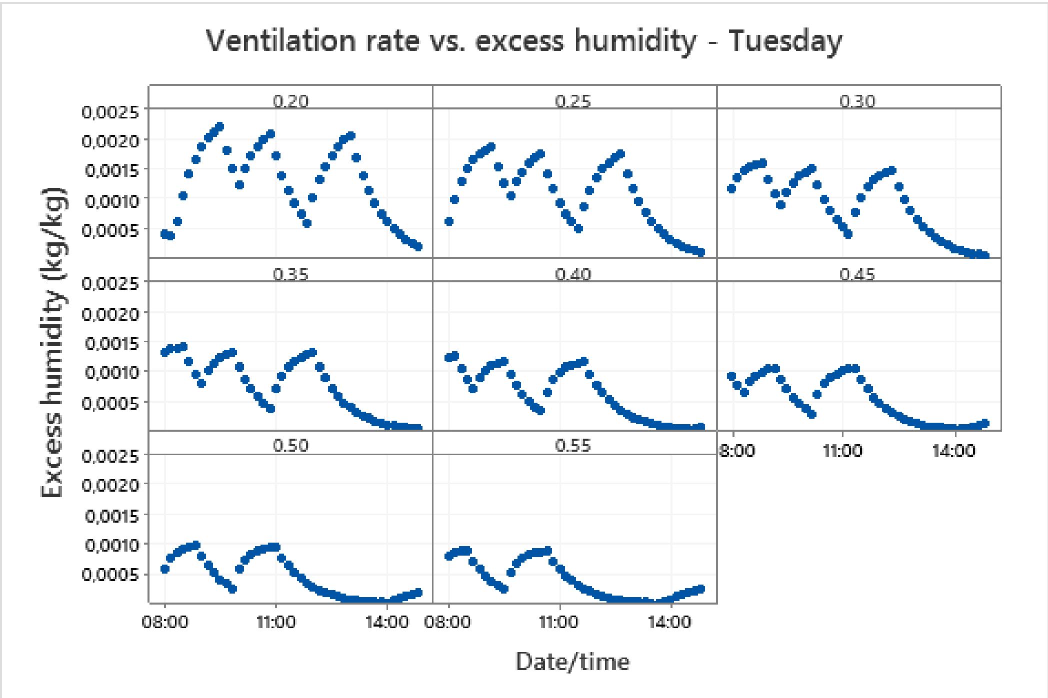

Figure 6.36 Excess humidity vs. ventilation rate. Simulated Tuesday schedule

The trend seems to be the same for both tested cases, and the excess humidity seems to be linearly decreasing with increasing ventilation rates. As mentioned, the excess humidity is dependent on the outdoor humidity, and Figure 6.37 shows real measurements from Trondheim in 2019.

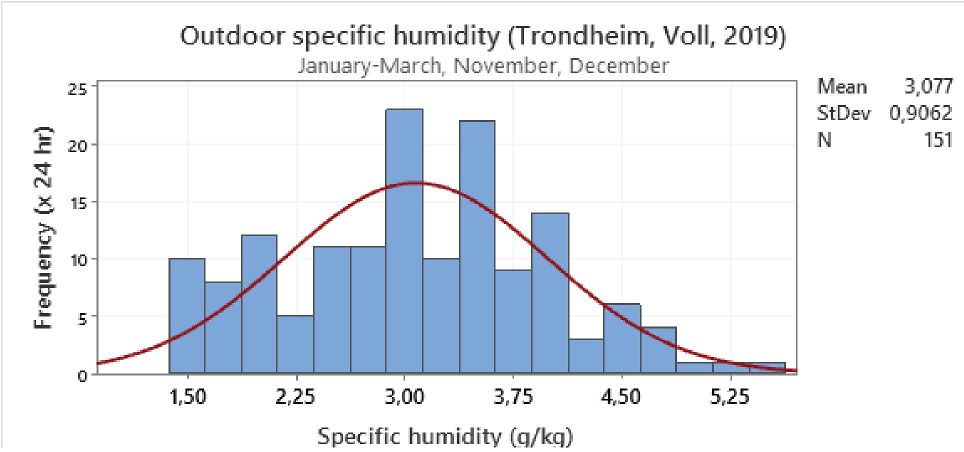

Figure 6.37 Outdoor specific humidity during winter 2019, Trondheim

The mean outdoor specific humidity in Trondheim during winter 2019 was 3.077 g water/kg air, as seen to the right in Figure 6.37. On an average day 20 % ventilation rate should be sufficient to obtain an acceptable IAQ and keep the RH below 45 %, given that indoor SH is only the sum of outdoor and indoor SH, and room temperature is 21 °C.

Statistically, according to the normal distribution shown in Figure 6.37, around 15 % of the winter days have outdoor humidity levels above 3.98 g/kg (70 % of measurements inside statistical mean + one standard deviation). This means that the excess humidity indoors should be less than $(5.80 - 3.98)\frac{g}{kg} = 1.8\frac{g}{kg}$ around 15 % of the operating days, which must be considered a normal scenario. To do this, the ventilation rate should be 35 % or higher.

The CO_2 concentrations corresponding to each ventilation rate scenario is presented in Figure 6.38 and Figure 6.39.

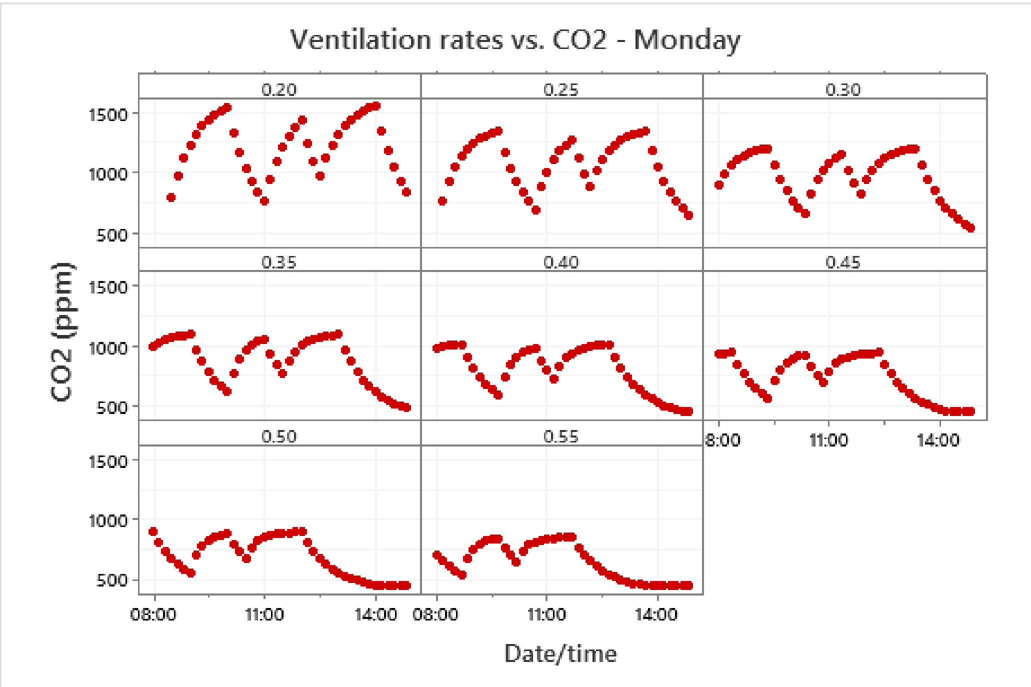

Figure 6.38 CO_2 vs. ventilation rate. Simulated Monday schedule

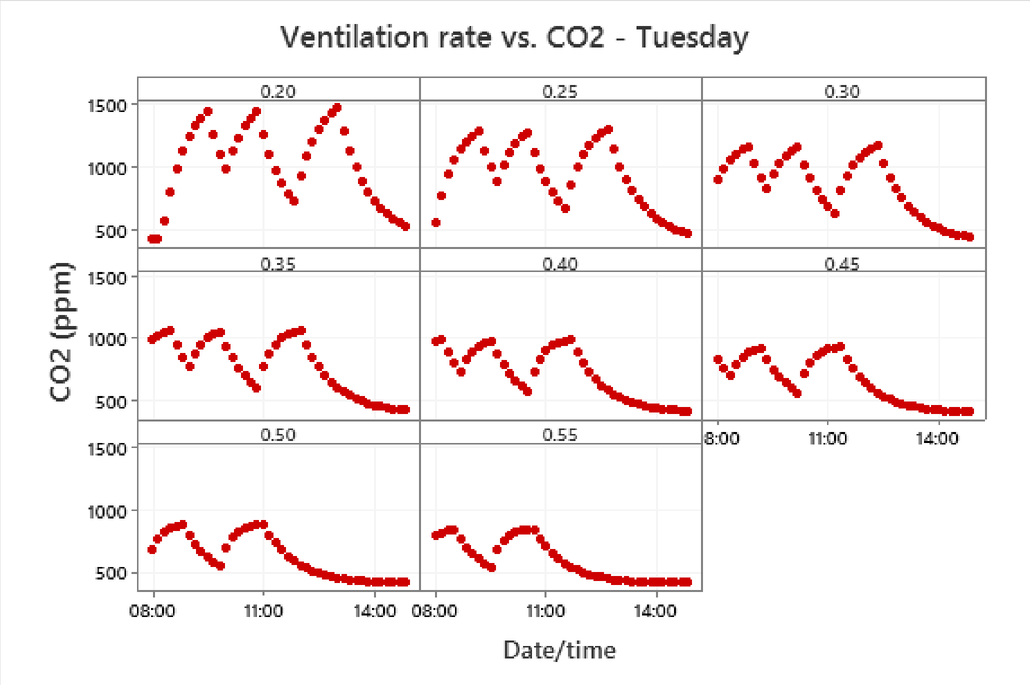

Figure 6.39 CO_2 vs. ventilation rate. Simulated Tuesday schedule

The figures above show that the ventilation rates of 20 % during occupancy causes CO_2 around 1500 ppm. This is quite high compared to normal guidelines, but still well below the CO_2 concentrations proven to have physiological effects on humans. If no other correlating pollutants are present, 1500 ppm CO_2 should not severely reduce IAQ.

Case 3 – Proposed ventilation rates from Health Vent project

As discussed in chapter 4.5 and Carrer et al. (2018), a health-based ventilation rate of 4 L/s per person has been proposed to remove human bio-effluents, if measures are taken to reduce pollution from other sources. This equals a ventilation rate of 108 L/s (27 persons in the classroom), which equals 389 m^3/h (23 % of nominal ventilation rate). Carrer et al. (2018) have done simulations on classrooms with 2 m^2 per person and has found that these ventilation rates can cause average CO_2 concentrations of 1500-1600 ppm during occupancy. The simulations also found that the proposed ventilation rate can cause problems with high relative humidity indoors some days.

The CONTAM simulations of this scenario show like for case 1 and 2, that the proposed ventilation rate can cause CO_2 concentrations up to 1600 ppm. An annual simulation show that this is the case year-round, due to the static simulation model. The annual RH is presented in Figure 6.40, and show that the RH during summer can get high, assumedly because the outdoor specific humidity rises. The simulations assume 23 °C indoor during summer, 21 °C rest of the year, a base ventilation of 5 %, and ventilation during occupancy of 23 %.

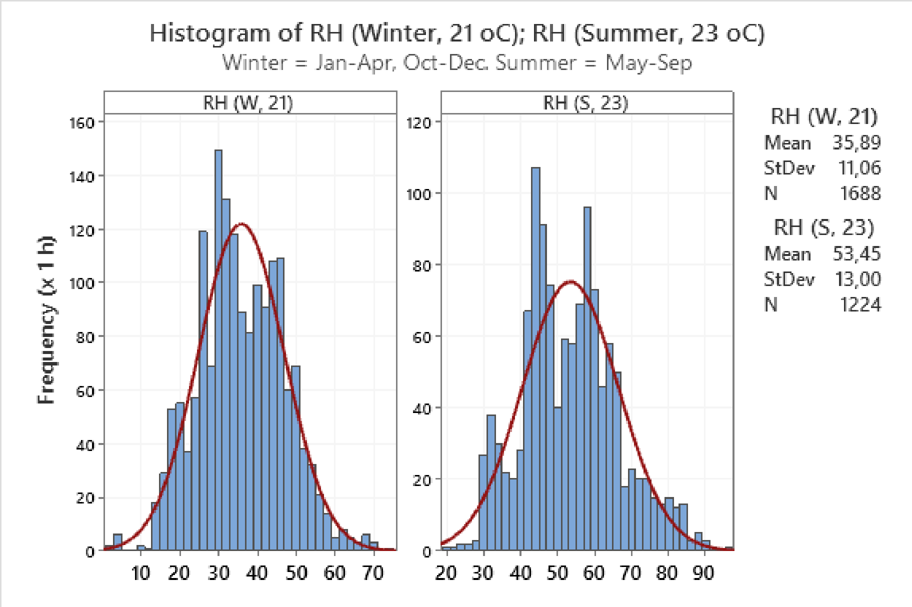

Figure 6.40 Simulated summer and winter indoor RH

If these simulations are correct, the RH when using the HealthVent ventilation rates should be expected to rise above 70 % regularly, which in turn can cause condensation on surfaces both during summer and winter. As the provided weather file is not qualitatively verified against the actual weather in Trondheim during the measurements, these results should be checked further. Despite this, the weather data is expected to be within realistic limits, and the results should be taken into consideration before suggesting the HealthVent ventilation rates for this classroom.

6.5 Potential energy savings

Chapter 6.3 and 6.4 have discussed the measurement results of the IAQ in the classroom, and how much the ventilation rates can be reduced without reducing IAQ. The measurements and simulations show that reducing the ventilation rate can increase IAQ, in addition to the original goal of saving energy. Energy use from ventilation systems are discussed in chapter 4.4, and is simplified for this thesis to only include the SFP factor. This factor tells how much energy the ventilation system uses to move one unit of ventilation air from intake to occupant to extract.

The SFP value is not measured for the ventilation system at the school where the measurements are taken, but the technical support from Trondheim Eiendom have informed that the system is designed to use a maximum of 1.5 kW/(m^3/s) at 100% load.

To establish a baseline for calculating energy savings, a reminder of the system data is provided:

- Designed maximum ventilation rate: 1750 m^3/h
    - Ventilation rates given in % is based on this design ventilation rate
- Setpoints during real-life operation: $V_{max} = 75\ \%$, $V_{min} = 15\ \%$
- Average measured ventilation rate during occupancy: 50-65 %. Based on the base-case established in chapter 6.4.1, following setpoints are used for the real classroom ventilation
    - Base ventilation = 15 %
    - Ventilation during occupancy = 58 %

To calculate energy for ventilation, the use time and ventilation power is needed. The ventilation power is equal to the SFP, and the use time is set based on the following assumptions:

- Ventilation system is turned on between 06:30-16:00 (9.5 h per day) and 47.5 h per week
- The classroom is occupied approximately 19 hours per week
- School year is 38 weeks in total
- Ventilation is not run during weekends or holidays

The energy used for ventilation is calculated from:

$$E_{vent} = V_{nominal} * SFP * T_{use} * v_{setpoint}$$

Where

$$E_{vent} = Energy\ use\ for\ ventilation\ [kWh]$$

$$V_{nominal} = Nominal\ (design) ventilation\ rate\ [m^3/s]$$

$$SFP = Specific\ fan\ power = 1.5 \left[\frac{kW}{m^3/s}\right]$$

$$T_{use} = Use\ time\ [hours]$$

$$v_{setpoint} = Ventilation\ setpoint\ [-]$$

These assumptions give an annual running time of 1083 hours at base ventilation and 722 hours at occupancy ventilation rate. This gives a total annual energy use for ventilation of:

$$\left[1750 \frac{m3}{h} * \frac{1}{3600} \frac{h}{s} * 1.5 \frac{kW}{m^3/s}\right] (0.58 * 722h + 0.15 * 1083) = 424\ kWh$$

The three different ventilation rates proposed in chapter 6.4.2 is presented in Table 6.5. The operating times and their respective ventilation rate is set using the statistical data of the RH levels, which should be kept below 60 %. All %-values are based on the installed ventilation effect of 1750 m^3/h.

Table 6.5 Suggested alternative ventilation rates and references

	Base ventilation	Occupancy ventilation	Comment
Base case	15 %	58 %	
Case 1	15 %	40 %	Obtain 1000 ppm CO_2 during occupancy
Case 2	15 %	35 % (613 h) 50 % (109 h)	35 % RH sufficient 85 % of the time
Case 3	5 %	23 % (307 h) 50 % (415 h)	415 h > 60 % RH during working day
TEK 17	2,5 %	49 % (857 m^3/h)	27 persons, 62 m^2
Real system	15 %	50-65 %	

All cases above are based on simulations in chapter 6.4, which in turn have several deficiencies. These ventilation rates, and their respective energy use, should therefore be considered a theoretical potential rather than a realistic potential. Based on the suggested ventilation rates in Table 6.5, the energy use and energy savings for each case is presented in Table 6.6.

Table 6.6 Reduced energy use for ventilation

	Annual energy use	Change
Base-case	424 kWh/year	--
Case 1	329 kWh/year	-22.4 %
Case 2	315 kWh/year	-25.7 %
Case 3	242 kWh/year	-42.9 %

7 Discussion

7.1 Suggested IAQ limits

Indoor air quality is a complex composition of chemical and physical pollutants that all have different effects on humans and the indoor environment. Indoor environment includes thermal environment, acoustic environment, physical environment, among others. IAQ is tightly connected with indoor environment but does not include all factors. This is important when setting maximum limits regarding for the different IAQ factors. To avoid misinterpretation and overreaction, it is also important to communicate them understandably. An example of this is VOC, which is measured by several commercial sensors. VOC in indoor environments have hundreds of different pollution sources, many of them harmless, and elevated concentrations is not equal to elevated health risks. If such sensor data is misinterpreted, countermeasures may have negative effects regarding IAQ. Some also think that cold air is fresh air, which is very often not the case.

When suggesting maximum exposure limits for indoor environments it is important to provide sufficient context. Is it a domestic or industrial environment? What is the ambient climate like? Is there any heavy traffic near? Is the room meant for lasting occupancy or just passing by? These questions are important to understand where the measures to improve IAQ must be applied. If the ambient air is polluted, it should be cleaned before it enters the occupancy zone, not after. The IAQ should also consider which pollutant sources are present indoors to take suitable actions to reduce or control their emissions. Pollutants such as odour and mould are hard to measure, and their source should be removed or controlled, instead of increasing ventilation when they cause problems.

When sufficient actions are taken to minimize pollutants present indoors, exposure limits for measurable pollutants can be determined. When setting these limits, there are several sources that provide suggestions based on thorough medical research. Examples of this are WHO (2010), FHI (2015), or similar national and international standards. Many of the proposed guidelines are given for pollutants that require costly equipment and knowledge to operate, like particulate matter, NO_2 and CO. Such pollutants are often measured by the municipality or government, who send out warnings when the measured levels are too high. These pollutants are most common outdoors, and if the outdoor levels are below threshold levels, indoor measures are not necessarily needed. An overall risk assessment should be conducted early, to find which outdoor pollutants are important to keep an eye on.

The remaining pollutants produced or emerging indoors that have adverse health effects should be measured. Examples of such are CO_2, relative humidity, formaldehyde, radon, etc. Some of these, like formaldehyde and radon are potent, and can cause serious health effects, while CO_2 is less dangerous. Some pollutants such as such as formaldehyde and PM are dangerous over time, while short peaks are not considered a risk. It is therefore important to consider both the potency of a pollutant, and its expected exposure time.

Generally, the existing air quality guidelines are sufficient for use in normal climates and for most non-industrial buildings. The exception is buildings that are close to heavy pollution sources such as industry or traffic. The guidelines, on the other hand, should not be used blindly to control the ventilation system in buildings. For example, if outdoor pollution levels are high, increasing ventilation will probably reduce IAQ. Design of health-based ventilation control should therefore be done based on the available sensor technology and reasonable control strategies.

7.2 Methods

7.2.1 Laboratory calibration setup

The test chamber worked satisfyingly, and is big enough to fit all the sensors, but small enough for the air to mix easily. The setup works best for tests that do not not require much equipment, like CO_2, but is harder to use during tests that require more equipment like large chipboards, candles, and the electric heater. It is valuable, though, that all sensors can be calibrated at the same time, not only because it saves a lot of work, but also that measurements for all sensors are taken under equal conditions, which makes it easier to produce comparable results. The test chamber has no integrated mixing fans, so an improvised mixing fan was used during the calibrations. The mixing fan should have been placed centrally in the chamber, but due to practical difficulties it was blowing towards one of the sides. Since the box is small, this is assumed not to have reduced the quality of the calibrations.

Since the calibrations was done during winter, the relative humidity in the laboratory was low, often below 30 %. This is not optimal, and the Greywolf sensor, for instance, recommend measurements to take place in environments with RH above 20 %. The RH in the lab occur in real buildings and the sensors should be able to handle it. Therefore, it is assumed not to have altered the quality of the calibration. For future calibrations it is advised to fulfil the recommended operating conditions.

Due to lack of time and resources, the calibration experiments were done only once, and not under different conditions. For example, the formaldehyde sensor is mainly tested for higher concentrations than it is subjected to during its intended conditions. Considering that many gas sensors does not work linearly, as discussed in chapter 3, this reduce the validity of the WZ-S calibration. The experiments also show that the sensors give varying results for equal experiments, and future calibrations should include several tests under different conditions, with many datapoints. This will increase the validity of the calibration curves and provide more insight in the sensor response. This is especially important for gas sensors that are proven to have non-linear and individual responses.

It is a setback that a reliable reference sensor was not available for all sensor parameters. If a reliable reference sensor for TVOC is available, it can give useful data on the relationship between formaldehyde and TVOC. Because the calibration of the WZ-S formaldehyde sensor reduces the formaldehyde measurement, it is not made a priority to acquire a reliable reference sensor.

7.2.2 Field measurement setup

Due to the COVIC-19 restrictions, field measurements could not be performed after the sensors was upgraded. Therefore, measurement data from the preparatory project work is used to assess the IAQ in the classroom. These measurements are described in chapter 5.4.

The measurements from the project is done from October to January, and no measurements are done during summer months. This should have been done to give a full review of the IAQ in the classroom, since summer measurements would have provided valuable data of how RH develops over the year. It is interesting to see whether the formaldehyde and VOC measurements increases with higher temperatures, and by how much.

The placement of the sensors in the classroom is not optimal. The breathing zone sensor is placed on a cabinet door, which may increase the measured CO_2 levels if occupants come too close. This is, on the other hand, also a problem for the BMS room sensor, which is placed right above an occupied desk. This can cause increased CO_2 measurements, which will increase the ventilation rate in the classroom higher than need be. Despite this, both sensors provides similar results, and does not seem to be heavily affected by their placement.

The Arduino sensor hardware was, during the measurements, not optimally designed. The main problem is the SCD30 temperature sensor that measure too high temperatures due to the internal heat from the sensor, and the reduced measurements when the air speed around the sensor increases. The latter is assumed to happen because the air movement removes the accumulated internal heat, but as this makes the sensor act nonlinear, it reduced the quality of the measurements. By upgrading the hardware to reduce the air speed inside the sensor should reduce the problem. The first problem was fixed in January 2020, when the SVM30 sensor was installed, and future measurements should therefore be of higher quality.

7.2.3 Simulation model

The simulation model is introduced to this thesis as part of the re-writing of the task objectives, following the COVID-19 restrictions. Therefore, several simplifications are made to the CONTAM simulation model. One is that the DCV ventilation is implemented as a scheduled VAV, due to limited time and knowledge regarding CONTAM. When occupants are present, the ventilation increase to a given setpoint, and the system runs at base ventilation when there are no occupants. This setup can reproduce the real measurements but do not work optimally to predict IAQ consequences for changed ventilation schedules. If a DCV controller is implemented in the simulation model, the actual energy use for ventilation based on alternative setpoints can be properly tested. For example, when running the ventilation system to keep the RH below 45 % during winter, the current solution can only show how many hours the RH is above 45 % and assume that the ventilation rate should be increased during this period.

The occupancy model in the simulations does not fully imitate the actual occupancy patterns, as both the occupancy and emission rates from occupants are implemented as static models. In real life the activity level and weekly schedule is more dynamic and vary randomly. Therefore, the results from the simulations should be considered valid for normal behaviour, but a safety margin should be included to account for changes in occupancy and activity from day to day.

The weather file used during the simulations is based on actual measurements from Trondheim, but do not include which year they are from. The outdoor humidity in the weather file fluctuate noticeably from day to day and is a bit higher than the recorded data from 2019. Therefore, the validity of the weather file is not confirmed, which reduced the quality of the results from all simulations assessing SH/RH. Despite this, the outdoor humidity data are within reasonable limits, and does not fully reduce the quality of the results.

7.3 Results

7.3.1 Sensor performance

One of the objectives of this thesis is to assess the performance of the Arduino sensor system that is developed. A method for assessing sensor performance is presented in chapter 3.1, which introduces sensitivity, selectivity and stability as three important factors. During the laboratory tests, five different sensor parameters are calibrated: CO_2, formaldehyde, temperature, RH and PM. The stability score cannot be assessed fully for any of the sensors since the experiments are only conducted once. If the stability is to be tested, several tests over a longer period is required. Identical experiments can also be done after a year or so, to check if and how the sensor response have changed.

Temperature/RH

The SHTC1 temperature and RH sensor generally show good results, with high R^2 values and low deviations in the residual plots (high sensitivity score). However, the temperature sensors have a slightly different response during the two different tests, which reduce the sensitivity-score some. Since both sensors are physical sensors, the selectivity score is not as relevant for these as for the gas sensors.

CO_2

The CO_2 sensor show R^2 values close to 100 % and have little offset in the residual plots. However, the tests were only conducted once, and should be repeated under different conditions to compare the response. The sensor did not seem to be offset by other parameters and scores highly on analyte selectivity.

Formaldehyde

The formaldehyde sensor seems to amplify the sensor output more at higher concentrations but keeping the response linear. This is, by definition, good sensor sensitivity. However, the sensor changed characteristic and had different response patterns for different tests. This proves that the sensor reacts cross-sensitive analytes, which can alter both the calibration results and classroom measurements. The sensor output also fluctuate when measuring frequently but using 30-minute average measurements improves the results. The R^2 values is around 60 %, and the residual plots show an offset of $\pm$ 50 μg/m^3, which is very high. The calibration equation also reduces the actual measurements significantly, which reduces most of the measured concentrations close to zero. This can either mean that formaldehyde concentration in the classroom environment is not a problem, or that the sensor calibration is incorrect.

PM

The particulate matter sensor does not provide useful results. The sensor producer claims that the sensor can differ between four different PM categories, but output data from the experiments show that all output parameters are equal, meaning they measure the same pollutant. Since the sensor producer claims that the measuring uncertainty increase exponentially for increased particle sizes, the sensor is assumed to measure small particles rather than coarse particles (Gram, 2019). The experiments are therefore done with a $PM_{2.5}$ sensor as reference. Two different experiments are done, but these show opposite reactions, which makes the sensors unreliable both regarding sensitivity and selectivity. Further tests should be done to find out how the sensor is working, and which particles it reacts to.

The calibrations show that general cautions should be taken when using the sensors, which is well in line with the finds regarding low-cost sensors in chapter 3. One is that even though the sensors claim to be precalibrated and tested, the claimed performance of the sensors should not be taken for granted. Second is that most sensors seem to perform differently under varying ambient conditions. The sensors should therefore be tested and calibrated in different environments, especially in the environment equal to where they are intended to operate normally.

7.3.2 Sensor correction classroom measurements

This correction procedure had to be used because of the rewriting of the task, but the method may be useful for further use. By having two sensors in the same zone, both sensors can be regularly compared to each other to see whether their performance have reduced or changed over time. This method should not have been used for two reasons. One is that the existing sensor is not known to be calibrated. Second is that the sensor is not optimally placed, as mentioned earlier. The sensor is installed approximately 1 m above an occupied desk, which can cause the measurements to report too high concentrations.

7.3.3 Classroom measurements and air quality

Chapter 6.3 present the Arduino measurements from the classroom, using the calibration curves found in chapter 6.1 and 6.2. The measurements are done during winter and show that the CO_2 levels in the classroom are approximately 850 ppm during occupancy and that the RH levels generally are lower than the minimum limit. These results underline that the ventilation rates in the classroom is oversized, and not seasonally adapted. The low RH levels during winter can cause physical discomfort, reduced efficiency for the students, and possibly increase the spread of virus and bacteria. In theory, the ventilation rate can easily be reduced, but as discussed in chapter 4.3, all components in the systems have upper and lower bounds for where they operate correctly. Control measurements to find the actual upper and lower bounds for the ventilation system should be done. Measurements during summer should also be done before concluding whether the ventilation rates are generally too high or not. If they are not too high during summer, the setpoints should be changed from summer to winter. With the current solution, the IAQ in the classroom is reduced, and the ventilation system uses more energy than needed.

The data received from Trondheim Eiendom regarding ventilation rate is only the %-opening of the DCV damper, not the real ventilation rate. Therefore, the ventilation rate should be controlled to check if the damper opening measurements are correctly connected with the actual airflow. If the measurements are not, the ventilation rate might be higher than intended, which can lead to both increased energy use and lower RH because of the overventilation.

Ventilation systems are often dimensioned using national and international standards, as discussed in chapter 4.5. The ventilation system in the assessed classroom is overdimensioned compared to the TEK17 demands, which are only 49 % of the nominal ventilation rate. The standards do not have any seasonal or regional adaptations, and the ventilation system is running at the same algorithm summer and winter. This results in very low RH during winter, which can easily be solved by reducing the ventilation rate. This will not only increase IAQ but can also reduce energy for ventilation significantly. Future standards regarding ventilation and health should consider varying ambient conditions, climate, and other relevant factors better.

Ventilation is not the only option for controlling IAQ. Primary source control should be prioritized before assessing the need for ventilation. In the assessed classroom, several measures are taken to remove the primary pollution sources, like moving the wardrobe and garbage outside the classroom, and not using soaps and detergents for cleaning. This implies that the CO_2 level probably can exceed 1000 ppm without major risk of noticeably reducing the general IAQ. For buildings where static pollutants dominate, and there is less occupant load, this may not be the case.

It is important to remember that there are several parameters that are not measured. Mould spores are an example of this, whose health effects are discussed in chapter 2.4. Mould spores can be measured by taking manual air and surface samples that needs analyzation in a laboratory. Such samples can be taken once per year, to check if there are any development or increase of mould. Pollutants originating outdoors, like NO_2, NOx, CO, and PM is not further analysed as part of this thesis but should be taken into consideration by the building owners when assessing the air quality in the school. The assessment of IAQ in this thesis is, therefore, limited to the parameters that is possible to measure with the Arduino sensor.

7.3.4 Simulation results

The simulation results can be split into two parts, one being the imitation of the real measurements, and the second being the simulation of IAQ when changes are done to the ventilation rate. The first part shows good results both regarding CO_2 concentration in the classroom and H_2O concentrations. Formaldehyde is also simulated, but as the calibrations reduces the real measurements, this is not assessed any further than the base case. Both the real measurements and simulations show that the formaldehyde is removed quickly when the ventilation is started and is not assumed to have adverse health effects for the occupants in the classroom. Because of the simplified ventilation schedule method, the results from the second part is not as strong as they should be, since they only use statistics to determine how good the ventilation schedule perform. By implementing a more dynamic DCV controller, the results will be more realistic. Despite this, the simulations give valuable insight regarding the importance of measuring RH in the ventilated zone.

The proposed ventilation rates in chapter 6.4 should either obtain or improve the IAQ, while reducing the energy use for ventilation. The estimates show that the energy use can be reduced by approximately 22 % compared to the base case, only by increasing the CO_2 setpoint for the ventilation system as shown for case 1. Case 3 show that further reductions can be made by using health-based ventilation rates proposed by a European research project, but that this should not be done without controlling the RH in the ventilated zone. The RH is extra important for buildings in cold climates, as condensation will occur earlier on colder surfaces.

When estimating the energy saving from reducing the ventilation rate, a flat SFP value of 1,5 $kW/(m^3/s)$ is assumed, based on the information from Trondheim Eiendom. A more realistic scenario is that the SFP is reduced when the total ventilation rate in the ventilation system is reduced. Because there are no available measurements to confirm this, it is not taken into consideration. Since ventilation system is assumed to be oversized, and the suggestion from this thesis is to further reduce the ventilation rate, the energy efficiency might be reduced if the AHUs are run outside their optimal area, as described in chapter 4.3. The amplitude of each of these effects are not known, and is not implemented in the SFP calculations.

7.4 Review of research questions

Several research questions was raised in chapter 1.2, whose goal is to focus the research of the thesis on a set of priority areas. The questions are cited and answered below:

What type of pollutants can be found in a normal indoor environment, and which of these have adverse effects on a healthy indoor environment? Which of these are most relevant for controlling a ventilation system?

IAQ is a complex and dynamic composition of gases and particles. The occurrence of these depends on many factors, among others, which building materials are used, building maintenance, number and activity of occupants, geography, outdoor air emission sources, and more. The composition is also changing, with new products and refurbishing taking place frequently. Therefore, it is hard to generalise one set of pollutants that is important to monitor, but sources like WHO and FHI provide a reliable starting point.

For Norwegian schools, the following pollutants are identified as important to measure: CO_2, RH, formaldehyde, VOC, and PM. All these pollutants are normally found in Norwegian indoor environments, and future research should determine whether the normally occurring concentrations have adverse health effects, and which are most relevant for controlling a ventilation system.

Is the performance of the sensors, evaluated by their sensitivity, stability, and selectivity, acceptable for use in a ventilation control system? Which limitations apply?

The stability of the sensors requires long-term tests under equal conditions and cannot be done as part of this thesis. The temperature, CO_2, and RH sensors perform satisfyingly both regarding sensitivity and stability, meaning they give linear output and does not react on cross-sensitivities. It is advised to make calibration curves based on several different calibration tests, as the sensors react different under changing ambient conditions. The temperature sensor should not be placed directly in an airflow unless the casing is designed to reduce the air velocity over the temperature sensor.

The formaldehyde and PM sensors do not perform acceptably for use in a ventilation system. Both sensors score low on selectivity, which means they react to other pollutants than intended. The test of the PM gave varying results, and the sensitivity cannot be assessed. The formaldehyde sensor provides reasonable data regarding sensitivity, but the sensor has low selectivity and is not recommended to use for ventilation control at this point. Due to the lack of reliable reference sensors, the new SGP30 TVOC sensor was not tested.

Can the developed Arduino system be used to assess the IAQ and ventilation control in a real classroom?

Yes, the Arduino sensor system can provide extra information that can be used to do an overall assessment of the classroom IAQ. The measurements in the classroom in November 2019 show that the RH values are generally lower than the recommendations during winter. Low RH have both short and long-term effects like sensory irritation, reduced efficiency, or increased spread of bacteria and viruses. The proposed solution is to reduce the ventilation rate, especially during winter when the outdoor humidity is low. Simulations show that it may be possible to save up to 25 % of the energy used for ventilation by improving the RH levels indoor. A low-cost solution is to include RH measurements to the ventilation control system and include this as a controlling parameter.

The calibration of the formaldehyde sensor reduced formaldehyde concentrations significantly. This means, contrary to earlier assumptions, that formaldehyde in the measured classroom is not assumed to appear in concentrations that may have adverse health effects. Further research should check for correlations between formaldehyde and TVOC, as they are both considered volatile organic compounds (VOC).

Is it possible to make an IAQ simulation model using CONTAM, that imitate a real classroom? Can this model be used to predict how changes in ventilation rate affect IAQ?

The developed CONTAM model can replicate the real measurements in a good way, both regarding CO_2, SH, and ventilation rates. The model can only simulate SH indoor and outdoor, due to missing temperature data in the simulated zones. By assuming constant indoor/outdoor temperature, the RH can be calculated. Due to lack of time and resources, the model only used a simplified VAV version, and do not implement a DCV controller. The differences between model and reality may be caused by the restrictions mentioned earlier, or that the CONTAM model is an idealised model. For the model to correctly simulate the H_2O and RH levels in the classroom, the weather file should be close to the actual ambient conditions.

By adjusting the ventilation rates in the CONTAM model, it is possible to simulate how changes in ventilation rate affect the indoor air parameters. By manually changing the ventilation rate, it is possible to tune the relationship between CO_2, RH, and ventilation rate. This method can be used as a coarse method to predict how changes in ventilation rate affect some IAQ parameters, and further measurements should be done to compare with the CONTAM model. Further work to implement a DCV controlled is advised, to decrease the uncertainty in the predictions and provide more exact simulation results.

How big energy savings can be acquired by reducing the ventilation rate in a classroom using DCV, without reducing IAQ?

Three different scenarios for reduced ventilation rates are tested. The first control the CO_2 during occupancy at 1000 ppm, the second control RH below limit values, and the third use health-based ventilation rates proposed by Carrer et al. (2018). A simplified calculation using a constant SFP showed ventilation energy reductions of 22.4 %, 25.7 % and 42.9 %, respectively. The first case is assumed to be most realistic. The second case have uncertainties regarding run time and should be simulated using a DCV controller to reduce the inaccuracies. The third case show elevated RH values indoors, and the inaccuracies in the proposed ventilation schedule are high. Future research should implement a functional DCV controller, as this will further strengthen the IAQ measurement and energy reduction estimates.

The results from the simulations do not fully consider the limitations in the ventilation system and its components. It is assumed that the real ventilation system cannot regulate the ventilation rate between 0-100 % without reducing the ventilation efficiency. Therefore, it is important that future research establish which limits apply for regulation of the ventilation rate, both in the classroom and the whole school. The simulation results are made with the assumption that the occupant emissions are far greater than the static emissions, and that the room is fully mixed. The results may not be valid for rooms and buildings that does not match this description.

8 Conclusions

The objective of this master thesis is to test the reliability of an Arduino based sensor and use the sensor to measure and assess IAQ in a realistic environment. The measurements should be used to improve an existing ventilation strategy, with the final goal being an improved IAQ with minimum use of energy. The results from the research in this master thesis show that there is a potential for using low-cost sensors and IoT technology to achieve a holistic approach to IAQ, and improve IAQ while saving energy.

A set of pollutants with adverse health effects is identified through a literature review, and the most important pollutants to measure are CO_2, temperature, RH, formaldehyde, TVOC and PM. Maximum limits of exposure are identified for formaldehyde (100 µg/m^3) and $PM_{2.5}$ (15 µg/m^3 24-hour average, and 8 µg/m^3 one year average). No upper limit is proposed for TVOC, while CO_2, temperature and RH have varying limits. Reliable sources like WHO and FHI both include these as important pollutions, and future research may use these sources as a complete guideline.

The Arduino sensor calibrations show that the SHTC1 T/RH and SCD30 CO_2 sensors perform satisfyingly regarding selectivity and sensitivity, and can be used for IAQ measurements of temperature, RH and CO_2. The WZ-S formaldehyde sensors have adequate sensitivity but score low on selectivity and should be used in real measurements under supervision only. The SPS30 PM sensor scores low on both parameters and should not be used for real measurements until otherwise is proven. Low-cost sensors have the potential of improving IAQ knowledge in several areas but should only be used if thorough calibrations and tests are done to assess their performance.

Measurements were done in a real classroom during winter 2019, while new measurements after sensor calibrations could not be completed in 2020 due to COVID-19 restrictions. The classroom generally has good IAQ with formaldehyde concentrations close to zero, and CO_2 concentrations during occupancy around 850 ppm. However, the RH is very low in the breathing air, and never exceeds the proposed lower limit of 30 % between November 13 and December 13. This can cause a series of adverse health effects, including dry eyes and throat, reduced concentration, and increased spread of viruses and influenza. These results indicate that CO_2 as a single control parameter for DCV is not sufficient to ensure healthy IAQ.

Low RH values are often a consequence of too high ventilation rates. To investigate how alternative ventilation rates impact IAQ, a simplified CONTAM simulation model of the classroom is developed. .The model can simulate CO_2, formaldehyde, SH, and ventilation rates in a realistic matter. Three different cases of alternative ventilation rates are tested. The first case shows that a 30 % reduction of ventilation rate during occupancy can keep the CO_2 concentration around 1000 ppm, while the RH levels are within proposed limits. The second case is DCV controlled by RH, but due to the varying outdoor SH, the simplified CONTAM model makes it hard to determine the resulting ventilation rates. The last case utilizes a health-based ventilation rate of 4 L/s per person, proposed by a European research project, but the simulations show that the maximum RH limit may be exceeded frequently. Hence, the ventilation rate must be increased above the fixed rate in some periods to avoid too high RH.

The energy consumption for ventilation is calculated by assuming a constant SFP. The estimated energy savings for the three simulated cases compared to the current control is 22.4 %, 25.7 % and 42.9 %, respectively. For the two latter cases, increased ventilation rates to ensure RH levels below the maximum proposed limit are included in energy consumption calculations.

The results clearly show that there is a potential for increasing the IAQ while reducing energy use. However, these results are bound with uncertainties that need further research to falsify or strengthen the conclusions.

9 Further work

The simulation model needs to be further developed to include a functional DCV controller, to properly test how the alternative setpoints affects the ventilation rate over time. To increase the accuracy of the simulation results, further work to improve the occupancy model, weather file, formaldehyde measurements, or other relevant pollutants are advised.

Future research should focus on how a physical system react to changes in ventilation rate compared to the simulation model. If the systems do not react similarly, the model should be improved, or other simulation software should be considered. To correctly assess the IAQ-ventilation relationship in the classroom, control measurements to verify the estimated ventilation rates from the BMS is advised. The three proposed cases for reduced ventilation rates do not consider the limitations of the ventilation system in the classroom. These need to be established to determine if the proposed limit is practically achievable or not. It is advised to consider adding more IoT sensors to get further information regarding window and door openings, occupancy, or other factors that may impact the IAQ or ventilation system.

To properly assess the IAQ in the classroom, the sensors need to be reliable. All sensors should be tested further to get calibration equations that are valid for the whole operating area, and under varying conditions. The TVOC, formaldehyde, and PM sensor are proven not to provide reliable data and should be thoroughly tested to determine if they are adequate to use at all. Over the last few years, several commercial low-cost gas sensors and IAQ monitors have emerged, and research to compare these sensors with the Arduino sensors from this thesis may be tested. The system hardware is still rather primitive, and small changes to the casing can e.g. improve the temperature measurements in the supply air duct.

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Appendices

Appendix A: Sensor datasheets

Appendix B: Risk assessment

Appendix A: Sensor datasheets

A1: Sensirion SCD30 datasheet

A2: Sensirion SVM30 datasheet

A3: Sensirion SPS30 datasheet

A4: Dart Sensors WZ-S datasheet

A5: Graywolf FM-801 datasheet

A6: Pegasor AQ Indoor datasheet

Datasheet Sensirion SCD30 Sensor Module

CO_2, humidity, and temperature sensor

- NDIR CO_2 sensor technology
- Integrated temperature and humidity sensor
- Best performance-to-price ratio
- Dual-channel detection for superior stability
- Small form factor: 35 mm x 23 mm x 7 mm
- Measurement range: 400 ppm – 10.000 ppm
- Accuracy: ±(30 ppm + 3%)
- Current consumption: 19 mA @ 1 meas. per 2 s.
- Fully calibrated and linearized
- Digital interface UART or I²C

Product Summary
CMOSens® Technology for IR detection enables carbon dioxide measurements of the highest accuracy at a competitive price.
Along with the NDIR measurement technology for detecting CO_2 comes a best-in-class Sensirion humidity and temperature sensor integrated on the very same sensor module. Ambient humidity and temperature can be measured by Sensirion's algorithm expertise through modelling and compensating of external heat sources without the need of any additional components. The very small module height allows easy integration into different applications.
Carbon Dioxide is a key indicator for indoor air quality. Thanks to new energy standards and better insulation, houses have become increasingly energy-efficient, but the air quality can deteriorate rapidly. Active ventilation is needed to maintain a comfortable and healthy indoor environment and improve the well-being and productivity of the inhabitants. Sensirion sensor solutions offer an accurate and stable monitoring of CO_2 in the air, as well as temperature and humidity. This enables our customers to develop new solutions that increase energy efficiency and simultaneously support the well-being of everyone.

Content

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1 Sensor Specifications[1]

CO_2 Sensor Specifications

Parameter	Conditions	Value
CO_2 measurement range	I2C, UART PWM	0 – 40'000 ppm 0 – 5'000 ppm
Accuracy[2]	400 ppm – 10'000 ppm	± (30 ppm + 3%MV)
Repeatability[3]	400 ppm – 10'000 ppm	± 10 ppm
Temperature stability[4]	T = 0 … 50°C	± 2.5 ppm / °C
Response time[5]	$\tau_{63\%}$	20 s
Accuracy drift over lifetime[6]	400 ppm – 10'000 ppm ASC field-calibration algorithm activated and SCD30 in environment allowing for ASC, or FRC field-calibration algorithm applied.	± 50 ppm

Table 1: SCD30 CO_2 sensor specifications

Humidity Sensor Specifications[7]

Parameter	Conditions	Value
Humidity measurement range	-	0 %RH – 100 %RH
Accuracy[8]	25°C, 0 – 100 %RH	± 3 %RH
Repeatability[3]	-	± 0.1 %RH
Response time[5]	$\tau_{63\%}$	8 s
Accuracy drift	-	< 0.25 %RH / year

Table 2: SCD30 humidity sensor specifications

Temperature Sensor Specifications[7]

Parameter	Conditions	Value
Temperature measurement range[9]	-	- 40°C – 70°C
Accuracy[8]	0 – 50°C	± (0.4°C + 0.023 × (T [°C] – 25°C))
Repeatability[3]	-	± 0.1°C
Response time[5]	$\tau_{63\%}$	> 10 s
Accuracy drift	-	< 0.03 °C / year

Table 3: SCD30 temperature sensor specifications

[1] Default conditions of T = 25°C, humidity = 50 %RH, p = 1013 mbar, V_{DD} = 3.3 V, continuous measurement mode with measurement rate = 2 s apply to values listed in the tables, unless otherwise stated.
[2] Deviation to a high-precision reference in the calibrated range (400 – 10'000 ppm) of the SCD30. Accuracy is fulfilled by > 90% of the sensors after calibration. Rough handling, shipping and soldering reduces the accuracy of the sensor. Full accuracy is restored with FRC or ASC recalibration features. Accuracy is based on tests with gas mixtures having a tolerance of ± 1.5%.
[3] RMS error of consecutive measurements at constant conditions. Repeatability is fulfilled by > 90% of the sensors.
[4] Average slope of CO_2 accuracy when changing temperature, valid at 400 ppm. Fulfilled by > 90% of the sensors after calibration.
[5] Time for achieving 63% of a respective step function. Response time depends on design-in, heat exchange and environment of the sensor in the final application.
[6] CO_2 concentrations < 400 ppm may result in sensor drifts when ASC is activated. For proper function of ASC field-calibration algorithm SCD30 has to be exposed to air with CO_2 concentration 400 ppm regularly.
[7] Design-in of the SCD30 in final application and the environment impacts the accuracy of the RH/T sensor. Heat sources have to be considered for optimal performance. Please use integrated on-board RH/T compensation algorithm to account for the actual design-in.
[8] Deviation to a high-precision reference. Accuracy is fulfilled by > 90% of the sensors after calibration.
[9] RH/T sensor component is capable of measuring up to T = 120°C. Measuring at T > 70°C might result in permanent damage of the sensor.

Electrical Specifications

Parameter	Conditions	Value
Average current[10]	Update interval 2 s	19 mA
Max. current	During measurement	75 mA
DC supply voltage (Vdd_{min} - Vdd_{max})	Min. and max. criteria to operate SCD30	3.3 V – 5.5 V
Interface	-	UART (Modbus Point to Point; TTL Logic), PWM and I^2C
Input high level voltage (V_{IH}) I2C	Min. and max. criteria to operate SCD30	1.75 V - 3.0 V
Input high level voltage (V_{IH}) Modbus	Min. and max. criteria to operate SCD30	1.75 V – 5.5 V
Input low level voltage (V_{IL}) I2C/Modbus	Min. and max. criteria to operate SCD30	- 0.3 V – 0.9 V
Output low level voltage (V_{OL}) I2C/Modbus	I_{IO} = +8 mA, Max. criteria	0.4 V
Output high level voltage (V_{OH}) I2C/Modbus	I_{IO} = -6 mA, Min. criteria	2.4 V

Table 4 SCD30 electrical specifications

Operation Conditions, Lifetime and Maximum Ratings

Parameter	Conditions	Value
Temperature operating conditions	Valid for CO_2 sensor.	0 – 50°C
Humidity operating conditions	Non-condensing. Valid for CO_2 sensor.	0 – 95 %RH
DC supply voltage	Exceeding specified range will result in damage of the sensor.	- 0.3 V – 6.0V
Voltage to pull up selector-pin	Max criteria	4.0 V
Voltage to pull up selector-pin	Min criteria	1.75 V
Storage temperature conditions	Exceeding specified range will result in damage of the sensor.	- 40°C – 70°C
Maintenance Interval	Maintenance free when ASC field-calibration algorithm[11] is used.	None
Sensor lifetime	-	15 years

Table 5: SCD30 operation conditions, lifetime and maximum ratings

[10] Average current including idle state and processing. Other update rates for small power budgets can be selected via the digital interface.
[11] CO_2 concentrations < 400 ppm may result in sensor drifts. For proper function of ASC field-calibration algorithm SCD30 has to be exposed to air with 400 ppm regularly.

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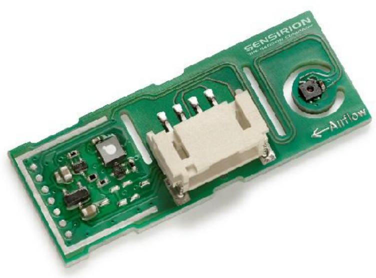
Datasheet SVM30

Multi-gas, humidity and temperature sensor combo module

- Measures indoor air quality parameters total VOC (tVOC), CO_2-equivalent (CO2eq), relative humidity RH and temperature T
- Automatic baseline compensation and humidity compensation of MOX gas sensor
- Outstanding long-term stability and reliability
- Fully factory calibrated and tested
- Digital I2C interface
- 5V supply voltage
- Dimensions: 39 x 15 x 6.5 mm

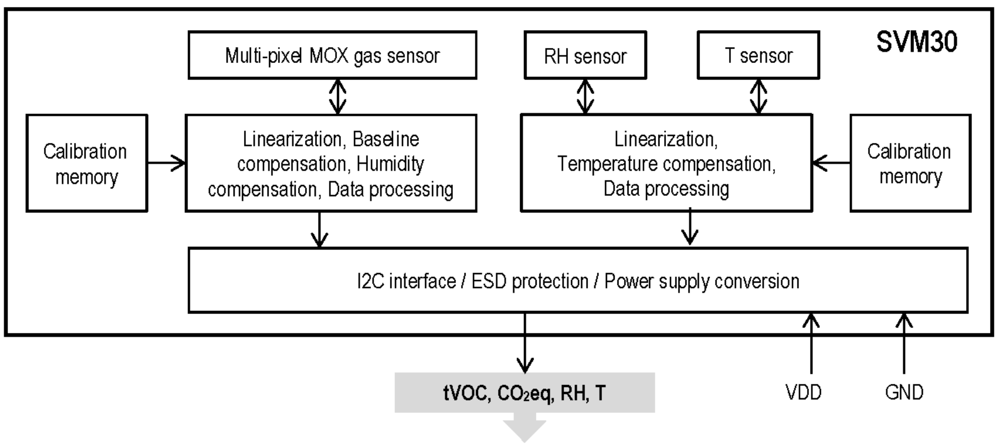


Product Summary
The SVM30 is a Multi-gas, humidity and temperature sensor combo module containing an SGP30 gas sensor as well as an SHTC1 humidity and temperature sensor.

The SGP30 gas sensor on the SVM30 combines multiple metal-oxide sensing elements − the pixels – on one chip, thereby offering the possibility to measure a total VOC signal (tVOC) and a CO_2 equivalent signal (CO_2eq) with one single sensor-chip. The SVM30 further offers calibrated air quality output signals as well as compensation of humidity cross-sensitivity. The sensing element features an unmatched robustness against contamination by siloxanes present in real-world applications enabling a unique long-term stability and low drift.

The humidity and temperature sensor on SVM30 covers a humidity measurement range of 0 to 100 %RH and a temperature measurement range of –20 to 85 °C with a typical accuracy of ±5 %RH and ±1°C.

The gas and RH/T sensor components are designed with Sensirion's CMOSens® technology. This technology offers a complete sensor system on a single chip, including the sensing elements, analog and digital signal processing, A/D converter, calibration and data memory and a digital communication interface supporting I2C standard mode. Sensirion's state-of-the-art production process, including full calibration and testing of the sensors, guarantees high reproducibility and reliability.



1 Gas, humidity and temperature sensor specification

1.1 Gas sensing performance

The values listed in **Table 1** are valid at 25°C, 50% RH and typical VDD.

Parameter	Signal	Values	Comments
Measurement range[1]	Ethanol signal	0 ppm to 1000 ppm	
	H_2 signal	0 ppm to 1000 ppm	
Specified measurement range	Ethanol signal	0.3 ppm to 30 ppm	The specifications below are defined for this measurement range[2]. The specified measurement range covers the gas concentrations expected in indoor air quality applications.
	H_2 signal	0.5 ppm to 3 ppm	
Accuracy[3,4]	Ethanol signal	see **Figure 1** typ.: 15% of meas. value	Accuracy of the concentration *c* determined by $\ln\left(c/c_{ref}\right) = \frac{(s_{ref}-s_{out})}{a}$ *a* = 512 s_{out}: EthOH/H_2 signal output at concentration *c* s_{ref}: EthOH/H_2 signal output at 0.5 ppm H_2 Ethanol signal: c_{ref} = 0.4 ppm
	H_2 signal	see **Figure 2** typ.: 10% of meas. value	H_2 signal: c_{ref} = 0.5 ppm
Sensitivity	Ethanol signal	-1.0	Sensitivity *n* is defined by $\frac{s_{ref} - s_{out}}{512} = -n \cdot \ln\left(c/c_{ref}\right)$ The typical numerical value of *n* is *n* = -1 for both, the Ethanol and H_2 signal. The sensitivity is understood as an average value over the specified measurement range as determined by a least square fit.
	H_2 signal	-1.0	
Sensitivity tolerance[3]	Ethanol signal	typ. tolerance: ±7% rel. error max. tolerance: ±14% rel. error	
	H_2 signal	typ. tolerance: ±7% rel. error max. tolerance: ±14% rel. error	
Long-term drift[3, 5]	Ethanol signal	see **Figure 3** typ.: 1.3% of meas. value	Change of accuracy over time: Siloxane accelerated lifetime test[6]
	H_2 signal	see **Figure 4** typ.: 1.3% of meas. value	
Resolution	Ethanol signal	0.2 % of meas. value	Resolution of Ethanol and H_2 signal outputs in relative change of the measured concentration
	H_2 signal		
Sampling frequency	Ethanol signal	Max. 40 Hz	Compare with minimum measurement duration in **Table 13**
	H_2 signal		

Table 1 Gas sensing performance.

[1] Exposure to ethanol and H_2 concentrations up to 1000 ppm have been tested. For applications requiring the measurement of higher gas concentrations please contact Sensirion.
[2] ppm: parts per million. 1 ppm = 1000 ppb (parts per billion)
[3] 90% of the sensors will be within the typical accuracy tolerance, >99% are within the maximum tolerance.
[4] Valid at an air flow of > 1m/s.
[5] The long-term drift is stated as change of accuracy per year of operation.
[6] Test conditions: operation in 250 ppm Decamethylcyclopentasiloxane (D5) for 200h simulating 10 years of operation in an indoor environment.

Accuracy ethanol signal

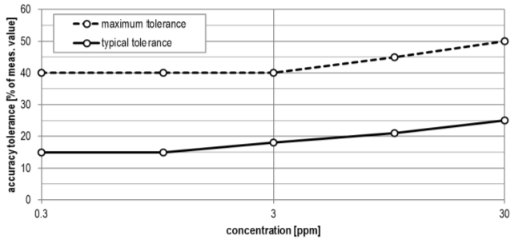


Figure 1 Typical and maximum accuracy tolerance in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 24h before the characterization.

Accuracy H_2 signal

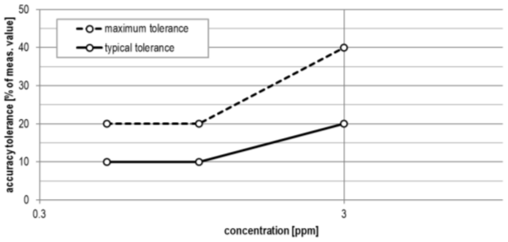


Figure 2 Typical and maximum accuracy tolerance in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 60h before the characterization.

Long-term drift Ethanol signal

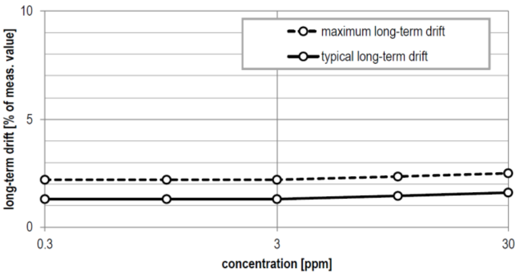


Figure 3 Typical and maximum long-term drift in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 24h before the first characterization.

Long-term drift H_2 signal

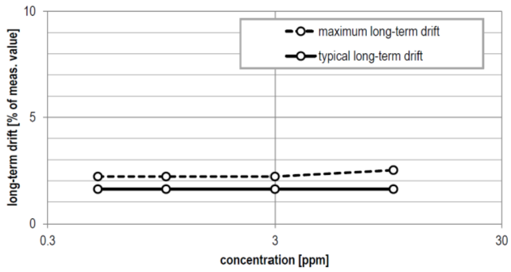


Figure 4 Typical and maximum long-term drift in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 60h before the first characterization.

1.2 Air Quality Signals

Parameter	Signal	Value	Comments
Output range	TVOC signal	0 ppb to 60000 ppb	Maximum possible output range. The gas sensing performance is specified for the measurement range as defined in **Table 1**
	CO_2eq signal	400 ppm to 60000 ppm	
Resolution	TVOC signal	0 ppb - 2008 ppb	1 ppb
		2008 ppb – 11110 ppb	6 ppb
		11110 ppb – 60000 ppb	32 ppb
	CO_2eq signal	400 ppm – 1479 ppm	1 ppm
		1479 ppm – 5144 ppm	3 ppm
		5144 ppm – 17597 ppm	9 ppm
		17597 ppm – 60000 ppm	31 ppm
Sampling rate	TVOC signal	1 Hz	The on-chip baseline compensation algorithm has been optimized for this sampling rate. The sensor shows best performance when used with this sampling rate.
	CO_2eq signal	1 Hz	

Table 2 Air quality signal specification

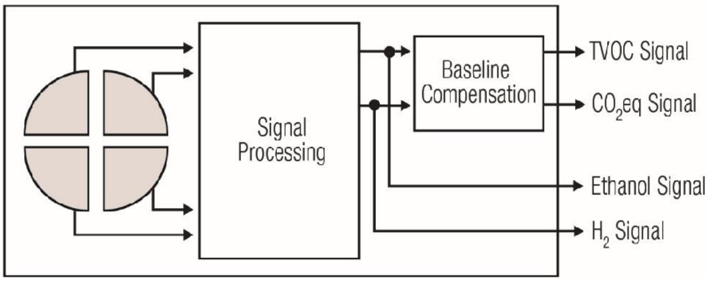


Figure 5 Simplified version of the functional block diagram showing the signal paths of the gas sensor SGP30.

1.3 Relative humidity

Parameter	Conditions	Value	Units
Accuracy tolerance[7]	In range of 25 ... 75 %RH and 5 ... 55 °C	±5.0	%RH
Repeatability[8]	-	0.1	%RH
Resolution[9]	-	0.01	%RH
Hysteresis	-	±1	%RH
Operating range	non-condensing environment[10]	0 ... 100	%RH
Response time[11]	τ 63%	8	s
Long-term drift[12]	Typ.	<0.25	%RH/y

Table 3: Humidity sensor specification

1.4 Temperature

Parameter	Conditions	Value	Units
Accuracy tolerance[7]	In range of 5 ... 55 °C	±1	°C
Repeatability[8]	-	0.1	°C
Resolution[9]	-	0.01	°C
Operating range	-	–20 ... +85	°C
Long-term drift [13]	Typ.	<0.02	°C/y

Table 4: Temperature sensor specification

1.5 Recommended operating conditions

The sensors show best performance when operated within recommended normal temperature range of 5...55°C and absolute humidity range of 4...20 g/m^3. Long-term exposure (operated and not operated) to conditions outside the recommended range, especially at high humidity, may affect the sensor performance. Prolonged exposure to extreme conditions may accelerate aging. Furthermore, it may temporarily offset the RH signal (e.g. +3%RH after 60h at >80%RH). After returning into the normal temperature and humidity range the RH-sensor will slowly come back to calibration state by itself. To ensure stable operation of the gas sensor, the conditions described in the document *SGP Handling and Assembly Instructions* as well as the *Infosheet Handling*

[7] Typical accuracy tolerance according to the document "Sensirion Humidity Sensor Specification Statement". Valid for an air flow of > 1 m/s.
[8] The stated repeatability is 3 times the standard deviation (3σ) of multiple consecutive measurement values at constant conditions and is a measure for the noise on the physical sensor output.
[9] Resolution of A/D converter.
[10] Condensation shall be avoided because of risk of corrosion and leak currents on the PCB.
[11] Time for achieving 63% of a humidity step function, valid at 25°C and 1 m/s airflow. Humidity response time in the application depends on the design-in of the sensor.
[12] Typical value for operation in normal RH/T operating range. Max. value is < 0.5 %RH/y. Value may be higher in environments with vaporized solvents, out-gassing tapes, adhesives, packaging materials, etc. For more details, please refer to Handling Instructions.
[13] Max. value is < 0.04°C/y.

A3: Sensirion SPS30 datasheet

SENSIRION
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Datasheet SPS30

Particulate Matter Sensor for Air Quality Monitoring and Control

- Unique long-term stability
- Advanced particle size binning
- Superior accuracy in mass-concentration sensing
- Small, ultra-slim package
- Fully calibrated digital output

Product Summary

The SPS30 Particulate Matter (PM) sensor is a technological breakthrough in optical PM sensors. Its measurement principle is based on laser scattering and makes use of Sensirion's innovative contamination-resistance technology. This technology, together with high-quality and long-lasting components, enables accurate measurements from its first operation and throughout its lifetime of more than eight years. In addition, Sensirion's advanced algorithms provide superior accuracy for different PM types and higher-resolution particle size binning, opening up new possibilities for the detection of different sorts of environmental dust and other particles. With dimensions of only 41 x 41 x 12 mm^3, it is also the perfect solution for applications where size is of paramount importance, such as wall-mounted or compact air quality devices.

Content

1 Particulate Matter Sensor Specifications

Default conditions of 25 °C and 5 V supply voltage apply to values in the table below, unless otherwise stated.

Parameter	Conditions	Value	Units
Mass concentration accuracy[1]	0 to 100 µg/m³	±10	µg/m³
	100 to 1'000 µg/m³	±10	%
Mass concentration range	-	0 to 1'000	µg/m³
Mass concentration resolution	-	1	µg/m³
Mass concentration size range[2]	PM1.0	0.3 to 1.0	µm
	PM2.5	0.3 to 2.5	µm
	PM4	0.3 to 4.0	µm
	PM10	0.3 to 10.0	µm
Number concentration range	-	0 to 3'000	1/cm³
Number concentration size range[2]	PM0.5	0.3 to 0.5	µm
	PM1.0	0.3 to 1.0	µm
	PM2.5	0.3 to 2.5	µm
	PM4	0.3 to 4.0	µm
	PM10	0.3 to 10.0	µm
Sampling interval	-	1	s
Start-up time	-	< 8	s
Lifetime[3]	24 h/day operation	> 8	years
Acoustic emission level	0.2 m	25	dB(A)
Weight	-	26	g

Table 1: Particulate Matter sensor specifications.

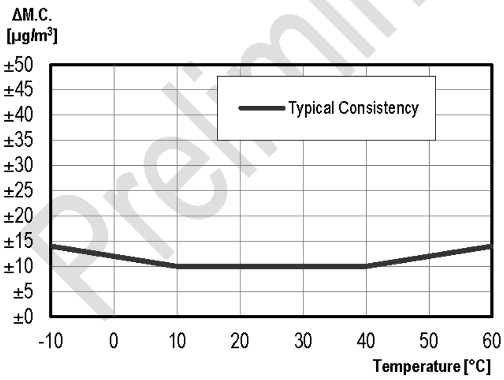


Figure 1: Typical consistency tolerance for PM2.5 in µg/m³ between 0-100 µg/m³.

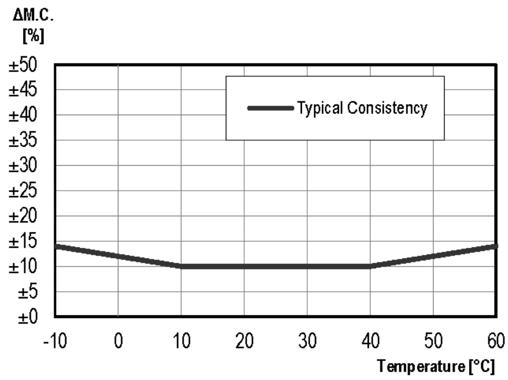


Figure 2: Typical consistency tolerance for PM2.5 in % between 100-1000 µg/m³.

[1] Deviation to TSI DustTrak™ DRX Aerosol Monitor 8533 reference. PM2.5 accuracy is verified for every sensor after calibration using a defined potassium chloride particle distribution. Ask Sensirion for further details on accuracy characterization procedures.

[2] PMx defines particles with a size smaller than "x" micrometers (e.g., PM2.5 = particles smaller than 2.5 µm).

[3] Validated with accelerated aging tests. Ask Sensirion for further details on accelerated aging validation procedures. Lifetime might vary depending on different operating conditions.

1.1 Recommended Operating Conditions

The sensor shows best performance when operated within recommended normal temperature and humidity range of 10 – 40 °C and 20 – 80 %RH, respectively.

2 Electrical Specifications

2.1 Electrical Characteristics

Default conditions of 25 °C and 5 V supply voltage apply to values in the table below, unless otherwise stated.

Parameter	Conditions	Value	Units
Supply voltage	-	4.5 to 5.5	V
Idle current	Idle-Mode	< 8	mA
Average supply current	Measurement-Mode	60	mA
Max. supply current	First ~200 ms after start of Measurement-Mode	80	mA
Input high level voltage (V_{IH})	-	> 2.31	V
Input low level voltage (V_{IL})	-	< 0.99	V
Output high level voltage (V_{OH})	-	> 2.9	V
Output low level voltage (V_{OL})	-	< 0.4	V

Table 2: Electrical specifications.

2.2 Absolute Minimum and Maximum Ratings

Stress levels beyond those listed in Table 3 may cause permanent damage to the device. These are stress ratings only and functional operation of the device at these conditions cannot be guaranteed. Exposure to the absolute maximum rating conditions for extended periods may affect the reliability of the device.

Parameter	Rating
Supply voltage VDD	-0.3 to 5.5 V
Interface Select SEL	-0.3 to 4.0 V
I/O pins (RX/SDA, TX/SCL)	-0.3 to 5.5 V
Max. current on any I/O pin	±16 mA
Operating temperature range	-10 to +60 °C
Storage temperature range	-40 to +70 °C
Operating humidity range	0 to 95 %RH (non-condensing)
ESD CDM (charge device model)[4]	±4 kV contact, ±8 kV air
Electromagnetic field immunity to high frequencies[5]	3 V/m (80 MHz to 1000 MHz)
High frequency electromagnetic emission[6]	30 dB 30 MHz to 230 MHz; 37 dB 230 MHz to 1000 MHz
Low frequency electromagnetic emission[7]	30-40 dB 0.15 MHz to 30 MHz

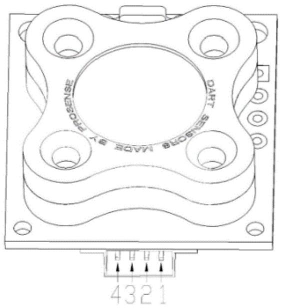
Table 3: Absolute minimum and maximum ratings.

[4] According to IEC 61000-4-2.
[5] According to IEC 61000-4-3.
[6] According to CISPR 14.
[7] According to CISPR 22.

A4: Dart Sensors WZ-S datasheet

Definition of Pins

PIN	DEFINITION
Pin1	Vin(5V)
Pin2	GND
Pin3	RXD (0～3.3V data input)
Pin4	TXD(0～3.3V data output)



Technical Specification

MODEL	WZ-S
Detection Principle	Micro fuel cell
Detectable Gas	HCHO
Detection Range	0-2ppm
Overload	10ppm
Input Voltage	5-7V
Warm up time	<3min
Response Time (T90)	<40S
Recovery Time (T10)	<60S
Resolution	0.001ppm
Operating temperature range	-20℃～50℃
Operating Humidity Range	10%－90%RH（non-condense）
Storage Condition	0～20℃
Lifetime	5 years in air
Warranty Period	12 months
Weight	4g

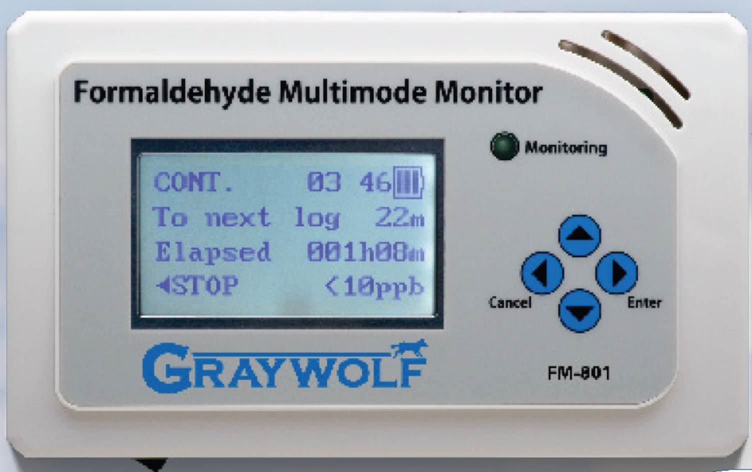
GRAYWOLF

Advanced Environmental Instrumentation

Surveyed Documented Reported

FM-801

Formaldehyde Multimode Monitor



Innovative New Method of Formaldehyde Measurement

Detachable Sensor Cartridge

- Portable base unit utilizes photoelectric photometry to read the absorbance change that HCHO induces in the sensor, then re-zeros between readings.
- Small colorimetric sensor cartridge, 43x17x4mm (1.7x0.7x0.16in), easy-to-use, reusable*, highly accurate for passive diffusion sampling.
- Note: limited sensor cartridge availability. The manufacturer of the sensor cartridges is scheduled to stop production at the end of 2021, due to licensing restrictions. The sensors have a strict 1 year shelf life from date of manufacture.
- Base unit w/sensor inserted can operate as an on-site meter for short-term (30minute) sampled measurement and/or for continuous monitoring/trend logging*.
- Base unit interfaces to GrayWolf's AdvancedSense®, WolfPack® or tablet PCs running WolfSense® LAP for simultaneous display and logging of additional parameters (and for powerful annotation features).

Measurement Principle

Colorimetric reaction to exposure

Sensor element employs the chemical reaction between formaldehyde and β-diketone impregnated in a porous glass. The concentration of rutidine derivatives yellows the sensor in proportion to the formaldehyde concentration and the duration of exposure. The difference of absorbance between samples is measured by radiating a constant wave-length light (absorptiometric method) and then an algorithm converts to ppb or µg/m3 HCHO.

*** Sensor reuse depends on HCHO exposure (approximately 4 x 30 minute tests at 1ppm, approximately 150 tests at 80ppb, approximately 1000 tests <10ppb HCHO)**

GRAYWOLF®
SENSING SOLUTIONS
Ph. 1-203-402-0477
Fax: 1-203-402-0478

Email:
Salesteam@GrayWolfSensing.com

Website:
www.GrayWolfSensing.com

FM-801

Formaldehyde Multimode Monitor

✓Measure Smart ✓Report Efficiently

Specifications

Model Name	FM-801
Detection Principle	Photoelectric Absorptiometric
Detection Range	<20ppb to 1,000 ppb, < 25 µg/m3 to 1230 µg/m3
Accuracy	+/- 4ppb <40ppb, +/- 10% of reading ≥40ppb
Resolution	1 ppb (standard display reads down to 10ppb, and above that at 1ppb increments)
Concentration Units	ppb or µg/m^3
Display	Digital LCD
Sampling Method	Passive diffusion sampling
Operating Temp. and RH	-10 to 40°C (14 to 104°F), 20 to 90 %RH (non-condensing)
Sensor Shelf Life	1year from mfg. date (stamped on pouch). It is recommended that the sensor is not used >3 months from date pouch is opened and not at all if exposed to <10%RH when open
Memory (base unit)	up to 250 sensors and 4500 data points
Power Source	2 x AA size batteries, or AC adapter
Standard Accessories	Sensor cartridge x 5 pcs, carrying case, USB connection cable, AA size batteries, AC adapter, mini tripod/stand, WolfSense PC data transfer & reporting software

Sensitivity to Interference Gas

	Concentration/ Exposure duration	FM-801 readout value (ppb)
Benzene	2000 ppm / 8 h	0 (<10)
Toluene	2000 ppm / 8 h	0 (<10)
Xylene	2000 ppm / 8 h	0 (<10)
Ethylbenzene	2000 ppm / 8 h	0 (<10)
Methanol	2000 ppm / 8 h	0 (<10)
Ethanol	2000 ppm / 8 h	0 (<10)
1-Buthanol	2000 ppm / 8 h	0 (<10)
2-Methyl-3-buten-2-ol	2000 ppm / 8 h	0 (<10)
Acetone	2000 ppm / 8 h	0 (<10)
2-Buthanol	2000 ppm / 8 h	0 (<10)
Acetic Acid	2000 ppm / 8 h	0 (<10)
Ethyl Acetate	2000 ppm / 8 h	0 (<10)
Isoprene	2000 ppm / 8 h	0 (<10)
alpha-pinene	2000 ppm / 8 h	0 (<10)
beta-pinene	2000 ppm / 8 h	0 (<10)
Chloroform	25 ppm / 5 h	69
Limonene	200 ppm / 8 h	9 (<10)
Styrene	200 ppm / 8 h	13
Propionaldehyde	200 ppm / 8 h	13
n-Nonylaldehyde	200 ppm / 8 h	13
Benzaldehyde	200 ppm / 8 h	9 (<10)
Acetaldehyde	200 ppm / 8 h	22
Nitrogen Dioxide	1 ppm / 1h	-42 (<10)
Ozone	1 ppm / 1h	-56 (<10)
Sulfur Dioxide	1 ppm / 1h	-2 (<10)

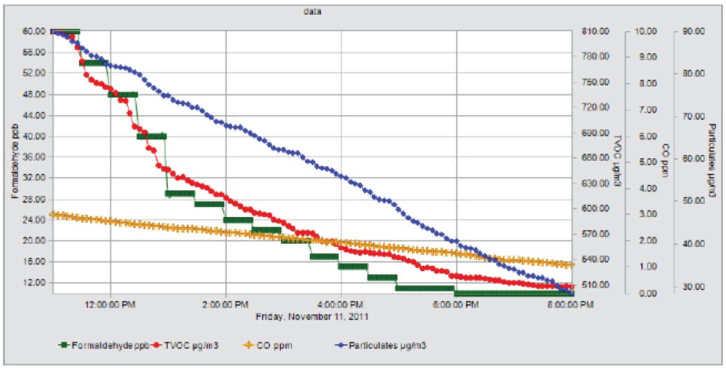
SPECIFICATIONS ARE SUBJECT TO CHANGE WITHOUT FURTHER NOTICE

FM-801 (on included **ACC-BELTCL-1** belt clip) shown connected to GrayWolf AdvancedSense Pro

Display real-time HCHO graphs, attach text/audio notes and access many other powerful features when interfaced to AdvancedSense, WolfPack or DirectSense WIN7/8 notebooks/tablets

Provided with GrayWolf's versatile WolfSense® PC data transfer and reporting software. Download readings stored on the FM-801 base unit when used as a stand-alone, or when optionally interfaced to compatible GrayWolf platforms

CE Compliant to CE regulations



Graph formaldehyde trend logs from an FM-801; singly or together with other parameters from any compatible GrayWolf platform

GRAYWOLF SENSING SOLUTIONS
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800-218-7997
Fax: (1)203-402-0478
Email: Salesteam@GrayWolfSensing.com
www.GrayWolfSensing.com

8 Pegasor AQ™ Indoor Specifications

Sensor type	Electrical Particle Charging and electrometry
Concentration Range (mass)	0.01 - 200 mg/ m^3
Concentration Range (number)	<500 - >10,000,000 p/cc
Particle size range	0.01 - 2.5 μm
Particle size cutter (D50)	2.5 μm
Sampling rate	I Hz
Resolution	0.001 mg/m^3 (with 1 min integration time) or 0.1% of reading
Pump	Maintenance free diaphragm pump
Flow rate	3 l/min
Stability	No observed drift during operation period
Configurable to PM, PN or PA measurements	Yes
Temperature and relative humidity measurements	Yes, with Vaisala HUMICAP®sensor
CO2 measurement	Yes, with Vaisala CARBOCAP® sensor
Operation interface	4.3" Colour display touch screen
Battery Type	Li-Ion
Battery operation time	10h, 24h or 100h depending of the sampling rate
AC power supply	External power supply, 100 - 240 VAC, 50/60 Hz 65 W max
Battery charging	During operation and separately in service case. Spare battery pack available as an option.
Quick charger	Yes, optional
Operating temperature range	0 – 50 °C (non condensing)
Storage Temperature	-20 – 60°C
Dimensions	150 x 200 x 300mm
Weight	c 3.0 Kg

9 Vaisala Sensor Specifications

9.1 CARBOCAP® GM 10 Carbon dioxide sensor

Performance	
CARBON DIOXIDE	
Measurement range	0 … 5000 ppm
Accuracy	
+20 … +30 °C (+ 68 … + 86 °F)	± (30 ppm + 2 % of reading)
+10 … +20 °C, +30 … +40 °C (+50 … +68 °F, +86 … +104 °F)	± (35 ppm + 2.7 % of reading)
-5 … +10 °C, +40 … +55 °C (+23 … +50 °F, +104 … +131 °F)	± (45 ppm + 3.8 % of reading)
Stability in typical HVAC applications	Total accuracy at room temperature ±75 ppm at 600 and 1000 ppm incl. 5 years drift*
Carbon dioxide sensor	Vaisala CARBOCAP® GM10

9.2 HUMICAP® 110 Humidity and Temperature Probe

Performance	
RELATIVE HUMIDITY	
Measurement range	0 … 100 %RH
Accuracy (incl. non-linearity, hysteresis and repeatability)	
temperature range	0 … +40 °C
0 … 90 %RH	±1.5 %RH
90 … 100 %RH	±2.5 %RH
temperature range	-40 … 0 °C, +40 … +80 °C
0 … 90 %RH	±3.0 %RH
90 … 100 %RH	±4.0 %RH
Factory calibration uncertainty (+20 °C)	
0 … 90 %RH	±1.1 %RH
90 … 100 %RH	±1.8 %RH
Humidity sensor	Vaisala HUMICAP® 180R
Stability	±2 %RH over 2 years
TEMPERATURE	
Measurement range	-40 … +80 °C
Accuracy over temperature range	
0 … +40 °C,	±0.2 °C
-40 … 0 °C, +40 … +80 °C	±0.4 °C
Temperature sensor	Pt1000 RTD Class F0.1 IEC 60751
DEW POINT	
Measurement range	-40 … +80 °C
Accuracy (incl. non-linearity, hysteresis and repeatability)	
temperature range	0 … +40 °C
when dew point depression < 15 °C	±1 °C
when dew point depression 15 … 25 °C	±2 °C
temperature range	-40 … 0 °C, +40 … +80 °C
when dew point depression < 15 °C - dew point depression = ambient temperature - dew point	±2 °C
ANALOG OUTPUTS	
Accuracy at 20 °C	±0.2 % of FS
Temperature dependence	±0.01 % of FS/°C

Appendix B: Risk assessment

Appendix B1: Risk assessment

NTNU / HSE	Hazardous activity identification process	Prepared by	Number	Date
		HSE section	HMSRV2601E	09.01.2013
		Approved by		Replaces
		The Rector		01.12.2006

Unit: *Department of Energy and Process Engineering* **Date:** 03.06.2020

Line manager: Terese Løvås

Participants in the identification process: Hans Martin Mathisen (supervisor), Thomas Berg Jørgensen (student), Maria Justo Alonso (co-supervisor).

Short description of the main activity/main process: Master project for student Thomas Berg Jørgensen. "IOT for ventilation of zero emission buildings (ZEB)".

Is the project work purely theoretical? (YES/NO): NO *Answer "YES" implies that supervisor is assured that no activities requiring risk assessment are involved in the work. If YES, briefly describe the activities below. The risk assessment form need not be filled out.*

Signatures: *Responsible supervisor:* [illegible] *Student:* Thomas B. Jørgensen

ID nr.	Activity/process	Responsible person	Existing documentation	Existing safety measures	Laws, regulations etc.	Comment
1	Work in height using stepladder	Thomas B. Jørgensen		Caution while using and setting up ladder. Use according to instructions		
2	Laboratory work	Thomas B. Jørgensen		Safety course, personal protective equipment		Passed course and lab tour completed before lab work

NTNU	Risk assessment	Prepared by	Number	Date	
HSE/KS		HSE section	HMSRV2603E	04.02.2011	
		Approved by		Replaces	
		The Rector		01.12.2006	

Unit: *Department of Energy and Process Engineering* **Date:** 03.06.2020

Line manager: Terese Løvås

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Signatures: *Responsible supervisor:* [signature] *Student:* Thomas B. Jørgensen

Activity from the identification process form	**Potential undesirable incident/strain**	**Likelihood:**	**Consequence:**			**Risk Value (human)**	**Comments/status Suggested measures**
		Likelihood (1-5)	Human (A-E)	Environment (A-E)	Economy/ material (A-E)		
Work in height using stepladder	Fall injuries	2	B	A	B	2B	Safe pacement of stepladder, according to instructions. Appropriate working position
Laboratory work	Exposure to gaseous pollutant (mainly CO_2) and pressurized container	2	B	B	A	2B	Careful use of gas container and its content. Knowledge of escape paths in case of use in closed rooms

NTNU	Risk assessment	Prepared by	Number	Date
HSE/KS		HSE section	HMSRV2603E	04.02.2011
		Approved by		Replaces
		The Rector		01.12.2006

Likelihood, e.g.:
1. *Minimal*
2. *Low*
3. *Medium*
4. *High*
5. *Very high*

Consequence, e.g.:
A. Safe
B. Relatively safe
C. Dangerous
D. Critical
E. Very critical

Risk value (each one to be estimated separately):
Human = Likelihood x Human Consequence
Environmental = Likelihood x Environmental consequence
Financial/material = Likelihood x Consequence for Economy/materiel

Potential undesirable incident/strain
Identify possible incidents and conditions that may lead to situations that pose a hazard to people, the environment and any materiel/equipment involved.

Criteria for the assessment of likelihood and consequence in relation to fieldwork
Each activity is assessed according to a worst-case scenario. Likelihood and consequence are to be assessed separately for each potential undesirable incident. Before starting on the quantification, the participants should agree what they understand by the assessment criteria:

Likelihood

Minimal 1	Low 2	Medium 3	High 4	Very high 5
Once every 50 years or less	Once every 10 years or less	Once a year or less	Once a month or less	Once a week

Consequence

Grading	Human	Environment	Financial/material
E Very critical	May produce fatality/ies	Very prolonged, non-reversible damage	Shutdown of work >1 year.
D Critical	Permanent injury, may produce serious serious health damage/sickness	Prolonged damage. Long recovery time.	Shutdown of work 0.5-1 year.
C Dangerous	Serious personal injury	Minor damage. Long recovery time	Shutdown of work < 1 month
B Relatively safe	Injury that requires medical treatment	Minor damage. Short recovery time	Shutdown of work < 1week
A Safe	Injury that requires first aid	Insignificant damage. Short recovery time	Shutdown of work < 1day

The unit makes its own decision as to whether opting to fill in or not consequences for economy/materiel, for example if the unit is going to use particularly valuable equipment. It is up to the individual unit to choose the assessment criteria for this column.

NTNU	Risk assessment	Prepared by	Number	Date	
		HSE section	HMSRV2603E	04.02.2011	
		Approved by		Replaces	
HSE/KS		The Rector		01.12.2006	

Risk = Likelihood x Consequence
Please calculate the risk value for "Human", "Environment" and, if chosen, "Economy/materiel", separately.

About the column "Comments/status, suggested preventative and corrective measures":
Measures can impact on both likelihood and consequences. Prioritise measures that can prevent the incident from occurring; in other words, likelihood-reducing measures are to be prioritised above greater emergency preparedness, i.e. consequence-reducing measures.

NTNU	Risk matrix	prepared by	Number	Date
		HSE Section	HMSRV2604	8 March 2010
		approved by	Page	Replaces
HSE/KS		Rector	4 of 4	9 February 2010

MATRIX FOR RISK ASSESSMENTS at NTNU

CONSEQUENCE						
	Extremely serious	E1	E2	E3	E4	E5
	Serious	D1	D2	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Not significant	A1	A2	A3	A4	A5
		Very low	Low	Medium	High	Very high
		LIKELIHOOD				

Principle for acceptance criteria. Explanation of the colours used in the risk matrix.

Colour	Description
Red	Unacceptable risk. Measures must be taken to reduce the risk.
Yellow	Assessment range. Measures must be considered.
Green	Acceptable risk Measures can be considered based on other considerations.