Master's thesis

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

Ingeborg Hutcheson Fiskvik

Using Low-Cost Sensor Technology to Monitor and Evaluate Indoor Air Quality

Investigation of the correlation between measured and perceived air quality

Master's thesis in Energy and Environment
Supervisor: Hans Martin Mathisen
Co-supervisor: Maria Justo Alonso
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Preface

This thesis represents the work conducted for the master's thesis under the Department of Energy and Process Engineering of the Norwegian University of Science and Technology (NTNU). The thesis is written during the spring of 2023 under the supervision of Professor Hans Martin Mathisen and Senior Research Scientist Maria Justo Alonso, and counts 30 credits in the subject TEP4910 - Energy and Indoor Environment, Master's Thesis. The research is based on field measurements and experiments investigating the accuracy of low-cost sensors, the evaluation of indoor air quality, and the correlation between measured and perceived air quality.

I would like to extend my gratitude to fellow students for their insightful discussions and participation in experiments. I would also like to thank Senior Adviser Monca Berner, Siv Aase, and Hilde Irene Skjervold from Enova, who have helped with field measurements at Powerhouse Brattørkaia.

A special thank you to my supervisors Hans Martin Mathisen and Maria Justo Alonso, for guidance and knowledge throughout the semester. They have also contributed to solving problems met along the way and helped with adjustments of the scope when challenges occurred.

Ingeborg Hutcheson Fiskvik

Trondheim, June 2023

Abstract

Indoor air quality directly impacts the health, comfort, and performance of a building's occupants. Poor indoor air quality can result in health problems, reduced work efficiency, and lower occupant satisfaction. In contrast, a favorable indoor climate promotes well-being, prevents illnesses, and benefits vulnerable groups of the population. Given that people spend the majority of their time indoors, prioritizing indoor air quality becomes crucial for overall occupant health and satisfaction. However, current objective methods for regulating indoor air pollutants often overlook the subjective perception of occupants, emphasizing the need to prioritize both health and comfort in achieving good indoor air quality. In recent years, there has been significant progress in air pollution monitoring through low-cost sensors in conjunction with scientific instruments, leading to debates among scientists about their limitations and applications.

This master s thesis is limited to the health-relevant pollutants and parameters TVOC, formaldehyde, CO_2, particulate matter ($PM_{2.5}$), temperature, and relative humidity. Pollutants and parameters out of this will not be evaluated when analyzing indoor air quality.

Low-cost Arduino-based sensors are calibrated to investigate their accuracy compared to high-grade instruments. As there is no reference device measuring TVOC and formaldehyde, these low-cost sensors are not calibrated. The same low-cost sensors are used to measure the indoor air quality in two office buildings in Trondheim; the ZEB Laboratory and Powerhouse Brattørkaia. The field measurements from the two offices are also used to investigate how concrete and wood affect the temperature and humidity levels. Furthermore, an odor experiment with full-scale offices in a laboratory is conducted to investigate the correlation between varying percentages of recirculated air inducing different air quality concentrations and perceived air quality. This includes a subjective evaluation of air quality, thermal comfort, and odor.

The calibration of low-cost sensors revealed their susceptibility to drift over time, with lower accuracy than stated in the datasheets. Despite these limitations, the low-cost sensors demonstrated beneficial calibration equations for temperature, humidity, and CO_2, but low correlation values for particulate matter ($PM_{2.5}$). The results show that regular calibration is important to minimize drift and enhance sensor accuracy, especially when the sensors are older.

The field measurements from the ZEB Laboratory and Powerhouse Brattørkaia were compared to limit values and guidelines from NIPH and WHO. The findings indicated overall acceptable levels of CO_2, temperature, relative humidity, and formaldehyde. However, elevated levels of $PM_{2.5}$ and TVOC was detected. As the exact sources for the high levels are unknown, further research is required to limit these emissions and reduce the concentrations to meet the guidelines.

It is important to consider both measured and perceived air quality when evaluating indoor air quality, as they provide objective and subjective information. Measured indoor air quality helps identify pollutant sources and implement mitigation strategies, while perceived air quality ensures occupant comfort. The odor experiment showed a generally strong correlation between measured parameters and perceived air quality. However, no clear trend between odor acceptability and intensity, and measured concentrations was observed, emphasizing the subjective nature of odor.

Sammendrag

Innendørs luftkvalitet er noe som påvirker helsen, komforten og ytelsen vår direkte, hvor dårlig luftkvalitet kan føre til helseproblemer, redusert arbeidseffektivitet og tilfredshet. I motsetning, vil god luftkvalitet fremme trivsel, forebygge sykdommer, og er fordelaktig for sårbare grupper i samfunnet. Gitt at mennesker tilbringer mesteparten av tiden innendørs, er luftkvalitet avgjørende for deres generelle helse og trivsel. Det eksisterer objektive metoder for regulering av luftkvaliteten innendørs. Denne overser midlertidig ofte den subjektive oppfatningen til mennesket. For å oppnå et godt inneklima, er det viktig å prioritere begge deler. De siste årene har det vært en betydelig fremgang i måling av luftforurensning gjennom billige sensorer tilgjengelig kommersielt. Bruken av dette sammen med vitenskapelige instrumenter, har ført til debatter blant forskere om deres begrensninger og anvendelser.

Denne masteroppgaven er begrenset til de helserelevante forurensninger og parametrene TVOC, formaldehyde, CO_2, svevestøv ($PM_{2.5}$), temperatur og relativ fuktighet. Forurensninger og parametere utenom dette vil ikke bli evaluert ved analyse av inneluftkvalitet.

De billige Arduino-basere sensorene er kalibrert for å undersøke nøyaktigheten sammenlignet med sensorer av høyere prisklasse og nøyaktighet. Da det ikke er noen tilgjengelig referansesensor for TVOC og formaldehyd, er ikke disse kalibrert. De samme rimeligere sensorene brukes til å måle luftkvaliteten i to kontorbygg i Trondheim; ZEB-laboratoriet og kraftverket Brattørkaia. Feltmålingene fra de to kontorene brukes også til å undersøke hvordan betong og treverk påvirker temperatur- og fuktighetsnivåene. Videre er et lukteksperiment i fullskala kontorer i et laboratorium gjennomført for å undersøke sammenhengen mellom ulike prosentandeler resirkulert luft og opplevd luftkvalitet. Dette inkluderer en subjektiv vurdering av luftkvaliteten, termisk komfort og lukt.

Kalibreringen av lavprissensorene viste at de er påvirket av drift over tid med avtagende nøyaktighet. Til tross for begrensninger, demonstrerte lavprissensorene fordelaktige kalibreringsligninger for temperatur, fuktighet og CO_2, men lave korrelasjonsverdier for svevestøv ($PM_{2.5}$). Resultatene viser at regelmessig kalibrering er viktig for å minimere drift og forbedre nøyaktigheten, spesielt når sensorene er eldre.

Feltmålingene fra ZEB-laboratoriet og Powerhouse Brattørkaia ble sammenlignet med grenseverdier og retningslinjer fra Folkehelseinstituttet og WHO. Funnene indikerte generelle akseptable nivåer for CO_2, temperatur, relativ fuktighet og formaldehyd. Imidlertid ble forhøyede nivåer av $PM_{2.5}$ og TVOC påvist. Siden de eksakte kildene til de høye nivåene er ukjente, kreves det ytterligere undersøkelser for å kunne senke disse konsentrasjonene og oppfylle retningslinjene.

Det er viktig å ta hensyn til både målt og opplevd luftkvalitet ved vurdering av inneluftkvalitet, da de gir objektiv og subjektiv informasjon. Målt innendørs luftkvalitet bidrar til med å identifisere forurensningskilder og implementere strategier for å minimere disse, mens opplevd luftkvalitet sikrer beboernes komfort. Lukteksperimentet viste generelt en sterk sammenheng mellom målte parametere og opplevd luftkvalitet. Det ble imidlertid ikke observert noen klar trend mellom lukt og målte konsentrasjoner, noe som understreker luktens subjektive natur.

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List of Abbreviations

AHU	Air Handling Unit
AQI	Air Quality Index
BEMS	Building Energy Management System
CLT	Cross Laminated Timber
COPD	Chronic Obstructive Pulmonary Disease
EC	Electrochemical Sensor
EPA	United States Environmental Protection Agency
FA	Formaldehyde
Glulam	Glue Laminated Timber
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IR	Infrared
ISO	The International Organization of Standardization
LSP	Light-Scattering Particle
MOS	Metal Oxide Semiconductor
NaN	Not a Number
NDIR	Non-dispersive Infrared
NIPH	Norwegian Institute of Public health
PAS	Photo-acoustic Spectroscopy
PAQ	Perceived Air Quality
PD	Percentage Dissatisfied
PID	Photo-ionisation Detectors
PM	Particulate Matter
ppb	Parts per billion
ppm	Parts per million
RH	Relative Humidity
RTD	Resistance Temperature Detectors
SBS	Sick Building Syndrom
TVOC	Total Volatile Organic Compound
VOC	Volatile Organic Compound
VSAD	Variable Supply Air Diffuser
WPM	Words per Minute
ZEB	Zero Emission Building

Contents

Chapter 1

Introduction

Indoor air quality (IAQ) can be defined by the concentration of pollutants and thermal conditions that affects the health, comfort, and performance of a building's occupant [1]. Whilst poor IAQ can lead to long- and short-term health problems, decreased work efficiency, and lower occupant satisfaction, a favorable indoor climate can enhance occupant well-being, prevent illnesses, and particularly benefit vulnerable groups of the populations like children, the elderly, and individuals with respiratory diseases [2]. Considering that individuals spend approximately 90% of their time indoors, prioritizing IAQ is imperative for occupant health and satisfaction [3].

There are several methods to evaluate indoor air quality. Existing objective methods for regulating indoor air pollutants primarily focuses on the health effects of measured concentrations, and meeting guidelines and limit values. Thus, the subjective perception by the occupants is overlooked. Therefore, it is important to emphasize that good IAQ should not only ensure good health, but also comfort.[4]

Over the last decade, there has been a transformative shift and progressive evolution in approaches and strategies for air pollution monitoring, particularly through the utilization of low-cost sensors alongside high-grade scientific instruments. The field of sensor technology has witnessed remarkable advancements, leading to a wide range of affordable sensors being made available in the commercial market. These sensors have been extensively employed in various studies, sparking debates among scientists regarding their limitations and applications.[5]

1.1 Problem Description

The following presents the original problem description.

The Zero Emission office building at Gløshaugen is the first of its kind in Norway. It is a living lab, meaning that, besides being an ordinary office, it can also be used for experimental studies. The building was finalized in 2019, has three different ventilation strategies, and is constructed of wood. For almost one whole year, measurements have been taken with low-cost Arduino sensors for measuring the concentration of air pollutants, as well as the development of relative humidity and temperature. Measurements have also been taken at an office in Powerhouse Brattørkaia.

These measurements will be used to analyze the indoor air quality in the building and the possibilities for improvements by controlling the ventilation. Another aspect that will be explored is how massive wood may affect and potentially improve indoor humidity compared to an equivalent building not constructed with cross-laminated timber from the same year of construction. The impact different ventilation strategies have on the concentration of pollutants will also be investigated.

The following tasks are to be considered:

1. Literature study on indoor air quality and air pollutants. Relate to:
   (a) Wood and ordinary buildings, and
   (b) Sensor technology for measurements of indoor air quality
2. Collect data from ongoing measurements in ZEB lab and Powerhouse Brattørkaia
3. Analyze and compare collected data
4. Develop a theoretical control strategy for the twin room ventilation at ZEB lab with a physical demonstration at Varmeteknisk laboratory
5. Analyze results of control
6. Reporting

1.2 Scope and Limitations

Due to unforeseen circumstances, part of the scope and problem description was changed halfway through the thesis. The following parts of the problem description were removed:

- Developing a theoretical control strategy for the twin room ventilation at the ZEB Laboratory with a physical demonstration at Varmeteknisk laboratory.
- The possibilities for improvements in indoor air quality by controlling the ventilation.
- The impact different ventilation strategies have on the concentration of pollutants.

Instead, the problem description and scope was changed to:

1. Literature study on indoor air quality and air pollutants. Relate to:
   (a) Wood and ordinary buildings, and
   (b) Sensor technology for measurements of indoor air quality
2. Collect data from ongoing measurements in ZEB lab and Powerhouse Brattørkaia
3. Evaluation of how well low-cost Arduino-based sensors work for monitoring and analyzing indoor air quality
4. Investigation of correlation between different percentages of recirculated air inducing varying concentrations of air quality parameters, and the perceived air quality

The scope of this master´s thesis was narrowed down by limiting the health-relevant pollutants and parameters to volatile organic compounds (VOC), formaldehyde (FA), CO_2, particulate matter (PM), temperature, and relative humidity (RH). Pollutants and parameters outside this scope are not evaluated when analyzing indoor air quality.

1.3 Research Questions

Based on the problem description, the thesis will revolve around the following research questions:

- How well do low-cost Arduino sensors work for monitoring and analyzing indoor air quality?
- Assessment of indoor air quality in ZEB Laboratory and Powerhouse Brattørkaia. How are the temperature and relative humidity levels affected by the material selection?
- Based on the findings from the odor experiment, what is the correlation between measured air quality and perceived air quality?

1.4 Structure of Thesis

This master's thesis begins by introducing theory and literature relevant to the research conducted. Chapters 2 and 3 are based on the literature review conducted for the specialization project [6] as preparatory work for the master's thesis. These chapters have since been reviewed, and additional relevant theory has been implemented. Chapter 2 presents indoor air quality. This includes typical pollutants, sources, related health effects, and limit values and guidelines. Chapter 3 introduces low-cost sensor technology, followed by an overview of ventilation strategies and material choices in the ZEB Laboratory and Powerhouse Brattørkaia in chapter 4. Chapter 5 gives an overview of the methods for field measurements and experiments. The methodology for the calibration of sensors, as described in section , is obtained from the specialization project. The results are presented in chapter 6. The results and potential sources of errors are discussed in chapter 7. This chapter also answers the research questions. Lastly, chapter 8 gives a conclusion to the thesis, and further work is suggested in chapter 9.

Chapter 2

Indoor Air Quality

Indoor air quality can be defined by the concentration of pollutants and thermal conditions that affects the health, comfort, and performance of a building's occupant [1]. The latter may not appear as significant. However, as the biggest cost for an office is the wages of the employees, the indoor climate should facilitate an efficient work environment [7]. Whilst poor IAQ may result in irritation, long- and short-term health problems, decreased work efficiency, and lower occupant satisfaction, a good indoor climate can improve the well-being of occupants, prevent illness, and especially benefit vulnerable groups of the population, such as children, elderly and those with respiratory diseases [2]. Given that the average person spends about 90% of their time indoors, it is important to prioritize IAQ for overall indoor environmental quality and occupant health and satisfaction [3].

2.1 Indoor Air Pollutants; Sources and Health Effects

The indoor air quality and concentration level of pollutants can affect the quality of life and work effectiveness and may result in various health effects [1]. While some health effects may appear shortly after exposure, others may appear years after. There are several sources of pollution in an indoor environment, and by identifying these sources, it is possible to limit emissions and reduce the concentration.

Immediate symptoms may include irritation of the eyes, nose and throat, headaches, dizziness and fatigue. These effects are short-term and treatable, where the symptoms may cease if the person is removed from exposure. It is often difficult to determine if the symptoms result from exposure to indoor air pollution, as these symptoms are similar to a cold or other viral diseases. Thus, it is important to pay attention to the time and place symptoms occur. Additionally, if exposure is repeated or concentrations are of high levels, one may become sensitive to biological or chemical pollutants. Whether a person reacts to a pollutant depends on age, preexisting medical conditions, and individual sensitivity. For instance, people with diseases such as asthma may experience symptoms appearing, aggravated, or worsened after immediate exposure.[8]

Health effects that occur years after exposure or after long or repeated periods of exposure can be severely debilitating or fatal. These effects include respiratory diseases, heart disease, and cancer. However, there is considerable uncertainty around what concentrations or periods of exposure are necessary to develop specific health problems. Further research is thus needed to better understand which health effects are caused by exposure to the average pollutant concentrations found in homes and which occur from higher concentrations for short periods.[8]

Poor IAQ is typically the result of sources that release gases or particles in the air, whereas the single most common cause of pollutant buildup is inadequate ventilation [1]. Identifying the pollution sources makes it possible to limit emissions. There are several pollution sources, including combustion, tobacco products, building materials and furnishings, cleaning products, occupants, pets, and outdoor sources. While sources such as building materials release pollutants more or less continuously throughout the building's lifetime, other sources, such as tobacco, are related to human activity and can thus be regulated by the occupant.[8] Figure 2.1.1 illustrates some pollutants found in the indoor environment.

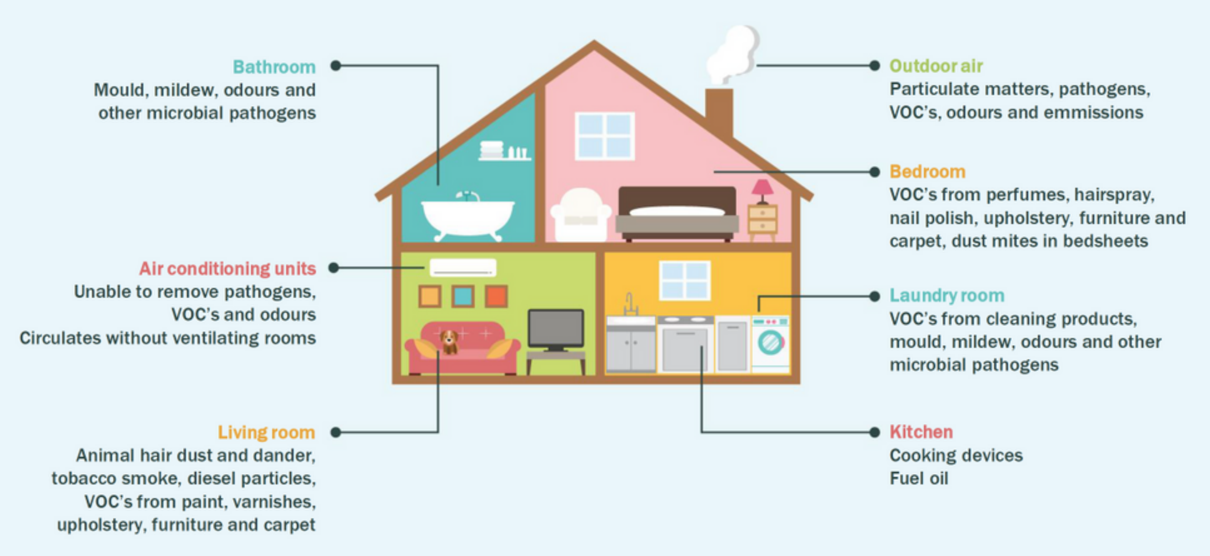


Figure 2.1.1: Typical sources of indoor pollutants [9].

There are several studies and extensive research on acceptable concentrations of pollutants and their health effect. The IAQ parameters considered for this thesis are based on the previous work of Gram [10], Jørgensen [11] and Marman [12], and consist of CO_2, particulate matter (PM), volatile organic compound (VOC), formaldehyde (FA), relative humidity (RH) and temperature. CO_2, RH, FA and fine particulate matter are all relevant IAQ parameters for avoiding building damage and health risks. Even though RH and temperature are not categorized as pollutants, they are included as they are important IAQ parameters. Additionally, high temperatures and humidity levels are factors that may increase the concentration of some pollutants [1]. The mentioned pollutants and IAQ parameters are presented further with a focus on typical sources, common health effects, limit values and measures to reduce the level of concentration.

2.1.1 CO_2

The main indoor source of CO_2 in indoor environments comes from humans as CO_2 is released through respiration [13]. Typical outdoor sources of CO_2 are traffic, electricity production, and industry, and can be brought inside through the ventilation system. Outdoor concentrations of CO_2 depend on the location, and in October 2022, the monthly mean globally averaged over marine surface sites was 416.22 ppm [14]. As outdoor concentrations of CO_2 typically are low, outdoor sources are not considered significant contributors to the indoor CO_2 load [15].

Multiple studies demonstrate a clear correlation between high concentrations of CO_2 and perceived poor indoor environment, reduced work effectiveness, and increased occurrence of health problems such as headaches and mucous membrane irritation [15]. A study by Shendall et al. of the correlation between the CO_2 levels in American classrooms and student attendance concluded that a 1000 ppm increase of the indoor CO_2 level was associated with a decrease in annual average attendance and student absence. Additionally, CO_2 levels above recommended values had a significant inhibitory effect on learning and work effectiveness.[16] Another study by Gupta investigated the link between indoor environment and workplace productivity in a mechanically ventilated office in southern England. Through physical monitoring, occupant surveys and performance tasks, the study revealed that task performance was affected by indoor environmental conditions such as CO_2. At CO_2 levels above 800 ppm, task scores were 15% lower than those conducted at CO_2 levels below 800 ppm.[17] The consequences of lower CO_2 concentrations are less known for cognitive functions, i.e. mental functions such as sensory perception, ability to concentrate, memory and logical abilities, problem-solving, and language. On the other side of the specter, concentrations of CO_2 up to 9000 mg/m^3 (5000 ppm) do not by itself have any unwanted effects on health, sensory perception, or work performance.[15]

The quality of the indoor air is often measured by the concentration of CO_2. According to the Norwegian Institute of Public Health (NIPH), the standard requirement for CO_2 content in the air is 1800 mg/m^3 (1000 ppm). If the concentration surpasses this value, it is a sign that the ventilation is inadequate in relation to the number of people in the room. If the CO_2 concentration in a room is high, there is also a probability of other pollutants in the room.[13] To maintain acceptable CO_2 concentrations, the correct amount of ventilation with relation to the person load in the room is important, in addition to shorter continuous use of the room or shorter breaks throughout the residence time [15].

2.1.2 Volatile Organic Compounds

Volatile organic compounds (VOCs) comprise a multitude of gaseous compounds present in the air we breathe, with several remaining unidentified. Indoor air has been observed to contain several distinct VOCs, making it difficult to distinguish between them. As a result, the total VOC (TVOC) is frequently employed as a measurement parameter [15].

The most important sources of volatile organic compounds are found indoors and can be categorized into stationary and variable sources, as illustrated in figure 2.1.2. Stationary sources include degassing from building materials, surface treatments, and furnishing. Stationary sources will release small stable quantities of VOC to the indoor air over time. However, the release of volatile substances will usually be significantly greater from new products than from older products, but is relatively stable over time. The release of volatile substances will also increase with higher temperatures and humidity. Whereas stationary sources always are present to some degree, variable sources are only present in certain time intervals and are often linked to human activity. Typical variable sources are smoking, cleaning supplies, paint residue, hobby supplies and cooking [15]. Typical sources of VOC in an office, is office equipment such as copiers and painters, correction fluids, and carbonless copy paper [18].

VOCs are recognized for having short- and long-term adverse health effects. These health effects vary greatly from those highly toxic to those with no known health effects. Additionally, the level and time of exposure will also have an impact on the extent and nature of the health effect.[18] For the commonly occurring levels of VOC in Norwegian indoor environments, there is no reliable evidence that these levels pose any health risks. However, irritation and sensory effects have been observed at high concentrations. These may occur when painting or using solvents indoors. The risk of cancer has also been evaluated as a result of VOC, where data from animal testing and occupational exposure has provided evidence of this. However, the risk of cancer varies greatly and is, in most cases, assumed to be very low.[15]

Figure 2.1.2: Common products that emit VOCs [19].

With the exception of certain substances, there are no certainties that the level of VOC in Norwegian indoor environments poses a health risk. Thus, no limit value of VOC concentration is set, with the exception of benzene, naphthalene, and tetrachloroethylene. Additionally, NIPH advises against using measures of VOC for indoor environments to determine health risks. Even though no limit value of concentration is set, one should avoid unnecessary exposure and be aware of typical sources. To reduce the concentration of VOC, NIPH recommends adequate ventilation. Additionally, it is advised against smoking inside. Other measures to reduce the concentration of VOC include good exhaust in the kitchen, good draft in the pipe, and clean-burning stoves.[15]

2.1.3 Formaldehyde

The most important sources of formaldehyde come from indoors [15]. Typical sources include resin, resins used to manufacture composite wood products, building materials, and insulation. FA is also a byproduct of combustion and can be found in emissions from un-vented, fuel-burning appliances, and cigarette smoke.[20]

Short-term inhalation of FA may cause irritation of the eyes, nose and throat in addition to lacrimation, sneezing, coughing, nausea, difficulty breathing, and unpleasant smell. There is also an increased risk of cancer between the nasal cavity and throat at significantly higher concentrations (occupational exposure) than what is found in normal indoor air. At these concentration levels, there is also an increased risk for leukemia. However, the risk of cancer is negligible in normal indoor environments.[15]

According to NIPH the recommended limit value of FA is 100 $\mu g/m^3$ (30-minute average). As most wood products contain and release a certain quantity of FA, which is highest for new materials, the concentration of FA will be elevated in new or newly renovated buildings. These values may exceed the recommended value of 100 $\mu g/m^3$. Thus, ensuring adequate ventilation in newly renovated buildings and rooms is important. This is an effective and simple measure to reduce the concentration of FA in the indoor air. The choice of material when renovating will also be a substantial factor for the level of FA. Generally, the use of formaldehyde resins in wood products such as chip-boards is heavily reduced in Norway, and the best products report contents at levels with natural wood. However, products imported from other countries may contain high levels of formaldehyde.[15]

2.1.4 Particulate Matter

Particulate matter is a mixture of solid particles and liquid droplets in the air. Some particles, such as dust, dirt, and smoke, are large or dark enough to be seen with the naked eye, whereas others are so small they can only be detected using a microscope. PM can be divided into the size of the particles; PM_{10} is inhalable particles with a diameter of 10 μm and smaller, and $PM_{2.5}$ is fine inhalable particles with diameters of 2.5 μm and smaller.[21]

The main sources of PM from indoors include smoking, cooking, lighting candles, oil lamps, and fireplaces. However, PM from outdoor sources may also contribute to high concentrations of PM in indoor environments. Outdoor sources include transportation with internal combustion engines, industry, and combustion with coal, oil, or wood. There are also several biological components in PM, such as pollen, mold, and bacterial residue.[15] Typical indoor and outdoor sources of $PM_{2.5}$ are illustrated in figure 2.1.3.

Knowledge of the health effects from PM in indoor air is relatively limited. However, the few studies on the matter indicate a possible correlation between PM and the development and deterioration of airway symptoms. Low-grade exposure to PM from outdoor air has however proven to reduce lung function for sensitive individuals, increase cough and bronchitis, asthma attacks, cardiovascular disease, increased incidents of hospitalization for respiratory and cardiovascular diseases, and premature death.[15] The particles that pose the greatest health risk, are fine particles smaller than 2.5 μm [21].

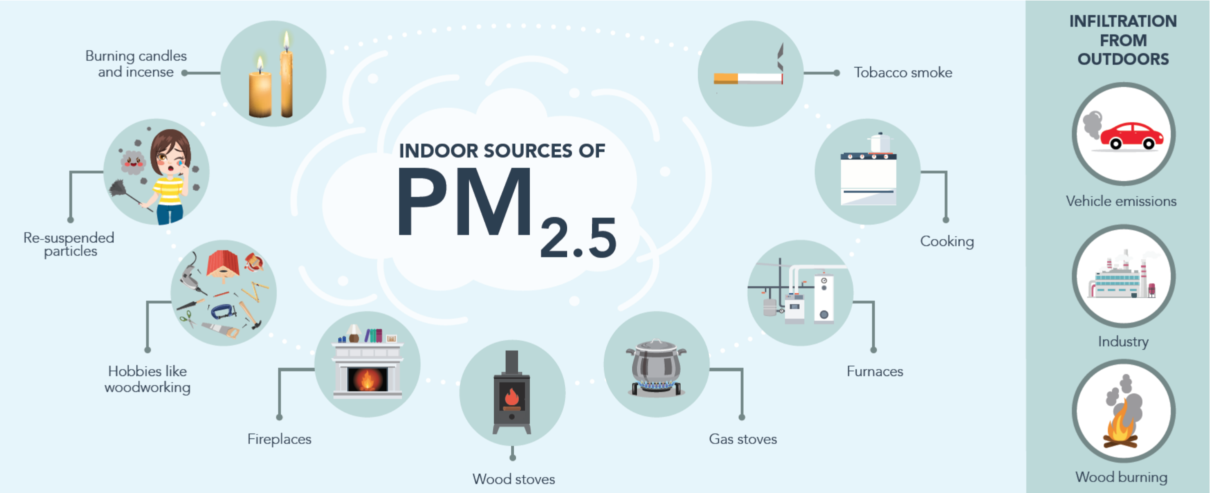


Figure 2.1.3: Indoor and outdoor sources of $PM_{2.5}$ [22].

The recommended limit values for PM_{10} and $PM_{2.5}$ are given in table 2.2.1. There are several measures one can implement to reduce the number of particles in indoor environments. These include avoiding smoking indoors, ensuring adequate draft in wood stoves and fireplaces, limiting the use of candles and incense, and avoiding using gas stoves without deduction. Regular cleaning will also help reduce the number of particles. For vacuums, HEPA filters should be utilized or a central vacuum. One should also be aware of the nearby environment in regards to i.e. traffic. It may also be beneficial to be strategic with the placement of the fresh air intake. Additional measures include HEPA filters in the ventilation system. NIPH does not recommend measuring the PM concentrations as a routine for IAQ matters and underlines that it is more important to eliminate possible sources and implement measures to eliminate or reduce emissions from these.[15]

2.1.5 Temperature

According to ASHRAE Standard 55 [23], thermal comfort is defined as *"that condition of mind that expresses satisfaction with the thermal environment"* and is the factor which the greatest number of subjects complain about after noise and acoustics [24]. Both high and low temperatures can cause health problems such as reduced concentration and performance, in addition to headaches [25].

Cold indoor temperatures are often associated with low outdoor temperatures. Occupants may experience cold air from drafts from windows or supply diffusers and cold surfaces, such as external walls with poor insulation.[25] In addition to inflaming the lungs and inhabiting circulation, cold air increases the risk of respiratory conditions, such as asthma attacks or symptoms, worsening of chronic obstructive pulmonary disease (COPD), and infection. Cold indoor temperatures have also been associated with increased blood pressure and poor mental health.[26]

High indoor temperatures increase our sensitivity to air pollutants, such as PM. This is because elevated temperatures contribute to drying out the tar fluid in the eyes. This can result in pain and inflammation in the eyes, especially for people who wear lenses.[25] Several studies have shown a correlation between high indoor temperatures and adverse health effects. During the heat wave in 2003 in France, the number of deaths at home was considerably higher compared with years without extreme heat conditions.[26] In addition to contributing to several health effects of varying severity, high indoor temperatures may also increase emissions from materials (paint, furniture, textiles). This may lead to inflammatory reactions in the mucous membranes of the respiratory tract, worsening asthma and allergic diseases.[25]

According to TEK17 the recommended values for operative temperature should be between 19-26°C for light work, 16-26°C for medium work, and 10-26°C for heavy work as summarized in table 2.1.1 to accommodate the function and use of the room. Furthermore, when heating is required, it is recommended that the temperature is kept below 22°C.[27] In some cases a higher indoor minimum temperature than 19°C may be necessary to accommodate vulnerable groups such as the elderly, children, and those with chronic illnesses [26]. Additionally, there should be no more than a 3-4°C temperature difference between feet and head as this causes unacceptable discomfort [27].

Table 2.1.1: Recommended values for operative temperature [27].

Activity group	**Light work**	**Medium work**	**Heavy work**
Temperature	19-26°C	16-26°C	10-26°C

There are several studies conducted on the correlation between temperature and work performance, where some studies indicate that the most comfortable temperature yields optimal work performance. According to Seppänen Et al. analysis of literature, there is a general decrement in work performance when temperatures surpass those that are considered thermally neutral. The analyzed studies included physiological modeling, the performance of various tasks in laboratory experiments, and measured productivity at work in real buildings. According to the research, work performance decreases by an average of 2% for every degree Celsius increase in temperature above 25°C. A summary of the studies on the decrement of performance and productivity is illustrated in figure 2.1.4. The figure shows that productivity is unaffected by temperatures between 21 and 25°C.[28]

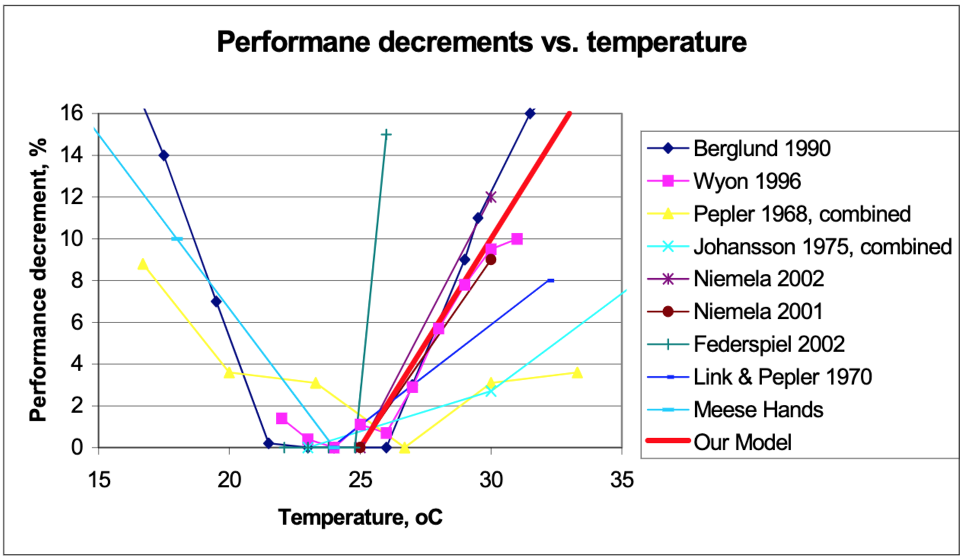


Figure 2.1.4: Summary of the studies on the decrement of performance and productivity [28].

2.1.6 Relative Humidity

Relative humidity (RH) can be defined as *”the ratio of the partial pressure of the water vapor in the air to the saturation pressure of water vapor at the same temperature and total pressure”* according to ASHRAE Standard 55 [23]. To reduce the survival time of viruses and thus the risk of disease, a RH between 40 and 60% is recommended [29]. This range of RH appears optimal for the health of the occupants and work performance and lowers the risk of infection [30].

Low indoor air humidity affects the mucous membrane of the nose and can cause what feels like dry and tired eyes, which may effect the work performance [30]. Thus, the indoor humidity is recommended to be no less than 30% to avoid damage to the mucous membrane. For RH below 10% nasal dryness is a common symptom. There is often a lower indoor humidity during winter, and symptoms are thus reported more frequently during this time of year.[29]

High indoor humidity (>70%) can contribute to smell, mold, and building damage. It is however normal that the RH surpasses 70% in the late summer when the outdoor air is hot and humid [31]. Several studies have researched the health effects of high indoor humidity and concluded that there is a correlation between RH and respiratory-related diseases.[15] Additionally, it has been proven to aggravate asthmatic symptoms [29]. Another factor to consider is the impact higher humidity has on FA, as levels of FA increases significantly with higher RH [31].

2.2 Limit Values and Guidelines

Table 2.2.1 presents a summary of limit values and guidelines for pollutants, in addition to the acceptable rate for temperature and relative humidity.

Table 2.2.1: Summary of limit values and guidelines for indoor air quality parameters.

Pollutant	**Guidelines**	**Comment**
CO_2	< 1000 ppm [13]	
Volatile organic compound	No upper limit. [15]	Avoid unnecessary exposure and be aware of typical sources.
Formaldehyde	$< 100\ \mu g/m^3$ [15]	30 min average
Particulate matter	No IAQ limit, outdoor limits apply: $PM_{2.5}$ (annual average) $< 5\ \mu g/m^3$ [32] $PM_{2.5}$ (24hr average) $< 15\ \mu g/m^3$ [32] PM_{10} (annual average) $< 15\ \mu g/m^3$ [32] PM_{10} (24hr average) $< 45\ \mu g/m^3$ [32]	For 24hr average, 3 to 4 exceeding days is possible.
Relative humidity	40-60% [15]	Winter: Below 45% to reduce condensation risk [15].
Temperature	19-26°C [27]	For light work.

2.3 Material Selection

In order to achieve a good indoor environment, various strategies are beneficial to mitigate potential sources of indoor and outdoor pollution. One such measure is the selection of materials.

The choice of materials does not only affect the indoor environment, but also the properties and aesthetic appeal of a space. The selection of materials and interior furnishings should be based on an evaluation of the installation and maintenance requirements, as well as the performance of the material over its service life. It is recommended to opt for materials that are low in toxicity, emits low levels of pollutants, are easy to clean and maintain, emit minimal or no odor, and are not susceptible to moisture damage that can foster mold growth.[33]

2.3.1 Cross Laminated Timber

Over the last decade, there has been an increase in the number of large structures of cross laminated timber (CLT) in Norway. In addition to having favorable mechanical properties, low climate gas emissions, and versatile design options, claims that the use of wood can positively impact the indoor environment contributes to the rise in timber constructions.[29]

As a material with hygroscopic properties, wood has the ability to balance the moisture level in the indoor air. This means it can inhibit both excessive moisture loads and dry indoor air.[29] Additionally, it can regulate the indoor temperature. Timber also has the ability to absorb NO_x and FA. However, this is dependent on accurate surface treatment of the wood.[34]

In addition to absorbing certain substances, wood emits various organic chemical substances, mostly VOC and FA. The types of wood that emit the most compounds are spruce and pine, while ash, beech, and oak emit the least. Pine emits the highest levels of volatile substances (terpenes and hexanal).[34]

Recent studies have suggested positive health effects from exposure to biogenic VOCs associated with natural elements such as timber, despite the generally negative perception of VOC. Several studies have also examined the potential health effects of short-term exposure to high levels (up to 18 mg/m^3) of VOCs emitted from pine wood, where no adverse health effects were found.[35] In rare cases, terpenes, a class of VOCs, may cause an allergic reaction. However, terpenes in the indoor environment is not known to cause any adverse health effects.[34] A substantive body of literature attests to positive health effects associated with the inhalation of plant-produced terpenes. These include a reduction in stress, cortisol levels, reduced heart rate, and increased activity of natural killer cells. Even though exposure to terpenes in itself may not constitute any health issues, it is important to note that terpenes are highly reactive and oxidation reactions involving terpenes may generate byproducts irritating to the respiratory system.[35]

Another cause of concern is the FA emissions from adhesives used in some engineered wood products, such as CLT, and from the wood itself. Regarding CLT, the majority (70-90%) of VOC emissions are terpenes.[35] FA emissions from glued building materials were more in focus in the past, and the FA levels found in modern chip-boards are generally low, below the limit levels for indoor environment [34].

2.3.2 Carpeted Flooring

The prevalence of carpeted flooring in public buildings appears to be increasing over the last few years, with a primary objective to minimize noise, particularly in open-plan offices [36]. However, research indicates that carpeted flooring can have a negative impact on perceived indoor air quality, and may be associated with adverse health effects among individuals, particularly those with asthma and allergies [37]. Carpet and rug producers argue that previous knowledge and risk assessments are outdated and that modern rugs no longer represent a problem, even for those with asthma and allergies [37]. However, studies find more dust and allergies in carpets compared to smooth floors [36].

Carpets acts as reservoirs for dust, pollen, mold spores, pesticides, and other materials which may originate indoors or are brought from outside. Through regular and effective cleaning, such particles can be removed. However, inadequate maintenance can result in the accumulation of significant amounts of dust and debris.[38] Compared to hard floors, carpeted floors require more comprehensive cleaning procedures with higher financial costs. Additionally, whilst hard floors form visible aggregates, carpets hide dirt and dust.[37] Carpets may also emit VOCs that can cause an odor and irritate the mucous membranes, especially for sensitive individuals [36]. Studies do however indicate that newer carpets have reduced levels of VOC emissions and a shorter emission duration [37].

Several studies have investigated the release of pollutants from carpets back into the indoor environment. Such pollutants may be processed and re-released, leading to potential subsequent exposure. The majority of these studies suggest that indoor environments with carpeted flooring are associated with increased levels of pollutants as a result of the resuspension of deposited material, compared to environments with smooth flooring. However, it is important to note that the presence of pollutants in carpeting and the resulting resuspension does not necessarily result in health consequences unless the pollutants are hazardous and the exposure levels are sufficient to cause harm.[37]

2.4 Evaluation of Indoor Air Quality

IAQ is defined as the *"quality of air inside non-industrial buildings, described in terms of odor, chemical and biological pollutants, is related to the ventilation rate, air distribution patterns, and pollution sources to ensure human health, olfactory comfort and perceived comfort"*[39]. There are several methods for evaluating IAQ, whereas many are based on objective measurements of indoor parameters. These methods include:

1. Concentrations measurements
2. Ventilation performance
3. Exposure assessment
4. Air quality index (AQI) from EPA (United States Environmental Protection Agency)

Whilst these objective methods aim to regulate indoor air pollutants considering their health effects, they do not consider the subjective perception of the occupants. Good IAQ should not only ensure human health, but also human comfort.[4]

Perceived air quality (PAQ) is quantitatively expressed by the percentage of dissatisfaction. However, no limit is set for acceptable PAQ. Acceptable IAQ is defined as *"air in an occupied space towards which a substantial majority of occupants express no dissatisfaction, and that is not likely to contain contaminants at concentrations leading to significant health risk"* by ASHRAE standard 62-1989R. This definition does, however, not mention quantitative requirements for PAQ. ASHRAE also developed the concept of "acceptable perceived IAQ", which is defined as *"air in an occupied space toward which a substantial majority of occupants express no dissatisfaction on the basis of odor and sensory irritation"*. Even though both concepts are described qualitatively without accurate quantitative requirements, several quantitative methods are available for the evaluation of indoor air quality. Some examples of these methods are the percentage of dissatisfaction and odor evaluation [4]

Sensory indicators can also be retrieved through subjective questionnaires and generally include two aspects: (1) express the feeling of the environment and (2) express the health influence of the environment [4]. There are many different designs of a PAQ assessment questionnaire. One strategy, primarily called “The Örebro Model”, has been used since the middle of the 1980s, where the MM Questionnaires constitute a basic part of this model. Since the first standardized questionnaire was released in 1989, different versions have been developed for specific environments such as schools, daycare centers, offices, and hospitals.[40] A different questionnaire was designed by Wargocki et al. in 1999 and was used to assess the PAQ in an office with two different pollution loads. The questionnaire consisted of six parts; acceptability of air quality, odor intensity, irritation, perception of environment, sick building syndrome (SBS) symptoms, and the effort to complete tasks, as illustrated in figure 2.4.1.[4]

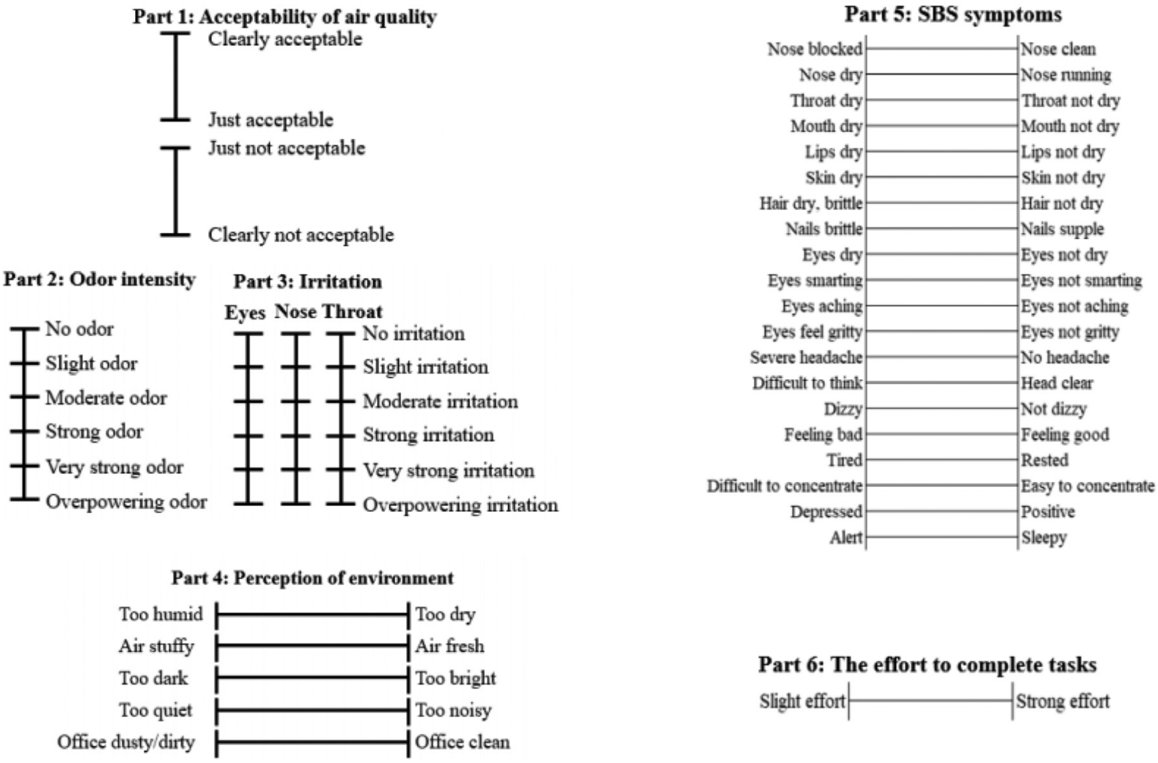


Figure 2.4.1: Questionnaires for subjective air quality assessments by Wargocki et al. [4]

2.4.1 Odor

An odor is defined as a pleasant or unpleasant smell caused by chemical compounds emitted to indoor air by the International Organization of Standardization (ISO). Indoor sources of odor include construction products, materials, furnishing, technical equipment, structural damage, animals, or the occupants themselves. For odor evaluations, it is important to consider the age of the building, furniture, and installations, the condition of the building, and the time of last changes made to the building. Additionally, it is important to consider the environmental conditions of the room and how these may affect the perception of odor. ISO 16000-30:2014 is a standard that describes the procedure for sensory panel analysis of odor in buildings.[41]

Determination of Acceptability

Acceptability is a measure of the quality of indoor air as it is an evaluation parameter for the expected percentage of dissatisfied occupants. To determine the acceptability of an odor, an untrained panel of at least 15 individuals is required. The accuracy of the assessment improves with the increase in the number of participants. To determine the predicted percentage dissatisfied (PD), the following yes-no question is used; *"Imagine you are exposed to this odor in your everyday life. Would you consider this odor acceptable?"*. The PD-value can be calculated using equation 2.4.1, where n_d is the number of dissatisfied people (number of people who answered no) and n is the total number of participants.[41]

$$PD = \frac{n_d}{n} \cdot 100\% \tag{2.4.1}$$

Acceptability can also be evaluated by the degree of dissatisfaction using a continuous scale ranging from clearly acceptable (1) to clearly unacceptable (-1), as depicted in figure 2.4.2. When rating the acceptability, the following question should be asked: *"Imagine you are exposed to this odor in your everyday life. How would you rate this odor on the following scale?"*.[41]

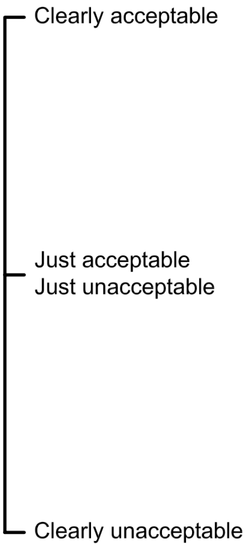


Figure 2.4.2: Odor acceptability scale [41].

Determination of Intensity

The odor intensity can be evaluated using a six-category scale, as depicted in figure 2.4.3. The category scale consists of values ranging from 0, indicating no odor, to 6, indicating extremely strong odor. Only whole numbers should be given as answers. By the use of an untrained panel, at least 15 people are required, but 20 to 25 is recommended.[41]

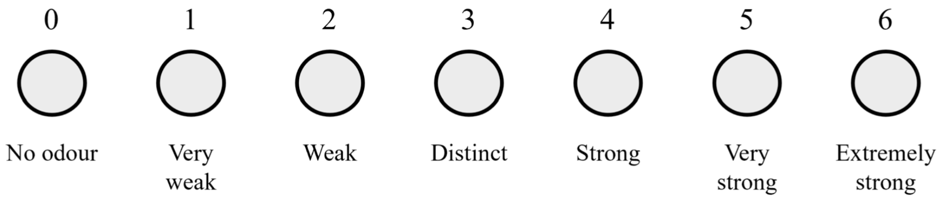


Figure 2.4.3: Odor intensity scale. Edited from original.[41]

Determination of the Hedonic Tone

The hedonic tone indicates whether an odor is perceived as pleasant or unpleasant and is often used together with the evaluation of perceived odor intensity. The perception of odors is influenced by several factors, such as the specific odorant or mixture of odorants, the concentration of the odorant, which determines the intensity of the smell, and the individual panel member's personal experience and background with different odors. The hedonic tone is determined by a 9-level scale as depicted in figure 2.4.4, ranging from extremely unpleasant (-4) to extremely pleasant (4), where 0 is neutral.[41]

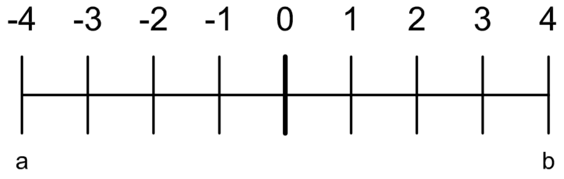


Figure 2.4.4: Scale for determining hedonic tone. a is extremely unpleasant, and b is extremely pleasant.[41]

Chapter 3

Low-Cost Sensor Technology

Over the last decade, there has been a paradigm shift and progressive evolution of the approaches and strategies for air pollution monitoring through low-cost sensors used exclusively or simultaneously with high-grade scientific instruments. As the sensor technology field has made remarkable strides, a wide selection of low-cost sensors has become available on the commercial market. These sensors have also been utilized in several studies, thus opening a debate among scientists regarding limitations and applications.[5]

This chapter presents some of the different technologies used in sensors for measuring CO_2, VOC, formaldehyde, particulate matter, temperature, and relative humidity. Additionally, their strength and weaknesses are described.

3.1 Sensor Definitions

To assess the performance of sensors, the terms sensitivity, selectivity, stability, accuracy, and precision are often used.

Sensitivity refers to the minimum input of a physical parameter that will create a detectable output change [42].

Selectivity can be defined as the capability of a sensor to measure a concentration of a substance in a complex mixture without interference from other components in the mixture [43].

Stability pertains to how much the characteristics of a sensor remain consistent over time. Any alterations in stability, also referred to as drift, can be attributed to factors such as aging of components, reduced sensitivity of components, and changes in the signal-to-noise ratio.[44]

Accuracy is a measure of closeness, whilst **precision** is a measure of how well each air reading repeats. These terms are illustrated in figure 3.1.1. The accuracy and precision of a sensor can vary across manufacturers as well as within a product line made by the same company. The accuracy and precision of a sensor can also be affected by placement, time in use, method for processing data, temperature, relative humidity, and the presence of multiple contaminants in the air.[45]

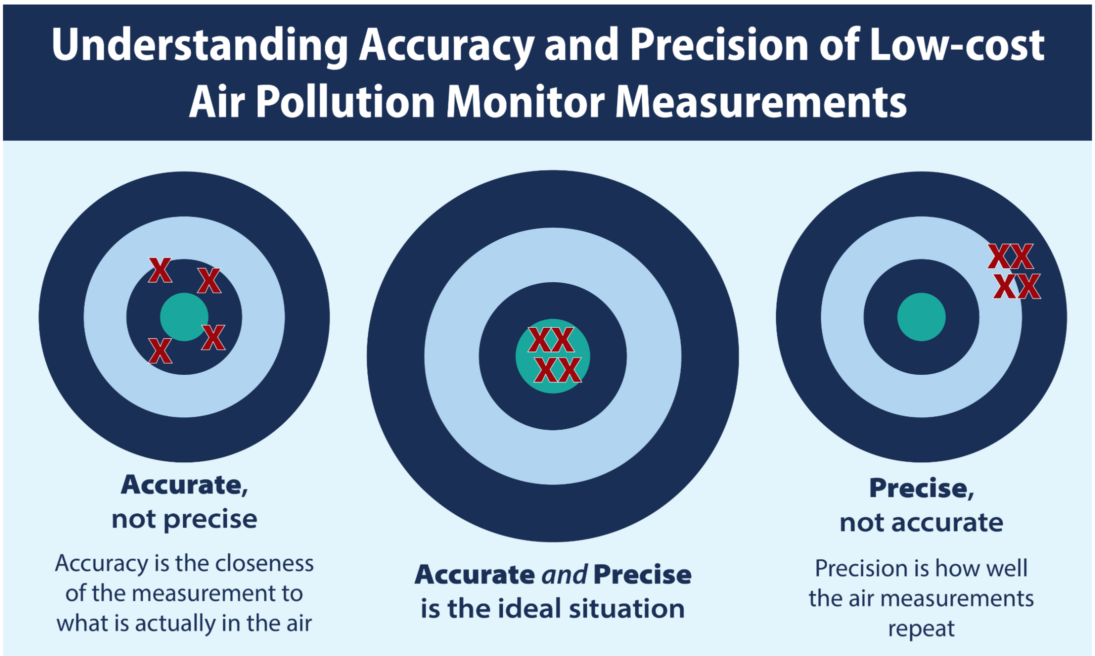


Figure 3.1.1: Accuracy and precision of low-cost sensors [45]

3.2 CO_2

Nondispersive Infrared Sensors (NDIR)

The most common low-cost sensing technology for measuring CO_2 concentrations are non-dispersive infrared (NDIR) sensors. The sensors take basis in CO_2 molecules absorbing an infrared (IR) light as it passes through the length of a tube [46]. As the CO_2 absorption band is very close to the IR radiation, the amount of absorbed radiation is proportional to the total CO_2 concentration in the tube [47]. Thus, the CO_2 concentration can be estimated by measuring the change in IR radiation that flows through the tube in the sensor [46].

NDIR sensors are simple and small units, requiring little power and maintenance [48]. CO_2 LCS report accuracies of typically ± 30 ppm to ± 50 ppm, which can be considered as an acceptable error for most indoor applications [49]. Disadvantages of NDIR sensors include cross-sensitivity to several gases, such as water vapor, and high detection limits, meaning they cannot measure small concentrations of pollutants [48]. Interference caused by water vapor and gas matrix has been partially solved by using optical filters and interference correction factors [50]. NDIR sensors are also susceptible to drift and high costs. However, due to their long lifespan, NDIR sensors are a good choice for long-term deployment in dry areas for outdoor air quality measurements.[48] A concern worth mentioning is the thermal stability and response time. To achieve the desired accuracy, the optical system must maintain thermal stability. If the light source in the sensor generates heat over 10 mW, heat is generated. Thermal stability may take 15 - 20 minutes to achieve.[49]

Photoacoustic Spectroscopy Sensors (PAS)

Photoacoustic Spectroscopy (PAS) sensors is another way of monitoring CO_2 and other trace gases. Conventional PAS sensors consist of a laser source, an acoustic cavity and a microphone, and are based on the concept of converting light to sound. [51] A PAS sensor works by a laser emitting wavelengths of the absorption of the target gas. This is used to generate acoustic signals detected by the acoustic sensors, which then can be used to determine the gas concentration.[52]

The PAS sensor has several advantages, including high selectivity, high detection sensitivity, continuous reliability, fast response time, and real-time detection [53, 54]. The PAS sensor is however influenced by environmental factors such as temperature, humidity, and pressure, affecting the detection accuracy. It is therefore necessary to carry out system accuracy correction research before any field test in order to improve the detection accuracy and stability of the system.[54]

3.3 Volatile Organic Compound and Formaldehyde

While CO_2 is a direct indication of the number of occupants in an environment, VOC is emitted from several sources unrelated to occupancy. There are several sensing technologies for monitoring VOC and FA, where the most common ones include Metal Oxide Semiconductors (MOS), Electrochemical Sensors (EC), and Photo-ionisation Detectors (PID).[48] An air sample may consist of 100 - 200 different types of VOCs with diverse chemical structures. Thus, LCSs determines VOC as an operational metric referred to as TVOC that covers a broad range of individual substances. A common downside of available VOC LCS is the varying response factor, which may lead to significant inaccuracies. This is particularly prevalent in the case of complex mixtures comprised of 20 or more constituents, where critical components may be entirely missed or false positives may obstruct the assessment of IAQ.[49]

Metal Oxide Semiconductor Sensors (MOS)

MOS-based sensors are considered one of the two most promising candidates for real-time monitoring of VOC concentrations [5], and consist of a heating element and a semiconducting metal oxide sensing element [48]. When the heater warms the surface of the sensing element (up to 300 - 500°C), a chemical reaction occurs on the surface, enabling it to detect gases. As the reaction causes a change in the electrical conductivity of the sensing element, the detected gas level can be measured by using an external circuit. The main advantage of MOS sensors is their high sensitivity, long lifespan, and resilience against extreme weather conditions, making them suitable for long-term deployment.[48] Studies conducted both in laboratories and on-field revealed that the sensor response was affected by chemical interference and the sensor sensitivity was affected by environmental parameters, such as temperature and humidity, showing higher sensor errors for elevated levels of RH [48, 49].

Electrochemical Sensors (EC)

The other promising candidate for monitoring VOC concentrations is EC. When gas enters the sensor, an electrochemical reaction occurs inside, producing an electric current [55]. Compared to the MOS sensor, the EC sensor is resistant to environmental changes (temperature and humidity) and has a low power draw due to the lack of need for an electric heater [56]. Additionally, they have high sensitivity and good specificity [48]. Their operating range is however narrower than in MOS sensors [56]. Additionally, low humidity and high temperatures can cause the electrolyte of the sensors to dry out, thus breaking the sensor [48].

Photo-ionisation Detectors (PID)

PID sensors can detect different VOCs and concentrations from part per million (ppm) to part per billion (ppb) [57], and operate by illuminating compounds using high-energy UV photons. As the compounds absorb the UV photons, they become ionized, resulting in an electric current. This current can be captured by a detector inside the sensor. Higher concentrations of the measured component mean more ions produced and thus a greater current.[48] The performance of PID sensors in regard to sensitivity, level of detection and ability to detect different compounds depends strictly on the design features. Whilst the most commonly used lamp emits energy at 10.6 eV, the 11.7 eV lamp can detect a broader range of compounds. The downside of the 11.7 eV lamp is its short lifetime of 500 hours of continuous operation, requiring frequent lamp changes resulting in higher maintenance time and cost.[49] The main disadvantage of PID sensors is their high sensitivity to high humidity levels, making them poorly suited for dense long-term deployment. They are however well suited for the analysis of small particles and gases in controlled small-scale experiments as they are able to analyze samples of low concentrations in ambient temperature and pressure.[48]

3.4 Particulate Matter

Commercial low-cost sensors for detecting PM, often referred to as Light-Scattering Particle (LSP) Sensors, are based on a light-scattering operating principle [5]. LSP sensors are composed of an air inlet, a light sensor, and a light source (IR or laser). When air enters the sensor, the light source is focused on a sensing point. This light is scattered when particles pass through, which generates a measurable signal. By using a lens, the scattered light is focused onto a photodiode. It is the configuration of the lens that determines the resolution of which particle size can be detected. The sensor produces a signal that can be measured to estimate the number of particles in the air, which is proportional to the scattered light.[48]

Several studies have focused on the performance of LSP sensors, highlighting several shortcomings. These include a lower limit of detection, susceptibility to temperature and humidity, variable response depending on particle size, and lack of sensitivity to particles with a diameter lower than 0.3 μm.[5] Low-cost PM sensors also have varying accuracy. The inaccuracies depend on properties like particle size distribution, shape, and density of the particles. Thus proper calibration is important to achieve accurate measurements.[58] The advantages of LSP sensors are their small size and low cost compared to other PM sensors [48].

3.5 Temperature

There are several sensing technologies for monitoring temperature, where the three main sensors are thermocouples, thermistors, and Resistance Temperature Detectors (RTDs) [59]. Thermocouples are one of the simplest sensors from a practical view. A thermocouple consists of two metal wires generating voltage related to the temperature difference between them.[60] The RTD bases the temperature measurements on the resistance changes in a metal resistor inside. The thermistors are similar to the RTD sensor, but instead of a metal resistor, it contains a ceramic or polymer resistor.[59] As the RTD sensor is expensive, only the thermocouples and thermistors are considered low-cost.

Where all three sensors respond quickly to temperature changes, thermocouples are the fastest and will respond nearly three times faster than a RTD sensor. RTD sensors are however more accurate than thermocouples. Comparing RTD sensors with thermistors, RTD sensors are more suited for temperature compensations and thermistors for precision measurements. Additionally, whereas RTD readings stay stable for a longer period, thermocouples tend to drift. Some of the advantages and disadvantages of each sensor are summarised in table 3.5.1.[59]

Table 3.5.1: Summary of advantages and disadvantages for the temperature sensors thermocouples, thermistors, and RTD.

Sensor type	Advantages	Disadvantages
Thermocouple	Temperature range Self-powered No self-heating	Cold-junction compensation Accuracy Stability
Thermistor	Sensitivity Accuracy Cost Surface mount	Non-linearity Self heating Narrow ranges
RTD	Accuracy Stability Linearity	Lead resistance error Response time Vibration resistance Size

3.6 Relative Humidity

As there are different methods to calculate humidity, sensors for monitoring humidity can be divided into two groups; relative humidity sensors and absolute humidity sensors. For this thesis, only RH will be used as a parameter for IAQ and thus explained further. The two most common low-cost sensors for monitoring RH are the capacitive and resistive humidity sensors.[61]

Capacitive Sensors

Capacitive sensors use two electrodes to monitor the capacitance of a thin metal strip placed between the electrodes. Changes in the capacitance of the metal is directly proportional to the change in humidity.[61] The capacitive sensors are known to provide stable results over prolonged usage and can detect a wide range of RH [62], in addition to high sensitivity [63]. They do however have a slow response time and are temperature dependent [63]. Capacitive humidity sensors are used in a wide range of applications, often where factors like cost, rigidity, and size is of concern. Some of these applications are HVAC systems and refrigerators.[62]

Resistive Sensors

The resistive humidity sensors use a small polymer that changes with the humidity. This affects the system's ability to store charge directly.[61] The resistive sensors are used in several applications, including industrial, domestic, and commercial [62]. Resistive sensors offer the advantage of high sensitivity, small size, low cost, and good linearity [63]. They are however sensitive to chemical vapors, and other contaminants [62], in addition to slow response and drift [63].

3.7 Strength and Weaknesses

On a general basis, low-cost sensors are cheaper, have user-friendly interfaces, are low maintenance, small in size, and allow for easy handling, allowing for temporary and mobile installations. Low-cost sensors are however affected by low accuracy, reproducibility, and high inter-sensor variability. Additionally, they are susceptible to environmental parameters, such as humidity, which may lead to uncertainties concerning the reliability of the collected data. Due to the wide range of accuracy and precision, several studies recommend calibrations using scientific-grade instruments as reference to extend their effectiveness.[5]

Table 3.7.1 summarizes the strength and weaknesses of some of the low-cost sensors. As these characteristics are only based on a limited fraction of all studies conducted on the topic, the characteristics presented in table 3.7.1 include, but are not limited to, the individual sensing technology.

Table 3.7.1: Summary of strength and weaknesses of low-cost sensors [48]

Type	**Cost**	**Size**	**Lifespan**	**Sensitivity**	**Drift**	**Accuracy**	**Calibration**	**Response time**
NDIR	High	Small	Long	High	(0.4± 0.4)%	High	Frequent	≈ 20 s
MOS	Low	Small	Long	High	Yes	Low	Frequent	Fast
EC	Low	Small	Short	High	2-15% per year	Good	Reasonable	≈ 120 s
PID	High	Small	Long	High	20% in weeks	High	Frequent	Fast ≈ 1 s
PAS	Low	-	-	High	-	High	-	Fast
LSP	Ultra-low	Small	Good	Poor	None	Low	Frequent	≈ 30 s

3.8 Sensor Placement

When obtaining relevant information about the air quality, a major factor is the placement of the sensors and an understanding of the data to precisely identify the pollutant sources and propose effective solutions [64]. The contamination level within an occupied space will vary, and thus placement of the sensor is important to evaluate. Mysen, Schild and Cablé [65] identifies the following conditions as influencing factors to the placement of sensors:

- Ventilation strategy
- Air diffuser location
- Location and characteristics of contaminant source
- Temperature conditions
- Room geometry
- Sensor type

In addition to these influencing factors, there are guidelines and recommendations for the placement of different sensors. In general, the placement of the sensor should be representative for the air quality and temperature of the room. Thus placing a sensor close to an open door may be disadvantageous. In some cases, placing a sensor near the door is practical as the power supply for the sensor can be routed with the power for the light switches. In these cases, the sensor should be placed a reasonable distance from light switches with dimmer as these emit heat.[66]

The height at which sensors should be placed depends on the ventilation principle [65]. In cases with displacement ventilation, the sensors should be placed at normal breathing height. For a classroom, this would be approximately 1 m, as this is the average height for a seated person. When there is little movement in the room that circulates the air, this height provides adequate air quality in the breathing zone with minimal airflow rates.[66] The height of the sensor is also important for mixing ventilation, even though there is a constant pollution concentration in the room. In theory, the sensor could be placed anywhere in the room or at the exhaust, but not too close to contaminant sources or supply diffusers. However, in practise, there will be concentration and temperature gradients. For this reason, the sensor should be placed centrally in the occupied zone.[65] If the sensor is placed at a higher point in the room, the temperature set-point should be adjusted up [66].

Gas sensors measuring i.e CO_2 and VOCs should not be placed close to trash cans or similar high-emitting objects [66]. A study by Mahyuddin and Awbi looked at four situations, all of which were evaluated at three different heights (0.2, 1.2 and 1.8). They found the highest concentration of CO_2 at 1.8 m rather than breathing height. Thus, to provide a representative and accurate picture of the IAQ, they found that more than one sensor may be necessary at low airflow rates. Another study found the vertical position of less significance as the variations were small and that the placing of sensors should not be of importance in rooms with well-mixed air. This study did however conclude that large variations of CO_2 concentrations may be due to the presence of stagnant air and sensor placement is thus of importance.[31]

When it comes to temperature sensors, these should be placed on inner walls, and they should not be placed directly in sunlight, nor in places where they are affected by heat sources.[66]

Chapter 4

Buildings of the Future

In 2020 buildings accounted for almost 40% of the global energy consumption and carbon emissions [67]. This is further compounded by the pressure on the earth´s resources and the current state of the climate. In light of this, it has become increasingly important to develop buildings that comply with stricter energy regulations and adapt to the changing climate challenges, as well as the advancement and testing of innovative technology that addresses these concerns. The development of the ZEB Laboratory and Powerhouse Brattørkaia, two offices in Trondheim finalized in 2019, are such examples and aim to address these needs and promote more sustainable and energy-efficient buildings.

These are also two buildings made from different materials, and it is thus interesting to examine if the material choice has an effect on the air quality and to what extent. This chapter presents the building anatomy for the two buildings and ventilation strategies to better understand how these buildings operate. The theoretical framework presented in this chapter is based on a combination of reports and on-site visits to the buildings.

4.1 ZEB Laboratory

The ZEB Laboratory, depicted in figure 4.1.1, is a 2000 m^2 living office laboratory located in Trondheim, Norway, at NTNU Gløshaugen campus [68]. A zero-emission building (ZEB) produces enough renewable energy to compensate for the building´s greenhouse gas emissions over its life span [69]. The ZEB Laboratory has a ZEB-COM ambition [68], meaning that it aims to produce enough renewable energy to compensate for greenhouse gas emissions from construction, operation, and production of building materials. This ambition does not consider demolition or recycling of the building.[69]

Figure 4.1.1: The ZEB Laboratory: Southern and Western facade (Photo: Matthias C. Herzog).

Building Anatomy

The loadbearing structure of the ZEB Laboratory is made from wood. Glue Laminated Timber (glulam) is used for the columns, and cross-laminated timber (CLT) elements are used for the floors and elevator shafts. The outer walls are insulated with glass wool and framed with wood.[70] A new innovative compact roof has been developed with wooden support and a smart vapor barrier [71]. A risk with unventilated wooden roofs is moisture. However, in the ZEB Laboratory, the roof is constructed in a way so that the moisture risk can be considered low.[72] PV-cells are located on the roof and south facade.[70] The U-values [W/m^{2}K] of the building components are: 0.15 (wall), 0.09 (roof), 0.10 (floor on ground) and 0.77 (window) [72].

Indoors, linoleum is used for flooring, and drywall and paint for the inner walls in addition to some glass walls in meeting rooms. Some areas also have exposed massive wood. The floor plans for the ZEB Laboratory can be found in section 5.3. The floor plans also illustrate some of the furniture in the building to give an idea of the internal loads of occupants and technical equipment.

Ventilation Strategies, Cooling and Heating

The ZEB Laboratory is four stories high and enables the exploration of different ventilation strategies in combination with user satisfaction and energy use. The different ventilation strategies implemented in the building are natural ventilation, mechanical ventilation, and a combination of both (hybrid ventilation).[70] Each floor is also equipped with its own solution for supplying air, as illustrated in figure 4.1.2. On the first floor, air is supplied through vents in the raised/lined floor. On the second floor, air is supplied through permeable plates in the ceiling. On the third floor the air is supplied through slits in the ceiling and on the fourth floor it is supplied through traditional displacement ventilation.[72]

The central mechanical ventilation system relies on the principle of displacement ventilation, even though different distribution systems are designed for each floor. In the exhaust, a heat recovery unit with an annual average efficiency of 80% is installed. No mechanical cooling system is installed.[70] To fulfill the requirements for the thermal indoor environment, the building is supplemented with natural ventilation during warmer periods and at night for night cooling of the building [73]. Additionally, the windows are equipped with blinds, both automatic and manual throughout the building, to protect from the sun.

While some windows in the building open manually, others are equipped with an automatic opening system. The position and design of the windows are to assure cross ventilation when opened. The main staircase passing through all four floors is designed to work as an extract for both mechanical and natural ventilation.[70]

Throughout the building, there are several radiators, in addition to waterborne floor heating.

Twin Rooms Test Facility

The twin rooms are located on the second floor of the ZEB Laboratory and are two identical office spaces equipped with independent HVAC systems. With dedicated air handling units (AHU) processing the air before entering the room, there are possibilities for both heating and cooling of the internal environment. This occurs via heating/cooling coils connected to the central hydraulic system and additional heating batteries. The twin rooms are also equipped with sensors monitoring all parameters influencing the comfort of the occupants and a control system for the indoor environment, energy supply, ventilation strategies, cooling, space heating, lighting, and window shading.[70]

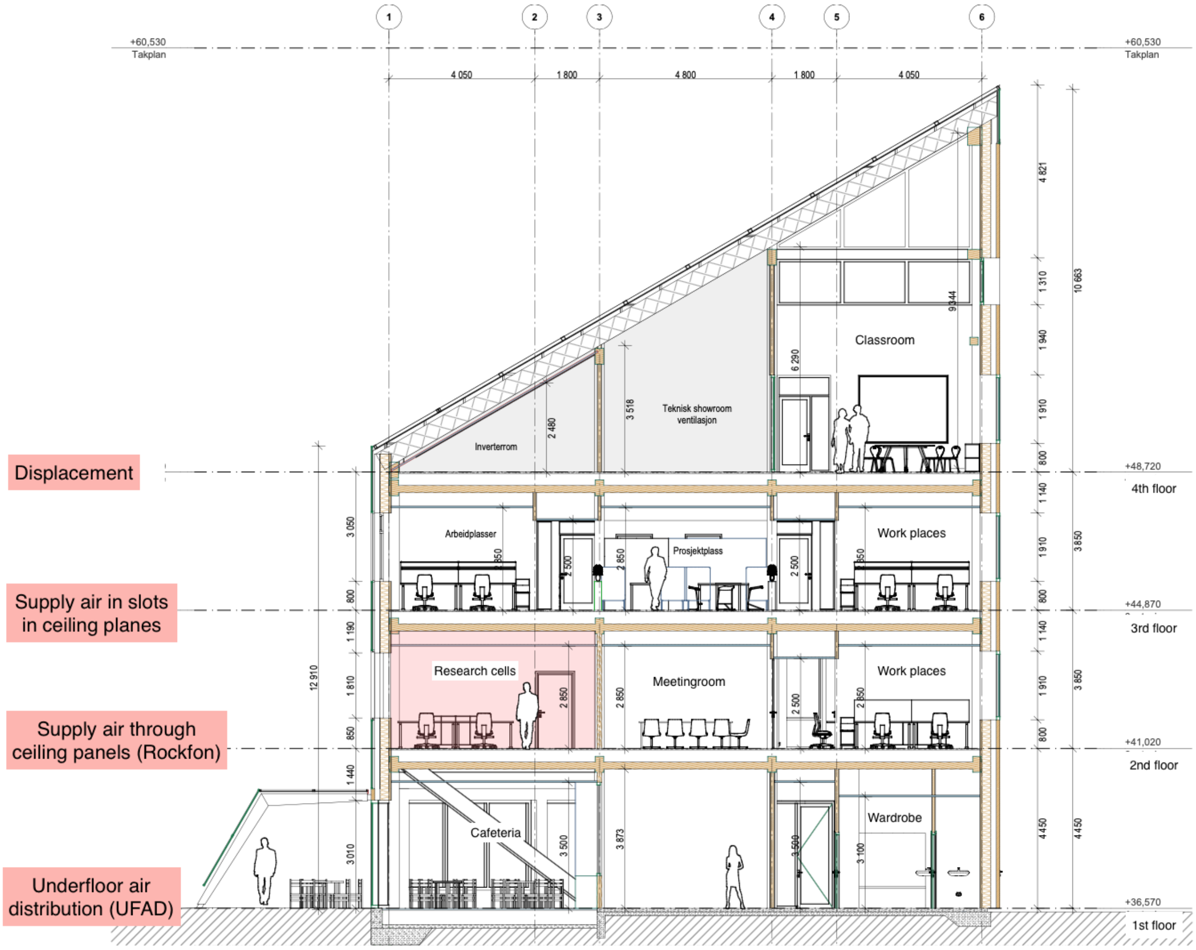


Figure 4.1.2: Cross section of the ZEB Laboratory with different air distribution systems [72]. The figure has been changed from the original.

Control Systems

As the ZEB Laboratory is both an office and laboratory, an advanced control system is required in addition to an accurate acquisition and storage of all data, valuable for both control and research analysis [71]. A Building Energy Management System (BEMS) serves as the foundation for the control platform. The building is mainly operated by NTNU Campus Service. However, the building, or parts of the building, can be overtaken and operated by a research simulation server.[70] In this mode, researchers can use their own algorithms to test new control strategies or to provide specific conditions needed for research [71].

The ZEB Laboratory is designed with an indoor positioning system delivered by Siemens that detects the position of the occupants of the building. The presence of the occupants is acquired real time through wireless communication between the smartphones of the occupants and wireless sensors mounted in the ceiling. Using triangulation algorithms, the user position is established and the data are sent to a cloud solution. By using a mobile app, this data can be used to i.e. locate colleagues, equipment, and be guided to meeting rooms or exits. The visibility of each portable device can be chosen as either visible or not, meaning possible or impossible to locate.[70]

4.2 Powerhouse Brattørkaia

Powerhouse Brattørkaia is one of the world's northernmost and largest plus energy office buildings located on the coast of Trondheim, Norway. A plus energy building generates more energy in its operational phase than it consumes through the production of building materials, construction, operation and disposal of the building.[74] Some of the measures implemented in Powerhouse Brattørkaia are the production of renewable energy through solar cells on roof and facade, use of sea water for heating and cooling of the building, and efficient lighting which reduces the energy consumption for artificial lighting by 50% compared to an equivalent commercial building. The yearly surplus energy is stored in batteries and supplies neighboring buildings and infrastructure, such as charging stations for electric buses, creating a microgrid as illustrated in figure 4.2.1.[75]

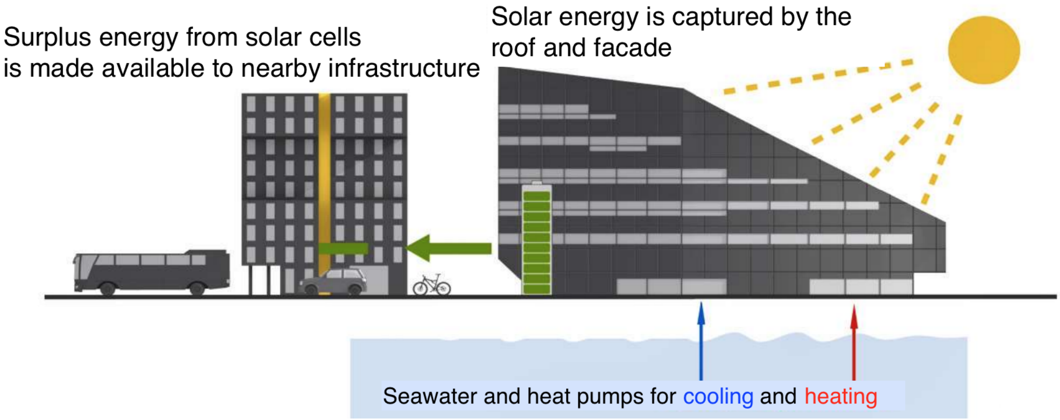


Figure 4.2.1: Brattørkaia microgrid [76]. The figure is modified from the original.

The structure of the building utilizes thermal mass in the form of low-emission concrete, which is visible through cutouts in the ceiling as depicted in figure 4.2.2. The low-emission concrete has a lower CO_2 emission and energy consumption than usual. The concrete mass absorbs and retains heat and cold, which helps regulate the temperature in the building and minimizes the need for electric heating and cooling.[75, 77]

Figure 4.2.2: Exposed concrete in Powerhouse Brattørkaia [77]

The two sensors placed to measure the air quality in Powerhouse Brattørkaia are located on the fourth floor. On this level, carpets are used on the floor, ceiling tiles with gaps and exposed concrete for the ceiling, and a mixture of drywall, paint, glass, and strip wood panels are utilized for the internal walls.

Powerhouse Brattørkaia employs a demand controlled ventilation (DCV) system and utilizes indoor air quality sensors, temperature, and movement for regulation and control. The system has been designed with energy efficiency in mind, utilizing displacement ventilation to supply fresh air at low speeds directly to the occupied spaces through floor-mounted grates and valves. To ensure optimal air quality, it is crucial that these floor-mounted valves remain unobstructed by furniture or other equipment. Additionally, manual override switches are provided on each floor to allow for adjustments to the ventilation system if necessary. There are also possibilities for night heating or cooling when needed.[78]

Chapter 5

Methodology

This chapter describes the methodology for the work conducted for this master's thesis. First, the sensors used for measuring IAQ parameters are described with their respective specifications. The IAQ parameters in this thesis are limited to temperature, relative humidity, CO_2, $PM_{2.5}$, formaldehyde, and TVOC. Furthermore, the procedure for the calibration of the sensors is presented. No calibration could be performed for formaldehyde and TVOC as no reference sensor was available. Information on the field measurements conducted at the ZEB Laboratory and Powerhouse Brattørkaia is also described in this chapter. This includes the placement of sensors, which sensors are used where, and the total measurement period. Furthermore, the procedure for the odor experiment is described. This includes a description of the test facility, experimental procedure, selection of panel members, and uncertainty analysis. Lastly, the approach for analyzing and visualization of measurement is explained.

5.1 Sensor Specification

Throughout this master's thesis, low-cost sensors have been used for short-term and long-term measurements, in specific experiments, or for measuring IAQ in offices over a longer period.

Each sensor box is identified with an ID number and contains several sensors used to measure the IAQ parameters. All sensors are placed on an Arduino board in an open plastic case, and the outputs are transmitted to a Raspberry Pi, where it is logged and stored as a .csv-file. The sensors take about 30 minutes to stabilize, and thus all measurements prior to this should be disregarded when analyzing the results. The following section presents the specific specifications for each sensor, such as measurement range, accuracy, and drift. This information is obtained from the datasheet for each sensor and can be found in appendix A.

SCD30 - CO_2, Temperature and Humidity

The Sensirion SCD30 sensor module consists of an NDIR CO_2 sensor and integrated temperature and humidity sensors. The SCD30 has a built-in dual-channel principle for the measurement of CO_2 concentrations, which automatically compensates for long-term drifts, ensuring accurate measurements. The SCD30 has a lifetime expectancy of 15 years and requires no maintenance when ASC field calibration algorithm is used. Table 5.1.1 summarizes some of the key specifications for the SCD30 sensor for CO_2, humidity, and temperature.

Table 5.1.1: SCD30 sensor specifications for CO_2, humidity and temperature.

CO_2 Sensor Specifications		
Parameter	*Condition*	*Value*
CO_2 measurement range		0 - 40 000 ppm
Accuracy	400 ppm - 10 000 ppm	± (30 ppm + 3%)
Accuracy drift over lifetime	400 ppm - 10 000 ppm	± 50 ppm
Humidity Sensor Specifications		
Parameter	*Condition*	*Value*
Humidity measurement range		0 - 100% RH
Accuracy	25°C, 0 - 100% RH	± 3% RH
Accuracy drift		< 0.25% RH/year
Temperature Sensor Specifications		
Parameter	*Condition*	*Value*
Temperature measurement range		-40°C - 70°C
Accuracy	0 - 50°C	± (0.4°C + 0.023 x (T[°C] - 25°C))
Accuracy drift		< 0.03°C/year

SPS30 - Particulate Matter

The Sensirion SPS30 sensor is used to measure particulate matter and can measure particle sizes 0.5 to 10 μm. The SPS30 particulate matter sensor is an innovative optical sensor that utilizes laser scattering and Sensirion's contamination-resistance technology to provide precise measurements. With its high-quality components and advanced algorithms, it can detect various sorts of environmental dust and particles with superior accuracy. With a lifetime expectancy of 10 years, the SPS30 ensures long-lasting and reliable performance. Key specifications are summarized in table 5.1.2.

Table 5.1.2: SPS30 sensor specifications for $PM_{2.5}$.

Parameter	**Condition**	**Value**
Mass concentration range		0 - 1000 $\mu g/m^3$
Mass concentration accuracy	0 - 100 $\mu g/m^3$	± 10 $\mu g/m^3$
Lifetime	24h/day operation	> 8 years
Temperature operating conditions		-10 - +60°C
Humidity operating conditions		0 - 95%

SGP30 - TVOC

The Sensirion SPG30 is a multi-pixel gas TVOC sensor for indoor air quality applications. The SGP30 sensor has an outstanding long-term stability and low drift due to its robustness against contaminating gases present in real-world applications. Specifications can be found in table 5.1.3.

Table 5.1.3: SPG30 sensor specifications for TVOC.

Parameter	Signal	Value
Output range	TVOC	0 - 60 000 ppb
Temperature operating conditions		-40 - +85°C
Humidity operating range		10-95%

WZ-S - Formaldehyde

The WZ-S module is a formaldehyde sensor that utilizes Dart Sensors wafer components. By combining a formaldehyde sensor with advanced electronic control technology, formaldehyde concentrations are directly converted into ppm and $\mu g/m^3$. WZ-S is pre-calibrated in the factory, and there is thus no need for customer calibration. Key specifications are presented in table 5.1.4.

Table 5.1.4: WZ-S sensor specifications for formaldehyde.

Parameter	Value
Detection gas	Formaldehyde (HCHO)
Detection range	0 - 2 ppm
Operating temperature range	-20 - +50°C
Operating humidity range	10 - 90% RH
Lifetime	5 years (in air)

From the datasheet, the gas concentration of formaldehyde can be found by using equation 5.1.1.

$$Gas\,concentration = concentration(high\,byte) * 256 + concentration(low\,byte) \tag{5.1.1}$$

5.2 Calibration of Sensors

Sensor calibration is conducted by measuring the concentration of different pollutants in the indoor air in a controlled environment, using a high-performance sensor for reference measurements. The purpose of conducting a calibration is to correct the raw data provided by the low-cost sensor. Pegasor AQ is used as the reliable reference device, and it is assumed that this provides correct concentrations of the measured pollutants. Pegasor AQ measures CO_2, $PM_{2.5}$, temperature, and RH. As there is no reference device measuring TVOC and FA, these will not be calibrated. The calibration is conducted in a test chamber of 1.5x1x1 m^3, as depicted in figure 5.2.1.

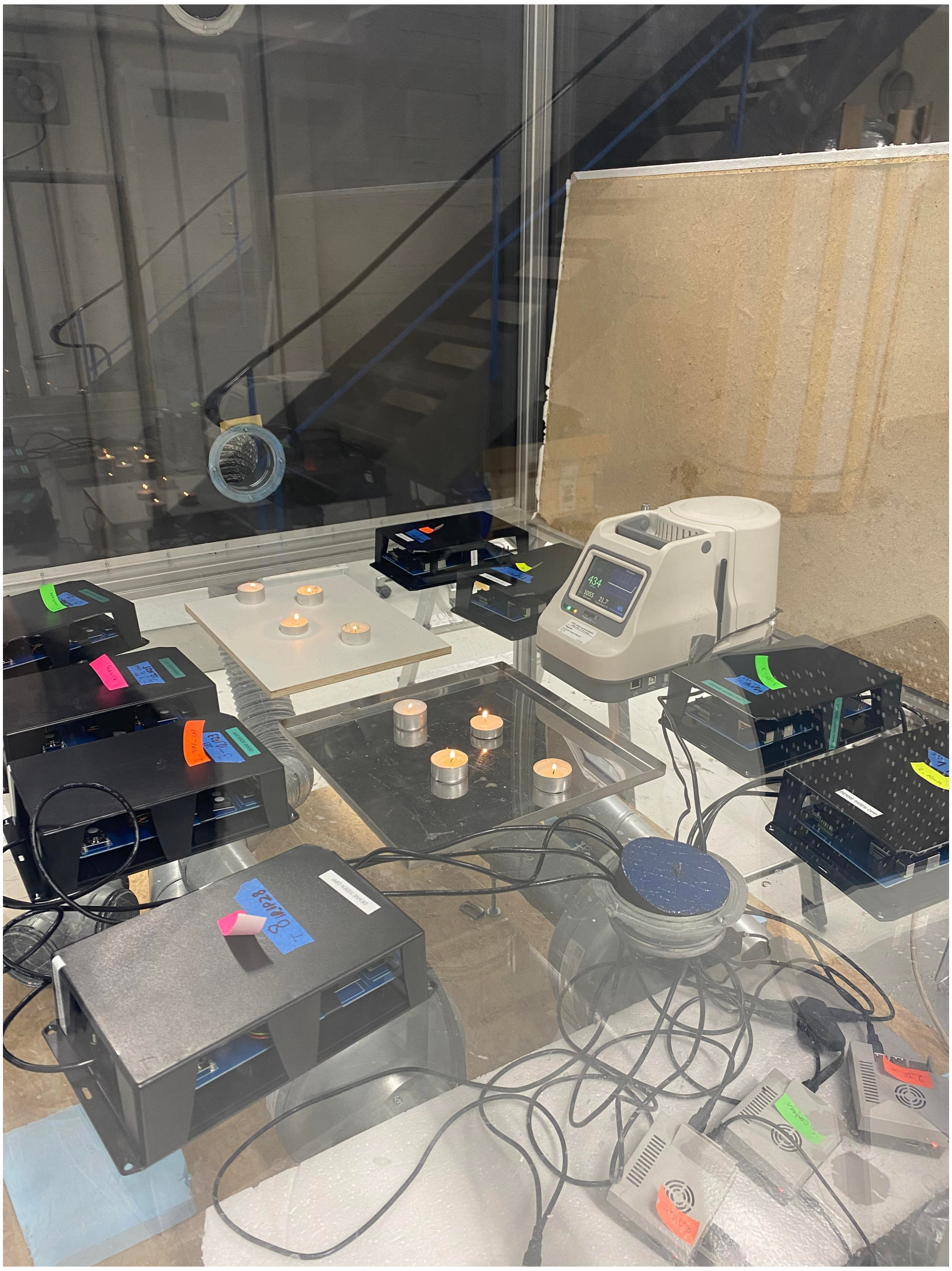


Figure 5.2.1: Calibration of sensors.

Sensor boxes ID21 to ID28, used to measure the IAQ in the ZEB Laboratory is calibrated. For sensor boxes ID21, ID22, ID23, ID24, ID27, ID28, new calibration files were made on the 9th of March 2023, whilst for sensor boxes ID25 and ID26, old calibration files from 9th of July 2022 and 8th of March 2022 were used. New calibration files are made over a time span of 12 hours, where the sensor box is placed in a zone with fresh air and low CO_2 levels. Other sensor boxes used during this master's thesis were calibrated at the end of 2022 in conjunction with the specialization project.

Experiment 1: Wetted Chipboard

Two chipboard plates are placed in the test chamber to emulate emissions from building materials, as depicted in figure 5.2.1. The plates are also wetted so that the water pushes gas residing in the plate out in the chamber where it is mixed in the air. The chipboards are pollutant sources of formaldehyde, and the experiment will also be used for calibration of humidity. During the experiment, the chamber is completely closed. The experiment started at 10:50, and finished at 11:40.

Experiment 2: Candles

After the CO_2 concentration in the chamber is stabilized, eight candles are placed in the middle of the test chamber, as depicted in figure 5.2.1. The candles are a source of fine particles, heat and CO_2 emissions. The CO_2 level is kept below 3000 ppm, as the sensors are intended to be calibrated for normal indoor concentrations. After the candles are placed in the chamber and lit, the chamber remains closed. When the CO_2 concentration approaches 3000 ppm the hatch is opened for a couple of minutes to reduce the concentration before it is closed again. The next time the CO_2 level approaches 3000 ppm, the candles are blown out and the hatch is left semi-open, to observe the decreasing concentration. Table 5.2.1 summarizes the specific times for every action conducted during the experiment.

Table 5.2.1: Specific times for every action conducted during experiment 2 with candles.

Time	Comment
11:43	Candles are lit, hatch is closed
11:54	Hatch is opened completely, CO_2 levels drop
12:07	Hatch is closed
12:23	Lights are blown out when CO_2 level is high

Regression

Linear regression is used on the measured data from each specific sensor with the Pegasor as a reference, thus obtaining a linear curve, also called calibration curve. Each calibration curve has a corresponding calibration equation. Excel is used to obtain the calibration curves and equations. The R-squared value is an indication of the wellness of fit of the obtained calibration equations [79].

5.3 Field Measurements

Field measurements were conducted in the ZEB Laboratory at NTNU Gløshaugen and Powerhouse Brattørkaia over a longer period. Details about the respective office buildings can be found in chapter 4. This includes information about the building's anatomy, material usage, ventilation strategies, and control systems.

ZEB Laboratory

Table 5.3.1 summarizes which rooms were monitored, which sensors were used where, and the total measurement period. In total, eight sensors are utilized to monitor the IAQ across the four floors.

Table 5.3.1: Monitored rooms in ZEB Laboratory, placement of sensors, and total measurement period.

Sensor ID	Room	Floor	Total Measurement Period
26	Cafeteria	1	2022-05-09 to 2023-03-08
25	Main entry	1	2022-03-30 to 2023-04-18
21	Open office, North	2	2022-03-30 to 2023-04-18
27	Twin room, East	2	2022-03-30 to 2023-04-18
23	Twin Room, West	2	2022-05-19 to 2023-04-18
28	Open office, North	3	2022-03-30 to 2023-04-18
24	Open office, South	3	2022-03-30 to 2023-04-18
22	Classroom	4	2022-03-30 to 2023-04-18

Figure 5.3.1 illustrates where the sensors, marked as red dots, are placed on each floor at the ZEB Laboratory. The sketch is simplified.

Powerhouse Brattørkaia

Table 5.3.2 summarizes which rooms were monitored, which sensors were used where, and the total measurement period. One sensor is placed in an open office landscape on a shelf between desks, and the other sensor is placed on the window sill in a smaller meeting room. Both sensors are located on the 4th floor.

Table 5.3.2: Monitored rooms in Powerhouse Brattørkaia, placement of sensors, and total measurement period.

Sensor ID	Room	Floor	Total Measurement Period
911911	Meeting room, North	4	2022-12-21 to 2023-04-18
666666	Open office, South	4	2022-12-21 to 2023-04-18

Figure 5.3.2 illustrates where the sensors, marked as red dots, are placed.

Figure 5.3.1: Floor plan of ZEB Laboratory, floors 1 to 4.

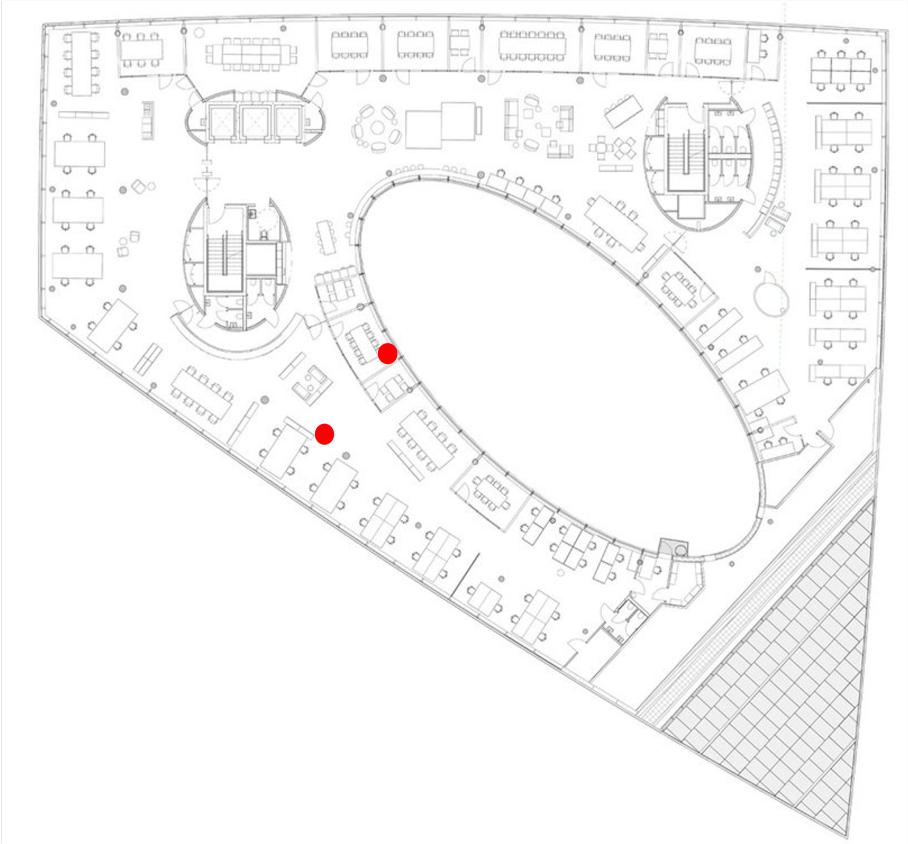


Figure 5.3.2: Floor plan of Powerhouse Brattørkaia [80].

5.4 Perception of Air Quality - Odor Experiment

An odor experiment was conducted to investigate if there is any correlation between the percentage of recirculated air with varying levels of IAQ parameters and the perceived air quality. The experiment was conducted in a test facility consisting of three rooms, with one occupant in each room and an untrained panel on the outside evaluating the odor from each room.

5.4.1 Test Facility

Information about the test facility is gathered from the previous work in Marman [12]. However, minor adjustments have been made to the facility, and the following descriptions are thus revised.

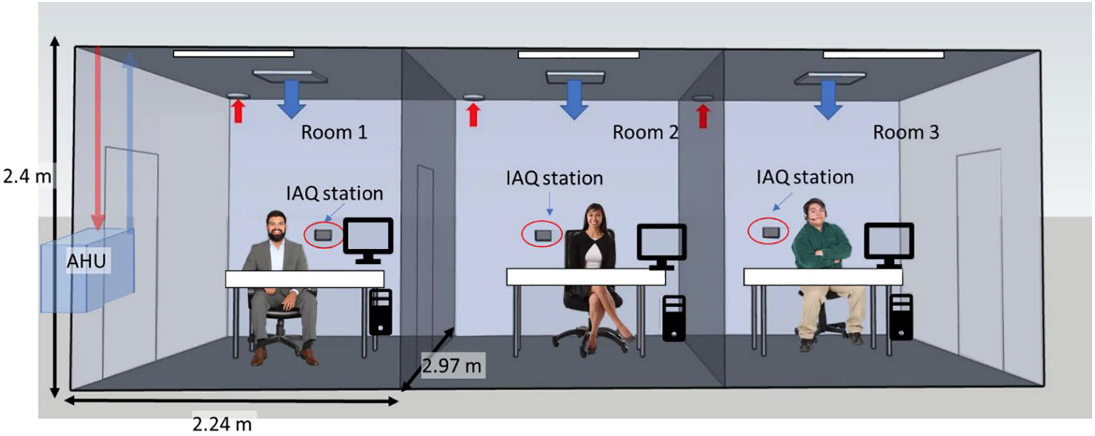


Figure 5.4.1: Schematic of the test facility with dimensions and placements of low-cost sensors and ventilation [81].

The test facility consisting of three equal rooms was built inside the laboratory of the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU), similarly as depicted in figure 5.4.1. Each room is about 7 m^2 and is furnished with a desk, chair, and computer screen. The rooms are hereafter referred to as rooms 1, 2, and 3, corresponding to the depicted rooms from left to right in figure 5.4.1. Sensor box ID25 was placed in room 1, ID123456 in room 2, and ID987654 in room 3.

From each room, a hole was drilled and a metal pipe was placed to transfer air from inside the room and out for the panel members to smell. Additionally, a "sniff-box", as depicted in figure 5.4.2, was used. The sniff box is made of glass, is air-tight, and is fitted with two holes; one where the air from the room enters and one where the air exits for the panel members to smell. The "sniff-box" is equipped with a fan that pushes the air in the box out.

The facade, roof, and inner walls separating the three rooms are constructed of Glava EPS s80. Plastic sheets are mounted on both sides of the inner walls to reduce infiltration between the rooms. The U-values of the external walls, roof, and floor are estimated to 0.1 W/(m^2K), the internal walls 0.15 W/(m^2K), the external doors 0.8 W/(m^2K), and the internal door 1.2 W/(m^2K).

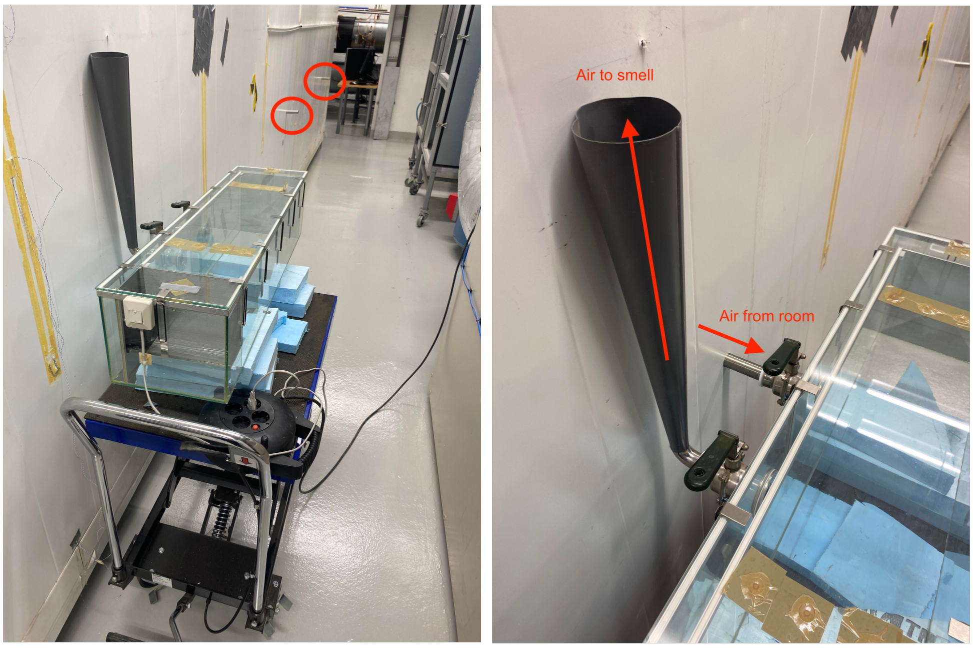


Figure 5.4.2: "Sniff-box" used to push air out of each room for panel members to smell.

The ventilation system in the test facility is a demand-controlled system with mixing air distribution and an air handling unit of the type UNI 3 for Flexit. Figure 5.4.3 illustrates a schematic of the ventilation system. The blue pipes mark the supply air, red marks extract, and the purple is recirculation. A HEPA filter is applied to the recirculation duct to filter the exhaust air, which is being reintroduced to the room.

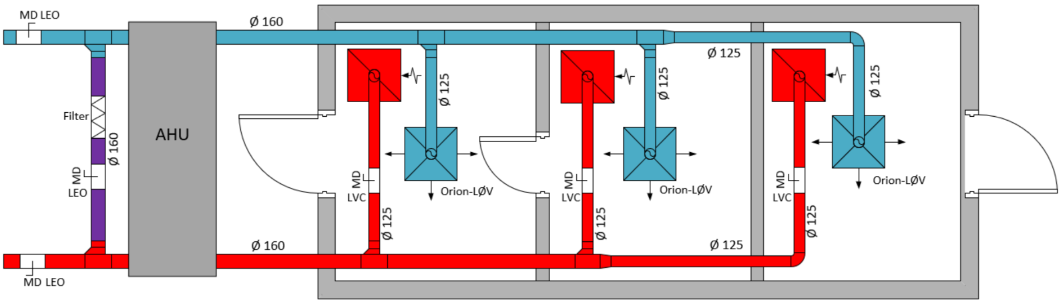


Figure 5.4.3: Ventilation floor plan.

The diameter of the main ducts is 160 mm, while the ducts linking the supply and exhaust ducts to the diffusers have a diameter of 125 mm. In each room, there is an Orion-LØV supply terminal and an LVC exhaust terminal. The dampers employed at the main inlet, main outlet, and recirculation duct are of the type LEO.

It is important to note that the air supplied to the facility is extracted from and exhausted to the laboratory at NTNU as the test rig is situated inside the laboratory. As a result, the supply air may deviate from normal outdoor air, with higher temperature and pollution levels. Therefore, an air cooler was attached to the supply air duct for a lower supply temperature. The air cooler was set to 17°C.

5.4.2 Experimental Procedure

The experiment was conducted over two days, with two tests each day. The supply and extract ventilation rate was 33 m^3/h for each room for all four tests. Even though TEK17 recommends 26 m^3/h, an airflow rate of 33 m^3/h was chosen as the ventilation system of the test rig is not dimensioned correctly, making it difficult to achieve lower ventilation rates. The total fresh air intake for all three rooms and recirculated air ratio differed for each test. For example, for the second test with 25% recirculation of air, the fresh air intake would be 75 m^3/h and the remaining 25 m^3/h recirculated air.

Table 5.4.1 summarizes when each test was conducted, the percentage of recirculated air, and the gender and age of occupants in each room. To achieve a stable concentration of measured parameters in the rooms, the occupants were detained in their rooms with closed doors for 75 minutes before the panel members outside could evaluate the odor from each room. Between the first and second tests each day, all valves were opened, the ventilation rate was set to maximum, and all doors were open to ensure similar air quality levels at the start of each test.

Table 5.4.1: Overview of time of tests, percentage of recirculated air, and occupant in each room.

Day 1			
Test 1 - 0%	**Room 1**	**Room 2**	**Room 3**
10.15 - 11.30	Female A, 24	Male A, 25	Female B, 25
Test 2 - 25%	**Room 1**	**Room 2**	**Room 3**
13.15 - 14.30	Female A, 24	Male A, 25	Female B, 25

Day 2			
Test 3 - 75%	**Room 1**	**Room 2**	**Room 3**
10.15 - 11.30	Female A, 24	Female C, 25	Male B, 24
Test 4 - 50%	**Room 1**	**Room 2**	**Room 3**
13.15 - 14.30	Female A, 24	Female C, 25	Male B, 24

A different number of panelists attended each test; 18 panelists for test 1 with 0% recirculated air, 15 panelists for the test with 25% recirculated air, 17 panelists for the test with 75% recirculated air, and 16 panelists for the test with 50% recirculated air. Each odor evaluation with the panelist took 15 - 20 minutes to complete explanations and questionnaires. Prior to the odor evaluation, each panelist was handed two cups; one with a single coffee bean and one with freshly ground coffee. The reasoning behind this was for the panelists to have a reference to a weak and intense odor. The questionnaire handed to each panel member is based on ISO 16000-30:2014, and can be found in appendix D. Odor from one room was evaluated at a time to achieve sufficient time between the odor evaluation of each room.

In addition to the questionnaire handed to the panelists on the outside, a separate questionnaire was also given to the occupants in each of the three rooms about the perception of thermal comfort and air quality. These questions can be found in appendix C and are based on the Örebro model. The Örebro model is used by various studies, making it easy to compare with other studies and buildings. The occupants were also asked to perform a typing test at the beginning and end of each test, which evaluates words per minute (WPM) and acceptability [%]. This test was found on typing.com, and the 1-minute test was utilized.

The perception of odor is influenced by the temperature and relative humidity of room air. Thus, the temperature and RH should stay constant during the sensory test, and conditions shall be logged. The temperature in the room should not exceed 25°C with fluctuations of ± 3°C allowed. The RH of the room should be 50 ± 5%.[41]

5.4.3 Selection and Instruction of Panel Members

The selection of panel members is based on the requirements established by ISO 16000-30:2014. As the odor experiment uses untrained panel members, the standard recommends at least 15 people, but ideally 20 to 25 persons.[41]

To qualify as a panel member, the following criteria shall be fulfilled:

- Motivated and available to carry out the experiment
- Over 18 years old
- Does not suffer from allergies or health conditions that can affect the sense of smell
- Is not sick with something affecting smell at the time of the sensory test (e.g. a cold, the flu, or COVID)
- Not chew gum, eat, or drink anything besides water 30 minutes before and during the test
- Not smoke or use ”snus” two hours before and during the test

The occupants in rooms 1, 2, and 3 were given similar instructions. Additionally, they were asked to refrain from showering the same day and avoid using hygiene products containing perfume.

5.4.4 Uncertainty Analysis

Errors and uncertainties are always present in measurements, and it is thus important to recognize them to minimize their impact on the result. The accuracy achieved through the sensory tests can be expressed by means of a confidence interval, assuming the observed criteria are distributed normally.

The accuracy requirements for the odor experiments are defined by the ISO standard for indoor air (ISO 16000-30:2014). The accuracy of the measurements is determined by a confidence interval. The odor acceptability assessment is considered accurate if the half-width of the 90% confidence interval of the mean does not exceed 0.2. For odor intensity, the 90% confidence interval must not exceed 1.[41] Equation 5.4.1 calculates the two-sided confidence interval, where μ is the actual mean value, while $\overline{x}$ is the estimated mean value, n is the panel size, α is the probability of error in the experiment, and $t_{(1-\alpha/2);n-1}$ is the $(1-\alpha/2)$ percentile of the t-distribution.

$$P(\mu \in [\overline{x} \pm \frac{s}{\sqrt{n}} \cdot t_{(1-\alpha/2);n-1}]) = (1-\alpha) \tag{5.4.1}$$

Equation 5.4.2 and 5.4.3 calculate the estimated mean value and standard deviation.

$$\overline{x} = \frac{\sum x}{n} \tag{5.4.2}$$

$$s = \sqrt{\frac{\sum(x-\overline{x})^2}{n-1}} \tag{5.4.3}$$

5.5 Measurement Retrieval and Data Analysis

Data from the sensors are retrieved manually with a memory stick. When measuring over a longer period, the sensors should be checked regularly to prevent the sensors from shutting down unexpectedly.

When analyzing the raw data, obvious incorrect data was changed to NaN (Not a Number). Examples of these values are CO_2 concentrations below 400 ppm, temperature levels below 0°C or above 100°C, and RH levels below 0% or above 100%. This was done to get a better understanding of how the sensors work, whilst still getting an accurate representation of the air quality. After sorting the raw data, the calibration equations were used to correct the data.

Chapter 6

Results and Analysis

The following chapter presents the results derived from the experiments and field measurements described in chapter 5. First, the calibration equations and R^2 from the calibration of sensors are presented, which are used to correct the raw data from the sensors. As there was no high-performance reference sensor for TVOC and FA, these parameters were not calibrated. All other parameters are calibrated unless other is specified. Subsequently, the indoor air quality from the field measurements in the ZEB Laboratory and Powerhouse Brattørkaia is presented. The temperature and humidity levels for the two buildings are then compared more closely during the same time interval. Lastly, the results from the odor experiment are presented. This includes the measured parameters in the test facility, the answers from both the occupants and panelists, and the accuracy of the sensory assessment by the panelists.

Several of the results presented in this chapter are generated using boxplots. These graphs depict the mean values, with the range between the highest and lowest values indicated by whiskers. The box represents the central 50% of the data range, or the middle data range, while the line in the box represents the median value.

6.1 Calibration of Sensors

This section contains the results from the calibration of some of the sensors used during this master's thesis. The calibration equations and R^2 values for sensors boxes ID911911, ID666666, ID123456, and ID987654 are obtained from a similar experiment conducted in 2022 in conjunction with the specialization project as preparatory work for this master's thesis. Sensor boxes ID21 to ID28 were calibrated in March 2023 in conjunction with this master's thesis, as described in section 5.2. Supplementing step response plots and calibration curves for sensors ID21 to ID28 are presented in appendix B. The calibration equations and R^2 values are summarized in table 6.1.1.

Overall high R^2 values can be observed for the temperature sensors, with the exception of sensor boxes ID21 and ID28, with R^2 values of 0.5873 and 0.5407, and ID123456 with an R^2 value of 0.728. When referring to higher R^2 values, values above 0.9 are considered.

For the RH sensors, more variance in the R^2 values can be observed. Only four out of 12 sensors in total have R^2 values above 0.9. The two lowest R^2 values can be observed for sensor boxes ID911911 and ID123456, with values of 0.557 and 0.472.

The R^2 values for the CO_2 sensors have the highest R^2 values overall, where nine of 12 sensors have R^2 values over 0.9. The lowest R^2 value for the CO_2 sensors is 0.7008 (ID28).

Overall low R^2 values can be observed for the particulate matter sensors, with the highest value of 0.6098 (ID21). The lowest R^2 value is 0.1918 (ID26). No calibration equation for sensor box ID123456 is available, as this sensor did not perform measurements during the experiment. The sensor has measured particle concentrations on other occasions, and the sensor should have been calibrated again to achieve an R^2 value and calibration equation.

Table 6.1.1: Calibration equation and R^2 values.

Sensor ID		**Temperature**	**Relative Humidity**	**CO_2**	**$PM_{2.5}$**
ID21	**EQ**	Y = 1.037x - 2.9529	Y = 0.6873x + 19.143	Y = 1.0394x + 58.742	Y = 0.9376x + 2.3335
	R^2	0.5873	0.7908	0.9246	0.6098
ID22	**EQ**	Y = 1.0164x - 2.2951	Y = 0.957x + 1.0969	Y = 0.9307x - 28.934	Y = 0.546x + 12.948
	R^2	0.9744	0.9085	0.9634	0.4379
ID23	**EQ**	Y = 1.181x - 6.3065	Y = 0.9283x + 15.421	Y= 1.0137x + 148.74	Y = 0.7671x + 13.505
	R^2	0.8917	0.9311	0.934	0.4126
ID24	**EQ**	Y = 1.028x - 2.9534	Y = 0.8779x + 8.9942	Y = 0.9453x + 44.98	Y = 0.6434x + 23.017
	R^2	0.9113	0.7679	0.9726	0.3164
ID25	**EQ**	Y = 1.4436x - 13.207	Y = 0.9718x + 14.193	Y = 0.9334x + 170.41	Y = 0.7889x + 4.9451
	R^2	0.9653	0.9194	0.8503	0.5187
ID26	**EQ**	Y = 1.5153x - 14.839	Y = 1.2621x + 7.0163	Y = 1.0857x - 76.83	Y = 0.3503x + 37.551
	R^2	0.9703	0.8847	0.9383	0.1918
ID27	**EQ**	Y = 1.3031x - 8.5663	Y = 0.8998x + 11.125	Y = 0.8648x + 39.195	Y = 0.6545x + 7.2082
	R^2	0.986	0.8711	0.9331	0.5113
ID28	**EQ**	Y = 1.2956x - 6.9806	Y = 0.8138x + 17.09	Y = 0.8482x + 315.31	Y = 0.7737x + 13.36
	R^2	0.5407	0.866	0.7008	0.4416
ID911911	**EQ**	Y = 1.4588x - 15.117	Y = 1.1587x + 3.9416	Y = 1.587x -308	Y = 0.484x + 7.2358
	R^2	0.927	0.557	0.843	0.482
ID666666	**EQ**	Y = 1.1403x - 5.695	Y = 0.994x + 4.9519	Y = 1.084x -37.319	Y = 0.484x + 2.1252
	R^2	0.968	0.933	0.919	0.385
ID123456	**EQ**	Y = 1.4108x -13.538	Y = 1.2658x - 15.809	Y = 0.9756x + 1.7546	-
	R^2	0.728	0.472	0.925	-
ID987654	**EQ**	Y = 1.5586x - 17.731	Y = 1.1102x + 2.507	Y = 0.874x + 138.05	Y = 0.4826x + 2.2896
	R^2	0.987	0.915	0.9346	0.482

The R^2 value is an indication of the wellness of fit of the obtained calibration equations. Whilst a high R^2 value and corresponding calibration equation will be able to correct the raw data and thus minimize the deviation from the reference sensor, a low R^2 value and corresponding calibration equation can make this deviation larger and thus aggravate the results. It is thus important to achieve high R^2 values when the calibration equation is used to correct data for further analysis. For sensors with low R^2 values it could have been better to use the raw data directly instead of the calibrated data.

Due to time limitations, linear regression was utilized, and no further regression methods were explored. This method does not take temperature and humidity into account, which some sensors are affected by. Thus, for the sensors with R^2 values on the lower side, further regression analysis should have been explored. This would have resulted in more accurate data.

6.2 Indoor Air Quality in ZEB Laboratory

This section presents the measured data collected from the sensors placed in the ZEB Laboratory. For all sensors and parameters, some periods of data are missing. This is because of an error in the sensor itself, an error with the Raspberry Pi, or if the sensor has been used elsewhere. All sensors were used for the calibration experiment on the 9th of March, and sensor box ID25 (main entry) was used from the 23rd to the 24th of March. Information about the placement of sensors and total measurement period can be found in chapter 5.3.

As the sensors measure every minute, the data is presented as hourly averages in green and 24-hour averages in red. It is thus important to note that the average values may lower some concentrations and peaks. Thus, supporting boxplots from minute values are included for some parameters.

6.2.1 CO_2 Levels

Figure 6.2.1 illustrates the CO_2 levels in the ZEB Laboratory. CO_2 levels in all zones are mostly under the guideline limit of 1000 ppm, indicating adequate ventilation in relation to the number of occupants. Overall higher CO_2 levels can be observed in twin room west (2) and open office north (3) compared to the other zones. Lower CO_2 levels and fewer peaks can be observed during summer break for the main entry, twin room east, open office north (2), open office south (3), and the classroom. During this period lower CO_2 levels can also be observed for the canteen, where more people also tend to eat their lunch outside. Fluctuations in CO_2 levels can be observed for all zones, representing the varying CO_2 levels between weekdays and weekends.

6.2.2 Temperature Levels

Figure 6.2.2 illustrates the temperature levels in different zones in the ZEB Laboratory. For some zones, stable temperatures can be observed over the different seasons. However, for the zones main entry, canteen, and classroom, higher variations can be observed. For these zones the temperature is higher during the summer months and lower during winter. For the main entry and canteen, temperatures close to 10°C can be observed at the beginning of January.

Boxplots without outliers of the temperature levels in the ZEB Laboratory are illustrated in figure 6.2.3. Maximum temperatures of around 26°C can be observed, with mean temperatures between 20 and 22°C. The exception is the canteen and main entry with similar maximum temperatures, but lower mean temperatures of 18°C and lower minimum compared to the other zones.

Figure 6.2.1: Hourly average (green) and 24-hour average (red) CO_2 levels in ZEB Laboratory.

Figure 6.2.2: Hourly average (green) and 24-hour average (red) temperature levels in ZEB Laboratory.

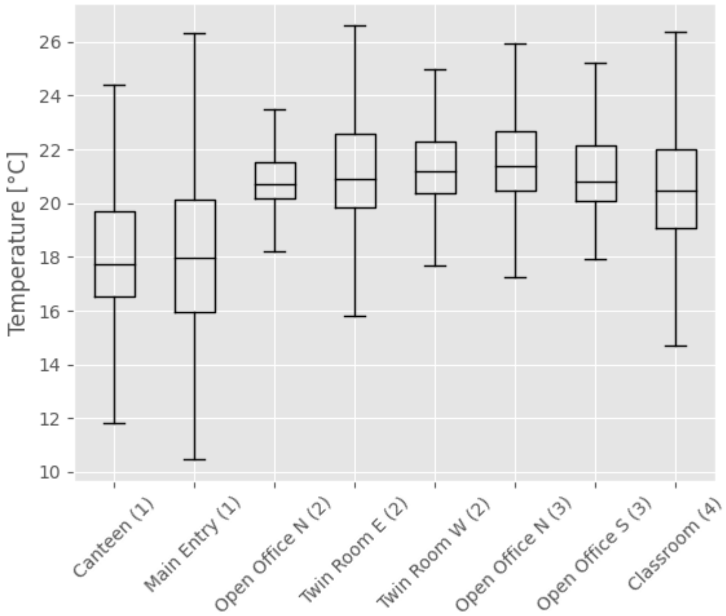


Figure 6.2.3: Boxplot of temperature levels in ZEB Laboratory.

6.2.3 RH Levels

Figure 6.2.4 shows boxplots, without outliers, of the humidity levels in the ZEB Laboratory. Maximum values range from around 80% to 55%, and minimum values range from 25% to 10%. Mean values are observed to be between 30 and 50%.

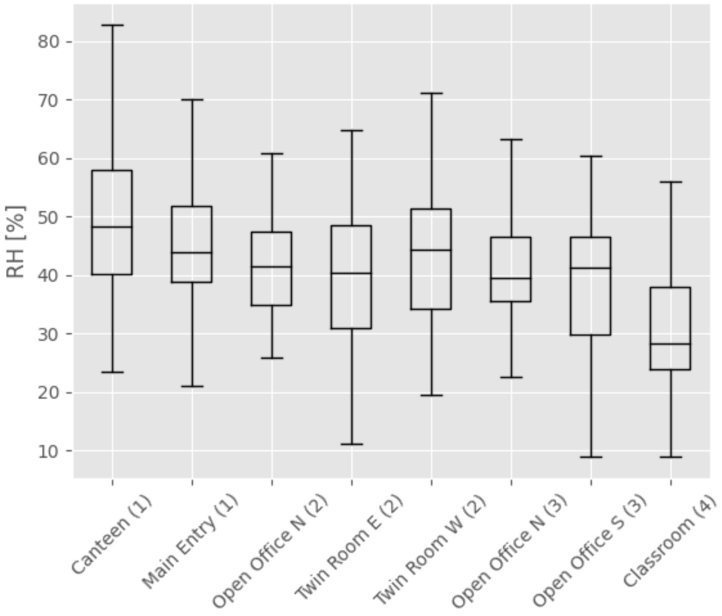


Figure 6.2.4: Boxplot of humidity levels in ZEB Laboratory.

The RH for the different zones across the year is illustrated in figure 6.2.5. As predicted, the humidity in the different zones changes with the seasons, with higher RH levels during summer and lower levels during winter.

Figure 6.2.5: Hourly average (green) and 24-hour average (red) humidity levels in ZEB Laboratory.

6.2.4 PM$_{2.5}$ Levels

Figure 6.2.6 illustrates the PM$_{2.5}$ levels in the ZEB Laboratory. Varying levels can be observed for the different rooms. The highest overall values of PM$_{2.5}$ can be observed in the cafeteria, with levels around 40 $\mu g/m^3$, which can be expected as it is located next to two trolleys where one can place dirty dishes and an air supply duct in the floor. The lowest PM$_{2.5}$ levels can be observed in the open office on the second floor. The other zones have levels of PM$_{2.5}$ varying from 5 to 25 $\mu g/m^3$.

Figure 6.2.6: Hourly average (green) and 24-hour average (red) particulate matter (2.5 μ) levels in ZEB Laboratory.

6.2.5 TVOC Levels

Figure 6.2.8 illustrates the TVOC levels across the ZEB Laboratory. No obvious trends can be observed from the graphs, with varying levels across the seasons and zones. Higher levels of TVOC up to 5000 ppb are also observed for some of the zones. Even though some peaks of TVOC can be observed up to 25 000 ppb, the y-axis is limited to 5000 ppb.

Figure 6.2.7 depicts two boxplots, one with and one without outliers, and illustrate the maximum and minimum values of TVOC. This figure shows that the mean value for all zones is below 500 ppb, but with maximum values ranging from under 200 ppb to over 2000 ppb. The figure also shows the TVOC levels with outliers. An interesting observation is the outliers at the same level for the canteen (1), open office N (2), twin room E (2), twin room W (2), open office N (3), open office S (3), and the classroom, at just below 20 000 ppb. What this is due to is unknown.

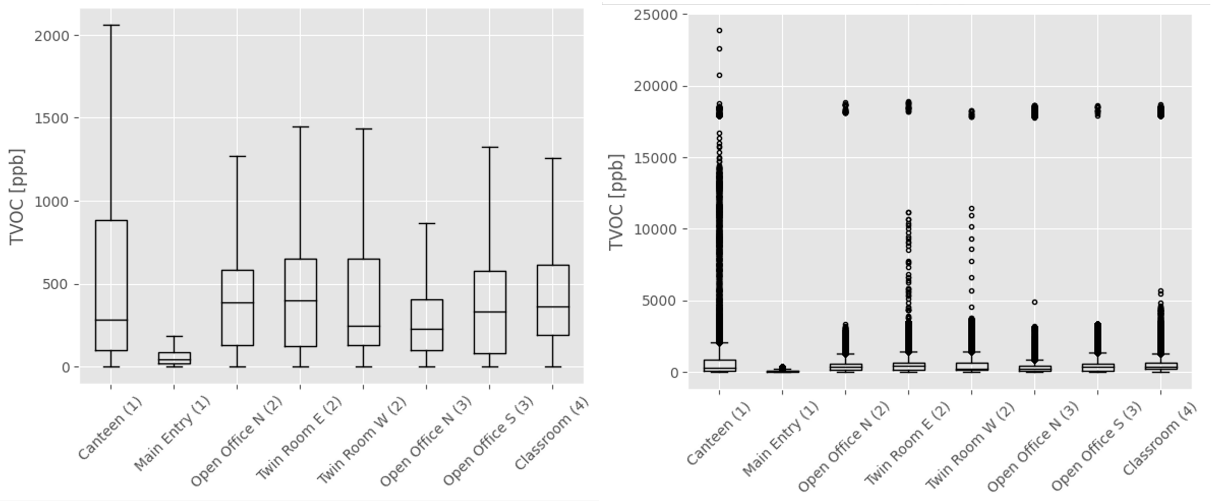


Figure 6.2.7: Boxplot of TVOC levels in ZEB Laboratory. Without outliers (left) and with outliers (right).

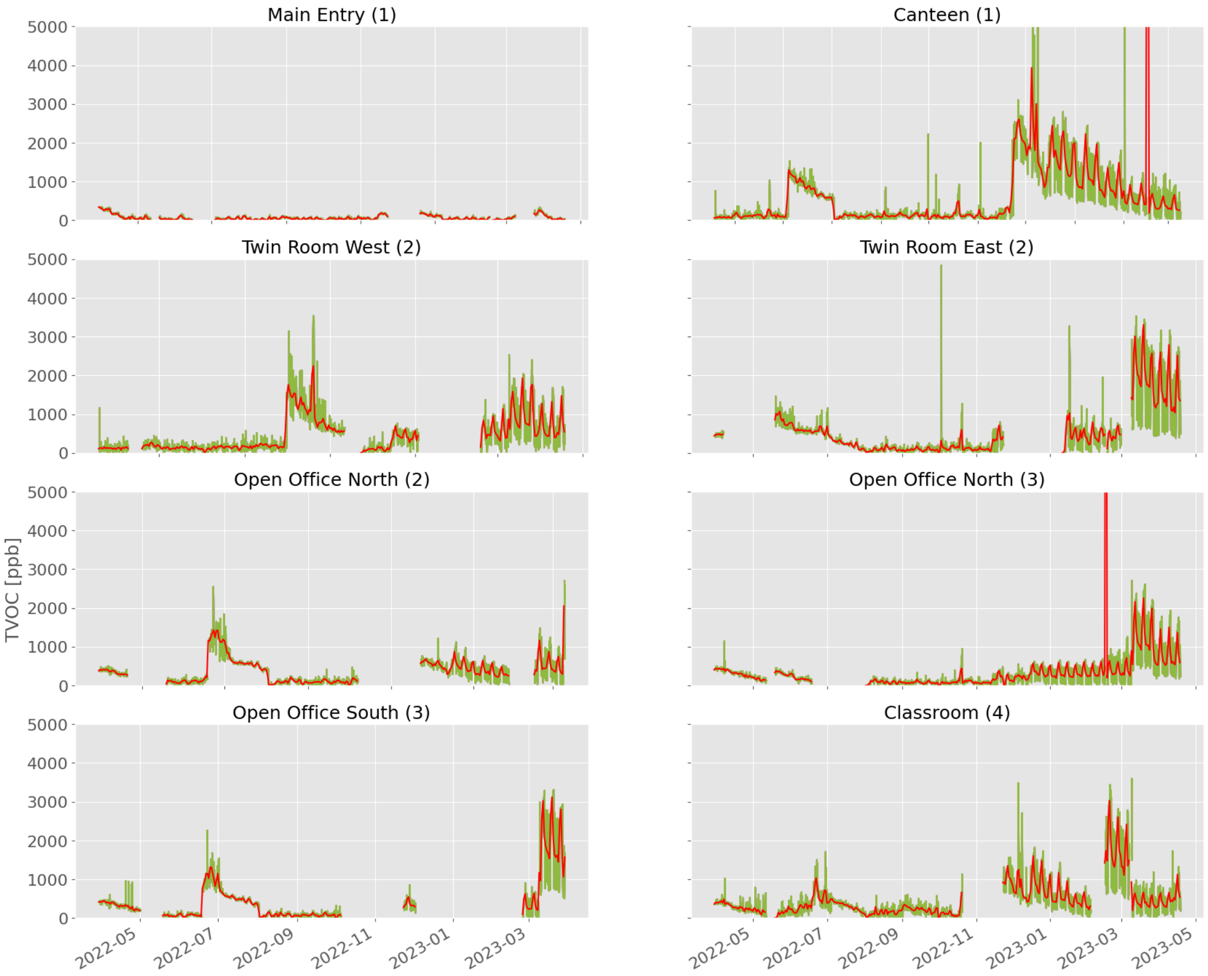


Figure 6.2.8: Hourly average (green) and 24-hour average (red) TVOC levels in ZEB Laboratory.

6.2.6 Formaldehyde Levels

Figure 6.2.9 illustrates the formaldehyde levels in the ZEB Laboratory. No obvious trends can be seen from the graphs. For most of the zones, it seems as if the formaldehyde levels are slightly higher after 2023-01-01, with larger oscillations. The reason for this is unknown.

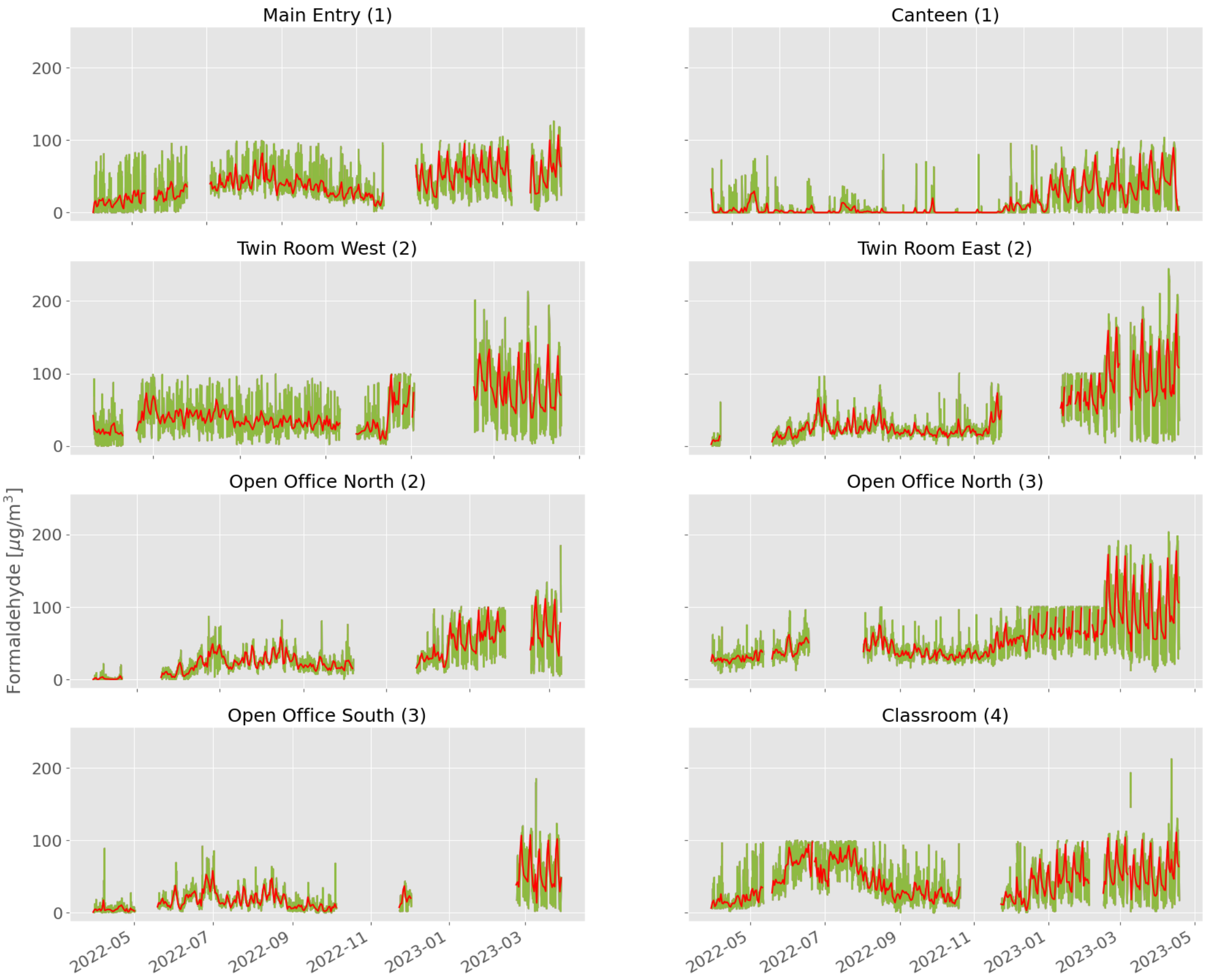


Figure 6.2.9: Hourly average (green) and 24-hour average (red) formaldehyde levels in ZEB Laboratory.

Figure 6.2.10 illustrates the boxplots for formaldehyde, with and without outliers, for the different zones in the building. Maximum values can be observed to range from under 50 $\mu g/m^3$ to over 120 $\mu g/m^3$, with mean values ranging from 0 $\mu g/m^3$ to 40 $\mu g/m^3$. The boxplot with outliers does however show measured levels up to 250 $\mu g/m^3$.

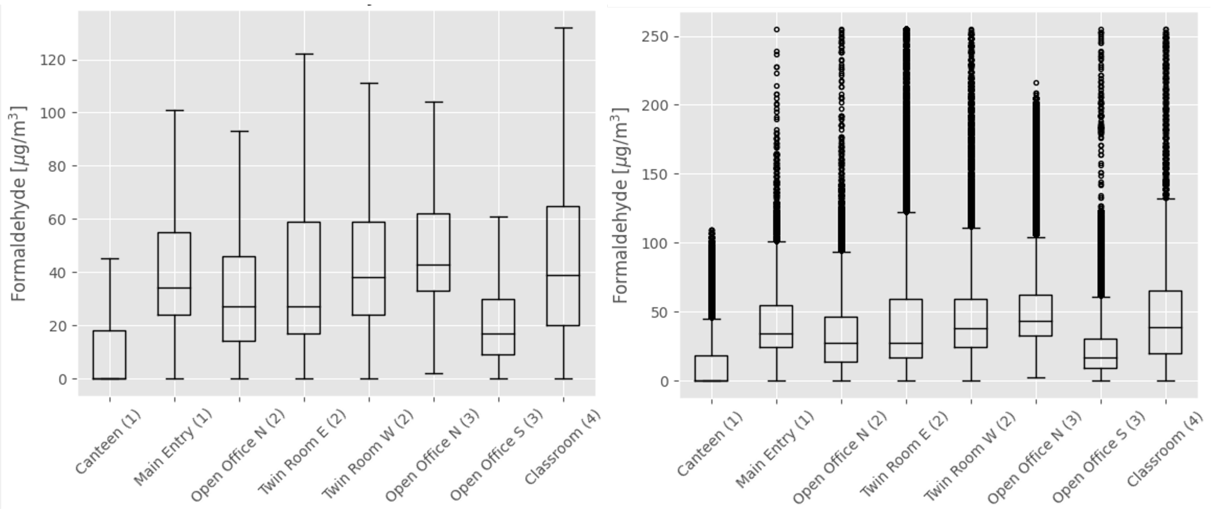


Figure 6.2.10: Boxplot of formaldehyde levels in ZEB Laboratory. Without outliers (left) and with outliers (right).

6.3 Indoor Air Quality in Powerhouse Brattørkaia

This section presents the measured data collected from the sensors placed in Powerhouse Brattørkaia. For both sensors and parameters, some periods of data are missing. This is because of an error in the sensor itself or with the Raspberry Pi. Information about the placement of sensors and total measurement period can be found in chapter 5.3. As the sensors measure every minute, the data is presented as hourly averages in green and 24-hour averages in red.

6.3.1 CO_2 Levels

The CO_2 levels in Powerhouse Brattørkaia, are illustrated in figure 6.3.1. Higher variations in CO_2 levels in the meeting room can be observed, as this is a small room used periodically, and when used, it is often by several people. Lower overall CO_2 concentrations can be observed for the open office, with oscillations varying from weekdays to weekends. Lower CO_2 concentrations can also be observed for Christmas and Easter break.

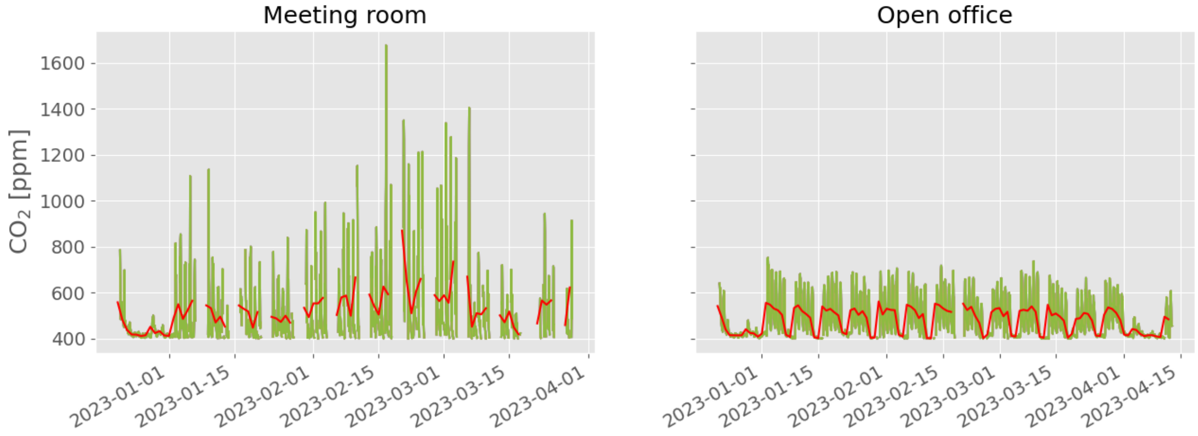


Figure 6.3.1: Hourly average (green) and 24-hour average (red) CO_2 levels in Powerhouse Brattørkaia.

6.3.2 Temperature Levels

Figure 6.3.2 illustrates the temperature levels in Powerhouse Brattørkaia. The temperature in the open office is overall on the higher side and can be observed to increase with the seasons, as expected. The temperature in the meeting room has higher oscillations, as it is a small room used periodically.

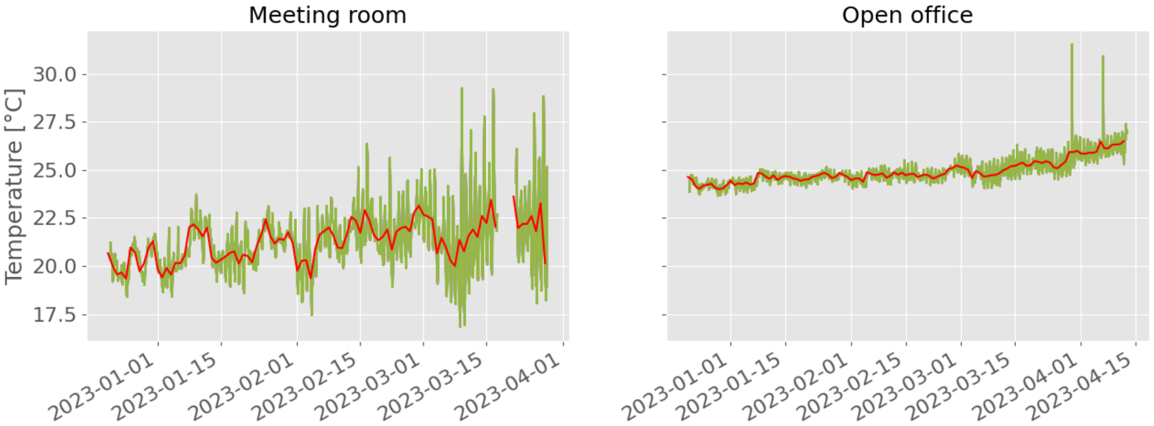


Figure 6.3.2: Hourly average (green) and 24-hour average (red) temperature levels in Powerhouse Brattørkaia.

6.3.3 Humidity Levels

The humidity levels in Powerhouse Brattørkaia are illustrated in figure 6.3.3. The humidity levels are overall on the lower side, with maximum levels of 35% in the meeting room and 30% in the open office. Humidity levels are typically on the lower side during winter. The humidity levels are also quite oscillating.

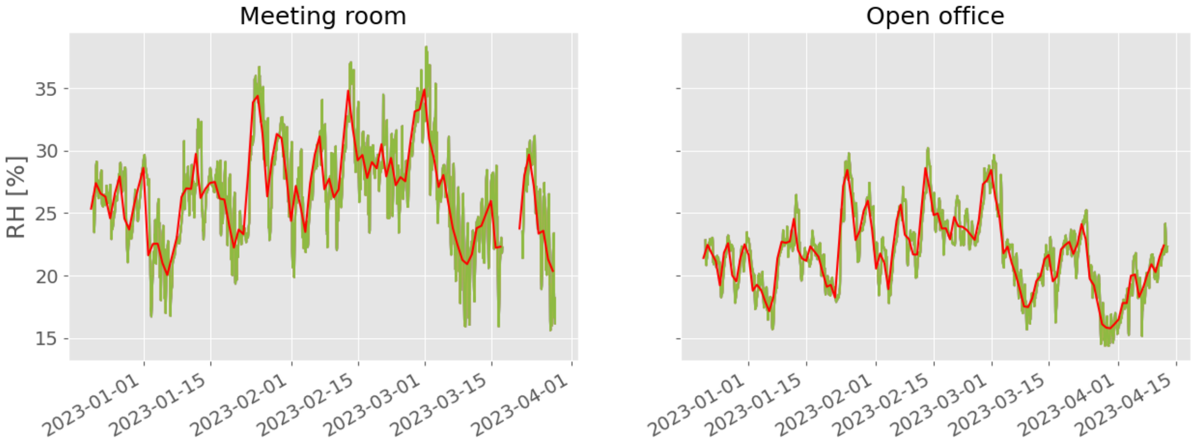


Figure 6.3.3: Hourly average (green) and 24-hour average (red) humidity levels in Powerhouse Brattørkaia.

6.3.4 $PM_{2.5}$ Levels

Figure 6.3.4 illustrates the $PM_{2.5}$ levels in Powerhouse Brattørkaia. Whilst $PM_{2.5}$ levels are overall high throughout the measured period in the meeting room, the opposite can be observed for the open office with significantly lower values. The reason for the high $PM_{2.5}$ levels in the meeting room is unknown.

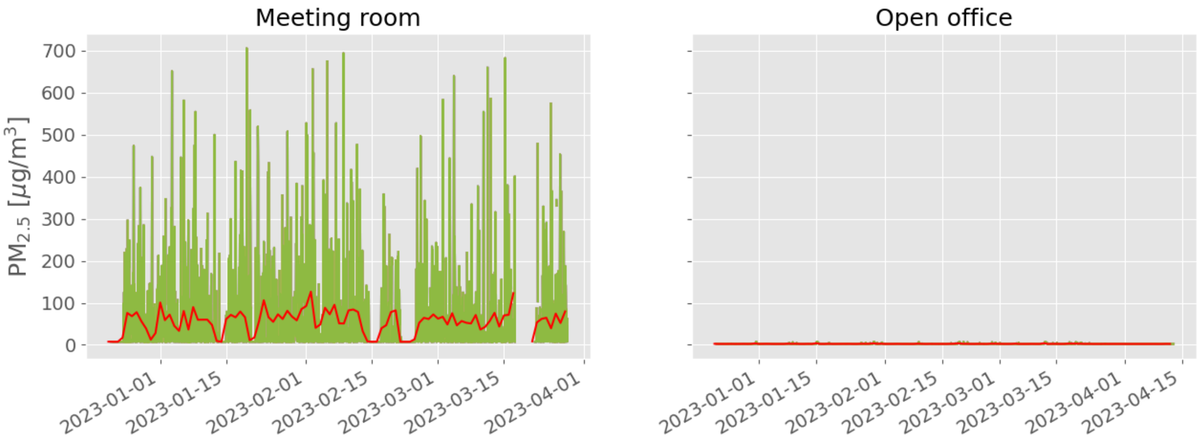


Figure 6.3.4: Hourly average (green) and 24-hour average (red) particulate matter (2.5 μ) levels in Powerhouse Brattørkaia.

As there is such a significant difference in the $PM_{2.5}$ levels between the rooms, the $PM_{2.5}$ concentrations are also illustrated through boxplots as seen in figure 6.3.5. Without outliers, the maximum $PM_{2.5}$ levels in the open office are below 3 $\mu g/m^3$, whilst it is almost 8 $\mu g/m^3$ in the meeting room. For the meeting room peaks up to 700 $\mu g/m^3$ are also observed.

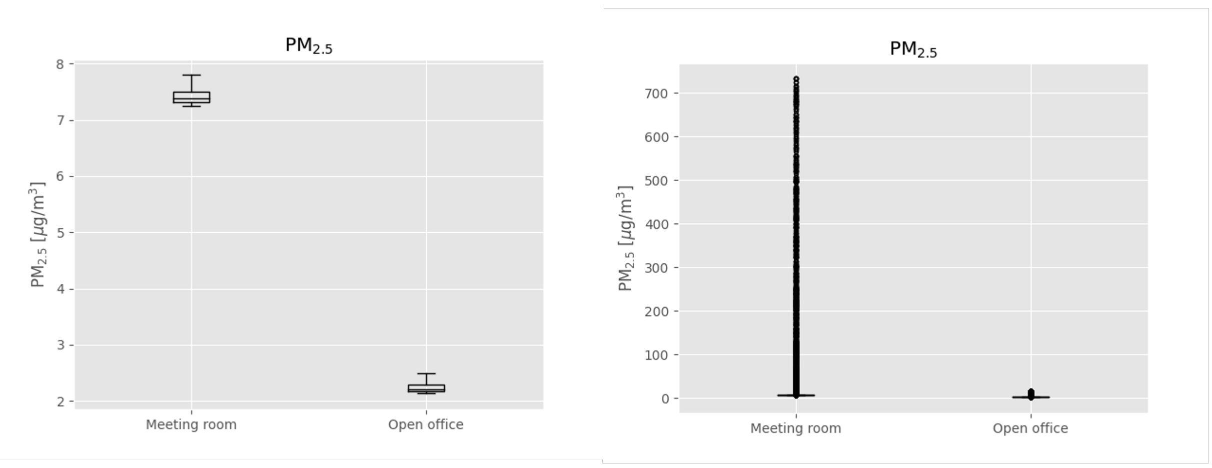


Figure 6.3.5: Boxplot of particulate matter levels in Powerhouse Brattørkaia. Without outliers (left) and with outliers (right).

6.3.5 TVOC Levels

Figure 6.3.6 illustrates the TVOC levels in Powerhouse Brattørkaia. Similar values and ranges can be observed for both rooms. The meeting room has slightly higher TVOC values and reaches slightly higher peaks up to 700 ppb, whilst the maximum TVOC levels observed for the open office is 600 ppb. An interesting observation is the high increase in TVOC levels from the first measurements to the beginning of January.

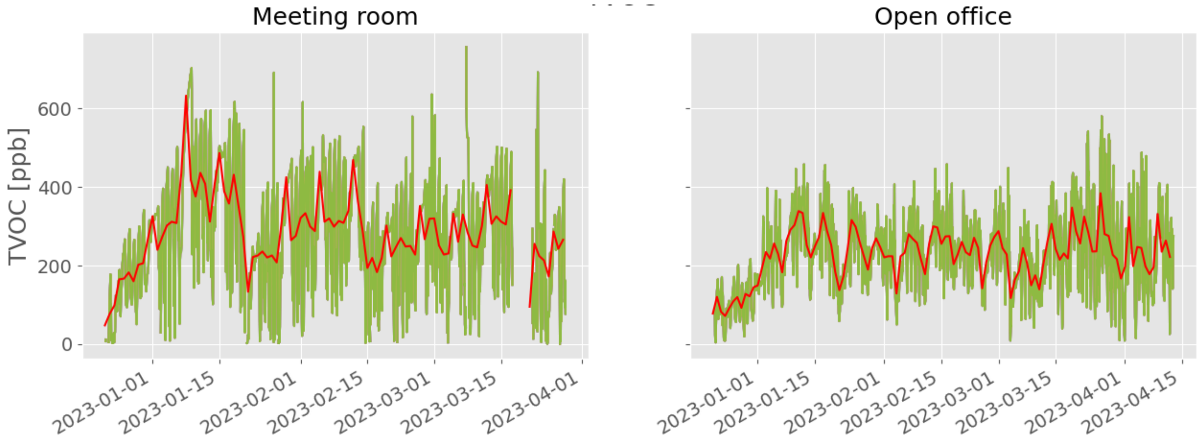


Figure 6.3.6: Hourly average (green) and 24-hour average (red) TVOC levels in Powerhouse Brattørkaia.

6.3.6 Formaldehyde Levels

The formaldehyde concentrations in Powerhouse Brattørkaia are illustrated in figure 6.3.7. 24-hour average values stay below 150 $\mu g/m^3$ in both rooms, with the exception of a peak in the meeting room of around 200 $\mu g/m^3$. Lower values can be observed during Christmas break.

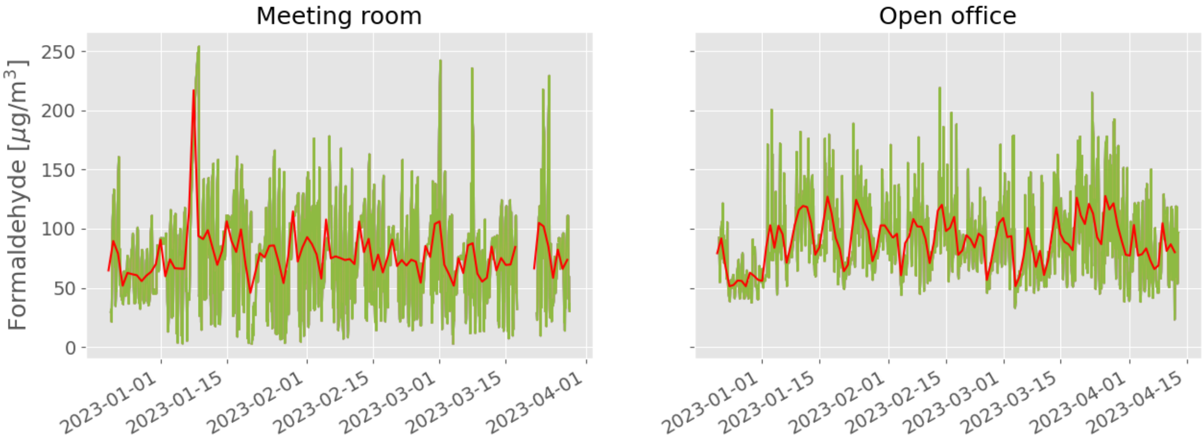


Figure 6.3.7: Hourly average (green) and 24-hour average (red) formaldehyde levels in Powerhouse Brattørkaia.

6.4 Effect of Material Choice on Humidity and Temperature

As the ZEB Laboratory and Powerhouse Brattørkaia are built from different materials, respectively massive wood and concrete, it is interesting to investigate how this affects the IAQ, especially the temperature and humidity levels. As humans emit heat and moisture, periods with no or few occupants present have been highlighted. The zones that have been chosen to compare are the open office in Powerhouse Brattørkaia and the open Office North (3) in the ZEB Laboratory.

Figure 6.4.1 illustrates the hourly average temperature levels in the ZEB Laboratory and Powerhouse Brattørkaia during Christmas and Easter break. For both periods, the temperature levels are higher in Powerhouse Brattørkaia and more stable, whilst the temperature level in the ZEB Laboratory is more fluctuating.

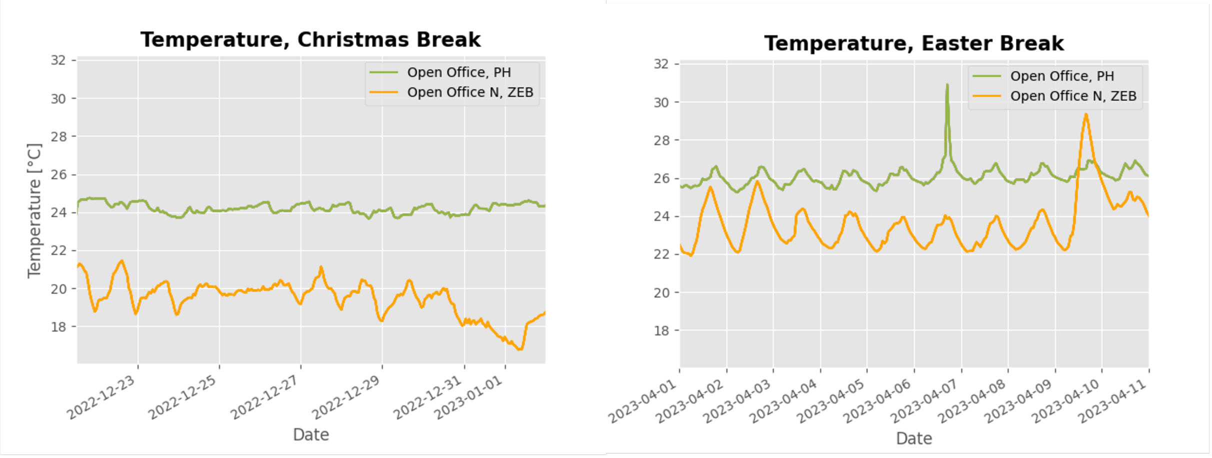


Figure 6.4.1: Hourly average temperature levels in ZEB Laboratory and Powerhouse Brattørkaia for Christmas and Easter break.

Figure 6.4.2 illustrates the hourly average humidity levels in the ZEB Laboratory and Powerhouse Brattørkaia during Christmas and Easter break. Higher humidity levels can be observed in the ZEB Laboratory for both periods.

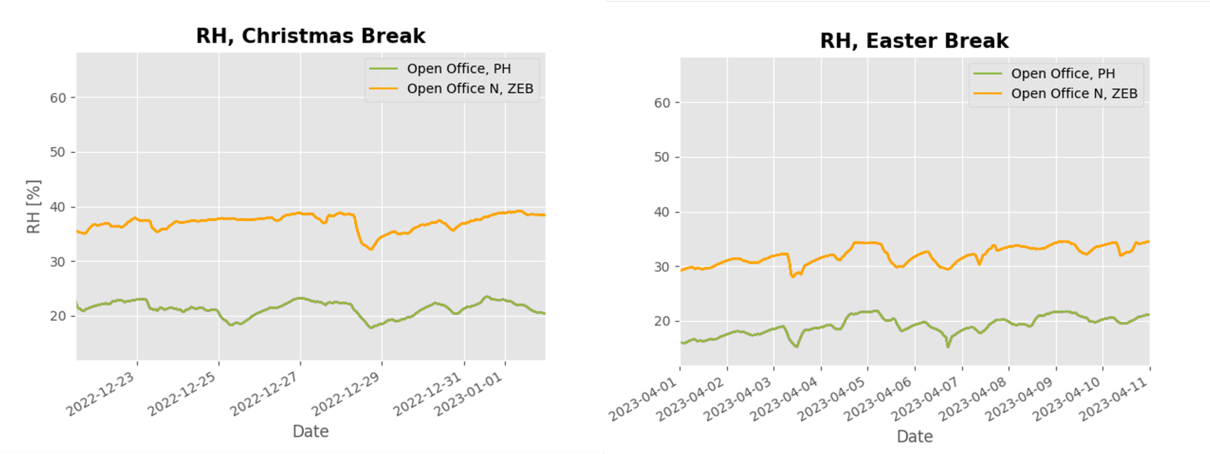


Figure 6.4.2: Hourly average humidity levels in ZEB Laboratory and Powerhouse Brattørkaia for Christmas and Easter break.

6.5 Perceived Air Quality

The results presented in this chapter are obtained from an odor experiment conducted over a period of two days at the end of March, as described in chapter 5.4. Four tests were executed in total, two each day, with four different percentages of recirculated air (0%, 25%, 50% and 75%). The panelists evaluated the different odor samples by answering a questionnaire based on ISO 16000-30:2014, which can be found in Appendix D. Perceived thermal comfort and air quality was also evaluated in each room by the occupants. These questions can be found in Appendix C.

6.5.1 Measured Parameters of Laboratory Test Facility

Each room was equipped with a sensor box measuring temperature, RH, CO_2, formaldehyde, particulate matter, and TVOC. Figures 6.5.1 to 6.5.7 illustrate how the indoor air quality develops during the tests. It is important to state that the panel members were introduced to the odor from each room at the end of each test, meaning the answers from the questionnaire are based on the physical parameters in each room 75 minutes from test start.

As expected, the temperature is increasing for all tests in all rooms. The tests conducted first during the day, with 0% and 75% recirculated air, have lower temperatures compared to the tests conducted last of the day.

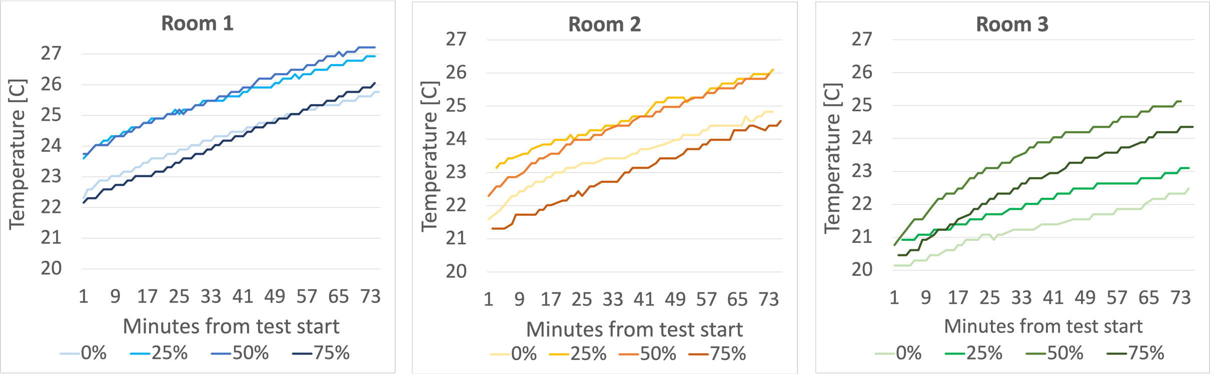


Figure 6.5.1: Development of temperature for rooms 1, 2, and 3 for different percentages of recirculated air.

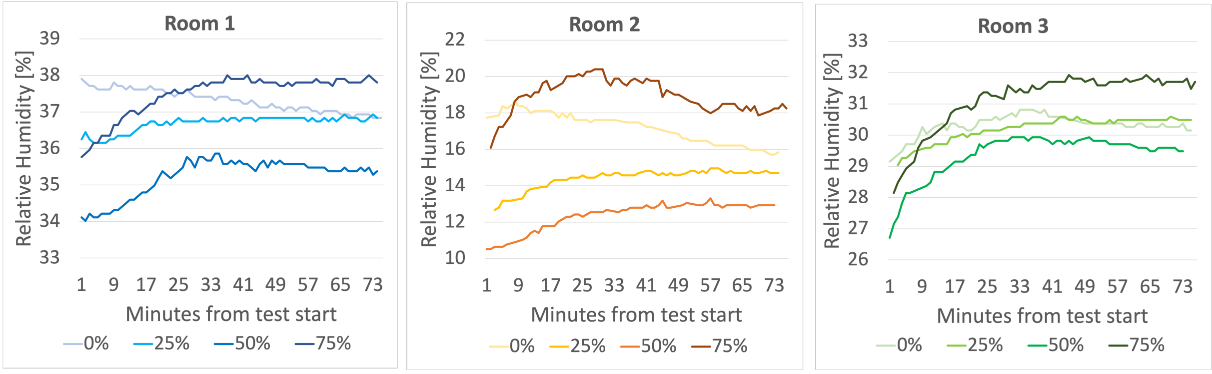


Figure 6.5.2: Development of relative humidity for rooms 1, 2, and 3 for different percentages of recirculated air.

For relative humidity, varying levels can be observed for the different rooms. Whilst room 1 and 3 has humidity values above 30, room 2 has humidity levels below 20. Due to the varying humidity levels, figure 6.5.3 illustrates the original values for RH (not calibrated).

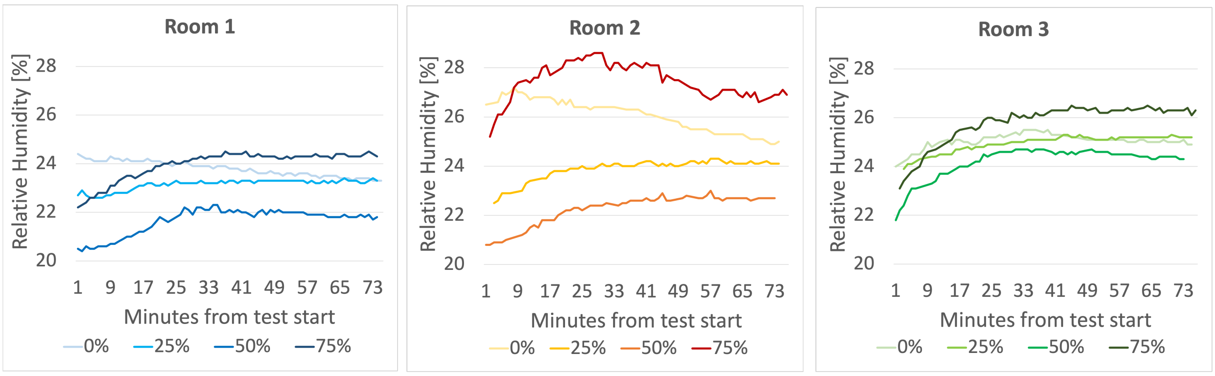


Figure 6.5.3: Development of relative humidity for rooms 1, 2, and 3 for different percentages of recirculated air. Raw data, values not calibrated.

The reason for the lower humidity values for room 2 can be explained by the regression analysis. Whilst the sensors used in room 1 and 3 have high R^2 values for RH, 0.9194 and 0.915 respectively, room 2 has a lower R^2 value of 0.472.

From figure 6.5.4, increasing CO_2 levels can be observed during each test. The CO_2 levels are also increasing with higher percentages of recirculated air. Higher CO_2 levels can be observed in room 2 with 0 and 25% recirculated air. For the tests with 50 and 75% recirculated air, higher CO_2 concentrations can be observed in room 3. The explanation for these elevated values is the male occupant in the situated room.

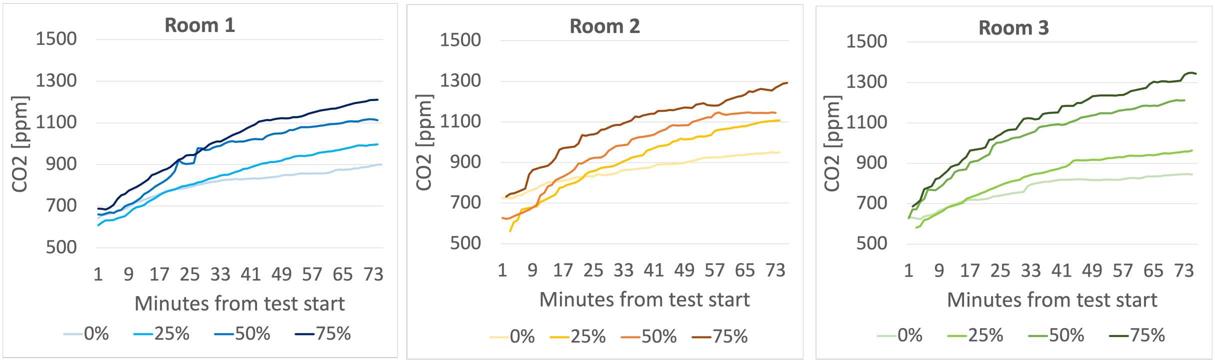


Figure 6.5.4: Development of CO_2 for rooms 1, 2, and 3 for different percentages of recirculated air.

No calibration equation exists for the sensor used in room 2, and thus the $PM_{2.5}$ concentrations for rooms 1 and 3 are the only ones displayed. It is also important to mention that whilst the concentrations for rooms 1 and 3 are above 5 and 2 $\mu g m^3$, the uncalibrated $PM_{2.5}$ levels for room 2 are all under 1. From figure 6.5.5, rapidly decreasing $PM_{2.5}$ levels can be observed for the test with 50% recirculated air. Why the $PM_{2.5}$ levels are decreasing more rapidly during this test compared to the other tests is unknown.

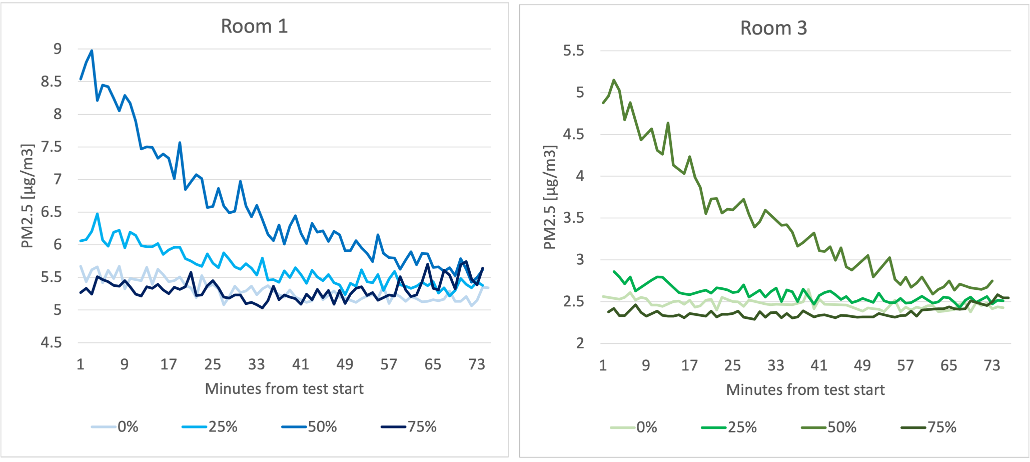


Figure 6.5.5: Development of $PM_{2.5}$ for rooms 1, 2, and 3 for different percentages of recirculated air.

Figure 6.5.6 shows the TVOC levels for rooms 2 and 3. For room 1, the sensor only measured 0. TVOC levels are observed to be the lowest overall for the test with 25% recirculated air and highest for the test with 50% recirculated air.

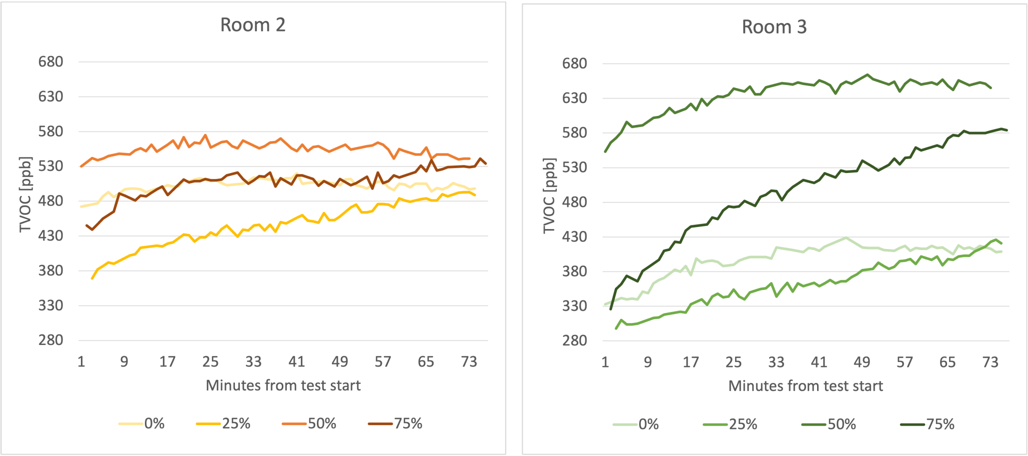


Figure 6.5.6: Development of TVOC for rooms 1, 2, and 3 for different percentages of recirculated air.

Figure 6.5.7 shows the formaldehyde levels for rooms 1, 2, and 3. The highest formaldehyde levels can be observed in room 2 and the lowest in room 1. Whilst the formaldehyde levels in room 1 have a slight increase throughout the tests, the levels in rooms 2 and 3 are more abnormal. The reason for this is most likely due to an error in the sensor itself.

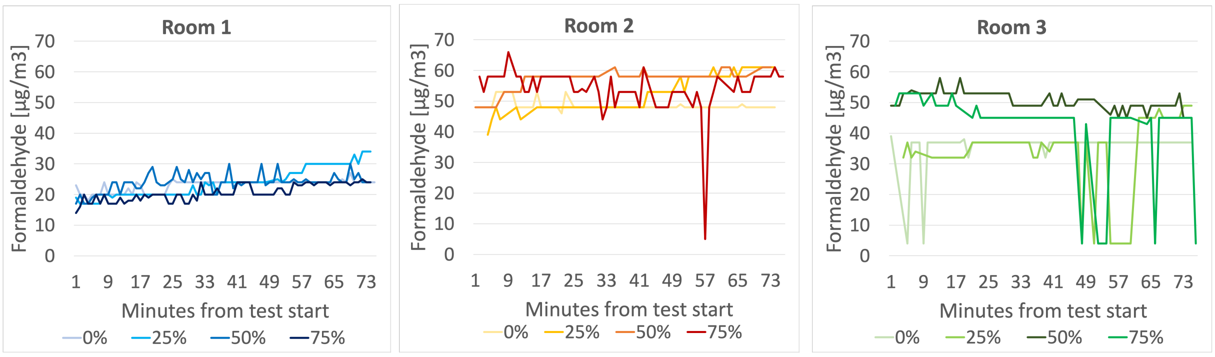


Figure 6.5.7: Development of formaldehyde for rooms 1, 2, and 3 for different percentages of recirculated air.

6.5.2 Occupants Perception of Indoor Climate

It is interesting to investigate how an occupant's perception of the indoor climate corresponds to the measured parameters for air quality. The questions handed to the occupants in the three rooms were intended to investigate this, in addition to a typing test to see how the air quality affected their cognitive abilities.

Cognitive Test

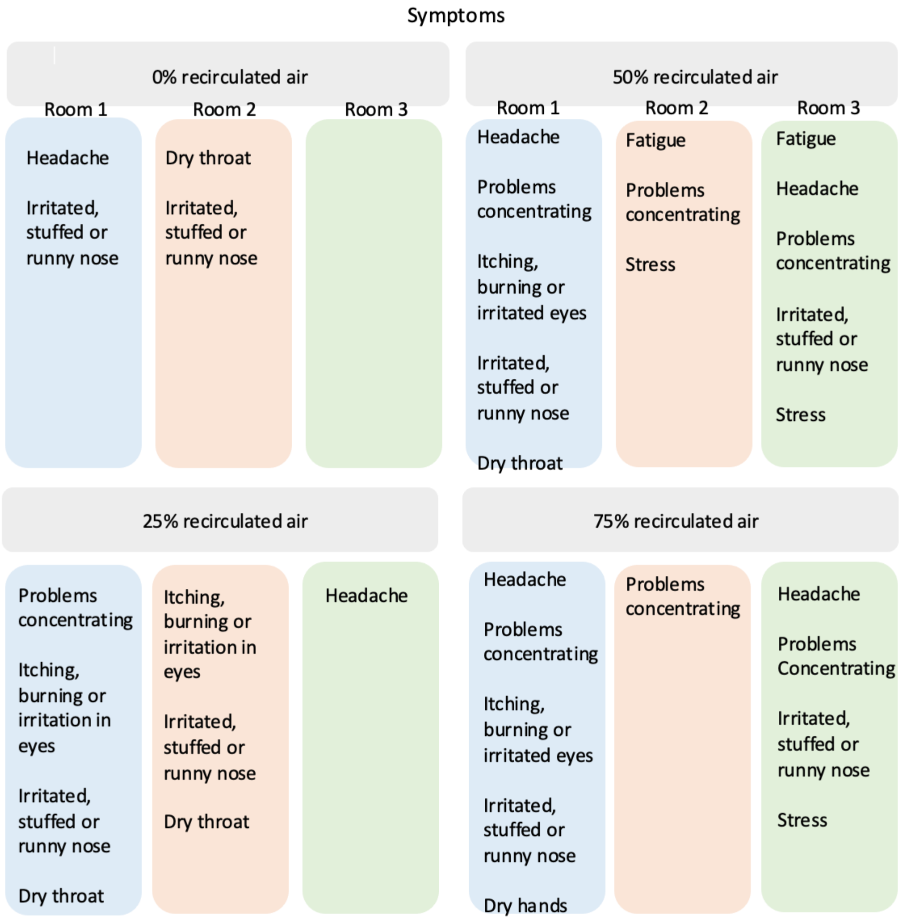
Table 6.5.1: Words per minute and accuracy for each test with different percentages of recirculated air.

		Room 1	Room 2	Room 3
0% recirculated air				
Start	WPM	40	33	39
	Accuracy [%]	94	92	94
End	WPM	46	37	54
	Accuracy [%]	94	93	96
25% recirculated air				
Start	WPM	50	43	52
	Accuracy [%]	96	94	96
End	WPM	44	41	51
	Accuracy [%]	94	92	96
50% recirculated air				
Start	WPM	46	45	37
	Accuracy [%]	94	95	92
End	WPM	46	51	44
	Accuracy [%]	94	97	96
75% recirculated air				
Start	WPM	51	46	36
	Accuracy [%]	97	95	91
End	WPM	44	35	43
	Accuracy [%]	95	92	93

Table 6.5.1 summarizes the results from the typing test. The test is measured in WPM and accuracy. For the test with 0% recirculated air, all participants achieved higher WPM and accuracy on the test at the end. On the test with 25% recirculated air, all participants' results decreased. With 50% recirculated air, one participant scored the same at the start and beginning, and the other two had better results. At the test with 75% recirculated air, two participants had worsening results, whilst the third participant had improving results.

Air Quality and Thermal Comfort

The first question asked was if the occupants were experiencing any symptoms as a result of the condition of the air in the room. Figure 6.5.8 summarizes the answers from the occupants. For the test with 0% recirculated air, symptoms such as headache, dry throat, and irritated, stuffed, or runny nose were reported. For the test with 25% recirculated air the same symptoms were reported, in addition to problems concentrating, itching, burning, or irritation in the eyes, and dry throat. The test with 50% recirculated air was the test with the most reported symptoms, some of which were fatigue and stress. For the test with 75% recirculated air, similar, but fewer, symptoms were reported than the test with 50% recirculated air, which may seem unexpected. This is likely due to the fact that the test with 75% recirculated air was performed first on the second day, and the test with 50% recirculated air was performed after.



Symptoms

0% recirculated air

Room 1	Room 2	Room 3
Headache Irritated, stuffed or runny nose	Dry throat Irritated, stuffed or runny nose	

50% recirculated air

Room 1	Room 2	Room 3
Headache Problems concentrating Itching, burning or irritated eyes Irritated, stuffed or runny nose Dry throat	Fatigue Problems concentrating Stress	Fatigue Headache Problems concentrating Irritated, stuffed or runny nose Stress

25% recirculated air

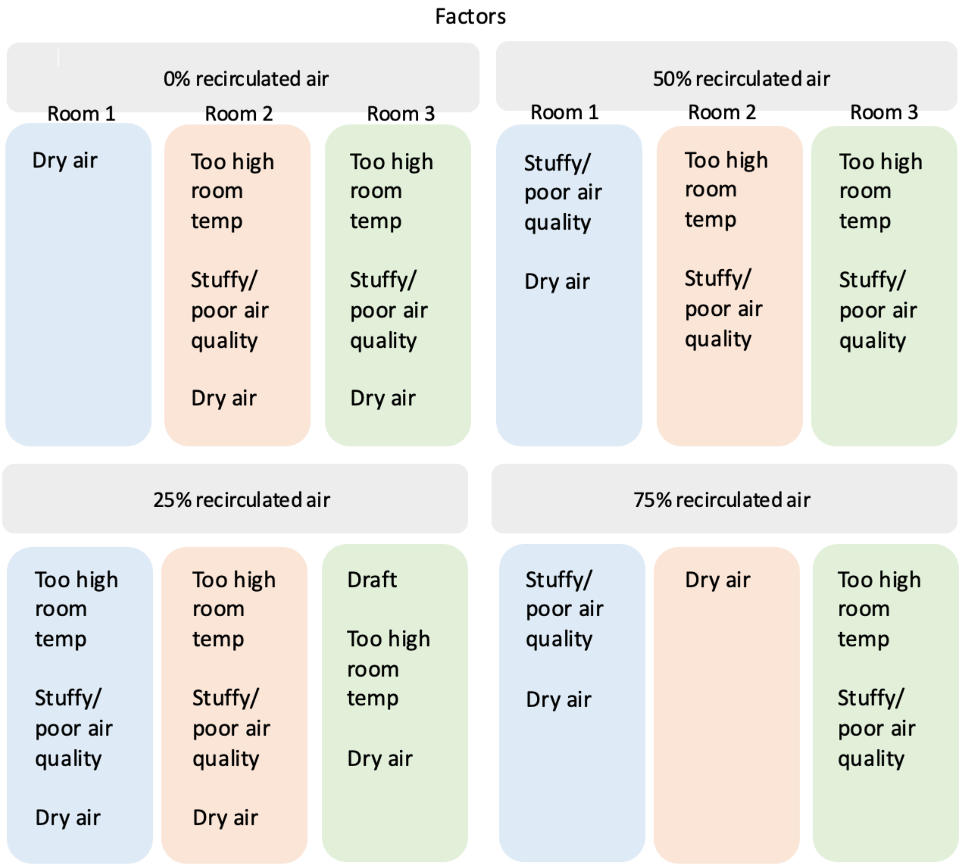
Problems concentrating Itching, burning or irritation in eyes Irritated, stuffed or runny nose Dry throat	Itching, burning or irritation in eyes Irritated, stuffed or runny nose Dry throat	Headache

75% recirculated air

Headache Problems concentrating Itching, burning or irritated eyes Irritated, stuffed or runny nose Dry hands	Problems concentrating	Headache Problems Concentrating Irritated, stuffed or runny nose Stress

Figure 6.5.8: Occupants symptoms as a result of the condition of air.

The second question the occupants were asked was if they were experiencing any of the following factors: draft, too high room temperature, varying room temperature, stuffy/poor air quality, dry air, or unpleasant smell. The answers to this question are summarized in figure 6.5.9. Dry air and too high room temperature were the factors most common, followed by stuffed/poor air quality.



Factors

0% recirculated air

Room 1	Room 2	Room 3
Dry air	Too high room temp Stuffy/ poor air quality Dry air	Too high room temp Stuffy/ poor air quality Dry air

50% recirculated air

Room 1	Room 2	Room 3
Stuffy/ poor air quality Dry air	Too high room temp Stuffy/ poor air quality	Too high room temp Stuffy/ poor air quality

25% recirculated air

Too high room temp Stuffy/ poor air quality Dry air	Too high room temp Stuffy/ poor air quality Dry air	Draft Too high room temp Dry air

75% recirculated air

Stuffy/ poor air quality Dry air	Dry air	Too high room temp Stuffy/ poor air quality

Figure 6.5.9: Experienced factors by occupants.

The last questions asked the occupants were their experience of the room temperature and air quality. Additionally, a follow-up question was asked if the occupant was feeling cold, and if so, where. The results are summarized in table 6.5.2. The temperature was experienced as acceptable, good, and poor two times. The air quality was experienced as mostly poor or very poor. The only times the air quality was experienced as acceptable was the first test with 0% recirculated air.

Table 6.5.2: Occupants' experience of room temperature and air quality.

	Room 1	**Room 2**	**Room 3**
0% recirculated air			
Temperature	Acceptable	Acceptable	Good
Air quality	Acceptable	Poor	Acceptable
25% recirculated air			
Temperature	Poor	Acceptable	Acceptable
Air quality	Poor	Poor	Poor
50% recirculated air			
Temperature	Acceptable	Acceptable	Poor
Air quality	Poor	Very poor	Very poor
75% recirculated air			
Temperature	Acceptable	Acceptable	Acceptable
Air quality	Poor	Poor	Very poor

6.5.3 Sensory Assessment - Panel

This chapter presents the answers from the questionnaire by the panelists, in addition to a sensitivity analysis of the answers. Even though the questionnaire originally included a question about hedonic tone, these answers have been disregarded as they are evaluated as irrelevant to the scope.

Percentage Dissatisfied

The first question in the questionnaire is whether the odor is acceptable if exposed to in everyday life. The question is asked as a yes/no question to determine the percentage of dissatisfied and is calculated by comparing the number of panelists who answered no to the total number of panelists, as denoted in equation 2.4.1.

Figure 6.5.10 illustrates the results from the percentage of dissatisfied evaluation. Overall, room 3 has the highest percentage dissatisfied for almost all percentages of recirculated air, followed by room 2. Room 1 on the other hand, has overall lower percentages for all tests.

Odor Acceptability

To assess odor acceptability, the same question as for the percentage of dissatisfied is used. The panelists rate the acceptability on a scale ranging from clearly acceptable (1) to clearly unacceptable (-1). Figure 6.5.11 illustrates the results for all three rooms with different percentages of recirculated air. Marked in the figure are the mean values and the range of responses. All tests show a wide range from highest to lowest evaluated acceptability. For room 1, all mean values are above zero, whilst for room 3, all mean values are below zero. For room 2, half are above zero, and the other half are below. The highest acceptability is for room 1 at 75% recirculated air. Room 1 has the highest acceptability for all percentages of recirculated air.

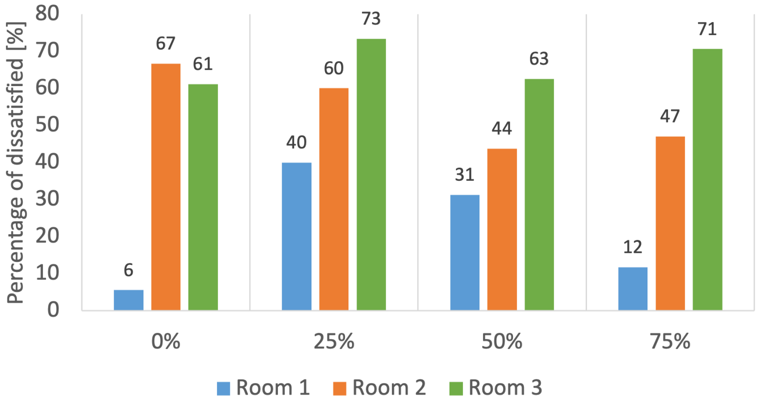


Figure 6.5.10: Percentage of dissatisfied for each room and percentage of recirculated air.

Odor Intensity

The assessment of odor intensity is rated on a scale from no odor (0) to extremely strong odor (6). Figure 6.5.12 presents the outcome from the sensory panel tests. The mean odor intensity varies from 1.25 up to 3.56, which is between very week and strong intensity. Room 1 has the lowest mean odor intensity for all percentages of recirculated air, followed by room 2.

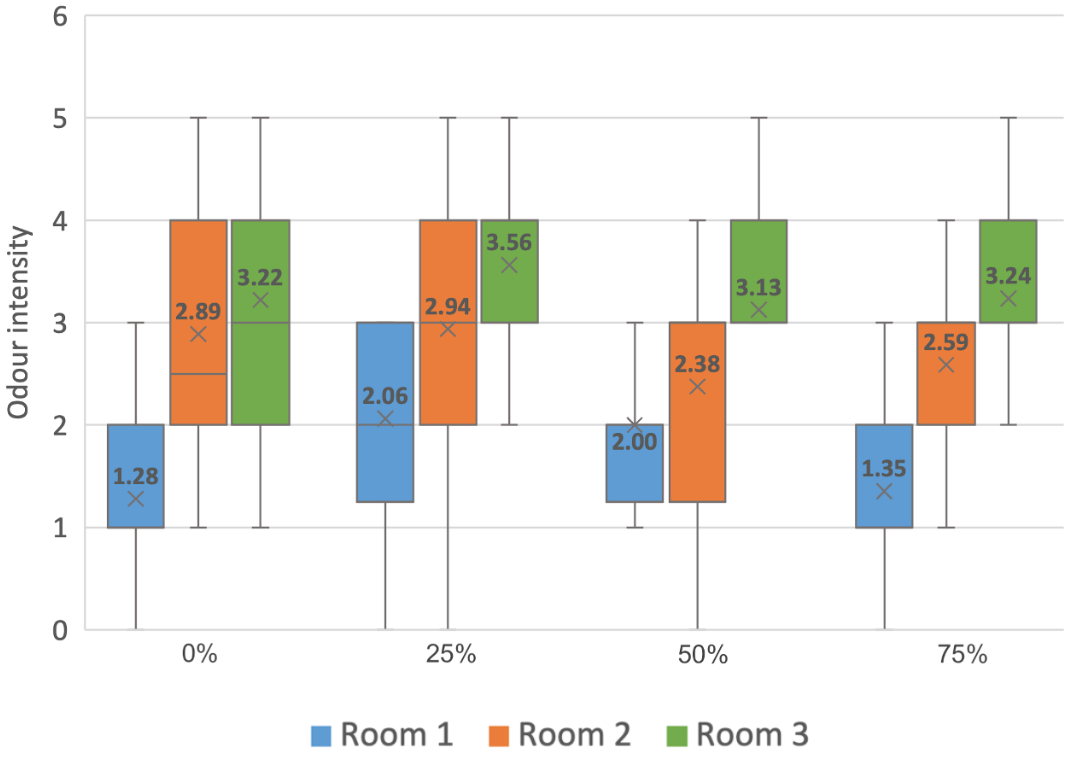


Figure 6.5.12: Odor intensity for all three rooms with different percentages of recirculated air.

Accuracy of Sensory Assessments

Table 6.5.3 presents the mean values for air acceptability and odor intensity for the odor experiment. The table also includes the 90% confidence interval of the mean. For odor acceptability,

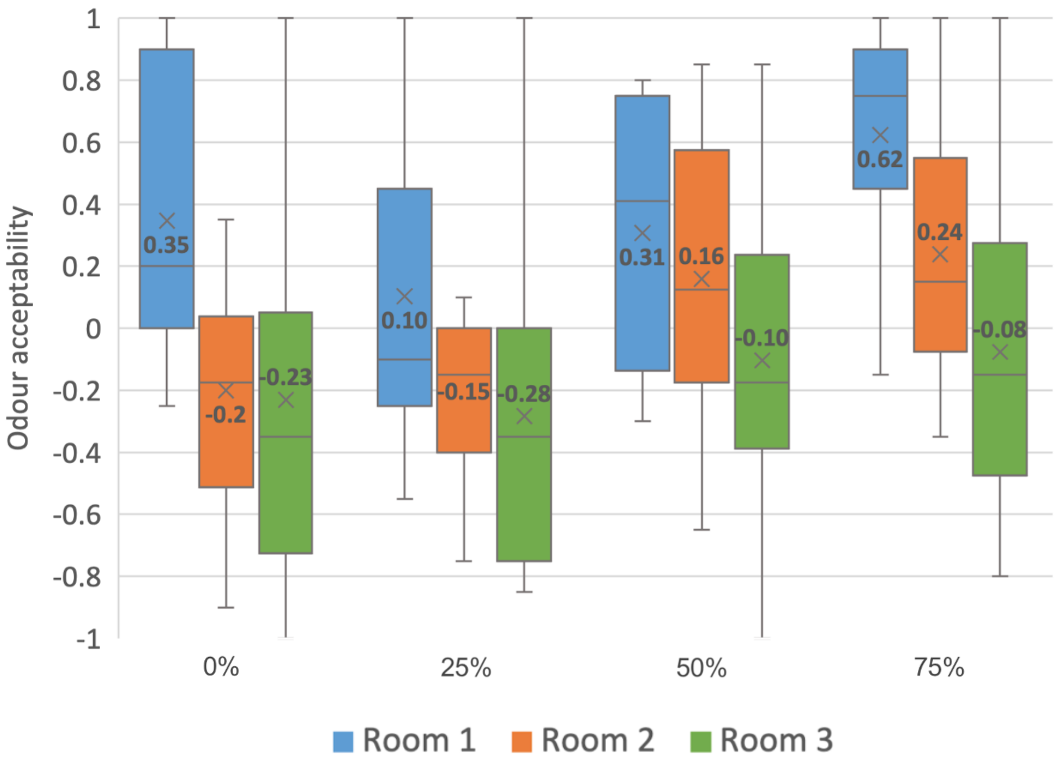


Figure 6.5.11: Odor acceptability for all three rooms with different percentages of recirculated air.

the confidence interval shall not exceed 0.2 for the measurements to be considered accurate. For all four tests, room 3 exceeds 0.2, and for the test with 25% recirculated air, all rooms exceed this value. Otherwise, the confidence interval is 0.2 or lower. For odor intensity, the confidence interval shall not exceed 1, and all tests stay below the accuracy requirement.

Table 6.5.3: Mean values for odor acceptability and intensity, and their 90% confidence interval.

	Odor Acceptability	**Odor Inensity**
0% recirculated air		
Room 1	0.34 ± 0.18	1.28 ± 0.34
Room 2	-0.2 ± 0.19	2.89 ± 0.49
Room 3	-0.23 ± 0.25	3.22 ± 0.50
25% recirculated air		
Room 1	0.10 ± 0.23	2.20 ± 0.44
Room 2	-0.09 ± 0.22	3.13 ± 0.61
Room 3	-0.28 ± 0.23	3.80 ± 0.61
50% recirculated air		
Room 1	0.31 ± 0.18	2.13 ± 0.49
Room 2	0.16 ± 0.20	2.53 ± 0.55
Room 3	-0.10 ± 0.21	3.33 ± 0.60
75% recirculated air		
Room 1	0.62 ± 0.16	1.35 ± 0.39
Room 2	0.24 ± 0.15	2.59 ± 0.34
Room 3	-0.08 ± 0.21	3.24 ± 0.49

Chapter 7

Discussion

This chapter presents a general discussion based on the findings from the results, research questions, and relevant literature. Additionally, a summary of sources of errors related to the experiments is included.

7.1 Methods

The procedures conducted in this thesis are affected by various factors that may have had an impact on the final results. The sources of error related to the calibration of sensors and the odor experiment are discussed in the following section.

7.1.1 Lab Calibration of Sensors and Regression Analysis

Sensor calibrations were carried out for the indoor air quality parameters CO_2, temperature, relative humidity, and $PM_{2.5}$. The sensor calibration was only performed once, a couple of months after the sensors had already begun measuring in the ZEB Laboratory. The sensors were then returned to their designated position for further measurements. For six of the sensor boxes, new calibration files were made, whilst for sensor boxes ID25 (main entry) and ID26 (canteen), the old calibration files were kept due to technical difficulties. The exact effect this has had on the measurements overall is unknown, but should not have any significant impact on the analyzed results.

Due to a lack of equipment, the sensors measuring TVOC and formaldehyde were not calibrated. This is a setback as it would provide valuable insight into how these sensors work. Even though the fabricator states that the sensors are pre-calibrated and no further calibration is needed, a laboratory calibration would provide insightful information about their accuracy and drift. This would have been helpful when analyzing the field measurements from the ZEB Laboratory and Powerhouse Brattørkaia, in addition to the results from the Odor experiment, and made the results more realiable.

The chamber used for the calibration itself is of good size and has room for all the sensors and additional equipment. The chamber is still small enough for the air to mix easily. It is valuable that the chamber has room for several sensors simultaneously so that they can be calibrated under the same conditions. There is however no functioning integrated mixing fan, and there is therefore some uncertainty about how well the air in the chamber is mixed. As the chamber is small, it is assumed that the lack of a mixing fan does not have an effect on the quality of the calibrations.

When calibrating low-cost sensors for IAQ measurements, it is important to have different concentration levels. To achieve this, different measures and equipment were used. A wetted chipboard was used to reach different humidity levels, and candles were used for varying the CO_2, temperature, and $PM_{2.5}$ levels. Additionally, the hatch in the chamber was used when the CO_2 levels reached concentrations unrealistic to be found indoors. Thus, the varying concentration levels found indoors were replicated. Additionally, the response of a sensor is typically nonlinear, meaning it may not respond proportionally to changes in pollutant concentrations. Calibration across different concentration levels helps develop a response curve that accurately maps the sensor's output to the corresponding pollutant levels.

The data from the calibration experiment was analyzed using linear regression to obtain calibration equations and R^2 values for each sensor. Linear regression does however not consider the impact of temperature and humidity on the sensor, which some of the sensors can be affected by. With linear regression, the weight of each data point is not dependent on the distance from the fitted line, meaning unwanted disturbances are included. Thus, for those sensors with unsatisfactory R^2 values, a more extensive regression analysis should be performed before the calibration equations are used to correct the raw sensor readings. This was not achieved due to time limitations.

7.1.2 Perception of Air Quality - Odor Experiment

During the odor experiment, several challenges and difficulties were encountered, which in one way or another, have affected the results. The major challenge was that the air handling unit and system for the test facility was incorrectly dimensioned, in addition to other unknown technical difficulties. Other inconveniences that may have affected the results are human error or time limitations.

The fact that the air handling unit and system for the test facility were incorrectly dimensioned made it difficult to control the valves and achieve exact values for the ventilation rate in each room. Thus simplifications had to be made, resulting in ventilation rates of 33 m^3/h instead of the recommended values from TEK17 of 26 m^3/h. This has not had a major impact on the results, as the main focus and purpose of the experiment were still intact.

Due to an unknown technical fault in the system, the sensors in rooms 2 and 3, which were connected to the system, would suddenly stop measuring. The intervals in which they would measure would differ from 1 minute to 1 hour. Even though inconvenient, it was possible to begin the measurements again when this happened. This did however result in several gaps in measurements from the experiment. Furthermore, the sensors take around 30 minutes to stabilize, and thus all measurements prior to this should be disregarded when analyzing the results. This was not possible to achieve. It does not seem that this has affected the measurements of temperature, relative humidity, CO_2, TVOC, and $PM_{2.5}$ significantly. However, it did have an impact on the measurements of formaldehyde, resulting in strange and unreliable curves.

A cooler was used to lower the inlet temperature for the three rooms. This cooler emits cool air, which was connected to the inlet pipe, but also occasionally emits warm air from the back. The cooler was positioned so that the warm air was shooting at the back corner of room 1. As the cooler is on wheels, it could have easily been positioned differently. This does however explain why the temperature level in room 1 was always the highest of the three rooms, when it is expected to be room 2 in the middle. Overall it does not have any significant impact on the results and the main purpose of the experiment.

A ”sniff-box” was used to push air from the rooms out through a pipe for the panelists to evaluate the odor. The pipe from the ”sniff-box” is supposed to be positioned directly upwards. However, it was discovered last minute that for the participants to be able to reach the end of the pipe, it had to be slightly tilted to the side. Due to time limitations, no solution to this was found in time before the experiment, and it was decided not to reschedule the experiment due to the number of participants needed. It is unknown to which degree this has affected the results.

Other factors that may have had an impact on the results are the time between each test and the relative humidity in the rooms. The tests were conducted over two days, with two tests each day due to time limitations. By only conducting one test each day, the starting conditions in each room would have been more similar, in addition to the well-being of the occupants located in each room. The overall relative humidity in all three rooms was on the lower side for all four tests. As the perception of odor is influenced by relative humidity, the ISO 16000-30 standard for sensory testing of indoor air states that the relative humidity should be 50% ± 5%. This was not accomplished due to the lack of access to air humidifiers.

7.2 Review of Research Questions

The research questions form the foundation of the research conducted for this master's thesis. The research questions are answered and discussed in the following and are based on the results presented in chapter 6 and relevant theory.

Question 1: How well do low-cost sensors work for monitoring and analyzing indoor air quality?
Low-cost sensors for monitoring and analyzing indoor air quality have gained popularity over the last years due to their affordability and accessibility. There are, however, some variances in performance and reliability. It is, therefore, important to understand the limitations and strengths of each sensor to interpret IAQ data correctly.

A significant weakness in the field measurement setup is the larger periods of missing data or sudden stops of measurements. Thus, it is important to regularly check that the sensors are still measuring or install some type of technical solution that alerts when the sensors stop measuring. However, whilst collecting data from one of the sensor boxes, it would appear that the sensors were measuring when in fact, they only logged dates and timestamps. This is most likely an error in the Raspberry Pi, and not the sensor itself. It is nevertheless unfortunate and results in missing data. The significance of this problem depends on what the sensors are being used for and their placement. If a sensor is placed in a ventilation duct, for instance, this would be a problem, as it would be challenging to access regularly. In this situation, one would be more dependent on the sensors being able to measure over longer time periods without issues. However, for monitoring the air quality in an office or other open spaces indoors, this is only an inconvenience as one would still be able to collect sufficient data to assess the air quality.

A factor to consider is the long-term stability and durability of the low-cost sensors, as their performance might degrade over time due to environmental factors or sensor aging. It is thus important to monitor and maintain the sensors regularly to ensure reliable and consistent performance. According to the datasheet from the manufacturer for the SCD30 sensor module for measuring CO_2, temperature, and humidity, the module has a lifetime of 15 years with some reports on drift. For the CO_2 sensor, the accuracy drift over its lifetime is ± 50 ppm, the accuracy drift for temperature is 0.03°C/year, and the accuracy drift for humidity is $< 0.25\%$/year. Observing the measured values, higher drifts than what is stated in the datasheet can be observed for temperature and relative humidity. According to the datasheet for the SPS30 sensor measuring particulate matter, measurements are stated to be precise from its first operation and throughout its lifetime of ten years. However, increasing deviations with increasing concentrations can be observed between the measurements from the low-cost sensor and the reference sensor. When it comes to the SPG30 sensor for measuring TVOC, the datasheet states that the SGPG30 sensor guarantees high reproducibility and reliability throughout its lifetime. Whether this is accurate or not is unknown, as no calibration was performed.

Compared to reference-grade instruments, low-cost sensors generally have lower accuracy and precision. Even though they can provide useful insight into IAQ trends, their absolute measurements may have some level of error. It is thus important to validate the data from low-cost sensors by comparing it with reliable reference instruments to ensure accuracy. As discussed in the previous paragraph, low-cost sensors may experience drift, and thus regular calibration helps to minimize this and provides reliable and consistent measurements. Even though the datasheets for the sensors state minimal drift over the years, deviations of different magnitudes are observed. For the low-cost temperature sensors, all sensors measure higher values than the reference sensor, and for the low-cost humidity sensors, all sensors measure lower values than the reference sensor. Thus, calibration is important to adjust the offset before further analysis of the data. Regarding the WZ-S sensor measuring formaldehyde, the datasheet states that the module is pre-calibrated and can be integrated into a system directly. As no calibration was performed with this sensor, it is unknown to which degree this is correct or not. However, this is the sensor that has shown the least stability during experiments and field measurements. As the lifetime of this sensor is 5 years, it is suspected that it is at the end of this period. In the datasheet for the SCD30 module for the CO_2 sensor, it is stated that the sensor is maintenance-free when ASC field calibration algorithm is used, meaning exposed to air with 400 ppm CO_2 concentrations regularly. This was probably correct when the sensor was brand new and unused, but calibrations show that there is still a deviation larger than ± 50 ppm when this is performed, and thus calibration is still needed.

Despite their limitations, low-cost sensors have the potential to make a substantial contribution to the monitoring of indoor air quality due to their accessibility and affordability. These sensors can be valuable screening tools for detecting possible IAQ problems, tracking trends, and initiating measures to enhance IAQ. However, it is important to acknowledge that low-cost sensors have limitations, such as accuracy, and are susceptible to drift over time. It would for instance be unfortunate to use raw data to determine if the air quality is within limit values and guidelines, with a sensor measuring concentrations several levels too high or low. It is therefore advised to supplement or validate data with reference-grade instruments and regular calibrations to ensure greater confidence in the results.

Question 2: Assessment of indoor air quality in ZEB Laboratory and Powerhouse Brattørkaia. How are the temperature and relative humidity affected by the material selection?
Measuring indoor air quality typically involves assessing parameters such as temperature, humidity, CO_2 levels, TVOC, particulate matter, formaldehyde, and other potential pollutants. These measurements provide quantitative information about the air quality in terms of pollutant concentrations and adherence to established standards or guidelines. Additionally, it can provide insight into identifying potential sources that can help limit emissions and reduce concentrations.

The CO_2 levels for all zones in the ZEB Laboratory are under the guideline limit of 1000 ppm, with the exception of a few peaks. This indicates that the ventilation in the building is adequate in relation to the number of occupants in the zones. The CO_2 levels in Powerhouse Brattørkaia are overall on the lower side, under 1000 ppm in the open office space, whilst more fluctuating levels are observed for the meeting room. This is to be expected as the meeting room is on the smaller side, used periodically and often by multiple people at the same time. In the meeting room, CO_2 concentrations appear to surpass 1000 ppm on multiple occasions, indicating that the ventilation in this room might not be adequate in relation to the number of occupants in the room. Several studies demonstrate a clear correlation between high concentrations of CO_2 and perceived poor indoor air quality. A study by Gupta investigated the link between indoor environment and workplace productivity in an office and found that task scores decreased by 15% for CO_2 concentrations above 800 ppm compared to the task scores at CO_2 levels below 800 ppm. Thus, one could assume that the workplace productivity in the ZEB Laboratory and the open space office in Powerhouse Brattørkaia, is sufficient for their employees when it comes to CO_2 levels.

TEK17 recommends temperatures between 19 and 26°C for light work, and several studies on the correlation between temperature and work performance indicate that productivity is unaffected by temperatures between 21 and 25°C. Temperatures in the ZEB Laboratory range from 10 to over 30°C and vary with the seasons. Mean temperatures in most of the zones are 21°C, whilst the mean temperature in the main entrance and canteen is 18°C. A temperature level of 10°C was observed in the main entrance and canteen at the end of December 2022, and although it is quite low, this is a period the building is most likely not in use due to Christmas break, and the heat is turned off or lowered. The temperature in Powerhouse Brattørkaia is on the higher side overall for the open office space with temperatures mostly around 25°C or higher, whilst the temperature in the meeting room is more fluctuating and lies around 21°C. How each occupant is affected by the temperature is individual, and there will always be some that find the temperature too high or low. However, according to the recommendation from TEK17 and the studies on the correlation between temperature and work performances, the measured values in both ZEB Laboratory and Powerhouse Brattørkaia are mostly within these ranges, indicating an overall adequate thermal and work environment.

When comparing the temperature levels in the ZEB Laboratory and Powerhouse Brattørkaia with material selection in mind, more fluctuating temperature levels can be observed for the ZEB Laboratory, whilst the temperature level in the open office landscape in Powerhouse Brattørkaia remains stable. This can be explained by the utilization of concrete in Powerhouse Brattørkaia. The concrete absorbs and retains heat and cold, which helps regulate the temperature in the building. In this way, the need for electric heating and cooling is also minimized.

According to NIPH, variations in humidity within 20-60% will have little influence on how the indoor climate is experienced. In the ZEB Laboratory, humidity levels down to 10% are observed during winter months. Lower concentrations of relative humidity down to 15% are also observed in Powerhouse Brattørkaia. Low indoor air humidity affects the mucous membrane of the nose and can cause what feels like dry and tired eyes, which may affect work performance. There is often a lower indoor humidity during winter, and symptoms are thus reported more frequently during this time of year. Even though RH levels below 45% are recommended during winter to reduce condensation risk, humidity levels above 30% are recommended to avoid damage to the mucous membrane. Higher levels of humidity are also observed in the ZEB Laboratory, mostly during the summer months. During these months the humidity levels lie mostly around 60%, and 80% in the canteen. It is however normal that the RH surpasses 70% in the late summer when the outdoor air is hot and humid.

When comparing the relative humidity levels in the ZEB Laboratory and Powerhouse Brattørkaia for the same period, higher humidity levels are observed in the ZEB Laboratory for both Christmas and Easter break. This can be explained by the utilization of wood and CLT in the ZEB Laboratory. As wood has hygroscopic properties, it has the ability to balance the moisture level in the indoor air. This means it can inhibit both excessive moisture loads and dry indoor air. The periods of comparison are however both during winter periods and how the moisture levels would appear during warmer months is unknown.

For $PM_{2.5}$ no indoor limit is given, and thus outdoor limit values are used. The guidelines from WHO state that annual average concentrations of $PM_{2.5}$ should not exceed 5 $\mu g/m^3$, while 24-hour average exposures should not exceed 15 $\mu g/m^3$ more than 3 - 4 days per year. In the ZEB Laboratory, all rooms exceed the guidelines from WHO, with the highest concentration found in the canteen of around 40 $\mu g/m^3$ and the lowest in the open office N (2) with concentrations around 3 $\mu g/m^3$ followed by the main entry with concentrations around 6 $\mu g/m^3$. The $PM_{2.5}$ concentrations are mostly stable throughout the measured period. The reasoning for the vast variations in $PM_{2.5}$ concentrations throughout the ZEB Laboratory is unknown. In Powerhouse Brattørkaia, $PM_{2.5}$ concentrations of 2 $\mu g/m^3$ are observed in the open space office, whilst concentrations from 7 and up to 700 $\mu g/m^3$ are observed in the meeting room. As the concentrations in the majority of the zones are higher than the guidelines from WHO, the sources are unknown, and the effects of particulate matter is relatively limited, further investigation is needed to implement the necessary measures to reduce the concentrations.

When it comes to TVOC, no upper limit values exist. Even though no limit value of concentration is set, one should avoid unnecessary exposure and be aware of typical sources. Measurements from the TVOC sensors also do not state which gases are detected. It is thus challenging to know if the measured concentrations are harmful or not. What TVOC concentrations can provide, however, is a better understanding of air quality changes related to pollutant activities and to identify off-gassing from building materials or furniture. In the ZEB Laboratory, measured concentrations can be observed to range from 0 to 25 000 ppb. The lowest concentrations can be observed in the main entry with concentration levels below 200 ppb. This can be explained by the access to fresh air from the opening of the door every day. TVOC concentrations in the other zones are more fluctuating, but no apparent trends can be observed. More reasonable, but still fluctuating, concentrations can be observed in the Powerhouse Brattørkaia, with maximum concentrations of 600 ppb. Variable sources, such as smoking, cleaning supplies, paint residue, hobby supplies, and cooking, can explain the sudden peaks in TVOC concentrations. As these are sources connected to human activity, and the sources are unknown, there is a significant uncertainty connected to these measurements. Another uncertainty is the fact that the TVOC sensors have not been calibrated, and thus the accuracy of the sensors is unknown. Due to these uncertainties, it is challenging to determine if the high concentrations are due to specific sources caused by human activity or if it is an error with the sensor itself.

According to NIPH the recommended limit value of formaldehyde is 100 $\mu g/m^3$ (30-minute average). In the ZEB Laboratory, formaldehyde concentrations are observed to be below the recommended limit value of 100 $\mu g/m^3$ in all zones. Towards the end of the measurement period, increasing formaldehyde concentrations are observed with peaks up to 250 $\mu g/m^3$. The reason for this is suspected to be an issue with the sensors themselves. The same problem with the formaldehyde sensors were occurring with the sensors measuring at Powerhouse Brattørkaia. At Powerhouse Brattørkaia, fluctuating concentrations can be observed, with peaks up to 250 $\mu g/m^3$. The reason for the elevated formaldehyde levels in both locations is unknown. Typical indoor sources for formaldehyde include resin, resins to manufacture composite wood products, building materials, and insulation. Further investigation is needed with more reliable sensors to find the sources and reduce the concentrations.

Indoor air quality is a multifaceted mixture of chemical and physical pollutants, each with different impacts on human health and the indoor environment. Analyzing measured concentrations can offer insights into whether guidelines and limit values are being met and whether the ventilation system is sufficient. Even though measured concentrations provide important insight into indoor air quality, the occupants' feedback and symptomatology is also important to consider in conjunction with the IAQ measurements. Reported discomfort, health issues, or specific complaints associated with the indoor environment can be helpful to identify potential sources of concern or validate the measurements. The occupant's perception of the air quality has not been investigated for the ZEB Laboratory and Powerhouse Brattørkaia, but would provide additional insightful information on the air quality.

Question 3: Based on the findings from the odor experiment, what is the correlation between measured air quality and perceived air quality?

The correlation between measured indoor air quality and perceived air quality can vary depending on several factors. While measured IAQ provides objective data on the physical and chemical composition of the air, perceived air quality is subjective and influenced by each individual experiences, expectations, and sensitivities. Perceived air quality is influenced by various factors such as odors, sensory experience, comfort, and personal preference. Thus, it is something that can differ significantly among individuals, and factors like age, health status, and personal sensitivities can impact how people perceive the air they are breathing.

According to several studies, work performance and cognitive abilities decrease when the temperature is outside a certain range or the CO_2 level is above a certain concentration. A study by Gupta investigated the link between indoor environment and workplace productivity in an office and found that task scores were 15% lower for CO_2 levels above 800 ppm compared to task scores conducted at levels below 800 ppm. Another study by Shendall et al. on the correlation between CO_2 levels in American classrooms and student attendance found that CO_2 levels above recommended values had a significant inhibitory effect on learning and work effectiveness.

From the odor experiment, as explained in section 5.4, a typing test was performed by the occupants evaluating words per minute and accuracy. One typing test was performed at the beginning and end of each test with increasing percentages of recirculated air. For the tests conducted with 25% and 75% recirculated air, aggravated results can be observed, whilst for the tests conducted with 0% and 50% recirculated air, improving results are observed. Thus, no clear trend or conclusion can be drawn from the results. However, it is important to note that the start level of CO_2 for all tests was relatively on the higher side, between 600 and 700 ppm. Additionally, after talking to the participants, a clear understanding of how the typing test actually worked became clear after their first attempt, which can explain the improvement in results. In hindsight, each participant should have attempted the typing test beforehand and lower starting levels of CO_2 should have been achieved. This could have given clearer and more reliable results.

In certain cases, a strong correlation exists between measured air quality parameters and perceived air quality. However, in some cases, discrepancies may arise. For example, certain pollutants may be present in low concentrations that fall within acceptable limits, but individuals with specific sensitivities or health conditions may still experience discomfort or perceive the air as poor. Conversely, a space with excellent measured IAQ may still be perceived as poor if other factors like poor ventilation, lack of natural light, or psychological factors come into play.

From the odor experience, there seems to be a strong correlation between the measured IAQ parameters and the perceived air quality. A questionnaire was handed to the participants about perceived air quality and thermal comfort. Headaches and problems concentrating can be observed with increasing CO_2 levels, whilst itching, burning or irritation in the eyes, irritated, stuffed or runny nose, and dry throat are observed with lower humidity levels. Occupants also experienced dry air, too high room temperatures, and stuffy and poor air quality, also correlating with the measured air quality parameters. Furthermore, some occupants experienced fewer symptoms than others, thus underlining how subjective and independent perceived air quality is. The occupants were also asked to evaluate the temperature and air quality from very poor to very good. From the results, most occupants evaluated the temperature as acceptable, even though the temperature levels were measured up to 27°C. The air quality was mostly evaluated as poor, which is also logical when observing the measured values. This shows that people seem to be able to adapt to higher temperatures, but are more sensitive to other IAQ parameters.

Perceived air quality also includes odor. During the odor experiment, a questionnaire was handed to a group of panelists for odor evaluation. For the percentage of dissatisfaction, no trend is observed in correlation to measured IAQ parameters or the percentage of recirculated air. It seems as if there is a greater correlation between the percentage of dissatisfaction and which person is sitting in the room, thus underlining how odor is subjective and individual. The same applies to odor acceptability. However, the accuracy of the sensory assessment shows confidence intervals exceeding the requirement to be considered accurate, and thus the resulting odor acceptability can not be considered accurate. For odor intensity, the confidence interval is below the accuracy requirement. However, no clear trend between odor evaluation and measured parameters can be observed here either. For odor acceptability and intensity, answers can be observed to range from clearly unacceptable (-1) to clearly acceptable (1), or no odor (0) to strong odor (5), for the same room, thus underlining the subjective nature of odor.

Chapter 8

Conclusion

The aim of this master's thesis was to test the reliability and accuracy of low-cost Arduino sensors and use the sensors to measure indoor air quality at the ZEB Laboratory and Powerhouse Brattørkaia. The indoor air quality parameters chosen for the assessment are CO_2, temperature, relative humidity, $PM_{2.5}$, TVOC, and formaldehyde. These measurements were also used to investigate the effect material selection of a building has on temperature and relative humidity. Additionally, an odor experiment was conducted to investigate the correlation between the percentage of recirculated air inducing various levels of indoor air quality parameters, perceived air quality, and odor.

The sensor calibration shows that low-cost sensors are susceptible to drift over time. The low-cost temperature sensors measure higher values than the reference sensor, and the low-cost humidity sensor measures lower values than the reference sensor. Overall higher R^2 values were obtained for the low-cost temperature, humidity, and CO_2 sensors, with some deviations, indicating a good fit of the obtained calibration equations. Overall low R^2 values were obtained for the low-cost $PM_{2.5}$ sensors. Despite their limitations, low-cost sensors have the potential to make a substantial contribution to the monitoring of indoor air quality due to their accessibility and affordability. However, it is important to acknowledge the limitations of low-cost sensors, such as drift and accuracy. It is therefore important to perform regular calibrations to minimize drift and offset, resulting in increased accuracy of the sensor. No calibration was performed for the TVOC and formaldehyde sensors, and thus it is challenging to assess their accuracy with certainty. However, it is worth mentioning the problems encountered with the formaldehyde sensors, where they would alternate between having reasonable measurement outputs or 0. The most logical explanation for this was found to be the age of the sensors.

Through literature review, a set of pollutants with adverse health effects was identified with limit values and guidelines from NIPH and WHO. This information, in addition to known sources and health effects, was used to analyze the measurements in the ZEB Laboratory and Powerhouse Brattørkaia. The findings indicate that CO_2 levels in the ZEB Laboratory and Powerhouse Brattørkaia are generally within acceptable limits, except for occasional peaks in the meeting room in Powerhouse Brattørkaia. Temperature levels are within recommended ranges in both buildings, with Powerhouse Brattørkaia benefiting from concrete's thermal regulating properties. Humidity levels fluctuate in both buildings, with lower levels observed during winter and higher levels during summer. $PM_{2.5}$ concentrations exceed WHO guidelines in both buildings, requiring further investigation to identify sources and implement mitigation measures. TVOC concentrations fluctuate from levels around 0 ppb up to 20 000 ppb. The sudden peaks can be explained by human activity. However, as the sources for these vast varying concentrations are unknown, and the sensors have not been calibrated, significant uncertainties are connected to these results. Formaldehyde concentrations are below recommended limits, but show increasing levels towards the end of the measurement period.

It is important to consider that indoor air quality measurements provide objective information about the physical properties of the air, whereas perceived air quality reflects subjective experiences and individual sensitivities. Both aspects are important for assessing and improving indoor environments. Measured IAQ helps identify potential sources of pollutants and provides a basis for implementing mitigation strategies, while perceived air quality ensures that the indoor environment is comfortable and satisfactory for the occupants. The perceived air quality can vary among individuals and is influenced by factors such as odors, sensory experience, comfort, and personal preference. The odor experiment showed that the correlation between measured air quality parameters and perceived air quality is generally strong, but discrepancies can arise due to individual sensitivities. The resulting percentage of dissatisfaction, odor acceptability, and intensity from the experiment did not show any clear trends with measured parameters or the percentage of recirculated air. For odor acceptability and intensity, answers were observed to range from clearly unacceptable (-1) to clearly acceptable (1), or no odor (0) to strong odor (5), for the same room, thus underlining the subjective nature of odor.

Chapter 9

Further Work

To properly assess the indoor air quality in any building or zone, the low-cost sensors used need to be reliable and accurate. Thus, a more extensive calibration should be performed. The linear regression method used in this master's thesis does not account for humidity and temperature, which can influence some of the sensors. Additionally, low R^2 values were obtained for some of the sensors, and as these should be as close to 1 as possible, further tests are needed. Furthermore, no calibration was performed for TVOC and formaldehyde due to the lack of a reference sensor. A calibration of these parameters would provide valuable insight into the accuracy of these sensors. Lastly, the calibration experiment was only conducted once and should be conducted multiple times under the same conditions to evaluate the stability of the sensors.

When it comes to the assessment of the indoor air quality of the ZEB Laboratory and Powerhouse Brattørkaia, only objective measurements were used. However, as air quality can be perceived subjectively by each individual, a questionnaire about perceived air quality and thermal comfort in the respective buildings would provide valuable insight. This could help uncover sources for elevated concentrations or uncover discrepancies between measured IAQ and perceived air quality.

From the uncertainty analysis of the odor experiment, it can be observed that the confidence level for odor acceptability exceeds the accuracy requirement. According to the standard ISO 16000-30, the experiment should thus be conducted again. This was not accomplished due to time limitations. Furthermore, the experiment was conducted over two days, with two tests each day, also due to time limitations. However, the experiment should have been conducted over four days with one test each day. This would have provided more similar starting conditions for the rooms and health conditions for the occupants. This could have resulted in clearer trends and differences in results between the percentages of recirculated air.

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[79] Seyed Mojtaba Moosavi et al. *Linearity of Calibration Curves for Analytical Methods: A Review of Criteria for Assessment of Method Reliability.* en. Publication Title: Calibration and Validation of Analytical Methods - A Sampling of Current Approaches. IntechOpen, Feb. 2018. ISBN: 978-1-78923-085-7. DOI: `10.5772/intechopen.72932`. URL: `https://www.intechopen.com/state.item.id` (visited on 11/09/2022).

[80] *Powerhouse Brattørkaia - Snøhetta | The Plan.* en. Sept. 2019. URL: `https://www.theplan.it/eng/architecture/powerhouse-bratt%C3%B8rkaia-sn%C3%B8hetta` (visited on 05/09/2023).

[81] M. Justo Alonso et al. “Holistic methodology to reduce energy use and improve indoor air quality for demand-controlled ventilation”. en. In: *Energy and Buildings* 279 (Jan. 2023), p. 112692. ISSN: 0378-7788. DOI: `10.1016/j.enbuild.2022.112692`. URL: `https://www.sciencedirect.com/science/article/pii/S0378778822008635` (visited on 03/29/2023).

Appendix A

Datasheets for Sensors

This appendix presents the relevant pages from the datasheets for the following sensors;

- Sensirion SCD30: CO_2, temperature and humidity
- Sensirion SPS30: particular matter
- Sensirion SPG30: total volatile organic matter
- Dart WZ-S: formaldehyde

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

Table 1: SCD30 CO_2 sensor specifications

Humidity Sensor Specifications[7]

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

Table 2: SCD30 humidity sensor specifications

Temperature Sensor Specifications[7]

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

Table 3: SCD30 temperature sensor specifications

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[1] Default conditions of T = 25°C, humidity = 50 %RH, p = 1013 mbar, V_{DD} = 3.3 V, continuous measurement mode with measurement rate = 2 s apply to values listed in the tables, unless otherwise stated.

[2] Deviation to a high-precision reference in the calibrated range (400 – 10’000 ppm) of the SCD30. Accuracy is fulfilled by > 90% of the sensors after calibration. Rough handling, shipping and soldering reduces the accuracy of the sensor. Full accuracy is restored with FRC or ASC recalibration features. Accuracy is based on tests with gas mixtures having a tolerance of ± 1.5%.

[3] RMS error of consecutive measurements at constant conditions. Repeatability is fulfilled by > 90% of the sensors.

[4] Average slope of CO_2 accuracy when changing temperature, valid at 400 ppm. Fulfilled by > 90% of the sensors after calibration.

[5] Time for achieving 63% of a respective step function. Response time depends on design-in, heat exchange and environment of the sensor in the final application.

[6] CO_2 concentrations < 400 ppm may result in sensor drifts when ASC is activated. For proper function of ASC field-calibration algorithm SCD30 has to be exposed to air with CO_2 concentration 400 ppm regularly.

[7] Design-in of the SCD30 in final application and the environment impacts the accuracy of the RH/T sensor. Heat sources have to be considered for optimal performance. Please use integrated on-board RH/T compensation algorithm to account for the actual design-in.

[8] Deviation to a high-precision reference. Accuracy is fulfilled by > 90% of the sensors after calibration.

[9] RH/T sensor component is capable of measuring up to T = 120°C. Measuring at T > 70°C might result in permanent damage of the sensor.

Electrical Specifications

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

Table 4 SCD30 electrical specifications

Operation Conditions, Lifetime and Maximum Ratings

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

Table 5: SCD30 operation conditions, lifetime and maximum ratings

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[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

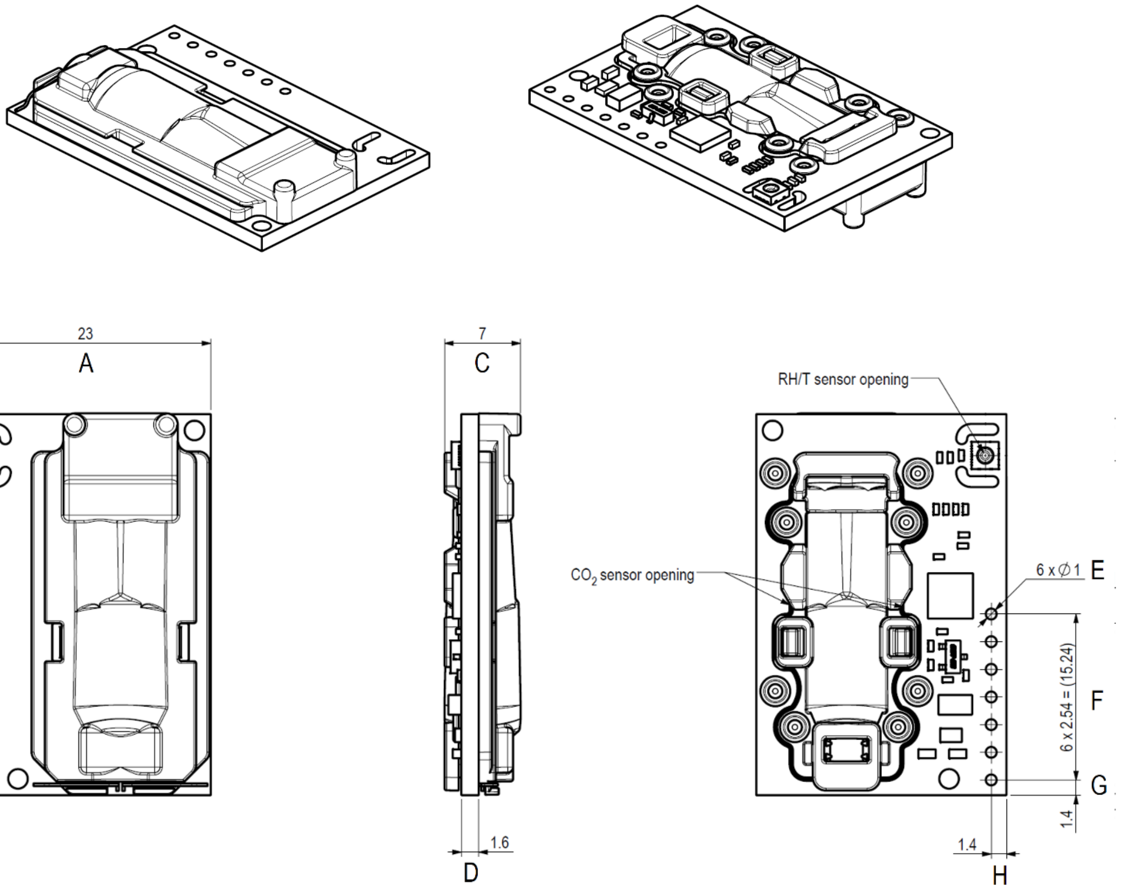

Figure 1 Product outline drawing of SCD30. Pictures on the left show top-view, pictures on the right bottom-view.

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

Table 6: Nominal dimensions and tolerances SCD30

Dimension	A	B	C	D	E	F	G	H
Nominal [mm]	23.00	35.00	7.00	1.60	1.00	15.24	1.40	1.40
Tolerance [mm]	± 0.20	± 0.20	± 0.70	± 0.20	± 0.15	± 0.30	± 0.15	± 0.15

3 Pin-Out Diagram

Pin	Comments
VDD	Supply Voltage
GND	Ground
TX/ SCL	Modbus: Transmission line (Push/Pull with 3V level) I²C: Serial clock (internal 45kΩ pull-up resistor, pulled to 3V, for higher voltages a level shifter is needed)
RX/ SDA	Modbus: Receive line (Input must not exceed 5.5V) I²C: Serial data (internal 45kΩ pull-up resistor, pulled to 3V, for higher voltages a level shifter is needed)
RDY	Data ready pin. High when data is ready for read-out
PWM	PWM output of CO_2 concentration measurement
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 I²C.

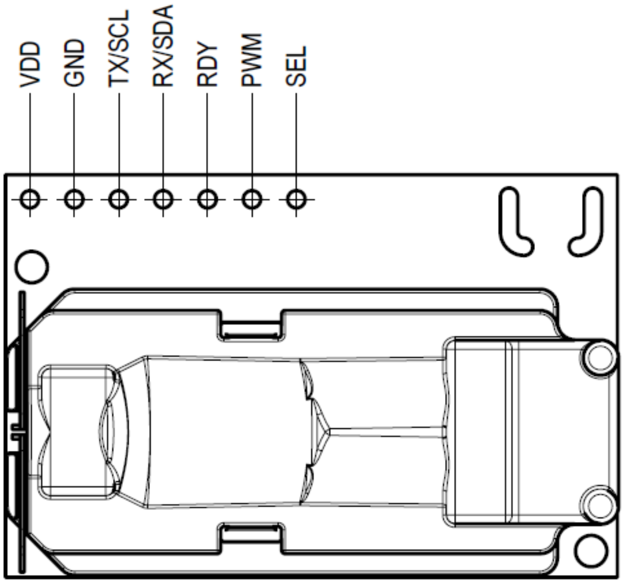

Figure 2: Pin-out of the SCD30.

4 Operation and Communication

Communication lines for I2C have an internal pull-up (45kOhm) to 3V, for higher voltages a level shifter is needed. Check VIH level of your I2C master to determine communication voltage. Please visit the download center of Sensirion webpage for the I2C, Modbus and PWM interface documentation [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.

Product	Description	Article Number
SCD30 sensor	CO_2, RH and T sensor module	1-101625-10
SEK-SCD30-Sensor	Standalone SCD30 sensor for EvalKit	3.000.061
SEK-SensorBridge	Sensor Bridge to connect SEK-SCD30-Sensor to computer	3.000.124

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

Datasheet SPS30

Particulate Matter Sensor for Air Quality Monitoring and Control

- Unique long-term stability
- Advanced particle size binning
- Superior precision in mass concentration and number 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 precise measurements from its first operation and throughout its lifetime of more than ten years. In addition, Sensirion's advanced algorithms provide superior precision for different PM types and higher-resolution particle size binning, opening up new possibilities for the detection of different sorts of environmental dust and other particles. With dimensions of only 41 x 41 x 12 mm^3, it is also the perfect solution for applications where size is of paramount importance, such as wall-mounted or compact air quality devices.

Content

1 Particulate Matter Sensor Specifications

1.1 Specification Overview

Parameter	Conditions		Value	Units
Mass concentration range	-		0 to 1'000	µg/m^3
Mass concentration size range	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
Mass concentration precision[1,2] for PM1 and PM2.5[3]	0 to 100 µg/m^3		±10	µg/m^3
	100 to 1000 µg/m^3		±10	% m.v.
Mass concentration precision[1,2] for PM4, PM10[4]	0 to 100 µg/m^3		±25	µg/m^3
	100 to 1000 µg/m^3		±25	% m.v.
Maximum long-term mass concentration precision limit drift	0 to 100 µg/m^3		±1.25	µg/m^3 / year
	100 to 1000 µg/m^3		±1.25	% m.v. / year
Number concentration range	-		0 to 3'000	#/cm^3
Number concentration size range	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
Number concentration precision[1,2] for PM0.5, PM1 and PM2.5[3]	0 to 1000 #/cm^3		±100	#/cm^3
	1000 to 3000 #/cm^3		±10	% m.v.
Number concentration precision[1,2] for PM4, PM10[4]	0 to 1000 #/cm^3		±250	#/cm^3
	1000 to 3000 #/cm^3		±25	% m.v.
Maximum long-term number concentration precision limit drift[2]	0 to 1000 #/cm^3		±12.5	#/cm^3 / year
	1000 to 3000 #/cm^3		±1.25	% m.v. / year
Sampling interval	-		1±0.04	s
Typical start-up time[5]	number concentration	200 – 3000 #/cm^3	8	s
		100 – 200 #/cm^3	16	s
		50 – 100 #/cm^3	30	s
Sensor output characteristics	PM2.5 mass concentration		Calibrated to TSI DustTrak™ DRX 8533 Ambient Mode	
	PM2.5 number concentration		Calibrated to TSI OPS 3330	
Lifetime[6]	24 h/day operation		> 10	years
Acoustic emission level	0.2 m	max.	25	dB(A)
Long term acoustic emission level drift	0.2 m	max.	+0.5	dB(A) / year
Additional T-dependent mass and number concentration precision limit drift[2]	temperature difference to 25°C	typ.	±0.5	% m.v. / °C
Weight	-		26.3 ±0.3	g

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[1] Also referred to as "between-parts variation" or "device-to-device variation".

[2] For further details, please refer to the document "Sensirion Particulate Matter Sensor Specification Statement".

[3] Verification Aerosol for PM2.5 is a 3% atomized KCl solution. Deviation to reference instrument is verified in end-tests for every sensor after calibration.

[4] PM4 and PM10 output values are calculated based on distribution profile of all measured particles.

[5] Time after starting Measurement-Mode, until a stable measurement is obtained.

[6] Lifetime is based on mean-time-to-failure (MTTF) calculation. Lifetime might vary depending on different operating conditions.

Laser wavelength (DIN EN 60825-1 Class 1)	LASER 1	typ.	660	nm

Table 1: Particulate matter sensor specifications. Default conditions of 25±2 °C, 50±10% relative humidity and 5 V supply voltage apply unless otherwise stated. 'max.' means 'maximum', 'typ.' means 'typical', '% m.v.' means '% of measured value'.

1.2 Recommended Operating Conditions

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

2 Electrical Specifications

2.1 Electrical Characteristics

Parameter	Conditions	Min	Typ	Max	Unit
Supply voltage	-	4.5	5.0	5.5	V
Supply current	Sleep-Mode	-	38	50	µA
	Idle-Mode	300	330	360	
	Measurement-Mode	45	55	65	mA
	Measurement-Mode, first 200ms (fan start)	-	-	80	
Input high level voltage (V_{IH})	-	2.31	-	5.5	V
Input low level voltage (V_{IL})	-	0	-	0.99	
Output high level voltage (V_{OH})	-	2.9	3.3	3.37	
Output low level voltage (V_{OL})	-	0	0	0.4	

Table 2: Electrical specifications at 25°C.

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	Min	Max	Unit
Supply voltage VDD	-0.3	5.5	V
Interface Select SEL	-0.3	4.0	
I/O pins (RX/SDA, TX/SCL)	-0.3	5.5	
Max. current on any I/O pin	-16	16	mA
Operating temperature range	-10	60	°C
Storage temperature range	-40	70	
Operating humidity range	0	95	% RH

Table 3: Absolute minimum and maximum ratings.

2.3 ESD / EMC Ratings

Immunity (Industrial level)

Description	Standard	Rating
Electro Static Discharge	IEC 61000-4-2	±4 kV contact, ±8 kV air
Power-Frequency Magnetic Field	IEC 61000-4-8	30A/m, 50Hz and 60Hz
Radio-Frequency EM-Field AM-modulated	IEC 61000-4-3	80MHz - 1000MHz, 10V/m, 80% AM @1kHz
Radio-Frequency EM-Field AM-modulated	IEC 61000-4-3	1.4GHz – 6GHz, 3V/m, 80% AM @1kHz

Emission (Residential level)

Description	Standard	Rating
Emission in SAC for 30MHz to 230MHz	IEC/CISPR 16	40dB(µV/m) QP @3m
Emission in SAC for 230MHz to 1000MHz	IEC/CISPR 16	47dB(µV/m) QP @3m
Emission in SAC for 1GHz to 3GHz	IEC/CISPR 16	70dB(µV/m) P, 50dB(µV/m) AP @3m
Emission in SAC for 3GHz to 6GHz	IEC/CISPR 16	74dB(µV/m) P, 54dB(µV/m) AP @3m

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 1 a description of the pin layout is given.

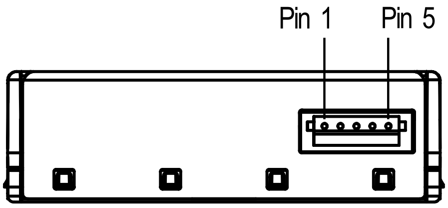

Figure 1: The communication interface connector is located at the side of the sensor opposite to the air outlet.

Pin	Name	Description	Comments
1	VDD	Supply voltage	5V ± 10%
2	RX	UART: Receiving pin for communication	TTL 5V and LVTTL 3.3V compatible
	SDA	I^2C: Serial data input / output	
3	TX	UART: Transmitting pin for communication	TTL 5V and LVTTL 3.3V compatible
	SCL	I^2C: Serial clock input	
4	SEL	Interface select	Leave floating to select UART
			Pull to GND to select I^2C
5	GND	Ground	Housing on GND

Table 4 SPS30 pin assignment.

The SPS30 offers both a UART[7] and an I^2C interface. For connection cables longer than 20 cm we recommend using the UART interface, due to its intrinsic robustness against electromagnetic interference.

Note, that there is an internal electrical connection between GND pin (5) and metal shielding. Keep this metal shielding electrically floating in order to avoid any unintended currents through this internal connection. If this is not an option, proper external potential equalization between GND pin and any potential connected to the shielding is mandatory. Any current though the connection between GND and metal shielding may damage the product and poses a safety risk through overheating.

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[7] Universal Asynchronous Receiver Transmitter.

Datasheet SGP30

Indoor Air Quality Sensor for TVOC and CO_2eq Measurements

- 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.

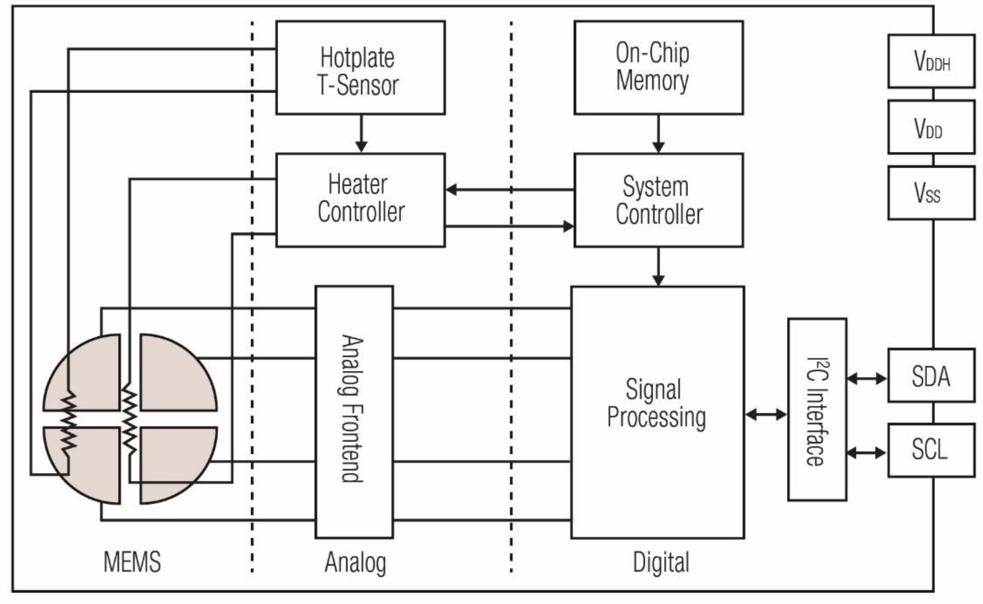

Figure 1 Functional block diagram of the SGP30.

1 Sensor Performance

1.1 Gas Sensing Performance

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

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

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

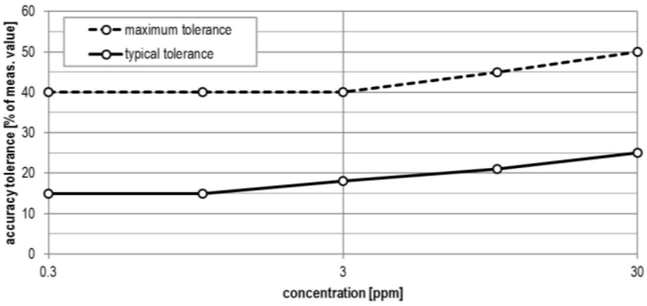

Figure 2 Typical and maximum accuracy tolerance in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 24h before the characterization.

Accuracy H_2 signal

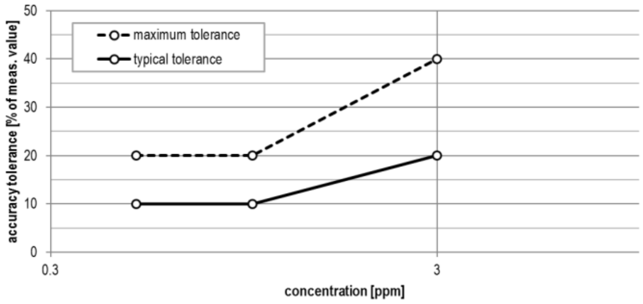

Figure 3 Typical and maximum accuracy tolerance in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 60h before the characterization.

Long-term drift Ethanol signal

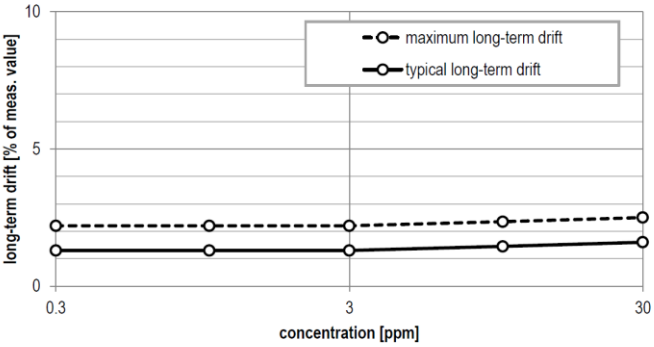

Figure 4 Typical and maximum long-term drift in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 24h before the first characterization.

Long-term drift H_2 signal

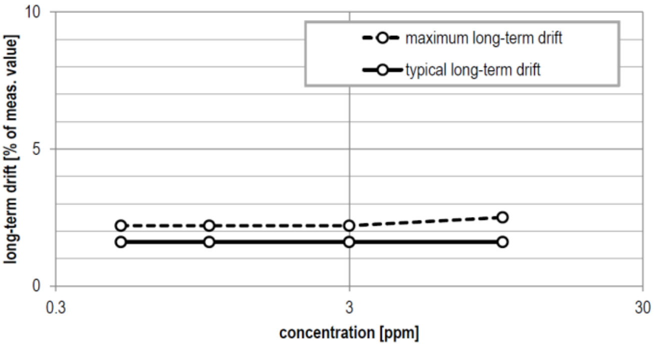

Figure 5 Typical and maximum long-term drift in % of measured value at 25°C, 50% RH and typical VDD. The sensors have been operated for at least 60h before the first characterization.

1.2 Air Quality Signals

Air quality signals TVOC and CO_2eq are calculated from Ethanol and H_2 measurements using internal conversion and baseline compensation algorithms (see **Figure 6**).

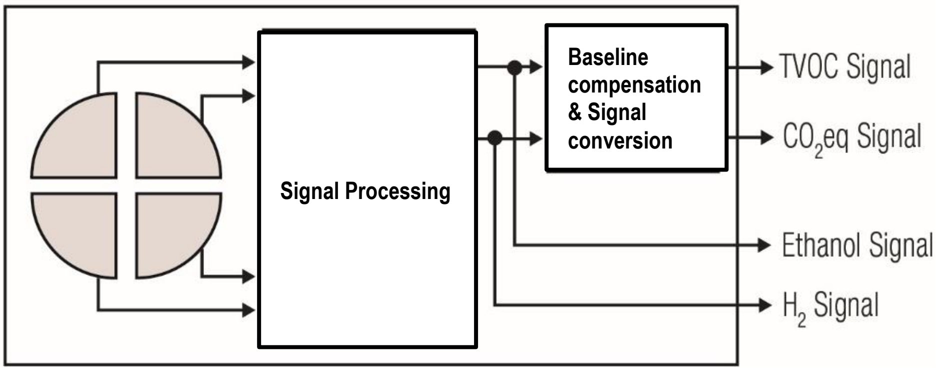

Figure 6 Simplified version of the functional block diagram (compare **Figure 1**) showing the signal paths of the SGP30.

Specifications of air quality signals are shown in **Table 2**.

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		
		Range	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.

1.3 Recommended Operating and Storage Conditions

Gas Sensing Specifications as detailed in **Table 1** are guaranteed only when the sensor is stored and operated under the recommended conditions. Prolonged exposure to conditions outside these conditions may accelerate aging.

The recommended temperature and humidity range for operating the SGP30 is 5–55 °C and 4–30 g m^{-3} absolute humidity, respectively (see **Figure 7** for the corresponding translation into relative humidity). It is recommended to store the sensor in a temperature range of 5–30 °C and below 30 g m^{-3} absolute humidity (see **Figure 8** for the corresponding translation into relative humidity). The sensor must not be exposed towards condensing conditions (i.e., >90 % relative humidity) at any time. To ensure a stable performance of the SGP30, conditions described in the document SGP Handling Instructions have to be met. Please also refer to the Design-in Guide for optimal integration of the SGP30 into the final device.

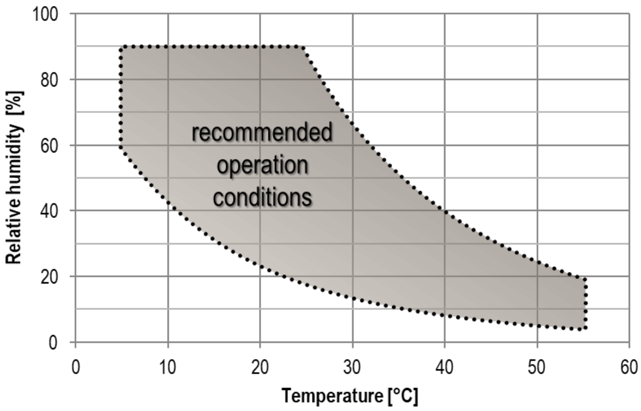

Figure 7 Recommended relative humidity and temperature for operating the SGP30.

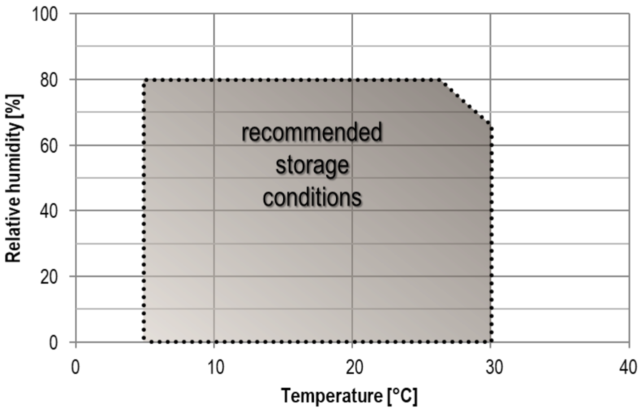

Figure 8 Recommended relative humidity and temperature for storing the SGP30.

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 "sgp30_iaq_init" or "sgp30_measure_raw" 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^2C fast mode.				

Table 3 Electrical specifications.

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

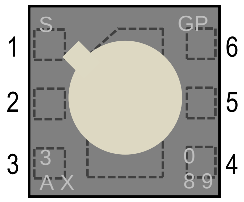

Table 4 Pin assignment (transparent top view). Dashed lines are only visible from the bottom.

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

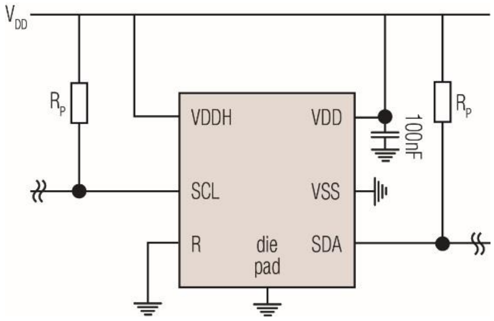


Figure 9 Typical application circuit (for better clarity in the image, the positioning of the pins does not reflect the positions on the real sensor).

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 9**. 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 I^{2}C 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 kΩ) 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 I^{2}C 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 for the electrical components 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 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 refer to Handling Instructions for Sensirion Gas Sensors on Sensirion webpage for full documentation.

---

[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

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

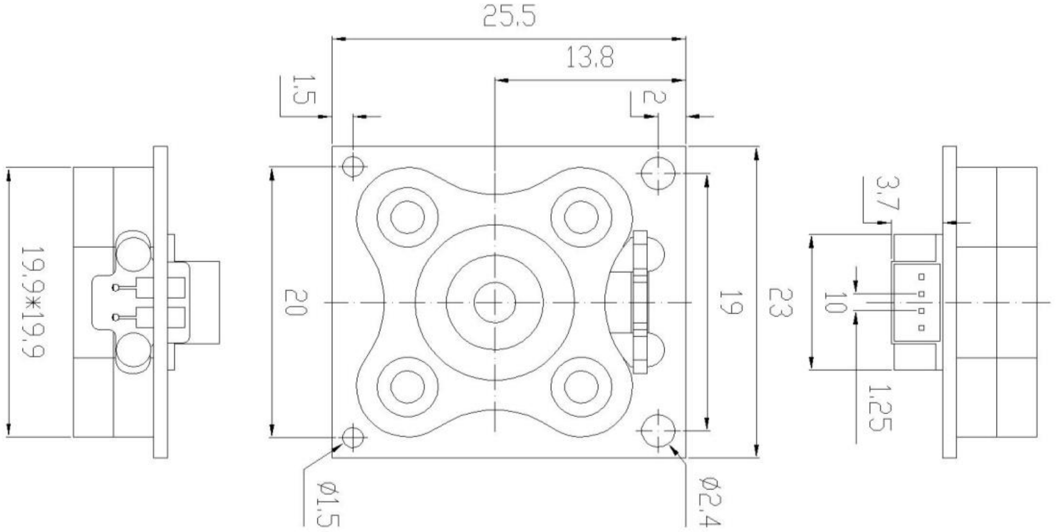
Long service life

Low power consumption

High stability

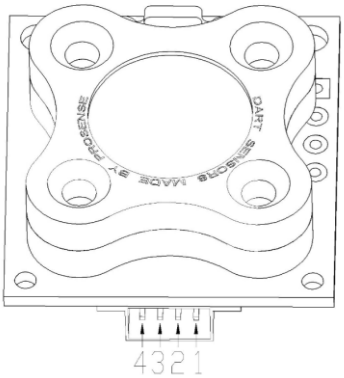
Pre-calibrated

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

Communication Protocol

➢ General Settings

Module makes use of serial communication.
Communication configuration parameters are:

Baud rate	9600
Data bits	8 bits
Stop bit	1 bit
Parity bit	None

➢ Communication Command

There are two communication types: active upload type and Q&A type. The default type is active upload and it sends gas concentration once every second. Commands are as follow:

0	1	2	3	4	5	6	7	8
Start	Gas	Unit ppb	No decimal byte	Concentration (High byte)	Concentration (low byte)	Full range (high byte)	Full range (low byte)	Checksum
0xFF	CH2O=0x17	Ppb=0x04	0x00	0x00	0x25	0x07	0xD0	0x25

Gas concentration = concentration (high byte)*256 + concentration (low byte)

Switch to Q&A mode：

0	1	2	3	4	5	6	7	8
Start	Reserved	Switch command	Q&A	Reserved	Reserved	Reserved	Reserved	Checksum
0xFF	0x01	0x78	0x41	0x00	0x00	0x00	0x00	0x46

Switch to active upload mode：

0	1	2	3	4	5	6	7	8
Start	Reserved	Switch command	Active upload	Reserved	Reserved	Reserved	Reserved	Checksum
0xFF	0x01	0x78	0x40	0x00	0x00	0x00	0x00	0x47

To read gas concentration：

0	1	2	3	4	5	6	7	8
Start	Reserved	Command	Reserved	Reserved	Reserved	Reserved	Reserved	Checksum

0xFF	0x01	0x86	0x00	0x00	0x00	0x00	0x00	0x79

To return:

0	1	2	3	4	5	6	7	8
Start	Command	Concentration (High byte)（ug/m3）	Concentration (low byte)（ug/m3）	Reserved	Reserved	Concentration (High byte)（ppb）	Concentration (low byte)（ppb）	Checksum
0xFF	0x86	0x00	0x2A	0x00	0x00	0x00	0x20	0x30

Gas concentration = concentration (high byte)*256 + concentration (low byte)

Checksum calibration

```
/*************************************************************************
*Function name：  unsigned char FucCheckSum(uchar *i,ucharln)
*Function description：  checksum calibration[Take Not(Byte1+Byte2+…Byte7) +1]
*Note：  Take Not(Byte1+Byte2+…ByteX (X>2)
*************************************************************************/
unsigned char FucCheckSum(unsigned char *i, unsigned char ln)
{
        unsigned char j, tempq=0;
        i+=1;
        for(j=0; j<(ln-2); j++)
        {
                tempq+=*i;
                i++;
        }
        tempq=(~tempq)+1;
        return(tempq);
}
```

Notes

- Avoid changing or moving sensor on the module.
- Avoid moving or changing electronic elements on PCB.
- Avoid exposure to organic vapour, organic solvent、high gas concentration.
- Protect from excessive vibration and shock.

No recommended for industrial safety/personal monitoring, refer to 2-FP5.

ProSense Technologies Co., Ltd.

Add:Room206, Building4, Lianjian S&T Park, LonghuaDistrict,Shenzhen,China;
Tel: +86 755 3669 0079
Email: sales@szprosense.com

Appendix B

Step Response and Calibration Curves

Figure B.0.1 illustrates the step response for the temperature for the eight LCS, along with that from Pegasor as a reference sensor. A slowly increasing temperature can be observed where the LCS follows the trend of the Pegasor for the most part, with the exception of sensors ID21, ID24 and ID28, where the temperature decreases at 12:01, whereas the temperature measured by the Pegasor stabilizes. Even though most of the sensors follow the same trend as the Pegasor, they measure higher temperatures compared to the Pegasor.

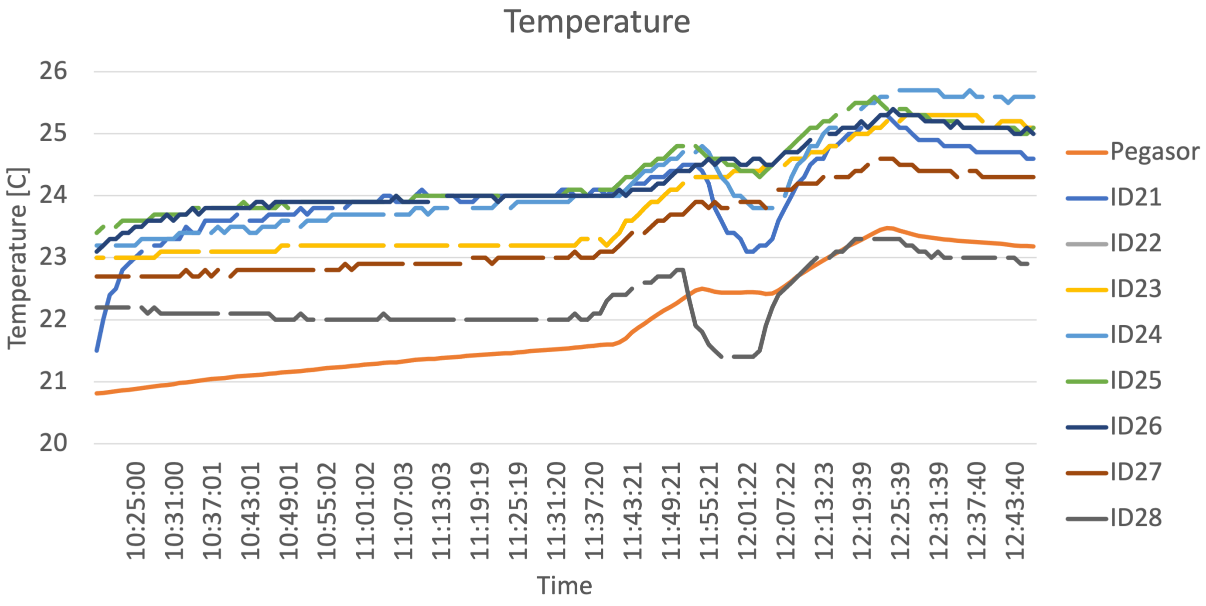


Figure B.0.1: Temperature levels measured by low-cost sensors and reference sensor.

Figure B.0.2 illustrates the step response for the low-cost RH sensors and the Pegasor. The humidity levels are slowly decreasing at the beginning of the experiment until it drops rapidly at 11:55 when the hatch is opened to light the candles. It can be observed that the LCS follows the same trend as the Pegasor, with varying deviations in magnitude. Whilst sensor ID23 measures humidity levels close to the Pegasor, other sensors such as ID25 and ID26 measure humidity levels lower than the Pegasor.

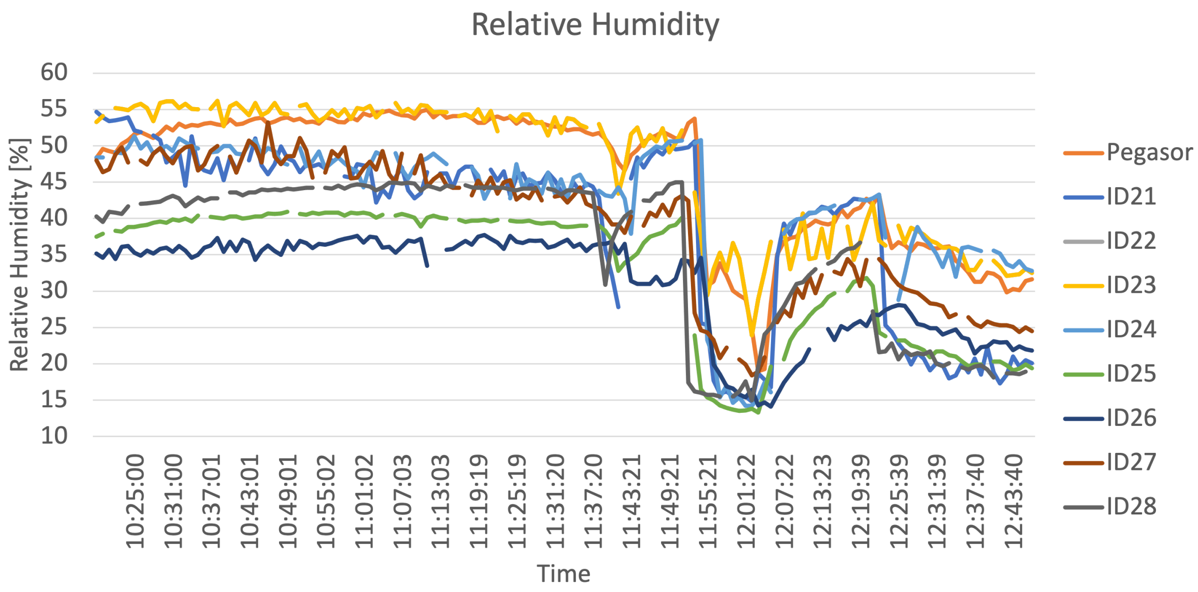


Figure B.0.2: Relative humidity measured by low-cost sensors and reference sensor.

Figure B.0.3 illustrates the step response for CO_2 concentrations measured by the LCS compared with measurements by the Pegasor. Two peaks can be observed in the figure, which corresponds to the time the tea candles are lit, and the hatch is opened or closed. It is evident that the LCS follows the same trend as the Pegasor, with some deviations in magnitude at higher concentrations of CO_2.

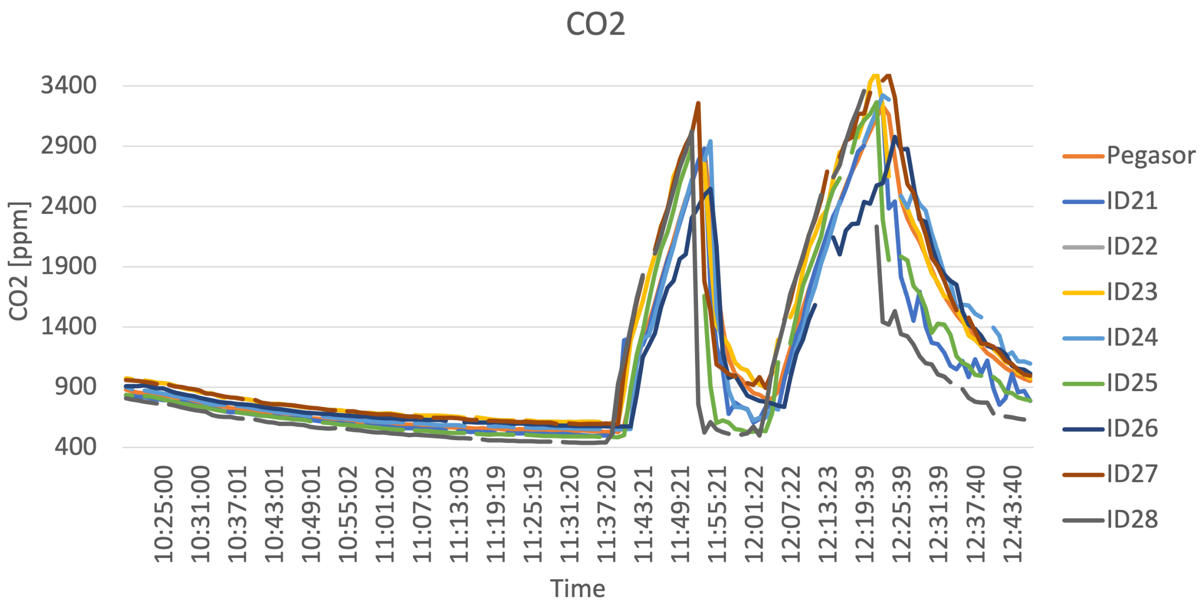


Figure B.0.3: CO_2 levels measured by low-cost sensors and reference sensor.

Figure B.0.4 illustrates the step response for the low-cost $PM_{2.5}$ sensors and the Pegasor. Two peaks can be observed from the figure; the first occurs when the candles are lit, and the second when the candles are extinguished. At the first peak, the Pegasor sensor measures higher $PM_{2.5}$ levels than the LCS, and at the second peak, the Pegasor measures lower concentrations.

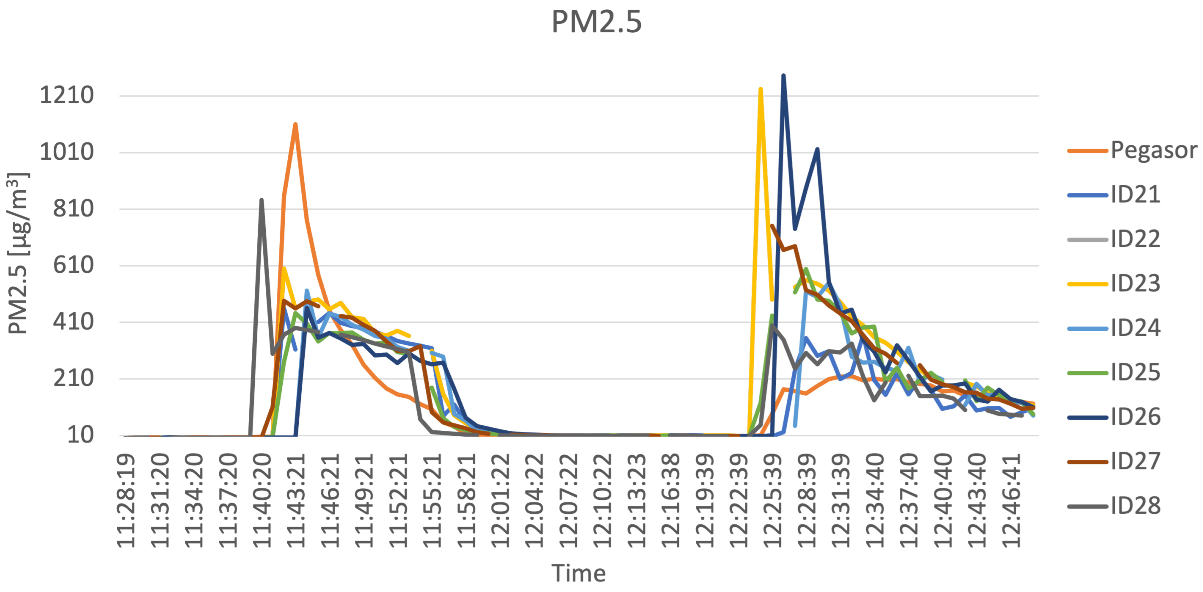


Figure B.0.4: PM$_{2.5}$ levels measured by low-cost sensors and reference sensor.

As the difference between the maximum and minimum concentration om PM$_{2.5}$, figure B.0.5 illustrates the lower PM$_{2.5}$ concentration from the middle of the experiment. From the figure, it can be observed that all LCS measure quite similar levels of PM$_{2.5}$, whilst the Pegasor measures lower concentrations.

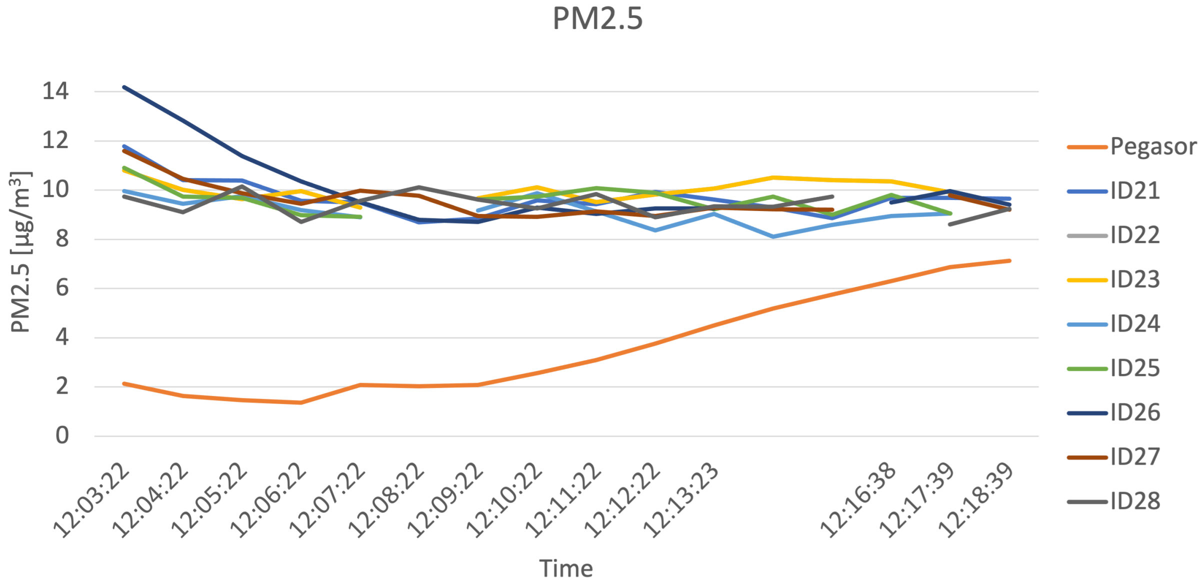


Figure B.0.5: PM$_{2.5}$ levels measured by low-cost sensors and reference sensor, from the middle of calibration experiment.

B.1 ID21

Figure B.1.1 illustrates the calibration curves for sensor box ID21. This includes the calibration curves for temperature, relative humidity, CO_2, and $PM_{2.5}$.

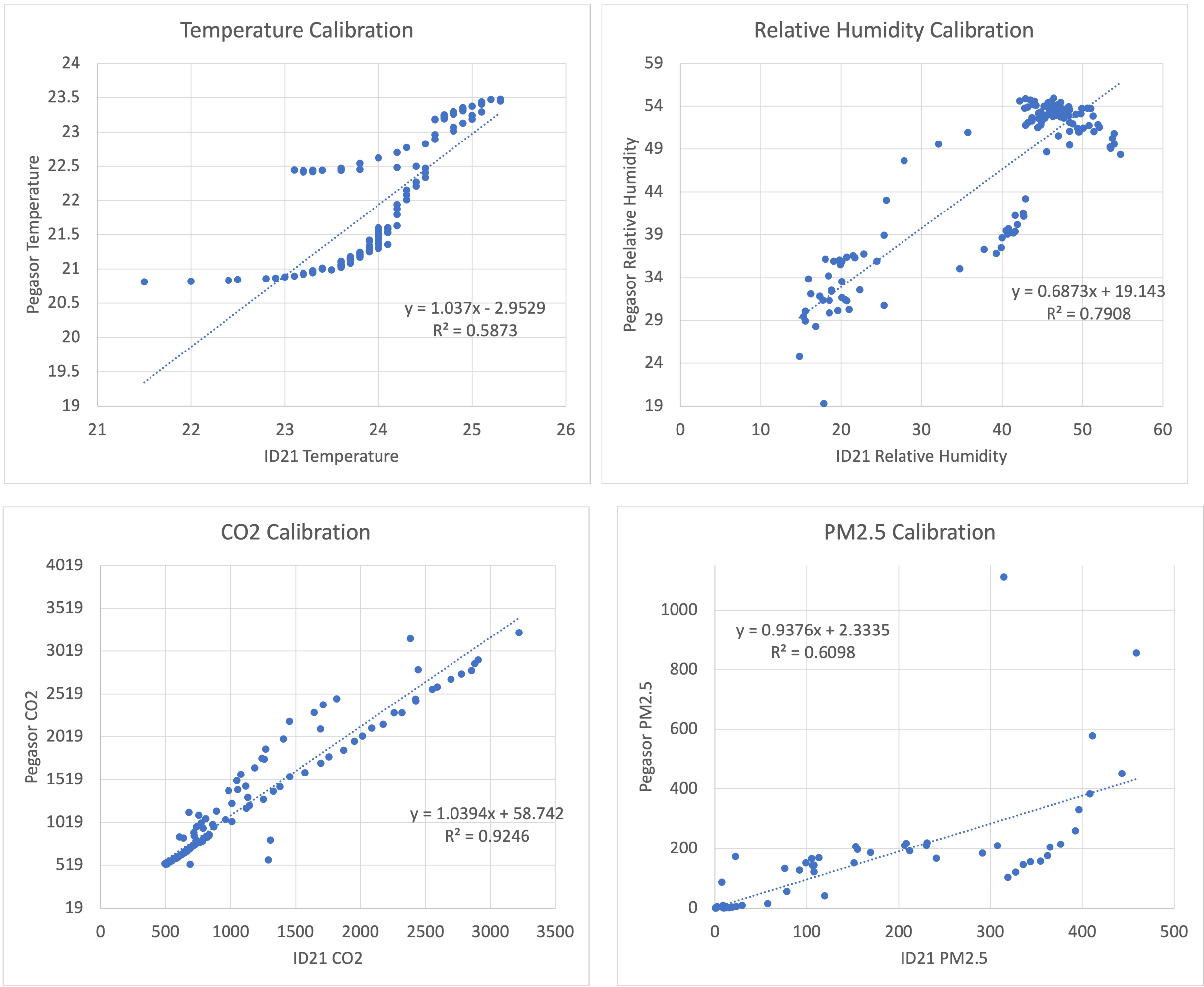


Figure B.1.1: ID21; temperature, relative humidity, CO_2, and $PM_{2.5}$ calibration curves.

B.2 ID22

Figure B.2.1 illustrates the calibration curves for sensor box ID22. This includes the calibration curves for temperature, relative humidity, CO_2, and $PM_{2.5}$.

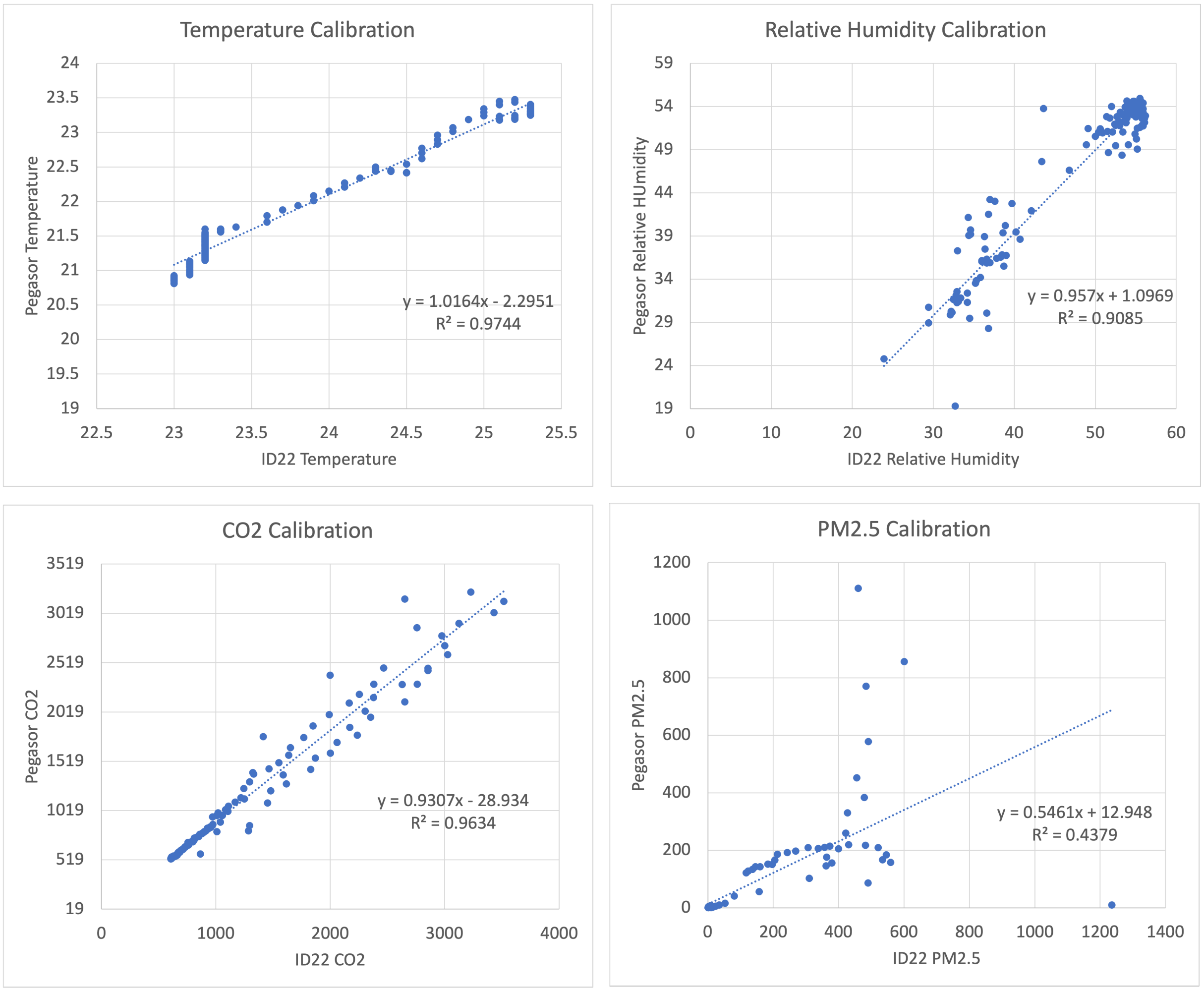


Figure B.2.1: ID22; temperature, relative humidity, CO_2, and $PM_{2.5}$ calibration curves.

B.3 ID23

Figure B.3.1 illustrates the calibration curves for sensor box ID23. This includes the calibration curves for temperature, relative humidity, CO_2, and $PM_{2.5}$.

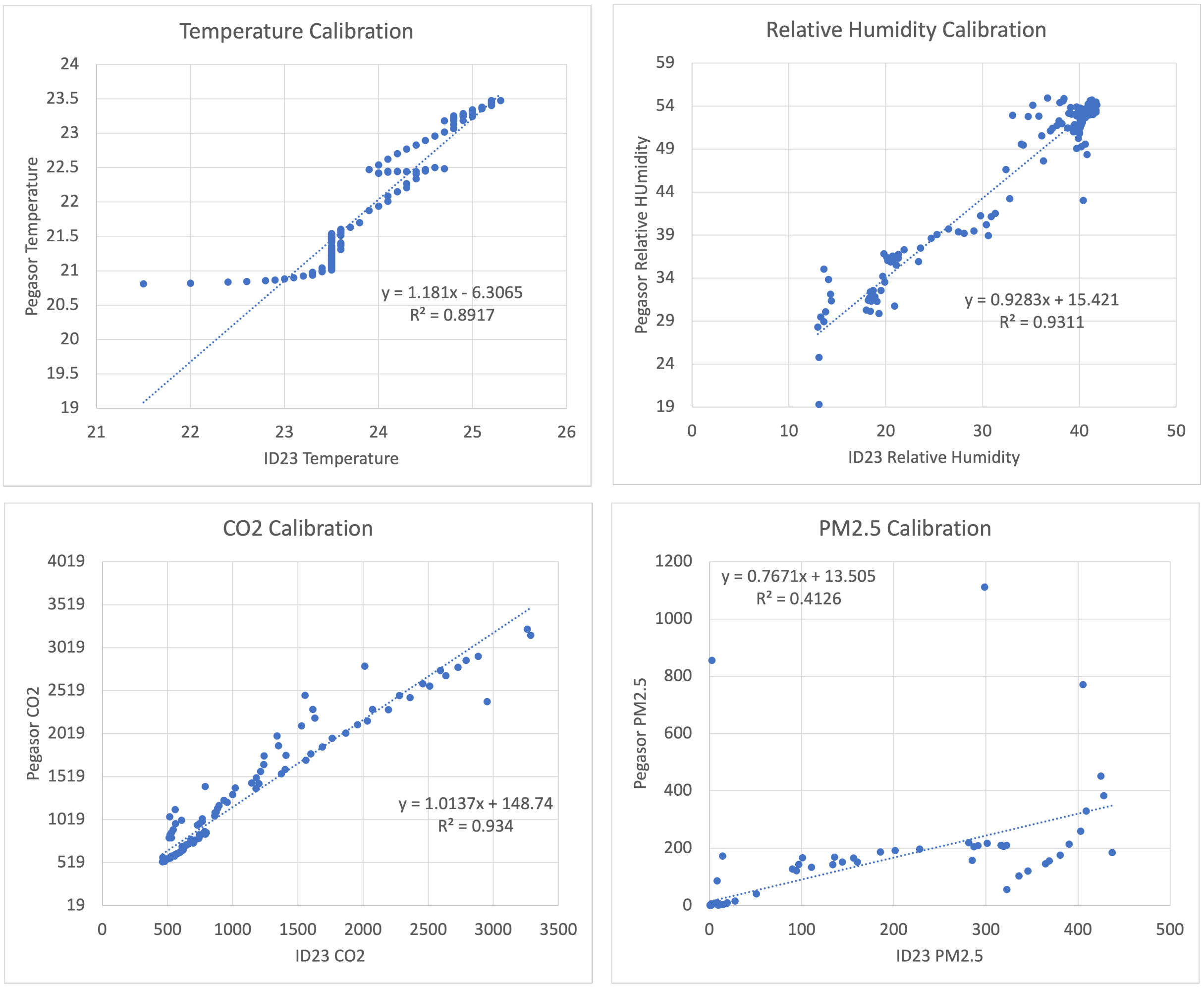


Figure B.3.1: ID23; temperature, relative humidity, CO_2, and $PM_{2.5}$ calibration curves.

B.4 ID24

Figure B.4.1 illustrates the calibration curves for sensor box ID24. This includes the calibration curves for temperature, relative humidity, CO_2, and $PM_{2.5}$.

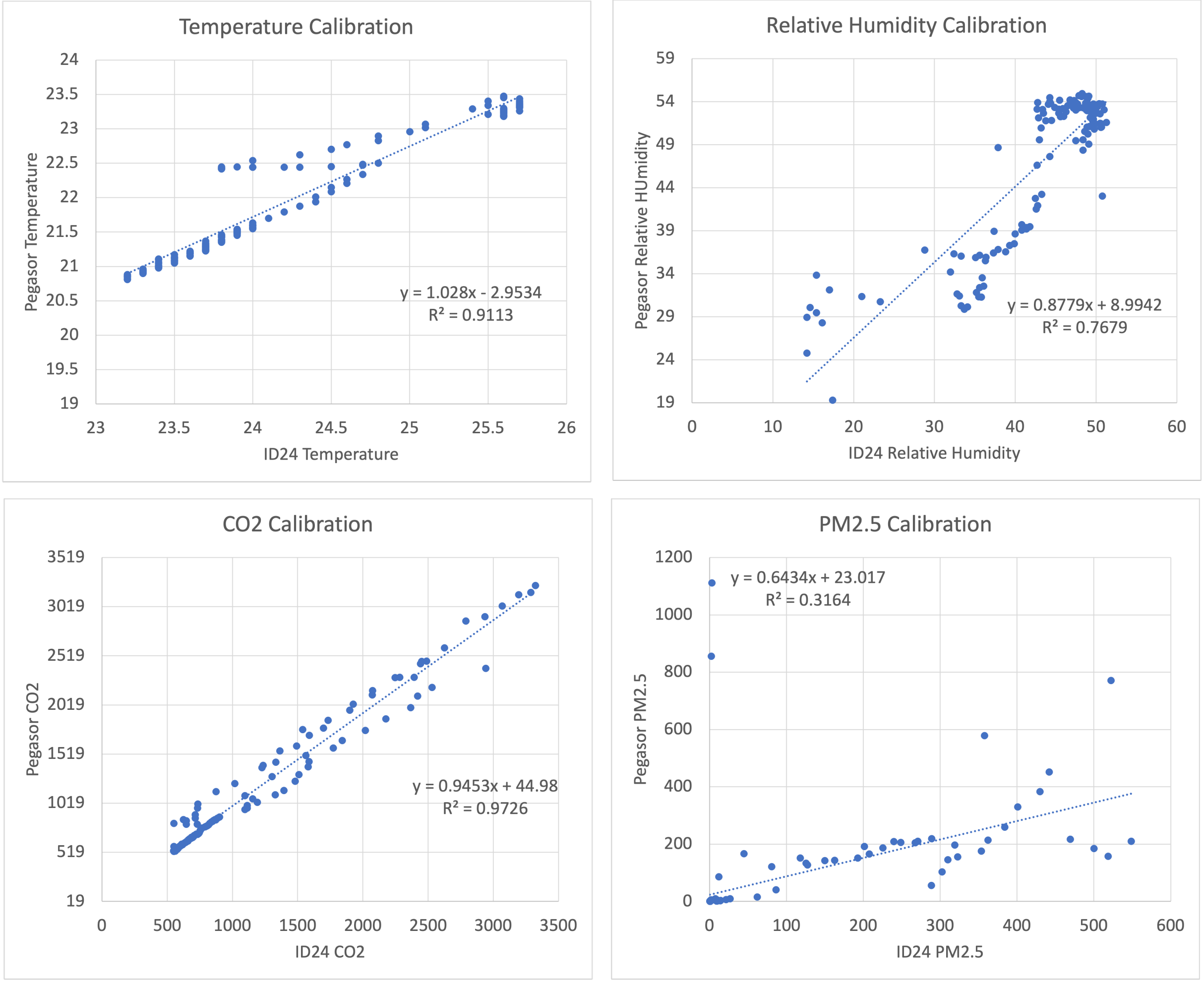


Figure B.4.1: ID24; temperature, relative humidity, CO_2, and $PM_{2.5}$ calibration curves.

B.5 ID25

Figure B.5.1 illustrates the calibration curves for sensor box ID25. This includes the calibration curves for temperature, relative humidity, CO_2, and $PM_{2.5}$.

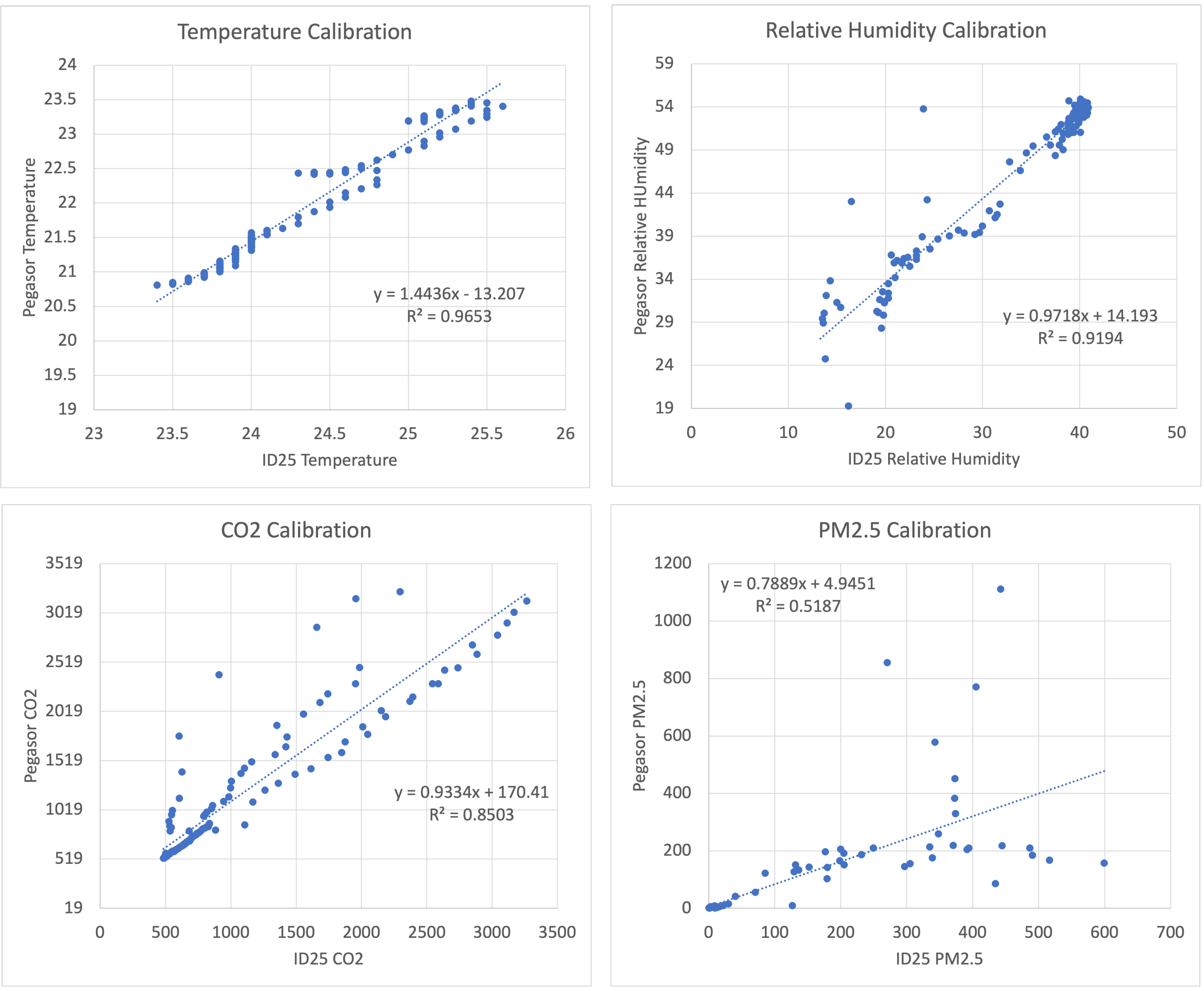


Figure B.5.1: ID25; temperature, relative humidity, CO_2, and $PM_{2.5}$ calibration curves.

B.6 ID26

Figure B.6.1 illustrates the calibration curves for sensor box ID26. This includes the calibration curves for temperature, relative humidity, CO_2, and $PM_{2.5}$.

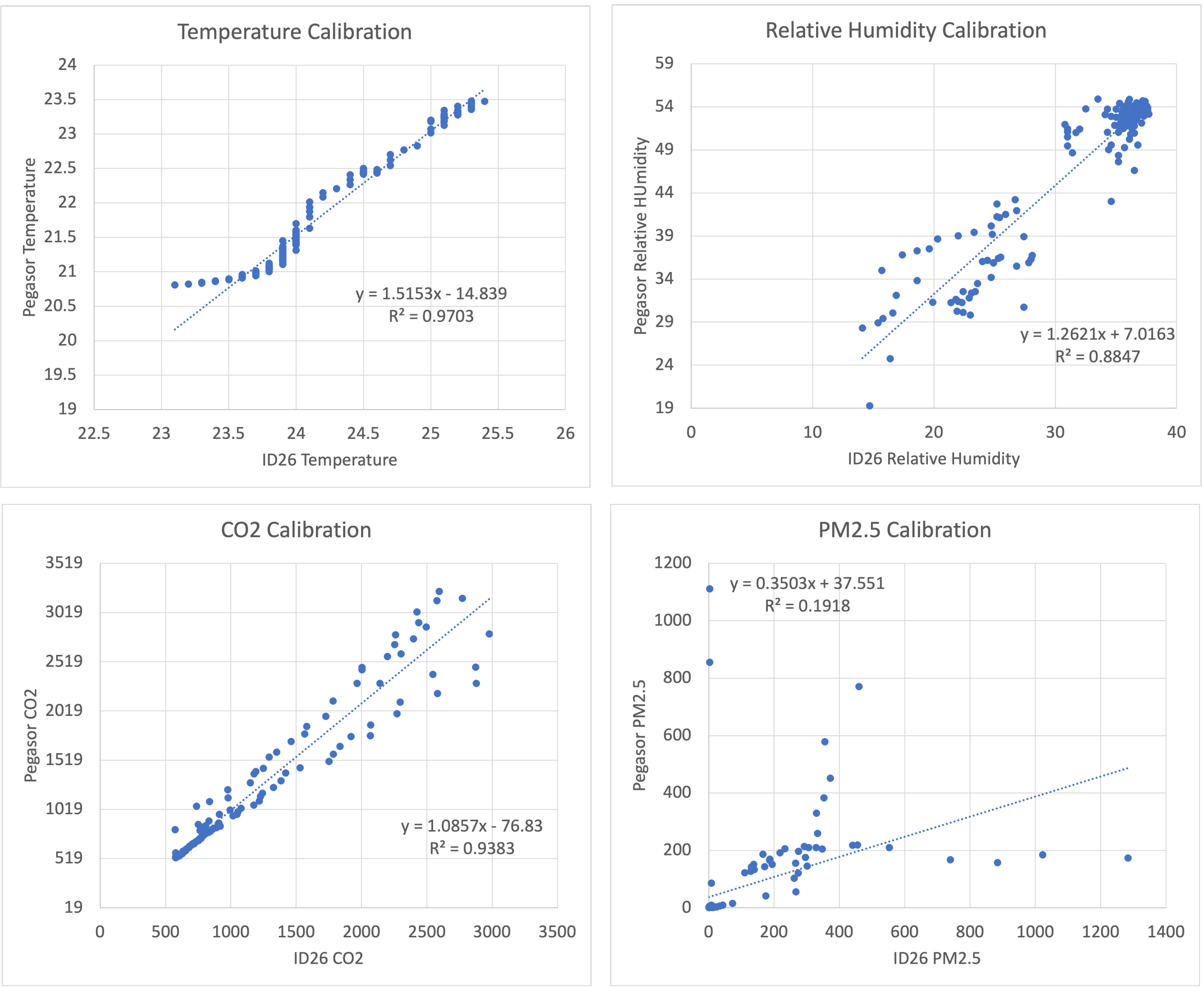


Figure B.6.1: ID26; temperature, relative humidity, CO_2, and $PM_{2.5}$ calibration curves.

B.7 ID27

Figure B.7.1 illustrates the calibration curves for sensor box ID27. This includes the calibration curves for temperature, relative humidity, CO_2, and $PM_{2.5}$.

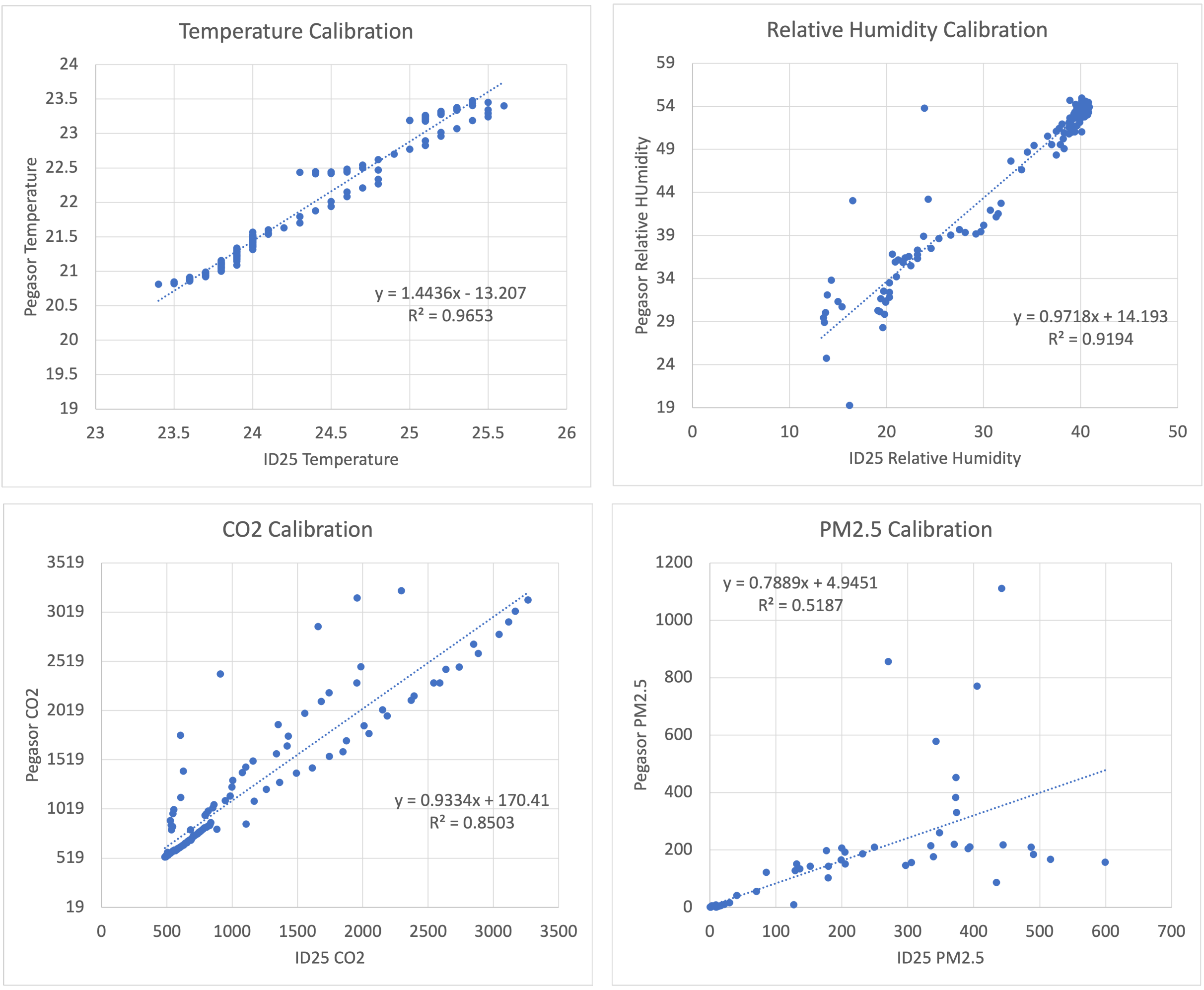


Figure B.7.1: ID27; temperature, relative humidity, CO_2, and $PM_{2.5}$ calibration curves.

B.8 ID28

Figure B.8.1 illustrates the calibration curves for sensor box ID28. This includes the calibration curves for temperature, relative humidity, CO_2, and $PM_{2.5}$.

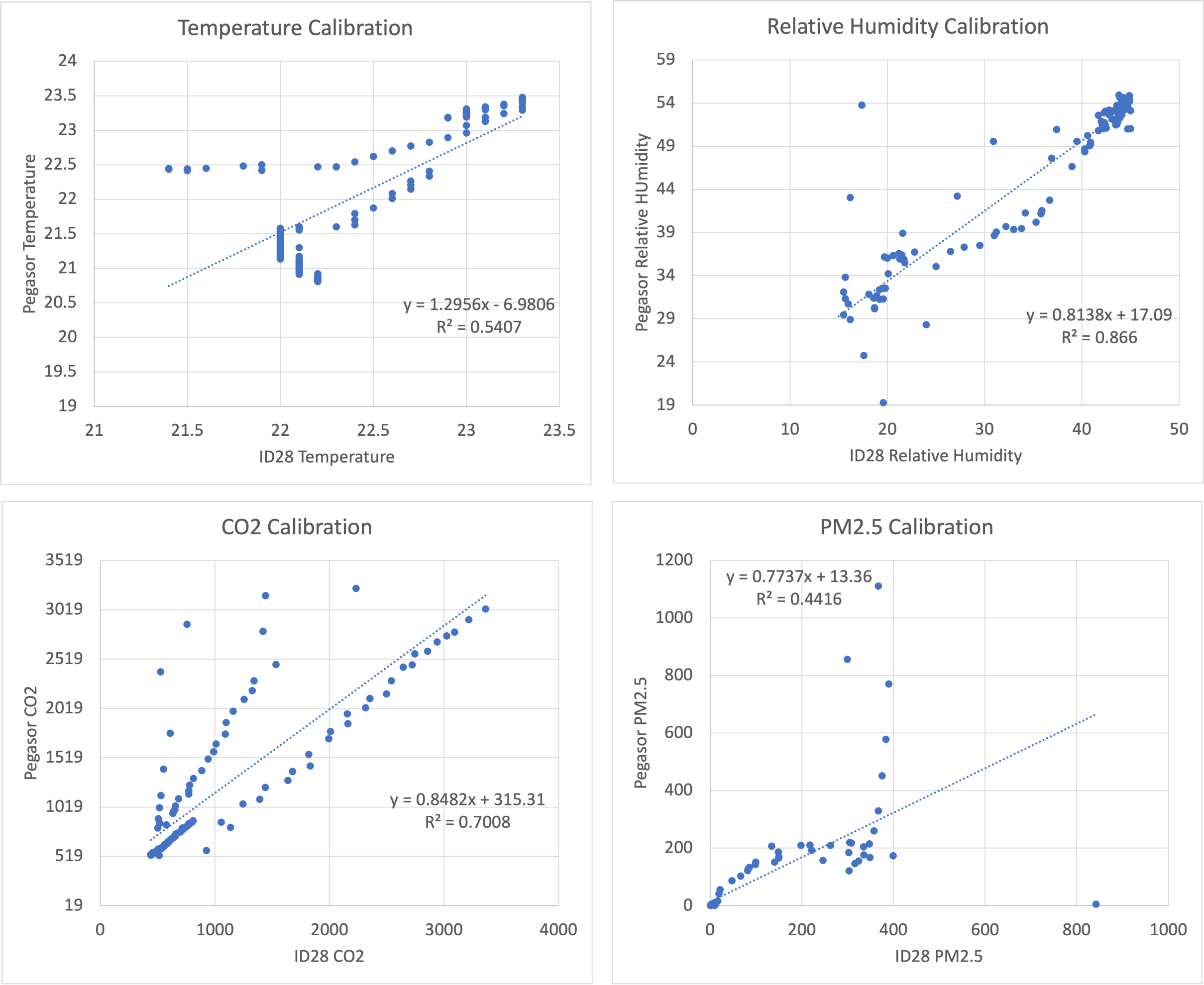


Figure B.8.1: ID28; temperature, relative humidity, CO_2, and $PM_{2.5}$ calibration curves.

Appendix C

Questionnaire - Occupants Perception of Thermal Comfort and Air Quality

The following page includes the questionnaire used for the odor experiment for the occupants located inside the three rooms.

Questions perception thermal comfort and air quality

Age:
Gender:

Are you experiencing any of these symptoms at the moment as a result of the condition of air in the room you are in? Check boxes

- ○ Fatigue
- ○ Headache
- ○ Problems concentrating
- ○ Itching, burning or irritation in the eyes
- ○ Irritated, stuffed or runny nose
- ○ Nosebleed
- ○ Dry throat
- ○ Cough
- ○ Dry hands, itchiness
- ○ Stress

Are you experiencing any of the following factors?

- ○ Draft
- ○ Too high room temperature
- ○ Varying room temperature
- ○ Too low room temperature
- ○ Stuffy/poor air quality
- ○ Dry air
- ○ Unpleasant smell

What is your experience of the room temperature:

- ○ Very good
- ○ Good
- ○ Acceptable
- ○ Poor
- ○ Very poor

If you feel cold, where?

- ○ Feet
- ○ Hands
- ○ Neck
- ○ Entire body

What is your experience with the air quality?

- ○ Very good
- ○ Good
- ○ Acceptable
- ○ Poor
- ○ Very poor

Appendix D

Questionnaire - Panel Assessment of Odor

The following pages include the questionnaire used for the odor experiment, which was handed out and explained to the untrained panel members prior to the test starting. The questions included are based on *ISO 16000-30: Sensory testing of indoor air* [41].

Odour experiment

Personal Information:

Age:____

Gender: ____

Do you snus? (yes/no) ______________________________________

Do you smoke? (yes/no) ______________________________________

Have you eaten anything in the last 30 min? (yes/no) ______________________

Have you drunk anything in the last 30 min? (yes/no) ______________________

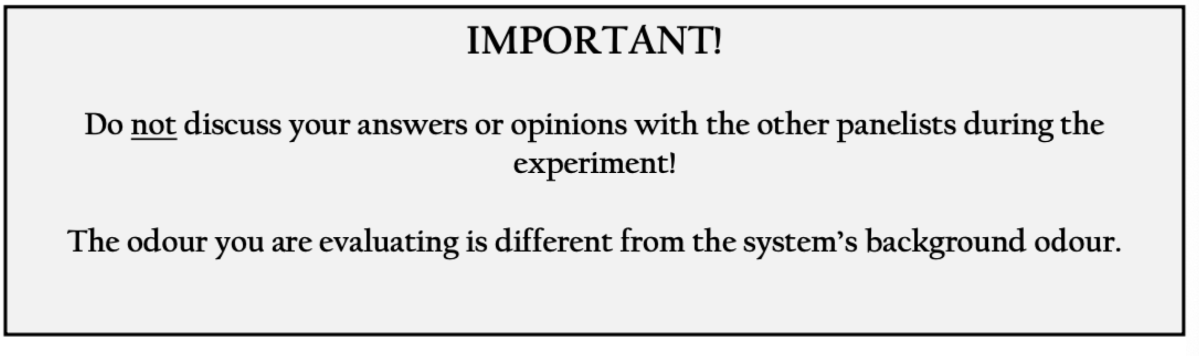
Do you have any allergy or disease that influences your sense of smell? (yes/no) __________

Have you been infected with COVID? (yes/no) __________________________

If yes on the previous, have you had COVID within the last six months? (yes/no) __________

As a panelist, you should:

- Be available to complete the experiment
- Not smoke or use tobacco two hours before the experiment
- Avoid products containing perfume
- Not drink, eat or chew gum 30 minutes before the experiment
- Not have allergies or other health conditions that influence your sense of smell



IMPORTANT!

Do <u>not</u> discuss your answers or opinions with the other panelists during the experiment!

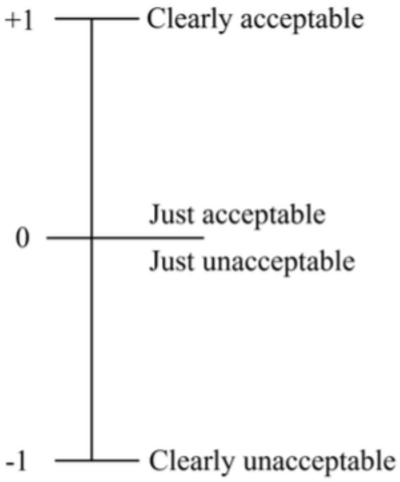
The odour you are evaluating is different from the system's background odour.

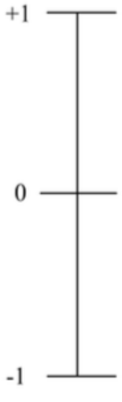
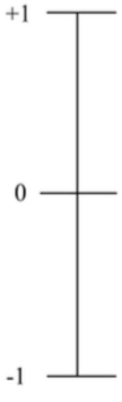
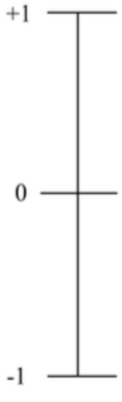
Odour Acceptability

Imagine you are exposed to this odour in your everyday life. Would you consider this odour acceptable?

	Room 1	Room 2	Room 3
Yes/No			

Imagine you are exposed to this odour in your everyday life. How would you rate this odour on the following scale?



Room 1	Room 2	Room 3
		

Odour Intensity

Rate the intensity of the odour on the following scale:

	0	1	2	3	4	5	6
Room 1	○ No odour	○ Very weak	○ Weak	○ Distinct	○ Strong	○ Very strong	○ Extremely strong
Room 2	○ No odour	○ Very weak	○ Weak	○ Distinct	○ Strong	○ Very strong	○ Extremely strong
Room 3	○ No odour	○ Very weak	○ Weak	○ Distinct	○ Strong	○ Very strong	○ Extremely strong

Hedonic Tone

Rate how pleasant/unpleasant you found the odour on the following scale:

		-4	-3	-2	-1	0	1	2	3	4	
Room 1	Extremely unpleasant	○	○	○	○	○	○	○	○	○	Very pleasant
Room 2	Extremely unpleasant	○	○	○	○	○	○	○	○	○	Very pleasant
Room 3	Extremely unpleasant	○	○	○	○	○	○	○	○	○	Very pleasant

Appendix E

Risk Analysis

7 QUANTIFYING OF RISK - RISK MATRIX

Activity from the identification process form	**Potential undesirable incident/strain**	**Likelihood:**	**Consequence:**			**Risk value (human)**	**Comment/ status Suggested measures**
		(1-5)	**Human (A-E)**	**Environment (A-E)**	**Economy/material (A-E)**		
Use of CO_2 bottle	CO_2 leakage	1	C	B	A	C1	
Candles	Fire	1	C	C	C	C1	
Mosquito coil	Fire	1	C	C	C	C1	

Conclusion: The *Participants has to make a comprehensive assessment to determine whether the remaining risks of the activity/process is acceptable.*

RISK MATRIX

CONSEQUENSE	(E) Catastrophic	**E1**	**E2**	**E3**	**E4**	**E5**
	(D) Extensive	**D1**	**D2**	**D3**	**D4**	**D5**
	(C) Moderate	**C1**	**C2**	**C3**	**C4**	**C5**
	(B) Negligible	**B1**	**B2**	**B3**	**B4**	**B5**
	(A) Insignificant	**A1**	**A2**	**A3**	**A4**	**A5**
		(1) Rare	(2) Unlikely	(3) Possible	(4) Likely	(5) Almost certain
		PROBABILITY				

The principle of the acceptance criterion. Explanation of the colors used in the matrix

COLOUR		**DESCRIPTION**
Red	🟥	Unacceptable risk Action has to be taken to reduce risk
Yellow	🟨	Assessment area. Actions has to be considered
Green	🟩	Acceptable risk. Action can be taken based on other criteria

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