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Oda Kristine Gram

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Department of Energy and Process Engineering

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Use of low cost pollutant sensors for developing healthy demand controlled ventilation strategies

A case study in four primary school classrooms

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Energy and environmental engineering
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Supervisor: Hans Martin Mathisen
Co-supervisor: Maria Justo-Alonso

Norwegian University of Science and Technology
Department of Energy and Process Engineering

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Abstract

In most developed countries, buildings account for about 40% of the total energy use, of which a significant fraction is consumed by HVAC systems. Demand controlled ventilation (DCV) is often proposed as a measure to reduce HVAC energy use, while maintaining adequate levels of outdoor air ventilation for indoor air quality control. This way the ventilation operates with reduced air flow rates during a significant part of the time. CO_2 production related to human occupancy is straightforward to use as an indicator of the air quality, making CO_2 the most used indicator for control of DCV; the ventilation rate is increased when CO_2 levels increase and vice versa. However, other pollutants in the indoor air may affect the performance and health of occupants, and pollutants such as particulate matter and volatile organic compounds (VOCs) may have increasing levels even in periods of low occupancy. If ventilation rates are reduced due to low occupancy, occupants may be exposed to high concentrations of pollutants with adverse health effects due to lower pollutant dilution. Usually, these other pollutants are not incorporated into DCV applications due to complex and expensive measurement techniques. In more recent years, new technologies have enabled for less expensive sensors measuring relevant pollutants and parameters.

Several health relevant pollutants in indoor air in primary school classrooms were identified in the literature reviews, and the most relevant pollutants were evaluated to be the VOC and carcinogen formaldehyde, TVOC (total amount of VOCs) and the particulate matter size fractions $PM_{2.5}$ and PM_{10}. Recommended limit value guidelines were found for formaldehyde, $PM_{2.5}$ and PM_{10}. A recommended limit value guideline does not exist for TVOC concentrations. Together with these pollutants, CO_2, temperature and humidity were also studied in the literary reviews. Relevant factory precalibrated low cost sensors for all these pollutants and parameters were found, implemented on a sensor rig and tested, first by performing initial sensor calibrations together with high performance reference instruments, and secondly by performing field measurements in primary school classrooms with CO_2 controlled DCV. The chosen sensors are SCD30 (CO_2, temperature, humidity), SPS30 ($PM_{2.5}$, PM_{10}), SGP30 (TVOC) and WZ-S (formaldehyde). The TVOC sensors were not implemented on the sensor rigs due to problems with handling their very small dimensions. Formaldehyde and PM_{10} sensor measurements were not calibrated due to a lack of relevant reference instruments and calibration procedures.

The results from the initial sensor calibrations show that the accuracy of the sensors is as stated in their datasheets. Future calibrations are recommended to look for possible drifts over time in the measurements. The results from the field measurements show that the limit value guideline for formaldehyde is exceeded regularly in all classrooms. This mostly occurs outside the operating hours, but short exceeds also occur within the operating hours during lunchtime. No clear difference in the formaldehyde levels for newer and older classrooms are found, but formaldehyde levels are higher in classrooms with wooden surfaces than in classrooms without wooden surfaces. Formaldehyde levels decrease rapidly when ventilation air flow rates are increased from minimum values, showing that the formaldehyde is indoor generated. Formaldehyde is recommended as a marker for control of DCV together with CO_2, to ensure that occupant generated and non-occupant generated pollutants are controlled simultaneously, resulting in a more healthy indoor air for the occupants. The $PM_{2.5}$ levels measured in the classrooms are mostly very low, but during a period of unusually high outdoor

$PM_{2.5}$ levels, the indoor levels became noticeably higher, and the limit value guideline for $PM_{2.5}$ was exceeded once in one of the four classrooms. No significant differences in the $PM_{2.5}$ levels indoors in high and low trafficked areas are found. No correlation between indoor $PM_{2.5}$ levels and ventilation air flow rates is discovered. PM_{10} field measurements were discarded because it was discovered that low cost particle matter sensors have an exponentially decreasing accuracy for increasing particulate size fractions. Indoor and outdoor $PM_{2.5}$ levels can be monitored by the building automation system, making it possible to indicate when windows should remain closed due to unusually high outdoor levels. It is not recommended to use $PM_{2.5}$ as a marker for control of DCV in primary schools.

Sammendrag

I de fleste industriland står bygg for omlag 40% av det totale energiforbruket, og en betydelig andel av dette går til drifting av ventilasjonsanlegg. Behovsstyrt ventilasjon (DCV) er et tiltak som ofte benyttes for å redusere ventilasjonssystemers energibruk, hvor mengden frisk luft som tilføres bygget tilpasses etter det målte behovet til enhver tid, og reduserte luftmengder dermed leveres en stor andel av tiden. Menneskelig CO_2-produksjon er enkel å bruke som indikator på den opplevde luftkvaliteten i et rom, og CO_2 er den mest brukte indikatoren for styring av DCV i dag; luftmengdene økes når CO_2 nivået øker og vice versa. Imidlertid kan andre forurensende stoffer i inneluften påvirke personers ytelse og helse, og svevestøv og flyktige organiske forbindelser (VOC) kan ha økende nivåer selv i perioder med lav tilstedeværelse. Hvis luftmengder reduseres på grunn av lav tilstedeværelse, kan personer bli utsatt for høye konsentrasjoner av forurensende stoffer med negative helseeffekter. Vanligvis er disse forurensningene ikke implementert i styringen av DCV på grunn av komplekse og dyre målingsteknikker, men i senere tid har teknoligiske framskritt resultert i utviklingen av rimeligere sensorer som måler relevante forurensninger og parametre.

Flere helserelevante forurensninger i inneluft i barneskoleklasserom ble identifisert gjennom litteraturstudier, og de mest relevante forurensende stoffene ble vurdert til å være den flyktige og kreftfremkallende organiske forbindelsen formaldehyd, TVOC (total mengde flyktige organiske forbindelser) og svevestøvfraksjonene $PM_{2.5}$ og PM_{10}. Anbefalte grenseverdier ble funnet for formaldehyd, $PM_{2.5}$ og PM_{10}. En anbefalt grenseverdi finnes ikke for TVOC-konsentrasjoner. Sammen med disse nevnte forurensende stoffene ble også CO_2, temperatur og luftfuktighet studert i litteraturstudiene. Relevante prekalibrerte, rimelige sensorer for alle nevnte forurensninger og parametre ble valgt, implementert på sensor-rigger og testet, først ved å utføre innledende sensorkalibreringer sammen med referanseinstrumenter med høy ytelse, og så ved å utføre feltmålinger i barneskoleklasserom med CO_2-styrt DCV. De valgte sensorene er SCD30 (CO_2, temperatur, luftfuktighet), SPS30 ($PM_{2.5}$, PM_{10}), SGP30 (TVOC) og WZ-S (formaldehyd). TVOC-sensoren ble ikke implementert på sensor-riggene på grunn av dens svært små dimensjoner og problemer med å håndtere disse. Kalibrering av formaldehyd- og PM_{10}-sensorer ble ikke utført på grunn av manglende kalibreringsprosedyrer.

Resultatene fra sensorkalibreringene viser at nøyaktigheten til sensorene er som angitt i databladene. Fremtidige kalibreringer anbefales for å lete etter mulig endring i ytelsen over tid. Resultatene fra feltmålingene viser at grenseverdien for formaldehyd overskrides jevnlig i alle klasserom. Dette skjer stort sett utenfor driftstiden, men korte overskridelser skjer også i driftstiden under lunchen. Det finnes ingen klar forskjell på formaldehydnivået i nyere og eldre klasserom, men formaldehydnivåene er høyere i klasserom med overflater i tre enn i klasserom uten overflater i tre. Formaldehydnivået minker raskt når ventilasjonen økes fra minimumsnivået, noe som viser at formaldehyd genereres innendørs. Formaldehyd anbefales som en indikator for styring av DCV sammen med CO_2, for å sikre at både menneskeskapte og ikke-menneskeskapte forurensninger kontrolleres. $PM_{2.5}$-nivåene målt i klasserommene er for det meste svært lave, men i løpet av en periode med uvanlig høye utendørs svevestøvnivåer ble innendørsnivåene merkbart høyere, og grenseverdien for $PM_{2.5}$ ble overskredet én gang i ett klasserom. Ingen signifikante forskjeller i $PM_{2.5}$-nivåene i høy- og lavtraffikerte områder er funnet. Ingen korrelasjon mellom innendørs $PM_{2.5}$-nivåer og ventilasjonsmengder er

oppdaget. PM_{10}-feltmålinger ble forkastet fordi det ble oppdaget at lavkostnad partikkelsensorer har en eksponentielt avtagende nøyaktighet for økende størrelsesfraksjoner av svevestøv. Innendørs og utendørs $PM_{2.5}$-nivåer kan overvåkes av sentraldriftsanlegget, noe som gjør det mulig å indikere når vinduer bør holdes stengt på grunn av uvanlig høye nivåer av utendørs svevestøv. Det anbefales ikke å bruke $PM_{2.5}$ som en indikator for styring av DCV.

List of Figures

List of Tables

Contents

Abbreviations

AHU Air handling unit
BAS Building automation system
CO_2 Carbon dioxide
COPD Chronic obstructive pulmonary disease
CP Coarse particles
CSV Comma-separated values
DCV Demand controlled ventilation
FHI Folkehelseinstituttet (Norwegian Institute of Public Health)
HVAC Heating, ventilation, air conditioning
I^2C Inter-intergrated circuit
IAQ Indoor air quality
IARC International Agency for Research on Cancer
MET Metabolic equivalent of task
NDIR Nondispersive infrared sensor
NHT New+high traffic
NLT New+low traffic
NOAEL No observed adverse effect levels
OHT Old+high traffic
OLT Old+low traffic
PAH Polycyclic aromatic hydrocarbon
PM Particulate matter
ppb Parts per billion
ppm Parts per million
RH Relative humidity
SBS Sick building syndrome
SFP Specific fan power
TSP Total suspended particles
TVOC Total volatile organic compound
TWA Time weighted average
UFP Ultrafine particles
VOC Volatile organic compound
WHO World Health Organization

Chapter 1

Introduction

1.1 Background

In most developed countries buildings account for about 40% of the total energy use, of which a significant fraction is consumed by HVAC systems. Demand controlled ventilation (DCV) is often proposed as a measure to reduce HVAC energy use, while maintaining adequate levels of outdoor air ventilation for indoor air quality control. When ventilation is reduced, energy is saved due to a lowered fan power consumption and because it is not necessary to heat or cool as much outside air. CO_2 production mostly related to human occupancy is straightforward to use as a proxy indicator for air quality. The ventilation rate is increased when CO_2 levels increase and reduced when CO_2 levels decrease. However, other pollutants in the indoor air may affect the performance and health of occupants. Pollutants such as particulate matter and volatile organic compounds (VOC) may have increasing levels even in periods of low occupancy. If ventilation is reduced due to low occupancy, occupants may be exposed to high concentrations of pollutants with adverse health effects due to lower pollutant dilution. Usually, these "other" pollutants are not incorporated into DCV applications, due to complex and expensive measurement techniques. In more recent years, new technologies have enabled for less expensive sensors, though with reduced accuracies compared to high performance research instruments.

1.2 Problem description and goal

A state-of-the-art review of knowledge covering health related pollutants and parameters which can be used to control DCV was initiated in the project thesis Gram (2018), and will be finished in this master's thesis. Sensors measuring the health relevant pollutants and parameters, with costs that are less likely to hinder their use in building ventilation controls, will be chosen and evaluated through initial calibrations in the lab and field measurements in classrooms in four primary schools; two newer and two older schools. The goal is to evaluate the possible existence of a more health relevant indicator or combination of indicators for control of ventilation. Based on the field measurements in the classrooms, one or several DCV control strategies are to be suggested. Additionally, the performance of the chosen sensors throughout the lab calibrations and classroom measurements will be evaluated with regard to their accuracy and ability to react to changes in indoor concentrations and parameter levels.

1.3 Scope and limitations

It is decided to narrow down the scope of this master's thesis by limiting the amount of health relevant environmental pollutants and parameters to volatile organic compounds (VOC), particulate matter, CO_2, temperature and humidity. Pollutants and parameters out of this scope will not be evaluated. State-of-the-art literature reviews will primarily be based on recent findings on these pollutants and parameters in primary schools in cold, Northern climates. When necessary the reviews will look at other indoor environments and/or climates, and at older findings when more recent findings are non-existent. This work is focused on evaluating sensors and suggesting control algorithms, which are important parts of the control system in DCV. Out of the scope are the actuating units and the controllers that accept the information from the sensors, make decisions based on the control algorithms, and output commands to the actuating units. To test the chosen sensors, complex hardware and software system developing is required, and this has to be done in collaboration with professional system developers. A definition of the pseudo code and the required specifications for the sensor rigs are provided to the system developers, and they make the sensor rigs based on this information.

1.4 Research questions

The research questions to be investigated in this master's thesis are made to aim the described problem towards reaching the goal of the project. The research questions are:

- What limit value guidelines exist for health damaging pollutants like different VOCs and particulate matter size fractions?
- Does low cost sensors measuring various relevant VOCs and particulate matter size fractions exist? If so, how are their stated performance, lifetime, calibration needs and dimensions?
- How do factory precalibrated sensors perform compared to the performance stated by their suppliers?
- Is it possible to use VOC and particulate matter sensors to control DCV?
- What is the importance of the flow pattern and ventilation principle in the room with regard to the location of the sensors measuring the state of the air in the room?
- Does CO_2 controlled DCV maintain VOC and particulate matter levels acceptably low at all times?
- Can minimum airflow for DCV keep VOC and particulate matter levels below their limit values if DCV is controlled only by CO_2 levels?
- Is it possible to achieve a more healthy indoor air by controlling ventilation after VOC and/or particulate matter levels?

1.5 Approach

State-of-the-art literature reviews on health relevant pollutants and on control of DCV are carried out, and sensors are chosen based on the results from these reviews. The chosen sensors and equipment required for reading the sensors are ordered, and four identical sensor rigs are made in collaboration with professional system developers. Lab calibration of the sensors on all sensor rigs are performed, followed by field measurement periods in the four classrooms. After the field measurements, graphical presentations statistical analysis of the measurement results are made, and possible DCV control algorithms are suggested based on the analysis results. An evaluation of possible commercial use of the chosen sensors are to be carried out.

For the literature reviews, relevant research papers are searched for in several databases like Oria, Scopus, Google Scholar and Science Direct. Key words used in these literature searches are "IAQ", "indoor air quality", "VOC", "volatile organic compounds", "PM", "$PM_{2.5}$", "PM_{10}" "particulate matter", "DCV", "demand controlled ventilation", "formaldehyde", "primary schools", "classrooms", "air pollutants", "sensors for DCV", "control of DCV", "control algorithms" etc. Search operators used are AND, OR, AND NOT, etc. The books "Ventilasjonsteknikk 1" and "Ventilasjonsteknikk 2" by Sturla Ingebrigtsen, the report "Anbefalte faglige normer for inneklima" from FHI, several reports on indoor and outdoor air from WHO, standards and regulations (like TEK17, NS-EN15251 and 444 Veiledning om klima og luftkvalitet på arbeidsplassen) and publications from EPA and IARC are used throughout the entire work process. Information on Arduino, Raspberry Pi and sensors are obtained from different online forums (makers.org, arduino.cc, projects.raspberrypi.org) and different suppliers (Sensirion, Olimex, Dart-Sensors).

1.6 Structure of the master's thesis

The work carried out on this master's thesis is divided into one theoretical part and one practical part. The theoretical part consists of literature reviews in chapter 2: Pollutants in indoor air: State of the art, chapter 3: DCV: Theory and principles and chapter 4: Room control strategies for DCV: State of the art. The results found in these literature reviews are used as basis for the work carried out in the practical part. The practical part consists of chapter 5: Methods, describing the methods used for choosing sensors, building the sensor rigs, calibrating the sensors, carrying out and analyzing field measurements and developing control strategies. In chapter 6: Results, results from the calibration procedures and field measurements are presented, commented and discussed continuously, and the results and methods used are further discussed in chapter 7: Discussion. Conclusions are given in chapter 8: Conclusions, and suggestions of relevant further work is given in chapter 9: Further work.

Chapter 2

Pollutants in indoor air: State of the art

2.1 Background

This is a state of the art review of knowledge related to pollutants in indoor air that could be used as indicators for control of DCV. The aim is to provide a healthy and safe IAQ in primary school classrooms. At present, the amount of data available regarding measurements of particulate matter mass concentrations and gas phase pollutants found in school indoor air is not as voluminous as the data available for outdoor air and for other indoor environments, such as industrial indoor environments. This is mainly linked to technical difficulties in indoor air monitoring in classrooms, which should be minimally invasive (Salthammer et al. (2016)).

The "Recommended professional standards for indoor climate" (FHI (2015)) is the most recent publication from the Norwegian Institute of Public Health (Folkehelseinstituttet) regarding recommended professional standards for health affecting pollutants in the indoor climate. "WHO Guidelines for Indoor Air Quality: Selected Pollutants" (WHO (2010)) is a review of existing knowledge regarding pollutants in the indoor air, with the aim of setting guideline limit values for the different health affecting pollutants. FHI (2015) is to a great extent based on this and older WHO publications, from a Norwegian point of view. EPA (U.S. Environmental Protection Agency) has published reviews like "Introduction to indoor air quality - A reference manual" (EPA (2018a)), "Technical overview of volatile organic compounds" (EPA (2017)) and "Indoor particulate matter" (EPA (2018b)). IARC (International Agency for Research on Cancer) is the specialized cancer agency of the WHO, and they have published reviews like "Agents Classified by the IARC Monographs" (IARC (2019)) and "IARC Monographs on the Evaluation of Carcinogenic Risks to Humans" (IARC (2006)). IAQ standards and guidelines have been established to reduce harmful concentrations of health affecting pollutants to an acceptable minimum, so that building occupants are protected from detrimental health effects. A common problem with defining absolute pollutant concentration guidelines in indoor air is related to the differentiation between what is believed to be safe concentrations and what is considered an acceptable risk (FHI (2015)).

For a long time, poor IAQ has been recognized as a cause of occupant discomfort, adverse health effects, increased absenteeism and degraded cognitive performance (Zwozdziak et al. (2016)). The effect of air pollutants on health depends on the type of pollutant, its ambient concentration, the duration of the exposure and the total lung ventilation period of exposed individuals (Zwozdziak et al. (2016)). The most common manifestation of poor IAQ is via non-specific symptoms of illnesses like headache, eye, nose or throat irritation, skin itch or rash, fatigue, malaise and difficulty concentrating and performing (Johnson et al. (2018)), and usually these symptoms can't be attributed to a specific cause. However their occurrence is often described as Sick building syndrome (SBS) (Johnson et al. (2018)), because the symptoms tend to increase in severity with the time people spend in a building, and improve over time or even disappear when people are away from the building. Among the indoor pollutants contributing to these symptoms are particulate matter and volatile organic compounds (VOCs) including aldehydes, especially formaldehyde (Johnson et al. (2018); Salthammer et al. (2016)). VOCs can be emitted from sources such as printers, cleaning and disinfection products, other consumer products, textiles, building materials, paints and furnishings. Particulate matter can origin from nearby traffic, sandy playgrounds, human cells and building materials. These pollutants can be generated indoors or may enter the indoor environment from the outdoors, via infiltration through leaks or openings in the building envelope or via air drawn in by the HVAC system (Johnson et al. (2018); Salthammer et al. (2016)).

Children spend most of their time outside their homes within the school environment, thus school IAQ can directly influence their health (Fsadni et al. (2018)). Compared to adults, children are more vulnerable to airborne pollutants because their lungs are developing, they breathe more air compared to their body size and they have higher levels of physical activity. They also have an underdeveloped ability to communicate concerns in response to pollutant levels. This results in children being more affected by air pollutants than adults (Salthammer et al. (2016); Chatzidiakou et al. (2012)). For many environmental exposures, children are a subpopulation of special interest, and the effects of poor school IAQ on the health and academic performance on school children is an active field of research. Associations have been shown between poor IAQ and adverse health effects such as asthma, absenteeism and impaired performance on standardized tests (Johnson et al. (2018)). WHO reports conclude that asthma is the most common chronic disease among children, and also the leading cause of hospitalization among children (WHO (2010)). In several northern hemisphere countries, a significant increase in asthma related hospital admissions among children with asthma peak in September, and this coincides closely with their return to school after summer vacation. This indicates that a sub-population of school aged children with asthma receive challenges triggering their asthma when returning to school (Chatzidiakou et al. (2012)). In Fsadni et al. (2018), a study of the impact of school IAQ on the respiratory health of children in Malta, significant associations was shown between high exposures to indoor air pollutants and inflammation in the upper an lower airway. In this study, the $PM_{2.5}$, formaldehyde, CO, NO_2 and ozone level indoors exceeded their respective thresholds.

Based on the findings in FHI (2015) and WHO (2010), the most health relevant pollutants in primary school classrooms in Norway seem to be VOCs in general, the VOC formaldehyde in particular and particulate matter small enough to reach the lower respiratory system. CO_2 is also among the assessed pollutants, both because it is the standard marker for control of DCV today (Ingebrigtsen (2018b)) and because it could be a potential marker for control of DCV in combination with other markers (Fisk and De Almeida (1998)). Possible relationships between pollutant levels and temperature and humidity levels will be evaluated. Assessments of the pollutants are made in sections 2.2-2.5. The overall goal is to investigate the possible use of the reviewed pollutants as markers for control of DCV.

2.2 CO_2

Introduction

CO_2 was one of the first gases identified in the air, and it was initially assumed to be very poisonous. After some time it was established that the gas was not poisonous in typical indoor concentrations, but that its concentration correlated with the perception of IAQ (Ingebrigtsen (2018a)). CO_2 is a colorless and odorless gas (FHI (2015)). It is not the CO_2 concentration itself that leads to a perception of bad IAQ, but rather the bioeffluents produced together with the CO_2 from humans (Ingebrigtsen (2018a)). Exposure to high levels of bioeffluents reduces perceived IAQ, increases the intensity of reported headache, fatigue, sleepiness and difficulty in thinking clearly, which are symptoms often described as SBS (Johnson et al. (2018)). CO_2 is measured as a substitute to bioeffluents from people. This is because the average CO_2 production from a a person is known, which means that CO_2 levels can be used to control the airflow to a room based on the people load (Ingebrigtsen (2018a)). Maintaining a CO_2 concentration at less than 500 ppm above outdoor levels, or below 1000 ppm in occupied spaces by exchanging enough indoor air with outdoor air provides acceptable bioeffluent levels not offensive to most people entering a room (Ingebrigtsen (2018a)). Thus CO_2 is used as an indicator of the perceived IAQ (Zhang et al. (2017); Johnson et al. (2018)).

Occurrence and control

In non-industrial indoor environments such as primary school classrooms, human metabolism is the major source of CO_2, leading to an increase in the indoor concentration relative to the outdoor concentration (Zhang et al. (2017)). The global ambient CO_2 concentration was 413.52 ppm on May 3rd 2019 (CO2-Earth (2019)). The CO_2 concentration in exhaled breath is two orders of magnitude higher than the concentration in the ambient air, usually in the range 40000-55000 ppm. The human CO_2 production is dependent on activity level, age and body size (Persily and Jonge (2017)). In a classroom with children aged 6-11 years sitting reading or writing, corresponding with an activity level of 1.2 met, the CO_2 production is $0.0030 L/s$ per person for boys and $0.0027 L/s$ per person for girls. A teacher aged 30-60 years has a CO_2 production of $0.0119 L/s$ per person for men and $0.0116 L/s$ per person for women at an activity level of 3 met, which corresponds to standing or walking slowly (Persily and Jonge (2017)). At the same activity level, adults produce 20% more CO_2 than children (Zhang et al. (2017)). Indoor levels of CO_2 depend primarily on human occupancy and on the rate of air exchanged with the outdoor air, and a high indoor concentration level of CO_2 is a result of inadequate ventilation in relation to the number of people present. Satisfactory ventilation rates should provide CO_2 concentrations below the recommended standard of 1000 ppm (Veiledning444 (2016)).

Reaching low CO_2 concentrations in classrooms is important in order to promote good learning processes and provide a stimulating environment (Chatzidiakou et al. (2012)). An important instrument to achieve low CO_2 levels is the development and implementation of ventilation strategies. One ventilation strategy is CO_2 controlled DCV, where the ventilation rate in a room or zone is increased when CO_2 levels increase and reduced when CO_2 levels decrease (Ingebrigtsen (2018b)), with the aim of maintaining CO_2 levels below a value of 1000 ppm or lower. For CO_2 controlled DCV, classrooms must be equipped with monitoring devices for CO_2 levels. Often devices monitoring room temperature and humidity levels are installed too, to maintain acceptable levels of these parameters as well (Ingebrigtsen (2018b)). Temperature and humidity levels do not affect the CO_2 levels, but the comfort of the occupants is dependent on the temperature and humidity levels in addition to the CO_2 levels (Ingebrigtsen (2018a)). Temperature levels should be between 20^{o}C and 22^{o}C during winter and 22^{o}C and 24^{o}C during summer and a RH should be between 40% and 60% (Salthammer et al. (2016)). In figure 2.1 recommendations for comfortable (green), acceptable (yellow) and non-acceptable (red) climatic condition ranges in classrooms are shown.

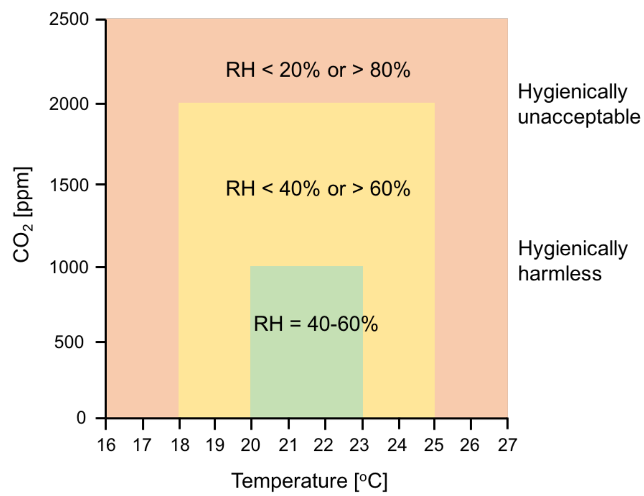


Figure 2.1: Recommendations for comfortable (green), acceptable (yellow) and non-acceptable (red) climatic condition ranges in classrooms.

Source: Made with inspiration from Salthammer et al. (2016).

Bothers and health effects

At CO_2 levels in indoor air in typical non-industrial environments, no psychological, physiological, toxicological or adaptive changes are observed (FHI (2015)). However, the study Jafari et al. (2015) looked at the association between SBS and indoor air pollutants in office buildings in Iran. The study found that as CO_2 levels increase in a building, the SBS symptoms in occupants such as nausea, headaches, nasal irritation, throat irritation and concentration difficulties increase as well. The lowest level where observed effects have occurred in experiments on humans and animals is at 10000 ppm (EPA (1991)), and a concentration that high is not relevant for classroom situations. Even though indoor CO_2 concentrations in non-industrial environments are not thought to be a direct cause of adverse health effects, they can be an easily measured surrogate for other occupant generated pollutant such as bioeffluents (often referred to as body odors) (Fisk and De Almeida (1998)). This has been verified by test chamber studies, which have shown that the CO_2 concentration indoors can be correlated to the intensity of bothers related with body odors (Fisk and De Almeida (1998)). High CO_2 levels are followed by the feeling of the air being heavy with a bothersome smell, which to a certain extent will bother individuals (FHI (2015)). At a CO_2 level of approximately 1000 ppm in a room, around 20% of all people entering the room will experience a bothersome odor level. For the people who are already in the room, 20% will experience a bothersome odor level at a CO_2 concentration of 2000 ppm (Persily (1997)). Regarding health effects related to CO_2 levels, increasing ventilation rates (from 1.3 to 12.8 l/s per person) with a corresponding decrease of mean indoor CO_2 (from 1050 to 780 ppm) resulted in a significant reduction of asthmatic symptoms in pupils from 11.1 to 3.4% over a two year period (Chatzidiakou et al. (2012)).

Risk assessment and recommended limit value guidelines for CO_2

CO_2 does not constitute a health hazard for typical concentration levels in non-industrial indoor climates (FHI (2015)). However, based on the fact that the CO_2 concentration level indoors is an indicator of the IAQ, the maximum concentration value is set to 1000 ppm (FHI (2015)). When following the regulations in VTEK (2017) §13-3 regarding airflow to a ventilated space, the CO_2 levels will be kept below 1000 ppm. Mysen and Schild (2014) states that because the CO_2 level is an indicator of the number of people and bioeffluent level in a room, ventilation rates should be controlled to maintain a maximum CO_2 level lower than 1000 ppm in primary schools, e.g. 900 ppm. This is due to children producing less CO_2 than adults.

2.3 Volatile organic compounds

Introduction

Volatile organic compounds (VOCs) is a collective term for organic chemical compounds, whose composition makes it possible for them to evaporate as gases under normal indoor atmospheric conditions of temperature and pressure (FHI (2015)). VOCs include a variety of organic chemicals, where some of them have or may have short and long term adverse health effects (EPA (2017)), and the outdoor sources have a lower impact on classroom concentrations compared to indoor sources (Salthammer et al. (2016)). Studies have found that the average levels of several VOCs are 2 to 5 times higher indoors than outdoors (EPA (2017)). A wide array of products emit different VOCs, and EPA (2017) have listed typical sources of different VOCs: Building materials, fuels, automobile exhaust, various household products, printers, papers, food, paints, varnishes, wax, cleaning products, disinfecting products, cosmetics and hobby products. Fuels and automobile exhaust are not relevant sources for primary school classrooms. There may be a large number of VOCs in common, non-industrial indoor environments such as primary school classrooms. The VOC types and quantities vary with the ventilation rates and the sources present in the respective premises (Johnson et al. (2018)). The effect of VOCs in indoor environments is to a great extent unknown, partly because detailed knowledge of many of the substances are lacking, partly because the VOC composition varies greatly and partly because the indoor air concentration of the substances where knowledge exists are well below the levels that are expected to trigger health effects (FHI (2015); WHO (2010)).

In warmer periods when the use of open windows is more common, the VOC levels indoors is closer to the VOC levels outdoors, while the VOC levels indoors is substantially higher than the VOC levels outdoors when windows are mostly shut (Johnson et al. (2018)). Indoor VOC emissions increase with increasing temperature levels, but are unaffected for varying air humidity levels (Liu et al. (2014)). Because it is possible to detect over 300 different VOCs indoors, each at a low concentration but higher than outdoors, the concept of total VOCs (TVOC) has been introduced in existing literature (FHI (2015); Guyot et al. (2018)). TVOC can only be used as an indicator of sensory effects, due to the greatly varying VOC composition, the complexity of associating TVOC to health outcomes and the unknown interaction of the compounds (FHI (2015)). However, TVOC levels in classrooms has been suspected to be the source of irritations, throat dryness and adverse health effects, and individual VOCs such as formaldehyde have been related directly to health effects (Chatzidiakou et al. (2012)).

The priority VOC compounds to be regulated indoors according to WHO (2010) are shown in table 2.1:

Table 2.1: Priority VOCs to be regulated indoors and their relevance in Norwegian primary school classrooms

VOC	**Typical sources**	**Possible sources in Norwegian primary school classrooms**
Acetaldehyde	Building materials (especially wooden products), laminate, linoleum, small amounts in coffee, bread and ripe fruit	All of the mentioned typical indoor sources
Benzene	Cigarette smoke, stored fuels, paint supplies, automobile emissions	None
Formaldehyde	Building materials (especially wooden products), combustion processes, cigarette smoke, furniture, textiles, paints, glues, adhesives, varnishes, laquers, cleaning products, cosmetics, electronic equipment, printers and paper products	All of the mentioned typical indoor sources, exept for combustion processes and cigarette smoke
Limonene	Main component of the oil in citrus fruit peels	Citrus fruit
Naphthalene	Cigarette smoke, automobile exhaust, wood combustion, main ingredient in traditional mothballs	None
Styrene	Cigarette smoke, automobile emissions, fiberglass, rubber, epoxy adhesives	None
Xylenes	Gasoline, automobile exhaust, solvents, markers, paint, floow polish, cigarette smoke	Markers, paint, solvents

Source: WHO (2010); EPA (2017)

Occurrence in indoor air

VOCs in indoor air originate from a combination of emissions from indoor building materials, human activities, consumer products, furniture, cleaning products, printers and outdoor sources. These sources combined with inadequate ventilation can lead to relatively high indoor TVOC concentrations (Veiledning444 (2016)). The indoor VOC sources can roughly be divided into stationary and variable sources (FHI (2015)). Stationary sources will yield a relatively small amount of VOCs to the indoor air, and this contribution will be relatively stable over time. However, the release from new building materials, surface treatments and interior products will usually be greater than from older ones, and the TVOC levels found in new or newly refurbished indoor environments can be significantly higher than the average level (FHI (2015)). These levels are usually greatest during the first period in a new or newly renovated building (Veiledning444 (2016)), and they will fall to more normal values after a few months or within a year. Porous building materials are not only sources of pollutant emissions such as VOCs, but can also be sinks of these pollutants (FHI (2015)). The knowledge of VOC transfer mechanisms in these materials is an important step in controlling indoor VOC concentration levels and for determining optimal ventilation rates for acceptable IAQ (Lee et al. (2005)). Variable sources of VOC in the indoor environment are many. Since the sources are present for limited time intervals they contribute to a greatly varying VOC content over time, both qualitatively and quantitatively. Cleaning products, cosmetics, food, paper, books and various hobby products are all examples of variable sources in primary school classrooms (FHI (2015)).

In many ways, primary school classrooms differ from other indoor environments. Often there is a high occupant density, and the rooms contain special furnishings such as chairs, tables, bookshelves, whiteboards, chalk boards and projectors. Toys, decorative items, books, paints, glues or modelling clay may also be present. As a consequence of the multitude of materials present and the activities that are carried out, a large number of different VOCs can be expected in classroom air and settled dust (Salthammer et al. (2016)). In Johnson et al. (2018), measured indoor TWA (time weighted average) TVOC concentrations in primary school classrooms ranged from 5-932 ppb. VOC species typically found included formaldehyde and those associated with fragrances (limonene) and solvents (xylenes). Indoor TVOC levels were substantially higher than outdoor levels, which were in the range of 0.1-52.2 ppb (TWA). In classrooms using marker boards, the VOC levels were higher than in classrooms using chalk boards, but in classrooms with chalk boards the particulate matter levels were higher than in classrooms with marker boards (Salthammer et al. (2016)).

Health effects

To assess health effects related to pollutants indoors and to propose possible limit values or other measures, a major project called INDEX was carried out by the WHO - Regional office for Europe. The levels of 40 single chemicals in indoor air were assessed. Among VOCs, the chemicals benzene, toluene, xylene, styrene, acetaldehyde, formaldehyde, naphthalene, limonene and α-pinene were classified as priority compounds to be regulated (WHO (2010)). Only formaldehyde, benzene and naphtalene were considered as first priority compounds based on actual concentration levels and known hazards (Koistinen et al. (2008)). The results from the INDEX project showed that formaldehyde - mainly from indoor sources - is generally a bigger problem in northern Europe, while benzene - mainly due to traffic pollution - is mostly a problem in southern Europe (FHI (2015)). High levels of naphthalene are due to the use of moth balls, and are therefore not considered to be a problem in Norway (FHI (2015)).

FHI (2015) states that among the many VOCs that can occur in indoor air, there are substances that can cause health damage if they are breathed in high concentrations. Knowledge of such effects is obtained from studies on occupational exposure, or from experiments on animals. However, for most of these substances effects can only be triggered after prolonged exposure to significantly higher concentrations than those found in indoor air. Nevertheless there are people who claim to react with different subjective symptoms upon exposure to chemical air pollutants, even in concentrations well below the levels where toxicological methods may suggest that health effects may occur (FHI (2015)). In Fisk and De Almeida (1998), evidence was found indicating that TVOC concentrations exceeding a few milligrams per cubic meter are likely to lead to health symptoms, however lower concentrations are not necessarily acceptable.

The organs that are exposed to the VOCs present in the air is highly dependant on the water solubility of each individual VOC. Very water soluble VOCs, like formaldehyde and other aldehydes, are quickly absorbed over the mucous membranes of the throat, nose and eyes. Less water soluble VOCs may penetrate deeper into the respiratory tract and possibly reach the pulmonary alveoli, which is the gas exchange zone in the lungs (FHI (2015)). Also, a number of VOCs can bind to the surface of air suspended particulate matter, thus making it possible for highly water soluble VOCs to be transported deeper into the respiratory tract than they would normally reach in gas form (Kalinić and Vadjić (2000)). Much of the interest around VOC in indoor air is largely due to speculations about their contribution to illness associated with stay in indoor environments. The possible health effects due to VOC exposure can be divided into three main groups; mucosal irritation, allergy, asthma and related respiratory symptoms, and cancer risk (FHI (2015)), presented in the following sections.

Mucosal irritation

VOCs can induce mucosal irritation by affecting the free nerve endings in the mucous membranes (FHI (2015)). Mucosal irritation is the sensory irritation symptoms that involve irritation of mucous membranes in the eyes, nose and throat and occasionally skin irritation, leading to e.g. dry throat, cough, tightness in chest, sore eyes, skin itches, sinus congestion or sneezing (WHO (2010)). Chamber studies have shown increased incidence of these symptoms in exposed individuals when VOCs has been added to the chamber air. However, these studies have used concentrations far above those found in most non-industrial indoor environments (FHI (2015)). At these levels, odors will cause the subjects to be aware that the exposure is high. This can affect the results, since both odor and mucosal irritation are important factors for the perception of air quality.

Although individual VOCs in indoor air, with the exception of formaldehyde, normally are not present in concentrations sufficient to provide mucosal irritation, it has been suggested that simultaneous exposure to several VOCs may lead to additive or synergistic effects (FHI (2015)). Possible connections between TVOC levels and mucosal irritation have been investigated by several major studies where participants have reported health issues in questionnaires. Correlations between high TVOC levels and symptoms of SBS, asthma and a feeling of dry, dusty air were found in three of the studies (Brasche et al. (2004); FHI (2015)). In Brasche et al. (2004) it was found that TVOC levels above $666 \mu g/m^3$ were associated with dry skin, and that TVOC levels above $900 \mu g/m^3$ were associated with mucosal irritation, sore throat, headache and fatigue.

Allergy, asthma and related respiratory symptoms

Allergy, asthma and related respiratory symptoms, and their connection to indoor VOCs have been investigated. In asthmatic people, breathing problems can be triggered when the mucous membranes of the airways become irritated (FHI (2015)). Such irritation may be related to indoor climate factors such as tobacco smoke, certain chemicals or strong odors. The connection between VOC and asthma is complicated by the fact that many such compounds can provide odor even at low concentrations. Odor itself can trigger asthma attacks on someone (FHI (2015); WHO (2010)). Mendell et al. (2002) found a clear increase in respiratory and allergic health effects among children in homes with higher concentrations of certain VOCs, especially formaldehyde. The conclusion so far is that more research is required before it can be determined whether VOCs in indoor environments leads to the development or worsening of allergy and asthma (FHI (2015)).

Cancer risk

Cancer risk from VOC exposures has been calculated using risk assessment models and exposure models. Some estimates are based on extrapolations from high dose exposures (typically occupational exposures) to low dose exposures, and other estimates are based on animal testing, extrapolating from animals to humans (FHI (2015)). Such models are usually conservative and overestimate the cancer risk. The calculation of the cancer risk related to different VOCs is based on the general assumption that the risk will be proportional to the exposure amount, and that there is no lower threshold. If this assumption is correct, it must be assumed that any exposure to known carcinogens entails a certain risk. VOCs found in indoor air that are considered to be carcinogenic or possibly carcinogenic, are formaldehyde, benzene, acetaldehyde, naphthalene and styrene, where formaldehyde is the most relevant VOC in normal Norwegian indoor environments such as primary schools (FHI (2015); WHO (2010)). Overall, when it comes to the cancer risk related to VOC exposures, the estimated cancer risks vary widely, and are assumed to be very low in most cases in non-industrial indoor environments such as primary school classrooms (FHI (2015)).

In table 2.3, the cancer risks of the priority VOC compounds to be regulated according to WHO (2010) are shown. However, there are no sure evidence that typical VOC component levels in Norwegian non-industrial indoor environments poses any health risks (FHI (2015)).

Table 2.2: Cancer risk of the priority VOCs to be regulated indoors

VOC	Classification	Basis
Acetaldehyde	Category 2B (possibly carcinogenic to humans)	Based on the increased incidence of nasal tumors in male and female rats, and laryngeal tumors in male and female hamsters after inhalation exposure.
Benzene	Group 1 (carcinogenic to humans)	Based upon convincing human evidence as well as supporting evidence from animal studies, benzene is characterized as a known human carcinogen for all routes of exposure.
Formaldehyde	Group 1 (carcinogenic to humans) and category 2 (mutagen)	Occupational studies and animal studies have noted statistically significant associations between exposure to formaldehyde and increased incidence of lung and nasopharyngeal cancer.
Limonene	Group 3 (not classifiable as to its carcinogenicity to humans)	This substance has not undergone a complete evaluation and determination under EPA's IRIS program for evidence of human carcinogenic potential.
Naphthalene	Group 2B (possibly carcinogenic to humans)	Available data are inadequate to establish a causal relationship between exposure to naphthalene and cancer in humans.
Styrene	Group 2A (probably carcinogenic to human)s	Probably carcinogenic, especially in case of eye contact, but also in case of skin contact, ingestion or inhalation.
Xylenes	Group 3 (not classifiable as to its carcinogenicity to humans)	This substance has not undergone a complete evaluation and determination under EPA's IRIS program for evidence of human carcinogenic potential.

Source: WHO (2010); EPA (2017); IARC (2019)

Risk assessment

There are no clear indications that the VOC levels in Norwegian indoor environments, neither in terms of single substances nor assessed overall, constitute a significant health risk (FHI (2015)). However, the most relevant VOC in normal Norwegian indoor environments is formaldehyde, which is classified as carcinogenic to humans. Regarding asthma disease, it can not be excluded that VOC exposure may affect the occurrence and severity of asthma attacks, but more knowledge is necessary before this can be fully determined. Chamber studies show that high TVOC concentrations (>25 mg/m^3) can cause acute irritation effects, but such concentrations may only occur in connection with painting or extensive use of solvents (FHI (2015)) and most likely not during the occupation time in primary school classrooms.

Recommended limit value guideline for TVOC

The professional basis for setting a health based standard for TVOC concentrations is insufficient for indoor air concentrations and for degassing from materials. This is due to the variable TVOC compositions, the limited knowledge on the effects of the individual VOCs and the effects of the countless combinations of VOCs. Thus, there is no international standard for TVOC concentrations. Based on a practical approach, unnecessary exposure should be avoided (FHI (2015)). The German Federal Ministry of Health has recommended a guideline for TVOC of 1000 $\mu g/m^3$ (Salthammer et al. (2016)). This guideline value is not used in Norway. However, in Norway the emission of TVOC in a low emission building is <0.2 $mg/(m^2h)$, while in a very low emission building it is <0.1 $mg/(m^2h)$ (NS-EN15251 (2007)). Some single VOCs have recommended limit value guidelines, such as formaldehyde (FHI (2015)).

Practical advice

As VOCs in indoor air mostly originate from indoor sources, adequate ventilation generally reduces TVOC levels in most indoor environments. Source control is important, and specific sources that contribute to elevated VOC levels should be removed, or as far as possible be limited by general caution (FHI (2015); Jiang et al. (2017)). VOCs can be adsorbed to suitable surfaces and be dispensed to the air even after the use phase, known as source and sink effects (Lee et al. (2005)). Unfortunate storage conditions for products that can emit VOCs are not uncommon, but should be avoided by eliminating the need for storage, or by storing the products in other places than the occupied zone. Today's standard is to choose building products, materials and fixtures that are documented low or no emission (VTEK (2017)), consequently with low VOC releases to the indoor environment (FHI (2015)). In new and newly refurbished buildings, it is expected that the VOC levels are elevated for a period of time. After the construction of new buildings or after renovation work, the premises should be cleaned and left unused for a period before use. It is an advantage that schools are renovated during the summer vacation, and left to degass for at least 1-2 weeks with high ventilation rates before the start of the school year (FHI (2015)).

2.4 Formaldehyde

Introduction

Formaldehyde is a naturally occurring organic compound with a boiling point of -19^oC (FHI (2015)). It is mainly used in the production of industrial resins, e.g. for particle boards and coatings, and the global annual production of 37% formaldehyde was about 20 million tons in 2010 (Salthammer et al. (2010)). Due to its widespread use, toxicity and volatility, formaldehyde poses a significant danger to the human health (WHO (2010)). It is an air toxic that is emitted from a variety of both indoor and outdoor sources, resulting in its presence in both indoor and outdoor air. The range of potential formaldehyde sources is extensive due to its prevalence as a chemical additive in many products and industrial processes, its occurrence in natural wood and as a byproduct of combustion from vehicles and burning of biomass (Lazenby et al. (2012)). Formaldehyde has been discussed as an indoor air pollutant since the mid 1960s, when adverse health effects from indoor exposure to formaldehyde, especially irritation of the eyes and upper airways, were first reported. Since then, formaldehyde has been known as one of the priority indoor air pollutants (Salthammer (2019)). IARC classified formaldehyde as a human carcinogen (group 1) in 2004 (IARC (2006)), and this evaluation was based on the relationship between nasopharyngeal cancer and leukemia related to formaldehyde exposure. The European Commission classified formaldehyde as a carcinogen (category 1B) and mutagen (category 2) in 2014 (Salthammer (2019)). The WHO re-evaluated and confirmed their indoor guideline value for formaldehyde as 100 $\mu g/m^3$ in 2010 (WHO (2010)) and FHI uses the same indoor guideline value (FHI (2015)). A NOAEL (no observed adverse effect levels) of 30 $\mu g/m^3$ was mentioned in the INDEX report, and this corresponds to the lowest odor threshold reported. A NOAEL found for sensory eye irritation was 0.5 ppm (Salthammer et al. (2010); Koistinen et al. (2008)).

The most used method for measuring formaldehyde levels in the air is by using a sorbent tube impregnated with 2,4-dinitrophenylhydrazine (2,4-DNPH), where the formaldehyde is trapped (WHO (2010)). Analysis is then conducted in the laboratory by high performance liquid chromatography and ultraviolet detection at 350 nm. Detection and quantification limits around 1 $\mu g/m^3$ can be achieved with this method.

Occurrence

The human exposure to formaldehyde is mainly originating from the indoor environment and not the ambient environment. Substantial sources have been building materials such as particle boards, formaldehyde resin and urea formaldehyde foam insulation (Salthammer et al. (2010)). Even natural wood contain and emit a certain amount of formaldehyde (FHI (2015)). Evaporation of formaldehyde from particle boards and other glued wood products has decreased significantly because the quality of these products has been improved by targeted product development (FHI (2015)). Other indoor sources are combustion processes such as smoking, cooking and poorly functioning ovens and fireplaces, but these are not relevant for Norwegian primary school classrooms. Major sources in addition to building materials appear to be furniture, consumer products such as textiles, do-it-yourself products (paints, wallpapers, glues, adhesives, varnishes and laquers), household cleaning products, cosmetics, electronic equipment, printers and paper products (WHO (2010)). All these sources are relevant in Norwegian primary school classrooms.

Formaldehyde sources can be permanent, temporary or intermittent (Salthammer (2019)). High occurrence of formaldehyde may be due several sources in combination with inadequate ventilation. The off-gassing of formaldehyde from permanent sources is usually greatest during the first time in a new or newly renovated building, and these emissions decrease significantly within the first year of use (Veiledning444 (2016); Salthammer (2019); Lazenby et al. (2012)). An inverse correlation between the indoor formaldehyde concentration and the air exchange rate has been found in several studies (Salthammer et al. (2010); Salthammer (2019)). In schools, the construction material can have an impact on the formaldehyde concentration (e.g. floor covering, ceiling tiles, wall paint) (FHI (2015)). Especially after refurbishment or renovation, the emissions from the newly introduced material can be substantial, and increased ventilation rates might be necessary for some time. Generally, construction material with a high surface to volume ratio are important to be considered for good IAQ (Salthammer et al. (2016)). The estimation of human formaldehyde exposure indoors is challenging, and requires comprehensive information on the indoor conditions, activities, indoor climate, ventilation, emission rates, infiltration from the outdoors, chemical reactions, possible sink effects and the influence of product aging (Salthammer (2019)).

Formaldehyde can be produced from oxidation processes between monoterpenes (α-pinene, β-pinene, 3-carene, limonene) and ozone, meaning that the production of formaldehyde from chemical reactions will coincide with high concentrations of monoterpenes and their reaction partners. Terpene concentrations can easily reach 100-200 ppb in indoor environments, and ozone concentrations of 10-50 ppb are not uncommon (Salthammer (2019)). In Jiang et al. (2017) it was found that the emission of formaldehyde and TVOC from particleboard increased significantly with temperature. At room temperatures, formaldehyde is the most abundant VOC (FHI (2015)). After heat treatment of the particleboard at 50-60^{o}C the emissions of formaldehyde and TVOC decreased significantly. Regarding indoor wall paint, undesirable byproducts, especially formaldehyde, might be formed from degradation of the paint ingredients during irradiation (Salthammer (2019)). Increasing humidity in the air could increase evaporation of formaldehyde from building materials (FHI (2015)). Formaldehyde is not found in house dust (Salthammer (2019)).

In the European INDEX study, the indoor formaldehyde level in the central and northern parts of Europe was estimated to be 30 μg/m^3, while the highest measurements showed levels up to 115 μg/m^3 (Koistinen et al. (2008)). Recent data on formaldehyde concentrations in Norwegian buildings are not available, but evaporation of formaldehyde from new building materials is significantly reduced, and today's extensive use of plasterboard in new buildings is believed to further reduce formaldehyde levels in indoor air (FHI (2015)). The emission of formaldehyde in a low emission building is <0.05 mg/(m^{2}h), while in a very low emission building it is <0.02 mg/(m^{2}h) (NS-EN15251 (2007)).

In Johnson et al. (2018), indoor formaldehyde levels above the level of detection (10 ppb) were detected in one of the 12 studied schools in urban Oklahoma. The TWA concentration was 15 ppb, and the peak was 18 ppb. It was unclear what sources might account for this. In the same study outdoor levels were measured, and the concentration was below the level of detection for all outdoor measurements during school hours. Outdoor formaldehyde concentrations in urban regions differ greatly, and in northern and central Europe values between 3 and 15 ppb are typical. The average formaldehyde concentrations in European ambient air are lower compared to many non-European areas (Salthammer (2019)). In a study in Sweden in 2001, the formaldehyde concentration was measured in 181 classrooms. The geometric mean was found to be 3 μg/m^3, with a range of <3-72 μg/m^3 (Salthammer et al. (2010)). Wood-based furniture may in particular increase the level of formaldehyde in a room, but elevated formaldehyde concentrations can also be caused by other sources (FHI (2015)).

Health effects

Due to formaldehyde having a high water solubility, it is mainly absorbed in the upper respiratory tract. It is assumed that approximately 90% of inhaled formaldehyde is absorbed in the nasal mucosa, and maximum 10% will normally reach the larynx and possibly penetrate the trachea. It is assumed that little or no formaldehyde reaches the gas exchange zone of the pulmonary alveoli (WHO (2010); Garcia et al. (2009)). Formaldehyde has a low permeation coefficient through skin, thus the dermal pathway can be neglected (Salthammer (2019)). Therefore, inhalation is the major route of exposure. Based on this, the mucous membranes in the nose and eyes are normally considered to be the most vulnerable areas for formaldehyde exposure. However, people don't breathe exclusively through their noses. Oral breathing will result in a significantly larger proportion of inhaled formaldehyde being absorbed in the lower respiratory tract (FHI (2015)). Oral breathing is typical for children, and also for individuals with chronic obstruction in the nasal cavity, which is common when suffering from asthma or allergic rhinitis (FHI (2015)). Increased physical activity will also lead to an increased amount of oral breathing, in addition to increased breathing rate and inhalation volume (Overton et al. (2001)). There are data indicating that up to 70% of formaldehyde may be bound to particles in the indoor air, depending on temperature. This may to some extent affect where in the respiratory system there is formaldehyde exposure (FHI (2015)). Sensory irritation at low concentrations is the predominant effect of formaldehyde, which at higher concentrations will progress to cytotoxic irritation with cell destruction. These effects are concentration dependent and not time dependent. The threshold concentrations for sensory and cytotoxic irritation are therefore very similar for acute and chronic exposures. Concentrations not leading to sensory irritation after acute exposures are not expected to result in adverse effects after prolonged exposures (Salthammer et al. (2010)).

The health effects of formaldehyde exposure can be divided into two main groups, the first being respiratory irritation, asthma and allergy, and the second being gentoxicity and cancer (FHI (2015)), described in the following sections.

Respiratory irritation, asthma and allergy

Short term, acute exposure to formaldehyde can cause eye, nose and throat irritation along with concentration dependent discomfort, tearing, sneezing, coughing, nausea, difficulty breathing and odor discomfort (FHI (2015); WHO (2010)). There is a considerable variation in the individual sensitivity to formaldehyde, and the threshold for odor discomfort appears to vary widely, in the approximate range of 50 $\mu g/m^3$ - 500 $\mu g/m^3$, with a clear increase in irritation symptoms at levels above 100 $\mu g/m^3$ (Jenkins (1978); FHI (2015)). It is unclear whether there is a causal relationship between formaldehyde and allergic asthma, or whether formaldehyde induces airway irritation resembling allergic reactions in children (Salthammer et al. (2010)). Several health effects have been associated with inhalation exposure to formaldehyde, and a number of studies have reported associations between formaldehyde concentrations and asthma like symptoms in children (Lazenby et al. (2012)), but due to weaknesses in the study designs, these results must be regarded as unclear (FHI (2015)). Neither experimental nor epidemiological studies of adults and children have identified lung effects at formaldehyde exposures below 1 mg/m^3, and this agrees with the high retention of formaldehyde in the nasal cavity (Wolkoff and Nielsen (2010)). However, it is well known that children generally are more vulnerable to harmful effects of air pollution and chemical exposure than adults, both due to their increased oral breathing and due to their airways not being fully developed (Bateson and Schwartz (2007)). Experiments with humans have shown that self perceived mild to moderate mucosal irritation seems to occur at a formaldehyde concentration of 380 μg/m^3, and the threshold for eye irritation seen as increased blink frequency is 630 μg/m^3 (WHO (2010)). There are no clear indications of increased susceptibility of sensory irritation to formaldehyde among individuals considered to be sensitive, like asthmatics, children or elderly. In Nielsen et al. (2013), which is a more recent review of studies on formaldehyde in indoor air, the base of WHO (2010) was supported.

Cancer risk

A possible correlation between formaldehyde exposure and cancer has been investigated in several experimental animal studies and studies of occupationally exposed humans (FHI (2015)). In humans, formaldehyde can cause cancer in the transition between the nasal cavity and the throat (WHO (2010); FHI (2015)). No prevalence of this cancer type has been observed at average concentration levels up to 1.25 mg/m^3 and exposure peaks up to 5 mg/m^3 (Salthammer et al. (2010)). A number of epidemiological studies have shown increased frequency of such cancer following occupational exposure to formaldehyde at significantly higher exposure levels than those found in common indoor environments (IARC (2006)). Long term exposure to formaldehyde concentrations of 7.5 mg/m^3 or more may induce cancer in the nasal cavity of rats (Swenberg et al. (2013)).

There are also indications of a correlation between occupational exposure to formaldehyde and cancer of blood and lymphatic organs, mainly leukemia (Swenberg et al. (2013); Salthammer et al. (2010)). However, even though effects on bone marrow and blood cells are possible, these effects occur only at higher concentrations than those possible of causing cancer in the nasal cavity (FHI (2015); WHO (2010)). This means that a limit value set to protect against cancer in the nasal cavity will also protect against leukemia, which is suggested by both long term inhalation studies with experimental animals and studies of people with high occupational exposure (FHI (2015); WHO (2010)). According to the IARC evaluation (IARC (2006)), the epidemiological evidence was strong but not sufficient to conclude that formaldehyde exposure causes leukemia in humans. Additionally, a plausible mechanism has not been identified on how leukemia may be induced after formaldehyde inhalation (Salthammer et al. (2010)).

Concentrations not resulting in cytotoxic irritation with an increased cell proliferation would represent a threshold for carcinogenic action upon the upper respiratory tract (FHI (2015)). Because cytotoxic irritation only occurs at concentrations clearly above those leading to sensory irritation, a carcinogenic action is not to be expected as long as sensory irritation is avoided. The sensory detection limits should therefore provide protection against tumor induction by formaldehyde (Salthammer et al. (2010)). Data on the genotoxic effects of formaldehyde indicate a non-linear dose response ratio, and this indicates that the cancer risk increases significantly for exposures above a threshold level, which is 2.5-3.7 mg/m^3 for rats (FHI (2015)). Overall, the IARC assessed the available data as sufficient to classify formaldehyde as carcinogenic to humans (Group 1) (IARC (2006)). Later, the European Commission classified formaldehyde as a carcinogen (category 1B) and mutagen (category 2) in 2014 (Salthammer (2019)).

Much attention has been focused on calculating the size of cancer risk in humans. It has been concluded that the risk of respiratory cancer due to formaldehyde exposure was exceedingly low for concentrations lower than 100 $\mu g/m^3$ (80 ppb), based on the effect of formaldehyde on cell division in animal experiments (Liteplo and Meek (2003)). Thus there is no reason to believe that formaldehyde causes health effects in the lower respiratory tract at concentrations below this limit. However there are few experimental and clinical studies that have focused on the effect of concentrations below this limit (FHI (2015)). All in all, protection against short term acute irritation due to formaldehyde exposure will also protect against potential carcinogenic effects (FHI (2015)).

Recommended limit value guidelines for formaldehyde

In order to protect the public and workers from experiencing sensory irritation due to formaldehyde exposure, the recommended formaldehyde guideline value of 100 $\mu g/m^3$ (80 ppb) as a 30 minutes average is set (FHI (2015); WHO (2010)). This guideline value will also prevent effects on lung function as well as nasopharyngeal cancer and myeloid leukaemia (WHO (2017)).

Practical advice

Techniques for lowering the formaldehyde concentration indoors have been widely discussed. The most relevant techniques in indoor environments today are the avoidance of sources and prevention of emissions already from the beginning of a building project, removal of the source from existing buildings, and increased ventilation rates (Salthammer et al. (2010); Wolkoff and Nielsen (2010)). Most wooden products contain and emit a certain amount of formaldehyde, even natural wood. Evaporation will usually be greatest for new materials, and gradually decrease over time (Ingebrigtsen (2018a)). Thus, in all new or recently refurbished buildings, elevated formaldehyde concentrations are expected. In some cases the elevated concentrations exceed the recommended guideline value (FHI (2015)). It is suggested to use measured formaldehyde emissions in buildings to develop minimum ventilation rates (Salthammer et al. (2010)). As a general advice, it should be avoided that children are placed in newly refurbished rooms or buildings (WHO (2010)). The use of formaldehyde resins in modern wooden products is greatly reduced, and the best products provide a formaldehyde content at the level of what occurs in natural wood (FHI (2015)). For Norwegian products there are several labelling schemes which impose strict requirements regarding the formaldehyde content, but imported building plates from other countries may contain high levels of formaldehyde (FHI (2015)). The off-gassing of formaldehyde from building materials increases with increasing temperature, and possibly with increasing humidity, but it decreases over time. This can be taken advantage of by venting out the new building before moving in, by raising the temperature while the ventilation system is in full operation, preferably over 2-3 weeks or more (Veiledning444 (2016)).

2.5 Particulate matter

Introduction

Particulate matter are particles small enough to be airborne for a longer period of time, and they consist of a varying mixture of components (FHI (2015)). The main components of particulate matter are organic compounds (mainly saturated and unsaturated hydrocarbon, such as VOCs and PAHs), inorganic compounds (mainly water-soluble inorganic salts and inorganic elements), biological components (skin flakes, bacteria, fungi, viruses, pollen and plant fibres) and carbon (Li et al. (2017)). The sizes of these particles vary. In primary schools important indoor sources are found to be resuspension of soil particles from shoes, clothes and surfaces, organic particulate matter from skin flakes and clothes fibres and calcium rich particles from chalks and building deterioration (Amato et al. (2014)).

The particulate matter composition, size and other characteristics are of great importance for the evaluation of possible health effects. For regulatory purposes, particulate matter has been classified by aerodynamic diameter (given in μm), because size is a critical determinant for the distribution and deposition in the respiratory tract. The PM_{10} fraction and its subgroups, especially $PM_{2.5}$, are considered to have the biggest importance to health, because these can reach the lower airways (FHI (2015); WHO (2005)). Different types of particulate matter can bind different chemical substances to their surface, and they can therefore be important carriers of harmful substances (FHI (2015); WHO (2005)). The particulate matter composition vary according to the predominant sources, season, weather conditions and space, and this contributes to particulate matter having a highly variable toxicity (FHI (2015)).

Particulate matter are classified into size categories, visualized in figure 2.2:

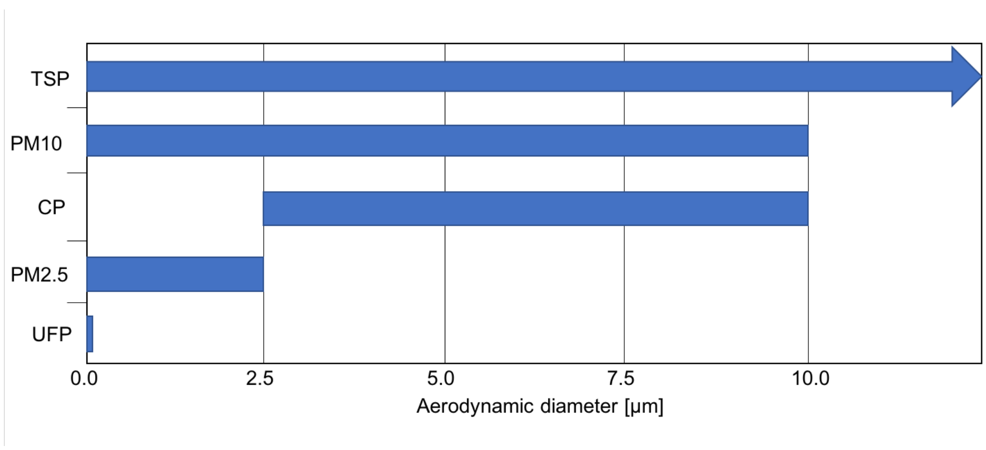


Figure 2.2: Size categories of particulate matter.

Source: Made with inspiration from Martins and Carrilho Da Graça (2018).

Explanation of the size categories in figure 2.2 are given in table 2.3:

Table 2.3: Size categories of particulate matter

Size category	Definition
TSP (total suspended particles)	Includes any solid or liquid matter in suspension in the air.
PM_{10}	Includes all particulate matter with an aerodynamic diameter of less than 10 μm, which are the inhalable particles that are sufficiently small to penetrate to the thoracic region
CP (coarse particles)	The fraction of PM_{10} that does not include $PM_{2.5}$. CP mainly reach the pharynx, larynx or trachea, or reach the upper parts of the bronchi. CP are to a large extent mechanically produced by the break-up of larger solid particles
$PM_{2.5}$	Includes all particulate matter with an aerodynamic diameter of less than 2.5 μm, which is the fine fraction of PM_{10} (often referred to as fine particles). These particles have a high probability of deposition in the smaller conducting airways and alveoli. $PM_{2.5}$ tend to originate from gases and combustion reactions such as vehicle emissions and industrial processes. $PM_{2.5}$ broadly represents around 50% of the total mass of PM_{10}
UFP (ultrafine particles)	UFP consists of $PM_{0.1}$ and includes all particulate matter with an aerodynamic diameter of less than 100 nm. UFP, like $PM_{2.5}$, tend to originate from gases and combustion reactions such as vehicle emissions and industrial processes. UFP can translocate from the alveoli to the circulatory system

Source: Martins and Carrilho Da Graça (2018); Zwozdziak et al. (2016); Wu et al. (2018); FHI (2015)

Occurrence in indoor air

The main indoor sources of particulate matter include human activities and building materials such as smoking, cooking, mineral fibres, printers, office equipment, skin flakes, droplet nuclei from sneezes and coughs, microorganisms, aerosol sprays, resuspension from surfaces and abrasion of surfaces (Chatzidiakou et al. (2012); Fisk et al. (2000); Li et al. (2017)). Primary school classrooms lack the strong indoor particulate matter sources such as smoking and cooking, resulting in indoor particulate matter concentrations often being lower than outdoor concentrations as a consequence of several particulate matter removal processes such as intentional particulate matter removal by filtration in the HVAC system, and particle deposition on indoor surfaces (Fisk et al. (2000)). Particulate matter also penetrate into the classrooms via ventilation and infiltration from the outdoor environment, and it is drawn in from sandy playgrounds via clothes and shoes (Chatzidiakou et al. (2012)). A high occurrence of particulate matter in indoor classroom air can result from inadequate cleaning of the premises or poor filtration of the air supplied to the premises (Veiledning444 (2016)). Chalk boards increase $PM_{2.5}$ levels in schools (Salthammer et al. (2016)). Although airborne particles eventually settle onto surfaces, one of the most common contributors to high $PM_{2.5}$ levels in all buildings is the resuspension of these particles due to occupant movement or increased ventilation airflows. This has the highest relevance in buildings where movement is frequent and where ventilation airflows are variable, such as in schools (Martins and

Carrilho Da Graça (2018)). Fabrics such as curtains and rugs can act as sinks and sources for particulates, thus they can increase the exposure time of these substances (Salthammer et al. (2016)).

In indoor air the PM_{10} fraction will be dominated by fine particles ($PM_{2.5}$), whether these particles originate from indoor or outdoor sources (FHI (2015)). Indoor particle number concentrations are dominated by the finest particles, due to ventilation filters that prevent a large amount of the coarse particulate matter from entering the building via the HVAC system. Indoor particulate matter concentrations in large sealed mechanically ventilated buildings vary considerably with time. Replacement of normal air filters with high efficiency filters can drastically reduce indoor number concentrations of UFP (Fisk et al. (2000)). In Johnson et al. (2018), a study in 12 third grade classrooms in urban Oklahoma, indoor TWA $PM_{2.5}$ concentrations ranged from 1.5 to 98.3 $\mu g/m^3$ (mean: 13.5 $\mu g/m^3$), and indoor TWA PM_{10} concentrations ranged from 0.5 to 84.3 $\mu g/m^3$ (mean: 18.7 $\mu g/m^3$), indicating a high variability in the levels. A study of indoor air in schools and kindergartens in Oslo showed an average level of $PM_{2.5}$ of 8.5 $\mu g/m^3$ (min: 2.6 $\mu g/m^3$, max: 12.9 $\mu g/m^3$) (Rakkestad et al. (2007)).

The amount of particulate matter in the ambient air of a building depends on the location of the building relative to trafficked roads, industry and urban areas. The location of the air intake to the building is of great importance, and placing it at the the part of the building which is least exposed to outdoor particulate matter is beneficial (FHI (2015)). Sources of outdoor $PM_{2.5}$ include road dust, vehicle emissions, industry combustion processes, other industry activities and secondary particles produced by chemical reactions of primary particles in the atmosphere (Li et al. (2017)). Road traffic is often the most important source of particulate matter (FHI (2015); WHO (2005)). In areas of high outdoor pollution, particulate matter from the outside air will dominate the indoor levels, and it is mainly $PM_{2.5}$ that is penetrating from the outside air. Although the particulate matter level indoors is dependent on the sources present, the $PM_{2.5}$ concentration in indoor air is generally equal to or lower than in outdoor air (FHI (2015)).

Health effects

Particulate matter can damage cells in all parts of the airways, directly by toxic effects on the cells or indirectly by initiating local inflammatory reactions. These reactions can in turn cause a systemic inflammatory state with damage to cells and tissues (Wu et al. (2018)), and this response is believed to be a major biologic mechanism underlying health events related to particulate matter exposure (FHI (2015)). Particulate matter may also be carriers of allergens, carcinogens, organic substances or other chemical substances, and these are more easily bound to $PM_{2.5}$ than to PM_{10} due to $PM_{2.5}$ having larger specific surface area and bigger absorption ability (Li et al. (2017); FHI (2015)). There is a general consensus that the smaller the size of the particles, the greater the health effects (Li et al. (2017)). Exposure to coarse particles appears to be at least as strongly associated with acute illness as fine particles, whereas the fine particles appear to be stronger associated with mortality than coarse particles, which also emphasizes that different particle sizes may have different effects (Brunekreef and Forsberg (2005)). Fine particulate matter pollution can enter the body through the inhalation airflow, transverse the respiratory tract and reach the pulmonary alveoli, triggering inflammatory responses from the body along this path and decreasing the immunity system's capability of response. Once in the lungs, $PM_{2.5}$ can enter the bloodstream en spread to other organs (Martins and Carrilho Da Graça (2018)). Young children are especially susceptible to respiratory illnesses (FHI (2015)). Even though the exposure-response relationship for $PM_{2.5}$ is reasonably understood for adults, the epidemiological studies on children's exposure-responses have in general produced inconsistent results (Salthammer et al. (2016)).

There is considered a clear connection between exposure to PM_{10} in outdoor air and development or worsening of pulmonary and cardiovascular disease, and this seems especially to apply to the sub fraction $PM_{2.5}$, however the effect on lung cancer from particulate matter exposure is much smaller than the effect from smoking (Schwarze et al. (2006); WHO (2005)). Rising $PM_{2.5}$ levels in outdoor air are associated with acute illness in the form of an increase in hospitalizations and doctor visits related with pulmonary and cardiovascular disease, and these contexts seem to be stronger for particulate matter originating from traffic and industry than from other sources (Petros et al. (2009)). An increase of outdoor PM_{10} from 50 to 100 $\mu g/m^3$ resulted in an increase of 40% in children school absence, an effect which lagged up to several weeks, and with younger children in the age 5-8 years primarily affected (Chatzidiakou et al. (2012)). Exposure to particulate matter in outdoor air is one of the most serious environmental related health problems in the global context (Roberto et al. (2011)).

Studies on particulate matter in indoor environments seem to indicate a possible association with the development or worsening of various respiratory symptoms (FHI (2015)). A number of studies show that exposure to particulate matter in outside air is associated with the deterioration and possibly also the development of asthma. There have also been found associations between particulate matter and the occurrence of COPD (chronic obstructive pulmonary disease), but the data are not considered strong enough to determine whether there is any direct connection (Eisner et al. (2010)). However, findings indicate that childhood asthma may be the main cause of the development of COPD. Children with severe persistent asthma are reported to have 10-30 times higher risk of developing COPD later in life (Svanes et al. (2010)). Thus, there is a basis for assuming that particulate matter can indirectly contribute to COPD development in the event of deterioration or development of asthma. The presence of various allergens, such as house dust, moulds, feathers, hair and fur in indoor environments contributes to the indoor PM_{10} levels and has a major effect acting as asthma triggers (Liu et al. (2018)).

In the study Zwozdziak et al. (2016), the aim was to assess the short-time effects of indoor particulate matter with different aerodynamic diameters ($PM_{2.5}$, PM_1) on the lung function data in 141 healthy schoolchildren aged 13-14 years. Exposure to elevated particulate matter concentrations caused a decrease in the lung function parameters in healthy schoolchildren, resulting in poorer spirometry results. A greater effect on lung parameters was observed for PM_1 than for $PM_{2.5}$. The study also discovered that children are more vulnerable to air pollution, due to greater ventilation rate per body weight and greater pulmonary surface compared to adults. Deep breathing pulls air pollutants faster and further into the lungs, bypassing the typical areas of deposition (Hai-Ying et al. (2018)). The pulmonary region of the lungs has slower clearance, meaning that particles remain there longer, resulting in a particle dose of two to four times higher among young children compared to adults (Hai-Ying et al. (2018)). Evidence from the study suggests that 50% of particles smaller than 4 μm in diameter penetrate into the lower respiratory tract in children (Zwozdziak et al. (2016)). In the literature review Martins and Carrilho

Da Graça (2018), a study in Shanghai found that high levels of $PM_{2.5}$ worsened the symptoms of children affected by asthma, and a study in the Netherlands found that an increase of $PM_{2.5}$ levels of 10 $\mu g/m^3$ relative to the previous day was correlated with a 0.8% risk increase in allcause mortality.

The literature review Liu et al. (2018) concludes that there is good evidence of the adverse effects of exposure of PM_{10} on the respiratory health of young children. Particulate matter exposure affects lung development in children, including irreversible deficits in lung function as well as chronically reduced lung growth rate and a deficit in long term lung function. There is no evidence of a safe level of exposure to particulate matter, or a threshold below which no adverse health effects may occur (FHI (2015)). The exposure is ubiquitous and involuntary, increasing the significance of this health determinant. The relationship between particulate matter and respiratory symptoms in children has not been consistent among studies, potentially owing to differences in the inflammatory response to different types of particulate matter in the air (WHO (2010)). The most frequently cited health effect among children living in areas with high concentrations of air pollutants is hospital admission due to respiratory symptoms, including wheezing, asthma and pneumonia (FHI (2015)). The most recent evidence indicates that not only the mass of particulate matter, but also the size and number of particulate matter as well as the chemical compositions are influencing respiratory diseases, especially in young children (FHI (2015)).

Quantitative relationships between health outcomes and particulate matter in outdoor air, taken from numerous independent studies, are currently best described by acute deaths in the population. Studies show an approximately linear dose-response relationship between levels of particulate matter in the outside air and mortality in the population down to the lowest measured levels and without any lower limit value for effects (Pope et al. (2009); Schwartz et al. (2002)). It appears that any reduction in $PM_{2.5}$ in the air is expected to give a positive health gain (Schwartz et al. (2002)). No particulate matter exposure threshold has ever been unequivocally described as safe and capable of providing a complete level of protection against all particulate matter related adverse health effects (Hai-Ying et al. (2018)). Anyhow, with the goal of limiting the health impacts of fine particle pollution, WHO has proposed guideline annual and short term (24 h) limits to human exposure (Li et al. (2017); WHO (2010)).

Recommended limit value guidelines for particulate matter

The recommended standard for $PM_{2.5}$ is 15 $\mu g/m^3$ (24 hour average) and 8 $\mu g/m^3$ (1 year average). The recommended standard for PM_{10} is 50 $\mu g/m^3$ (24 hour average) and 20 $\mu g/m^3$ (1 year average) (FHI (2015)); WHO (2005)). Some studies show that $PM_{2.5}$ concentrations lower than the recommended limit values still can damage health (Li et al. (2017)).

Practical advice

The negative impact of indoor particulate matter pollution on the lung function of healthy children requires an effective IAQ management program, to reduce children's health risks to a minimum (Zwozdziak et al. (2016)). Measures must be taken in order to control indoor particulate matter levels. Control strategies can be divided into indoor source control and control of the transmission from the outside air. Some strategies for indoor source control in primary school classrooms are good cleaning routines and having a designated area where shoes and outdoor clothes can be placed before entering the classroom (Li et al. (2017)). Control of the transmission from the outside air to the indoors in primary schools can be achieved with several measures. If the building is in proximity to trafficked roads or other areas with high air pollution, the position of the fresh air intake of the ventilation system should be at the least exposed part of the building. By using filters able to filtrate fine particles in the AHU (filtration class M5, M6, F7, F8 or F9 (KSKlimaService (2019))), technical installations and ventilation ducts are protected, and filtered, cleaner air is supplied to the building. In most cases, filters that can prevent particles larger than 1 μm from entering the ventilation system are installed (WHO (2010)). Filters must be replaced regularly to ensure optimal functionality, and the frequency of this is dependent on the air pollution load outside and on the air volumes handled in the AHU (FHI (2015); WHO (2005)). If open windows are avoided when the outside particulate matter concentration levels are high, high particulate matter concentrations are prevented from entering the room. This can be achieved by continuously monitoring indoor and outdoor particulate matter levels (Li et al. (2017)).

2.6 Obtained limit value guidelines for the reviewed pollutants

Specific limit values are obtained for CO_2, formaldehyde, $PM_{2.5}$ and PM_{10}, but not for TVOC. However for TVOC a building is characterized as low emission or very low emission if its TVOC emission is below specific values. Obtained guidelines for the reviewed pollutants are displayed in table 2.4:

Table 2.4: Obtained pollutant guidelines.

Pollutant and sources	Guidelines	Comments
CO_2. Indoor and outdoor sources. In primary schools the indoor sources are dominant.	1000 ppm (maximum value) FHI (2015)).	Guideline value is made on the basis of the indicator properties of CO_2 regarding bad IAQ and air change requirements.
VOC. Indoor sources are dominant.	NO (FHI (2015)), but if a building has a TVOC emission of <0.2 $mg/(m^2h)$ or <0.1 $mg/(m^2h)$ it is classified as a low or very low emission building (NS-EN15251 (2007)).	The professional basis for setting a health based standard for TVOC is insufficient for indoor air concentrations and for degassing from materials.
Formaldehyde. Indoor sources are dominant.	0.1 mg/m^3 (30 minute average concentration) (FHI (2015)).	The short-term guideline will also prevent effects on lung function as well as long-term health effects, including nasopharyngeal cancer and myeloid leukemia.
PM. In primary schools outdoor sources are dominant.	For $PM_{2.5}$: 15 $\mu g/m^3$ (24 hour average concentration), 8 $\mu g/m^3$ (1 year average concentration) (FHI (2015)). For PM_{10}: 50 $\mu g/m^3$ (24 hour average concentration), 20 $\mu g/m^3$ (1 year average concentration) (WHO (2005)).	Any reduction of the amount of particulate matter in the air is assumed to have a positive health effect.

Chapter 3

DCV: Theory and principles

3.1 Principles of DCV

Ventilation is the process of supplying fresh air to a space and removing contaminated air from a space, and its purpose is to control air contaminant levels, temperature and/or humidity levels within the space (Won and Yang (2005)). Adequate ventilation has been recognized as a condition that is necessary for high productivity and good health among the people situated within the building (Ingebrigtsen (2018a)). HVAC in thermally well insulated buildings in cold climates can account for more than 50% of the total energy costs. (Won and Yang (2005)). With DCV strategies, the concept consists in using controls to ventilate more at times when it provides an IAQ or energy advantage, and less when it provides a disadvantage (Guyot et al. (2018)). In a sensor based DCV system, the ventilation rate is variable because it is automatically and continuously adjusted in response to one or several measurable parameters that are indicative of the overall IAQ at a given time. DCV operates at reduced airflow rates during a significant part of the operation time, thus it consumes less energy for fan operation and heating/cooling the supply air (Merema et al. (2018)). In Merema et al. (2018) it was noticed that even at low airflow rates the ventilation efficiency was not affected. This shows that DCV can be effective in distributing the air even at reduced airflow rates. Compared to conventional ventilation strategies, this feedback based system has been recognized as a technology that can satisfy both lowering energy costs and maintaining good IAQ (Won and Yang (2005)).

3.2 The components of a DCV system

The most widely used ventilation method today is balanced ventilation, and DCV is mainly based on this ventilation method (Ingebrigtsen (2018a); Ingebrigtsen (2018b)). Ingebrigtsen (2018a) describes balanced ventilation. With the use of an AHU (air handling unit), ducts and valves, the required air volumes are supplied to the different rooms, and the same amount of air is withdrawn from the rooms. In some cases, the air is supplied to one room and withdrawn from another room, and the airflow passes between the rooms via a gap under the door or via valves. The heat from the extract air is transferred to the supply air via a heat exchanger so that the energy requirement is reduced. The AHU is also equipped with a filter, heating coil and often a cooling coil, so that pollutants are removed from the air and the correct supply air temperature is maintained.

3.2.1 Air handling unit (AHU)

In figure 3.1, an example of a setup of an AHU for balanced ventilation is shown. The different parts are 1. Outdoor air at air intake, 2. Damper for intake air, 3. Filter for outdoor air, 4. Rotary heat exchanger on supply air side, 5. Supply air fan, 6. Cooling coil, 7. Inspection part between coils, 8. Heating coil, 9. Noise attenuator for supply air, 10. Supply air to the building, 11. Extract air from the building, 12. Noise attenuator for extract air, 13. Filter for extract air, 14. Rotary heat exchanger on extract air side, 15. Extract air fan, 16. Damper for exhaust air, 17. Exhaust air.

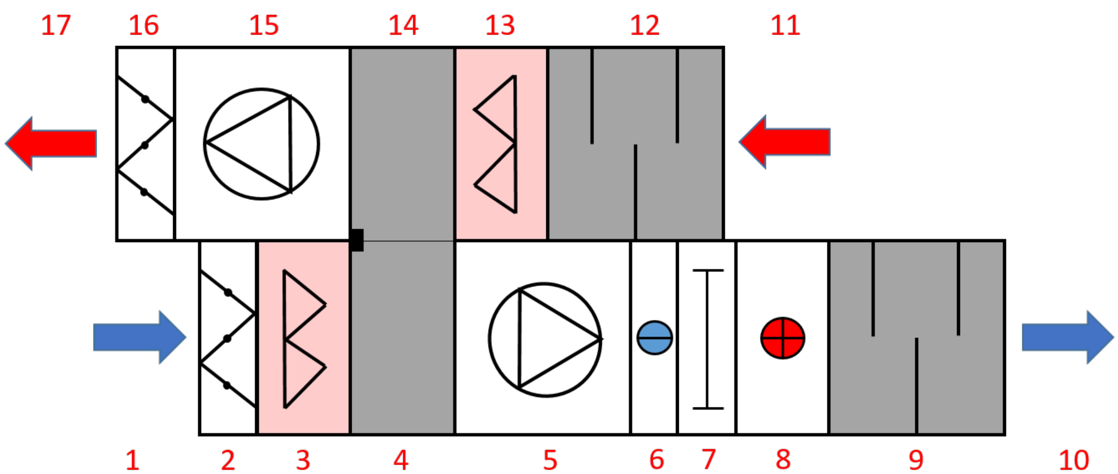


Figure 3.1: Example of a setup of an AHU for balanced ventilation

Source: Made with inspiration from Ingebrigtsen (2018a)

3.2.2 Filters

Due to increasing urban air pollution, simply exchanging the indoor air with outdoor air is in many regions not possible (FHI (2015)). This is because a possibly harmful concentration of outdoor air components will be drawn into the buildings. It is absolutely necessary to take ventilation and air cleaning procedures into account in the planning of schools (FHI (2015)). Air filters in the AHU should at least be of EU7/F7 class, which are high performance filters for filtration of fine dust (Veiledning444 (2016)). In figure 3.1 the filtration classes and level of separation for different particle sizes are shown for fine dust filters.

Table 3.1: Filtration classes and the level of separation for different particle sizes, for fine dust filters

Filtration class	**Separation of particles sized 1-5 μm [%]**	**Separation of particles sized < 5 μm [%]**
M5 (EU5)	65	98
M6 (EU6)	80	99
F7 (EU7)	90	100
F8 (EU8)	95	100
F9 (EU9)	98	100

Care must be taken to ensure good sealing around the filters so that particles are prevented from passing around the filter due to air leakages at the edges. Ordinary ventilation filters will not stop gases and vapors, but they will prevent particulate matter in the outdoor air such as road dust and pollens from having any significant effect on the IAQ, by preventing a large amount of the particulate matter from entering the indoor air. Some of the finest particulate matter will however pass the filter, and over time be deposited in air ducts and in the indoor environment (Veiledning444 (2016)). Using filters in the ventilation system results in a high pressure load, which increases the power consumption of the ventilation fans (Martins and Carrilho Da Graça (2018)).

3.2.3 Sensor based control system

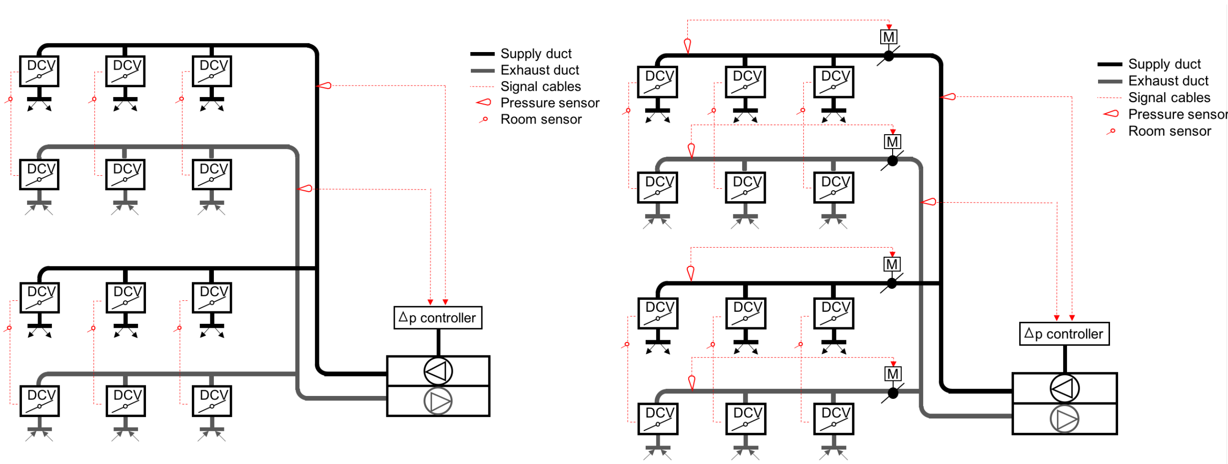
The control system in DCV is based on sensor measurements, and a fundamental prerequisite for DCV systems is that it is possible to find a measurable indicator of the IAQ. The most used indicators in DCV today today are CO_2 levels, and CO_2 levels combined with temperature levels (Ingebrigtsen (2018b)). Controllers accept the information from the sensors and make decisions based on the control algorithms, and output commands to the actuating units. The actuating units modulate the ventilation amount by regulating damper openings and fan speeds according to the commands (Ingebrigtsen (2018b)). Thus, sensors play a cruical role in DCV systems, and unreliable sensor technology has been and is one of the main barriers to widespread implementation of DCV systems (Won and Yang (2005); Fisk and De Almeida (1998)). Sensors for control of DCV can be recommended based on various criteria, such as measurement range, accuracy, sensitivity, long term performance, maintainability, easiness of calibration, size and price levels (Won and Yang (2005)).

3.3 Control strategies of DCV systems

The main principles for control of DCV are pressure-control, static pressure reset and damper-optimization (Mysen and Schild (2013); Mysen and Schild (2014); Ingebrigtsen (2018b)). These principles have in common that they receive signals from room sensors, indicating the room air state and providing a basis for supplying and extracting the correct amount of fresh air in the connected rooms and zones.

3.3.1 Pressure-controlled DCV

Pressure-controlled DCV is the most common DCV principle, shown in figure 3.2a. The supply and extract airflow rates in the rooms are controlled with motorized dampers according to the demand measured in each room. Changes in the ventilation demand causes changes in the damper positions, influencing the static pressure in the duct. A pressure sensor is placed in the duct, and this must be sensitive enough to discover changes in the static pressure. The pressure sensor is connected to a controller, which regulates the speed of the fan to maintain a constant static pressure at the location of the pressure sensor. Regulating the fan speed to maintain a constant static pressure rise over the fan results in unnecessary throttling during part-load condition, and pressure-controlled DCV requires more fan energy than damper-optimized DCV and static pressure reset DCV. However, the energy use in pressure-controlled DCV is minimized by locating the pressure sensor as far away from the fan as possible. This minimizes the average fan pressure, and results in a minimized fan energy use for this solution ((Mysen and Schild (2013); Mysen and Schild (2014); Ingebrigtsen (2018b))).



(a) DCV with constant pressure control.

(b) Pressure-controlled DCV with zone dampers.

Figure 3.2: Pressure-controlled DCV, two solutions. Created with inspiration from Mysen and Schild (2013).

When the AHU covers many rooms, a better solution is pressure-controlled DCV with zone dampers on each branch. See figure 3.2b. Each zone has a motorized damper controlled by a pressure sensor with a 0-10 V signal. The zone damper is regulated to maintain a constant pressure at the pressure sensor. Maintaining a constant pressure in each zone results in a small energy penalty if the pressure set point is chosen according to the minimum pressure requirements of the DCV dampers. This ensures that the minimum pressure in the AHU is suitable for the operational range of the DCV dampers ((Mysen and Schild (2013); Mysen and Schild (2014); Ingebrigtsen (2018b)).

3.3.2 Static pressure reset DCV

Static pressure reset DCV is a combination of pressure-control and damper-control. See figure 3.3. Each zone has a motorized damper controlled by a pressure sensor with a 0-10 V signal. The zone damper regulates the airflow rate to maintain a constant static pressure at the pressure sensor. A controller registers the angle of the zone damper and regulates both the fan speed and pressure set point in the main duct so that at least one zone damper is in its maximum open position. Maintaining a constant pressure in each zone results in an energy penalty, but this penalty is small if the pressure set point ensures that the minimum airflow rate allowed by the DCV dampers is reached, while avoiding using energy to build up an unnecessary high duct pressure. In static pressure reset DCV, the pressure sensor should be placed closer to the AHU than with pressure-controlled DCV ((Mysen and Schild (2013); Mysen and Schild (2014); Ingebrigtsen (2018b))).

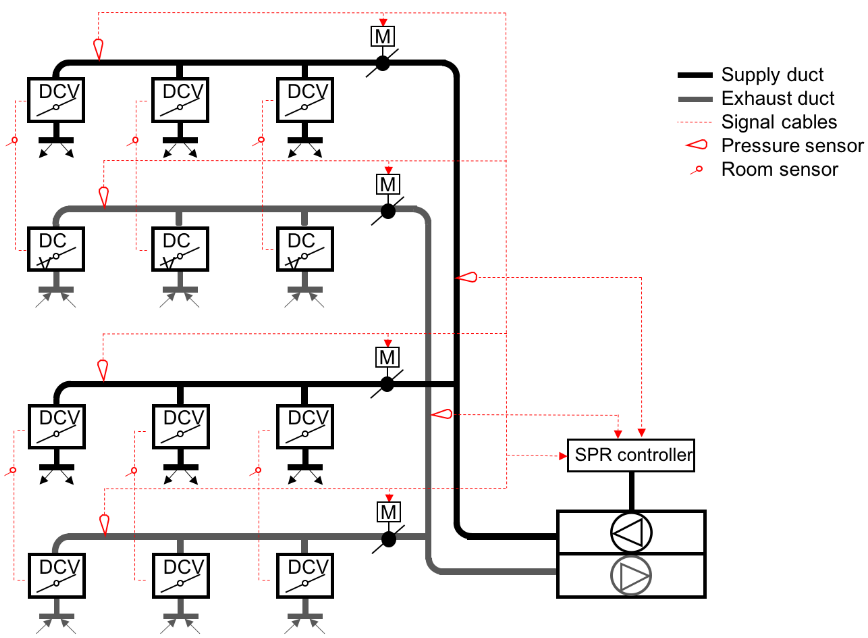


Figure 3.3: Static pressure reset DCV.

Source: Created with inspiration from Mysen and Schild (2013).

3.3.3 Damper-optimized DCV

In damper-optimized DCV, the airflow rate in the main duct is controlled according to the position of the dampers to ensure that at least one damper is in its maximum open position. See figure 3.4. The purpose is to ensure a minimum energy consumption from the fan by having a minimum pressure rise over it. This is achieved when when one critical duct path always is open. The required airflow rate, supplied airflow rate and damper angle are recorded for all DCV dampers, and this information is sent to a controller which regulates the fan speed ((Mysen and Schild (2013); Mysen and Schild (2014); Ingebrigtsen (2018b))).

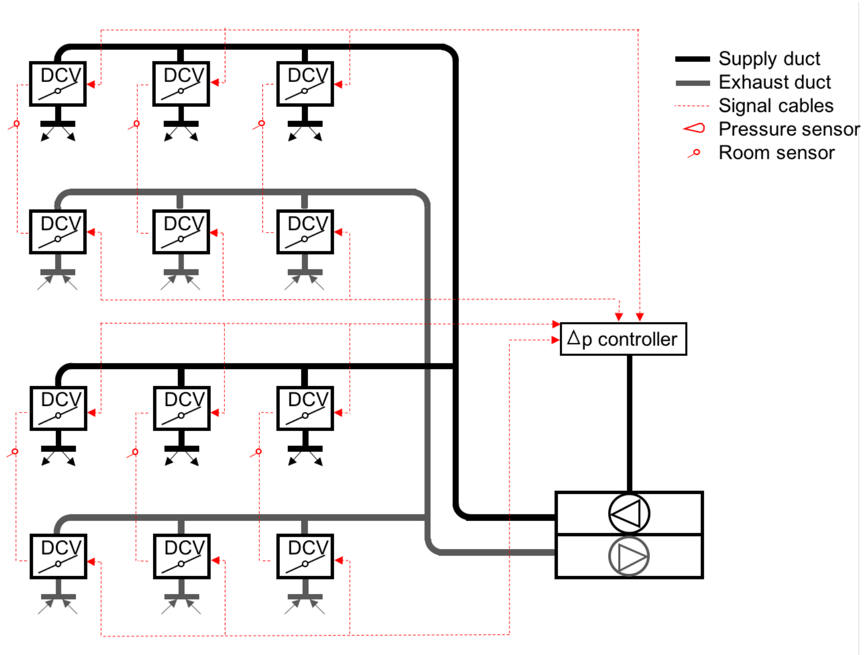


Figure 3.4: Damper-optimized DCV.

Source: Created with inspiration from Mysen and Schild (2013).

Chapter 4

Room control strategies for DCV: State of the art

The body of knowledge regarding CO_2 controlled DCV is voluminous, due to CO_2 being the most used indicator for control of DCV today. However, the body of knowledge regarding other pollutants such as VOCs and particulate matter as indicators for control of DCV is limited.

4.1 CO_2 as marker for control of DCV

Most DCV systems today are based on the monitoring of CO_2 concentrations (Ingebrigtsen (2018b)). CO_2 sensors are relatively inexpensive and straightforward indicators on the person load in a room or zone, making it possible to indirectly control the level of bioeffluents produced by the people (Fisk and De Almeida (1998)). The use of CO_2 as a proxy indicator for DCV is recommended for rooms with a variation in the number of users. CO_2 sensors in combination with temperature sensors is a typical choice, where the CO_2 sensors ensure that the airflow increases with the number of people present in the room, and the temperature sensors ensure a good thermal indoor climate. When the CO_2 level is low and the temperature level is satisfactory, the DCV is regulated towards the minimum ventilation rate. When the CO_2 level is rising and/or the temperature level gets too high or low, the DCV is regulated continuously towards the maximum ventilation rate (Ingebrigtsen (2018b)). In Merema et al. (2018), measurements showed significant differences between the CO_2 levels in the breathing zone and in the room air extract, indicating that the position of the CO_2 sensor controlling the airflow is of great importance for the operation of the DCV. When choosing a CO_2 sensor it is important to choose one that is stable over time. Less expensive models need to be calibrated often, which will increase maintenance costs (Ingebrigtsen (2018b)). Although there is a body of information on CO_2 based DCV systems, there are not many case studies on the IAQ performance of these systems regarding non-occupant related pollutants. This makes it difficult to determine whether non-occupant related pollutants are controlled in a CO_2 based DCV system (Ingebrigtsen (2018b)). The inability of CO_2 to be a surrogate for non-human pollutant sources has been recognized as a main drawback of CO_2 based DCV (Won and Yang (2005)).

Due to the increasing quantity of outdoor air pollutants, the use of CO_2 as a sole key parameter for DCV is no longer recommended (Salthammer et al. (2016)).

4.2 VOCs and TVOC as marker for control of DCV

CO_2 sensors don't respond to indoor pollutant emissions that are unrelated to occupancy, such as VOC emissions. Thus, CO_2 based DCV could lead to insufficient ventilation in buildings where the human pollutant load is not dominant (Won and Yang (2005)). Consequently there is an interest in the use of other gas pollutant sensors, primarily VOC sensors, often in conjunction with CO_2 sensors (Won and Yang (2005)). The cost of VOC sensors is decreasing and the performance is improving, however the VOC sensors available on the market today may still have inadequate sensitivity and stability for use in DCV (Ingebrigtsen (2018b)). Additionally the appropriate use of these sensors is complicated because there is a high variability in the potency of different VOCs to cause health effects (Fisk and De Almeida (1998)) and because maximum acceptable TVOC concentrations for mixtures of VOCs have not been established (section 2.3). While it is relatively easy to calculate or measure concentrations of pollutants with known damage in industrial environments, due to the concentrations being relatively high, these conditions are not easily controllable in typical non-industrial indoor environments like primary schools. Measurements in typical non-industrial indoor environments show that there are many different VOCs present, but these usually have very low concentrations (Ingebrigtsen (2018a)).

Because more than 300 VOCs have been measured in indoor air, the TVOC concentration is often used in sensor technologies and literature to characterize the total concentration with a single parameter in a simple way. The lack of a precise definition for TVOC and of a standardized procedure for its calculation is highlighted by several authors (Guyot et al. (2018)). Mixed gas sensors are often used to monitor TVOC levels, and these sensors are sensitive to a combination of non-oxidized gases such as hydrocarbons and carbon monoxide (Won and Yang (2005)). In Fisk and De Almeida (1998) it was recommended to use TVOC sensors together with CO_2 sensors, even though there are difficulties of doing this due to the high variability in toxicity of different VOCs and due to the lack of data on acceptable levels for mixtures of VOCs. Nevertheless, VOC based DCV strategies could at least avoid peak exposure during scheduled activities such as painting or other building refurbishments (Fisk and De Almeida (1998)). There is evidence that TVOC concentrations exceeding a few milligrams per cubic meter are likely to lead to health symptoms (FHI (2015)), however this doesn't necessarily make lower concentrations acceptable. One of the initial opportunities for the use of VOC sensors in DCV is to ensure that VOC concentrations do not exceed some relatively high level. This type of control system might reduce complaints during periods of temporary high indoor VOC emission rates (Fisk and De Almeida (1998)). Humans also emit VOCs, but these emissions are negligible compared to the building related emissions (Won and Yang (2005)). Thus, TVOC or an individual VOC could be considered as a surrogate for pollutants from non-human sources. Using an individual VOC has a drawback because it is difficult to find an individual VOC representing a wide range of VOC sources due to many VOCs being source specific (Won and Yang (2005)).

VOC emissions from building products and furnishings must be considered in a building, but these are not usually a major problem today because VOC sources are subjected to extensive quality control measures (Ingebrigtsen (2018a)). If low emission or very low emission materials are used in a building, this should be more than sufficient in order to ensure that TVOC levels are maintained at a low level for e.g. CO_2 based DCV systems (Fisk and De Almeida (1998)). However, using TVOC or VOC levels as an indicator for control of DCV is a possibility, due to VOCs mainly originating from indoor sources and because adequate ventilation generally reduces TVOC levels in most indoor environments (Fisk and De Almeida (1998)). Over the last decade, TVOC sensors have been promoted as an interesting alternative to CO_2 and temperature sensors in DCV systems (De Sutter et al. (2017)). In De Sutter et al. (2017), where TVOC concentrations were measured in Belgian dwellings, it was shown that due to occupant activities such as cooking and cleaning, high and short peaks in TVOC concentrations typically occur. It was concluded that the TVOC concentration was an especially useful parameter for event related or purge ventilation control. However, the average ventilation flow rate during TVOC control was about 50% larger than during CO_2 control, and during TVOC control the airflow rate was larger than the airflow rate for CO_2 control 40% of the time on average (De Sutter et al. (2017)).

4.3 Formaldehyde as marker for control of DCV

The indoor levels of different VOCs are often lower than their respective guideline values (for those having a guideline value), but the VOC formaldehyde is an exception to this (Won and Yang (2005)). Formaldehyde could be used as proxy indicator for DCV, given that a well suited formaldehyde sensor exists (Fisk and De Almeida (1998)), because formaldehyde has an existing limit value (2.6; FHI (2015)). In Emmerich and K. Persily (2001), a state-of-the-art review of CO_2 controlled DCV technology and application, formaldehyde concentrations were simulated to evaluate the impact of CO_2 controlled DCV strategies on pollution from a non-occupant source. None of the evaluated DCV strategies controlled the formaldehyde concentrations as well as a constant and fixed ventilation strategy. It was suggested to include a morning purge in DCV strategies when non-occupant generated pollutants are a concern, but this was not further investigated. In Won and Yang (2005) it is written that "To the author's knowledge, there has been no application research on using formaldehyde as a ventilation control parameter". Ventilation standards specify the minimum ventilation rates required in order to meet acceptable IAQ. However, these ventilation requirements might not always be sufficient for providing a health optimal IAQ, in particular for the formaldehyde level (Chenari et al. (2016)).

4.4 Parciculate matter as marker for control of DCV

Some studies has been performed to determine the relationship between indoor and outdoor particulate matter concentrations, but information on the determination of ventilation rates under significant influence of outdoor particles is limited (Yu et al. (2014)). Particulate matter sensors might be used to control ventilation rates in building or rooms with high particle generation rates (Fisk and De Almeida (1998)), but measurements of particulate matter concentrations are not recommended as routine in IAQ matters (FHI (2015)). If there are complaints of assumed high particle matter pollution, it is more important to localize possible sources and take measures to remove or reduce these sources (WHO

(2005)). Indoor particulate matter levels are dependent outdoor levels, indoor generation, infiltration, ventilation type, filter type, deposition and resuspension effects and occupant activities (EPA (2018b)). Some important steps to reduce exposure to indoor particulate matter in primary school classrooms are adequate cleaning procedures, a high efficiency filter in the AHU, an air intake located on the least polluted part of the building, and leaving outdoor shoes and clothes in a wardrobe before entering the classroom. It is important to change filters according to the manufacturer's directions to achieve the correct filter performance (EPA (2018b)). In Yu et al. (2014), both experimental and theoretical results support that the dilution of CO_2 with CO_2 based DCV causes an undesirable increase in particle concentrations indoors. This intricate relationship between CO_2 and particle matter poses a serious challenge in the development of an effective ventilation system when outdoor environments have high particulate matter levels.

In Marsik and Johnson (2008), a control strategy for $PM_{2.5}$ was developed and tested, based on indoor and outdoor target levels of $PM_{2.5}$. Only when the $PM_{2.5}$ level indoors or outdoors was exceeded, the $PM_{2.5}$ control algorithm was activated, and it was activated until the levels were below the target levels again. The $PM_{2.5}$ control algorithm was based on the fact that the cleaner the air entering the HVAC filter is, the cleaner the air entering the building is. In the test, the air entering the filter was a mixture of recirculated air and outdoor air. If the $PM_{2.5}$ concentration indoors was higher than the outdoor concentration, the air entering the filter was cleanest when the recirculated airflow was minimized and the airflow from the outdoors was maximized. The opposite is true for when the outdoor $PM_{2.5}$ concentration was higher than the indoor one. The position of the outdoor/recirculated air damper was determined based on the outdoor and indoor $PM_{2.5}$ concentration. This control algorithm was shown to reduce the $PM_{2.5}$ levels in the studied building by 65%, and this can have a significant health benefit during sudden episodes of high $PM_{2.5}$ levels.

Chapter 5

Methods

5.1 Sensor choices

Sensors with costs that are less likely to hinder their use in building ventilation controls are to be chosen and evaluated, and based on the findings in chapter 2, 3 and 4, the health relevant pollutants and parameters planned for evaluations are TVOC, formaldehyde, $PM_{2.5}$, PM_{10}, CO_2, temperature and relative humidity. The performance of the sensors in lab and field measurements, and their potential use in the control of DCV regarding improvements health of occupants will be evaluated. The chosen low cost sensors are SCD30 (CO_2, temperature and humidity), SPS30 (particulate matter), SGP30 (TVOC) and WZ-S (formaldehyde), and they fulfill the following criteria:

- They are factory precalibrated and stated to not require calibration by the user
- They measure the relevant parameters in ranges expected to occur in indoor, non-industrial air
- Sensor sizes are assumed to be acceptably small enough for use in building ventilation control
- The price levels are less likely to hinder their use in building ventilation controls
- Their overall performance seem adequate for use in building ventilation control

SCD30 - CO_2, temperature and humidity sensor module

The following information is retrieved from Sensirion (2018c). SCD30 from Sensirion is a precalibrated sensor module for HVAC and IAQ applications, which enables highly accurate and stable NDIR CO_2 measurement at a competitive price. A best in class temperature and humidity sensor is integrated on the same sensor module, making reading of ambient temperature and humidity possible without the requirement of any additional components. Due to a dual-channel principle for the measurement of CO_2 concentration, the SCD30 compensates for long-term drifts automatically by design. The very small module height allows easy integration into different applications. Datasheet and sensor website are found in A.1.1. Important sensor specifications are given in table 5.1.

Table 5.1: SCD30 sensor parameters

Sensor parameter	**Value**
Price	Approximately 450 NOK/unit (taxes included)
Sensor lifetime	15 years
Maintenance interval	None (maintenance free when ASC field calibration algorithm is used; long-term drifts are automatically compensated)
Size	35 mm x 23 mm x 7 mm
Temperature operating conditions	0-50^{o}C
Humidity operating conditions	0-95% RH
CO_2 sensor specifications	
Measurement range	0-40000 ppm
Accuracy	+/- 30 ppm
Repeatability	+/- 10 ppm
Temperature stability	+/- 2.5 ppm/^{o}C
Response time	20 s
Accuracy drift over lifetime	+/- 50 ppm
Temperature sensor specifications	
Measurement range	-40 - +70^{o}C
Accuracy	+/- (0.4^{o}C+0.023x(T[^{o}C]-25^{o}C))
Repeatability	+/- 0.1^{o}C
Response time	>10 s
Accuracy drift	<0.03^{o}C/year
Humidity sensor specifications	
Measurement range	0-100% RH
Accuracy	+/- 3% RH
Repeatability	+/- 0.1% RH
Response time	8 s
Accuracy drift	< 0.25% RH/year

Source: Sensirion (2018c)

SPS30 - Particulate matter sensor

The following information is retrieved from Sensirion (2018b). SPS30 from Sensirion is a precalibrated particulate matter sensor for HVAC and air quality applications. The sensor represents a new technological breakthrough in optical particulate matter sensors. The measurement principle is based on laser scattering and makes use of the innovative contamination-resistance technology from Sensirion. High quality and long lasting components together with this technology enables accurate measurements from the first operation of the device and throughout its lifetime of more than 8 years. Datasheet and sensor website are found in A.1.2. Important sensor specifications are given in table 5.2.

Table 5.2: SPS30 sensor parameters

Sensor parameter	Conditions	Value
Price	-	Approximately 400 NOK/unit (taxes included)
Sensor lifetime	24 h/day operation	> 8 years
Maintenance interval	-	None (accurate measurements from first operation and throughout lifetime)
Size	-	41 mm x 41 mm x 12 mm
Temperature operating conditions	-	-10 - +60^{o}C
Humidity operating conditions	-	0-95% RH
Start-up time	-	< 8 s
Sampling interval	-	1 s
Mass concentration accuracy	0-100 μg/m^3 100-1000 μg/m^3	+/- 10 μg/m^3 +/- 10%
Mass concentration range	-	1-1000 μg/m^3
Mass concentration resolution	-	1 μg/m^3
Mass concentration size range	$PM_{1.0}$ $PM_{2.5}$ PM_4 PM_{10}	0.3-1.0 μm 0.3-2.5 μm 0.3-4 μm 0.3-10 μm
Number concentration range	-	0-3000 1/cm^3
Number concentration size range	$PM_{0.5}$ $PM_{1.0}$ $PM_{2.5}$ PM_4 PM_{10}	0.3-0.5 μm 0.3-1.0 μm 0.3-2.5 μm 0.3-4.0 μm 0.3-10.0 μm

Source: Sensirion (2018b)

SGP30 - Multi-pixel TVOC sensor

The following information is retrieved from Sensirion (2018b). This is a precalibrated multi-pixel gas TVOC sensor which creates new possibilities for the measurement of IAQ. SGP30 offers a complete gas sensor system integrated into a very small package of 2.45 x 2.45 x 0.9 mm^3, featuring an I^2C interface and fully calibrated air quality output signals. SGP30 has an unmatched robustness against contamination by siloxanes resulting in a unique long term stability and accuracy. The sensor further combines multiple metal-oxide sensing elements - the pixels - on one chip to provide more detailed air quality signals. The unprecedented combination of long-term stability and multi-pixel technology makes SGP30 a good choice for IAQ monitoring. Datasheet and sensor website are found in A.1.3. Important sensor specifications are given in table 5.3.

Table 5.3: SGP30 sensor parameters

Sensor parameter	Signal	Value
Price	-	Approximately 90 NOK/unit (taxes included)
Sensor lifetime	-	-
Maintenance interval	-	None (unique long-term stability and low drift over lifetime)
Size	-	2.45 mm x 2.45 mm x 0.9 mm
Temperature operating conditions	-	-40 - +85°C
Humidity operating conditions	-	10-95% RH
Start-up time	-	15 s
Sampling interval	-	1 s
Output range	TVOC signal	0-60000 ppb
	CO_2eq signal	400-60000 ppm
Resolution	TVOC signal	0-2008 ppb: 1 ppb
	-	2009-11110 ppb: 6 ppb
	-	11110-60000 ppb: 32 ppb
	CO_2eq signal	400-1479 ppm: 1 ppm
	-	1479-5144 ppm: 3 ppm
	-	5144-17597 ppm: 9 ppm
	-	17597-60000 ppm: 31 ppm

Source: Sensirion (2018a)

Formaldehyde WZ-S sensor module

The following information is retrieved from DartSensors (2018). WZ-S is a precalibrated formaldehyde sensor module that uses Dart Sensors wafer components. It combines a novel formaldehyde sensor with advanced electronic control technology, converting formaldehyde concentration into ppb and $\mu g/m^3$ directly. When formaldehyde arrives at the working electrode it is oxidized instantaneously to generate an electric signal. The electric signal is then acquired and processed by a microprocessor into a ppm and $\mu g/m^3$ value and is outputted by standard digital signal. WZ-S is precalibrated in the factory, thus there is no need for customer calibration. This is the only precalibrated module recommended by Dart Sensors. The sensor is suitable for smart homes, portable and wearable devices, air conditioners, air cleaners, etc. It is not recommended for industrial safety or personal monitoring. It has a high precision, fast response, long service life, low power consumption and high stability. Datasheet and sensor website are found in A.1.4. Important sensor specifications are given in table 5.4.

Table 5.4: WZ-S sensor parameters

Sensor parameter	Conditions	Value
Price	-	Approximately 115 NOK/unit (taxes included)
Sensor lifetime	In air	5 years (12 months warranty period)
Maintenance interval	-	None (high stability over lifetime)
Size	-	25.5 mm x 23 mm x
Temperature operating conditions	-	-20 - +50^{o}C
Humidity operating conditions	Non-condensing	10-90% RH
Start-up time	For warm up	< 3 min
Detection principle	-	Micro fuel cell
Detectable gas	-	Formaldehyde (HCHO)
Detection range	-	0-200 ppb (overload at 10000 ppb)

Source: DartSensors (2018)

5.2 Developing and building the sensor rigs

Details on the sensor rigs are given in appendix A; descriptions of the hardware (A.2) software (A.3) and a detailed user guide (A.4). The assembly of the sensor rigs and the code development are carried out from scratch in collaboration with professional system developers. Four sensor rigs are made, each with one sensor box for measuring the state of the supply air and one sensor box for measuring the state of the air in the breathing zone. One sensor box consists of an open plastic case containing an Arduino UNO with 1 SCD30 sensor (CO_2, temperature and humidity), 1 SPS30 sensor ($PM_{2.5}$ and PM_{10}) and 1 WZ-S sensor (formaldehyde). The two sensor boxes on a sensor rig send all sensor outputs to a connected Raspberry Pi, where the sensor outputs are logged and stored in .csv-files. All source code made for the sensors on the Arduino and for the logging of data in the Raspberry Pi are given in appendix A.3.1 (PUST.ino), A.3.2 (TIL.ino), A.3.3 (Calibrate.ino), A.3.4 (setForcedCalibrationFactor.ino) and A.3.5 (main.py). At this point it was found to be impossible to solder the SGP30 TVOC sensor with the equipment available, due to the extremely small sensor dimensions, the high risk of short circuiting the sensor and the lack of specialist equipment. Due to time limitations it was decided that the SGP30 TVOC sensor had to be omitted in the sensor rigs in this master's thesis.

5.3 Initial calibration of sensors in lab

Sensor calibration is a method of determining the error of the sensor outputs by using reference instruments with well known performance. The results can be used to improve sensor performance by removing structural errors in the sensor outputs. Structural errors are differences between a sensors expected output and its measured output, which show up consistently every time a new measurement is taken. Any of these errors that are repeatable can be calculated so that during actual end use the measurements made by the sensor can be compensated in real-time to digitally remove errors.

Calibration provides enhanced performance by improving the overall accuracy of the underlying sensors. All sensors on the sensor rig are factory precalibrated and stated to be ready for use without calibration by user. This will be tested and verified by calibrating the sensors with relevant reference instruments in the lab, to look at whether the factory precalibration is satisfactory or whether there are repeatable errors in the sensor measurements compared to the measurements of the reference instruments, and correlation analysis will be carried out to find the calibration curve to digitally remove the errors in real-time.

Calibration of SCD30 CO_2 sensors

CO_2 will be calibrated against the reference instrument Vaisala GM70 CO_2 Meter (Vaisala GM70 Datasheet) which itself is recently calibrated and known to give highly accurate measurements. Together with the Vaisala, one sensor rig at a time is put in a semi-enclosed box and subjected to a step increase in the CO_2 concentration by introducing a small amount of CO_2 from a CO_2 gas container, providing identical conditions for the sensor rigs and the Vaisala. The response to the step increase is logged by the SCD30 CO_2 sensors and Vaisala until concentrations reach the ambient CO_2 concentration. Means and standard deviations for various known concentrations will be calculated for the SCD30 CO_2 sensors altogether. Calibration curves and correlation coefficients will be found for each SCD30 CO_2 sensor. In the calibration curves, y is the corrected SCD30 CO_2 concentration (when assuming correct CO_2 concentrations measured by Vaisala) and x is the concentration measured by the SCD30 CO_2 sensor. In figure 5.1 the calibration set-up is shown.

Figure 5.1: Calibration of CO_2 sensors in semi-enclosed box.

Calibration of SPS30 particulate matter sensors and SCD30 temperature and humidity sensors

$PM_{2.5}$, temperature and relative humidity will be calibrated against the reference instrument Pegasor AQ^{TM} Indoor (Pegasor specifications), which is assumed to give very accurate measurements. The calibration measurements will be carried out in a small room with no ventilation. During the measurements, the temperature and humidity will be varied by opening a window to the outdoor for a while, an then closing the window and turning an electrical oven on maximum effect for a while. The $PM_{2.5}$ levels will be varied by lighting 6 candles for a while with the window shut for two periods, and opening the window and blowing out the candles after each period. Due to a lack of reference instruments for PM_{10}, no calibration procedure will be carried out for this parameter.

Calibration of WZ-S formaldehyde sensors and SGP30 TVOC sensors

Similar calibration can not be carried out for formaldehyde, because appropriate methods and reference instruments are non-available per now. However, due to the WZ-S sensors being factory precalibrated, it will be assumed that their performance is satisfactory. All formaldehyde sensors will be tested together during increasing temperatures, to see whether they give the same outputs for identical conditions. Calibration of the SGP30 TVOC sensors would not have been possible for the same reasons as for formaldehyde, so if they had been implemented on the sensor rigs, calibration would be impossible per now due to a lack of appropriate methods and reference instruments.

5.4 Experimental plan of field measurements in classrooms

Field measurements will be carried out in four primary schools in Trondheim, in one classroom per school. All four classrooms must have CO_2 controlled DCV. It is desired to examine differences between newer and older classrooms (regarding formaldehyde levels (and TVOC levels if SGP30 sensors had been implemented on the sensor rigs)), and between classrooms with higher and lower nearby traffic (regarding particulate matter levels). Trondheim kommune has provided classrooms that seem to cover these demands, and the classrooms are called NHT (new+high traffic), OHT (old+high traffic), NLT (new+low traffic) and OLT (old+low traffic). See table 5.5 for a description of the schools. Trondheim kommune are providing logged airflows, room temperatures and CO_2 levels in the classrooms from their BAS.

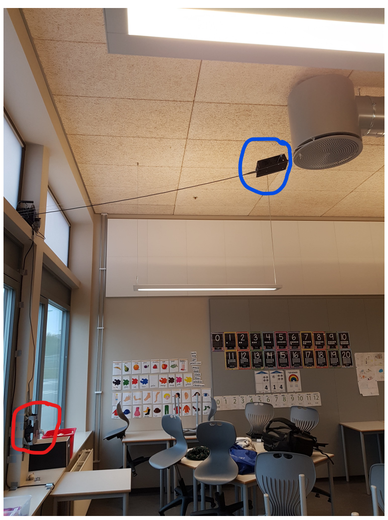
Table 5.5: Primary school descriptions regarding time since completion and distance to trafficked roads

Classroom	Year of facility improvements	Proximity to trafficked roads
NHT	Brand new school, completed in the summer of 2018	Assumed high nearby traffic. 200 m to a high trafficked road
OHT	A new extension to the existing school was completed in January 2016, the classroom is in the new extension	Assumed high nearby traffic. 700 m north east to high trafficked motor highway, 600 m south to medium trafficked road and 600 m west to medium trafficked road
NLT	A new extension to the existing school was completed in January 2017, and the rest of the school was also upgraded. The classroom is in the new extension	Assumed low nearby traffic. 200 m to a medium trafficked road
OLT	The entire school was completed in the spring of 2014	Assumed low nearby traffic. 100 m to a medium trafficked road.

In each classroom one sensor rig will be installed, measuring and logging the state of the supply air and the air in the breathing zone. It is recommended to place the sensors measuring the sate of the air in the breathing zone 1-1.5 meter above the floor on an inner wall that is never exposed to direct sunlight (Ingebrigtsen (2018b)). The measurements will be carried out over a period of several weeks in April and May, and the logged data will be retrieved once a week in every classroom in case the sensor rigs crash unexpectedly and need to be restarted. A restart of the measurements can only be done manually on-site. All classrooms contain whiteboards, books, paper, shelfs, desks, chairs, pencils, etc. Classroom NHT, OHT and NLT contain large wooden surfaces, especially NHT. Classroom OLT contain no wooden surfaces.

Classroom NHT

This classroom is in a school constructed in massive wood, and it is normally occupied by 25 2nd grade pupils and one teacher. Its area is 60 m^2, and the room contains 2 air supply diffusors at the roof and 2 air extracts by the door. The sensor box measuring the state of the supply air could not be placed inside the supply duct, so it had to be placed right next to one of the air supply diffusors, measuring a mixed state of the supply air and the room air. The sensor box measuring the state of the supply air is marked with a blue ring in figure 5.2, and the sensor box measuring the state of the breathing zone air is marked with a red ring in figure 5.2.



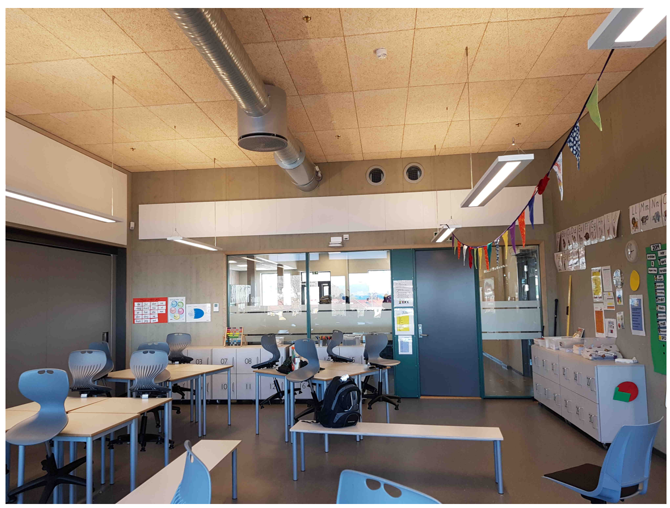


Figure 5.2: Sensor rig installed in classroom NHT, and the classroom seen from the sensor rig

Classroom OHT

This classroom is normally occupied by 36 3rd grade pupils and one to two teachers. Its area is 110 m^2, and the room contains 6 air supply diffusors and 1 air extract, all placed in the roof. The sensor box measuring the state of the supply air could not be placed inside the supply duct, so it had to be placed right next to one of the air supply diffusors, measuring a mixed state of the supply air and the room air.

The sensor box measuring the state of the supply air is marked with a blue ring in figure 5.3, and the sensor box measuring the state of the breathing zone air is marked with a red ring in figure 5.3.


Figure 5.3: Classroom OHT seen from the door, and sensor rig installed in the classroom

Classroom NLT

This classroom is normally occupied by 26 7th grade pupils and one teacher. Its area is 60 m^2, and the room contains 2 textile air supply diffusors in the roof and 1 air extract by the door. The sensor box measuring the state of the supply air could be placed inside the textile air supply diffusor, making it possible to measure the supply air before it enters the room. The sensor box measuring the state of the supply air is marked with a blue ring in figure 5.4, and the sensor box measuring the state of the breathing zone air is marked with a red ring in figure 5.4.

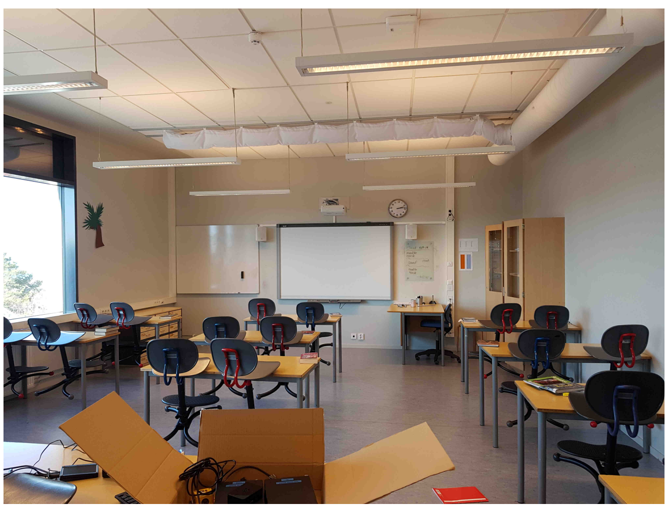
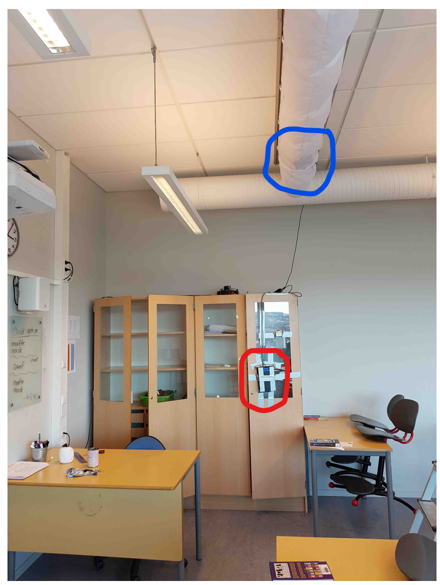



Figure 5.4: Classroom NLT seen from the door, and sensor rig installed in the classroom

Classroom OLT

This classroom is normally occupied by 20 1st grade pupils and one teacher. Its area is 60 m^2, and the room contains 8 air supply diffusors and 1 air extract, all placed in the roof. The sensor box measuring the state of the supply air could not be placed inside the supply duct, so it had to be placed right next to one of the air supply diffusors, measuring a mixed state of the supply air and the room air. The sensor box measuring the state of the supply air is marked with a blue ring in figure 5.5, and the sensor box measuring the state of the breathing zone air is marked with a red ring in figure 5.5.

Figure 5.5: Classroom OLT seen from the door, and the sensor rig installed in the classroom

5.4.1 Observation day in classroom NLT

An observation day in classroom NLT is planned, in order to register the number of people and the various activities that are carried out during that school day. Classroom NLT is chosen because it is the only classroom where it is possible to measure the state of the supply air inside the supply air duct.

5.4.2 Collection of outdoor particulate matter measurements

During the period of the field measurements, outdoor $PM_{2.5}$ and PM_{10} monitoring are performed at 4 measuring stations in Trondheim by Miljøenheten in Trondheim kommune: Bakke church, Elgeseter, E6-Tiller and Torget. Miljøenheten will provide measured outdoor particulate matter levels for the measurement period in the classrooms. The weather data and measured outdoor particulate matter levels will be used in the analysis of the measurement results from the classrooms to look for any possible cause-effect relationships.

5.5 Visualization and statistical analysis of measurements

The development over time for the measurands will be displayed graphically together with the supplied air flows to the classrooms for a visual representation of the measurements. The supplied air flows will be provided from the building automation system (BAS) by Trondheim kommune. Box and whiskers plots of the pollutants formaldehyde, $PM_{2.5}$ and PM_{10} will be made and compared for all four classrooms, where minimum, 25th percentiles, median, 75th percentiles and maximum values are displayed. For formaldehyde, the box and whiskers plots will be made both for occupied hours, unoccupied hours and all hours. Whether the pollutants exceed their guideline limit values will be pointed out, and also the timing of these possible exceeds. The sensor rig CO_2 and temperature measurements in the breathing zone will be compared with the CO_2 and temperature measurements in the breathing zone made by the BAS. Possible correlations between different measurands will be looked for and evaluated (CO_2 levels and air change rates, formaldehyde levels and air change rates, particulate matter levels and air change rates). The collected weather data and outdoor particulate matter levels will be seen in accordance with the particulate matter, formaldehyde, temperature and relative humidity levels indoors. Analysis of the results from the observation day in classroom NLT will be carried out to identify any cause-effect relationships for the measured pollutants and parameters.

5.6 Development of control strategies

Based on the analysis of the measurement results, possible control strategies will be suggested for control of formaldehyde levels and particulate matter levels in combination with no, one or several of the other parameters.

Chapter 6

Results

6.1 Initial sensor calibrations

6.1.1 Initial calibration of SCD30 CO_2 sensors

In figures 6.1, 6.2, 6.3 and 6.4 is seen that the CO_2 measurements made by the SCD30 sensors on all four sensor rigs track the Vaisala CO_2 measurements quite good for identical conditions, and sensor rig 1 and 3 seem to track the Vaisala measurements better than sensor rig 2 and 4. Statistical analysis of the trackings give the total SCD30 mean +/- standard deviation (for all eight SCD30 sensors combined) for some chosen Vaisala concentrations, showing the error to expect for a SCD30 CO_2 sensor:

- Vaisala: 450 ppm → SCD30: 514 +/- 21 ppm
- Vaisala: 700 ppm → SCD30: 799 +/- 32 ppm
- Vaisala: 1000 ppm → SCD30: 1069 +/- 93 ppm
- Vaisala: 1300 ppm → SCD30: 1357 +/- 106 ppm

The SCD30 means for the chosen Vaisala concentrations are consistently higher. For lower concentrations the difference between the SCD30 mean and the Vaisala measurement is greater than for higher concentrations. The opposite happens for the standard deviation, which increases for increasing concentrations.

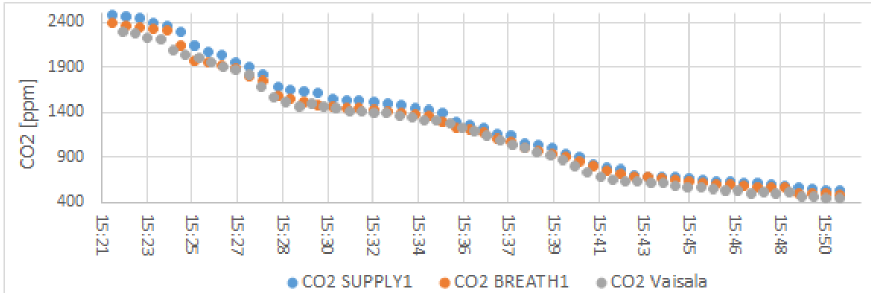


Figure 6.1: CO_2 step-response of sensor rig 1 and Vaisala.

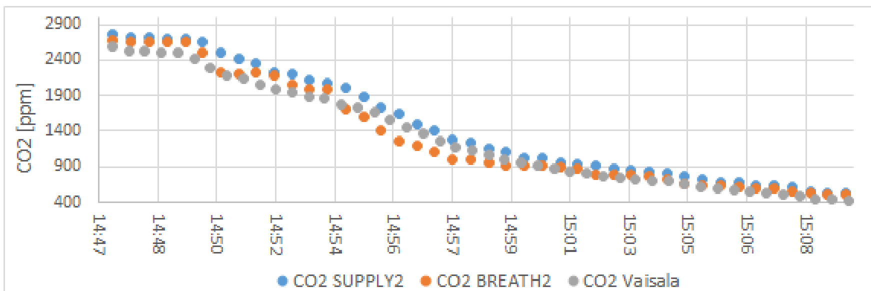


Figure 6.2: CO_2 step-response of sensor rig 2 and Vaisala.

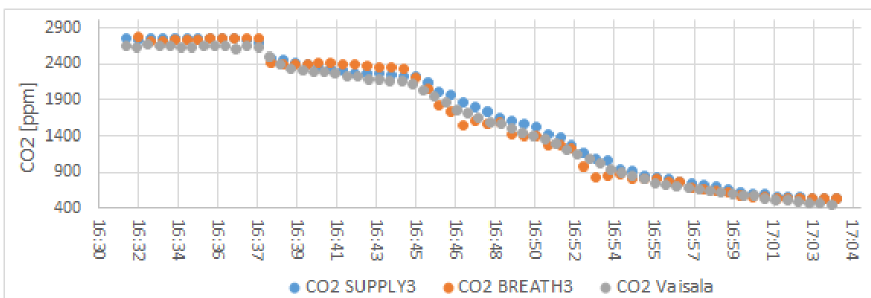


Figure 6.3: CO_2 step-response of sensor rig 3 and Vaisala.

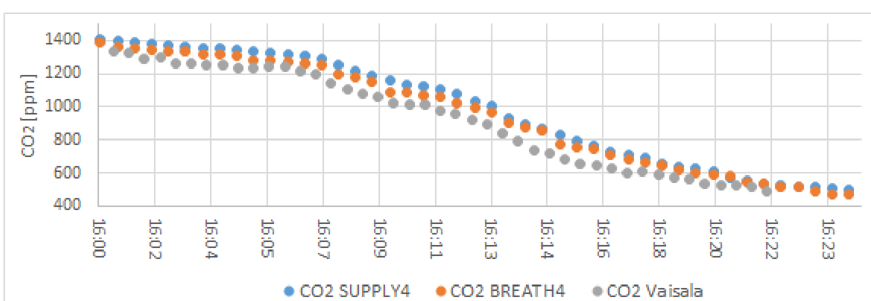
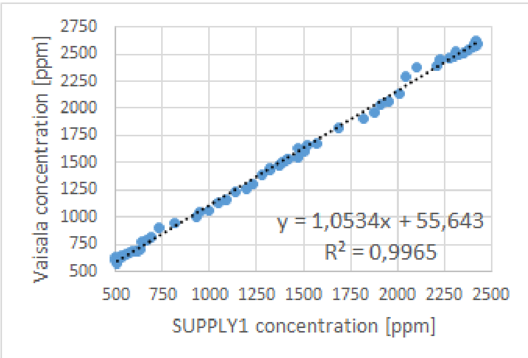


Figure 6.4: CO_2 step-response of sensor rig 4 and Vaisala.

CO_2 calibration of sensor rig 1

For sensor rig 1, the CO_2 calibration of SUPPLY1 against Vaisala (figure 6.7) gave a correlation coefficient of $R^2 = 0.9965$ and a calibration curve of $y = 1.0534x + 55.643$. SUPPLY1 CO_2 measurements has a standard deviation of 130 ppm from the Vaisala reference concentration for the measured concentration interval. The CO_2 calibration of BREATH1 against Vaisala (figure 6.7) gave a correlation coefficient of $R^2 = 0.9962$ and a calibration curve of $y = 1.0076x + 43.138$. BREATH1 CO_2 measurements has a standard deviation of 68 ppm from the Vaisala reference measurements for the measured concentration interval.



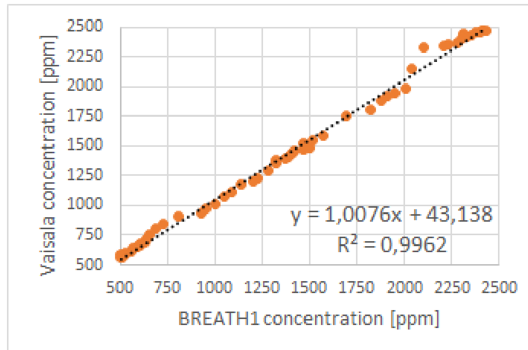
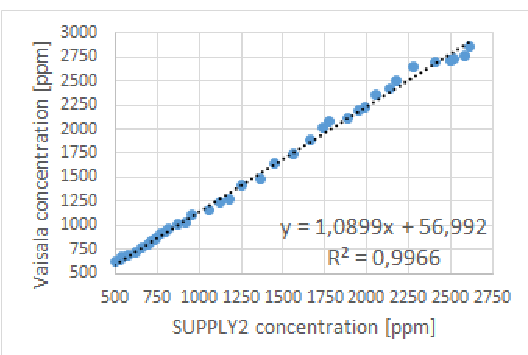


Figure 6.5: Correlation of CO_2 concentrations measured by sensor rig 1 (SUPPLY1 and BREATH1) and Vaisala

CO_2 calibration of sensor rig 2

For sensor rig 2, the CO_2 calibration of SUPPLY2 against Vaisala (figure 6.6) gave a correlation coefficient of $R^2 = 0.9966$ and a calibration curve of $y = 1.0899x + 56.992$. SUPPLY2 CO_2 measurements has a standard deviation of 187 ppm from the Vaisala reference measurements for the measured concentration interval. The CO_2 calibration of BREATH2 against Vaisala (figure 6.6) gave a correlation coefficient of $R^2 = 0.9836$ and a calibration curve of $y = 1.0547x - 28.939$. BREATH2 CO_2 measurements has a standard deviation of 115 ppm from the Vaisala reference measurements for the measured concentration interval.



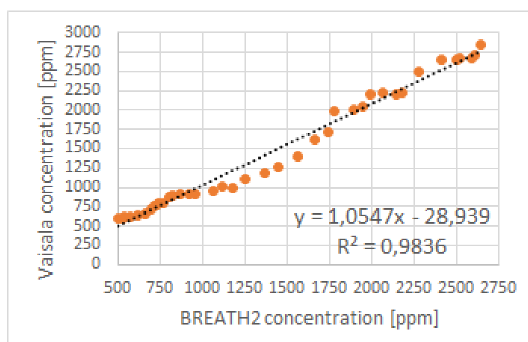


Figure 6.6: Correlation of CO_2 concentrations measured by sensor rig 2 (SUPPLY2 and BREATH2) and Vaisala

CO_2 calibration of sensor rig 3

For sensor rig 3, the CO_2 calibration of SUPPLY3 against Vaisala (figure **??**) gave a correlation coefficient of $R^2 = 0.9963$ and a calibration curve of $y = 1.0324x + 57.126$. SUPPLY3 CO_2 measurements has a standard deviation of 104 ppm from the Vaisala reference measurements for the measured concentration interval. The CO_2 calibration of BREATH3 against Vaisala (figure **??**) gave a correlation coefficient of $R^2 = 0.9823$ and a calibration curve of $y = 1.0518x - 32.743$. BREATH3 CO_2 measurements has a standard deviation of 100 ppm from the Vaisala reference measurements for the measured concentration interval.

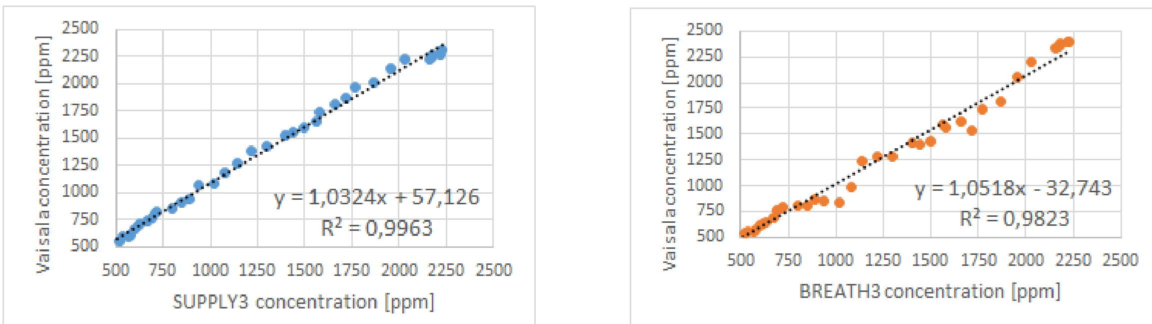


Figure 6.7: Correlation of CO_2 concentrations measured by sensor rig 3 (SUPPLY3 and BREATH3) and Vaisala

CO_2 calibration of sensor rig 4

For sensor rig 4, the CO_2 calibration of SUPPLY4 against Vaisala (figure 6.8) gave a correlation coefficient of $R^2 = 0.9881$ and a calibration curve of $y = 1.0643x + 43.189$. SUPPLY4 CO_2 measurements has a standard deviation of 109 ppm from the Vaisala reference measurements for the measured concentration interval. The CO_2 calibration of BREATH4 against Vaisala (figure 6.8) gave a correlation coefficient of $R^2 = 0.9893$ and a calibration curve of $y = 1.0366x + 37.156$. BREATH4 CO_2 measurements has a standard deviation of 79 ppm from the Vaisala reference measurements for the measured concentration interval.

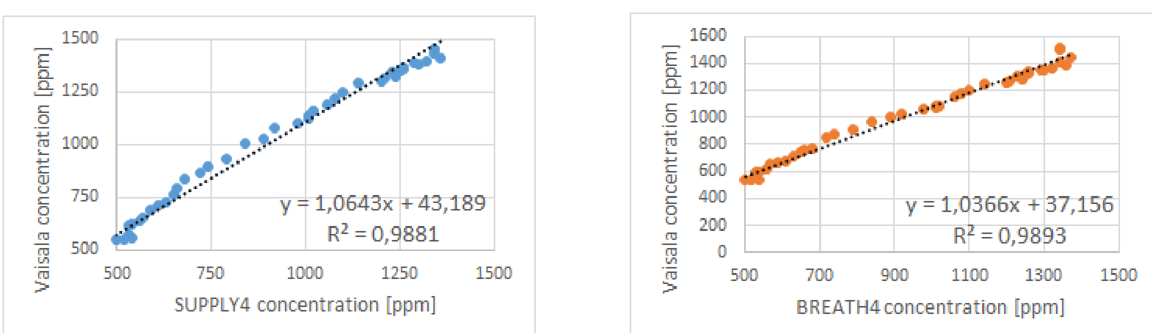


Figure 6.8: Correlation of CO_2 concentrations measured by sensor rig 4 (SUPPLY4 and BREATH4) and Vaisala

6.1.2 Initial calibration of $PM_{2.5}$ levels measured by SPS30 particulate matter sensors

In figure 6.9 is seen that the $PM_{2.5}$ measurements made by the SPS30 sensors on all four sensor rigs do not track the Pegasor $PM_{2.5}$ measurements as good as expected, however all the SPS30 sensors give quite identical $PM_{2.5}$ measurements at all times. Sudden increases and decreases in the mass concentrations are detected, but the measured levels are rarely very close to the reference levels measured by Pegasor. It is assumed that the Pegasor measurements of $PM_{2.5}$ are correct.

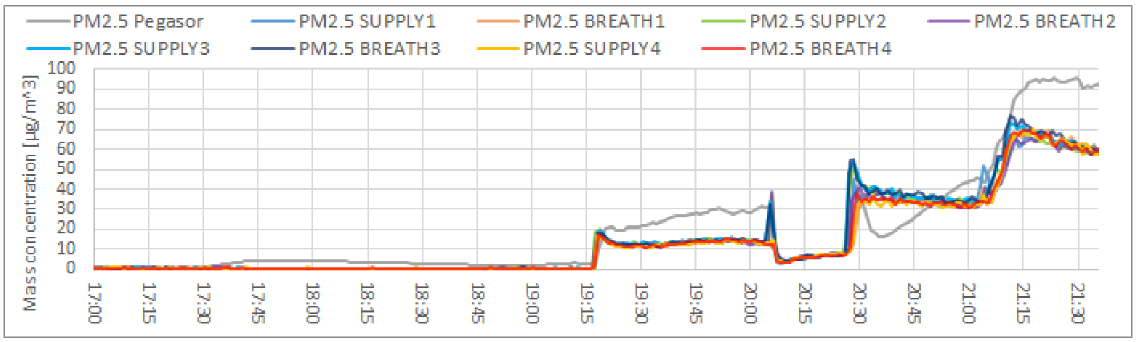


Figure 6.9: Simultaneous $PM_{2.5}$ calibration measurements of all sensor rigs against reference instrument Pegasor

$PM_{2.5}$ calibrations of sensor rig 1

For sensor rig 1, the temperature calibration of SUPPLY1 against reference instrument Pegasor (figure 6.10) gave a correlation coefficient of $R^2 = 0.7581$ and a calibration curve of $y = 1.156x + 1.5524$. The temperature calibration of BREATH1 against reference instrument Pegasor (figure 6.10) gave a correlation coefficient of $R^2 = 0.7583$ and a calibration curve of $y = 1.1265x + 1.8622$.

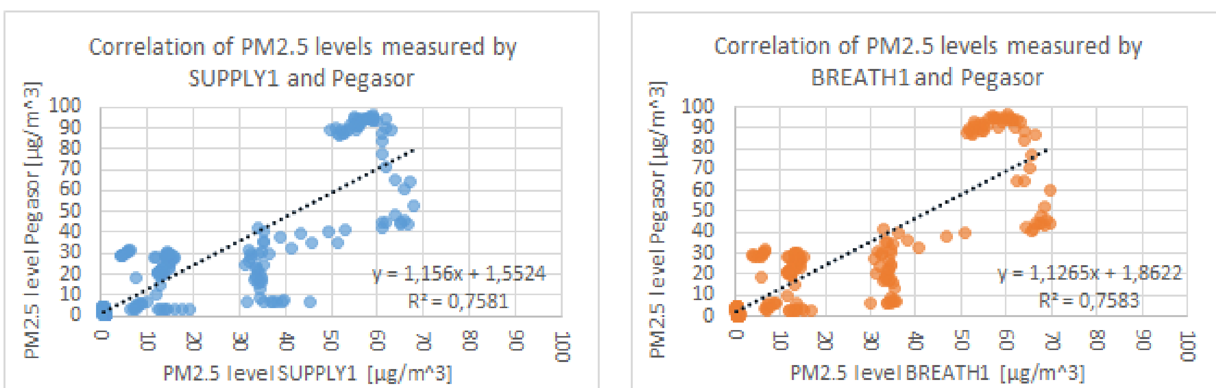
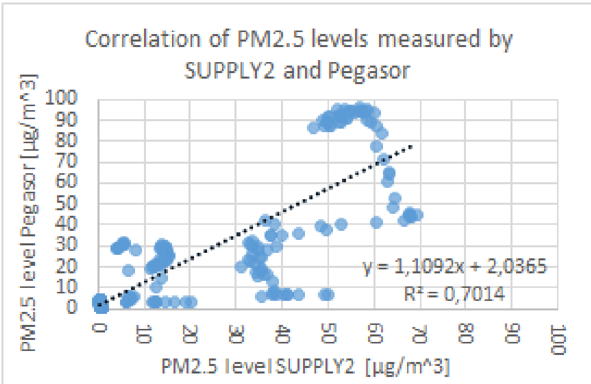


Figure 6.10: Correlation of $PM_{2.5}$ levels measured by sensor rig 1 (SUPPLY1 and BREATH1) and reference instrument Pegasor

$PM_{2.5}$ calibrations of sensor rig 2

For sensor rig 2, the temperature calibration of SUPPLY2 against reference instrument Pegasor (figure 6.11) gave a correlation coefficient of $R^2 = 0.7014$ and a calibration curve of $y = 1.1092x + 2.0365$. The temperature calibration of BREATH2 against reference instrument Pegasor (figure 6.11) gave a correlation coefficient of $R^2 = 0.7462$ and a calibration curve of $y = 1.1544x + 1.7162$.



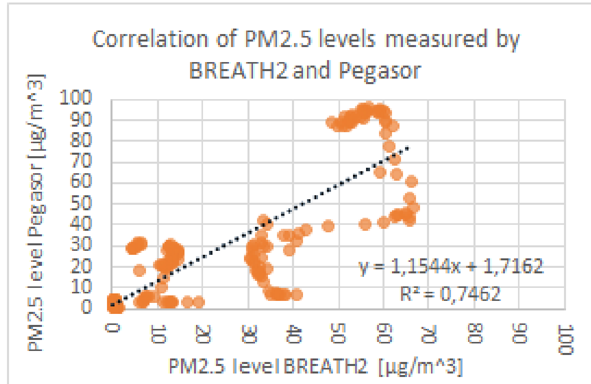
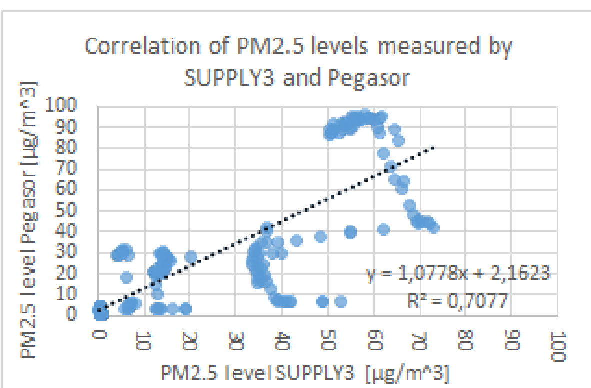


Figure 6.11: Correlation of $PM_{2.5}$ levels measured by sensor rig 2 (SUPPLY2 and BREATH2) and reference instrument Pegasor

$PM_{2.5}$ calibrations of sensor rig 3

For sensor rig 3, the temperature calibration of SUPPLY3 against reference instrument Pegasor (figure 6.12) gave a correlation coefficient of $R^2 = 0.7077$ and a calibration curve of $y = 1.0778x + 2.1623$. The temperature calibration of BREATH3 against reference instrument Pegasor (figure 6.12) gave a correlation coefficient of $R^2 = 0.7044$ and a calibration curve of $y = 1.0553x + 2.3583$.



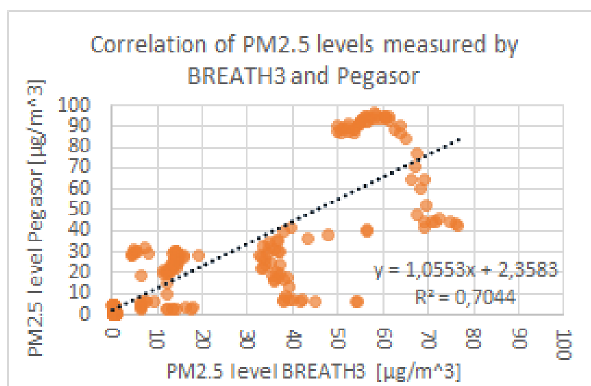


Figure 6.12: Correlation of $PM_{2.5}$ levels measured by sensor rig 3 (SUPPLY3 and BREATH3) and reference instrument Pegasor

$PM_{2.5}$ calibrations of sensor rig 4

For sensor rig 4, the temperature calibration of SUPPLY4 against reference instrument Pegasor (figure 6.13) gave a correlation coefficient of $R^2 = 0.7772$ and a calibration curve of $y = 1.1708x + 1.7844$. The temperature calibration of BREATH4 against reference instrument Pegasor (figure 6.13) gave a correlation coefficient of $R^2 = 0.7611$ and a calibration curve of $y = 1.1551x + 1.8927$.

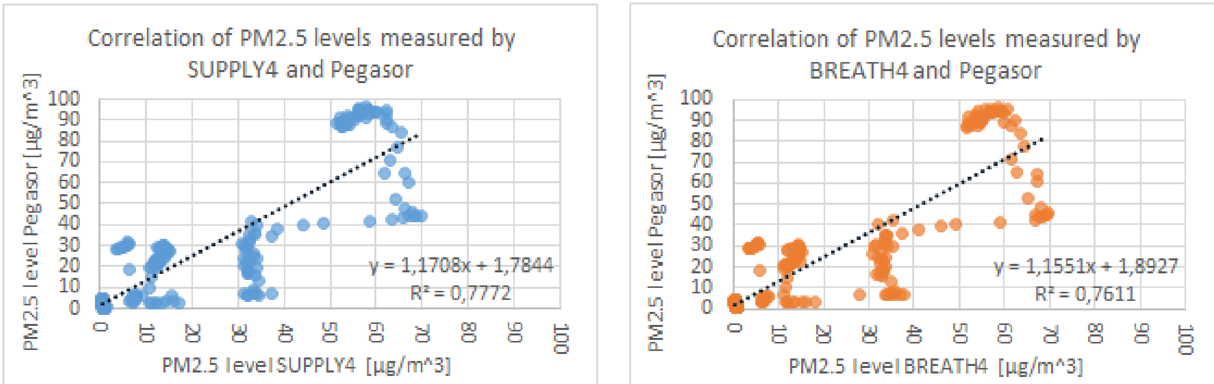


Figure 6.13: Correlation of $PM_{2.5}$ levels measured by sensor rig 4 (SUPPLY4 and BREATH4) and reference instrument Pegasor

6.1.3 Testing of WZ-S formaldehyde sensors

In figure 6.14, all formaldehyde sensors are tested at the same time under identical conditions. Windows had been open for a long time, and when the measurements were started, the windows were closed and an electrical oven was turned on max. When the time was 20:10, 6 candles were lit. It is seen that formaldehyde concentrations increase for increasing temperatures and for candle burning. The measurement results from all sensor rigs (SUPPLYx and BREATHx) show that all formaldehyde sensors measure quite similar concentrations for equal conditions, especially for lower concentrations, but at higher concentratons (>100 $\mu g/m^3$) the measured concentrations vary more.

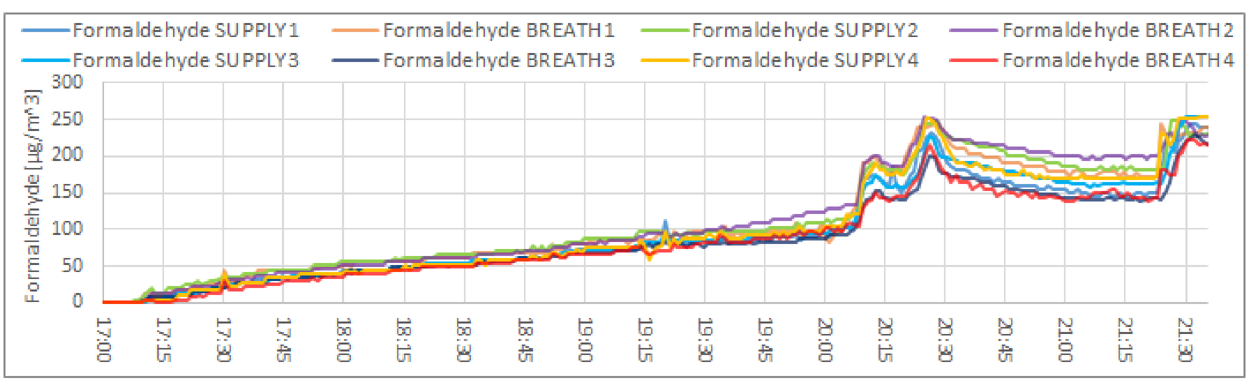


Figure 6.14: Simultaneous formaldehyde measurements carried out under identical conditions for all sensor rigs

6.1.4 Initial calibration of SCD30 temperature and humidity sensors

In figures 6.15 and 6.16 is seen that the temperature and relative humidity measurements made by the SCD30 sensors on all four sensor rigs track the Pegasor temperature and relative humidity measurements, but with substantial offsets. It is assumed that the Pegasor measurements of temperature and relative humidity are correct.

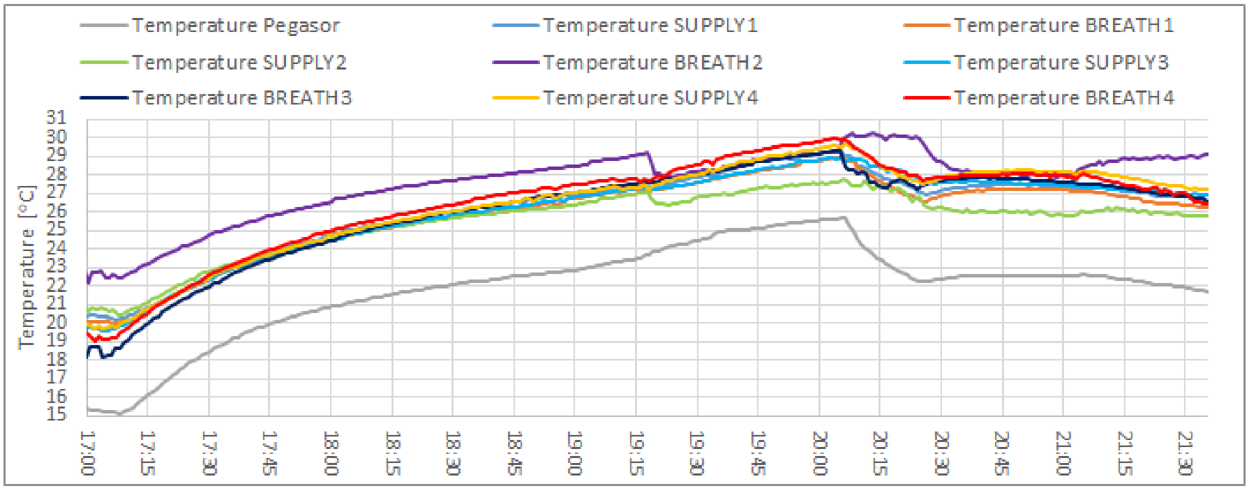


Figure 6.15: Simultaneous measurements under identical conditions for all sensor rigs for temperature calibration against reference instrument Pegasor

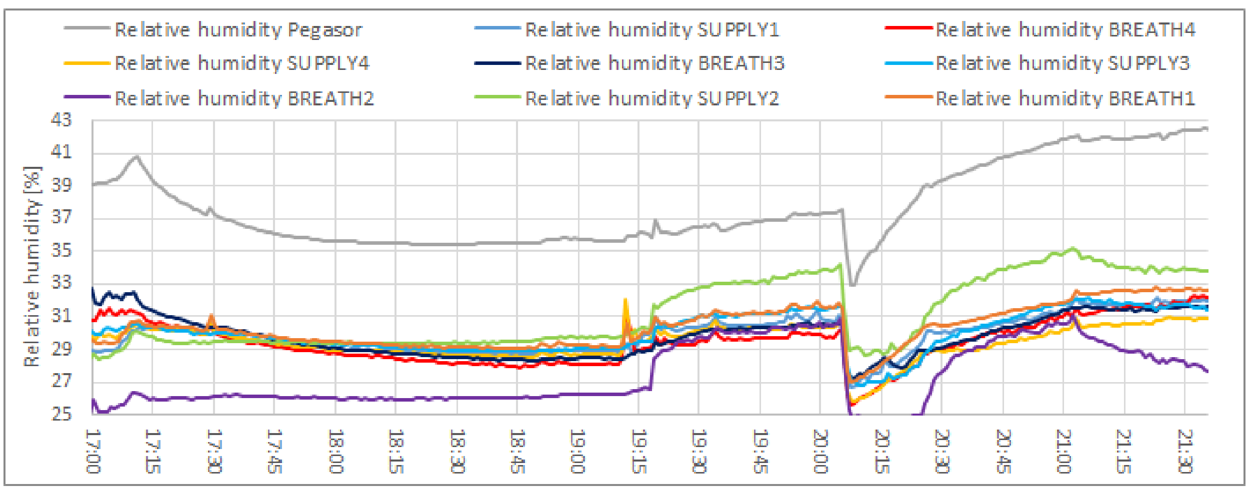


Figure 6.16: Simultaneous measurements under identical conditions for all sensor rigs for relative humidity calibration against reference instrument Pegasor

Temperature calibrations of sensor rig 1

For sensor rig 1, the temperature calibration of SUPPLY1 against reference instrument Pegasor (figure 6.17) gave a correlation coefficient of $R^2 = 0.9698$ and a calibration curve of $y = 1.0817x - 6.3767$. The temperature calibration of BREATH1 against reference instrument Pegasor (figure 6.17) gave a correlation coefficient of $R^2 = 0.9657$ and a calibration curve of $y = 1.0903x - 6.2925$.

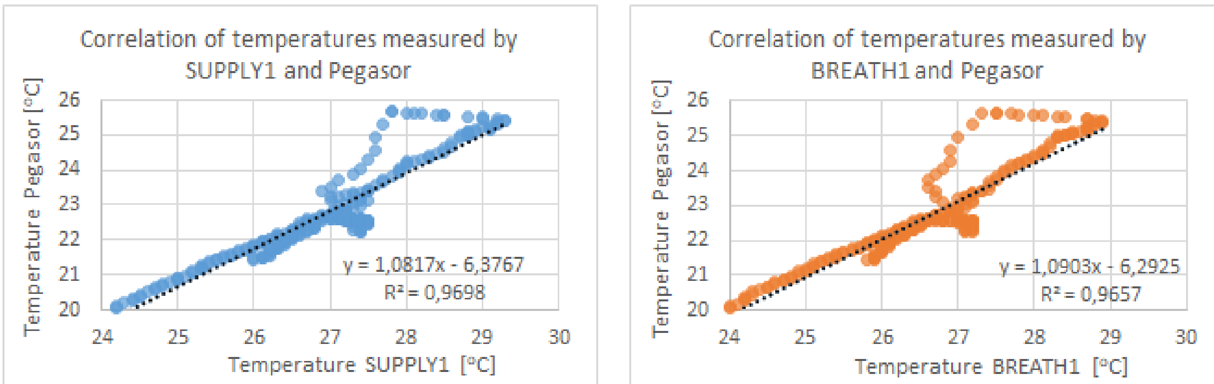


Figure 6.17: Correlation of temperatures measured by sensor rig 1 (SUPPLY1 and BREATH1) and reference instrument Pegasor

Temperature calibrations of sensor rig 2

For sensor rig 2, the temperature calibration of SUPPLY2 against reference instrument Pegasor (figure 6.18) gave a correlation coefficient of $R^2 = 0.9806$ and a calibration curve of $y = 1.4021x - 13.864$. The temperature calibration of BREATH2 against reference instrument Pegasor (figure 6.18) gave a correlation coefficient of $R^2 = 0.9072$ and a calibration curve of $y = 1.2427x - 12.58$.

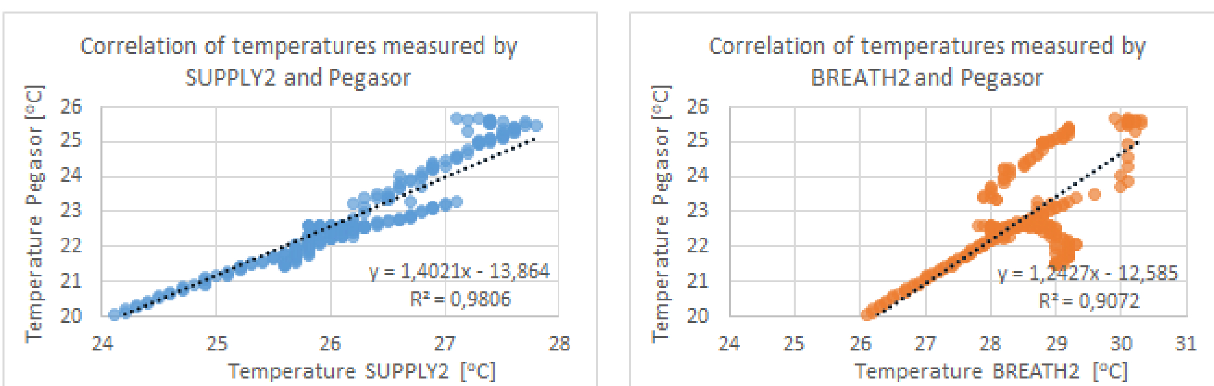


Figure 6.18: Correlation of temperatures measured by sensor rig 2 (SUPPLY2 and BREATH2) and reference instrument Pegasor

Temperature calibrations of sensor rig 3

For sensor rig 3, the temperature calibration of SUPPLY3 against reference instrument Pegasor (figure 6.19) gave a correlation coefficient of $R^2 = 0.9625$ and a calibration curve of $y = 1.0285x - 4.9326$. The temperature calibration of BREATH3 against reference instrument Pegasor (figure 6.19) gave a correlation coefficient of $R^2 = 0.9501$ and a calibration curve of $y = 0.8897x - 1.2505$.

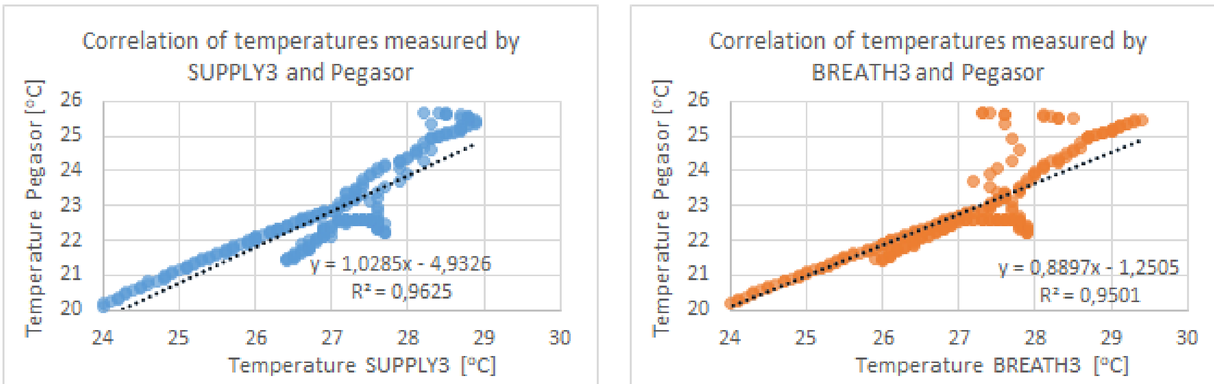


Figure 6.19: Correlation of temperatures measured by sensor rig 3 (SUPPLY3 and BREATH3) and reference instrument Pegasor

Temperature calibrations of sensor rig 4

For sensor rig 4, the temperature calibration of SUPPLY4 against reference instrument Pegasor (figure 6.20) gave a correlation coefficient of $R^2 = 0.9505$ and a calibration curve of $y = 0.962x - 3.5042$. The temperature calibration of BREATH4 against reference instrument Pegasor (figure 6.20) gave a correlation coefficient of $R^2 = 0.9695$ and a calibration curve of $y = 0.9173x - 2.3396$.

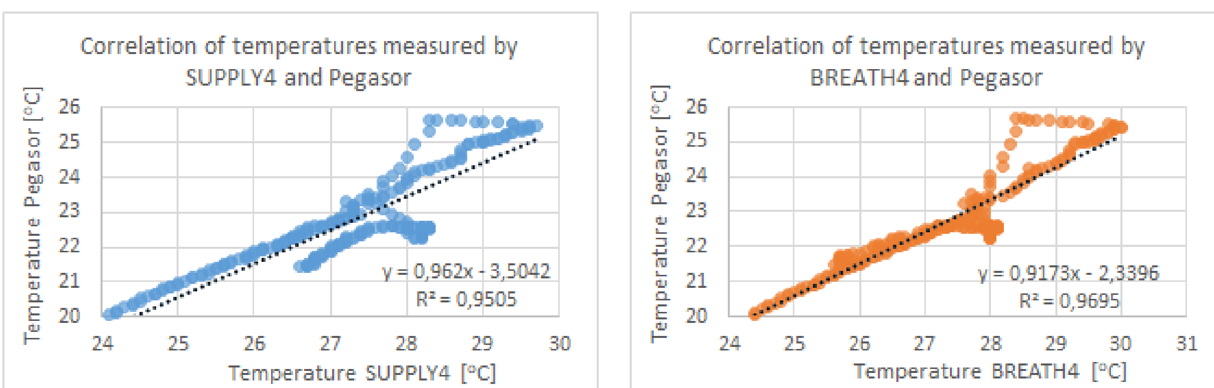


Figure 6.20: Correlation of temperatures measured by sensor rig 4 (SUPPLY4 and BREATH4) and reference instrument Pegasor

6.2 Field measurement results and analysis

6.2.1 Field measurement periods

In table 6.1, information of the field measurement period in each classroom is given.

Table 6.1: Field measurement periods with sensor rigs in the classrooms

Classroom	Sensor rig	Total measurement period	Unexpected measurement crashes
NHT	1	April 11th to May 24th, measurements from 18 normal schooldays and from 33 days in total	One crash on May 10th, measurements were restarted on May 20th
OHT	2	April 25th to May 24th, measurements from 14 normal schooldays and from 18 days in total	An initial crash occurred on April 25th, measurements were restarted on May 2nd. Another crash occurred on May 16th, measurements were restarted on May 20th
NLT	3	April 10th to May 22nd, measurements from 23 normal schooldays and from 43 days in total	No crashes occurred during measurement period
OLT	4	April 24th to May 23rd, measurements from 20 normal schooldays and from 30 days in total	No crashes occurred during measurement period

6.2.2 CO_2 levels

The DCV systems in all four schools are controlled by CO_2 levels. The CO_2 levels for all four classrooms are displayed in figures 6.21, 6.22, 6.23 and 6.24 for a chosen two week interval. In the figures, the CO_2 levels in the classrooms and the supplied airflow to the classrooms are shown. An inverse correlation between CO_2 levels and airflow rates is obvious from the measurement results. For classroom NHT (figure 6.21), OHT (figure 6.22) and OLT (figure 6.24) it is seen that placing the sensor box measuring the state of the supply air right next to an air supply diffuser does not give a good approximation of the supply air. This is seen because the CO_2 levels for the supply airflow are nearly identical to the CO_2 levels in the breathing zone. For classroom NLT (figure 6.23) the supply air is measured correctly, because it was possible to place the sensor box measuring the state of the supply air inside the supply air duct.

In classroom NLT, the CO_2 guideline limit of 1000 ppm was never exceeded. In classroom OHT, the guideline limit was exceeded for 8 schooldays (57% of the measured schooldays). In classroom NLT, the guideline limit was exceeded for 8 schooldays (13% of the measured schooldays). In classroom OLT, the guideline limit was was never exceeded.

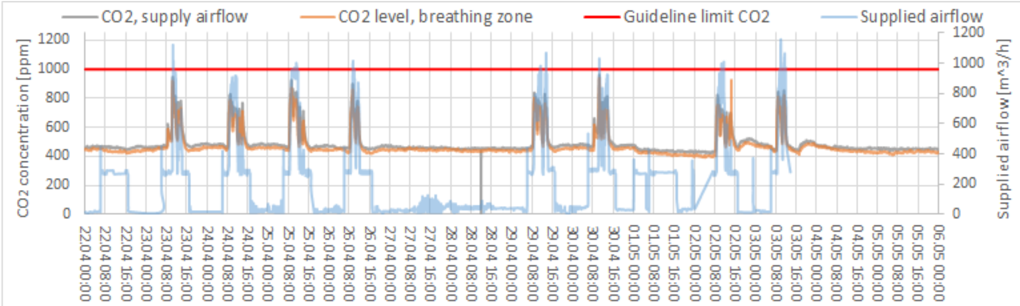


Figure 6.21: Classroom NHT, sensor rig 1: Two weeks of CO_2 levels

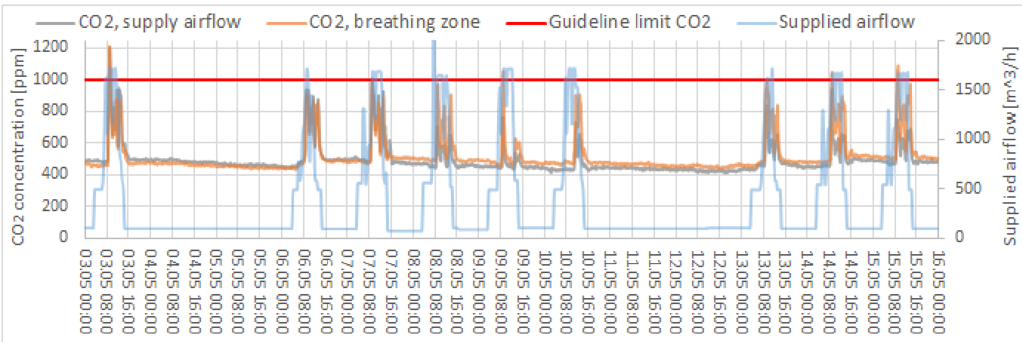


Figure 6.22: Classroom OHT, sensor rig 2: Two weeks of CO_2 levels

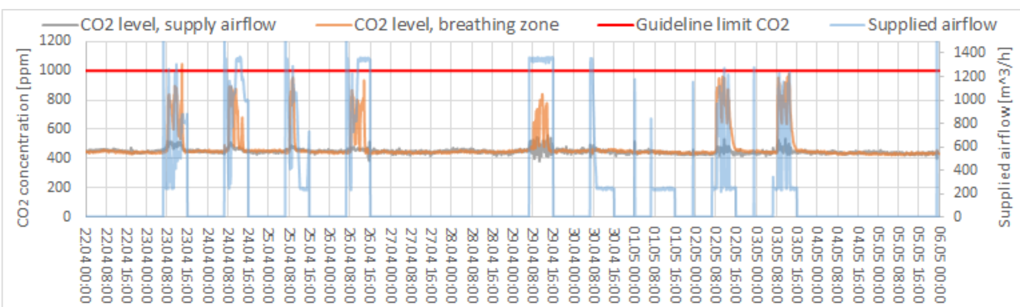


Figure 6.23: Classroom NLT, sensor rig 3: Two weeks of CO_2 levels

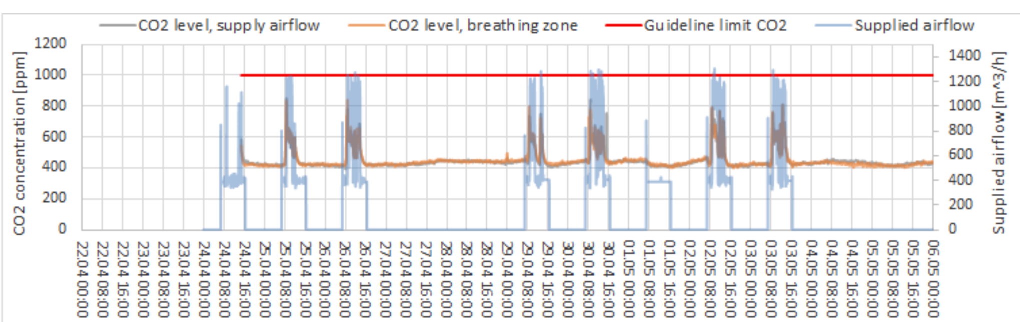


Figure 6.24: Classroom OLT, sensor rig 4: Two weeks of CO_2 levels

In figures 6.25, 6.26, 6.27 and 6.28, comparisons of the CO_2 levels in the breathing zone, measured by the sensor rig and BAS system, are shown for all classrooms. It is assumed that the BAS measures correct CO_2 levels. In classroom OHT (figure 6.26) and classroom OLT (figure 6.28) the BAS and sensor rig measurements give approximately the same CO_2 levels, making the sensor rig CO_2 measurements satisfactory. In classroom NHT (figure 6.25) the sensor rig CO_2 measurements have an offset of approximately +40 ppm relative to the BAS measurements. In classroom NLT (figure 6.27) the sensor rig CO_2 measurements have an offset of approximately +100 ppm relative to the BAS measurements. The varying accuracy of the sensor rig CO_2 measurements may indicate that the required initial calibration procedure described in the datasheet A.1.1 and code section A.3.3 might need to be redone before new measurements in the future.

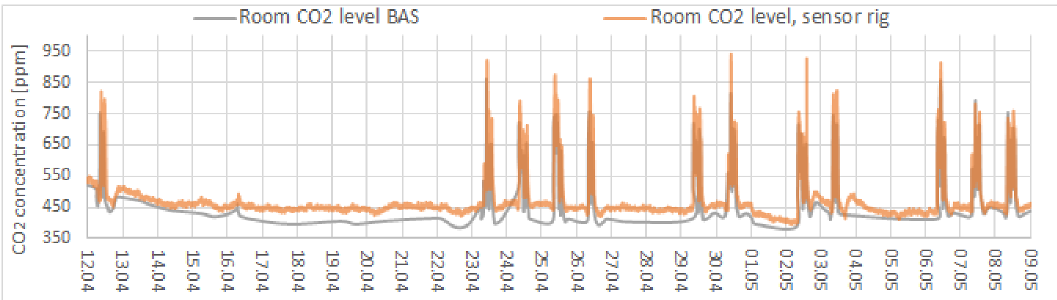


Figure 6.25: NHT: Comparison of the CO_2 level in the breathing zone, measured by sensor rig 1 and BAS

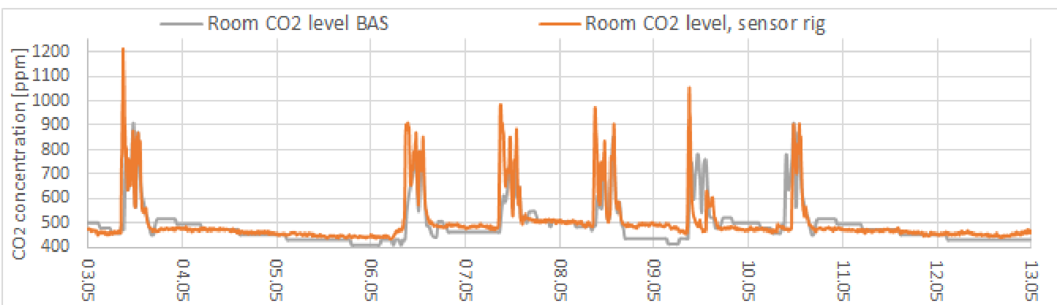


Figure 6.26: OHT: Comparison of the CO_2 level in the breathing zone, measured by sensor rig 2 and BAS

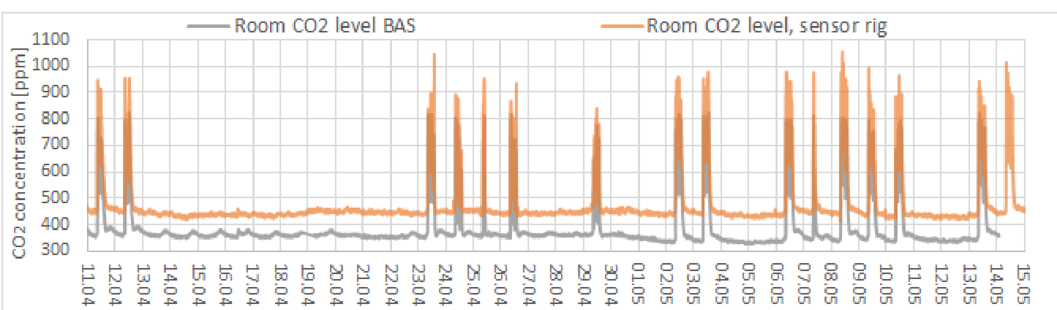


Figure 6.27: NLT: Comparison of the CO_2 level in the breathing zone, measured by sensor rig 3 and BAS

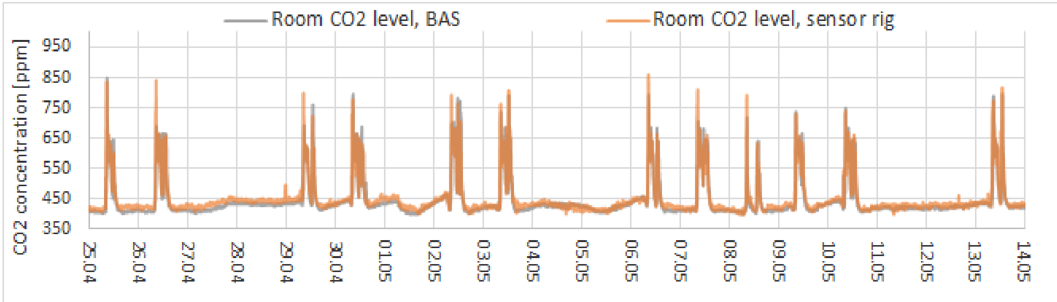


Figure 6.28: OLT: Comparison of the CO_2 level in the breathing zone, measured by sensor rig 4 and BAS

6.2.3 Formaldehyde levels

In all four classrooms, the 30 minute average guideline limit value (100 $\mu g/m^3$) for formaldehyde was exceeded on several occasions. However, for most cases this happens outside occupied hours. Occupied hours are between 07:00 and 17:00 on weekdays. The 30 minutes average formaldehyde levels for all four classrooms are displayed in figures 6.29, 6.30, 6.31 and 6.32 for a chosen two week interval. Classroom OLT is the only classroom where the limit value is rarely exceeded. It is seen that when the ventilation rates are increased from minimum at 07:00 in the morning, the formaldehyde levels in the classroom decrease rapidly. When the ventilation rate is decreased to minimum at 17:00 in the evening, the formaldehyde level increases gradually. This confirms an inverse correlation between the indoor formaldehyde concentration and the air exchange rate, stated in Salthammer et al. (2010). During weekends, the formaldehyde level gets relatively high if ventilation rates are kept at minimum. During lunch hours, between 11:30 and 12:00, high and short peaks in the formaldehyde concentration appears, often exceeding the guideline limit value. It is suspected that the sensor might be cross-sensitive to other compounds, because food and beverages should not emit that much formaldehyde. This is discussed with Dart Sensors, which is the developer of the WZ-S formaldehyde sensor. John King, the managing director of Dart Sensors, say that *"There are cross-sensitivities, but the chief ones are usually alcohols, and I would not expect too much of that to be present in the context of a school. There are also sensitivities to higher aldehydes. More broadly, anything volatile with an oxidizable alcohol or carbonyl group could be a candidate to account for your observations."*.

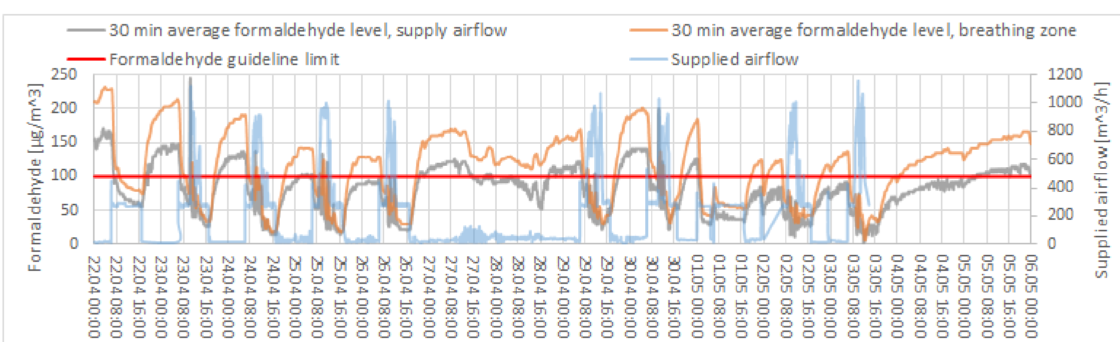


Figure 6.29: Classroom NHT, sensor rig 1: Two weeks of 30 minute moving average formaldehyde levels

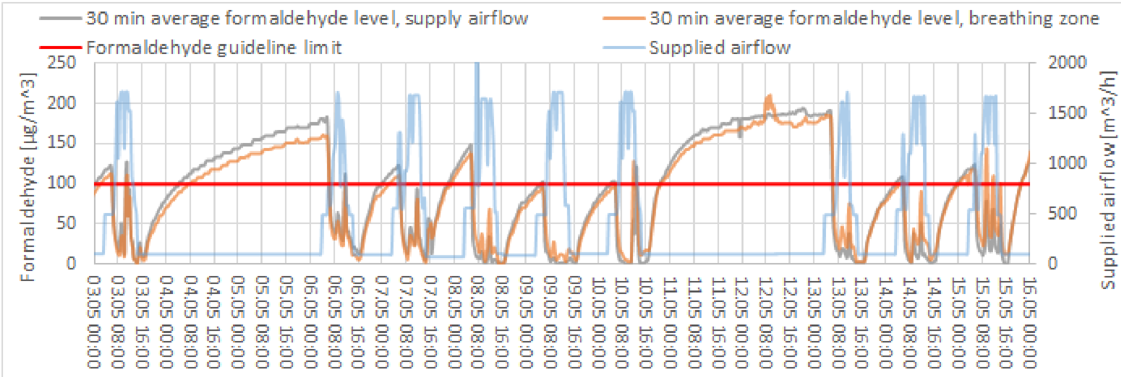


Figure 6.30: Classroom OHT, sensor rig 2: Two weeks of 30 minute moving average formaldehyde levels

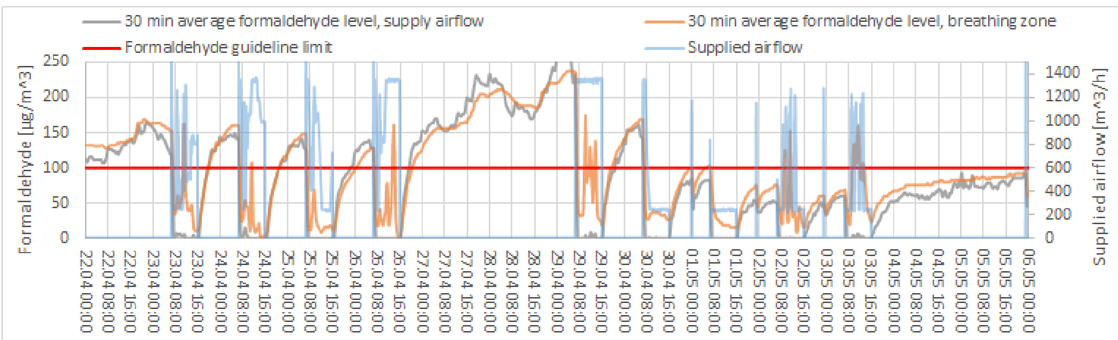


Figure 6.31: Classroom NLT, sensor rig 3: Two weeks of 30 minute moving average formaldehyde levels

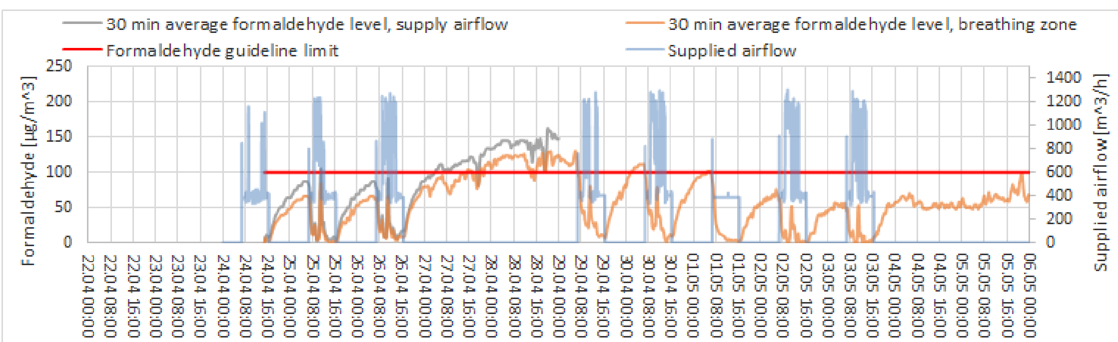


Figure 6.32: Classroom OLT, sensor rig 4: Two weeks of 30 minute moving average formaldehyde levels

In figures 6.33, 6.34 and 6.35, box and whiskers plots of the formaldehyde levels in all classrooms are showed for all hours, occupied hours and unoccupied hours. The box and whiskers plots show minimum values, 25th percentiles, median, 75th percentiles and maximum values. The box and whiskers plot for all hours shows that the formaldehyde levels in classrooms NHT, OHT and NLT are substantially higher than in classroom OLT.

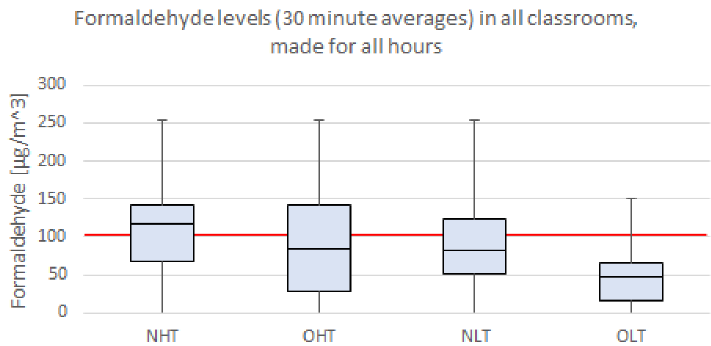


Figure 6.33: Box and whiskers plots of formaldehyde levels in all classrooms for all hours

During occupied hours (figure 6.34) the formaldehyde levels are relatively low for all four classrooms, and the levels in NHT and NLT are slightly higher than in OHT and OLT. The maximum level in OHT is significantly lower than in the other classrooms.

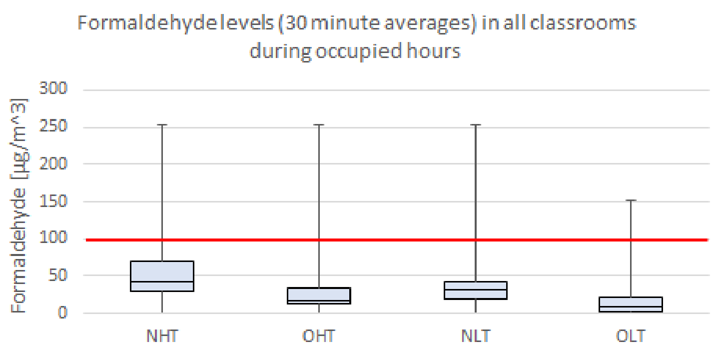


Figure 6.34: Box and whiskers plots of formaldehyde levels in all classrooms for occupied hours

During unoccupied hours (figure 6.35), the formaldehyde levels are significantly higher in all four classrooms compared to unoccupied hours. The limit value guideline is exceeded most of the time during unoccupied hours for classroom NHT, OHT and NLT, but not for OLT.

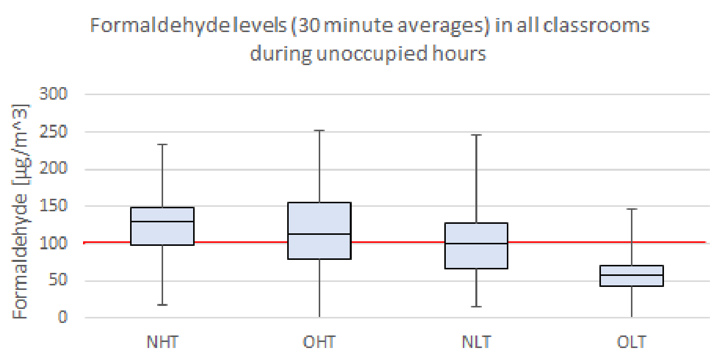


Figure 6.35: Box and whiskers plots of formaldehyde levels in all classrooms for unoccupied hours

6.2.4 Particulate matter levels

In figures 6.36, 6.38 and 6.39, 24 hour moving average $PM_{2.5}$ levels are shown for classroom NHT, NLT and OLT for a chosen two week interval (22.04-06.05). This two week interval was chosen because significant peaks in the $PM_{2.5}$ levels occurred here. In classroom OHT (figure 6.37), the sensor measurements did not begin until May 3rd due to the initial measurement crash on April 25th, possibly missing out on a similar measurement peak there. Measurements from all other days were very low for all classrooms, in the interval of 0-3 $\mu g/m^3$. The 24 hour average guideline limit of 15 $\mu g/m^3$ was exceeded in classroom NHT one time, on Sunday 29/4 and Monday 30/4, with a peak of 30 $\mu g/m^3$ (figure 6.36).

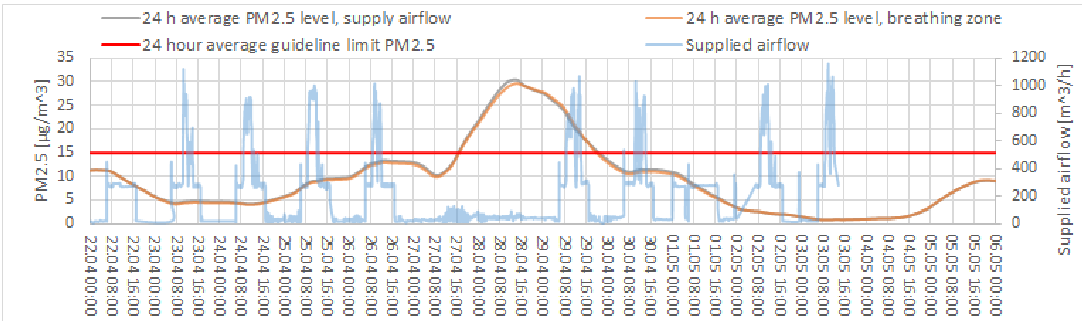


Figure 6.36: Classroom NHT, sensor rig 1: Two weeks of 24 hour moving average $PM_{2.5}$ levels

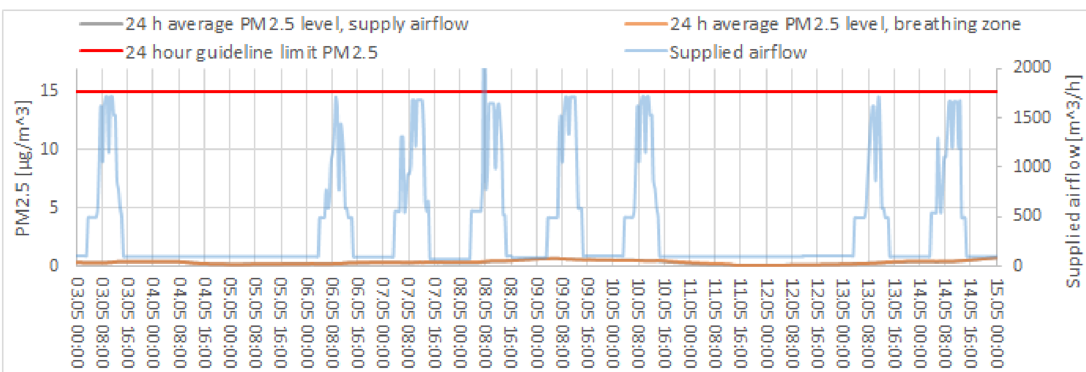


Figure 6.37: Classroom OHT, sensor rig 2: Two weeks of 24 hour moving average $PM_{2.5}$ levels

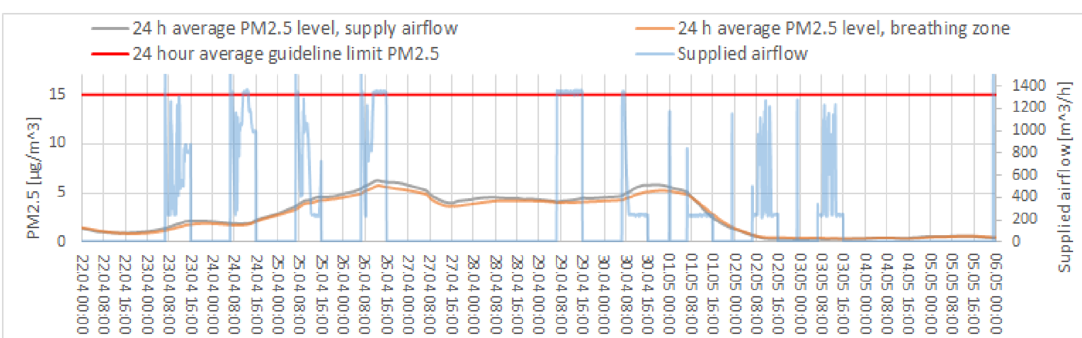


Figure 6.38: Classroom NLT, sensor rig 3: Two weeks of 24 hour moving average $PM_{2.5}$ levels

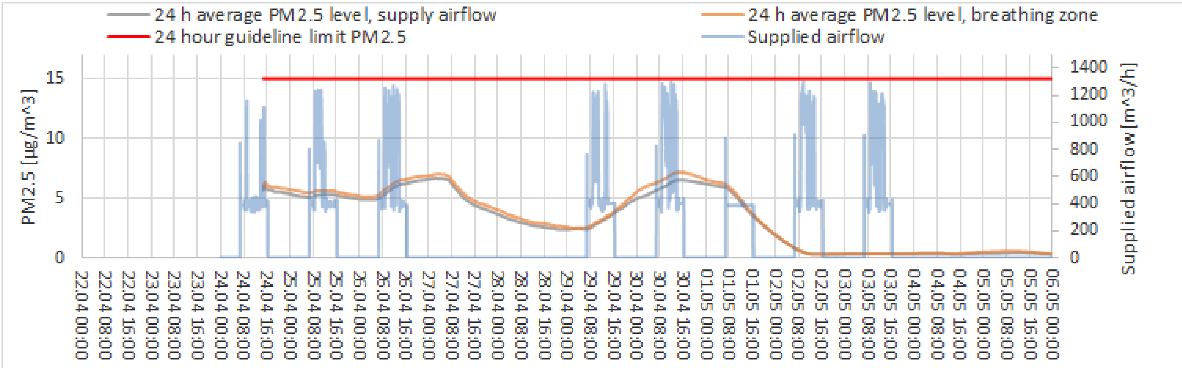


Figure 6.39: Classroom OLT, sensor rig 4: Two weeks of 24 hour moving average $PM_{2.5}$ levels

Data on outdoor $PM_{2.5}$ measurements were provided by Tore Nordstad in Miljøenheten from the four measurement stations in Trondheim. In figure 6.40, the outdoor 24 hour average $PM_{2.5}$ levels are shown. A significant increase in the levels occurred for the days 25.04-02.05, where all measurement stations reported values exceeding the limit value guideline. Tore Nordstad describes the period (translated from Norwegian): "*It was particularly dry and dusty during this period. The fine particles only rose in the air, they did not settle at night time, which is relatively uncommon, but can occur during very dry periods. It looked like this happened in the entire city. Wind helped swirl dust from both roads and courtyards, but probably also from crop fields, construction sites, gravel pits and similar*". This dusty period of high outdoor $PM_{2.5}$ levels is the same period as for the increase in the indoor levels in classrooms NHT (figure 6.36), NLT (6.38) and OLT (figure 6.39). This connection indicates that high outdoor particulate matter levels can result in high indoor particulate matter levels for fine particles. There is a chance that a window was left open in classroom NHT (figure 6.36) for the days when the limit value guideline was exceeded, but the operator or teacher at the school can not remember if this was the case. If no windows in the classroom were open during this period, it is reasonable to assume that the filter in the AHU is not working as it is supposed to.

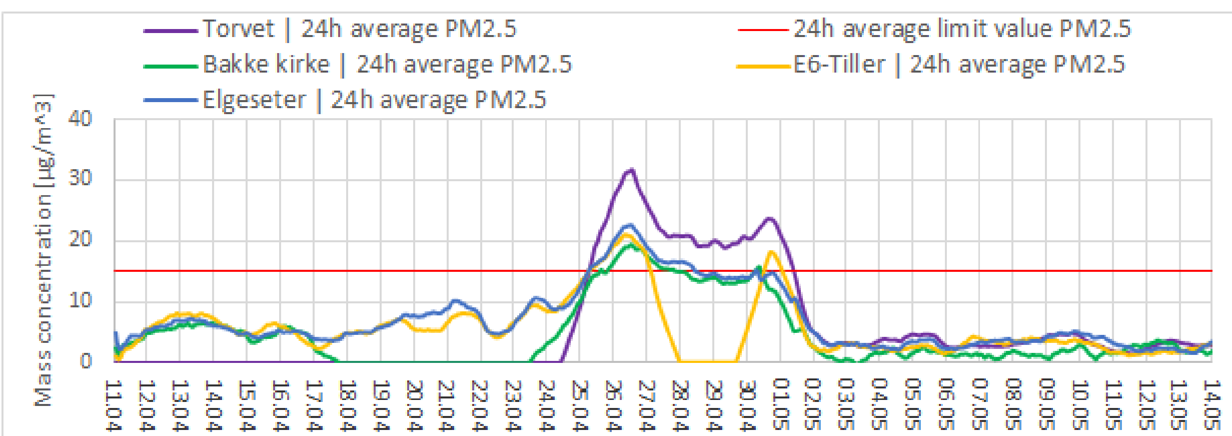


Figure 6.40: Outdoor 24 hour average $PM_{2.5}$ levels at four measurement stations in Trondheim

In figures 6.41, 6.42 and 6.43, the instantaneous $PM_{2.5}$ levels in classroom NHT, NLT and OLT are shown. For classroom NHT (figure 6.41) it often seems like the $PM_{2.5}$ levels decline when the ventilation rates are increased and that the $PM_{2.5}$ levels increase when ventilation rates are decreased. An explanation of this may be that the supply air is cleaner than the room air. For classroom NLT (figure 6.42) and OLT (figure 6.43) the opposite seems to occur; when ventilation rates are increased in the morning, the $PM_{2.5}$ rises suddenly, and when ventilation rates are decreased in the evening, the $PM_{2.5}$ decreases. An explanation to this may be that settled particles are resuspended to the air when the ventilation is increased, and that they settle again when the ventilation is decreased.

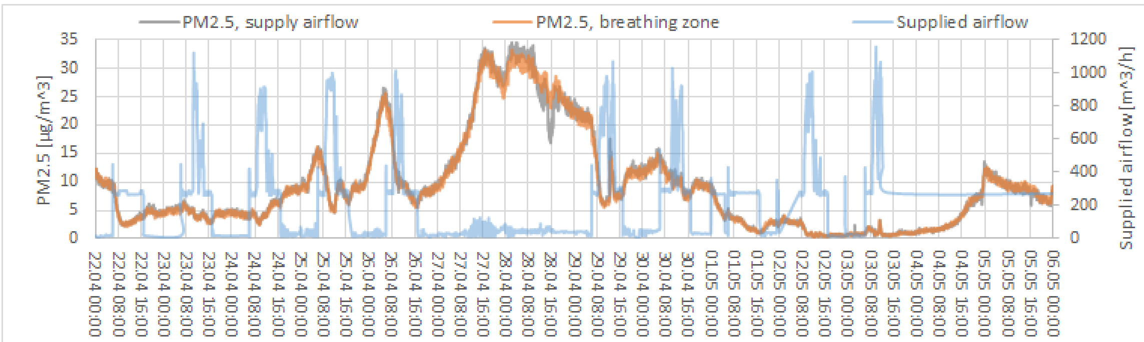


Figure 6.41: Classroom NHT, sensor rig 1: Two weeks of $PM_{2.5}$ levels

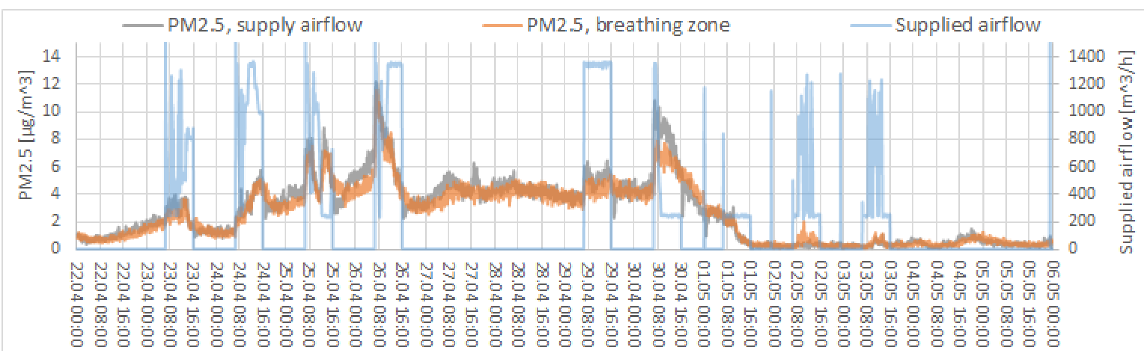


Figure 6.42: Classroom NLT, sensor rig 3: Two weeks of $PM_{2.5}$ levels

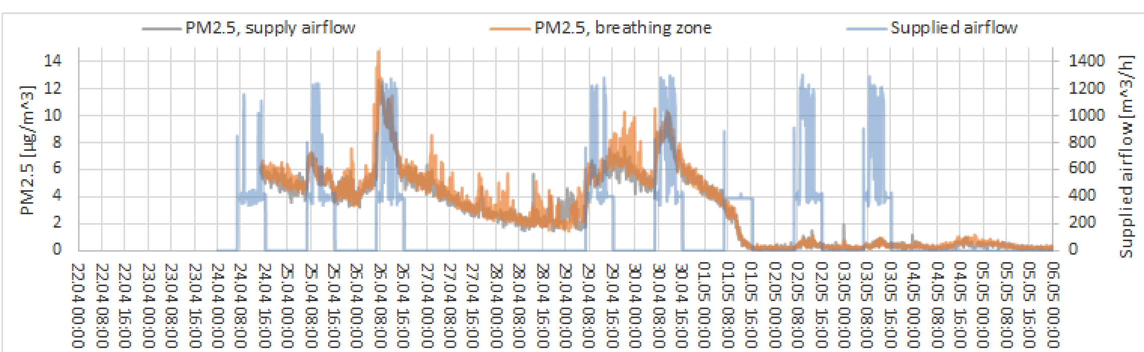


Figure 6.43: Classroom OLT, sensor rig 4: Two weeks of $PM_{2.5}$ levels

In figure 6.44, box and whiskers plots of the $PM_{2.5}$ and PM_{10} levels in all classrooms during their respective measurement periods are shown. The box and whiskers plots show minimum values, 25th percentiles, median, 75th percentiles and maximum values. The levels in classroom NHT are substantially higher than in the other classrooms. In classroom OHT the levels are exceedingly low, possibly due to the late start of the measurement period there, after the dusty period in the other classrooms. However, it is challenging to compare the classrooms when the plots are not made for the same measurement periods.

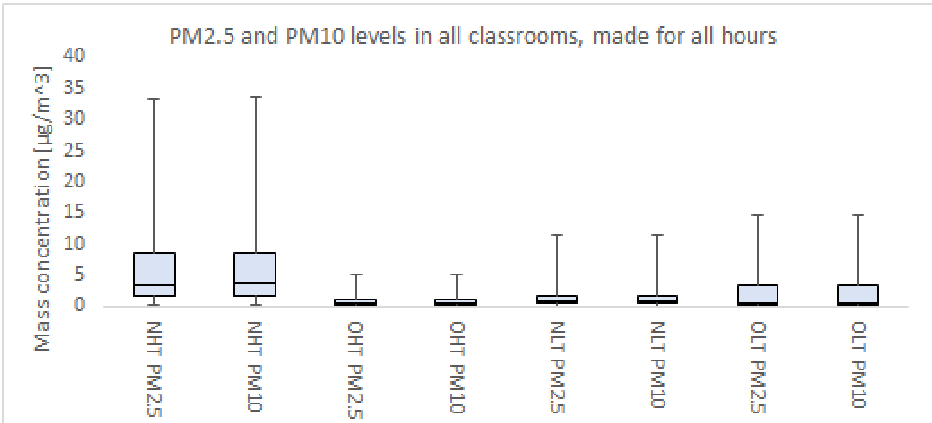


Figure 6.44: Box and whiskers plots of particulate matter levels in all classrooms during their respective measurement periods

In figure 6.45 box and whisker plots of $PM_{2.5}$ and PM_{10} levels in all classrooms for the same period (02.05-22.05) are shown, to better compare the classrooms. The figure show very low levels in all classrooms, and that NHT and OHT have only slightly higher levels than NLT and OLT.

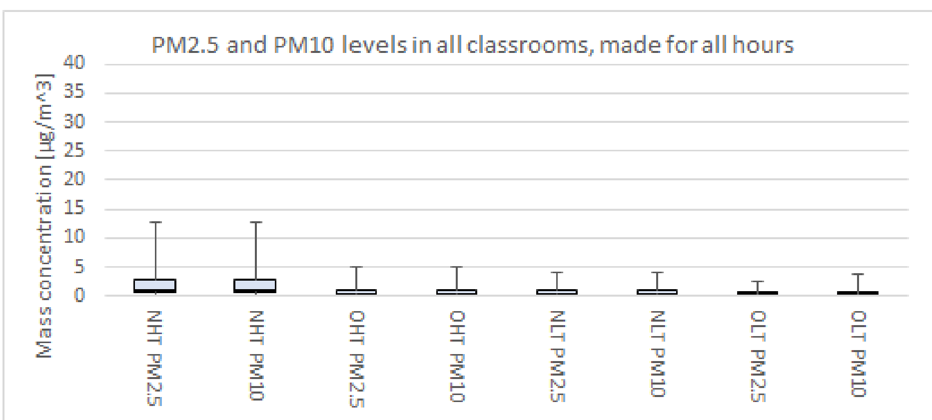


Figure 6.45: Box and whiskers plots of particulate matter levels in all classrooms for period May 2nd to May 22nd

It is seen in figures 6.44 and 6.45 that the PM_{10} measurements are almost identical to the $PM_{2.5}$ measurements for every measurement in every classroom, which is unlikely. This observation is discussed with Sensirion, which is the developer of the SPS30 Particulate matter sensor. Manuel

Meier at Sensirion says that "*One of the most significant differences between low-cost laser based PM sensors (as SPS30) and reference instruments is how the optical scatter signal is generated and processed. Reference instruments measure almost every particle in the volume flow (requires complex and expensive instrumentation). Therefore, the scattering process is very repeatable. The design of low-cost, laser based PM sensors is cost and size optimized. As a consequence of the much simpler optical design, only a small fraction of the actual aerosol passing through the sensor is detected, resulting in higher statistical measurement noise (common for all low cost PM sensors in the market). Since by nature, there are always more small airborne particles than large airborne particles, the statistical noise of the measurement output increases from PM0.5 to PM10 exponentially.*" This means that SPS30 measured $PM_{2.5}$ levels are more reliable than measured PM_{10} levels, and further PM_{10} analysis will not be made.

6.2.5 Comparison of the temperature levels in the breathing zone, measured by the sensor rig and BAS system

In figures 6.46, 6.47, 6.48 and 6.49 comparisons of the temperatures measured in the breathing zone, measured by the sensor rigs and BAS, are shown for all classrooms. The sensor rigs are all placed in close proximity (same height, 1-3 meters away in horizontal distance) to the BAS sensors. It is assumed that the temperatures measured by the BAS are correct. In all classrooms the sensor rigs measure temperatures that are approximately 4.5-5°C higher than the temperatures measured by the BAS. This is verified by the use of thermal cameras, shown in figures 6.50. When the thermal photos were taken, the actual room temperature was 22.5°C and the sensor rig temperature measurement was 27°C, which is the same temperature the thermal camera photos show.

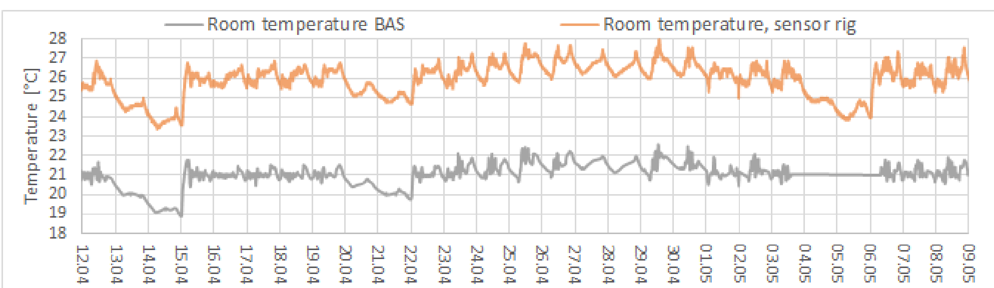


Figure 6.46: NHT: Comparison of the breathing zone temperature, measured by sensor rig 1 and BAS

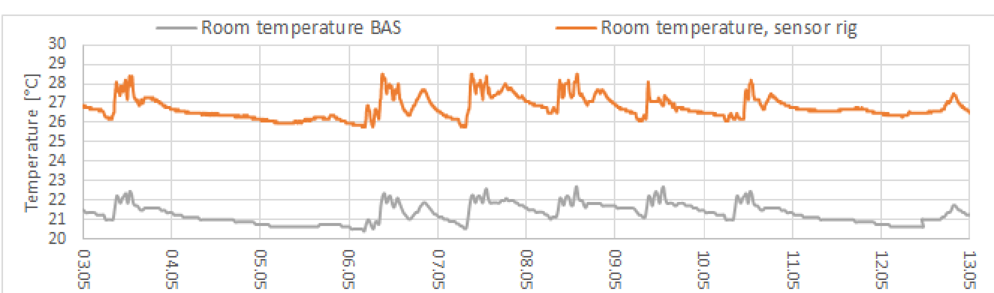


Figure 6.47: OHT: Comparison of the breathing zone temperature, measured by sensor rig 2 and BAS

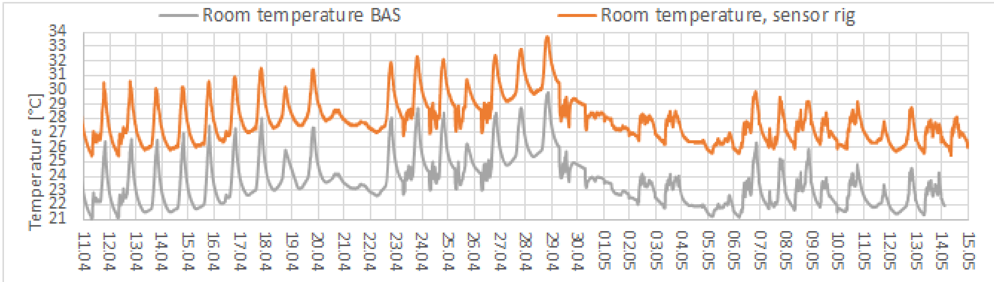


Figure 6.48: NLT: Comparison of the breathing zone temperature, measured by sensor rig 3 and BAS

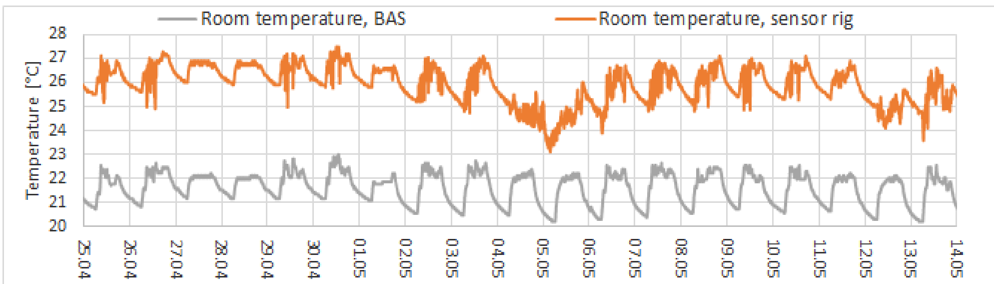


Figure 6.49: OLT: Comparison of the breathing zone temperature, measured by sensor rig 4 and BAS

Figure 6.50: Thermal camera photos of temperature sensor SCD30

6.3 Observation day in classroom NLT

26 pupils and one teacher arrived at 08:30 and had two lectures before 10:00. Everyone left the classroom for recess between 10:00 and 10:30. From 10:30 to 11:00 the pupils ate lunch at their desks. From 11:00 to 12:00 the pupils practiced for a summer show, and there were only five pupils in the classroom during this hour. Everyone left the classroom for a new recess between 12:00 and 12:30, followed by two lectures between 12:30 and 13:45. The school day ended at 13:45. In figures 6.51, 6.52, 6.53 and 6.54 the CO_2, formaldehyde and $PM_{2.5}$ levels in the classroom during the observation day are shown. The CO_2 level in the breathing zone exceeds 1000 ppm two times, around 10:00 and around 11:00. The 30 minute average formaldehyde level exceeds the formaldehyde guideline limit at around 11:00, during the lunch break. $PM_{2.5}$ levels were very low during the entire day.

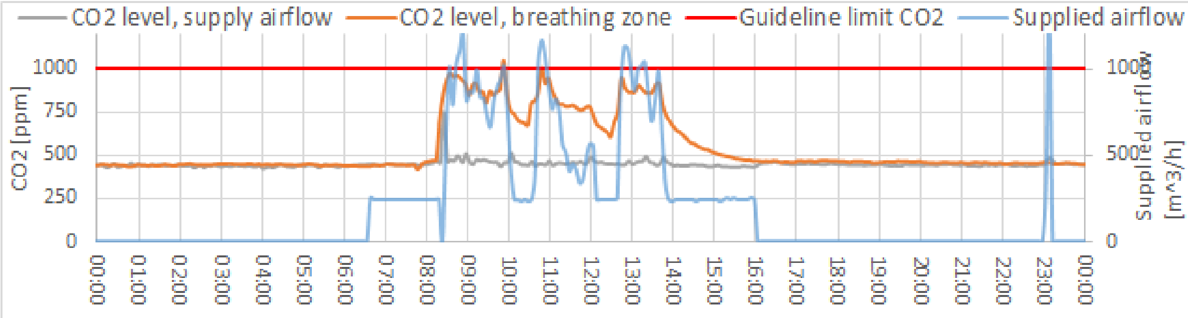


Figure 6.51: CO_2 levels in classroom NLT during observation day

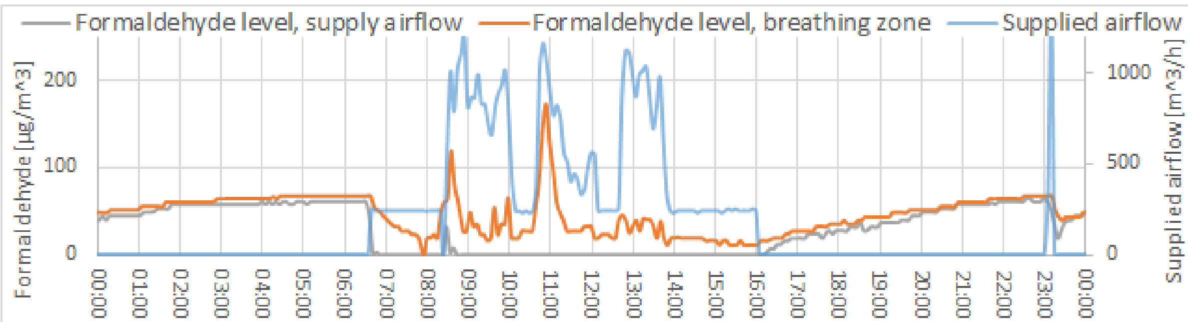


Figure 6.52: Formaldehyde levels in classroom NLT during observation day

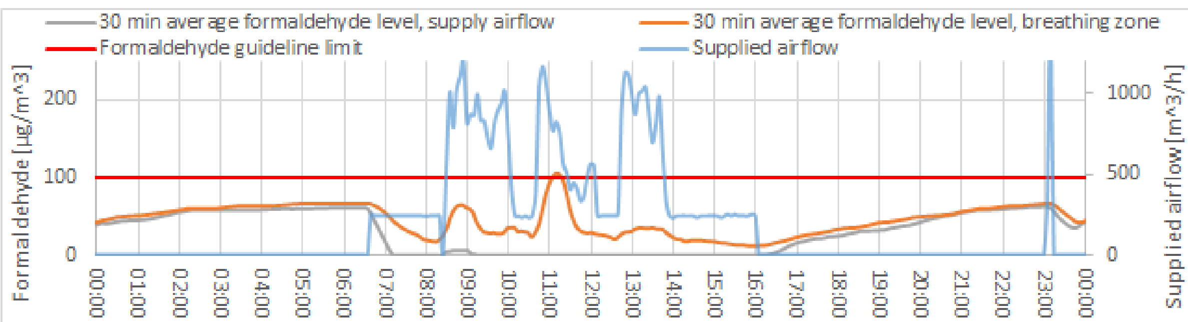


Figure 6.53: 30 minutes average formaldehyde levels in classroom NLT during observation day

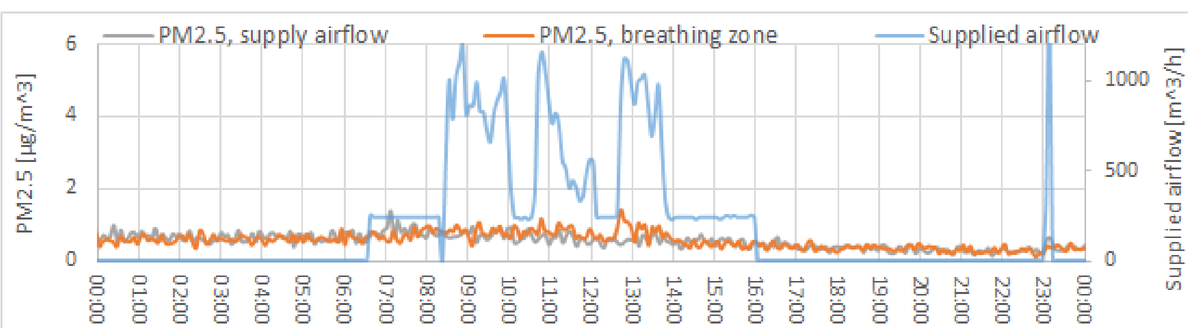


Figure 6.54: $PM_{2.5}$ levels in classroom NLT during observation day

6.4 Suggested control strategies

6.4.1 Formaldehyde control

Based on the field measurement results, possible control strategies can be suggested. It is discovered that the formaldehyde levels in the classrooms regularly exceed the limit value guideline level of 100 $\mu g/m^3$ as a 30 minute average concentration (section 6.2.3). This mainly happens outside the occupied hours of 07:00-17:00 on weekdays, because the air flow rates then are regulated to minimum values, resulting in a lower dilution of the room air compared to during occupied hours. Even though people are not expected to be in a classroom outside the occupied hours, there are several occasions where this happens during a year: meetings with parents, staff meetings and other events. Then there is a high probability of being exposed to high levels of formaldehyde when entering the classroom. The formaldehyde levels also often exceed the limit value guideline during lunchtime in the occupied hours, seen as short and high peaks in the formaldehyde levels. It is suspected that the formaldehyde sensors are cross-sensitive to other compounds, because food is not a source of formaldehyde. It is found that the formaldehyde levels in the classrooms decrease very rapidly when the ventilation is increased, showing a strong inverse correlation between formaldehyde levels and air flow rates, and that the formaldehyde is indoor generated. The formaldehyde levels are generally higher in classrooms with wooden surfaces than in classrooms without wooden surfaces.

A suggested control strategy for keeping formaldehyde levels below the limit value guideline at all times is to initiate high and short purges in the air flow rates when the formaldehyde levels are approaching the guideline limit, e.g. when the level is 90 $\mu g/m^3$ as a 30 minute average concentration. Short and high purges a few times during unoccupied hours are assumed not to require high amounts of additional energy consumption in the HVAC plant. This kind of formaldehyde level control in DCV should be implemented together with typical CO_2 controlled DCV in the control system, so that both occupant generated pollutant levels (CO_2 levels) and non-occupant generated pollutants (in this case formaldehyde levels) can be controlled simultaneously. Another formaldehyde control strategy could be to determine new minimum air flow rates based on the lowest air flow rate that keep the formaldehyde concentration below the limit value guideline at all times. In this control strategy, formaldehyde is not a marker for continuous control of DCV, but a marker for the determination of minimum air flow rates in the classroom.

6.4.2 Particulate matter control

Based on the field measurements, it is discovered that indoor particulate matter levels are dominated by outdoor particulate matter sources, that indoor sources are more or less non-existent and that particulate matter levels in classrooms are relatively low most of the time. However, during the period of high outdoor particulate matter levels (25.04-02.05), the $PM_{2.5}$ limit value guideline of 15 $\mu g/m^3$ as a 24 hour average was exceeded in one of the four classrooms (classroom NHT). It is not known whether a window was open in classroom NHT when this occurred. One simple control strategy could be to monitor indoor and outdoor particulate matter levels in the BAS, and indicate when the levels are high, so that opening of windows can be avoided for these occasions. Not including the period of high outdoor particle matter levels, the indoor $PM_{2.5}$ levels were consistently low (0-3 $\mu g/m^3$) in all classrooms at all times. The PM_{10} levels measured are evaluated to be unreliable due to the fact that they are almost identical to the measured $PM_{2.5}$ levels at all times (shown in 6.2.4), and it was discovered that low cost particle matter sensors have an exponentially decreasing accuracy for increasing particulate size fractions. The HVAC systems providing air to all four classrooms are equipped with class F7 air filters, which are stated to remove 90% of the finer particles (sizes 1-5 μm) and 100% of the coarser particles (sizes >5 μm). One $PM_{2.5}$ control strategy can be to monitor $PM_{2.5}$ levels indoors and outdoors, and to turn on an alarm in the BAS if the indoor/outdoor level ratio indicates that the filter does not remove particles as well as it is stated to do. This initiates a filter inspection by an operator in the building, to look for possible leaks around the filter and to decide whether the filter needs to be replaced. This control strategy does not control the air flow rates in the DCV system, it simply tells when the filter does not function optimally. Another $PM_{2.5}$ control strategy could be to turn off the ventilation during events of extremely high outdoor $PM_{2.5}$ levels, if this occurs outside occupied hours, to minimize the amount of particulate matter drawn into the building and classroom. This control strategy does control the air flow rates in the DCV system. However, $PM_{2.5}$ is not recommended as a marker for control of DCV.

Chapter 7

Discussion

7.1 The methods used

7.1.1 Routines for sensor calibrations and sensor performance testing

Sensor calibrations were carried out once for the measurands CO_2, $PM_{2.5}$, temperature and humidity. Performance testing of the formaldehyde sensors were also carried out once. These calibrations and performance testings were done prior to the field measurements, and no later calibrations or performance testing were carried out due to time limitations. In the CO_2 calibrations, creating a high CO_2 concentration in a closed volume that slowly decreased to ambient concentrations let the SCD30 CO_2 sensors and the reference instrument Vaisala measure a wide range of continuously decreasing CO_2 concentrations. The CO_2 calibration results show that the SCD30 CO_2 sensors have high correlations with the reference instrument Vaisala. The R^2 values for the correlation vary between 0.9823 and 0.9966. Several additional calibration rounds are recommended, to look for drifts in the measurements over time.

The calibration measurements for $PM_{2.5}$, temperature and humidity were carried out simultaneously before the start of the field measurements, and the variations of the $PM_{2.5}$, temperature and humidity levels were done quite fast. This resulted in a discontinuous range of the $PM_{2.5}$ concentrations being measured by the SPS30 particulate matter sensors and the reference instrument Pegasor, where measurements of several concentrations between the highest and lowest measured concentration lack, giving weaker calibration results. The measured $PM_{2.5}$ level of each SPS30 sensor is very similar for identical conditions, showing that they give the same measurement result independent of sensor used. However the SPS30 sensors seem to measure significantly lower $PM_{2.5}$ concentrations than Pegasor does, but within the accuracy of the SPS30 sensor (found in appendix A.1.2). When evaluating the SPS30 particulate matter sensors based on these calibration results, their performance is evaluated to not be satisfactory, due to low R^2 values when compared to the levels measured by the reference instrument Pegasor (R_2 in the range 0.7014-0.7772). However, if the wish is to indicate some particularly high or particularly low $PM_{2.5}$ concentrations, and the exact concentrations are not the primary interest, the SPS30 sensors could be interesting for commercial use. The measured temperature and relative humidity ranges were more continuous and showed that the SCD30 temperature sensors consistently measure too high temperature levels, resulting in the SCD30 humidity sensors consistently measuring too low humidity levels. The R_2 values for the correlation between sensor and Vaisala temperatures are high and vary between 0.9072 and 0.9806. The temperature levels measured by each SCD30 temperature sensor show varying temperatures measured for identical temperature conditions, showing that the temperature level measured is dependent on the SCD30 sensor used, and that each SCD30 sensor must be calibrated individually. If SCD30 temperature and humidity sensors were to be used commercially in DCV systems, the temperature levels would have to be corrected with calibration curves found from thoroughly carried out calibration procedures, and the relative humidity would have to be found for each corrected temperature by going via the specific humidity content in the air measured. Regarding the WZ-S formaldehyde sensors, their performance seem adequate for use in typical non-industrial indoor environments, based on the performance testing of all eight WZ-S sensors. However, they have not been evaluated together with a reference instrument due to the lack of such instrument, so this is based on the fact that the sensors are stated to be precalibrated.

7.1.2 Field measurement setup

The methods used in the field measurements in the four classrooms have some design weaknesses. The sensors are placed in semi-enclosed plastic boxes, leading to heat from the sensors and Arduino board building up in the boxes, resulting in temperature and relative humidity measurements at significantly higher temperatures than the room air temperature. The sensor box measuring the state of the supply air failed to do so in 3 of 4 classrooms (OHT, NHT, OLT) because it was not possible to place the sensor box inside the supply air duct. This made it impossible to evaluate the state of the supply air in these classrooms. However, the state of the air in the breathing zone seems to be correctly measured when comparing CO_2 and temperature levels measured in the breathing zone by the sensor rig and the BAS. In addition, the opening of windows and doors during the field measurement period was not registered, making it impossible to evaluate the effect this has on the state of the room air with regard to formaldehyde and $PM_{2.5}$ levels. The activities carried out at all times, and the number of people present at all times were not registered throughout the measurement period. This was only done during the observation day in classroom NLT. However, with registered sensor data from numerous consecutive days, patterns in the formaldehyde concentration and the $PM_{2.5}$ concentration could be seen nevertheless.

7.2 Field measurement results

The formaldehyde levels in the classrooms exceeded the limit value guideline for formaldehyde almost daily. This mostly occurred outside the occupied hours, but short and high peaks exceeding the limit value guideline also occurred during lunch hours. Formaldehyde levels decrease rapidly for increasing air flow rates to the classrooms, showing that the formaldehyde is indoor generated, and that there is a strong inverse correlation between formaldehyde levels and air flow rates. No clear difference in the formaldehyde levels for newer and older classrooms are found, but formaldehyde levels are higher in classrooms with wooden surfaces than in classrooms without wooden surfaces. Based on the field measurements, it is recommended to use formaldehyde as a marker for control of DCV together with CO_2, to ensure that occupant generated and non-occupant generated pollutants are controlled simultaneously, resulting in a more healthy indoor air for the occupants. Doing so, the energy consumed by the HVAC system is expected to increase. Regarding $PM_{2.5}$ levels, these are mostly relatively low in all classrooms, except for one period in all classrooms during a period of unusually high outdoor particulate matter levels, indicating that outdoor particulate matter is introduced to the classroom via occupants, via open doors and windows and via the HVAC system. However, the limit value guideline was only exceeded in classroom NHT during this period, for two consecutive days over a weekend. Whether a window was open in the classroom when this occurred was discussed with a school operator, and the answer was that open windows overnight and during the weekends happens regularly, but that it is uncertain whether it happened that weekend in NLT. PM_{10} levels measured indoors are evaluated to be unreliable due to the fact that SPS30 particulate matter sensors are exponentially less accurate for increasing particle size fractions. No significant differences between indoor $PM_{2.5}$ levels in high and low trafficked areas are found. No correlation between indoor $PM_{2.5}$ levels and ventilation air flow rate is discovered. Overall, indoor $PM_{2.5}$ levels are evaluated to be low and satisfactory, and it is not recommended to use $PM_{2.5}$ as a marker for control of DCV in primary school classrooms. If a control strategy is desired, it is recommended to monitor indoor and outdoor $PM_{2.5}$ levels by the BAS, making it possible to indicate when windows should remain closed due to unusually high outdoor levels. Regarding the CO_2 measurements made by the SCD30 sensors, these show that the SCD30 sensors have an acceptable performance, but that the different SCD30 sensors measure slightly different CO_2 levels for identical conditions. It is suggested to run the initial sensor calibration algorithm from the SCD30 datasheet (appendix A.3.3) on all eight sensor boxes one more time to see if the CO_2 measurements made by the SCD30 sensors get more consistent. Temperature measurements show that the measurements by the SCD30 sensors give consistently higher temperatures compared to the BAS. This is due to a build up of heat from the sensors and Arduino board in the semi-enclosed sensor boxes. This results in humidity measurements based on wrong temperatures. However, the correlation is high between the temperatures measured by the SCD30 sensors and the reference instrument. Temperature measurements need to be corrected by applying calibration curves to the measurement outputs, and humidity measurements need to be corrected by basing them on the corrected temperatures.

7.3 Sensor evaluations

The results from the initial sensor calibrations show that the accuracy of the low cost sensors is as stated in their datasheets, however further calibrations are recommended to look for possible drifts over time in the measurements. The use of the sensors in the classroom field measurements showed that all sensors deliver measurements non stop over several weeks. Even though some measurement crashes occurred in two of the four classrooms during the measurement period, this happened in the data logging in the Raspberry Pi and not in one of the sensors on the sensor rig. Testing of the sensors in control of a DCV system is recommended.

7.4 Review of the research questions

The research questions described in the introduction (1.4) were made to aim the described problem towards reaching the goal of the master's thesis. Final reviews of the research questions are made here.

What limit value guidelines exist for health damaging pollutants like different VOCs and particulate matter size fractions? From the work on this master's thesis, limit value guidelines are found for formaldehyde (100 $\mu g/m^3$ as a 30 minute average concentration), $PM_{2.5}$ (15 $\mu g/m^3$ as a 24 hour average concentration) and PM_{10} (50 $\mu g/m^3$ as a 24 hour average concentration). A limit value guideline for TVOC concentrations does not exist. A maximum CO_2 level of 1000 ppm is recommended.

Does low cost sensors measuring various relevant VOCs and particulate matter size fractions exist? If so, how are their stated performance, lifetime, calibration needs and dimensions? Low cost sensors measuring formaldehyde levels (WZ-S formaldehyde sensors), TVOC levels (SGP30 sensors), $PM_{2.5}$ levels and PM_{10} levels (SPS30 sensors) are found and testes in the work on this master's thesis. All these sensors are factory precalibrated and stated to not require calibration by the user. The stated performance, lifetime and dimensions are evaluated as sufficient for possible use in DCV control systems.

How do factory precalibrated sensors perform compared to the performance stated by their suppliers? From the initial sensor calibrations and the field measurements, it is found that the actual performance of the sensors match the performance stated by their suppliers. This applies for the sensors that were possible to calibrate (CO_2, temperature and humidity on SCD30, $PM_{2.5}$ on SPS30). Formaldehyde and PM_{10} measurements were not calibrated.

Is it possible to use VOC and particulate matter sensors to control DCV? With appropriate control algorithms for the control system in DCV, basically all VOC and particulate matter sensors (and sensors for other relevant pollutants and parameters) can be used to control DCV, making the possibilities limitless. The data technology has improved exponentially throughout history and will continue to do so, opening for new opportunities all the time. Thus, relevant control algorithms based on various relevant pollutants and parameters should continuously be developed and tested.

What is the importance of the flow pattern and ventilation principle in the room with regard to the location of the sensors measuring the state of the air in the room? In all four classrooms where field measurements were carried out, the ventilation principle was mixing ventilation. For mixing ventilation, the state of the air throughout the entire room should theoretically be identical, but due to actual ventilation efficiencies being lower lower than 1, the sensors measuring the state of the air in the room should be placed as close as possible to the breathing zone. It is recommended to place the sensors 1-1.5 meter above the floor on an inner wall that is never exposed to direct sunlight.

Does CO_2 controlled DCV maintain VOC and particulate matter levels acceptably low at all times? Formaldehyde is a VOC, and CO_2 controlled DCV does not maintain formaldehyde levels acceptably low at all times. This was proven from the classroom field measurements. Formaldehyde is a non-occupant generated pollutant, thus formaldehyde is emitted from building materials and other materials also when occupants are not present and air flow rates are at minimum, leading to increasing formaldehyde levels in the room, often exceeding the limit value guideline for formaldehyde. When occupants are present during the occupied hours and air flow rates are high, formaldehyde levels are acceptably low. An exception to this is during lunch hours, where short and high peaks often exceeding the limit value guideline occurs. Regarding particulate matter levels indoors, these seem to depend on the outdoor levels and not on the varying air flow rates. The indoor $PM_{2.5}$ levels in the classrooms are mostly very low.

Can minimum airflow for DCV keep VOC and particulate matter levels below their limit values if DCV is controlled only by CO_2 levels? Minimum air flow rates do not keep formaldehyde levels below the limit value guideline. When delivering minimum air flow rates to a classroom, the formaldehyde level rises and will in most cases exceed the limit value guideline after only a couple of hours. At minimum air flow rates, particulate matter levels are not reacting with an obvious pattern, indicating that a particulate matter levels and air flow rates do not correlate.

Is it possible to achieve a more healthy indoor air by controlling ventilation after VOC and/or particulate matter levels? Based on the fact that formaldehyde levels often exceed the formaldehyde limit value guideline, a more healthy indoor air would be achieved by controlling DCV after formaldehyde levels. Then, occupants would never be exposed to formaldehyde levels above the limit value guideline. Using particulate matter ($PM_{2.5}$) as a marker for control of DCV is not recommended, because no correlation between air flow rates and particulate matter levels are found.

Chapter 8

Conclusions

Several health relevant pollutants in indoor air in primary school classrooms were identified in the literature reviews, and the most relevant pollutants were evaluated to be the carcinogen and VOC formaldehyde, TVOC (total amount of VOCs) and the particulate matter size fractions $PM_{2.5}$ and PM_{10}. Recommended limit value guidelines were found for formaldehyde (100 $\mu g/m^3$ as a 30 minute average concentration), $PM_{2.5}$ (15 $\mu g/m^3$ as a 24 hour average concentration) and PM_{10} (50 $\mu g/m^3$ as a 24 hour average concentration). A recommended limit value guideline does not exist for TVOC concentrations. The results from the initial sensor calibrations show that the accuracy of the sensors is as stated in their datasheets. Future calibrations are recommended to look for possible drifts over time in the measurements. The results from the field measurements show that the limit value guideline for formaldehyde is exceeded regularly in all classrooms. This mostly occurs outside the operating hours, but short exceeds also occur within the operating hours during lunchtime. No clear difference in the formaldehyde levels for newer and older classrooms are found, but formaldehyde levels are higher in classrooms with wooden surfaces than in classrooms without wooden surfaces. Formaldehyde levels decrease rapidly when ventilation air flow rates are increased from minimum values, showing that the formaldehyde is indoor generated. It is concluded that formaldehyde should be recommended as a marker for control of DCV together with CO_2, to ensure that occupant generated and non-occupant generated pollutants are controlled simultaneously, resulting in a more healthy indoor air for the occupants. The $PM_{2.5}$ levels measured in the classrooms are mostly very low, but during a period of unusually high outdoor $PM_{2.5}$ levels, the indoor levels became relatively high, and the limit value guideline for $PM_{2.5}$ was exceeded once in one classroom. No significant differences in the $PM_{2.5}$ levels in high and low trafficked areas are found. No correlation between indoor $PM_{2.5}$ levels and ventilation air flow rates is discovered. PM_{10} field measurements were discarded because it was discovered that low cost particle matter sensors have an exponentially decreasing accuracy for increasing particulate size fractions. It is concluded that indoor and outdoor $PM_{2.5}$ levels can be monitored by the building automation system, making it possible to indicate when windows should remain closed due to unusually high outdoor levels. It is concluded to not recommended to use $PM_{2.5}$ as a marker for control of DCV in primary schools.

Chapter 9

Further work

Further development of various control strategies for DCV based on health relevant pollutants is needed. Testing and comparison of the different control strategies in the lab and in field studies is also needed, to be able to evaluate the actual performance of the control strategies. Field measurements during the summer, fall and winter should should also be carried out, to evaluate pollutant level differences between seasons. To be able to evaluate the SGP30 TVOC sensors for control of DCV, they have to be implemented on the sensor rigs with specialist equipment able to work with such small dimensions. Continuous calibration procedures of all the sensors on the sensor rigs should be carried out to look for drifts in the measurements and to evaluate the lifetime of the sensors and the performance over time. Regarding WZ-S formaldehyde sensors and SGP30 TVOC sensors, possible calibration routines should be looked for, and if found, these should be set up and tested in the lab. Other low cost sensors measuring the same pollutants and parameters as in this master's thesis should also be evaluated, to compare the performance of different low cost sensors measuring the same measurands. Possible additional health relevant pollutants and parameters should be searched for, and if low cost sensors measuring these pollutants and parameters exist, they should also be tested and evaluated.

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Appendix A

A.1 Sensor datasheets and websites

A.1.1 SCD30 - CO_2, temperature and humidity

Following is the relevant section of the datasheet for SCD30 included. The complete datasheet is available online at SCD30 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 I^2C

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

1 Sensor Specifications[1]

CO_2 Sensor Specifications

Parameter	Conditions	Value
CO_2 measurement range	-	0 – 40'000 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. 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) and I^2C
Input high level voltage (V_{IH})	Min. and max. criteria to operate SCD30	1.75 V – 5.5 V
Input low level voltage (V_{IL})	Min. and max. criteria to operate SCD30	- 0.3 V – 0.9 V
Output low level voltage (V_{OL})	I_{IO} = +8 mA, Max. criteria	0.4 V
Output high level voltage (V_{OH})	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
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.

2 Package Outline Drawing

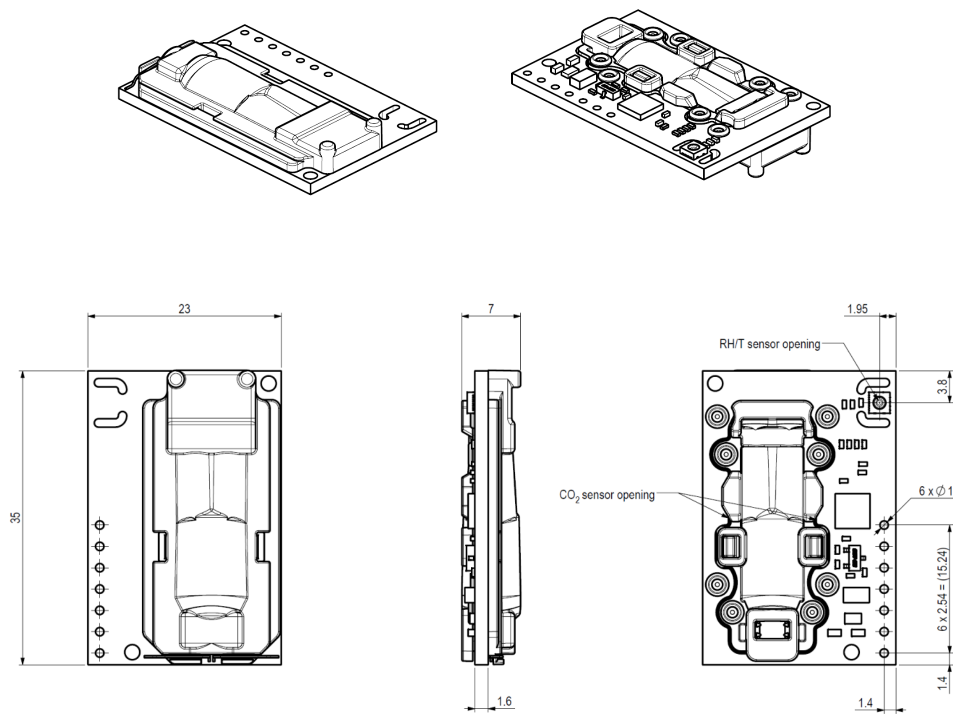


Figure 1 Product outline drawing of SCD30. Pictures on the left show top-view, pictures on the right bottom-view.

Sensor height is 7 mm at the thickest part of SCD30. The weight of one SCD30 sensor is 3.4 g.

3 Pin-Out Diagram

Pin	Comments
VDD	Supply Voltage
GND	Ground
TX/ SCL	Modbus: Transmission line (Push/Pull with 3V level) I^2C: Serial clock (internal 45kΩ pull-up resistor, pulled to 3V)
RX/ SDA	Modbus: Receive line (Input must not exceed 5.5V) I^2C: Serial data (internal 45kΩ pull-up resistor, pulled to 3V)
RDY	Data ready pin. High when data is ready for read-out
PWM	PWM output of CO_2 concentration measurement (PWM not supported yet)
SEL	Interface select pin. Pull to VDD (do not exceed 4V, use voltage divider in case your VDD is >4V) for selecting Modbus, leave floating or connect to GND for selecting I^2C.

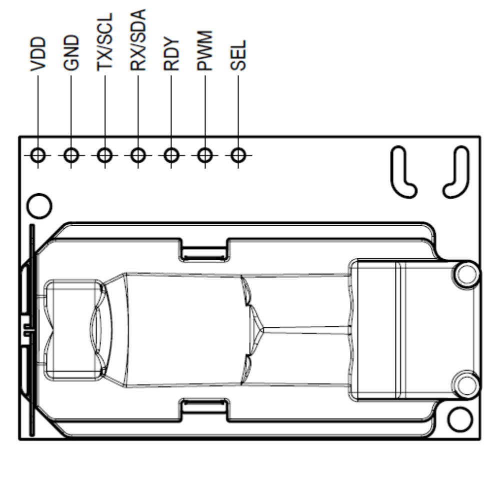


Figure 2: Pin-out of the SCD30.

4 Operation and Communication

Module includes internal pull-up resistors for I2C communication (45 kΩ), no external circuitry necessary. Please visit the download center of Sensirion webpage for a separate document[12].

5 Shipping Package

SCD30 sensor is shipped in stackable trays with 40 pieces each. The tray dimension is 363 mm x 257 mm x 19 mm. Stacking of trays results in an effective tray height of 13 mm.

6 Ordering Information

SCD30 and accessory can be ordered via the following article numbers. Please accept longer lead times until official start of production.

Product	Description	Article Number
SCD30 sensor	CO_2, RH and T sensor module	1-101625-01
SCD30 evaluation kit	SCD30 sensor, SEK sensor bridge and cables.	3.000.055
SCD30 on adapter	Standalone SCD30 sensor for EvalKit	3.000.061

[12] www.sensirion.com/file/scd30_interface_description

A.1.2 SPS30 - Particulate matter

Following is the relevant section of the datasheet for SPS30 included. The complete datasheet is available at SPS30 Datasheet.

SENSIRION
THE SENSOR COMPANY

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 mm³, it is also the perfect solution for applications where size is of paramount importance, such as wall-mounted or compact air quality devices.

Content

SENSIRION
THE SENSOR COMPANY

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/m^3	±10	µg/m^3
	100 to 1'000 µg/m^3	±10	%
Mass concentration range	-	0 to 1'000	µg/m^3
Mass concentration resolution	-	1	µg/m^3
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/cm^3
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.

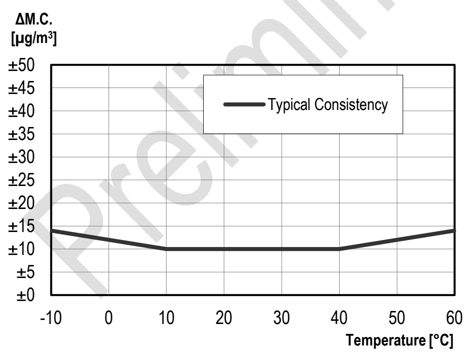


Figure 1: Typical consistency tolerance for PM2.5 in µg/m^3 between 0-100 µg/m^3.

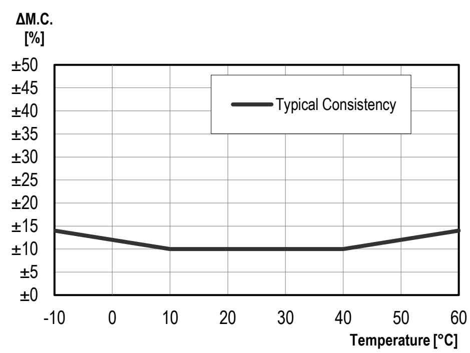


Figure 2: Typical consistency tolerance for PM2.5 in % between 100-1000 µg/m^3.

[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.

3 Hardware Interface Specifications

The interface connector is located at the side of the sensor opposite to the air inlet/outlet. Corresponding female plug is ZHR-5 from JST Sales America Inc. In Figure 3 a description of the pin layout is given.

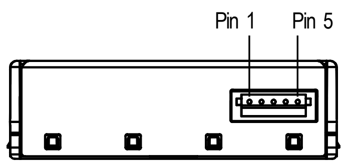


Figure 3 The communication interface connector is located at the side of the sensor opposite to the air outlet.

<table>
<tr><th>Pin</th><th>Name</th><th>Description</th><th>Comments</th></tr>
<tr><td>1</td><td>VDD</td><td>Supply voltage</td><td>5V ± 10%</td></tr>
<tr><td rowspan="2">2</td><td>RX</td><td>UART: Receiving pin for communication</td><td rowspan="2">TTL 5V and LVTTL 3.3V compatible</td></tr>
<tr><td>SDA</td><td>I²C: Serial data input / output</td></tr>
<tr><td rowspan="2">3</td><td>TX</td><td>UART: Transmitting pin for communication</td><td rowspan="2">TTL 5V and LVTTL 3.3V compatible</td></tr>
<tr><td>SCL</td><td>I²C: Serial clock input</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">SEL</td><td rowspan="2">Interface select</td><td>Leave floating to select UART</td></tr>
<tr><td>Pull to GND to select I²C</td></tr>
<tr><td>5</td><td>GND</td><td>Ground</td><td></td></tr>
</table>

Table 4 SPS30 pin assignment.

The SPS30 offers both a UART[8] and an I²C interface. For connection cables longer than 20 cm we recommend using the UART interface, due to its intrinsic robustness against electromagnetic interference.

3.1 Physical Layer

The SPS30 has separate RX and TX lines with unipolar logic levels. A transmitted byte looks as in Figure 4.

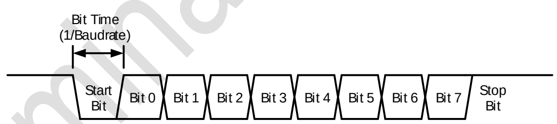


Figure 4 Transmitted byte.

[8] Universal Asynchronous Receiver Transmitter.

6 Technical Drawings

6.1 Product Outline Drawings

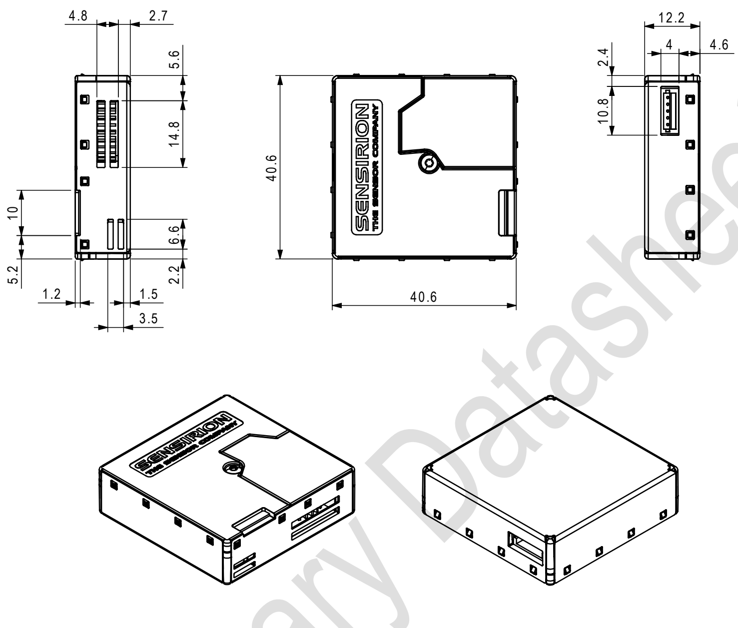


Figure 9: Package outline dimensions (in mm) of the SPS30.

A.1.3 SGP30 - TVOC

Following is the relevant section of the datasheet for SGP30 included. The complete datasheet is available at SGP30 Datasheet.

SENSIRION
THE SENSOR COMPANY

Datasheet SGP30
Sensirion Gas Platform

- Multi-pixel gas sensor for indoor air quality applications
- Outstanding long-term stability
- I^2C interface with TVOC and CO_2eq output signals
- Very small 6-pin DFN package: 2.45 x 2.45 x 0.9 mm^3
- Low power consumption: 48 mA at 1.8V
- Tape and reel packaged, reflow solderable

Product Summary

The SGP30 is a digital multi-pixel gas sensor designed for easy integration into air purifier, demand-controlled ventilation, and IoT applications. Sensirion's CMOSens® technology offers a complete sensor system on a single chip featuring a digital I^2C interface, a temperature controlled micro hotplate, and two preprocessed indoor air quality signals. As the first metal-oxide gas sensor featuring multiple sensing elements on one chip, the SGP30 provides more detailed information about the air quality.

The sensing element features an unmatched robustness against contaminating gases present in real-world applications enabling a unique long-term stability and low drift. The very small 2.45 x 2.45 x 0.9 mm^3 DFN package enables applications in limited spaces. Sensirion's state-of-the-art production process guarantees high reproducibility and reliability. Tape and reel packaging, together with suitability for standard SMD assembly processes make the SGP30 predestined for high-volume applications.

Block Diagram

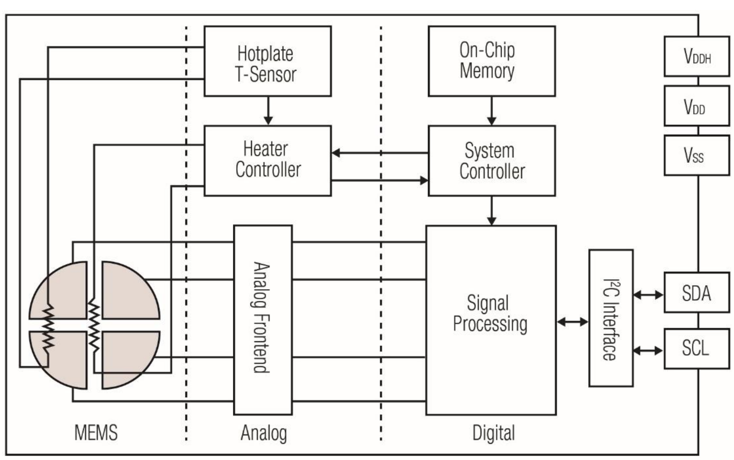


Figure 1 Functional block diagram of the SGP30.

1 Sensor Performance

1.1 Gas Sensing Performance

The values listed in Error! Reference source not found. are valid at 25°C, 50% RH and typical VDD.

<table>
<tr><th>Parameter</th><th>Signal</th><th>Values</th><th colspan="2">Comments</th></tr>
<tr><td rowspan="2">Measurement range[1]</td><td>Ethanol signal</td><td>0 ppm to 1000 ppm</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>H_2 signal</td><td>0 ppm to 1000 ppm</td></tr>
<tr><td rowspan="2">Specified range</td><td>Ethanol signal</td><td>0.3 ppm to 30 ppm</td><td colspan="2" rowspan="2">The specifications below are defined for this measurement range[2]. The specified measurement range covers the gas concentrations expected in indoor air quality applications.</td></tr>
<tr><td>H_2 signal</td><td>0.5 ppm to 3 ppm</td></tr>
<tr><td rowspan="2">Accuracy[3]</td><td>Ethanol signal</td><td>see Figure 2
typ.: 15% of meas. value</td><td rowspan="2">Accuracy is defined as
$\frac{c - c_{set}}{c_{set}}$
with c the measured concentration and c_{set} the concentration set point. The concentration c is determined by
$ln\left(c/c_{ref}\right) = \frac{(s_{ref} - s_{out})}{a}$
with
a = 512
s_{out}: Ethanol/Hydrogen signal output at concentration c
s_{ref}: Ethanol/Hydrogen signal output at 0.5 ppm H_2</td><td>c_{ref} = 0.4 ppm</td></tr>
<tr><td>H_2 signal</td><td>see Figure 3
typ.: 10% of meas. value</td><td>c_{ref} = 0.5 ppm</td></tr>
<tr><td rowspan="2">Long-term drift[3,4]</td><td>Ethanol signal</td><td>see Figure 4
typ.: 1.3% of meas. value</td><td colspan="2" rowspan="2">Change of accuracy over time: Siloxane accelerated lifetime test[5]</td></tr>
<tr><td>H_2 signal</td><td>see Figure 5
typ.: 1.3% of meas. value</td></tr>
<tr><td rowspan="2">Resolution</td><td>Ethanol signal</td><td rowspan="2">0.2 % of meas. value</td><td colspan="2" rowspan="2">Resolution of Ethanol and Hydrogen signal outputs in relative change of the measured concentration</td></tr>
<tr><td>H_2 signal</td></tr>
<tr><td rowspan="2">Sampling frequency</td><td>Ethanol signal</td><td rowspan="2">Max. 40 Hz</td><td colspan="2" rowspan="2">Compare with minimum measurement duration in Table 10</td></tr>
<tr><td>H_2 signal</td></tr>
</table>

Table 1 Gas sensing performance. Specifications are at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 24h before the first characterization.

[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] The long-term drift is stated as change of accuracy per year of operation.
[5] Test conditions: operation in 250 ppm Decamethylcyclopentasiloxane (D5) for 200h simulating 10 years of operation in an indoor environment.

Accuracy ethanol signal

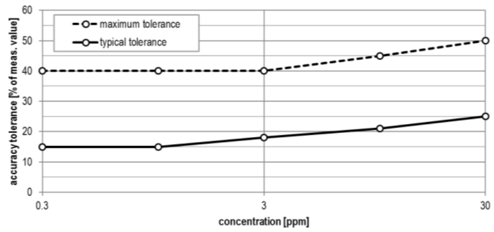


Figure 2 Typical and maximum accuracy tolerance in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 24h before the characterization.

Accuracy H_2 signal

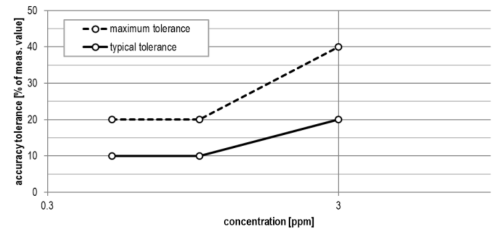


Figure 3 Typical and maximum accuracy tolerance in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 60h before the characterization.

Long-term drift Ethanol signal

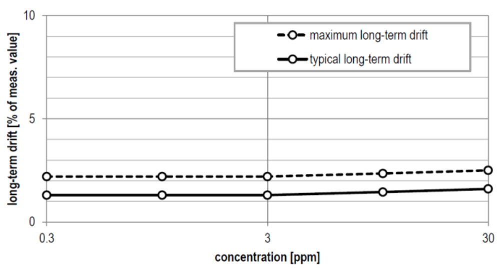


Figure 4 Typical and maximum long-term drift in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 24h before the first characterization.

Long-term drift H_2 signal

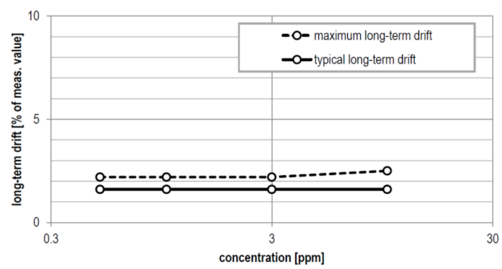


Figure 5 Typical and maximum long-term drift in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 60h before the first characterization.

1.2 Air Quality Signals

Parameter	Signal	Values		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 specifications.

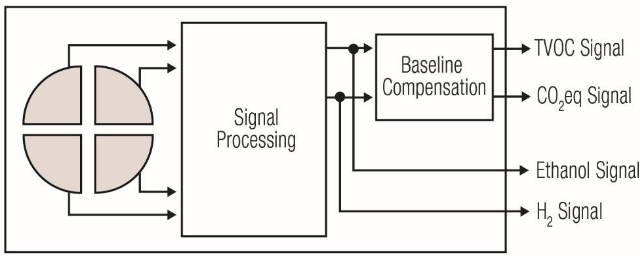


Figure 6 Simplified version of the functional block diagram (compare **Figure 1**) showing the signal paths of the SGP30.

1.3 Recommended Operating Conditions

The sensor shows best performance when operated within recommended normal temperature and humidity range of 5 – 55 °C and 4 –20 g/m^3, respectively. 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. To ensure stable operation of the gas sensor, the conditions described in the document *SGP Handling and Assembly Instructions* regarding exposure to exceptionally high concentrations of some organic or inorganic compounds have to be met, particularly during operation. Please also refer to the *Design-in Guide* for optimal integration of the SGP30.

2 Electrical Specifications

Parameter	Min.	Typ.	Max.	Unit	Comments
Supply voltage V_{DD}	1.62	1.8	1.98	V	Minimal voltage must be guaranteed also for the maximum supply current specified in this table.
Hotplate supply voltage V_{DDH}	1.62	1.8	1.98	V	
Supply current in measurement mode[6]		48.8		mA	The measurement mode is activated by sending an "Init_air_quality" or "Measure_raw_signal" command. Specified at 25°C and typical VDD.
Sleep current		2	10	µA	The sleep mode is activated after power-up or after a soft reset. Specified at 25°C and typical VDD.
LOW-level input voltage	-0.5		0.3*VDD	V	
HIGH-level input voltage	0.7*VDD		VDD+0.5	V	
Vhys hysteresis of Schmitt trigger inputs			0.05*VDD	V	
LOW-level output voltage			0.2*VDD	V	(open-drain) at 2mA sink current
Communication	Digital 2-wire interface, I^{2}C fast mode.				

Table 3 Electrical specifications.

[6] A 20% higher current is drawn during 5ms on V_{DDH} after entering the measurement mode.

3 Interface Specifications

The SGP30 comes in a 6-pin DFN package, see **Table 4**.

Pin	Name	Comments
1	V_{DD}	Supply voltage
2	V_{SS}	Ground
3	SDA	Serial data, bidirectional
4	R	Connect to ground (no electrical function)
5	V_{DDH}	Supply voltage, hotplate
6	SCL	Serial clock, bidirectional

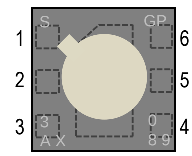


Table 4 Pin assignment (transparent top view). Dashed lines are only visible from the bottom.

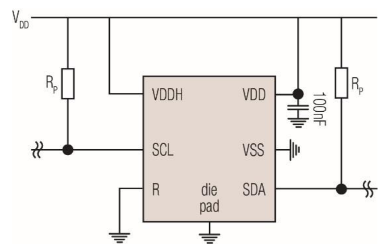


Figure 7 Typical application circuit (for better clarity in the image, the positioning of the pins does not reflect the positions on the real sensor).

The electrical specifications of the SGP30 are shown in **Table 3**. The power supply pins must be decoupled with a 100 nF capacitor that shall be placed as close as possible to pin VDD – see **Figure 7**. The required decoupling depends on the power supply network connected to the sensor. We also recommend VDD and VDDH pins to be shorted[7].
SCL is used to synchronize the communication between the microcontroller and the sensor. The SDA pin is used to transfer data to and from the sensor. For safe communication, the timing specifications defined in the I²C manual[8] must be met. Both SCL and SDA lines are open-drain I/Os with diodes to VDD and VSS. They should be connected to external pull-up resistors. To avoid signal contention, the microcontroller must only drive SDA and SCL low. The external pull-up resistors (e.g. $R_p = 10\ k\Omega$) are required to pull the signal high. For dimensioning resistor sizes please take bus capacity and communication frequency into account (see for example Section 7.1 of NXPs I²C Manual for more details[8]). It should be noted that pull-up resistors may be included in I/O circuits of microcontrollers.
The die pad or center pad is electrically connected to GND. Hence, electrical considerations do not impose constraints on the wiring of the die pad. However, for mechanical stability it is recommended to solder the center pad to the PCB.

4 Absolute Minimum and Maximum Ratings

Stress levels beyond those listed in **Table 5** 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.

[7] If VDD and VDDH are not shorted, it is required that VDD is always powered when VDDH is powered. Otherwise, the sensor might be damaged.
[8] http://www.nxp.com/documents/user_manual/UM10204.pdf

Parameter	Rating
Supply voltage V_{DD}	-0.3 V to +2.16 V
Supply voltage V_{DDH}	-0.3 V to +2.16 V
Storage temperature range	-40 to +125°C
Operating temperature range	-40 to +85°C
Humidity Range	10% - 95% (non-condensing)
ESD HBM	2 kV
ESD CDM	500 V
Latch up, JESD78 Class II, 125˚C	100 mA

Table 5 Absolute minimum and maximum ratings.

Please contact Sensirion for storage, handling and assembly instructions.

5 Timing Specifications

5.1 Sensor System Timings

The timings refer to the power up and reset of the ASIC part and do not reflect the usefulness of the readings.

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit	Comments
Power-up time	t_{PU}	After hard reset, $V_{DD} \geq V_{POR}$	-	0.4	0.6	ms	-
Soft reset time	t_{SR}	After soft reset	-	0.4	0.6	ms	-

Table 6 System timing specifications.

5.2 Communication Timings

Parameter	Symbol	Conditions	Min.	Typ.	Max.	Units	Comments
SCL clock frequency	f_{SCL}	-	0	-	400	kHz	-
Hold time (repeated) START condition	$t_{HD;STA}$	After this period, the first clock pulse is generated	0.6	-	-	µs	-
LOW period of the SCL clock	t_{LOW}	-	1.3	-	-	µs	-
HIGH period of the SCL clock	t_{HIGH}	-	0.6	-	-	µs	-
Set-up time for a repeated START condition	$t_{SU;STA}$	-	0.6	-	-	µs	-
SDA hold time	$t_{HD;DAT}$	-	0	-	-	ns	-
SDA set-up time	$t_{SU;DAT}$	-	100	-	-	ns	-
SCL/SDA rise time	t_R	-	-	-	300	ns	-
SCL/SDA fall time	t_F	-	-	-	300	ns	-
SDA valid time	$t_{VD;DAT}$	-	-	-	0.9	µs	-
Set-up time for STOP condition	$t_{SU;STO}$	-	0.6	-	-	µs	-
Capacitive load on bus line	C_B	-			400	pF	-

Table 7 Communication timing specifications.

A.1.4 WZ-S - Formaldehyde

Following is the relevant section of the datasheet for WZ-S included. The complete datasheet is available at WZ-S Datasheet.

Dart Sensors WZ-S formaldehyde module

Operation Manual

ProSense Technologies Co., Ltd.

Brief Introduction

WZ-S formaldehyde module from global detection expert DART SENSORS combines novel HCHO sensor with advanced electronic control technology, converting HCHO concentration into PPM directly. Once HCHO arrives at working electrode (anode) it is oxidized instantaneously to generate an electrical signal. The electrical signal is then acquired and processed by microprocessor into a PPM value and is output by standard digital signal. WZ-S HCHO module is pre-calibrated in the factory and can be integrated into your system directly.

Typical Applications

Smart home

Portable devices

Wearable devices

Air conditioners

Air cleaners

... …

Key Features

High precision

Fast response

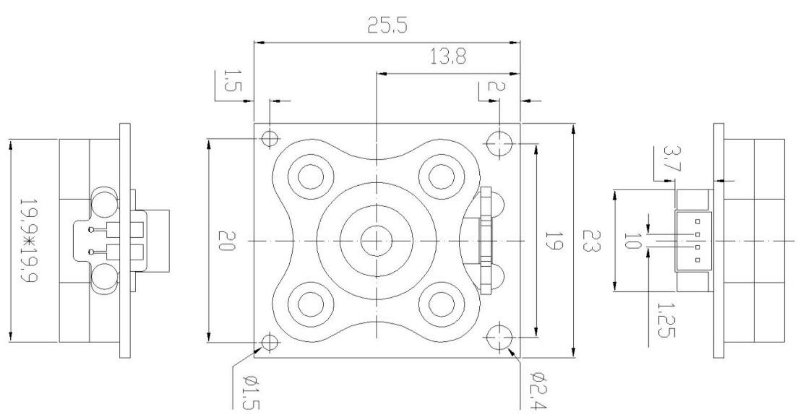
Long service life

Low power consumption

High stability

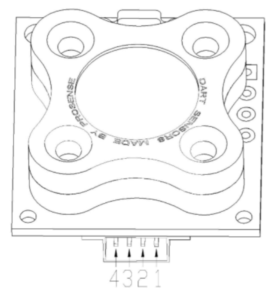
Pre-calibrated

Diagram



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

A.1.5 Vaisala Datasheet

Following is the datasheet for Vaisala included. The datasheet is available at Vaisala Datasheet.

VAISALA

GM70 Handheld Carbon Dioxide Meter

for Spot-Checking Applications

The Vaisala CARBOCAP® Handheld Carbon Dioxide Meter GM70 is the demanding professional's choice for hand-held carbon dioxide measurement. The meter consists of the indicator (center) and probe, used either with the handle (left) or pump (right).

Features

- Two optional sampling methods: diffusion or pump aspiration
- User-friendly meter with multilingual user interface
- Numerical and graphical display of measurements
- Data can be logged and transferred to PC via MI70 Link software

GM70 is a user-friendly meter for demanding spot measurements in laboratories, greenhouses and mushroom farms. The meter can also be used in HVAC and industrial applications, and as a tool for checking fixed CO_2 instruments.

GM70 has a short warm-up time and is ready for use almost immediately. It has a menu-based interface, a graphical LCD display and data logging capability.

Vaisala CARBOCAP® Technology

GM70 incorporates the advanced CARBOCAP sensor that has unique reference measurement capabilities. The measurement accuracy is not affected by dust, water vapor or most chemicals. The meter has a two-year recommended calibration interval.

Two Sampling Methods

The handle is for hand-held diffusion sampling. GM70 pump enables pump-aspirated sampling from locations difficult to access otherwise. It is also ideal for comparisons with fixed CO_2 transmitters.

Interchangeable Probes

GM70 uses the same probes as Vaisala CARBOCAP Carbon Dioxide Transmitter Series GMT220. By plugging different probes into the handle or pump, the user can easily change the measurement range of the GM70.

The meter can also be used as a calibration check instrument for Vaisala's fixed CO_2 instruments. GMW90 and GMP220 probes can also be adjusted by using the GM70 meter. GM70 has two probe inputs. Vaisala's relative humidity and dewpoint probes can also be used simultaneously with CO_2 measurement.

MI70 Link

The optional MI70 Link Windows® software and the USB connection cable form a practical tool for transferring logged data and real time measurement data from GM70 to a PC.

Benefits

- Proven Vaisala CARBOCAP® reliability
- Wide selection of measurement ranges
- Easy recalibration using the interchangeable probes
- Suitable for field checking of fixed CO_2 instruments
- Short warm-up time
- Compact and versatile

Technical Data

CO_2 Volume Concentration Measurement Performance, GMH70 Probe

Response Time (63 %)	
GMP221	20 s
GMP222	30 s
Measurement Ranges	
High concentrations, short probe (GMP221)	0 ... 2 % 0 ... 3 % 0 ... 5 %, 0 ... 10 %, 0 ... 20 %
Low concentrations, long probe (GMP222)	0 ... 2000 ppm, 0 ... 3000 ppm, 0 ... 5000 ppm, 0 ... 7000 ppm, 0 ... 10 000 ppm
Accuracy at 25 °C and 1013 hPa[1]	
GMP221	±(1.5 % of range + 2 % of reading) [2]
GMP222	±(1.5 % of range + 2 % of reading)
Temperature dependence, typical	-0.3 % of reading/°C
Pressure dependence, typical	+0.15 % of reading/hPa
Long-term stability	< ±5 %FS / 2 years
Warm-up time	30 s, 15 min full specifications

1) *Including repeatability, non-linearity and calibration uncertainty.*
2) *Applies for concentrations above 2 % of full scale.*

Measurement Environment

Temperature	-20 ... +60 °C (-4 ... +140 °F)
Relative humidity	0 ... 100 %RH, non-condensing
Operation pressure	700 ... 1300 hPa
Flow range (diffusion sampling)	0 ... 10 m/s

Probe, Handle & Pump Mechanical Specifications

Sensor	Vaisala CARBOCAP®
Housing Material	
GMP221/222 probe	PC plastic
GMH70 handle	ABS/PC blend
GM70 Pump	Aluminium casing
Weight	
GMH70 with GMP221/222 probe	230 g
GM70 Pump with GMP221/222 probe	700 g

Probe, Handle & Pump Operating Environment

Storage temperature	-30 ... +70 °C (-22 ... +158 °F)
Storage humidity	0 ... 100 %RH, non-condensing

MI70 Measurement Indicator

Operating Environment	
Operating temperature	-10 ... +40 °C (+14 ... +104 °F)
Operating humidity	0 ... 100 % RH, non-condensing
Storage temperature	-40 ... +70 °C (-40 ... +158 °F)
Inputs and Outputs	
Max. no of probes	2
Power supply	Rechargeable NiMH battery pack with AC adapter or 4xAA size alkalines, type IEC LR6
PC interface	MI70 Link software with USB or serial port cable
Analog Output	
Scale	0...1 VDC
Output resolution	0.6 mV
Accuracy	0.2 % full scale
Temperature dependence	0.002 %/˚C full scale
Minimum load resistor	10 kΩ to ground
Mechanical Specifications	
Housing classification	IP54
Housing materials	ABS/PC blend
Weight	400 g
Compatibility	
EMC compliance	EN61326-1, Portable Equipment
Other	
Menu languages	English, Chinese, Spanish, Russian, French, Japanese, German, Swedish, Finnish
Display	• LCD with backlight • Graphic trend display of any parameter • Character height up to 16 mm
Alarm	Audible alarm function
Data logging capacity	2700 real time data points
Logging interval	1 s to 12 h
Logging duration	1 min ... memory full
Resolution	0.01 %RH, 0.01 °C/°F, 0.01 hPa, 0.01 a_w, 10 ppm / 0.01 %CO_2

Battery Operation Time

Typical charging time	4 hours
Operation Times	
Continuous use (with handle)	better than 8 h at +20 ˚C (68 °F)
Continuous use (with pump)	better than 5 h at +20 ˚C (68 °F) without load
Data logging use (one probe)	up to 30 days depending on logging interval

Dimensions in mm (inches)

Spare Parts and Accessories

MI70 Link software with USB cable	219687
MI70 Link software with serial port cable	MI70LINK
Analog output cable for 0 ... 1 VDC	27168ZZ
Calibration adapter	26150GM
Weatherproof carrying case	MI70CASE3
Soft carrying case for diffusion handle and probe	MI70SOFTCASE
Battery, NiMH 4.8 V	26755
Spare probe (use the order form to define measurement range etc.)	GMP221, GMP222
Nafion Membrane Tubing	212807GM
Connection Cable for Fixed CO_2 Instruments	
GMT220, GMD20	GMA70
GMP343	DRW216050SP
GMW90 series	219980SP

CE

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A.1.6 Pegasor Datasheet

Following is the datasheet for Pegasor included.

BSRIA

Instrument Solutions
DATASHEET

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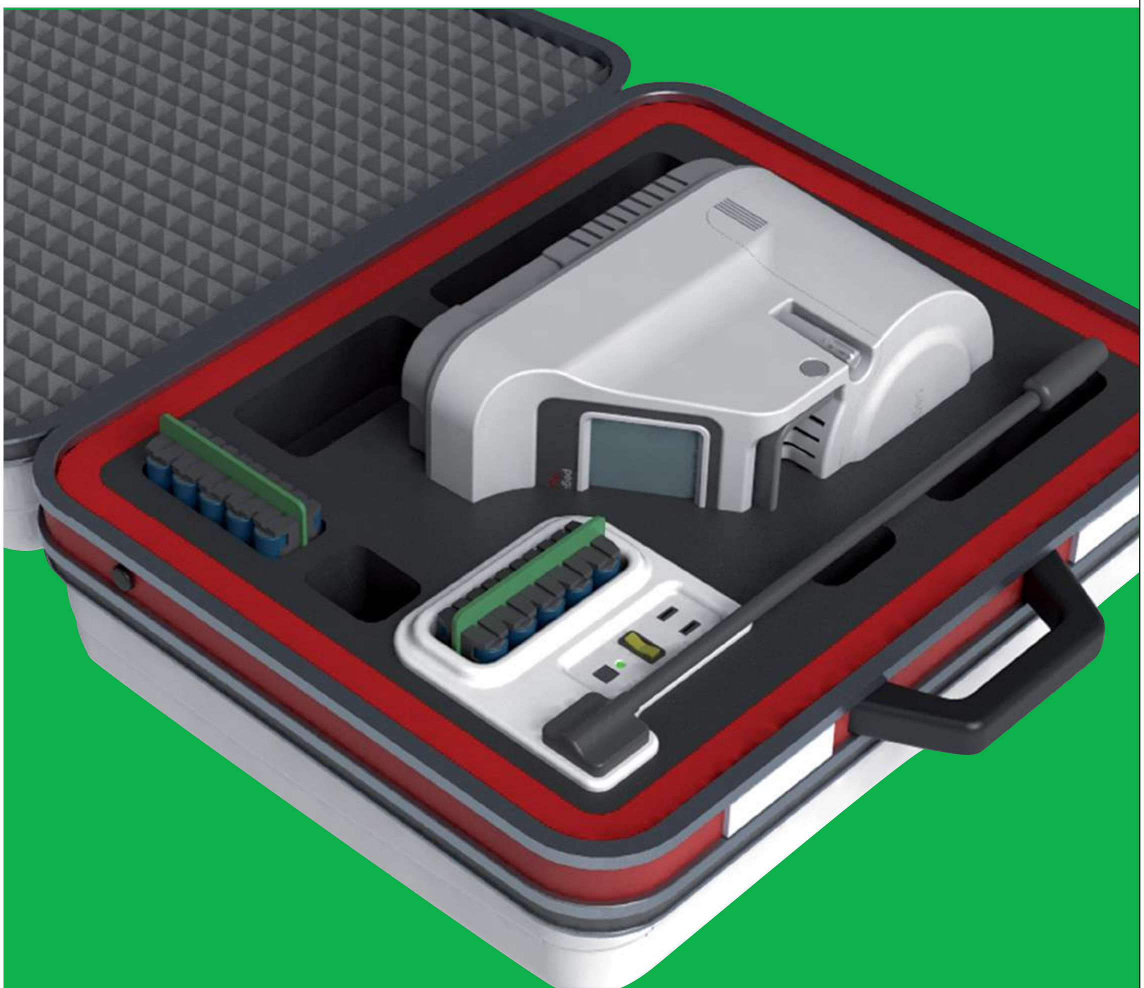
pegasor
PART OF
COORSTEK SENSORS

Pegasor AQ™ Indoor

Pegasor AQ™ Indoor



Accurate feedback on indoor air quality

What are we breathing

$PM_{2.5}$ pollution is a well-known problem and monitoring $PM_{2.5}$ concentration is a must. However, traditional $PM_{2.5}$ monitoring methods are not sensitive to the most harmful, ultrafine particles, diameter below 0.1 micrometers. All Pegasor instruments are capable to detect particles larger than 0,01 um and thus measure also the most dangerous particles.

pegasor
PART OF
COORSTEK SENSORS

Reliable Pegasor technology

Pegasor instruments electrically charge all particles entering the device and measure the electrical current carried by particles. The measurement result can be shown as particle mass concentration ($PM_{2.5}$), particle number concentration (PN) or active particle surface area concentration (PA). Pegasor products have extraordinary stability, low maintenance need and long measurement periods.

Pegasor AQ™ Indoor

Pegasor indoor measuring instrument is a perfect tool for all public and private places where real time monitoring of living environment with data storage is needed.

KEY FEATURES:

- Measures ultrafine particles
- Detects temperature, relative humidity and CO_2 concentration
- Self diagnostic procedure guarantees accurate continuous measurements
- Fits easily to any indoor environment
- Measured data can be read from the touch screen in graphical and numerical form
- Measured data can be stored on hard disk or USB and transferred to data storage, cloud service, or printed out as separate document
- Easy maintenance and long maintenance interval
- Reasonable pricing and very low cost of ownership

Applications

Pegasor data can be used for ventilation system and filtration efficiency monitoring, and indoor air quality classification.

Technical specification

Sensor type	Diffusion charging operating principle
Measuring range	0.001 – 200 mg/ m^3
Maximum responsive particle size	0.01 – 2.5 µm
Particle size cutter	$PM_{2.5}$
Sampling mode	Built in suction pump
Flow rate	3 L/min
Resolution	0.001 mg/m^3 (with 1 min integration time) 0.1% of reading
Sampling rate	1/sec
Operation interface	4,3" Color display touch screen
Time constant	1-300 s adjustable by user
Battery operation time	10h - 24h -100h (depending of the sampling rate)
Battery type	Li-ion
AC power supply	External power supply, 100 – 240 VAC, 50/60 Hz
Operating temperature range	0 - 50 °C
Storage temperature range	-20 – 60 °C
Communication interface	Ethernet with Modbus protocol, optionally wireless (3G/4G modem)
Automatic zero setting function	Yes
Document printer	Yes, with optional device
Service period	12 months, depending environment
Configurable to PM, PN or PA measurements	Yes
Temperature and relative humidity measurements	Yes, with Vaisala HUMICAP® sensor
CO_2 concentration measurement	Yes, with Vaisala CARBOCAP® sensor
Analog output mode	0 -10 V or 4 – 20 mA
Analog output range	Adjustable by user
Alarm output	Yes, for different alarms
Alarm setting point range	Adjustable
Built-in data storage	1 GB
Data storage type	Flash memory
Storage interval	1s – 1h
Maximum data points	> 1,000,000
Software	Pegasor
Dimensions (wxhxl)	150 x 200 x 300mm
Weight	< 1.5 kg
GPS for location indicator	Yes, optional

Connections

USB in, USB out	Yes
Bluetooth	Yes
WLAN	Yes, optional
Ethernet	Yes
3G/4G	Yes, optional
Analog (V and mA)	Yes


pegasor

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A.2 Hardware

In figure A.2 the hardware assembled inside the sensor boxes is shown. Number 1 is the SPS30 sensor, number 2 is the WZ-S sensor and number 3 is the SCD30 sensor, which in placed on top of shield on an Arduino UNO.

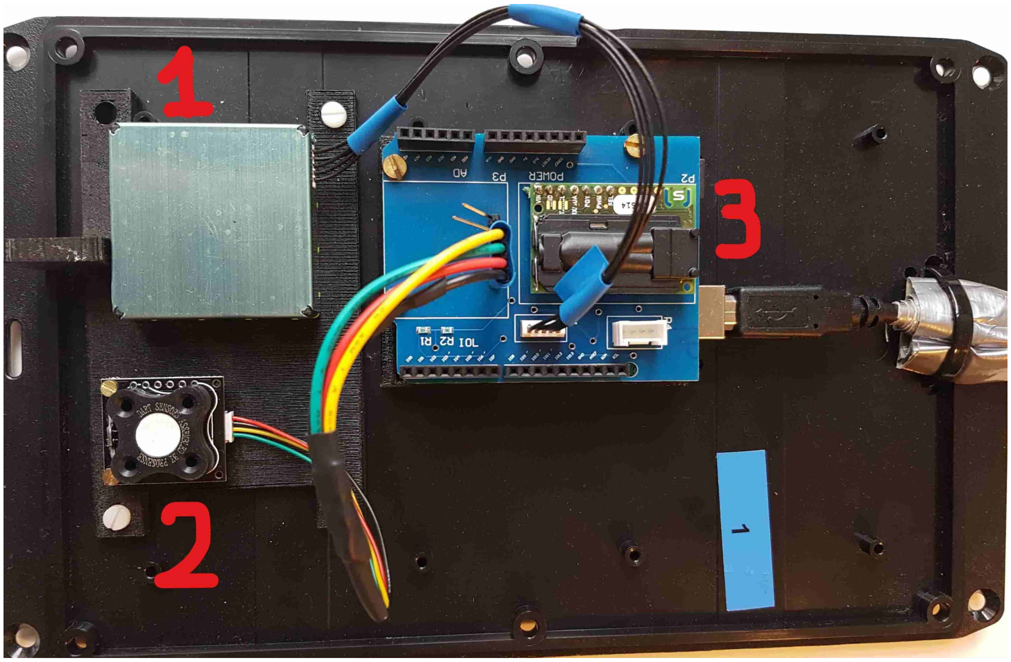

Figure A.1: Hardware of the sensor boxes

A.3 Software for Arduino, sensors and Raspberry Pi

Olav Aleksander Myrvang (olav.myrvang@ntnu.no) has developed the Arduino IDE codes on the Arduino side: PUST.ino (A.3.1), TIL.ino (A.3.2), Calibrate.ino (A.3.3) and setForcedCalibratonFactor.ino (A.3.4). PUST.ino and TIL.ino retrieve the outputs from all the sensors in the two sensor rigs PUST and TIL. Calibrate.ino is the 7 day auto self calibration of the CO_2 sensor on SCD30. setForcedCalibrationFactor.ino is another calibraton method for the CO_2 sensor on SCD30, where you input a known reference concentration, obviating the need for the 7 day calibration.

Even Johan Christiansen (even.j.christiansen@ntnu.no) has developed the code main.py (A.3.5) on the Raspberry Pi side. The intention with this code is to receive logged values from PUST Arduino sensor rig and TIL Arduino sensor rig via one USB cable for each rig and creating .csv-files with the logged values. One .csv-file is created for the PUST Arduino sensor rig, and one for the TIL Arduino sensor rig. These.csv-files are stored in the Raspberry Pi memory.

A.3.1 PUST.ino

Arduino IDE code (C++/C) for retrieving measurement data from the PUST sensor rig.

```
/* SPS30 simple test program for Arduino (with modified Wire.h lib)
 *  v. 1.0 19.01.2019), tested with ESP8266
 *
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 *
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 * modification, are permitted provided that the following conditions are met:
 *
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 *   https://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/
 *   0_Datasheets/Particulate_Matter/Sensirion_PM_Sensors_SPS30_Datasheet.pdf
 *
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 * SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS
 * INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN
 * CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE)
 * ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE
 * POSSIBILITY OF SUCH DAMAGE.
 */
//#define BUFFER_LENGTH 64 in Wire.h before

/*
  Reading CO2, humidity and temperature from the SCD30
  By: Nathan Seidle
  SparkFun Electronics
  Date: May 22nd, 2018
  License: MIT. See license file for more information but you can
  basically do whatever you want with this code.
  Feel like supporting open source hardware?
  Buy a board from SparkFun! https://www.sparkfun.com/products/14751
  This example prints the current CO2 level, relative humidity, and temperature in C.
  Hardware Connections:
  If needed, attach a Qwiic Shield to your Arduino/Photon/ESP32 or other
  Plug the device into an available Qwiic port
  Open the serial monitor at 9600 baud to see the output
```

```
*/

#include "Wire.h"
//Click here to get the library: http://librarymanager/All#SparkFun_SCD30
#include "SparkFun_SCD30_Arduino_Library.h"
#include <SimpleTimer.h>
#include "SoftwareSerial.h"

SoftwareSerial mySerial(7, 8);  //Pin 7 receives data, pin 8 transimits data.
int serial_value;
char zero=0, one=1, max_char=255, Hex=134;
SCD30 airSensor;
int Address = 0x69; // device address of SPS30 (fixed).
byte w1, w2,w3;
byte ND[60];
long tmp;
float measure;

byte expected_byte1 = 0x31;   //This is the ASII number for 1.
byte expected_byte2 = 0x32;   //This is the ASII number for 2.

void setup() {
  Wire.begin(); // Initiate the Wire library
  Serial.begin(9600);
  delay(100);

  airSensor.begin(); //This will cause readings to occur every two seconds

  delay(100);

  airSensor.setAutoSelfCalibration(false);  //This enables/disables the auto
  // self calibration.

  mySerial.begin (9600);
  Serial.flush();
  delay(100);
  mySerial.write (max_char);  //This command put the gas sensor in Q&A mode.
  mySerial.write (one);
  mySerial.write ("x");
  mySerial.write ("A");
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write ("F");
  delay(500);

}

void loop() {
/*
```

```
// RESET device
  delay(1000);
  SetPointer(0xD3, 0x04);
  delay(1000);
*/

//Start Measurement
  Wire.beginTransmission(Address);
  Wire.write(0x00);
  Wire.write(0x10);
  Wire.write(0x03);
  Wire.write(0x00);
  uint8_t data[2]={0x03, 0x00};
  Wire.write(CalcCrc(data));
  Wire.endTransmission();

  delay(10000);
/*
//Start Fan Cleaning
  Serial.println("clean");
  Start fan cleaning
  SetPointer(0x56, 0x07);
  delay(12000);
  Serial.println("clean end");
  delay(100);
*/
 while(1){

// Check if there is something on the serial port
  if (Serial.available()) {
    //read available data, save to recieved_data
    int recieved_data = Serial.read();

    //does the recieved data match our expectations?
    if (recieved_data == expected_byte2) {

      Serial.print("PUST");
      delay(50);
    }

   if (recieved_data == expected_byte1) {    //Starts new measurements.

     if (airSensor.dataAvailable())
      {
      Serial.print(";");
      //Serial.print(" temp(C):");
      Serial.print(airSensor.getTemperature(), 1);

      Serial.print(";");
      //Serial.print(" humidity(%):");
      Serial.print(airSensor.getHumidity(), 1);
```

```

      Serial.print(";");
      //Serial.print("co2(ppm):");
      Serial.print(airSensor.getCO2());

      }
    else
    {
      Serial.print(";");
      Serial.print("0");

      Serial.print(";");
      Serial.print("0");

      Serial.print(";");
      Serial.print("0");
    }

  delay(200);

  mySerial.write (max_char);  //This command reads the gas concentration.
  mySerial.write (one);
  mySerial.write (Hex);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write ("y");

  delay(200);

  for(int i=0;i<9;i++){
    if (mySerial.available() > 0){    //This section reads data from the gas sensor.
       serial_value=mySerial.read();
       Serial.print(";");
       Serial.print(serial_value);

       delay(5);
     }
  }
  delay(200);

  //Read data ready flag
  SetPointer(0x02, 0x02);
  Wire.requestFrom(Address, 3);
  w1=Wire.read();
  w2=Wire.read();
  w3=Wire.read();

  if (w2==0x01){                //0x01: new measurements ready to read
```

```
      SetPointer(0x03,0x00);
      Wire.requestFrom(Address, 60);
      for(int i=0;i<60;i++) { ND[i]=Wire.read();
      //    for(int i=0;i<30;i++) { ND[i]=Wire.read();      //without Wire.h lib
      //  modification only first 5 values
      //Serial.print(i);Serial.print(": ");Serial.println(ND[i],HEX);
      }
      // Result: PM1.0/PM2.5/PM4.0,PM10[ug/m3] , PM0.5,PM1.0/PM2.5/PM4.0,PM10 [[#/cm3],
      // Typical Particle Size [um]
      for(int i=0;i<60;i++) {
         if ((i+1)%3==0)
         {
           byte datax[2]={ND[i-2], ND[i-1]};
           //Serial.print("crc: ");Serial.print(CalcCrc(datax),HEX);
           //Serial.print("  "); Serial.println(ND[i],HEX);
           if(tmp==0) {
             tmp= ND[i-2];
             tmp= (tmp<<8) + ND[i-1];
            }
           else{
             tmp= (tmp<<8)+ ND[i-2];
             tmp= (tmp<<8) + ND[i-1];
             //Serial.print(tmp,HEX);Serial.print(" ");
             measure= (*(float*) &tmp);
             Serial.print(";");
             Serial.print(measure);

             tmp=0;
           }
         }
        }
    }
    delay(1400);

  //  Stop Meaurement
  //  SetPointer(0x01, 0x04);
        }
      }
  }
}

void SetPointer(byte P1, byte P2)
{
  Wire.beginTransmission(Address);
  Wire.write(P1);
  Wire.write(P2);
  Wire.endTransmission();
  }

// from datasheet:
byte CalcCrc(byte data[2]) {
```

```
  byte crc = 0xFF;
  for(int i = 0; i < 2; i++) {
    crc ^= data[i];
    for(byte bit = 8; bit > 0; --bit) {
      if(crc & 0x80) {
      crc = (crc << 1) ^ 0x31u;
      } else {
        crc = (crc << 1);
       }
    }
  }
  return crc;
}
```

Listing A.1: PUST.ino - Arduino IDE code (C++/C) for retrieving measurement data from the PUST sensor rig

A.3.2 TIL.ino

Arduino IDE code (C++/C) for retrieving measurement data from the TIL sensor rig.

```
/* SPS30 simple test program for Arduino (with modified Wire.h lib)
 *  v. 1.0 19.01.2019), tested with ESP8266
 *
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 *
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 *
 * * For details see vendors documentation:
 *   https://www.sensirion.com/fileadmin/user_upload/customers/sensirion/
 *   Dokumente/0_Datasheets/Particulate_Matter/Sensirion_PM_Sensors_SPS30_Datasheet.pdf
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 * INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN
 * CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE)
```

```
 * ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE
 * POSSIBILITY OF SUCH DAMAGE.
 */
//#define BUFFER_LENGTH 64 in Wire.h before

/*
  Reading CO2, humidity and temperature from the SCD30
  By: Nathan Seidle
  SparkFun Electronics
  Date: May 22nd, 2018
  License: MIT. See license file for more information but you can
  basically do whatever you want with this code.
  Feel like supporting open source hardware?
  Buy a board from SparkFun! https://www.sparkfun.com/products/14751
  This example prints the current CO2 level, relative humidity, and temperature in C.
  Hardware Connections:
  If needed, attach a Qwiic Shield to your Arduino/Photon/ESP32 or other
  Plug the device into an available Qwiic port
  Open the serial monitor at 9600 baud to see the output
*/

#include "Wire.h"
//Click here to get the library: http://librarymanager/All#SparkFun_SCD30
#include "SparkFun_SCD30_Arduino_Library.h"
#include <SimpleTimer.h>
#include "SoftwareSerial.h"

SoftwareSerial mySerial(7, 8);  //Pin 7 receives data, pin 8 transimits data.
int serial_value;
char zero=0, one=1, max_char=255, Hex=134;
SCD30 airSensor;
int Address = 0x69; // device address of SPS30 (fixed).
byte w1, w2,w3;
byte ND[60];
long tmp;
float measure;

byte expected_byte1 = 0x31;   //This is the ASII number for 1.
byte expected_byte2 = 0x32;   //This is the ASII number for 2.

void setup() {
  Wire.begin(); // Initiate the Wire library
  Serial.begin(9600);
  delay(100);

  airSensor.begin(); //This will cause readings to occur every two seconds

  delay(100);

  airSensor.setAutoSelfCalibration(false);  //This enables/disables the auto self
  // calibration.
```

```

  mySerial.begin (9600);
  Serial.flush();
  delay(100);
  mySerial.write (max_char);  //This command put the gas sensor in Q&A mode.
  mySerial.write (one);
  mySerial.write ("x");
  mySerial.write ("A");
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write ("F");
  delay(500);
}

void loop() {
/*
// RESET device
  delay(1000);
  SetPointer(0xD3, 0x04);
  delay(1000);
*/

//Start Measurement
  Wire.beginTransmission(Address);
  Wire.write(0x00);
  Wire.write(0x10);
  Wire.write(0x03);
  Wire.write(0x00);
  uint8_t data[2]={0x03, 0x00};
  Wire.write(CalcCrc(data));
  Wire.endTransmission();

  delay(10000);
/*
//Start Fan Cleaning
  Serial.println("clean");
  Start fan cleaning
  SetPointer(0x56, 0x07);
  delay(12000);
  Serial.println("clean end");
  delay(100);
*/
 while(1){

// Check if there is something on the serial port
  if (Serial.available()) {
    //read available data, save to recieved_data
    int recieved_data = Serial.read();

```

```
  //does the recieved data match our expectations?
  if (recieved_data == expected_byte2) {

    Serial.print("TIL");
    delay(50);
  }

 if (recieved_data == expected_byte1) {    //Starts new measurements.

   if (airSensor.dataAvailable())
    {
    Serial.print(";");
    //Serial.print(" temp(C):");
    Serial.print(airSensor.getTemperature(), 1);

    Serial.print(";");
    //Serial.print(" humidity(%):");
    Serial.print(airSensor.getHumidity(), 1);

    Serial.print(";");
    //Serial.print("co2(ppm):");
    Serial.print(airSensor.getCO2());

    }
   else
   {
    Serial.print(";");
    Serial.print("0");

    Serial.print(";");
    Serial.print("0");

    Serial.print(";");
    Serial.print("0");
   }

  delay(200);

  mySerial.write (max_char);  //This command reads the gas concentration.
  mySerial.write (one);
  mySerial.write (Hex);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write ("y");

  delay(200);

  for(int i=0;i<9;i++){
```

```
      if (mySerial.available() > 0){    //This section reads data from the gas sensor.
        serial_value=mySerial.read();
        Serial.print(";");
        Serial.print(serial_value);

        delay(5);
      }
    }
    delay(200);

    //Read data ready flag
    SetPointer(0x02, 0x02);
    Wire.requestFrom(Address, 3);
    w1=Wire.read();
    w2=Wire.read();
    w3=Wire.read();

    if (w2==0x01){                //0x01: new measurements ready to read
      SetPointer(0x03,0x00);
      Wire.requestFrom(Address, 60);
      for(int i=0;i<60;i++) { ND[i]=Wire.read();
      //     for(int i=0;i<30;i++) { ND[i]=Wire.read();      //without Wire.h lib
      // modification only first 5 values
      //Serial.print(i);Serial.print(": ");Serial.println(ND[i],HEX);
      }
      // Result: PM1.0/PM2.5/PM4.0,PM10[ug/m3] , PM0.5,PM1.0/PM2.5/PM4.0,PM10 [[#/cm3],
      // Typical Particle Size [um]
      for(int i=0;i<60;i++) {
         if ((i+1)%3==0)
         {
           byte datax[2]={ND[i-2], ND[i-1]};
           //Serial.print("crc: ");Serial.print(CalcCrc(datax),HEX);
           //Serial.print("   "); Serial.println(ND[i],HEX);
           if(tmp==0) {
             tmp= ND[i-2];
             tmp= (tmp<<8) + ND[i-1];
            }
           else{
             tmp= (tmp<<8)+ ND[i-2];
             tmp= (tmp<<8) + ND[i-1];
             //Serial.print(tmp,HEX);Serial.print(" ");
             measure= (*(float*) &tmp);
             Serial.print(";");
             Serial.print(measure);

             tmp=0;
           }
         }
       }
    }
    delay(1400);
```

```

  //   Stop Meaurement
  //   SetPointer(0x01, 0x04);
        }
      }
  }
}

void SetPointer(byte P1, byte P2)
{
  Wire.beginTransmission(Address);
  Wire.write(P1);
  Wire.write(P2);
  Wire.endTransmission();
  }

// from datasheet:
byte CalcCrc(byte data[2]) {
  byte crc = 0xFF;
  for(int i = 0; i < 2; i++) {
    crc ^= data[i];
    for(byte bit = 8; bit > 0; --bit) {
      if(crc & 0x80) {
      crc = (crc << 1) ^ 0x31u;
      } else {
        crc = (crc << 1);
       }
     }
   }
  return crc;
}
```

Listing A.2: TIL.ino - Arduino IDE code (C++/C) for retrieving measurement data from the PUST sensor rig

A.3.3 Calibrate.ino

Arduino IDE code for the required 7 day initial calibration of CO_2 sensor, as specified in datasheet A.1.1.

```
/* SPS30 simple test program for Arduino (with modified Wire.h lib)
 *  v. 1.0 19.01.2019), tested with ESP8266
 *
 * Copyright (c) 2019, Michael Pruefer
 * All rights reserved.
 *
 * Redistribution and use in source and binary forms, with or without
 * modification, are permitted provided that the following conditions are met:
 *
 * * Redistributions of source code must retain the above copyright notice, this
 *   list of conditions and the following disclaimer.
```

```
 *
 * * Redistributions in binary form must reproduce the above copyright notice,
 *   this list of conditions and the following disclaimer in the documentation
 *   and/or other materials provided with the distribution.
 *
 * * For details see vendors documentation:
 *   https://www.sensirion.com/fileadmin/user_upload/customers/sensirion/
 *   Dokumente/0_Datasheets/Particulate_Matter/Sensirion_PM_Sensors_SPS30_Datasheet.pdf
 *
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 * AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE
 * IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE
 * ARE DISCLAIMED. IN NO EVENT SHALL THE COPYRIGHT HOLDER OR CONTRIBUTORS BE
 * LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR
 * CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF
 * SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS
 * INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN
 * CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE)
 * ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE
 * POSSIBILITY OF SUCH DAMAGE.
 */
//#define BUFFER_LENGTH 64 in Wire.h before

/*
  Reading CO2, humidity and temperature from the SCD30
  By: Nathan Seidle
  SparkFun Electronics
  Date: May 22nd, 2018
  License: MIT. See license file for more information but you can
  basically do whatever you want with this code.
  Feel like supporting open source hardware?
  Buy a board from SparkFun! https://www.sparkfun.com/products/14751
  This example prints the current CO2 level, relative humidity, and temperature in C.
  Hardware Connections:
  If needed, attach a Qwiic Shield to your Arduino/Photon/ESP32 or other
  Plug the device into an available Qwiic port
  Open the serial monitor at 9600 baud to see the output
*/

#include "Wire.h"
//Click here to get the library: http://librarymanager/All#SparkFun_SCD30
#include "SparkFun_SCD30_Arduino_Library.h"
#include <SimpleTimer.h>
#include "SoftwareSerial.h"

SoftwareSerial mySerial(7, 8);  //Pin 7 receives data, pin 8 transimits data.
int serial_value;
char zero=0, one=1, max_char=255, Hex=134;
SCD30 airSensor;
int Address = 0x69; // device address of SPS30 (fixed).
byte w1, w2,w3;
```

```
byte ND[60];
long tmp;
float measure;

byte expected_byte1 = 0x31;   //This is the ASII number for 1.
byte expected_byte2 = 0x32;   //This is the ASII number for 2.

void setup() {
  Wire.begin(); // Initiate the Wire library
  Serial.begin(9600);
  delay(100);

  airSensor.begin(); //This will cause readings to occur every two seconds

  delay(100);

  airSensor.setAutoSelfCalibration(true);  //This enables/disables the auto self
  // calibration.

  mySerial.begin (9600);
  Serial.flush();
  delay(100);
  mySerial.write (max_char);  //This command put the gas sensor in Q&A mode.
  mySerial.write (one);
  mySerial.write ("x");
  mySerial.write ("A");
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write ("F");
  delay(500);

}

void loop() {
/*
// RESET device
  delay(1000);
  SetPointer(0xD3, 0x04);
  delay(1000);
*/

//Start Measurement
  Wire.beginTransmission(Address);
  Wire.write(0x00);
  Wire.write(0x10);
  Wire.write(0x03);
  Wire.write(0x00);
  uint8_t data[2]={0x03, 0x00};
  Wire.write(CalcCrc(data));
```

```
  Wire.endTransmission();

  delay(10000);
/*
//Start Fan Cleaning
  Serial.println("clean");
  Start fan cleaning
  SetPointer(0x56, 0x07);
  delay(12000);
  Serial.println("clean end");
  delay(100);
*/
 while(1){

// Check if there is something on the serial port
  if (Serial.available()) {
    //read available data, save to recieved_data
    int recieved_data = Serial.read();

    //does the recieved data match our expectations?
    if (recieved_data == expected_byte2) {

      Serial.print("Calibrate");
      delay(50);
    }

   if (recieved_data == expected_byte1) {    //Starts new measurements.

     if (airSensor.dataAvailable())
      {
      Serial.print(";");
      //Serial.print(" temp(C):");
      Serial.print(airSensor.getTemperature(), 1);

      Serial.print(";");
      //Serial.print(" humidity(%):");
      Serial.print(airSensor.getHumidity(), 1);

      Serial.print(";");
      //Serial.print("co2(ppm):");
      Serial.print(airSensor.getCO2());

      }
     else
     {
      Serial.print(";");
      Serial.print("0");

      Serial.print(";");
      Serial.print("0");

```

```
      Serial.print(";");
      Serial.print("0");
     }

    delay(200);

    mySerial.write (max_char);  //This command reads the gas concentration.
    mySerial.write (one);
    mySerial.write (Hex);
    mySerial.write (zero);
    mySerial.write (zero);
    mySerial.write (zero);
    mySerial.write (zero);
    mySerial.write (zero);
    mySerial.write ("y");

    delay(200);

    for(int i=0;i<9;i++){
     if (mySerial.available() > 0){    //This section reads data from the gas sensor.
        serial_value=mySerial.read();
        Serial.print(";");
        Serial.print(serial_value);

        delay(5);
      }
    }
    delay(200);

    //Read data ready flag
    SetPointer(0x02, 0x02);
    Wire.requestFrom(Address, 3);
    w1=Wire.read();
    w2=Wire.read();
    w3=Wire.read();

    if (w2==0x01){              //0x01: new measurements ready to read
      SetPointer(0x03,0x00);
      Wire.requestFrom(Address, 60);
      for(int i=0;i<60;i++) { ND[i]=Wire.read();
      //     for(int i=0;i<30;i++) { ND[i]=Wire.read();      //without Wire.h lib
      // modification only first 5 values
      //Serial.print(i);Serial.print(": ");Serial.println(ND[i],HEX);
      }
      // Result: PM1.0/PM2.5/PM4.0,PM10[ug/m3] , PM0.5,PM1.0/PM2.5/PM4.0,PM10 [[#/cm3],
      // Typical Particle Size [um]
      for(int i=0;i<60;i++) {
          if ((i+1)%3==0)
          {
            byte datax[2]={ND[i-2], ND[i-1]};
            //Serial.print("crc: ");Serial.print(CalcCrc(datax),HEX);
```

```
            //Serial.print("   "); Serial.println(ND[i],HEX);
            if(tmp==0) {
              tmp= ND[i-2];
              tmp= (tmp<<8) + ND[i-1];
             }
            else{
              tmp= (tmp<<8)+ ND[i-2];
              tmp= (tmp<<8) + ND[i-1];
              //Serial.print(tmp,HEX);Serial.print(" ");
              measure= (*(float*) &tmp);
              Serial.print(";");
              Serial.print(measure);

              tmp=0;
            }
          }
        }
    }
    delay(1400);

  //  Stop Meaurement
  //  SetPointer(0x01, 0x04);
        }
      }
  }
}

void SetPointer(byte P1, byte P2)
{
  Wire.beginTransmission(Address);
  Wire.write(P1);
  Wire.write(P2);
  Wire.endTransmission();
  }

// from datasheet:
byte CalcCrc(byte data[2]) {
  byte crc = 0xFF;
  for(int i = 0; i < 2; i++) {
    crc ^= data[i];
    for(byte bit = 8; bit > 0; --bit) {
      if(crc & 0x80) {
      crc = (crc << 1) ^ 0x31u;
      } else {
        crc = (crc << 1);
       }
     }
   }
  return crc;
}
```

Listing A.3: Calibrate.ino - Arduino IDE code for 7 day calibration of CO_2 sensor

A.3.4 setForcedRecalibrationFactor.ino

Arduino IDE code for forced recalibration of CO_2 sensor, to be used if Calibrate.ino (A.3.3) is not used.

```
/* SPS30 simple test program for Arduino (with modified Wire.h lib)
 *  v. 1.0 19.01.2019), tested with ESP8266
 *
 * Copyright (c) 2019, Michael Pruefer
 * All rights reserved.
 *
 * Redistribution and use in source and binary forms, with or without
 * modification, are permitted provided that the following conditions are met:
 *
 * * Redistributions of source code must retain the above copyright notice, this
 *   list of conditions and the following disclaimer.
 *
 * * Redistributions in binary form must reproduce the above copyright notice,
 *   this list of conditions and the following disclaimer in the documentation
 *   and/or other materials provided with the distribution.
 *
 * * For details see vendors documentation:
 *   https://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente
 *   /0_Datasheets/Particulate_Matter/Sensirion_PM_Sensors_SPS30_Datasheet.pdf
 *
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 * AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE
 * IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE
 * ARE DISCLAIMED. IN NO EVENT SHALL THE COPYRIGHT HOLDER OR CONTRIBUTORS BE
 * LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR
 * CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF
 * SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS
 * INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN
 * CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE)
 * ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE
 * POSSIBILITY OF SUCH DAMAGE.
 */
//#define BUFFER_LENGTH 64 in Wire.h before

/*
  Reading CO2, humidity and temperature from the SCD30
  By: Nathan Seidle
  SparkFun Electronics
  Date: May 22nd, 2018
  License: MIT. See license file for more information but you can
  basically do whatever you want with this code.
  Feel like supporting open source hardware?
  Buy a board from SparkFun! https://www.sparkfun.com/products/14751
  This example prints the current CO2 level, relative humidity, and temperature in C.
  Hardware Connections:
  If needed, attach a Qwiic Shield to your Arduino/Photon/ESP32 or other
  Plug the device into an available Qwiic port
  Open the serial monitor at 9600 baud to see the output
```

```
*/

#include "Wire.h"
//Click here to get the library: http://librarymanager/All#SparkFun_SCD30
#include "SparkFun_SCD30_Arduino_Library.h"
#include <SimpleTimer.h>
#include "SoftwareSerial.h"

SoftwareSerial mySerial(7, 8);  //Pin 7 receives data, pin 8 transimits data.
int serial_value;
char zero=0, one=1, max_char=255, Hex=134;
SCD30 airSensor;
int Address = 0x69; // device address of SPS30 (fixed).
byte w1, w2,w3;
byte ND[60];
long tmp;
float measure;

byte expected_byte1 = 0x31;   //This is the ASII number for 1.
byte expected_byte2 = 0x32;   //This is the ASII number for 2.
byte expected_byte3 = 0x33;   //This is the ASII number for 3.

uint16_t ForcedRecalibrationFactor =460;  //The CO2 reference concentration is set to
// 460 ppm, change according to your needs.

void setup() {
  Wire.begin(); // Initiate the Wire library
  Serial.begin(9600);
  delay(100);

  airSensor.begin(); //This will cause readings to occur every two seconds

  delay(100);

  airSensor.setAutoSelfCalibration(false);  //This enables/disables the auto self
  // calibration.

  mySerial.begin (9600);
  Serial.flush();
  delay(100);
  mySerial.write (max_char);  //This command put the gas sensor in Q&A mode.
  mySerial.write (one);
  mySerial.write ("x");
  mySerial.write ("A");
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write (zero);
  mySerial.write ("F");
  delay(500);

```

```
}

void loop() {
/*
// RESET device
  delay(1000);
  SetPointer(0xD3, 0x04);
  delay(1000);
*/

//Start Measurement
  Wire.beginTransmission(Address);
  Wire.write(0x00);
  Wire.write(0x10);
  Wire.write(0x03);
  Wire.write(0x00);
  uint8_t data[2]={0x03, 0x00};
  Wire.write(CalcCrc(data));
  Wire.endTransmission();

  delay(10000);
/*
//Start Fan Cleaning
  Serial.println("clean");
  Start fan cleaning
  SetPointer(0x56, 0x07);
  delay(12000);
  Serial.println("clean end");
  delay(100);
*/
 while(1){

// Check if there is something on the serial port

   if (1) {    //Starts new measurements.

     if (airSensor.dataAvailable())
      {
      Serial.print(";");
      //Serial.print(" temp(C):");
      Serial.print(airSensor.getTemperature(), 1);

      Serial.print(";");
      //Serial.print(" humidity(%):");
      Serial.print(airSensor.getHumidity(), 1);

      Serial.print(";");
      //Serial.print("co2(ppm):");
      Serial.print(airSensor.getCO2());

      }
```

```
     else
     {
      Serial.print(";");
      Serial.print("0");

      Serial.print(";");
      Serial.print("0");

      Serial.print(";");
      Serial.print("0");
     }

    delay(200);

    mySerial.write (max_char);  //This command reads the gas concentration.
    mySerial.write (one);
    mySerial.write (Hex);
    mySerial.write (zero);
    mySerial.write (zero);
    mySerial.write (zero);
    mySerial.write (zero);
    mySerial.write (zero);
    mySerial.write ("y");

    delay(200);

    for(int i=0;i<9;i++){
     if (mySerial.available() > 0){    //This section reads data from the gas sensor.
        serial_value=mySerial.read();
        Serial.print(";");
        Serial.print(serial_value);

        delay(5);
      }
    }
    delay(200);

    //Read data ready flag
    SetPointer(0x02, 0x02);
    Wire.requestFrom(Address, 3);
    w1=Wire.read();
    w2=Wire.read();
    w3=Wire.read();

    if (w2==0x01){                //0x01: new measurements ready to read
      SetPointer(0x03,0x00);
      Wire.requestFrom(Address, 60);
      for(int i=0;i<60;i++) { ND[i]=Wire.read();
      //     for(int i=0;i<30;i++) { ND[i]=Wire.read();      //without Wire.h
      // lib modification only first 5 values
      //Serial.print(i);Serial.print(": ");Serial.println(ND[i],HEX);
```

```
      }
      // Result: PM1.0/PM2.5/PM4.0,PM10[ug/m3] , PM0.5,PM1.0/PM2.5/PM4.0,PM10 [[#/cm3],
      // Typical Particle Size [um]
      for(int i=0;i<60;i++) {
         if ((i+1)%3==0)
         {
           byte datax[2]={ND[i-2], ND[i-1]};
           //Serial.print("crc: ");Serial.print(CalcCrc(datax),HEX);
           //Serial.print("  "); Serial.println(ND[i],HEX);
           if(tmp==0) {
             tmp= ND[i-2];
             tmp= (tmp<<8) + ND[i-1];
            }
           else{
             tmp= (tmp<<8)+ ND[i-2];
             tmp= (tmp<<8) + ND[i-1];
             //Serial.print(tmp,HEX);Serial.print(" ");
             measure= (*(float*) &tmp);
             Serial.print(";");
             Serial.print(measure);

             tmp=0;
           }
         }
        }
    }
    delay(1400);

  //  Stop Meaurement
  //  SetPointer(0x01, 0x04);
        }

if (Serial.available()) {
    //read available data, save to recieved_data
    int recieved_data = Serial.read();

    //does the recieved data match our expectations?
    if (recieved_data == expected_byte2) {

      Serial.print("PUST");
      delay(50);
    }

   if (recieved_data == expected_byte3){                                  //Send
   //"3" to set the Co2 calibration.
      airSensor.setForcedRecalibrationFactor(ForcedRecalibrationFactor);

      //This command sets the Co2 calibration.
   }
   }
      }
```

```
  }

void SetPointer(byte P1, byte P2)
{
  Wire.beginTransmission(Address);
  Wire.write(P1);
  Wire.write(P2);
  Wire.endTransmission();
  }

// from datasheet:
byte CalcCrc(byte data[2]) {
  byte crc = 0xFF;
  for(int i = 0; i < 2; i++) {
    crc ^= data[i];
    for(byte bit = 8; bit > 0; --bit) {
      if(crc & 0x80) {
      crc = (crc << 1) ^ 0x31u;
      } else {
        crc = (crc << 1);
       }
     }
   }
  return crc;
}
```

Listing A.4: setForcedRecalibrationFactor.ino - Arduino IDE code (C++/C) for forced recalibration of CO_2 sensor

A.3.5 main.py

Even Johan Christiansen (even.j.christiansen@ntnu.no) has developed the system on the Raspberry Pi side. The intention with this system is to receive logged values from PUST Arduino sensor rig and TIL Arduino sensor rig via one USB cable for each rig and creating .csv-files with the logged values. One .csv-file is created for the PUST Arduino sensor rig, and one for the TIL Arduino sensor rig.

```
#!/usr/bin/env python
#-*- coding: utf-8 -*-

# Importing modules
import serial
import time
import datetime

# Definition of UNIX shell colors
class bcolors:
    HEADER = '\033[95m'
    OKBLUE = '\033[94m'
    OKGREEN = '\033[93m'
    TEST = '\033[92m'
```

```python
    ENDC = '\033[0m'
    RED = '\033[91m'

# Holder for active serial ports
serialPorts = []

# Populated by the Ardunios by either "TIL" or "PUST"
# This decides the name of the logfile for this arduino.
typeOfSensorNode = []

# Holder for generated files
filenames = []
files = []

# messages[0] = '1' is used to ask the Arduino's for sensor data
# messages[1] = '2' is used for probing each active serial port and checking for an
# answer 'PUST' or 'TIL'
messages = ['1', '2']

# Time between each sensor log.
# Change this if you want to alter the frequency of data transfers.
timeBetweenDataTransfers = 10

# Number of connected devices.
# Change if you want to add more or less sensor nodes.
numberOfArduinoDevices = 2

# Serial Connection settings.
# Do not change.
baudrate = 9600
parity = serial.PARITY_NONE
stopbits = serial.STOPBITS_ONE
bytesize = serial.EIGHTBITS
timeout = 1

# Routine that probes the first 100 possible Arduino-COMs.
# This routine populates serialPorts.
def establishSerialConnections():
    counter = 0
    print(bcolors.OKGREEN + "\n--- Establishing serial connections ---" + bcolors.ENDC)
    while (counter < 100):
        try:
            ser = serial.Serial(
                port= "/dev/ttyACM" + counter.__str__(),
                baudrate = baudrate,
                parity = parity,
                stopbits = stopbits,
                bytesize = bytesize,
                timeout = 1
            )
            serialPorts.append(ser)
```

```
            ser.close()
            ser.open()
            print ("Found open device at /dev/ttyACM" + counter.__str__())

        except IOError:
            None

        counter += 1
    if len(serialPorts) < numberOfArduinoDevices:
        raw_input(bcolors.RED + "To few devices found, are you sure they are
        connected? \nPress enter to quit." + bcolors.ENDC)
        exit()
    elif len(serialPorts) > numberOfArduinoDevices:
        rawinput(bcolors.RED + "To many devices found, did you forget to adjust the
        numberOfArduinoDevices variable?" + bcolors.ENDC)
        exit()
    print(bcolors.OKGREEN + "--- Serial connections established --- \n\n" + bcolors.ENDC)

# Routine checking what type of sensorNode we found.
# This routine populates typeOfSensoNodes.
# It is also detrimental to ensure established connection.
# If the number of established connections is not the number of expected Arduinos,
# the program will shut down.
def checkDeviceConnectivity():
    print(bcolors.OKGREEN + "--- Checking if devices are sensor nodes ---" + bcolors.ENDC)
    establishedConnections = 0
    for portNumber in range(0, numberOfArduinoDevices):
        print ('Writing to Arduino at ' + serialPorts[portNumber].port.__str__())
        serialPorts[portNumber].write(messages[1])
        recievedData = serialPorts[portNumber].readline()

        print("First package from Arduino is: " + recievedData)
        if (recievedData == "TIL" or recievedData == "PUST"):
            print ('We found a sensor node')
            typeOfSensorNode.append(recievedData)
            establishedConnections += 1

    print(bcolors.OKGREEN + "--- Done checking if devices are sensor nodes --- \n\n"
    + bcolors.ENDC)
    if (establishedConnections == numberOfArduinoDevices):
        return True
    else:
        return False

# Routine generating filenames, using typeOfSensorNode.
# File names are hard coded to /home/pi/Desktop/log/filename.csv.
# Each file is named with millisecond precision, meaning files will never generate
# the same names.
def generateFileNames():
    for device in range(0, numberOfArduinoDevices):
        filenames.append("/home/pi/Desktop/log/"+typeOfSensorNode[device].__str__()+
```

```
        '_Arduino_nr_'+device.__str__()+'_'+datetime.datetime.now().__str__()+'.csv')
        print ("Created file: " + filenames[device].__str__())

# Routine creating actual measurement files and fills in first two rows.
def createMeasurementFiles():
    print(bcolors.OKGREEN + "--- Generating measurement files ---" + bcolors.ENDC)
    generateFileNames()
    for device in range(0, numberOfArduinoDevices):
        files.append(open(filenames[device], "w+"))
        files[device].write('Date;Time;Temperature;Relative Humidity;CO2;Formaldehyde
        Start;Control;High bit;Low bit;Reserved;Reserved;High bit;Low bit;Checksum;
        PM1.0;PM2.5;PM4.0;PM10;NCPM0.5;NCPM1.0;NCPM2.5;NCPM4.0;NCPM10.0;
        Typical Particle Size')
        files[device].write("\r\n")
        files[device].write('YYYY-MM-DD;HH:MM:SS.ssssss;oC;\%;ppm;255;134;ug/m3;ug/m3;
        0;0;ppb;ppb;Checksum[int];ug/m3;ug/m3;ug/m3;ug/m3;#/cm3;#/cm3;#/cm3;#/cm3;
        #/cm3;um')
        files[device].write("\r\n")
        files[device].close()
    print(bcolors.OKGREEN + "--- Done generating measurement files --- \n\n"
    + bcolors.ENDC)

# Function for reading from the nodes.
# All write functionality here should at a later point be written in a
# writeToFile-routine.
def readFromArduino_writeToFile():
    for device in range(0, numberOfArduinoDevices):
        print ('Reading from Arduino at ' + serialPorts[device].port.__str__())
        recievedData = serialPorts[device].readline()
        #print ("Recieved: " + recievedData.__str__())
        if (recievedData != None):
            print ('Read successfully from ' + serialPorts[device].port.__str__())
        else:
            print ('Failed')
        files[device] = open(filenames[device], "a")
        files[device].write(datetime.datetime.now().date().__str__())
        files[device].write(";")
        files[device].write(datetime.datetime.now().time().__str__())
        files[device].write(recievedData)
        files[device].write("\r\n")
        files[device].close()

# Routine for writing a message to all the sensor nodes.
def writeToArduino(message):
    for device in range(0, numberOfArduinoDevices):
        serialPorts[device].write(message)

# Brute force connection establisher for odd cases where Arduino wont respond
def bruteForceWrite(message):
    foundDevices = 0
    counter = 0
```

```
    for ports in serialPorts:
        print(bcolors.OKGREEN + "\n--- Probing " + ports.name + " ---" + bcolors.ENDC)
        ports.write(message)
        recievedData = ports.readline()
        if recievedData == "TIL":
            foundDevices += 1
            print ("I see an arduino")
        elif recievedData == "PUST":
            foundDevices += 1
            print ("I see an arduino")

        counter += 1
        print(bcolors.OKGREEN + "--- Finished probing device ---\n\n" + bcolors.ENDC)
    return foundDevices

establishSerialConnections()

startup = True

# Force while loop to continue until numberOfArduinoDevices Arduinos responds.
while startup:
    if (bruteForceWrite(messages[1]) == numberOfArduinoDevices):
        startup = False

# Safety check that connection is still in place. Legacy code that may be altered.
connection_established = checkDeviceConnectivity()
createMeasurementFiles()

# If connection is good, this is where the program loops.
if connection_established:
    print(bcolors.HEADER + "Connection is established, going into measurement mode \n \n"
    + bcolors.ENDC)
    while True:
        print(bcolors.OKGREEN + "--- Performing measurement ---" + bcolors.ENDC)
        writeToArduino(messages[0])
        readFromArduino_writeToFile()
        print(bcolors.OKGREEN + "--- Measurement done --- \n\n" + bcolors.ENDC)
        print((bcolors.TEST + "Waiting between measurements. Press CTRL+C to exit \n\n"
        + bcolors.ENDC))
        time.sleep(timeBetweenDataTransfers)
else:
    print ('Failed finding enough Arduino Devices, shutting down')
```

Listing A.5: Python code running in Raspberry Pi: main.py

A.4 Step by step user guide for the sensor rig

The parts needed for setting up one sensor rig are displayed in figure A.2: 1 Raspberry Pi, 1 power supply cable, 1 PUST sensor box, 1 TIL sensor box, 1 LCD screen with HDMI and USB cable, 1 mouse+keyboard with shared USB.

Figure A.2: All system components, unplugged

In figure A.3, the power and HDMI connection points are shown.

Figure A.3: Raspberry Pi, power and HDMI connection points

In figure A.4, the 4 USB connection points are shown.

Figure A.4: Raspberry Pi, 4 USB connection points

In figure A.5, the required connections to the Raspberry Pi are shown: 1 USB from PUST sensor box, 1 USB from TIL sensor box, 1 USB from LCD screen, 1 USB from mouse+keyboard, 1 HDMI from LCD screen, 1 power cable.

Figure A.5: Raspberry Pi with all required plugs connected

In figure A.6, all components are plugged and the system is connected to power. The Raspberry Pi desktop is automatically displayed on the LCD screen after system power up.

Figure A.6: All system components, plugged

In figure A.7, the Raspberry Pi desktop is shown. Everything needed for running the sensor rig is placed there. You will see that the time and date on the Raspberry Pi is wrong. It will find the correct time and date automatically when you connect it to internet. Sharing the internet from your phone works great. After opening the internet browser "Chromium" and establishing a connection to a random website, you will see that the time and date changes to the correct ones after a short while. This is important because your log files will get their time stamps from the time on the Raspberry Pi.

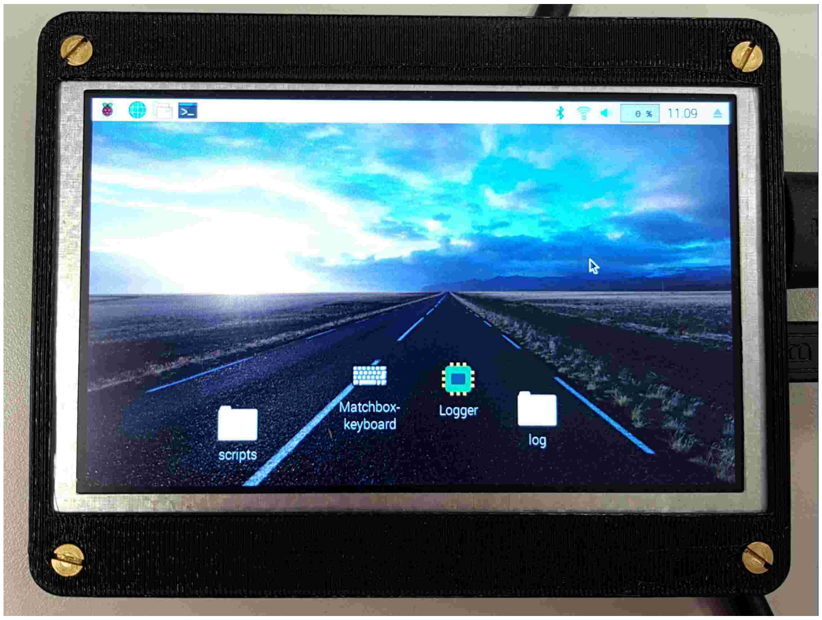

Figure A.7: Raspberry Pi desktop

In figure A.8, main.py is shown. This found in the folder "scripts" on desktop and opened with e.g. TextEditor. If you want to change the time between each sensor log, you change the value of "timeBetweenDataTransfers" to the number of seconds you need and remember to save your changes. In A.8 the time interval between each logging is 30 seconds.

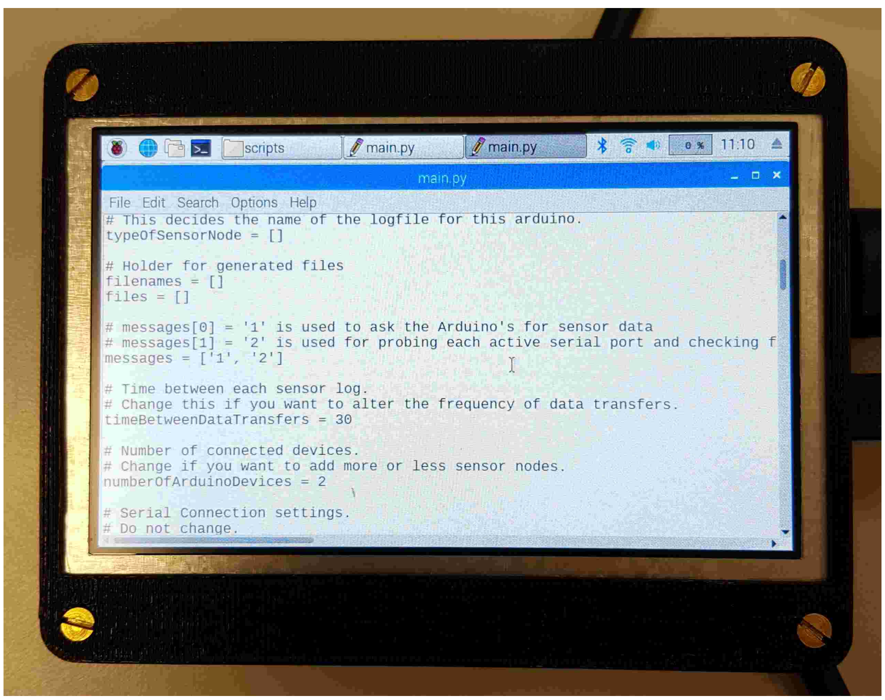

Figure A.8: Raspberry Pi script: main.py

In figure A.9, logging is initiated. This is done by double clicking the program "Logger" on desktop and waiting for the program to start up. When the purple line "Connection is established, going into measurement mode" appears, as seen in the figure, the program is running correctly and it will continue running until it is stopped (by simply closing the window, only do this when the green line "Waiting between measurements. Press CTRL+C to exit" is at the bottom of the page) or until the power supply is disconnected (try to avoid sudden disconnections of the power supply).

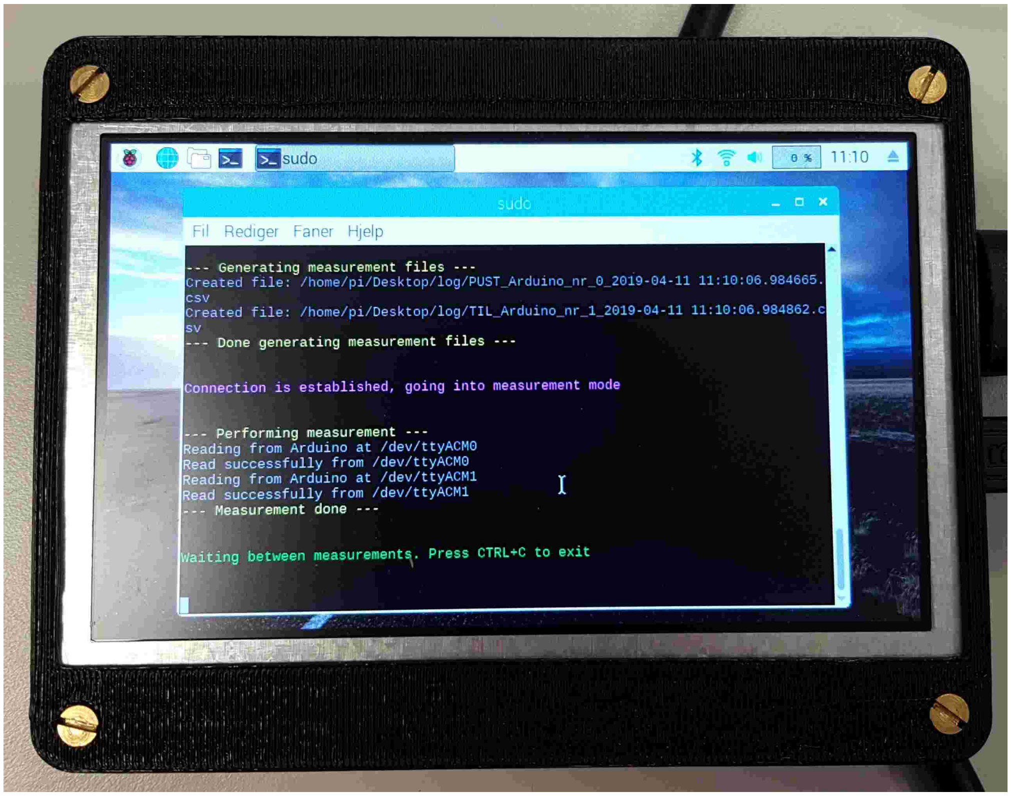

Figure A.9: Raspberry Pi logger program

In figure A.10 the .csv log files for PUST (BREATH) and TIL (SUPPLY) are shown. These are found in the folder "log" on desktop. The log files are created automatically when the "Logger" program is started, and they are updated every time the "Logger" program performs a new measurement.

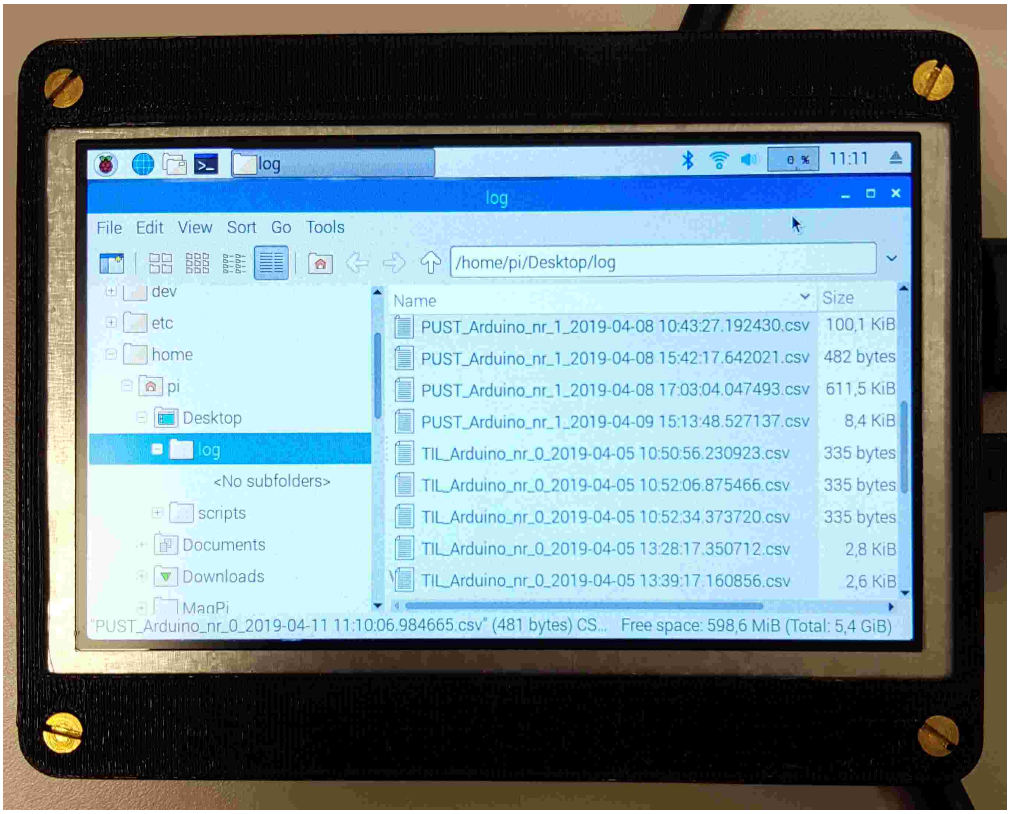

Figure A.10: Raspberry Pi .csv log files for PUST (BREATH) and TIL (SUPPLY)

In figure A.11, the internet browser "Chromium" is opened. Here you can log into your email account to send the log files you need to your own email account. It is also possible to transfer the log files via a USB memory stick in the Raspberry Pi, but due to the limited number of USB connection points on the Raspberry Pi, it is easier to use the email option when log files need to be transferred during running measurements.

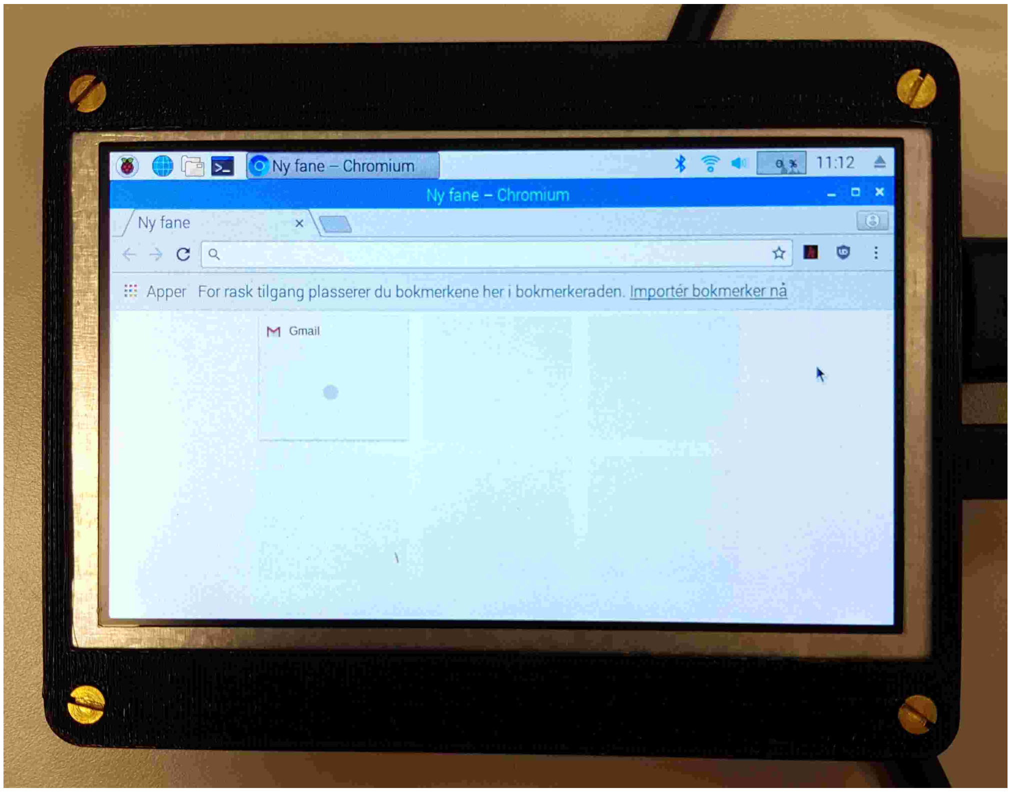

Figure A.11: Raspberry Pi Chromium browser

Appendix B

B.1 Risk assessment

The risk with using a stepladder was considered to be B2, which is in the green area. The green area represents an acceptable risk, and measures can be considered on the basis of other considerations.

NTNU HMS	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: Institutt for energi og prosessteknikk **Dato: 04.06.2019**

Linjeleder: Terese Løvås

Deltakere ved kartleggingen (m/ funksjon)**: Veileder Hans Martin Mathisen**
(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Kort beskrivelse av hovedaktivitet/hovedprosess: Masteroppgave Oda Kristine Gram, «Use of low cost pollutant sensors for developing healthy demand controlled ventilation strategies»

Er oppgaven rent teoretisk? (JA/NEI): *«JA» betyr at veileder innestår for at oppgaven ikke inneholder noen aktiviteter som krever risikovurdering. Dersom «JA»: Beskriv kort aktiviteteten i kartleggingskjemaet under. Risikovurdering trenger ikke å fylles ut.*

Signaturer: *Ansvarlig veileder:* [signature] Student: Oda Kristine Gram

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Bruke gardintrapp til å montere måleutstyr i klasserom	Oda Kristine Gram				

NTNU / HMS	Risikovurdering	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2603	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: Institutt for energi og prosessteknikk **Dato: 04.06.2019**

Linjeleder: Terese Løvås

Deltakere ved kartleggingen (m/ funksjon): Veileder Hans Martin Mathisen
(Ansv. Veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Risikovurderingen gjelder hovedaktivitet: Masteroppgave Oda Kristine Gram, «Use of low cost pollutant sensors for developing healthy demand controlled ventilation strategies»

Signaturer: *Ansvarlig veileder:* Hans Martin Mathisen *Student:* Oda Kristine Gram

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
1	Bruke gardintrapp til å montere måleutstyr i klasserom	Fall fra gardintrapp	2	B	A	A	A	B2	Bruke stødig gardintrapp, få ekstern person til å holde fast og støtte gardintrappen ved bruk.

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E **Svært Alvorlig**	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D **Alvorlig**	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C **Moderat**	Alvorlig personskade.	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B **Liten**	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1uke	Negativ påvirkning på troverdighet og respekt
A **Svært liten**	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1dag	Liten påvirkning på troverdighet og respekt

Risikoverdi = Sannsynlighet x Konsekvens
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS					
Svært alvorlig	E1	E2	E3	E4	E5
Alvorlig	D1	D2	D3	D4	D5
Moderat	C1	C2	C3	C4	C5
Liten	B1	B2	B3	B4	B5
Svært liten	A1	A2	A3	A4	A5
	Svært liten	Liten	Middels	Stor	Svært stor
	SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge	Beskrivelse
Rød	Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul	Vurderingsområde. Tiltak skal vurderes.
Grønn	Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.