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Doctoral thesis

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PREFACE

This thesis has been submitted to the Faculty of Engineering Science of the Norwegian University of Science and Technology (NTNU) for the partial fulfillment of the requirements for the degree of Doctor of Philosophy (PhD).

The work was carried out at the Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway, in the period August 2017 to July 2022, under supervision of Professor Hans Martin Mathisen and co-supervision of Professor Rikke Bramming Jørgensen from the Norwegian University of Science and Technology. William S. Dols, Mechanical Engineer at the National Institute of Standards and Technology (NIST, USA), acted as a mentor.

During this period, the PhD Candidate worked 75% of her time on the PhD studies and 25% % as a Research Scientist at SINTEF Community.

The research presented is funded by the Research Council of Norway through the Research Centre on Zero Emission Neighbourhood in Smart Cities (FME ZEN) through contract 257660.

Maria Justo Alonso

Trondheim, September 2022

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Delivering a thesis requires substantial effort and a lot of motivation and support. For the last five years, I have been given a chance to improve my knowledge of a topic so dear to me. Coming from a family of medical doctors, using engineering to accomplish better health, performance, and reduced energy use has been a motivational goal. However, nothing would have been accomplished without the kindness and support of many people, and it is my pleasure to acknowledge their role.

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I would like to thank Professor Rikke Bramming Jørgensen for having been the best co-supervisor one could have. You have been an enormous support, with a smile always on your face, reading and giving rigorous feedback to every document I have sent you in no time and most of all, you have enlightened me with endless knowledge and passion about health and Indoor Air Quality.

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A todos, gracias!

Trondheim, Norway

September, 2022

Maria Justo Alonso

ABSTRACT

The building sector is responsible for a large part of the world's total energy use. In many developed countries, the energy used for heating, ventilation, and air conditioning in residential and commercial buildings represents about half the total energy used in buildings [1]. Buildings have become more airtight and insulated over the last few years—a response to the acute need to reduce building energy demands. Reducing uncontrolled leaks has had a positive effect on reducing heating needs in cold climates. However, this has also brought increased attention to the need for ventilation systems that ensure the satisfactory renewal of the air, and thus a satisfactory indoor air quality (IAQ) that does not lead to other problems. Mechanical ventilation is customarily selected to ensure ventilation rates that satisfy building-code requirements. In offices, demand-controlled ventilation (DCV) reduces energy needs. With DCV, the airflow rates depend on the concentration of one or more indicators of building occupancy. The ventilation rates are maximized at the room/zone level during periods of full occupancy and reduced to minimum levels when the room/zone is vacant. The occupancy is measured as the increase of a selected parameter—usually, carbon dioxide (CO_2) and/or temperature. One of the challenges of choosing a single indicator, such as CO_2, is that, despite CO_2 being a proven indicator of bioeffluents, it is doubtful that it is an appropriate indicator for pollutants that are not directly connected to room occupancy.

Therefore, the main aim of this PhD study was to explore and develop a holistic methodology for improving ventilation control in order to reduce energy use and improve IAQ.

This work can be summarized as a step-by-step study aimed at addressing the following questions:

1. *Why is DCV, as performed today, not good enough?* Literature reviews and an analysis of correlations with pollutants have revealed that CO_2 and temperature are crucial factors in accounting for room occupancy, but they are not satisfactory for addressing the pollutants that occupants do not directly produce, such as particulate matter (PM). Thus, CO_2 and temperature alone cannot answer whether there is a satisfactory IAQ. Therefore, additional pollutants need to be measured, and some should be used to control ventilation.
2. *What should be measured to improve DCV?* To qualitatively and quantitatively evaluate the existing pollutants in rooms, a literature review on the typical pollutants

found in offices was carried out in order to map the existing prevailing challenges. Measurements were collected from three offices, four schools, and 21 home offices in order to verify the literature findings and corroborate their application in Norwegian cases.

3. *How can these extra parameters be measured affordably?* CO_2 and temperature have commonly been measured because they represent occupancy, and sensors for other parameters have been expensive up to now. With the development of low-cost sensors (LCSs), the possibility to affordably measure several extra parameters has opened up. In this work, a cap of €200 per sensing point was set on the price of the sensing equipment. The reasoning behind this amount was to be able to provide a solution that could be realistically deployed. However, LCSs suffer from accuracy, precision, and bias problems. Thus, calibrating these sensors had to be performed in a thorough manner. A calibration methodology was developed to handle the data collected, with the calibration experiments designed to allow for autocorrelation of the data.
4. *Which parameters should be used to improve the controls logics? Which are the most significant indicators?* In this work, CO_2, temperature, relative humidity, $PM_{2.5}$, total volatile organic compounds, and formaldehyde were measured. These parameters were selected because they have been previously reported as common office challenges and could be measured using LCSs. In ventilation control, it is important to use all the significant parameters, but every extra parameter adds a layer of complexity to the control. Therefore, two methodologies were used to select the significant parameters:
    - On one hand, cross-correlation functions (CCFs) with de-trended time series and indoor/outdoor ratios were used to evaluate the correlations between parameters. Uncorrelated room parameters (e.g., CO_2 and $PM_{2.5}$) needed to be introduced into the control strategies for the supply airflow rate to the zone/room. Correlated parameters between the indoor and outdoor air (OA) (e.g., $PM_{2.5}$ indoor and outdoor) were used to select the OA fraction.
    - On the other hand, to account for the influence of the building's characteristics on the pollutant concentrations, considering the correlations derived from samples collected from the same households (i.e., clusters), the generalized estimation equation method was used.
5. *When are the control strategies better? How can these be evaluated?* Simulation and measurements were used to evaluate the effects of the different control logics. Co-

simulation between CONTAM and EnergyPlus softwares was the platform selected because these simulation programs simultaneously enabled energy use and IAQ analysis. The models developed were validated using measurements from a three-office setup in the laboratory and an eight-office corridor. Improved controls on supply airflow rates and the share of recirculated returned air were evaluated. The annual simulation results were analyzed by looking at annual energy use and key performance indicators, defined as the share of the simulated time during which a parameter was below or within a defined range.

In addressing these questions, a holistic approach to improving DCV control logic was developed. This methodology can be used in simple to more-complex cases. Most of the individual questions were answered in journal articles devoted to this. Each step and the entire methodology were validated using measurements.

In conclusion, the findings of this study provide an applicable solution to the need to improve ventilation control logic in order to consider the contradictory requirements of improving IAQ while reducing energy usage. The findings may contribute to the deployment of more-advanced sensing technologies, thereby ensuring healthier and productivity-promoting indoor environments that use less energy.

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LIST OF SELECTED PUBLICATIONS

The scientific publications and other research output from this thesis where Maria Justo Alonso is the first author are listed here. This is a paper collection thesis type. The primary publications refer to the peer-reviewed journal articles that set the course of this work. These papers are listed with the author's contributions. The secondary publications refer to conference articles used to demonstrate specific questions related to the primary publications or give further examples. The four first primary articles were published upon submission of the introduction and the last primary article was submitted. All the secondary articles were published upon submission. Primary and secondary publications are attached in this PhD thesis.

Other research outputs include blogs, dissemination articles in specialized magazines, radio and podcast contributions.

Primary publications

1 Justo Alonso, Maria; Wolf, Sebastian; Jørgensen, Rikke Bramming; Madsen, Henrik; Mathisen, Hans Martin. (2021) A methodology for the selection of pollutants for ensuring good indoor air quality using the de-trended cross-correlation function. *Building and Environment.* **vol. 209**

Contribution: The type of this paper is Full Length Article. The PhD candidate is the main author responsible of writing original and reviewed draft, visualization, validation, methodology, investigation, formal analysis, data curation, conceptualization. Sebastian Wolf: Formal analysis, methodology, software, visualization, writing. Rikke Bramming Jørgensen: Writing review & editing, formal analysis. Henrik Madsen: Formal analysis. Hans Martin Mathisen: Writing review & editing, supervision

2 Justo Alonso, Maria; Dols, William Stuart; Mathisen, Hans Martin. (2022) Using Co-simulation between EnergyPlus and CONTAM to evaluate recirculation-based, demand-controlled ventilation strategies in an office building. *Building and Environment.* **vol. 211.**

Contribution: The type of this paper is Full Length Article. The PhD candidate is the main author responsible of conceptualization, investigation, methodology, software, visualization, writing original and reviewed draft. William Stuart Dols conceptualization, investigation, methodology, software, visualization and writing of original and reviewed draft. Hans Martin Mathisen Writing – review & editing, supervision.

3 Justo Alonso, Maria; Madsen Henrik; Liu,Peng; Jørgensen, Rikke Bramming; Jørgensen, Thomas Berg; Christiansen, Even Johan; Myrvang, Olav Aleksander; Bastien, Diane; Mathisen, Hans Martin. (2022) Evaluation of low-cost formaldehyde sensors calibration. *Building and Environment* **vol. 222**

Contribution: The type of this paper is Full Length Article. The PhD candidate is the main author responsible of Writing – original and reviewed draft, conceptualization, software, methodology, investigation, formal analysis, data curation. Henrik Madsen: Writing original and reviewed draft, methodology, formal analysis, conceptualization. Peng Liu: Writing – original and reviewed draft, formal analysis. Rikke Bramming Jørgensen: Writing – original and reviewed draft, formal analysis, supervision. Thomas Berg Jørgensen: Investigation. Even Johan Christiansen: Software, resources, investigation. Olav Aleksander Myrvang: Software, resources, investigation. Diane Bastien: Writing –original draft, resources. Hans Martin Mathisen: Writing – original and reviewed draft, supervision.

4 Justo Alonso, Maria; Moazami, Therese Nitter; Liu, Peng; Jørgensen, Rikke Bramming; Mathisen, Hans Martin. Assessing the Indoor air quality in 21 home offices in Trondheim, Norway – *accepted in Building and Environment journal*

Contribution: The type of this paper is Full Length Article. The PhD candidate did the Conceptualization, data curation, formal analysis, investigation, methodology, software and writing – original and reviewed draft. Therese Nitter Moazami collaborated with the main author in the conceptualization, data curation, formal analysis, investigation, software, and writing – original and reviewed draft. Peng Liu, Rikke Bramming Jørgensen and Hans Martin Mathisen Formal analysis, writing – original draft

5. Justo Alonso, Maria; Liu, Peng; Marman, Stine Flage; Jørgensen, Rikke Bramming; Mathisen, Hans Martin. Holistic methodology to reduce energy use and improve indoor air quality for demand-controlled ventilation. *Submitted to Energy and Buildings*

   Contribution: The type of this paper is Full Length Article. The main author did the conceptualization, data curation, formal analysis, investigation, methodology, software and writing – original and reviewed draft. The lab measurements were done in collaboration with Stine Flage Marman. Peng Liu, Rikke Bramming Jørgensen and Hans Martin Mathisen Formal analysis, writing – original draft.

Secondary publications (included in this thesis)

i. Justo Alonso, Maria; Jørgensen, Rikke Bramming; Mathisen, Hans Martin. (2021) Measurements of indoor air quality in four Norwegian schools. Healthy Buildings 2021 – Europe Proceedings of the 17th International Healthy Buildings Conference 21-23 June 2021 ISBN: 978-82-536-1728-2

   Contribution: Maria Justo Alonso was responsible for the Conceptualization, data curation, formal analysis, investigation, methodology, software and writing – original and reviewed draft. Rikke Bramming Jørgensen and Hans Martin Mathisen Formal analysis, writing – original draft, supervision.

ii. Justo Alonso, Maria; Jørgensen, Rikke Bramming; Mathisen, Hans Martin. (2021) Short-term measurements of indoor air quality when using the home office in Norway E3S Web of Conferences, ISSN 2267-1242

   Contribution: Maria Justo Alonso was responsible for the Conceptualization, data curation, formal analysis, investigation, methodology, software and writing – original and reviewed draft. Rikke Bramming Jørgensen and Hans Martin Mathisen Formal analysis, writing – original draft, supervision.

iii. Justo Alonso, Maria; Jørgensen, Rikke Bramming; Madsen, Henrik; Mathisen, Hans Martin. (2022) Pollutant correlation analysis in measurements at four classrooms in four Norwegian schools, Indoor Air conference 2022, Kuopio, Finland

Contribution: Maria Justo Alonso was responsible for the Conceptualization, data curation, formal analysis, investigation, methodology, software and writing – original and reviewed draft. Henrik Madsen supported in the statistical analysis and writing and Rikke Bramming Jørgensen and Hans Martin Mathisen Formal analysis, Writing – original draft and supervision

iv. Justo Alonso, Maria; Jørgensen, Rikke Bramming; Madsen, Henrik; Mathisen, Hans Martin. (2022) Performance assessment of low-cost Arduinos-based sensors under representative indoor air conditions, Indoor Air conference 2022, Kuopio, Finland

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Other Research outputs (not included in this thesis)

a. Innovasjonsrapport 2020. Forskningssenteret for nullutslippsområder i smarte byer (FME ZEN) Bergsdal et al, https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2723835?show=full

b. Åpner vinduene for bedre inneklima- Interview (2019) Nemitek.no. https://nemitek.no/inneklima-sintef-byggforsk-ventilasjonskjoling/apner-vinduene-for-bedre-inneklima/102772

Blog articles

c. Is opening a window the best way to ventilate a building? (2018) NTNU TechZone https://www.ntnu.no/blogger/teknat/en/2018/05/24/opening-windows-the-best-way-to-ventilate-a-building/

d. Guest researcher diaries: How to co-simulate with EnergyPlus and CONTAM and not smother in the attempt! (2018) SINTEFBlog.no https://blog.sintef.com/uncategorized-en/guest-researcher-diaries/

e. Home Office: 5 Tips For Good Indoor Air Quality (2020) SINTEF Blog https://www.sintef.no/en/latest-news/2020/home-office-5-tips-for-good-indoor-air-quality/

f. Fem tips for god luftkvalitet på hjemmekontoret (2020) gemini.no https://gemini.no/2020/03/fem-tips-for-god-luftkvalitet-pa-hjemmekontoret/

Radio/Podcast

g. TU-Teknisk sett: Podcast episode 379 -Det virkelig store potensialet for elsparing, interview (2021)

h. Perfekte ventilasjonsystemer – Interview NRK radio (2018)

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NOMENCLATURE

AHU Air handling unit

CCF Cross-correlation function

CH_2O Formaldehyde

CO Carbon monoxide

CO_2 Carbon dioxide

CV Coefficient of variation

CV-RMSE Coefficient of variance of the root mean squared error

DCV Demand-controlled ventilation

FME ZEN Research Centre on Zero-Emission Neighbourhoods

GEE Generalized estimation equation

HVAC Heating, ventilation, and air conditioning

IAQ Indoor air quality

IDF Input data file

Iid Independent and identically distributed

I/O Indoor/outdoor ratio

KPI Key performance indicator

LCS Low-cost sensor

MLE Maximum likelihood estimate

MNB Mean normalized bias

MOx Metal oxide

NMBE Normalized mean bias error

NDIR Nondispersive infrared

NTNU Norwegian University of Science and Technology

OA Outdoor air

OLSs Ordinary least squares

PRJ file CONTAM project file

PM Particulate matter

RH Relative humidity

REML Residual maximum likelihood

R^2 Coefficient of determination

SBS Sick building syndrome

TVOC Total volatile organic compound

VAV Variable air volume

VOC Volatile organic compound

WHO World Health Organization

1. INTRODUCTION

In this chapter, the research context for this study is laid out. The aim of the study, addressed through answering research questions to fill knowledge gaps, is presented.

1.1 Research background and motivation

Reduced energy consumption in buildings has been one of the prime motivations behind developing the latest European building regulations and standards [2]. The building sector accounts for about 40% of the global energy use [3], and energy consumption for heating, ventilation, and air conditioning (HVAC) potentially accounts for 30–40% of the overall energy consumption and about 40–60% of the total electricity used in buildings in cold climates [4,5]. Efficient buildings, such as passive houses [6] or zero-emissions buildings [7], are required to demonstrate a significant decrease in energy use. This is achieved primarily through reduced heat loss [8] (i.e., tighter building envelopes and reduced uncontrolled air leakage). Ventilation may account for more than 50% of the total energy loss from these buildings if no heat recovery is used [9]. Heat recovery can reduce these energy demands by 80–90%, according to several studies on cold climates [10,11]. Additionally, demand-controlled variation (DCV) is a very energy-efficient measure for when occupancy varies throughout the day—in Norway, the typical design occupancy is around 50% at maximum [12]. Thus, DCV can significantly reduce ventilation energy use by 30–60%, compared to constant air volume controls (CAV) [13,14].

Pollutants can infiltrate from outdoors or be generated indoors by different indoor activities [15]. Because the infiltration of outdoor air (OA) is reduced in tighter envelopes, ventilation becomes necessary in order to dilute interior pollutants. The indoor environment is one of the essential factors in a person's cumulative air-pollutant intake [16]. Thus, to ensure healthy indoor environments that provide comfort and encourage productivity, natural or mechanical ventilation is needed to remove adverse airborne pollutants and thus ensure a good indoor air quality (IAQ). Heat/energy recovery and DCV are usually proposed as energy-efficiency measures for cold-climate offices [10,17–19]. Mechanical ventilation with heat recovery and a heat coil reduces the risk of draughts and the infiltration of outdoor pollutants compared to the supply of unconditioned and unfiltered OA through vents or openings. With DCV, the ventilation airflow rates depend on the concentration of a selected airborne contaminant or an indicator for occupancy. During periods of full occupancy, the airflow rate is maximized, and when the room is vacant, the airflow rate is minimized. In this way, the energy consumed by ventilation and heating is reduced.

Selection of the parameter to use to control the ventilation is not trivial. Carbon dioxide (CO_2) and temperature are the typical occupancy indicators [20]. Temperature is also often an indicator of several other heat loads, such as sunlight. However, other airborne contaminants should always be ventilated and do not necessarily correlate with occupancy. Temperature is not a pollutant, but rather an environmental parameter that affects the perception of the IAQ because it affects both the relative humidity (RH), to which it is correlated, and the degassing of indoor materials. Common OA pollutants, such as particulate matter (PM), total volatile organic compounds (TVOCs), carbon monoxide (CO), ozone (O_3), and nitrogen oxides, can infiltrate into the indoor environment. Formaldehyde (CH_2O) may be found/produced indoors and is related to building materials, cleaning agents, paints, adhesives, cooking fumes, wood smoke, biological pollutants, among several other things [21–23]. Exposure to pollutants over the short and long term has been linked to deleterious health outcomes, varying from minor upper respiratory irritation to chronic respiratory and heart disease, acute respiratory infections in children, and chronic bronchitis in adults, as well as aggravating pre-existing heart and lung conditions and prompting asthmatic attacks [24], potentially leading to premature mortality and reduced life expectancy [25].

Indoor air RH is essential due to its associated comfort and health effects [26]. Relative humidity affects the rate of degassing of CH_2O and volatile organic compounds (VOCs) from indoor materials [27], and has been correlated to the perception of IAQ [28], the formation of molds and allergens [29], and the survival of pathogens [26]. Ventilation or air conditioning should keep the RH below mold or mite growth thresholds [30]. The survival rate and transmission efficiency of the influenza virus has been proven to increase at low RHs [26,31]. Contrarily, RHs over 40% can dramatically reduce the infectivity of certain other viruses [32]. Coronavirus infectivity, for instance, seems to decay faster at close to 60% RH than at other levels [33]. Recent research by Aganovic et al. [34] found that, for non-enveloped viruses, such as adenovirus and rhinovirus, increasing the RH would increase the probability of infection, whereas for enveloped viruses, such as SARS-CoV-2 or influenza, an increased RH would decrease the probability of infection. From their data, increasing ventilation always resulted in reduced infection risk, regardless of virus type [34]. In the winter in cold climates, the problems associated with RH are related to the excessively dry conditions [26]. In these cases, strategies for humidification are seldom recommended [35], primarily because of the risk of mold.

Some authors have concluded that there is a need to take CO_2 as both an IAQ indicator and a pollutant that impacts health and cognitive functions [36,37], even at concentrations below 1,000 ppm [38]. Other authors have suggested controlling other parameters [39–42] in addition to CO_2 and temperature. Morawaska et al. [43], for instance, confirmed that there are no ventilation guidelines to precisely control the concentration of viruses, benzene, CO, CH_2O, and other chemicals, indoors [43].

The World Health Organization (WHO) has defined threshold concentrations for various contaminants based on their effects on human health [44], but the list does not include all possible airborne pollutants that can cause health effects. Still, many of the recommended parameters with thresholds are not typically measured. Logue [45] determined that, in the United States (US) and countries with similar lifestyles, air pollutant concentrations in residences often exceed health-based standards for chronic and acute exposure. The WHO concluded that about 3.8 million deaths can be linked to household air pollution, annually [46]. The coronavirus pandemic brought attention to the effect of ventilation on the spread of sickness. Aganovic et al. [47] concluded that increased ventilation rates always reduce infection risk, independently of virus type. Morawaska et al. [43] asked for a paradigm shift in ventilation control to address the transmission of respiratory infections in order to avoid suffering and to protect against economic losses.

How to measure these parameters reliably and cost-effectively is an important question. There is a growing interest in monitoring using low-cost sensors (LCSs). However, their accuracy, drift, and reliability are still in question, with preliminary tests [48–53] having suggested their poor to uncertain reliability. A recent literature-review analysis of 112 studies on LCSs [54] concluded that only a few studies followed the US Environmental Protection Agency's (EPA's) sensor performance guidelines [55].

Low-cost sensors can provide continuous measurements that can be integrated to control actuators [56]. Guyot et al. [57] reviewed the existing smart residential ventilation and found that the most advanced ventilation control used CO_2, temperature, RH, and TVOCs (mostly in bathrooms). Chiesa [56] developed an Internet of Things (IoT) application that used CO_2, VOCs, atmospheric pressure, RH, and temperature to control ventilation. They concluded that the proposed IoT application defined airflow rates that maintained IAQ indices [58].

In Norway, the building codes [59] advise against recirculating return air unless the room is vacant. Recirculating extracted air is not advisable for avoiding IAQ problems due to previous experiences with lousy control of the IAQ while using recirculation. In other countries, such as the US, China, and Canada, this is an accepted general procedure for reducing energy use for heating, cooling, and dehumidification. However, challenges with RH and temperature, high CO_2, and other indoor airborne pollutant concentrations, or increased fan energy, may arise depending on the fraction of OA.

Control studies on DCV have focused on scattered parts of its optimization, such as forecasting pollutants [60], evaluating the real-life performance of DCV solutions [61], optimizing the ventilation control [62,63], the pollutants used in the control [57], and the simulation strategies employed [64–70].

1.2 Research questions and research tasks

This work aimed to find a holistic method for improving DCV control in commercial buildings using (or not) the recirculation of return air to improve the ventilation control logic, bearing in mind reduced energy use, CO_2, temperature, several other airborne pollutants, and RH.

The research questions described below prompted the main activities described in Figure 1-1. The answers to these questions provided the main contributions (see Section 5.2) to this PhD thesis.

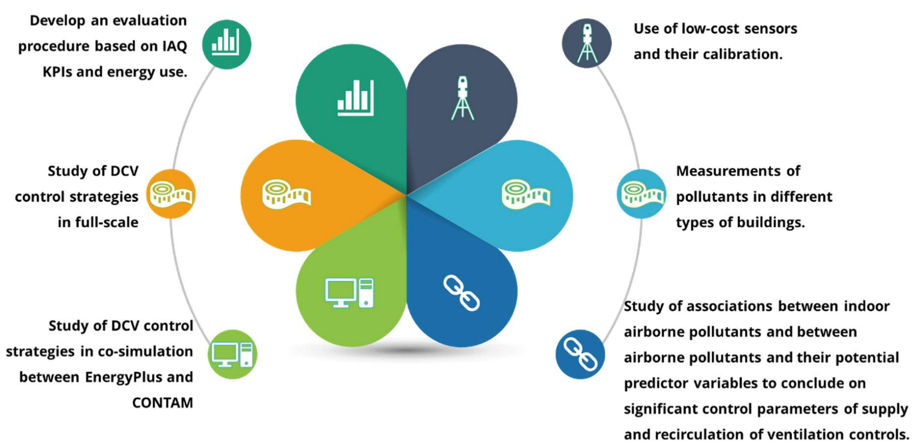

Figure 1-1. Main activities undertaken to achieve the overarching aim of this study.

The following research questions (RQs) and tasks were proposed, representing a step-by-step approach to achieving the aim of this study.

RQ 1: Can CO_2 be a proxy for all other indoor air pollutants? How can the correlation between pollutants be studied?

- Task 1.1: Literature review.
- Task 1.2: Develop a methodology to accomplish correlation studies.
- Task 1.3: Test the methodology using measurements from different types of buildings with different types of use.

RQ 2: How do the selected low-cost IAQ sensors perform?

- Task 2.1: Develop an IAQ station comprising LCSs for measurements of CO_2, temperature, RH, CH_2O, TVOCs, and $PM_{2.5}$.
- Task 2.2: Establish a methodology for calibrating a low-cost CH_2O sensor given autocorrelated data and test CH_2O sensor performance.
- Task 2.3: Evaluate the performance of $PM_{2.5}$, CO_2, RH, and temperature sensors based on the previous methodology.

RQ 3: Can energy use be reduced while maintaining good IAQ?

- Task 3.1: Propose simulation software that can simulate the effect of different DCV control logics in energy use and IAQ.
- Task 3.2: Build validated models for individual case studies in order to analyze different strategies to control supply-air delivery and return-air recirculation rates, including the use of DCV strategies, and perform yearly simulations.
- Task 3.3: Improve ventilation control strategies based on their effect on the concentrations of pollutants and annual energy use.

RQ 4: What is the status of the IAQ in home offices and schools in Trondheim?

- Task 4.1: Measure the IAQ in 21 home offices and four Trondheim schools.

- Task 4.2: Examine whether CO_2-based DCV in schools is satisfactory for maintaining the other measured indoor air parameters within the range of, or below, a defined health-based threshold.
- Task 4.3: Determine which building characteristics can be used as significant predictors for reducing pollutant concentrations.

RQ 5: Can an office ventilation control be improved using a multiparameter-based DCV controlled by LCSs?

- Task 5.1: Set up a demonstration of three full-scale cell offices in the laboratory.
- Task 5.2: Validate a simulation model of the setup.
- Task 5.3: Evaluate the performance of different control systems using a key performance indicator (KPI) for annual energy use and IAQ KPIs.

The questions described in the abstract are simplified didactic versions of the RQs given in more detail in this chapter. Figure 1-2 shows the logical connections between the RQs and the defined tasks and the articles and papers that provided answers to these questions and the research method employed. Figure 1-3 additionally shows a timeline overview, where the milestones of the PhD are organized by topic. The candidate took a net time of four years, working 75% of the time at the Norwegian University of Science and Technology (NTNU), to develop this PhD work, with the remaining 25% being spent at SINTEF Community, where she worked as a scientific researcher.

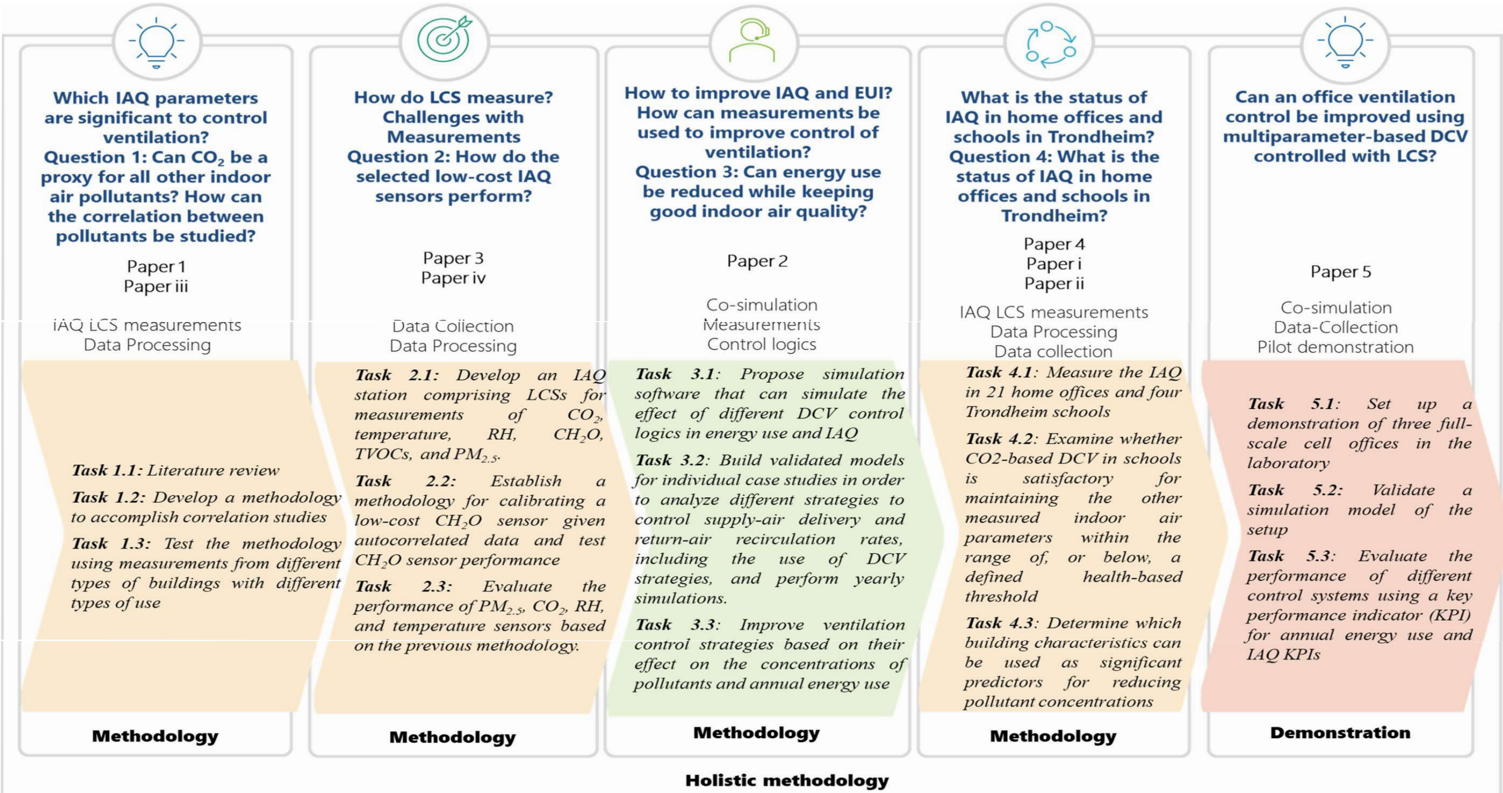

Figure 1-2. RQs in connection to articles, tasks, and deliverables.

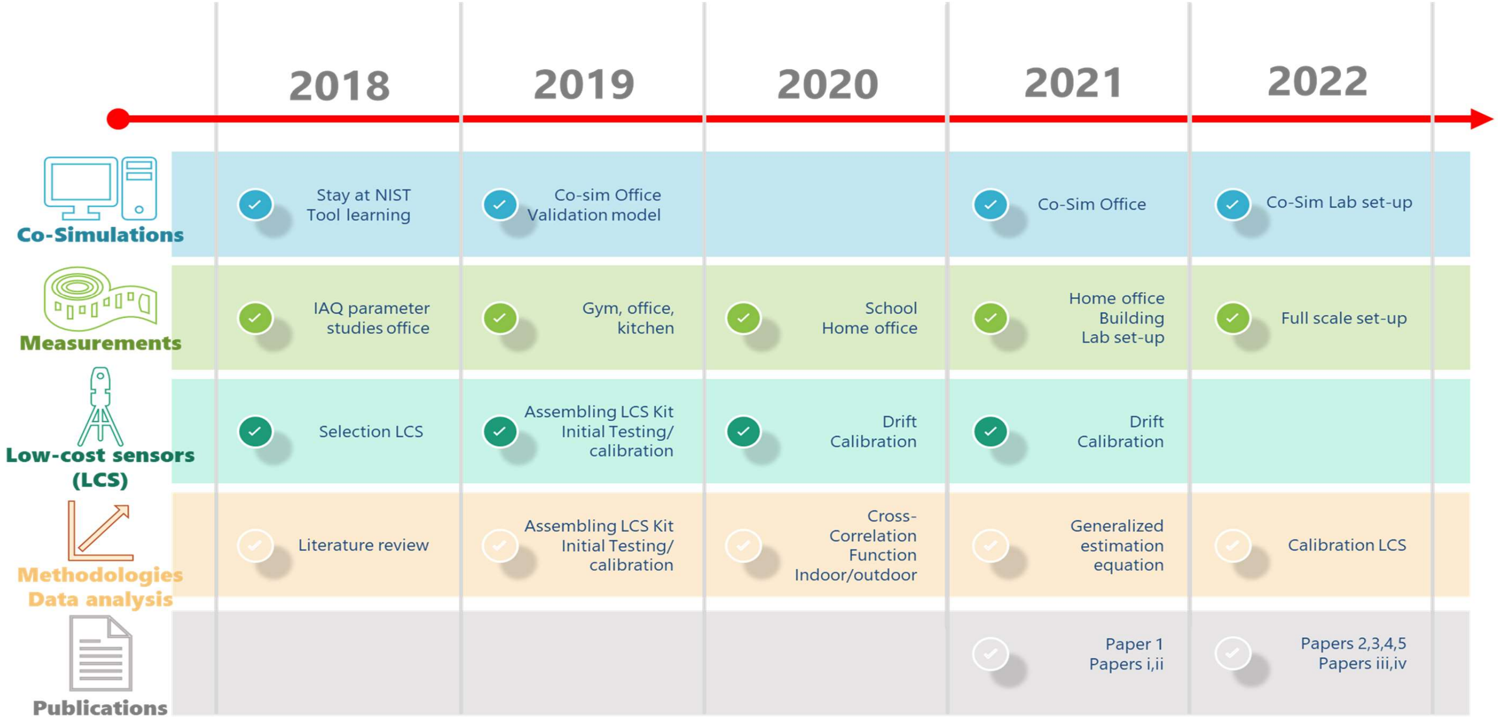

Figure 1-3. Timeline, organization of the research, and milestones achieved during the course of the study.

2. AIRBORNE POLLUTANTS, LCSs, AND THEIR CALIBRATION

The purpose of this chapter is to present a description of the journey towards developing low-cost sensing stations and their calibration. The chapter begins with a description of the data collected in the author's office that motivated the start of this PhD work. A limited literature review was used to justify why using CO_2 and temperature as the control parameters for the DCV was insufficient. This review targeted RQ 1. The chapter proceeds with RQ 2, with a description of selected airborne contaminants and parameters that may affect health and comfort, which could be measured during the PhD work using LCSs. The chapter finishes with a presentation of the selected LCSs and their calibration. This section corresponds to RQ 1, Task 1.1 and RQ 2, Tasks 2.1, 2.2, and 2.3, and the work has been presented in Paper 3 and Conference Paper iv.

2.1 Background to this thesis: Measurements from the university office

The $PM_{2.5}$, CO_2, RH, and temperature levels were measured in a 42-m^2 office at the NTNU in Trondheim, dimensioned for six occupants and with a constant supply airflow rate of 350 m^3/h. Concentration measurements were collected over the course of a week, but activity logging data were only collected for one day. During measurement collection, the windows were kept constantly closed and the room's door was only opened to access the room. On the activity-logging day, four to five occupants were in the office from 9:00 to 19:00. At 15:00, 16 people entered the room and stayed inside until 15:08. Figure 2-1 presents an overview of selected pollutants as a function of time.

From these measurements, the CO_2 levels were found to be mainly below 750 ppm. Only during the visit by 16 students did the CO_2 rise to close to 850 ppm. This level was just a peak, as the students came in for only a short visit. In the office, a large amount of OA is supplied per person, explaining why the concentration of CO_2 was low, to the extent that a DCV control would reduce the supplied airflow rates and thus reduce the energy use. Although the CO_2 was far below 1,000 ppm, the daily mean of $PM_{2.5}$ was 19 $\mu g/m^3$. This value exceeds the Norwegian daily recommendation of 15 $\mu g/m^3$ [71]. Reducing the supplied air may have been beneficial if the pollutants came from outdoors through the ventilation system and the filter. However, the $PM_{2.5}$ concentrations in the supply air were not monitored. City measurements taken close to the office did not correlate with the indoor measurements. In this case, deciding on a supplied airflow rate based only on the CO_2, while not knowing the origin of the $PM_{2.5}$, would not be robust.

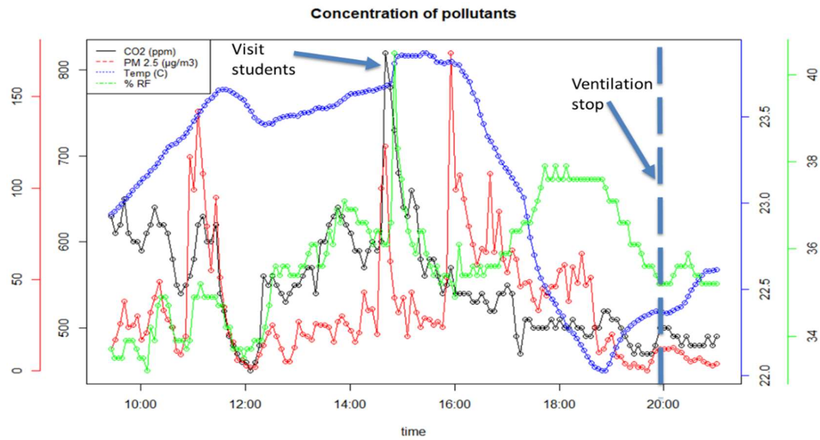

Figure 2-1. Measurements of CO_2 concentration, $PM_{2.5}$, temperature, and RH taken over the course of a single day in the studied office at the NTNU in Trondheim.

The general assumption in any room is that the $PM_{2.5}$ infiltrates from outdoors and that reducing supplied airflow rates would be beneficial in controlling that. However, there were three prominent peaks of $PM_{2.5}$ in the measurements from the office, the first relating to lunch being eaten in the room, the second relating to the entrance of the 16 students, and the third relating to vehicular traffic. Thus, reducing the airflow rate would have been beneficial only in relation to the last peak. Reducing airflow rates would encourage higher $PM_{2.5}$ concentrations for the lunch and student-visit peaks. Monitoring the room and supply-air values was hypothesized as being more suitable for discerning the origin of pollutants. However, the only standard measurements taken in most buildings are CO_2 and the temperature in the room.

The occupants of the office, when questioned, answered that their performance was low due to “heavy air and high temperature.” The temperature was constantly below 24°C. Seppänen et al. [72] recommended temperatures below 23°C to increase office performance, whereas Chenari et al. [73] recommended keeping temperatures below 22°C to reduce sick building syndrome (SBS) symptoms. In this case, the heating was not monitored, but if the radiators were off, increasing the supply of air (the OA was at 19°C) could have been beneficial by reducing the temperature in the room.

The RH was never below 32%. A reduction in airflow rate would have increased the RH.

The most important lesson to be gleaned from Figure 2-1 is that the $PM_{2.5}$, RH, and temperature peaks did not necessarily occur simultaneously with peaks in CO_2. Using CO_2 as a marker for $PM_{2.5}$ is not satisfactory, given the peaks were not simultaneous and, in this case, the origin of the $PM_{2.5}$ did not even seem to be constant. The constant high ventilation rates per person ensured low CO_2 concentrations, but it could not keep the particle levels low. In this case, it may even be that the high ventilation rate increased the $PM_{2.5}$ concentrations and, in colder periods, the high airflow rates may explain the low RH in the room. However, from these measurements, increased airflow rates would be beneficial in reducing the indoor temperature because the OA was colder than the indoor air.

These measurements were an eye-opener and became the founding stone of this PhD work.

2.2 Why are CO_2 and temperature not sufficient indicators of the IAQ and thus insufficient control parameters for DCV

In standard office work, humans produce CO_2 proportional to their body mass and metabolic rate [74]. Because of this known production, CO_2 levels are often understood to be an indicator of the number of people in relation to the ventilation [75,76]. Carbon dioxide concentrations are related to the perception of human bioeffluents and the level of human-related odors [77,78]. Limits for CO_2 have existed for more than 150 years [79]. However, many have used the 1,000 ppm value from Pettenkofer[79], not understanding that its basis is the perception of the human body odor of building occupants. Using CO_2 as an indicator of OA ventilation requirements must adapt to the fact that ventilation requirements should depend on the type of space being ventilated, the occupant density, and the occupants' characteristics and activities [78]. Such adaptation is not frequent. The CO_2 concentration should not be used to regulate ventilation rates because the same concentration could be too little for a gym and too much for a church in terms of body odor, for example.

There is still some discussion on the actual threshold that should be maintained. The literature on its direct effect on health, well-being, and work performance is inconsistent [78]. Indoor concentrations of CO_2 greater than 1,000 ppm have been associated with SBS symptoms [80]. However, much of the background research has been done using observations that did not control other contaminants or environmental parameters [78] additional to the CO_2. Several groups have recently explored the cognitive effects of short-term exposure (2–8 h) to pure CO_2 (in a controlled environment with no significant concentrations of other pollutants) at concentrations of 600 and 5,000 ppm [81–83]. The results are inconsistent. There have been several reported associations between CO_2 and decreased cognitive performance at concentrations close to 1,000 ppm [36,37,84,85], with a further one being ambiguous [86].

It is relatively easy to measure CO_2, the most-common type of sensors being nondispersive infrared (NDIR), which calculate gas concentrations by measuring absorbed infrared rays. This technology is very accurate and selective, as the detection occurs in a narrow wavelength band [87]. However, it is generally accepted that, in a closed space, its concentration varies with the location (horizontally and vertically) and that this can represent a risk for the representativeness of a single-point measurement [88], and thus for it being a proxy for changes in the air if there is no knowledge about the airflow distribution. For this reason, Carrer et al. [39] questioned using CO_2 to measure the ability of ventilation to dilute and remove pollutants. Also, a constant generation of CO_2 by humans cannot be ensured if humans change their current (or prior) activity level. However, the differences between indoor and outdoor CO_2 concentrations are often used to evaluate ventilation rates and air distribution [78].

Carbon dioxide does not provide an overall indication of IAQ; for example, traffic emissions infiltrating the room from outdoors and emissions from building materials do not correlate with human presence. Ramalho et al. [40] investigated correlations between CO_2 concentrations and selected indoor pollutants (CH_2O, acetaldehyde, benzene, $PM_{2.5}$, PM_{10}) in 567 dwellings and 310 educational buildings (nurseries, kindergartens, and schools). They concluded that the correlations between CO_2 and pollutant concentrations were weak or very weak. Choe et al. [89] found that air cleaners could reduce PM concentrations while CO_2 concentrations remained high. Wu et al. [90] presented measurements from green buildings in which the CO_2 and PM were lower than in ordinary buildings, but VOCs were higher. Therefore, some authors have specified that CO_2 should only be used to signal occupant-related pollutants [42,91]. Most authors agree that CO_2 can be helpful in IAQ assessment, an example being how it is used to control DCV [78].

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has recommended studying ***Strategies for DCV using CO_2 and other indicators of occupancy that overcome limitations of current approaches and control contaminants that are not linked to occupancy*** [78]. This PhD study was aimed precisely at this target.

2.3 Other selected parameters that can and should be measured using LCSs

In this section, the parameters measured for this PhD study, additional to CO_2 and temperature, are described. Section 2.3 starts with an elaboration of which parameters should/can be measured to describe the air quality and evaluate their health effects. This is followed with how the parameters can be measured using LCSs.

Coarse, fine, and ultrafine particles (i.e., PM) can infiltrate indoor air via leakages [92], openings, and ventilation (mechanical or natural). Filters can significantly reduce infiltration via mechanical ventilation [93]. Because of these, mechanical ventilation is often considered to carry less PM than natural ventilation when the OA has high PM concentrations [94]. However, having a filter does not mean that no particles will infiltrate because the effectiveness of the filters will also depend on the size of the particles, the filter rating, the precision of the mounting, the humidity, and the filter condition [95]. Chen and Zhao [96] also pointed out the importance of the geometry of building envelope cracks and air exchange rates regarding PM infiltration. However, PM is also produced indoors via human activities and skin and hair [97],96]. Morawska et al. [99] assessed that 10–30% of the total disease burden from PM exposure was due to indoor-generated particles.

The health effects of indoor PM are often extrapolated from outdoor PM studies because the relationship between indoor PM and health is less understood [100,101]. The effect of PM on health depends on the chemical composition, size, shape, deposition, resuspension, and hygroscopic growth of the particles. These latter three factors appear to depend very much on the RH [102]. Several studies have related PM to cardiovascular disease [101]. Chronic $PM_{2.5}$ exposure affects the respiratory and cardiovascular systems [103]. Chronic bronchitis, stroke, heart disease, the thickening of arterial walls, diabetes, and reduced lung function have also been connected to $PM_{2.5}$ exposure [104–106]. In addition, PM may also be a carrier of viruses, such as influenza [26].

Currently, several LCS manufacturers claim to be able to measure PM, with a coefficient of determination (R^2) of up to 0.99 between calibrated and measured values for sensors calibrated in the operative environment, but as low as 0.5 otherwise [107]. The sensors' accuracies depend on the measuring principle, the measured particles' size distribution, and how close these are to the calibrated spectrum and the RH level [108]. Particulate-matter sensors are often calibrated in the factory using the same test aerosol, yielding identical detection ranges for the different size bins [109].

Most of the available LCSs are optical sensors in which the measuring principle is based on measuring the shadows of passing particles [110]. Thus, these sensors can be quite accurate for smaller PM fractions (e.g., $PM_{1.0}$), but less accurate the larger the size of the particles, such as PM_{10} [109]. However, the health guidelines focus on $PM_{2.5}$ and PM_{10} [111]. Most available PM LCSs compensate for temperature and RH effects and have low intramodel variability [109].

Formaldehyde is widely deployed in products used for manufacturing building materials, furniture, and numerous household and cleaning products [112]. Formaldehyde is a byproduct of combustion from candles, incense sticks, mosquito coils, cigarettes, and wood-burning fireplaces [113] and is used as a preservative in some food packaging [114]. Air-cleaning devices, textiles, cooking, carpets and surface coatings, plywood, and medium-density fiberboard (MDF) are also sources of CH_2O [113]. Salthamer et al. [115] claimed that CH_2O and benzene are common issues in offices, and they are generally reported for causing sensory irritation before they are smelled. Formaldehyde has been classed as a potential human carcinogen by the US EPA, and as a Group 1 carcinogen by the International Agency for Research on Cancer, as well as a sensitizing agent that can cause an immune system response and sensory irritation [112].

The WHO has recommended a threshold of 100 $\mu g/m^3$ for an average of 30 min for CH_2O [44]. This threshold is, however, seldom measured due to the high cost of accurate assessments.

There are very few LCSs that claim to measure CH_2O. Most (low-cost) measurements of CH_2O use colorimetry, infrared absorption, or sensors incorporating semiconductor metal oxide (MOx) thin films, MOx films, or MOx nanoparticles [116]. However, these technologies at low concentrations (<0.1 ppm) suffer strong cross-sensitivities to alcohols and other interferents [116].

Volatile organic compounds represent a wide variety of organic substances. Sources of VOCs in indoor air can include building materials, furnishings, cooking, household products, cleaning products, and products used for personal hygiene, for example, and they are often connected to smells. Indoor VOC concentrations generally fall below threshold levels for sensory irritation of the eyes and airways, but above odor thresholds [108]. Even though there has been confirmation of the various dangerous effects linked to individual VOCs, established scientific knowledge concerning their direct health risks is absent [117]. In the LCS industry, sensors measure an agglomerated value of all the existing VOCs—known as TVOCs. Relevant indoor-limit values exist for only a few of these VOCs, making it challenging to use a single TVOC as a useful marker for IAQ in all public buildings.

Although TVOCs sensors have been progressively presented as a cheap and energy-efficient alternative to CO_2 sensors in DCV [118], they do not react to CO_2 peaks, and there is no established correlation between TVOCs concentrations and perceived air quality [118] or health effects. Because TVOCs measurements are non-specific, they react to all pollutant sources, which would make them very sensitive in DCV systems [118].

Many TVOCs sensors use heated film or MOx nanoparticles. These are based on the reaction of oxygen adsorbing onto the MOx particles, producing a change in the measured electrical resistance [119]. This measurement principle is very similar to that used in CH_2O measurements, and so the data from these two types of sensors often produce correlations.

The RH is often monitored, but is seldom used to control ventilation in cold climates, except for swimming pools and bathrooms in residential buildings. In cold climates, OA with a very low absolute humidity content results in very low humidity levels during winter.

Gładyszewska-Fiedoruk et al. [120] claimed that, if humans are the most significant contributors to moisture generation, CO_2 and RH should be highly correlated, at least in naturally ventilated buildings. However, correlations cannot be determined for mechanical ventilation where the air is cooled or dehumidified [121].

A common complaint in response to cold-climate office-environment IAQ questionnaires is perceived dry air. Some questionnaires have revealed relationships between low RH (5–30%) and an increased prevalence of complaints about perceived dry and stuffy air, as well as sensory irritation of the eyes and upper airways [26]. The perception of dry air can be connected to mucous membrane irritation of the eyes and upper airways in the presence of sensory irritants [122]. Additionally, the reported “stuffy or dry air” may be affected by the alteration of the dynamics, composition, deposition, and resuspension of the inhaled particles, possibly in concert with sensitive eyes or mucus membranes in the upper airways at low RHs [26].

Air quality is perceived as stuffier and increasingly more unsatisfactory in rooms with increasing enthalpy (RH and temperature) [123], a perception that may be linked to increased VOC emissions [124]. Emission profiles of VOCs from building materials are not constant with RH, and VOC emissions also depend on temperature and water solubility [125]. The perception of odor and stuffy air may increase with increasing RH in a room. The perceived stuffiness can derive from altered VOC emission profiles due to thermodynamic effects [26].

Most guidelines recommend keeping RH levels at between 40 and 60%.

Capacitive sensors are commonly used to measure RH. The capacitive measurements are based on changes in the MOx electrical capacity with RH. The performance of RH LCSs is often deemed satisfactory [126].

Temperature is often measured simultaneously with CO_2. Measurements of temperature using LCSs are widespread and often very accurate, using either band gap or thermistor methods. Low and high temperatures can be risk factors for human health [127]. The WHO has recommended the temperature to be above 18°C due to health risks, but there is no equivalent value for excessively high temperature thresholds due to the limited number of studies [128]. Temperatures above 26°C are linked to an increased risk of acute symptoms, including thinking difficulties, poor concentration, fatigue, and depression [129].

2.4 Development of a IAQ station

Based on the need to measure extra parameters, as explained in Sections 2.2 and 2.3, a IAQ station was built for this study. The cap price for the station was set at €200 based on the 2018 market costs and availability. This cap included the sensors, an Arduino board, and a Raspberry Pi in order to develop/test a solution that could be used outside the research world. This cap was chosen after contacting several consultants and asking for the typical cost of a single sensor and its cabling connections.

LCS selection and connection

The LCSs were Arduino sensors and were connected via a customized shield card. Arduinos are open-source hardware and software, often used for prototyping. They are expected to develop significantly over the coming years. This is why they were chosen to demonstrate their suitability. However, the capacity of Arduino boards is limited, and communication protocols seldom warn of problems with capacity. To avoid this limitation, the Arduino board was only used to collect the data sent to the Raspberry Pi. The Raspberry Pi was in charge of processing the data and sending feedback to the actuators. The logged values were sent to the Raspberry Pi via USB cable and stored in text files. Introducing the Raspberry Pi meant higher current needs than using only the Arduino, but this solution was chosen due to its robustness. The power adapter for the Raspberry Pi can power the Arduino from a USB port. Several examples of such architecture [130] served as inspiration.

The LCSs were selected based on user friendliness (there was information available on the internet regarding mounting) and pre-calibration from the factory (according to the producers, they should not need any pre-use calibration). The existence of positive evaluations in the scientific literature was also a strength, although this was available for only a very few sensors due to their novelty. Table 2-1 provides information on the selected LCS collected from their manufacturers' datasheets and Figure 2-2 shows the IAQ station.

The results of a joint study performed by the EPA and the US South Coast Air Quality Management District [100] were used to choose the PM LCS [101]. The selected sensor was the Sensirion SPS30 due to its low cost and relatively high R^2 (0.83) for $PM_{2.5}$. However, only recently was it made clear that this sensor's valid detection range was approximately 0.7–1.3 µm (i.e., PM_1) [98]. The measurements of PM in fractions larger than $PM_{2.5}$ were discarded after the first comparisons with reference sensors due to their poor accuracy. They are not included in this thesis due to the severity of data misinterpretation when a sensor is extended to cover particle sizes that it cannot actually observe [98].

Regarding the CH_2O sensor, only one LCS was found. At the time of sensor selection, no peer-reviewed information regarding the selected Dart WZ-S was found. Nevertheless, it was deemed worthy of testing and evaluating, and introducing into the ventilation control logic.

Air temperature and RH were measured using a SHTC1 from Sensirion, and the TVOCs using a SGP30 from Sensirion. The sensors SGP30 and SHTC1 were integrated into an Arduino Shield SGP30_SHTC1 from Sensirion. Temperature and RH were used to correct the TVOCs measurements in this case. Recently, Demanega et al. [131] proved a strong correlation between this TVOCs sensor and professional-grade monitors, but there was only poor quantitative agreement.

Table 2-1. Properties of the LCSs used, with data retrieved from the producers' datasheets

Sensor name	**Parameter**	**Sensor type**	**Accuracy**	**Measurement range**
Sensirion SPS30 [132]	Particles concentration	Optical	0 to 100µg/m^3 => ±10 µg/m^3 100 to 1,000 µg/m^3 => ±10%	Resolution 1µg/m^3
DART WZ-S CH_2O module [133]	CH_2O	Electrochemical MOS	≤0.02 ppm CH_2O equivalent <±2% repeatability	0.03–2 ppm

Sensirion SCD30 [134]	RH	Capacitive	±3% RH at 25°C	0–100 %
Sensirion SCD30 [134]	CO_2	NDIR	±30 ppm ± 3% (500–1,500 ppm)	400–10,000 ppm
Sensirion SCD30 [134]	Temperature	10K NTC thermistor	±(0.4°C + 0.023 x [T°C – 25°C])	-40–+70°C
SHTC1_RH [135]	RH	Capacitive	±3% RH at 25°C	0–100% RH
SHTC1_Temperature [135]	Temperature	Band gap temperature	±0.3°C	-30–+100°C
Sensirion SVM30 [135]	TVOC	Multi-pixel MOx	15% of MV [1]	0–60,000 ppb

Note: [1]Typically, 1.3% accuracy drift per year.

Temperature and RH were also measured to compensate for the CO_2 measurement using the SCD30. No information was available about this sensor because it was only launched in 2018, just two months before it was purchased. In this case, the company's reputation was used as the basis for selection.

The individual prices of the sensors in 2018 were as follows: €47 for the SCD30, €29 for the Arduino Shield SGP30_SHT1, €39 for the SPS30, €15 for the Dart WZ-S CH_2O module, and €72 for the Raspberry Pi. Today, these prices would be higher because prices for electronics have risen significantly in the last 12 months due to post-COVID and war distribution problems.

The codes for most of the sensors were Arduino codes on GitHub. The codes for the Raspberry Pi were developed and adapted for this work. The available codes were examples of how the sensors could be used and were adapted to communicate with all the sensors simultaneously on both platforms.

The Arduino Shield SGP30_SHTC1 was connected using a code from Adafruit [136] and Sensirion AG [137], both available on GitHub. The SPS30 sensor communicated using codes [138,139], while the code available at Sparkfun [138] was used for the CO_2 SCD30 sensor for inspiration.

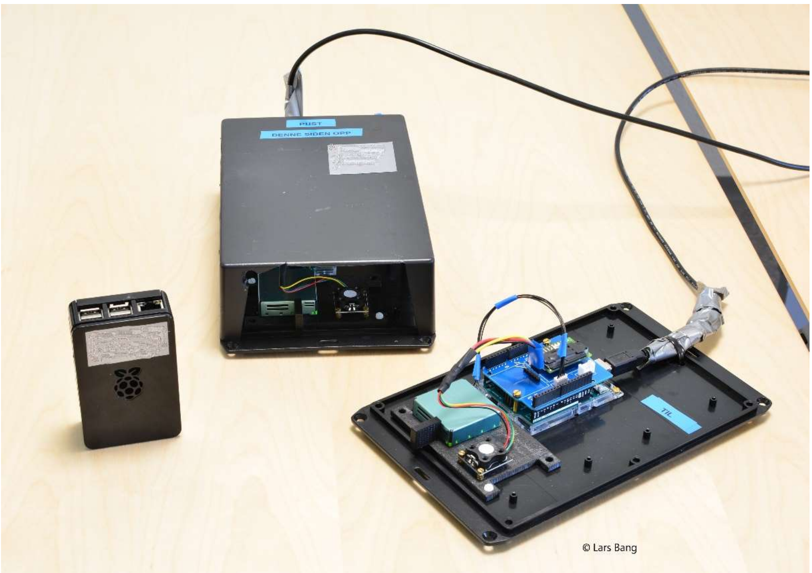

Figure 2-2. IAQ station connected to the Raspberry Pi. Photo: Lars Bang

Steps in the development of the IAQ stations

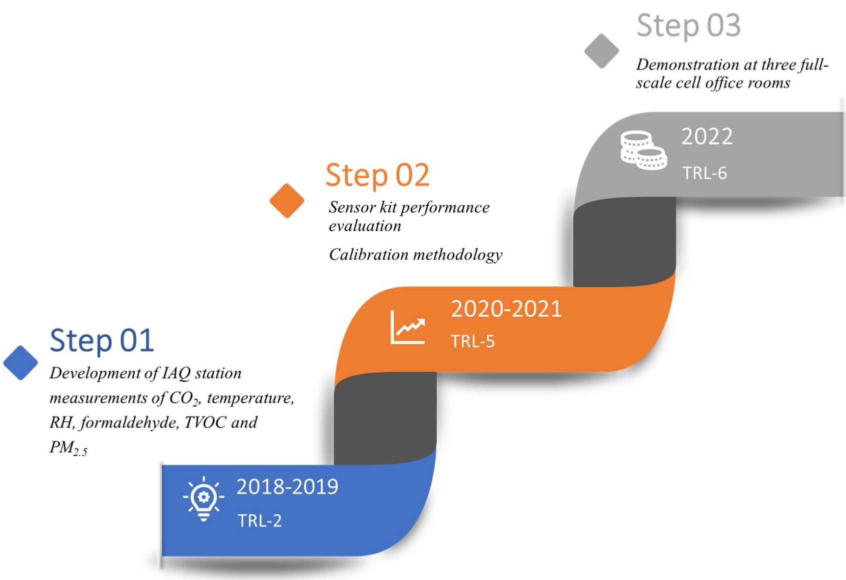

Figure 2-3. Steps in the development of the IAQ station.

Figure 2-3 shows the steps followed in the development of the IAQ stations. Step 1 (Task 2.1 of this PhD study) concluded with selecting and mounting the sensors, as shown in Figure 2-2. Tasks 2.2 and 2.3 in the RQs correspond to Step 2. These two tasks focused on the evaluation of the performance of the sensors under representative conditions. The evaluation of the sensors took almost two years, as the drift and changes in their precision or possible bias with time were evaluated. Paper 3 provides a detailed overview of the analysis of the CH_2O sensor, whereas Paper iv gives information about the calibration of the $PM_{2.5}$, CO_2, temperature,and RH.

Calibration chamber setup

Papers 3 and iv provide information about the calibration of eight identical IAQ stations using measurements from a laboratory-based 1.5-m^3 mini Plexiglas environmental chamber at NTNU. Figure 2-4 shows the layout of the calibration chamber .

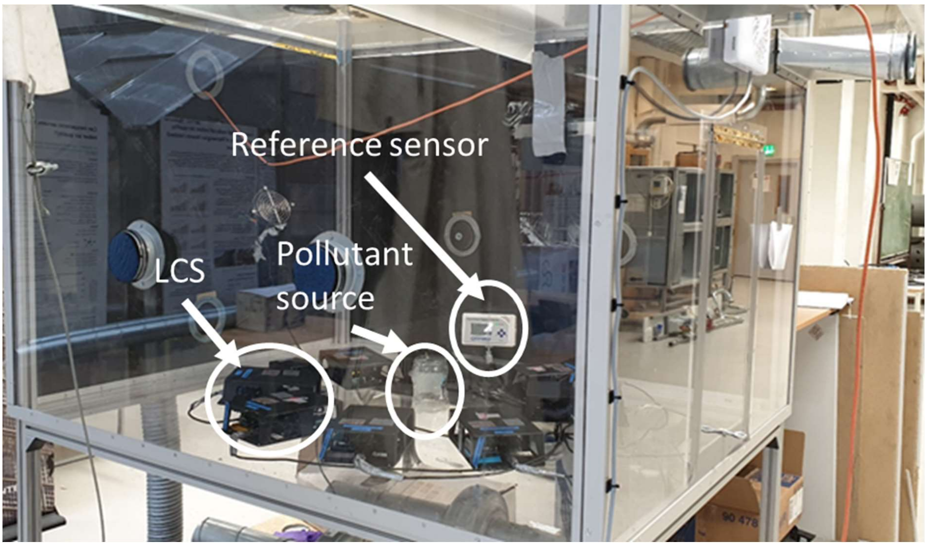

Figure 2-4. Image showing the experimental setup, with the formalin source at the center and the eight equal IAQ stations and the Graywolf reference CH_2O sensor arranged in a circle equidistantly from the source. Image taken from Paper 3 [140].

The sensors were exposed to the same CH_2O, CO_2, temperature, and humidity sources as the laboratory-grade equipment. The TVOCs sensor was not calibrated because no reference sensor was available, but measurements were collected in order to evaluate the intra-unit consistency. Some of the experiments were repeated after one year. The data obtained by the low-cost and professional-grade sensors were compared so as to establish a model representing the sensor behavior from which to estimate the residuals (i.e., the error in the model-based predictions). The measurements were heterogeneous in length. The data were collected every minute, and averaged in the case of the CH_2O LCS to 30 min.

Analysis of the experimental data

Typically, a calibration process would include steady-state exposures to different levels of sufficiently distinct concentrations. However, even experiments conducted in a randomized sequence with otherwise steady-state conditions will often lead to some autocorrelation. Autocorrelation happens even in steady-state measurements where some manipulable explanatory variables are selected, and the experiments are organized so the explanatory variables can be randomized. In most cases, some other variables are not considered/manipulable (e.g., the TVOCs in the CH_2O calibration), and such variables might also have an effect. Some experimental conditions are difficult to control or are not recognized, which may lead to some autocorrelation, particularly in experiments where the samples are taken at a high sampling rate. For instance, if the sensor presents a bias, this can lead to autocorrelations. Therefore, there is always a risk of having autocorrelations, which need to be accounted for.

In the case of this PhD work, the sensors, as well as the reference instrument, were exposed to rather heterogeneous "real-life" conditions. The measurements comprised time series of data, and the calibration focused on establishing a model for the relationship between the different factors describing these conditions. A calibration model is a regression model developed from the response of a sensor to known sources (customarily measured using a reference sensor). A good calibration model does not need a good fit of the measurements fed into it, but does need to precisely predict/estimate new/unseen measurements within the calibration range that will account for autocorrelations of the measurements.

As explained in Paper 3, measurements had to be taken carefully in order to achieve a good calibration. For instance, if an additional measurement was taken only one second after the previous measurement, then the additional information provided by this new measurement would be limited. Two such measurements are said to be serially correlated, using statistical terminology, and such a correlation in time for the same phenomenon is often called an autocorrelation.

Most often, standard ordinary least squares (OLS) is used for analyzing data from calibration studies. OLS techniques assume that the measurements are independent and identically distributed (iid). The validity of using simple linear models or the effects of the experimental design are seldom discussed. Calibration quality is usually addressed as the R^2 between the evaluated and reference instruments [54]. However, R^2 should only be used if the residuals are iid (meaning not correlated) and evenly distributed. The iid status needs to be checked in every model fitting. During regular use of these sensors, it is common to measure "constantly" (i.e., measurements being taken within a very short interval), with the autocorrelation of the measurements being a real problem that the calibration needs to handle. Therefore, high autocorrelation must be considered in a proper data analysis in order to obtain reliable conclusions.

In this PhD work, a procedure for estimating the autocorrelation weighting, based on the first-order Markov, was created. To the authors' knowledge, the method presented in Paper 3—considering and weighting the autocorrelation using first-order Markov scaling—had not been used in the sensor-calibration field, and therefore this represents an essential contribution resulting from this PhD work. This method enables calibration using dynamically sampled data and data sampled from time to time at a high sampling rate. This method allows for the efficient use of samples and then takes care of the autocorrelation by the methods suggested in the paper [140].

This calibration development was necessary for evaluating the dynamics of the sensors when the sensors are used in real life. The final goal of the IAQ stations was to demonstrate the use of LCS in the control of ventilation, thus, calibration involving a more dynamic evaluation that considered the frequency of the sampling as well was needed.

2.5 Calibration procedure and results

The calibration procedure followed the steps described below, taken from Paper 3:

1. Check that all sensors react similarly to exposure to the reference source. Before corrections can be studied, it must be ensured that all the units are responding similarly to the same events [110]. Malings [141] defined intra-unit consistency as the variability being less than 20% between equal units.
2. Log transform the data to make it more normally distributed.
3. Examine the calibration model most suitable to the available data—in this case, considering autocorrelated measurements and heterogeneous sampling lengths. The

model sought was fitted using maximum likelihood (ML) and the residual maximum likelihood (REML) method with all the measured variables.

4. Repeat the fitting of the model with only the most significant variables, chosen using the Akaike information criterion. This criterion studies the model's fit relative to using or not using extra parameters. It requires that the models are constructed using the same estimate principle.
5. Evaluate the results based on the EPA's suggested performance goals by applying the mean normalized bias (MNB) and coefficient of variation (CV), according to Williams [48]. This evaluation was performed according to the values described in Table **2-2**. The EPA guidelines allow a common comparison guideline for the reliability of sensors based on the two statistical measures.

Table 2-2. EPA's suggested performance goals based on the application of the MNB and CV, according to Williams [48]

	MNB range	**CV range**
Tier I: Education and information	-0.5 < MNB < 0.5	CV < 0.5 for all pollutants
Tier II: Hotspot identification and characterization	-0.3 < MNB < 0.3	CV < 0.3 for all pollutants
Tier III: Supplemental monitoring	-0.2 < MNB < 0.2	CV < 0.2 for all pollutants
Tier IV: Personal exposure	-0.3 < MNB < 0.3	CV < 0.3 for all pollutants
Tier V: Regulatory monitoring	-0.07 < MNB < 0.07	CV < 0.07 for O_3
	-0.1 < MNB < 0.1	CV < 0.1 for CO and $PM_{2.5}$
	-0.15 < MNB < 0.15	CV < 0.15 for NO_2

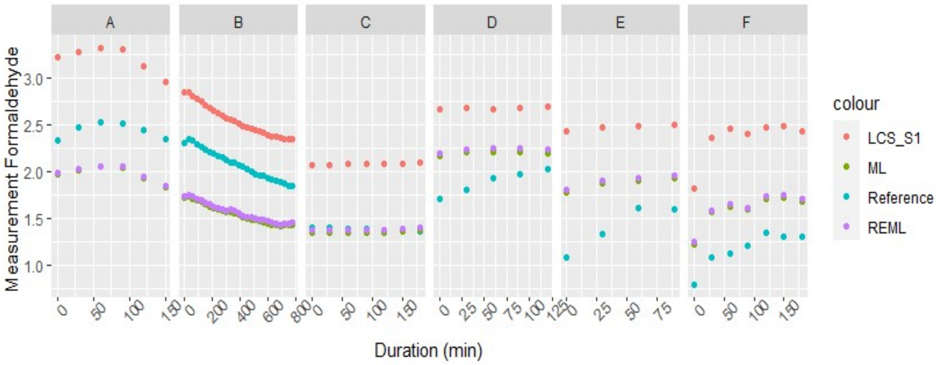

Figure 2-5. Prediction of calibrated values using ML and REML methods. Results grouped by test. See Paper 3 for more details about the tests [140].

Figure 2-5 (from Paper 3) shows that the CH_2O LCS reliably predicted the CH_2O concentration trends. However, these sensors suffered from precision problems due to cross-sensitivities with other gases. Drift may be another problem with these sensors. The calibration measurements were taken up to one year apart. In the interim, the sensors were exposed to different concentrations of CH_2O during measurement-taking in schools and home offices. The results may represent drift due to the loss of baseline or the accumulation of material on the oxidizing membrane of the sensor. The CH_2O sensor measurement principle relies on the diffusion principle. Clogging of the membrane may incur incorrect measurements or overpredictions. However, the sensors were seldom exposed to very high CH_2O concentrations. After three years of using the sensors, two of the eight sensors had stopped working two years before the sensor's expected five-year lifetime [133]. See Paper 3 for more details on the tests and results.

Paper iv includes a report on the performance of the IAQ stations using the same methodology used for measuring the temperature, $PM_{2.5}$, and CO_2. The main conclusions drawn from the results were that SCD30 performed better that SHT1 in measuring RH and temperature. However, the significant parameters for calibration of the RH and temperature models were not always the same. The author's best guess for the different effects was the setup for the experiment—perhaps the air was not fully mixed or some IAQ stations shadowed others. These experiments need further study.

Temperature and RH were significant additional parameters for the calibration model of some $PM_{2.5}$ sensors, but not consistently. The SPS30 was very accurate in tests where most of the PM was in the range of PM_1. When larger PM fractions were generated, the sensor could not observe them, underestimating their presence, most likely due to particle loss in the path from the inlet to the light detector or decreases in the amount of light scattered over the angular detection range per unit mass [142]. Kuula et al. [109] concluded that the sensor would perform near-regulatory grade if limited to measurements in the range of <0.9 μm and PM_1. The findings from this PhD work are in good agreement with those of Kuula et al. [109].

In the case of CO_2, environmental fluctuations influence the performance of NDIR sensors. Therefore, they are often studied in combination with temperature and RH [143]. This work has proved this to be wise because they are significant parameters for all tested sensors. All the sensors reacted very similarly to the exposures (see Paper iv for more details).

The calibration estimates developed were used to correct the measurements presented in this PhD. The only sensor not calibrated against a laboratory reference sensor was for TVOCs, but all the TVOCs sensors presented good intra-unit consistency.

2.6 Conclusions and main lessons learned from Chapter 2

According to the literature review, several parameters additional to CO_2 and temperature should be used to control ventilation, with LCSs enabling the creation of IAQ stations that can measure several additional parameters. However, the off-the-shelf LCSs have little documentation and need further evaluations and calibration before they can be used. For this PhD work, IAQ stations were developed using LCSs available in 2018. These may be outperformed today, and some of the presented problems may already have been fixed, but the created solution remains a proof of concept. Calibration was essential to assess the reliability of the prototype.

The main highlights that can be drawn from Chapter 2 are:

- Measuring CO_2 and temperature is not satisfactory for DCV when controlling contaminants not directly linked to room occupancy.
- LCSs were selected and tested for monitoring RH and non-occupancy-linked parameters, such as $PM_{2.5}$, CH_2O, and TVOCs.
- An IAQ station was developed, tested, and calibrated for this PhD work.
- The individual LCSs required calibration. The developed calibration procedure was needed to account for autocorrelations that the sensors were dealing with in regular use and as the calibration data were being collected. When sensors collect data continuously at a very high

frequency, there is little difference between measurement and high autocorrelation. In such cases, OLS cannot be used, and models that consider autocorrelation are necessary.

- Two alternative methods for evaluating the calibration were used—ML and REML. A procedure for estimating a weighting according to the autocorrelation based on a first-order Markov was created. The Akaike information criterion was used to select the most significant parameters.

3 MEASUREMENTS OF POLLUTANTS IN DIFFERENT TYPES OF BUILDINGS AND A CORRELATION ANALYSIS

In this chapter, measurements are used to describe the IAQ in 21 home offices and four schools in Trondheim using the IAQ stations described in Chapter 2. A methodology to study the correlation between parameters is demonstrated and applied to all these cases in order to analyze the correlations and determine the parameters that can be used to control ventilation logic. For the home offices, an additional study was performed to determine which building characteristics could significantly predict reductions in pollutant concentrations. The answers to RQ 1, Tasks 1.2 and 1.3 and RQ 4, Tasks 4.1, 4.2, and 4.3, which have been published in Papers 1, 4, and 5 and Conference Papers i, ii, iii, and iv, are presented in this chapter.

3.1 Characterization of airborne pollutants and parameter levels in 21 home offices and four schools

Papers 4 and iv contain the main results of the home-office mapping study. The initial idea of this PhD work was to focus on offices. However, due to the COVID-19 pandemic, using regular offices was advised against for two years. Therefore, the focus of the work changed to collecting data from home offices during the pandemic. The IAQ stations described in Chapter 2.4 were used for taking measurements in 21 home offices for at least a week during winter in Trondhein, Norway.Eleven of these were measured again for the same duration in summer.

The IAQ measurements in these home offices were analyzed by cluster per house in order to quantify the fraction of time that health-based recommendations were not met (see Paper 4 for more details). The working hours were defined based on feedback from the users concerning worked periods. Most measured cases had natural or hybrid ventilation with extract in the bathrooms and kitchens. The RH during winter was below 40% in most cases and, on average, almost 10% higher in houses with natural rather than mechanical ventilation. Note that the ventilation strategy was collected, but not the airflow rates supplied, creating a weakness in the analysis. The temperature was outside a range of 22–24°C for 80% of the working hours. This temperature range has been found to promote optimal productivity and learning conditions [142,143].

Formaldehyde, TVOCs, and CO_2 were also measured in these home offices. The CH_2O was higher than 100 µg/m^3 over 30 min in 19 of the houses for less than 11% of the working hours. These values were slightly higher when only the winter measurements were collected. The measured concentrations surpassed the average values measured in a comparable study [144], probably because the building envelopes in Norway are tighter. The TVOCs were measured in the ranges defined by the WHO [144] as "greatly" and "significantly" increased 73% of the entire measured time. In the case of CO_2, seven out of 21 cases registered above 1,000 ppm for more than 5% of the measured time, with 11 out of 21 cases registering above 1,000 ppm for more than 10% of the measured time during winter. This percentage increased if working hours were analyzed. These values are in line with those from other field studies in Norway.

Paper i included the status of the IAQ in four schools that used CO_2-based DCV. For this, at least two months' of measurements were analyzed, and up to one year in one school. From these measurements, the CH_2O levels were seen to be higher than in most measured home offices and higher than reported in previous works, such as Ribeiro *et al*. [145]. Two out of four schools turned the ventilation off outside school hours. Stopping ventilation during the night resulted in higher CH_2O levels in this period, with peak concentrations at 6 am when the ventilation started at full power.

The CO_2 was mostly below 1,000 ppm, the temperatures usually between 20 and 23°C, the RH mostly below 30%, and the $PM_{2.5}$ levels low (3 to 5 µg/m^3). Considering the entire measured time, the RH was below 20% for 56% of the time that the CO_2 was below 1,000 ppm. Formaldehyde was above 100 µg/m^3 for 30% of the time CO_2 was below 1,000 ppm, and $PM_{2.5}$ was above 15 µg/m^3 for 2% of the time the CO_2 was below 1,000 ppm. Looking at the period between 8 am and 4 pm, the RH was below 20% for 69% of the time, CH_2O was above 100 µg/m^3 for 19% of the time, and $PM_{2.5}$ was never above 15 µg/m^3.

In these schools, even at CO_2 concentrations below 1,000 ppm: 1) the CH_2O concentration surpassed the WHO recommendation 30% of the time; and 2) the RH was below 20% for 56% of the time. The CO_2- and temperature-based DCV resulted in overlooking peaks of CH_2O and maintaining RH levels below 20%.

These two characterization works proved the need to control several parameters in addition to the customary CO_2 and temperature.

3.2 Methodology for the study of correlations between indoor air pollutants and parameters for selecting ventilation control parameters

As explained in Sections 2.2 and 3.1, using only CO_2 and temperature as control parameters is insufficient regarding other airborne pollutants that may promote more concerning health, comfort, or productivity effects. However, a selection protocol for the required pollutants was needed due to there being limited experience in controlling ventilation based on several extra IAQ parameters. The ASHRAE guideline 36 [146] provided some deterministic sequences for DCV control, but in this PhD work, the focus was on a more probabilistic selection of pollutants to control in order to account for the analysis of the measured pollutant concentrations. For this probabilistic study, correlations among the pollutants were used. Correlations between the indoor parameters may indicate a common reason for the increases in the parameters, albeit not necessarily a causal link. In any case, the methodology proposed in Paper 1 suggests using one of the correlated parameters in the control logic to represent the other correlated parameter. If two parameters are correlated, there is a mathematical way to express the dependency, and thus control the supplied airflow rate, so that both correlated parameters are maintained within a given range or below a certain threshold. When one pollutant undergoes a change, the correlated one will react predictably in relation to that.

Several studies have based their correlation analysis criteria on Pearson's or Spearman's analyses using non-pre-whitened time series [147–151]. However, these only look at simultaneous correlations, and if the analyzed time series were collected with sensors that had different time responses, the non-simultaneous correlation coefficients would be neglected.

In Papers 1, 5, and iii, the recommended methodology calculated the correlation of two time series using linear correlation at different time lags [152]. The methodology is summarized in its entirety in figure 3-1. The correlation analysis uses the cross-correlation function (CCF) in de-trended time series. The CCF calculates the Pearson correlation coefficient for the simultaneous and "time-shifted" lag data. However, the correlations are not pure interseries correlations unless the time series are de-trended. They are affected by the autocorrelation of each of the two series (intraseries correlation) [153]. Unless studying de-trended correlations, nothing can be assured about the causal relationship between two time series.

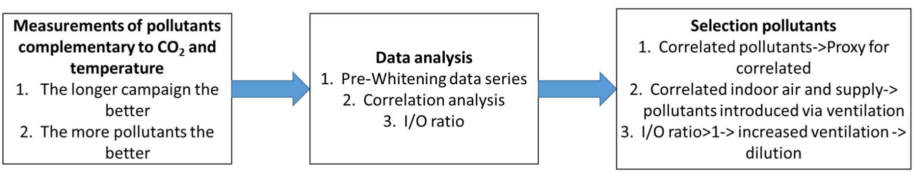

Figure 3-1. Summary of the methodology employed for selection of the pollutants to be used to control ventilation (from Paper 1 [154]).

The correlation coefficients between two time series following the same trend often suggest a higher correlation. However, these high correlation values may be due to autocorrelations in the respective time series rather than a real correlation between the two series [155]. Thus, it is helpful to de-trend the data. In this work, pre-whitening the data is recommended for de-trending time series. De-trending data should always be done before deriving correlations in time series [156,157]. Considering two time series, *x* and *y*, of equal length, the following three pre-whitening steps are:

1. Determine a time series model for *x*. An autoregressive integrated moving-average model (ARIMA) was used for trend removal [152], although other models could have been used. This step aimed to describe *x* up to the white noise residuals (e.g., a time series without autocorrelation).
2. Transform (filter) *y* using the model for *x* (using the same coefficients).
3. Calculate the CCF between the residuals from Step 1 and the filtered *y*-values from Step 2.

The cross-correlation that was left in Step 3 corresponded to the correlation between the time series, and was proportional to the impulse response function between x and y.

The methodology for analyzing the CCF among pollutants and parameters was used to decide which parameters to use in order to control the airflows supplied to the room and the OA fraction (also called the fraction of recirculation of return air).

In the analysis of supply airflows, two highly and significantly correlated (different) parameters meant that one could be removed because the other would be a good proxy for the removed parameter.

The recirculation airflow rates were analyzed between the same pollutant or parameter in the supplied air and the room air. If two pollutants correlate, the OA affects the concentration of pollutants in the room. Then, correlated parameters should be used in the control logic of the recirculation. If the pollutants are not correlated, they are probably either being filtered out by the filters or produced indoors, and so increasing the recirculation airflow rate would not be beneficial in diluting their concentrations. For example, if $PM_{2.5}$ was correlated indoors and outdoors, it would mean a share of it could pass through the filter. In this case, increasing the recirculation (reducing the OA fraction) would have a protective effect because a lower mass of $PM_{2.5}$ would be being introduced in the room.

Finally, to define the source of the parameter, indoor/outdoor (I/O) ratios have often been suggested [158]. An I/O ratio below one would mean that the main source of the pollutant was outside the room. With $PM_{2.5}$ as an example, if the I/O ratio was below one, the $PM_{2.5}$ source would be outdoors, probably traffic. In this case, increasing OA ventilation rates would not be beneficial in diluting the outdoors-generated pollutant because more PM would be brought it.

This methodology was tested in the work for Paper 1, with measurements from a gym, an office, and a kitchen. For these three cases, at least one week of measured data was used to analyze the correlations. The airborne pollutants and parameters (CH_2O, CO_2, $PM_{2.5}$, temperature, and RH) in the supply and room air were measured (except for the kitchen, where only the kitchen air was measured), and correlations were developed. Very different activities were performed in the three rooms. However, the three rooms had in common that: 1) the airflow supply was higher than the minimum Norwegian standard recommended [59] to reduce the high temperatures; 2) the occupancy was lower than designed for; and 3) there was no occupancy-related ventilation control. Thus, concentrations of CO_2 were generally low for all three rooms.

In most of the measured cases, the absolute humidity and temperature were correlated, neither CO_2 nor temperature captured most of the peaks in $PM_{2.5}$, and CH_2O was correlated to temperature and CO_2. If these measurements were used to make a demand-controlled airflow supply, CO_2 and temperature would not be sufficient indicators because, at the least, $PM_{2.5}$ would need to be introduced into the control logic (see Paper 1 for more details).

If the correlations were used to demand-control the recirculation of OA, the temperature, absolute humidity, and $PM_{2.5}$ would need to be controlled in the office. However, only temperature and absolute humidity would need to be controlled in the gym because this basement room did not experience the infiltration of $PM_{2.5}$. This room had no windows, and most of the $PM_{2.5}$ was produced when the gym was in use. In the measured cases, most pollutants and parameter increases were related to indoor activities, as the I/O ratios show. Therefore, increasing the supply of OA would be favorable for diluting pollutants or reducing RH and temperature in this room.

In Paper 1, it was stated that one of the study limitations was that the analysis of the measurements was based on a one-week measurement period during summer during which the rooms had very low occupancy. The study behind Paper iii was conceived in order to analyze up to one whole year of measurements in four schools using the same methodology. In the school where one whole year of data was analyzed, it was found that the correlations may have been more affected by the specific happenings in the rooms and the seasonal effects when using shorter datasets of measurements. Reducing the dataset from one year to two months did not yield changes in the parameter's correlation or significance. Using one random week of measurements from every season (not presented in the article) yielded results comparable to the one-year measurements. This approach may ease the data collection procedure.

3.3 Study of the potential predictor variables for the home office measurements

Once the concentrations were mapped in the 21 home offices (see Paper 4), the aim was to find potentially explanatory variables whose control could help keep airborne pollutant levels low. Because data collected from the same household was likely to be correlated, the generalized estimation equation (GEE) method was used. The GEE is a population-level approach based on a quasi-likelihood function, and it allows correlations within clusters of responses on the dependent variable to be accounted for while assuming no between-cluster correlations exist. The TVOCs, CH_2O, and CO_2 were selected as continuous dependent variables and analyzed in separate models in order to identify each pollutant's specific determinants (independent variable). Continuous predictors included in the models were RH (in %) and air temperature (°C). Categorical predictors were seasons (winter/summer), trickle vent status (open/closed), ventilation strategy (natural/hybrid/mechanical), pets (yes/no), wood stove (yes/no), floor material (carpet/wooden flooring or cork/parquet/carpets and wooden flooring), building location (city centre/suburban non-forested area/suburban forested area), house type (single-family house/semi-detached house/apartment/multifamily house), and main room (home office/bedroom/living room/open kitchen).

The status of the trickle vent, the air temperature, and the RH were important predictor variables for the CH_2O and TVOCs concentrations. Regarding CO_2, the difference among the seasons was statically significant, but no statistical difference was observed between the different ventilation strategies.

These findings suggest that RH and air temperature significantly predict CH_2O, TVOCs, and CO_2 indoor concentrations. These two parameters were probably related to changes in the ventilation (although ventilation airflow rates were not measured). The trickle vent status was a significant predictor of CH_2O and TVOCs, and although it was not significant in predicting CO_2, higher levels were measured when this vent was closed. Having a wood stove was significant and positively related to CH_2O concentrations, whereas, although TVOCs were also measured as higher, on average, in cases with a wood stove, this was not a significant predictor. Finally, measurements in winter resulted in higher values for the three pollutants, but the season was only a significant predictor of CO_2 and CH_2O.

These results were mostly in agreement with those in the existing literature concerning the explanatory variables. The reader is referred to Paper 4 for more details.

These results also show that controlling the concentration of CO_2 may not be sufficient to provide for healthy IAQ because high TVOCs or CH_2O occurrences happen simultaneously with concentrations of CO_2 below 1,000 ppm.

3.4 Conclusions and main lessons learned from Chapter 3

The two characterization works on home offices and schools proved the need to control several parameters in addition to the customary CO_2 and temperature. In the presented measurements, peaks of other pollutants occurred simultaneously with concentrations of CO_2 below 1,000 ppm and temperatures within a range of 22–24°C, showing that maintaining these within these ranges was not sufficient for ensuring a good IAQ.

Correlations between the parameters indoors may indicate a common reason for the increase in the parameters, albeit not necessarily a causal link. If two parameters are correlated, there is a mathematical way to express the dependency and thus simplify the number of control variables. Using one correlated variable allowed the supplied airflow rate to be controlled in order to maintain both correlated parameters within a given range or below a threshold. Analysis of the CCF in de-trended time series among the pollutants and parameters was employed to decide which parameters to use to control the airflows supplied to the room. In the analysis of supply airflows, two highly and significantly correlated (different) parameters meant that one could be removed because the other would be a good proxy for the removed parameter. The same CCF analysis was performed on the same pollutant or parameter in the supplied air and the room air in order to control the recirculation airflow rates. It was concluded that, if two pollutants correlate, the OA affects the concentration of pollutants in the room. In that case, the correlated parameters should be used in the control logic of the recirculation. Finally, to define the source of the parameter, I/O ratios were suggested. An I/O ratio below one indicated that the primary source of the pollutant was outside of the room.

MEASUREMENTS OF POLLUTANTS IN DIFFERENT TYPES OF BUILDINGS AND A CORRELATION ANALYSIS

A second study proposed for this thesis was the analysis of potential predictor variables. Potential explanatory variables would offer a control to keep airborne pollutant levels low. In this case, a GEE analysis was performed on clusters of the 21 home offices. The GEE allowed for the accounting of correlations within clusters of responses on the dependent variable, while assuming no between-cluster correlations existed. Continuous and categorical predictors allowed the study of TVOCs, CH_2O, and CO_2 as continuous dependent variables. Maintaining the significant predictor variables at high or low values allowed the continuous dependent variables to be kept low.

The main highlights that can be taken from Chapter 3 are:

- A methodology to analyze the correlation among pollutants using a CCF and pre-whitened data was demonstrated in order to select the pollutants that could be used in controlling room supply air and recirculation air.
- The de-trended CCF method was used in four kinds of rooms—an office, an industrial kitchen, a gym, and a school. The measurements from the school demonstrated that using one week of measurements in summer and winter was sufficient to be able use this method, but that the longer the collected data was collected for, the more robust the method was.
- The determination of pollutant origins via the I/O concentration ratio was demonstrated.
- The parameters significant in controlling pollutants can be determined using GEEs.
- A study of IAQ in 21 home offices during the COVID-19 pandemic was used to examine the frequency of pollutant health thresholds passed and the significant predictor variables.

4 STUDY OF FULL-SCALE AND SIMULATED DCV CONTROL STRATEGIES

In this chapter, the methodology used to improve the ventilation control logics is presented. The chapter starts with a summary of how the simulation program used was chosen, followed by a description of the simulation cases and their validations, and the methodology for selecting the most beneficial improvements for the ventilation logic based on energy use and IAQ.

This chapter contains answers to RQ 3, Tasks 3.1, 3.2, and 3.3, and RQ 5, Tasks 5.1, 5.2, and 5.3, which have been published in Paper 2 and Paper 5 under revision.

4.1 Selection of the simulation software to be used

Up to this point, all the presented work has focused on considering several extra parameters for ventilation control. However, introducing these new parameters into ventilation control strategies may be cumbersome because parameters with different origins and emission profiles may send contradictory control feedback. Therefore, the first step presented in the thesis was reducing the number of extra parameters to only the essential ones by looking at their correlations. The next step involved a search for simulation software for handling the ventilation's main parameters—energy use and IAQ control. This has been presented in Papers 2 and 5. Validated simulations can help in the safe and rapid trial-and-error improvement of ventilation control.

Many programs are used today to simulate control strategies for DCV, such as EnergyPlus [64], IDA ICE [65], TRNSYS [66], CONTAM [67], and Modelica [68]. However, these simulation programs either simulate energy and not pollutants (in addition to CO_2/temperature) in detail, or vice versa. Co-simulation has been proposed as a solution in this PhD work. CONTAM–EnergyPlus [69] or CONTAM–TRNSYS [70] are often used when both parameters need to be evaluated. For this PhD work, the first was selected, as both software packages were open-source, and co-simulation IAQ and energy use could be studied. However, although the tools for IAQ and energy simulation were available, previously published works had not focused on the simultaneous effects of extended IAQ and energy use while using DCV and recirculating return air.

CONTAM is a widely used program that can simulate multi-zonal whole-building airflow and contaminant transport [159]. EnergyPlus is a well-known software program that can be used to perform whole-building energy analyses [160].

According to Paper 2, CONTAM can perform interzone and infiltration airflow calculations given the driving forces, including ambient temperature, wind speed and direction, and HVAC system airflows. CONTAM also provides a rich set of contaminant transport analysis capabilities that allow it to simultaneously account for a wide variety and number of contaminants, indoor and outdoor pollutant sources, and contaminant removal mechanisms, including particle filtration and deposition. However, CONTAM does not perform heat transfer calculations, so indoor temperature schedules have to be user-defined. EnergyPlus can perform system sizing to determine the HVAC system requirements, including system airflow rates to meet thermal loads during runtime, and can calculate the indoor zone temperatures required by CONTAM. EnergyPlus can also simulate two contaminants—CO_2 and a generic contaminant. However, it cannot implement filters within the HVAC system or simulate particle penetration through the building envelope. Using co-simulation between CONTAM and EnergyPlus captures the interdependencies between airflow and heat transfer and allows for sharing these data between the two simulation tools [161].

Figure 4-1 summarizes the coupling between EnergyPlus and CONTAM. The NIST-developed Contam3DExporter tool reads in the CONTAM project (PRJ) file and creates an EnergyPlus input data file (IDF) [161]. More information about this process can be found in Paper 2 [69] or Dols *et al.* [161].

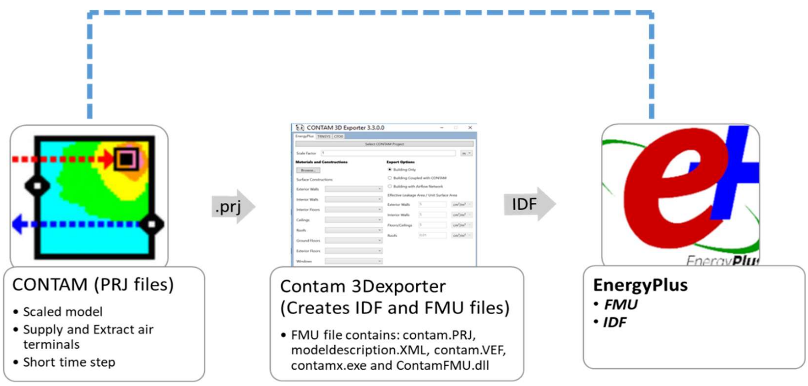

Figure 4-1. Schematic of the coupled building-model creation process [69].

4.2 Demonstration setup of three full-scale offices in the laboratory

Three full-scale offices were designed and built inside a climate chamber in the Energy and Process Department laboratory at NTNU. The building of the laboratory setup was delayed and was only ready three months before the end of the PhD. Several reasons justified this delay, but the major ones were the laboratory lockdown due to COVID-19 and the communication problems between the IAQ stations, the dampers, and the air-handling unit (AHU). However, after tremendous efforts by the laboratory staff, the laboratory was ready to validate the simulation models, and this contribution was very important.

The dimensions and layout of the three equal offices are marked in Figure 4-2. More information about the ventilation supply, exhaust terminals, and the AHU with rotary heat exchanger can be found in Paper 5.

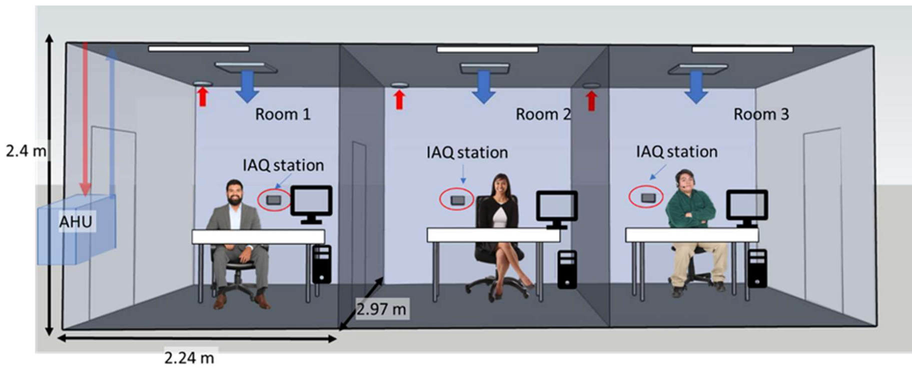

Figure 4-2. Sketch of the three offices showing their dimensions and placement of the LCSs and the ventilation [162].

All the offices had an independent supply air control (variable air volume (VAV)-units) based on the feedback from the IAQ stations placed on the wall behind the occupants, in the center of the wall, 1.12 m from each sidewall and 1.2 m high. The supply and exhaust airflow rates were always kept in balance.

In this laboratory setup, recirculation of the return air was possible. Recirculation is not a standard solution in Norway, where the building codes do not recommend it [59]. However, recirculation of return air is a state-of-the-art practice in many other countries, such as China, Canada, and the USA. In these cases, the minimum OA fraction is influenced by the requirements to meet IAQ standards and the desire to reduce heating, cooling, and dehumidification demands from the AHU coils [163]. However, if the OA fractions fall too low, airtight buildings may degrade the IAQ [164,165]. In certain situations, a combination of weak indoor sources, high outdoor concentrations, and indoor pollutant removal mechanisms can increase pollutants when using recirculation and some heat recovery ventilators [166]. However, as explained in Paper 2, well-controlled recirculation of a fraction of the return air can produce a protective effect against outdoor pollutants and reduce energy use [69]. This is mainly because the I/O pollutant concentration ratios depend on the OA supply and filters [167].

Figure 4-3 shows the control architecture. The IAQ station collected information about the concentrations of pollutants and sent it to the Raspberry Pi, which calculated the required airflows to the room. With the requirements of the individual rooms, the system also calculated the necessary supply for the AHU. The OA fraction was calculated based on the IAQ station measurements of the joint return air and the laboratory (OA) air.

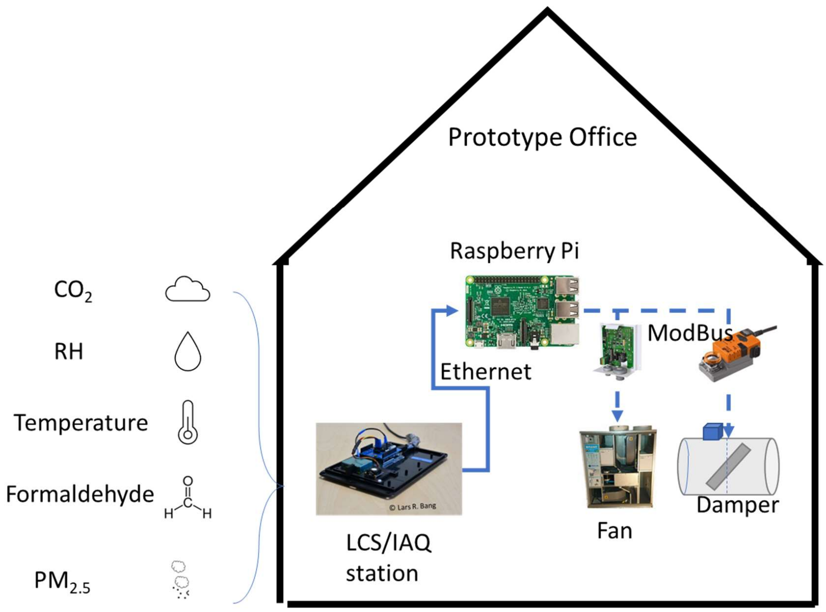

Figure 4-3. Overview of the developed control system [162].

4.3 Validated models and methodology for the simulation of supply air delivery and return air recirculation rates

Two validated simulations were developed during this PhD work and are presented in Papers 2 and 5.

The first model (presented in Paper 2) represented the simulation of an eight-office corridor located in the Energy and Process Department building at the NTNU. The thermal properties (U-values) of the corridor corresponded to Norwegian Building Code TEK 07 [34]—external wall 0.18 W/m^2 K, roof 0.13 W/m^2 K, floor 0.15 W/m^2 K, windows 1.2 W/m^2 K, and infiltration rate 50 Pa/1.5 h. The windows were in the north face, the total window area was 11.88 m^2, and the gross window/wall ratio was 8.16%. Measurements of energy use for 2018 and pollutant concentrations measured over two weeks (April 16–30, 2018) were available. The co-simulation model was compared to standardized values from Norwegian Building Code TEK 07 [168]. The building model was used to simulate the same corridor using values for the ventilation airflow rates, occupancy, plug loads, etc. The simulated annual energy use and that required by TEK 07 were within 5% of each other. Thus, the model was considered valid for energy-use simulations.

The second model has been presented in Paper 5, and represented the setup described in Section 4.2. The model was validated for energy use and pollutant sources in this second case. Three types of tests were accomplished in the rooms: 1) calculation of the average production of pollutants (CO_2, CH_2O, $PM_{2.5}$, and TVOCs), heat, and moisture by 24 students; 2) testing with pressurization to quantify leakages. In one test, all the offices had similar 50-Pa pressurization in the ambient laboratory. Three other tests involved pressurization of 5 Pa over that of the adjacent rooms; and 3) testing with thermal mannequins breathing at an average rate, calculated in the first test, following a predetermined schedule with a responsive DCV based on CO_2 in order to test the simulation and the setup.

In the second case, the U-values of the walls, roofs, and floors were estimated to be 0.1 W/(m^2 K). The external doors were simulated with a U-value ≤ 0.8 W/(m^2 K). There were no windows. The internal walls were constructed of polystyrene panel insulation with a U-value of 0.15 W/(m^2 K). The internal door was a standard door with a U-value ≤ 1.2 W/(m^2 K). The heat recovery of the ventilation was simulated using a sensible efficiency of 78% and 40% of latent efficiency. The filters were F7 $ePM_{2.5}$ 65 to 80% for the supply air and F9 $ePM_{2.5}$ > 95% for the recirculated air.

The second model's normalized mean bias error (NMBE) and CV–root-mean-square error (RMSE) for the different IAQ parameters are presented in Table 4-1. These are below the values recommended by ASHRAE 14 [169] and, therefore, considered validated. The energy use was validated using the results from the test with mannequins. The NMBE of the validated simulation was 2% and the CV–RMSE was 1.7%. Thus, the energy simulation was also considered validated.

Table 4-1. Summary of the NMBE and CV–RMSE of the validation simulation

	Temperature			RH			$PM_{2.5}$			CO_2			CH_2O		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
NMBE (%)	0.13	-0.09	0.05	0.9	1.15	2.4	-0.52	-0.8	1.3	-0.09	-0.19	0.07	1.94	2.10	0.57
CV–RMSE (%)	0.310	0.257	0.244	1.19	1.41	3.47	28.3	20.3	25.6	24.2	29.36	28.9	3.36	3.96	2.99

Once the simulation software was validated, the control strategy focused on improving the control of the supplied air to every room and the control of the OA fraction.

In Paper 2, control sequences were developed for the supply airflow and the recirculation ratio, and then all the possible combinations of both strategies were tested (not presented in Paper 2). The selection of pollutants that could be used was based on common sense. In Paper 5, selection of the ventilation logics was based on the methodology of pollutant selection based on the correlations described in Section 3.2 in this thesis. In this way, the non-correlated pollutants were used to control the supply, and then the thresholds and the airflow response were improved. For control of the OA fraction, only the best control logic of the supply air control was combined with the proposed recirculation control logics, thereby reducing the number of simulations and only focusing on the parameters where supply and room air were correlated, as explained previously.

Additionally, more-advanced optimization strategies could have been used. However, the focus of this thesis work was to develop relatively simplified strategies so that the solutions could be used in real life. The selection of correlated parameters may have been more complicated, but the statistical knowledge required was reduced using R scripts to analyze the measured data.

4.4 Methodology for evaluating the performance of different control logics using KPIs for annual energy use and IAQ

To evaluate the best-performing logics, two main parameters were considered—energy use and IAQ.

The energy use was compared annually, the goal being to use the smallest amount of kWh/m²/yr. Two levels of IAQ KPIs were developed. An IAQ KPI is an overarching parameter that considers all measured parameters simultaneously. It calculates the fraction of time elapsing when all measured airborne pollutants are below the defined thresholds, or when temperature and RH are inside the ranges defined in Table 4-2. This parameter provides an overview of the IAQ, but is not helpful in making any improvement in the control logics because it is not explicitly referred to any parameter.

Table 4-2. Summary of pollutant target thresholds—CO_2, CH_2O, $PM_{2.5}$, and the recommended range for the parameters temperature and RH

Parameter	Limit	Reference
CO_2	1,000 ppm	[170]
CH_2O	110 µg/m³ in 1 min	[171]
$PM_{2.5}$	15 µg/m³ in 1 min	[111] defined over 24 h, but 1 min was used here
Temperature	22–24°C	[172]
RH	30–60%	[31,173]

The KPI IAQ was determined according to Eq. (1) by adding together all the time steps when all the thresholds/ranges from Table 4-2 were met simultaneously in the studied rooms, then dividing this by the total number of time steps. The parentheses in Eq. (1) show a logical evaluation of the three rooms simultaneously. If the conditions were met simultaneously for all the rooms, the result for the current time step would be 1. If one of the rooms did not satisfy a single criterion, the solution to the equation would be 0. The value of the KPI ranged between 0 and 100%. The sub-index R in the equation represents the evaluation performed simultaneously for all the rooms, and WSP represents the whole simulated period.

$$KPI_{IAQ} = \frac{\sum_{i=1}^{WSP} (CO_{2\_R}<1000 \,\&\, Temp_R<24 \,\&\, Temp_R>22 \,\&\, Formaldehyde\_R<110 \,\&\, RH_R<60 \,\&\, RH_R>30 \,\&\, PM_{2.5\_R}<15)}{Number\ of\ simulated\ time\ steps} * 100 \quad (1)$$

The remaining KPIs were calculated following Eqs. (2)–(6) for each time step, using the same logic as for the IAQ KPI, but for a single parameter/pollutant. These provide the possibility to make improvements in the control, as they refer to a single parameter. However, using these in combination with the IAQ KPI was beneficial because the modifications in a single parameter may have had a global effect, which is what the IAQ KPI is for. The $PM_{2.5}$ limit, defined according to WHO [111], was based on 24-h averages, although 1-min averages were used in the calculations in Paper 5 because this was the time step in the control model. This may have overweighted the $PM_{2.5}$ effect. However, in the absence of a 1-min guideline, this was used as the control feedback and sent every minute. Given a 1-min value, this threshold must be changed. The KPIs defined in Eqs. (2)–(6) represent the thresholds of the pollutants that were not surpassed, or the parameters that were within the recommended range. A perfect control would score 100% in all these KPIs.

$$KPI_{CO2} = \frac{\sum_{1}^{WSP} (CO_{2\_R}<1{,}000)}{Number\ of\ simulated\ time\ steps} * 100 \tag{2}$$

$$KPI_{CH_2O} = \frac{\sum_{1}^{WSP} (CH_2O_R<110)}{Number\ of\ simulated\ time\ steps} * 100 \tag{3}$$

$$KPI_{PM2.5} = \frac{\sum_{1}^{WSP} (PM_{2.5\_R}<15)}{Number\ of\ simulated\ time\ steps} * 100 \tag{4}$$

$$KPI_{temp} = \frac{\sum_{1}^{WSP} (Average\ room\ air\ temperature_R < 24\ \&\ Average\ room\ air\ temperature > 22)}{Number\ of\ simulated\ time\ steps} * 100 \tag{5}$$

$$KPI_{RH} = \frac{\sum_{1}^{WSP} (Average\ room\ air\ RH_R < 60\ \&\ Average\ room\ air\ RH > 30)}{Number\ of\ simulated\ time\ steps} * 100 \tag{6}$$

By analyzing the results for energy use and the different KPIs simultaneously, the individual effects of controlling the airflow rates or increasing or decreasing the OA fraction can be easily studied.

In the case described in Paper 5, improvements in the ventilation control from CAV to the best DCV with recirculation resulted in a reduction in energy use of 7.6 kWh/m^2 annually and an increase in the IAQ KPI of 45.6%. Most of the improvements happened in these simulations in the temperature KPI. The same simulations in Paper 5 were repeated using Beijing's OA quality and Trondheim's weather files. In this case, the most significant improvements were accomplished in the $PM_{2.5}$_KPI.

The results of Paper 2 showed that all the simulated DCV strategies yielded reductions in energy use compared to a baseline, schedule-based strategy. Using CO_2-based DCV may result in increased levels of indoor particulate ($PM_{2.5}$) from outdoors but using $PM_{2.5}$ monitoring in the ventilation control strategies reduced indoor concentration of $PM_{2.5}$ and energy usage. The simulation case of Beijing revealed that the indoor levels of $PM_{2.5}$ can be reduced below the World Health Organization requirement while keeping CO_2 levels acceptable. These results are in line with those in Paper 5. Paper 5 revealed that the model successfully developed control sequences that simultaneously reduced annual energy use and the number of hours outside the recommended IAQ guidelines compared to the baselines. In cold cities as Trondheim with excellent outdoor air quality recirculation could reduce energy use and increase the RH in winter. Assuming low outdoor air quality, simulations demonstrated that the use of recirculation had a protective effect on the indoor concentrations of $PM_{2.5}$. However, when using recirculation, it is essential to control the IAQ to avoid excessive pollutants, RH, and temperatures.

The methodology in its entirety proposes a stepwise approach to reducing the occurrence of certain airborne pollutants over a given threshold and some indoor air parameters outside their recommended ranges while incurring no increase in energy use.

This methodology has the benefit of having been built in a stepwise fashion: 1) the selection of parameters for ventilation control was probabilistic. The pollutants in the control were selected for each case. These were not deterministically CO_2 or temperature; on the contrary, they were selected in each case based on what was needed from the measurements, focusing on CCF results and looking at correlated and non-correlated parameters, so that the important parameters were present in the simulation; and 2) the simulation provided feedback on the IAQ, and this the energy parameters and a simple control sequence could be developed (as presented in this work), and can be further developed using the simulation capabilities of EnergyPlus and CONTAM.

4.5 Conclusions and the main lessons learned from Chapter 4

Introducing the newly identified parameters into ventilation control strategies may be cumbersome and sometimes contradictory because parameters with different origins and emission profiles may send contradictory control feedback. Therefore, the first step presented in the introduction to this thesis involved reducing the number of extra parameters to the essential ones by looking at correlations. CONTAM–EnergyPlus handled the ventilation's main parameters, energy use, and IAQ control, and thus was selected for simulating different ventilation control strategies of the supplied and recirculated air. The simulation models were validated using a purpose-built three-office laboratory setup. This additionally used the IAQ stations discussed in Chapter 2.

The validated models allowed different control strategies to be tested using a tailor-made KPI analysis. This KPI analysis was used to choose the best control strategies based on the IAQ and energy use.

The main highlights that can be taken from Chapter 4 are:

STUDY OF FULL-SCALE AND SIMULATED DCV CONTROL STRATEGIES

- The co-simulation between EnergyPlus and CONTAM allowed the study of indoor pollutant levels and energy savings when using DCV and air recirculation.

- Co-simulation allowed the demonstration of ventilation control schemes that can account for IAQ and energy savings.

- Measurements with LCSs were used to validate the co-simulation model. The significant parameters for the ventilation control were chosen based on CCFs. The ventilation control addressed the airflow supply and recirculation of return air.

- A methodology for improving ventilation control by reducing energy use and increasing the IAQ KPI.

5 CONCLUSIONS

5.1 Main conclusions

This PhD study began with the realization that IAQ cannot be monitored and controlled only by looking at concentrations of CO_2 and temperature. It became clear that controls on DCV that were based only on these two parameters were unsatisfactory regarding other parameters that affected health and performance. Thus, the need to measure other parameters and handle collected data to make it useful for use in DCV control was clear. This was the motivation for starting this PhD work. A position was created in the Research Centre on Zero-Emission Neighbourhoods (ZEN) in Smart Cities that enabled the founding of a study to improve DCV and reduce energy use and improve IAQ.

After five years of work, LCS IAQ technologies have significantly improved. Each year/month, new sensors with new capabilities are being released on the market, enabling more reliable measurements of different airborne pollutants in the indoor air and OA. The LCSs used in this PhD work were selected from among those available four years ago. A literature review of airborne pollutants was undertaken in order to characterize the common pollutants in indoor air, and then a market analysis was performed to find out which parameters were possible to measure, given that the IAQ station was given a cap price of €200.

Much work was devoted to the calibration and evaluation of these sensors. Based on the results of this study, it can be concluded that the selected sensors can be used after thorough calibration. The out-of-the-box measurements suffered from bias that it was not possible to entirely correct, even after calibration (e.g., for the CH_2O sensors). The PM sensor performed accurately for PM_1 and $PM_{2.5}$, although slightly less accurately for the latter. The sensor was unreliable for larger fractions, and for this use, it would not be recommended. For RH, temperature, and CO_2, the sensors performed very reliably up to Tier V, according to the EPA classification [48]. The TVOCs sensor could not be calibrated due to the lack of reference measurements, and the only conclusion that can be drawn from this is that the eight sensors have good intra-unit consistency. The calibration procedure and data handling were the main contributions from this PhD work and will be further discussed in Section 5.2.

Once the sensors started collecting data, the next step was to select the main contributors that would help achieve a satisfactory IAQ. A methodology for analyzing the correlations was selected. This methodology used the CCF on de-trended time series. The CCF calculated the

Pearson correlation coefficient for the simultaneous and "time-shifted" lags. In this way, possible differential time responses between the different sensors, or release speeds of different pollutants, would also be captured. To have pure inter-pollutant or inter-parameter correlation, it was necessary to de-trend the data. For this study, pre-whitening was the strategy selected for de-trending the time series. De-trending data should always be performed to ensure the correlations are proportional to the impulse response function between the two time series before deriving the correlations. However, it is common in the IAQ literature to use Pearson correlations directly, thus the importance of raising this point in the methodology was clear. The methodology for selecting pollutants itself is also considered to be one of the main contributions of this work, and is further described in Section 5.2.

A second process applied to the data involved an analysis of the predictor variables. In this case, the data processing was different. Because data from the same households were assumed to be correlated, the GEE method was used to account for this correlation. The GEE is a population-level approach, based on a quasi-likelihood function, that allows an accounting of responses on the dependent variable for correlations within clusters, while assuming no between-cluster correlations exist. This way, the predictor variables for having high or low concentrations of selected continuous dependent variables can be selected. For instance, it was concluded that the status of the trickle vent, the air temperature, and the RH were important predictor variables for CH_2O concentrations. Thus, to reduce CH_2O concentrations, with the trickle vent open, a low temperature or low RH were significant measures.

The simulation was seen as the simplest way to test different control strategies. However, the building of the laboratory setup was greatly delayed, and was only ready three months before the end of the PhD, as previously discussed.

The simulations were performed using a co-simulation between CONTAM and EnergyPlus. Together, these two programs have proved to be an efficient tool for analyzing energy use and IAQ—two interdependent ventilation characteristics that can be simultaneously improved.

Finally, in order to develop clear indicators and comparison points, KPIs were developed. Many KPIs have been highlighted in the literature, but the ones proposed here were easy to understand, calculate, and use in practice, following the methodology proposed in the thesis. Based on the published results, this methodology is helpful because it resulted in significant improvements in the IAQ and a reduction in energy use.

5.2 Main contributions of this PhD work

Calibration methodology

For sensors that measure with a very frequent interval, it is typical that the measurements will have autocorrelations. The autocorrelations, in this case, were important because they showed how the sensor performed when data was collected very often. Frequent data collection is often presented as one of the strengths of LCSs. Thus, it needs to be considered in calibrations. Rather than making steady-state measurements in this work, measurements corresponding to more-common measurements with different sampling periods were used. This was commonly done in the published literature, with the authors commonly using OLS to develop the correlation parameters. However, OLS and R^2 should only be used if a model's residuals are iid, (not correlated) and evenly distributed. In this PhD work, a procedure for estimating a weighting based on the autocorrelation and a first-order Markov was created. To the authors' knowledge, the method presented in Paper 3—considering and weighting the autocorrelation using a first-order Markov scaling—has not previously been used in the sensor-calibration field, and it is thus an essential contribution of this PhD work. This method enables calibration using dynamical data and data sampled from time to time or at a high sampling rate. It also allows for the efficient use of samples and then takes care of the autocorrelation via the MLE and REML methods suggested in Paper 3. The final goal of the IAQ stations was to demonstrate their utility in the control of ventilation, and thus a more dynamic evaluation was needed.

This calibration development was necessary for evaluating the dynamics of the sensors when the sensors were used as in real life. But the same strategy can be used with any other type of sensor. Even in cases with experiments conducted in a randomized sequence with otherwise steady-state conditions, there is a risk of having autocorrelations. There will always be explanatory variables that can be manipulable; however, in most cases, there are other variables that cannot be manipulated (an example could be the TVOCs in Paper 3), and such variables might also have an effect. Typically, some experimental conditions are difficult to control or are not recognized, and such conditions may lead to some degree of autocorrelation, particularly in experiments where the samples are taken at a high sampling rate. If the sensor presents a bias, this can also lead to autocorrelations.

Selection of significant pollutants

Two steps were considered in choosing the pollutants/parameters that could be introduced into the control strategies.

- *How could the supply of airflow to the rooms be controlled?* This analysis was based on correlations between different parameters in the supply and room air. Two highly and significantly correlated parameters meant that one could be removed because the other would be a good proxy for that parameter.
- *How could the OA fraction be controlled? Where is the source of the pollutant?* The analysis of recirculation airflow rates was performed between the same pollutant or parameter in the supplied air and the room air. If two pollutants correlated, the OA quality would affect the concentration of pollutants in the room and could be used in the control logic of the recirculation. If the pollutants were not correlated, they were probably either collected by the filters or produced indoors, and then increasing the recirculation airflow rate would not be beneficial in diluting their concentration.

  To determine a pollutant's source, I/O ratios were suggested. An I/O ratio below 1 would mean that the main source of the parameter was produced outside the room. When an I/O ratio is below one, increasing the OA ventilation rates would not be beneficial in diluting the outdoors-generated pollutant because more pollutants would be brought it.

CONTAM–EnergyPlus co-simulation

Through co-simulation, different control logics could be studied using the validated simulation of pollutant sources and infiltrations, and the AHU with heat recovery. Although not new, the use of this CONTAM–EnergyPlus co-simulation has been well accepted by the research community and, four months after the publication of Paper 2, it has already been cited seven times according to Google scholar.

With co-simulation, a methodology using energy management systems (EMSs) in EnergyPlus allowed the control of supply to the room and the recirculation of fractions of return air. Simulation results were used to see which pollutants may have affected other pollutants/parameters, and whether all or just several of them could be used for the controls, clarifying the effects of interdependency and the simultaneous effect on energy use and IAQ.

IAQ and energy-use KPIs

In order to rapidly evaluate the effect of the different logics, KPIs were developed and used. Two overarching KPIs—for energy use and IAQ—provided a general summary of the performance of the control logic. Then, for IAQ, this value was split into five, considering the five measurements taken with calibrated sensors. The IAQ KPI could have been expanded to several parameters if more validated/calibrated measurements were available, as is expected in the future with the introduction to the market of different LCSs. The individual IAQ KPIs shed light on the parameters that would likely improve the general KPI.

Holistic methodology for the improvement of the ventilation control logic

Figure 5-1 illustrates the main contributions towards attaining the primary goal of the PhD work—to improve ventilation control strategies based on energy use and IAQ.

Using calibrated LCS data, CCFs provide information about the parameters that could be used in the concrete control over ventilation. These were introduced into the validated co-simulation CONTAM–EnergyPlus and, utilizing the KPI analysis, the ventilation control was improved, resulting in healthier (based on a low concentrations of airborne pollutants) and more efficient ventilation systems.

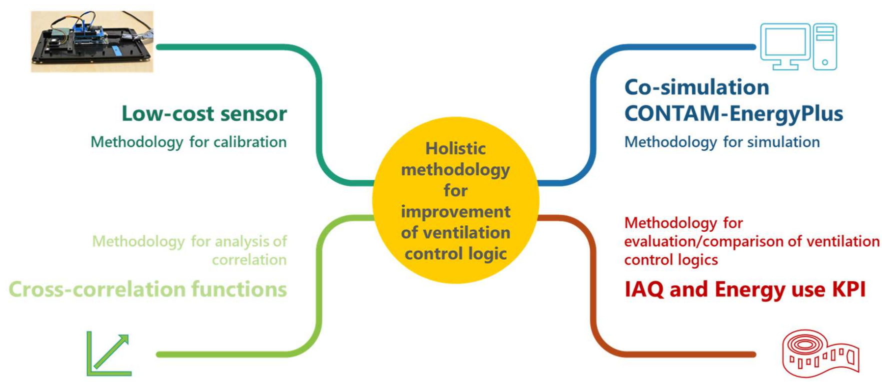

Figure 5-1. Sketch showing the main outcomes of this PhD work and how they contributed to the general goal of a holistic methodology for the improvement of ventilation control logic.

5.3 Limitations

- The quality of the sensors. Some sensors carried on having biases even after the calibration. However, these LCSs represented the state of the art at the time of purchase.

A new round of calibration could be performed for the CH_2O sensor using a reference sensor with fewer cross sensitivities, and other sources of CH_2O could have been tested. In this work, the work done to improve their reliability has been presented and the expected improvements in LCSs have been provided. New tests should be performed.

- Connecting the Raspberry Pi to the regular ventilation was not easy. There were several communication problems, and some commands in the AHU and the dampers could not be modified. The connection process was cumbersome, but we expect improved communication possibilities between LCSs (Arduino or Raspberry Pi) and standard ventilation systems.

5.4 Further work

- Validation of the improved ventilation systems is required. The last step to close the circle in Paper 5 could have been to test the improved ventilation strategies in the laboratory or at the Zero Emission Building (ZEB) Laboratory in Trondheim.
- Further work could be done on optimizing the ventilation systems, using more advanced optimization methodologies, and on developing a methodology that could be deployed without a deep knowledge of optimization.
- Novel LCSs should be tested so that more parameters can be introduced into the ventilation systems.
- Simplified co-simulation possibilities could be developed for installation in the Raspberry Pi, so that simulations could be run on the fly, providing feedback to the control systems. Another possibility would be to set the co-simulation in the cloud and make the simulation in the cloud. For this, a digital twin may be needed.
- With the newly changed energy pricing regulations that look more at the peak demand than the energy use, a second parameter that could have been studied is the peak power demand.
- The solution could be tested at full scale/in a commercial building. This would require that the data from the LCS-station be included in a building management system, or at least that they would communicate.

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APPENDIX- PUBLICATIONS

This section contains the publications that make up the thesis.

PAPER 1

Justo Alonso, Maria; Wolf, Sebastian; Jørgensen, Rikke Bramming; Madsen, Henrik; Mathisen, Hans Martin. (2021) A methodology for the selection of pollutants for ensuring good indoor air quality using the de-trended cross-correlation function. *Building and Environment.* **vol. 209**

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A methodology for the selection of pollutants for ensuring good indoor air quality using the de-trended cross-correlation function

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ABSTRACT

CO_2 is customarily used to control ventilation as it is a proxy for bio-effluents and pollutants related to the presence and activity of people in the room. However, CO_2 could not be a satisfactory indicator for pollutants that do not have a metabolic origin, i.e., emissions from building materials or emissions from traffic. A methodology to select pollutants besides or instead of CO_2 is presented in this article. This methodology sets to study (i) the suitable location to measure air pollutants and (ii) which parameters to measure. The answers to these two questions are based on correlation analysis between pollutants and indoor/outdoor ratios.

Measurements of CO_2, air temperature, relative humidity, formaldehyde, and particulate matter have been taken in an office, an industrial kitchen, and a gym and are used to show how to apply the methodology. Correlations were studied in detrended (pre-whitened) time series. Studying correlations in detrended time series via cross-correlation functions is recommended because correlation coefficients may be overestimated because of the trends in the time series. In contrast to Pearson's correlation coefficient, the cross-correlation function studies the correlation between pollutants concurrently (as Pearson) but also at different time lags.

From the measurements we can conclude on the need to measure at least one parameter representing: 1) pollutants related to human activities 2)pollutants that infiltrate from processes like combustion or traffic outdoors, 3)pollutants related to combustion indoors, 4)pollutants related to degassing from building materials, 5) pollutants related to other "non-combustion-related activities" indoors and moisture loads.

1. Introduction

Buildings have evolved from having high rates of uncontrolled and unfiltered leakages to very tight envelopes with very reduced leakages to save energy [1–3]. Ventilation and filtering of air are necessary to secure the minimum requirements for indoor pollutants levels and thermal comfort in modern buildings [4,5]. The indoor environment is among the essential factors for a person's cumulative air pollutant intake [6]. Outdoor air pollutants enter the indoor air via infiltrations and ventilation systems. Pollutants are generated also indoors as a result of different activities [7]. All adverse airborne pollutants, disregarding their origin, must be ventilated away to ensure good indoor air quality. The World Health Organization defines the maximum threshold concentrations for various contaminants based on health effects [8]. These guidelines intend to inform national policymakers on the selection of appropriate targets for healthy air quality. However, national thresholds vary among countries and standards define different requirements of VR. In the USA and many countries in Asia, HVAC system sizing and VR are chosen to provide comfort, not health, though ASHRAE Standard 62.1 defined the acceptable indoor air quality to be without any known contaminants at harmful concentrations [4]. Logue [9] proved that in residences in the US and countries with similar lifestyles, air pollutant concentrations indoors exceed health-based standards for chronic and acute exposures in many measured cases. The WHO concluded that about 3.8 million people die annually due to household air pollution [10].

Thus there is a growing interest in monitoring IAQ by using low-cost sensors and developing platforms that can integrate sensing with actuating at low cost [11]. Guyot et al. [12] analyzed literature related to smart residential ventilation. In their review, they refer to ventilation controls using CO_2, temperature, relative humidity, and total volatile

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Nomenclature

AR	Autoregressive model
ARIMA	Autoregressive integrated moving average model
ARMA	Autoregressive moving average
CAV	Constant air volume
CCF	Cross-correlation function
CO_2	Carbon Dioxide
DCV	Demand-Controlled Ventilation
HVAC	Heating, ventilation, and air-conditioning
HOCH	Formaldehyde
IAQ	Indoor Air Quality
I/O	Ratio between indoor and outdoor pollutant concentrations
IoT	Internet of things
MA	Moving average model
MET	Metabolism
NOx	Nitrogen oxides
O_3	Ozone
PCP	Pentachlorophenol
PM	Particulate matter
PAH	Polycyclic Aromatic Hydrocarbon
RH	Relative humidity
SBS	Sick Building Syndrome
TVOC	Total Volatile organic compound
UFP	Ultrafine particles
VR	Ventilation Rate
VOC	Volatile organic compound
WHO	World Health Organization

organic compounds (mostly in bathrooms). Chiesa [11] developed an IoT application that controlled ventilation based on CO_2, volatile organic compounds, atmospheric pressure, RH, and temperature. They concluded that the proposed system defined proper airflow rates so that IAQ indexes are maintained. This article builds upon the possibility of using several parameters for ventilation control and develops a method that will be helpful to unveil correlations among pollutants to choose which ones are necessary and which ones are "nice to have". The same methodology can also be used to know where sensors should be placed so that they are useful for a ventilation control.

1.1. CO_2 as a marker for demand-controlled ventilation

CO_2 is often monitored as a proxy for occupancy in rooms [13,14]. People produce CO_2 proportionally to their body mass and metabolic rate. CO_2 concentrations are also understood as an indicator of the hygiene of the indoor air.

DCV is a ubiquitous choice to save energy in buildings where the occupancy varies throughout the day, e.g., in office buildings. The demand is defined from the level of one or several parameters. CO_2-DCV targets keep CO_2 below a set point concentration. If CO_2 indoor levels are below the defined threshold, VR can be reduced [15]. The airflow rate decrease is the mechanism by which CO_2-DCV realizes energy savings [16].

Carrer et al. [17] questioned using CO_2 as a measure of the ventilation's ability to dilute and remove pollutants. More than 50% of the pollutants present in offices are not emitted by humans [18]. In addition, the air supplied to the room can be taken from outdoors (via mechanical ventilation plus filter or infiltrating via cracks), it can be recirculated from the extracted air or infiltrated from other rooms. Depending on the air's origin or its pollutants concentration, it has different "dilution power".

Ramalho et al. [19] investigated correlations of CO_2 concentrations and selected indoor pollutants (formaldehyde, acetaldehyde, benzene, $PM_{2.5}$, PM_{10}) in 567 dwellings and 310 educational buildings (nurseries, kindergartens, and schools). They concluded that the correlations between CO_2 and pollutant concentrations were weak or very weak. Their study concluded that the probability of exceeding pollutant health guideline values correlates with high CO_2 concentration, but the possibility of exceedance is still high at low CO_2 levels. Choe et al. [20] found that air cleaners could reduce PM concentrations while CO_2 concentrations were still high. Wu et al. [21] presented measurements in green buildings with one-to three-star ratings. In their case, CO_2 and PM where lower than in ordinary buildings but VOC was higher. Therefore, some authors specify that CO_2 should only be used as a signal of occupant-related pollutants [22,23]. Others suggest that CO_2 should be observed as an IAQ indicator and a pollutant impacting health and cognitive functions [24,25]. Some authors suggest also controlling other parameters [17,19,23,26]. However, to the knowledge of the authors, there is no clear guideline why or when several pollutants should be measured in addition to CO_2 and temperature. Morawaska et al. confirm that there are no ventilation guidelines to specifically control the concentration of benzene, carbon monoxide, formaldehyde, and other chemicals, indoors [27] In this article we set the goal of developing a methodology to know which parameters should be measured in different types of rooms based on detrended correlation studies. Sun et al. [28] show the need of increasing the number of pollutants measured when correlating health outcomes and concentrations of pollutants. In their case they propose to use weights for the correlations. Here we propose a stepwise approach,1) measuring several pollutants, 2) study de-trended correlations and 3) Parameters that are correlated don't need to be further measured as correlation equations can be deployed. Uncorrelated pollutants need to be continuously measured. In the next section, selected pollutants that can be measured with low-cost sensors will be discussed.

1.2. Other (selected) indoor air pollutants: sources

Fine particles and UFP (<0.1 μm) can infiltrate buildings through leakages [29] and ventilation (mechanical or natural) openings. Mechanical ventilation using filters can reduce the I/O of $PM_{2.5}$ compared to natural ventilation [30]. The chosen filters in the HVAC systems, the precision of the mounting and their condition will also affect the I/O ratio. Chen & Zhao [31] concluded that the I/O varied importantly also due to the cracks geometry in building envelopes, and the air exchange rates. The principal indoor sources of $PM_{2.5}$ are smoking, cooking, fuel combustion for heating, human activities, hair, skin, and burning incense [32]. Indoor UFP can be generated from candles, cleaning and aerosol products, cooking, and other sources [33]. Morawska et al. [34] assessed that 10–30% of the total burden of disease from PM exposure was due to indoor-generated particles.

Particle's chemical composition, size, shape, deposition, and resuspension and hygroscopic growth appear to depend on RH [35]. RH affects also the rate of degassing of formaldehyde and VOC from indoor materials [36], the formation of molds and allergens and pathogens [37]. Gładyszewska-Fiedoruk [38] claimed that if humans are the most significant contributors to moisture generation, CO_2 and RH are also highly correlated, at least in naturally ventilated buildings. For air conditioning, where the air is cooled or dehumidified, correlations cannot be determined [38].

Salthammer summarized sources and intensity of formaldehyde in European housing [39] Formaldehyde is widely used in the manufacture of building materials and numerous household products. It is also a by-product of combustion from candles, incense sticks, mosquito coils, cigarettes, wood-burning fireplaces [39] and a preservative in some food packing [40]. Air cleaning devices, textiles, cooking, carpets and surface coatings, plywood, MDF are also sources for formaldehyde [39]. Huang et al. [41] concluded that formaldehyde, acetaldehyde, or benzene can be derived from cooking activities.

Sources of VOC in indoor air could be building materials, furnishings, cooking, household products, cleaning products, products for personal hygiene, etc. [42].

Nitrogen oxides (NO_x), Ozone (O_3), Pentachlorophenol (PCP), Polycyclic Aromatic Hydrocarbon (PAH), bio effluents, tobacco smoke are also main indoor pollutant substances, but they will not be further studied in this article as low-cost sensors for measuring them were not found.

Thus, additionally to occupancy measured by CO_2, and thermal loads measured by temperature, the following parameters should be monitored:1) pollutants that infiltrate from processes like combustion or traffic outdoors, 2) pollutants related to combustion indoors, 3) pollutants related to degassing from building materials, 4) pollutants related to other "non-combustion-related activities" indoors and moisture loads so that the main sources for pollutants are covered.

1.3. Other (selected) indoor air pollutants: main health effects

Indoor air humidity, defined as the perceived dry air or dryness (usually of eyes, upper airways, mucosae, or skin), is essential due to the associated health effects [37]. Fewer tears are produced, and precorneal and epithelial damage has been observed at low RH [37]. Dry air perception can be connected to mucous membrane irritation of eyes and upper airways in the presence of sensory irritants [43]. The reported "stuffy or dry air" may be affected by alteration of the composition, dynamics, deposition and resuspension of inhaled particles, possibly in concert with sensitive eyes or mucous membranes in the upper airways at low RH [37]. Cain et al. [44] claimed that temperature and RH altered VOC emission profiles and this correlated to the perception of IAQ.

Moisture and microbial contamination in the building structure and HVAC systems have adverse health effects [45]. The growth of microorganisms (fungi, bacteria, viruses) and the occurrence of allergens were linked to high RH [46]. Thus, indoor RH should be kept below mold-or-mites growth thresholds by ventilation or air conditioning [45]. However, too low indoor temperatures and low RH were associated with increased occurrence of respiratory tract infections. Influenza virus increased survival rate and transmission efficiency at low RH [37,47]. Contrarily, RH>40% dramatically reduced the infectivity of some other virus [48]. Coronavirus seemed to decay faster close to 60% RH than at other levels [49]. In general, there is a good agreement in the literature that many viruses decay faster in the range 40–60% [50–52].

Multiple studies with varying populations and regions showed consistent correlations between PM and cardiovascular problems. The data demonstrated a dose-dependent relationship between PM in ambient air and human disease [53]. Chronic $PM_{2.5}$ exposure affects the respiratory and cardiovascular systems [54]. Chronic bronchitis, stroke, heart disease, and thickening of arterial walls, diabetes, and reduced lung function were also connected to $PM_{2.5}$ exposures [55–57].

The relations between indoor particulate matter (PM_{10}, $PM_{2.5}$) and associated health risks are less known [53,58]. Venn et al. [59] proved an increasing risk of wheeze with increasing proximity for children living within 150 m of a main road. Peters et al. [60] concluded that decreases in peak expiratory flow, feeling ill during the day, and coughing were associated with the concentration of fine and UFP on asthmatics. PM impacts the IAQ and health, but may also be the carrier of viruses such as influenza [37].

According to the INDEX project results [61], the EU's risk assessment of IAQ agrees on prioritizing: formaldehyde, carbon monoxide, nitrogen dioxide, benzene, and naphthalene. Formaldehydes exist in the indoor air at a concentration that is larger than the outdoor air [39]. Formaldehyde has been classified as a potential human carcinogen by the US EPA and International Agency for Research on Cancer as a Class 2A carcinogen. Also, it irritates humans mostly in the upper airways, mucosae, and eyes [62]. Formaldehyde is a sensitizing agent that can cause an immune system response and sensory irritation [63].

VOCs at typical indoor environment concentrations may yield adverse health effects, depending on their composition. VOC concentrations indoors are generally below thresholds for sensory irritation in eyes and airways, but above odor thresholds [64]. Even if there is confirmation of a variety of dangerous effects probably linked to VOC, established scientific knowledge about direct health risks of VOCs is absent [65].

To sum up, when it comes to health effects the following parameters should be measured as exposures as these pollutants have important health effects: 1) RH as it affects the perception of IAQ and mostly the survival of viruses, 2) PM as the exposure to them is connected to cardiovascular and breathing problems and 3) formaldehyde as it is known as an irritant and a potential human carcinogen.

1.4. Exposure vs. concentration measurements

Most of the epidemiological studies discuss the relations between exposures and sickness. The NAS report [66] defines personal exposure as $E = \frac{1}{T}\int C(t)dt$ where E is personal exposure, C(t) is the time-variant concentration, and t is the time that the person experiences a specific concentration. Children and adults may be exposed differently as the particles have different spatial positions and particle size distribution [67–69]. Wilson & Suh [70] concluded that the relevant epidemiologic parameter was the concentration of the ambient particles that have penetrated the indoor microenvironment and remained suspended. The settling velocity is directly proportional to the particle diameter (to the square) and the density of the particle. Particles smaller than 10 μm can remain suspended for longer periods [71,72]. Guak & Lee [73] studied the relationship between personal exposure and ambient concentration of PM_{10} and $PM_{2.5}$ for different time-activity patterns. They concluded that personal exposure and $PM_{2.5}$ were highly correlated.

Therefore, in this study, it is assumed that when measuring concentration, an imperfect indicator of exposures is obtained, but that there is a correlation between concentrations and exposures.

1.5. Objectives of the study

Today, DCV deploys CO_2 and temperatures as control parameters as they are linked to comfort and productivity and sensors are highly available. From the conclusions of chapters 1.2 and 1.3 RH, $PM_{2.5}$ and formaldehyde should be measured additionally to CO_2 and temperature to account for the main pollutants from non-metabolic activities and their health effects. We hypothesize that the other pollutants may be at adversely high concentrations, despite CO_2 and temperature values being below thresholds.

The main objectives of this article were:

1) Development of a methodology for selecting which pollutants to use as control parameters for flow rates and to control the share of outdoor air in the supplied air:
   a. A methodology to determine which pollutants can be proxy for others was deployed using CCF. With CCF the study can focus on the i) present time correlation: looking for a mutual relationship between two pollutants at the same point in time, and ii) determining the correlation between the variables at different time lags. The CCF pattern is affected by the underlying time series structures, by the autocorrelation or trends of each of the two variables. Thus, it is helpful to de-trend the data by pre-whitening.
   b. An I/O -study approach was used to allow a deeper insight into the origin of the pollutants (indoor or outdoor). Based on the

origin of the pollutant, increasing ventilation with outdoor air would be either beneficial or harmful for the IAQ.

2) *Examine the suitability of the methodology with 3 case studies.* RH, $PM_{2.5}$ and formaldehyde have been measured for at least one week, additionally to CO_2 and temperature in an office, a gym and a canteen/kitchen. The results were used to evaluate the suitability of the method and not to do a thorough mapping of correlations for the studied types of rooms and situations.

To the knowledge of the authors: i) pre-whitening of data for studying correlations in detrended time series has not been applied for selection of pollutants to control DCV before. ii) the same combination of pollutants has not been previously evaluated.

2. Methods

2.1. Methodology for data analysis

Fig. 1 summarizes the methodology of this work.

The data analysis focused on correlations between the selected parameters: CO_2, RH, temperature, formaldehyde, and $PM_{2.5,}$ as well as between the location where parameters were measured: the corresponding breathing height in each room (see Fig. 2) and the supply air terminals.

Previous studies have based their criteria for correlation on Pearson's analyzes with non-pre-whitened time series [74–78]. The correlation coefficient between two time series following the same trend often suggests a high correlation. However, the high value may be due to auto-correlation in the respective time series, rather than due to a real correlation between the two series [79]. The correlation patterns are affected by underlying time series structures of each of the two variables and the trends that each series has. Thus, it is helpful to de-trend the data. By pre-whitening data, detrended time series are attained. Pre-whitening of data should always be done before deriving correlations in trended time series [80,81]. Unless studying de-trended correlations, nothing can be assured about the causal relationship of these two-time series.

In this article, the calculation of the correlation of two time series is expressed by the linear correlation of different time lags between the two series [82] via the cross-correlation function (CCF). The correlation that the CCF shows is not pure inter-series-correlation, it is also affected by the autocorrelation of each of the two series (intra--series-correlation). By using CCF instead of simple Pearson coefficients, "time-shifted" correlations can be also studied. The Pearson correlation only studies the contemporaneous relationship between the two-time series and not how the variation of one parameter may affect another in time. Let's consider formaldehyde, the emission of this pollutant can be affected by RH and temperature. If we only look at Pearson coefficients, there may be no relationship, but if we studied several lags of time an effect of the variation of RH may be a predecessor of a peak in formaldehyde. In addition, not all the sensors have the same response time, or not all the reactions happen equally fast, thus studying the cross-correlation function is more complete.

One approach to isolate the correlation between the time series is to remove the autocorrelation, i.e., to detrend the series [83]. This approach is called pre-whitening.

Considering two time series, x, and y, of equal length. The three steps of pre-whitening are:

1. Determine a time series model for x, in this case, an Autoregressive Integrated Moving-Average Model (ARIMA) was used for trend removal [82]. The goal of this step is to describe x up to residuals that are white noise, e.g., a time series without autocorrelation.
2. Transform (filter) y by using the model used for x (using the same coefficients).
3. Calculate the CCF between the residuals from step 1 and the filtered y-values from step 2.

The cross-correlation that is left in step 3 corresponds to the correlation between the time series. It is proportional to the impulse response function between x and y. If pre-whitening was not done, then the CCF would have been affected by the autocorrelations in the signals. Y has (normally/always) autocorrelation, but this is not a problem if x is "white".

ARIMA models belong to the class of linear time series models. Hence, it was assumed that the concentration of all pollutants behaved linearly over time, i.e., each measurement could be represented as a linear combination of its past values. ARIMA models were chosen because they are the most general form of linear time series models, and they include simpler models such as AR (Auto-regressive), MA (moving average), or ARMA (autoregressive moving average) models. Note that it was not our foremost goal to identify a perfect model to describe the time series, but rather a model whose residuals are close to white noise, to remove autocorrelation from the series.

Some pollutants were generated in the considered space and some infiltrated from outdoors. In a room with a high concentration of outdoor produced pollutants, increasing the airflow rate would not be beneficial for diluting their concentration. For example, in a room where the concentration of pollutants from traffic was too high, increasing the ventilation airflow rate from outdoors would further increase the concentration of these pollutants (supposing that these pollutants were not filtered. Filter efficiency plays a big role in the concentration of pollutants). To define the best ventilation procedure to dilute measured pollutants I/O has been evaluated. When an I/O was below one, it meant that the pollutant was produced outside the room. In this case, it would not be useful to increase outdoor air ventilation rates to dilute the outdoors generated pollutant. For example, in a room where plastics and old papers are stored, the formaldehyde values can be high. In this case, the I/O of formaldehyde may be over 1 and increasing the ventilation rate of outdoor air would reduce the formaldehyde concentration.

2.2. Measurement spaces

The criteria for selecting the measured spaces were as follows:

1) Similar exposure to outdoor pollutants as they were all placed in the same building. East-oriented with similar airtightness,
2) Same ventilation solution, constant air volume (CAV) and equal ceiling-mounted diffuser whose jets generated strong mixing of the air in the room assumed to be, fully mixed

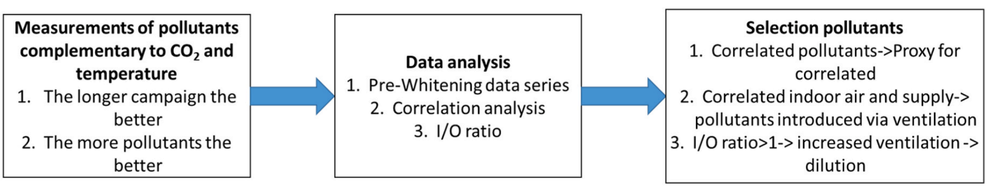

Fig. 1. Summary of methodology for the selection of the pollutants to be used to control ventilation.

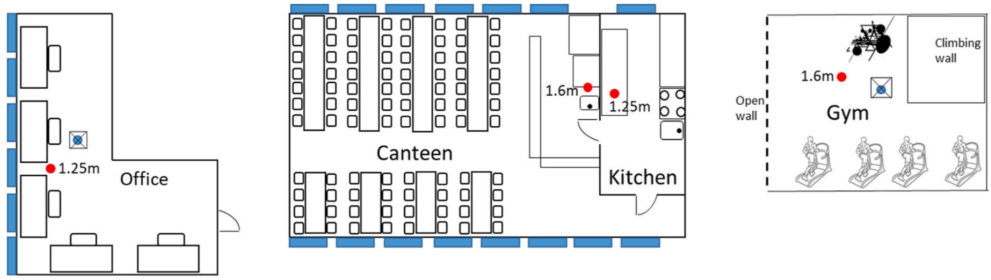

Fig. 2. Placement of measuring equipment. The blue dot shows the positioning in the supply air terminals and the red dots the positioning of the measurement equipment and the breathing height. Blue rectangles show the windows. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3) Different activities performed in the room and
4) Connection to the same air handling unit (AHU). The AHU was East oriented, on the sixth floor, about 30 m away from the street measured in a straight line

Owing to these criteria and to validate the Methodology for data analysis, measurements were performed at the supply terminal of an office and a gym and breathing height in an office, a canteen, a kitchen and a gym. All the measured spaces were in the same building in Trondheim, Norway less than 40 m away from the road (measured in a straight line). Fig. 2 shows the layout of the rooms and the placement of sensors. The red dots represent the location and height of the measurement at "breathing height" in the three rooms and the blue dots represent the measurement at the supply air terminal. Table 1 summarized the equipment and characteristics of the three measured locations.

The 36 m^2 office on the second floor was dimensioned for five occupants and had a constant airflow rate of 300 m^3/h from 06:00 to 20:00 during working days. Outside this period or during weekends, the ventilation was off. The measurements lasted three weeks during June. The room was renovated with new walls, painting, windows, and a ventilation system about one year before the measurements.

Measurements in the 100 m^2 canteen and the 15 m^2 kitchen lasted one week. These two rooms were placed on the 6th floor. The kitchen was used by one cook that was responsible for baking bread, general cooking, and washing. The canteen was occupied from 11:30 to 13:30. Up to 50 people could be sitting at the most crowded periods. The canteen measurements were done close to the kitchen door. The supply and exhaust airflow rates were not measured, but the ventilation was constant during the same periods as the office. The canteen and kitchen had not been renovated in the last years.

The 50 m^2 gym was in the basement of the building. Measurements at the gym lasted twenty days. The occupancy was irregular from 15 people to long-vacant periods (users reported use of the room in a diary). The supply and exhaust airflow rates were not measured, but they were constant from 06:00 to 20:00 during weekdays. This gym was open to a large corridor (no wall, see dashed line in Fig. 2). The gym was built one year before measurements, and the ventilation system was not upgraded.

Table 1
Description of equipment and parameters measured.

	Office	Kitchen/ Canteen	Training room
Area (m^2)	36	15 + 100 (two rooms)	50
Occupants #	5 desks. 2–3 occupants during measurements	Variable, 0–50 persons	Variable, 0–8 persons
Ventilation principle	CAV mix ventilation 350 m^3/h	CAV mix ventilation	CAV mix ventilation + one wall open to the lab
Floor	Second	Sixth	Underground −1
Duration	Three weeks	One week	20 days

2.3. Equipment

The activities in these rooms were very different and the pollutants produced were expected to be different in quantity and type. Table 2 shows the expected contaminants based on the different types of activities.

Fig. 3 shows pictures of the installation of the sensors.

Measurements were done with low-cost sensors. Low-cost sensors were preferred as they could economically replace the "normal" CO_2-temperature sensor typically installed in these types of rooms. Table 3 summarizes the sensors, the accuracy, the measuring range, and the response time. More information about the calibration can be found in Ref. [84] (under publication). Demanega et al. discuss as well the performance of the particle sensors Sensirion SPS30 [85], Tryner et al. discussed the use of SCD30 CO_2 sensor [86] that measures as well humidity and temperature. Measurements were taken every 1 min.

In all measurements, the sensors were protected from direct contact with the users, direct disturbance from the ventilation supply air and solar irradiation. Measurements happened at a single point to mimic the normal measurement procedure when measuring CO_2 and temperature. For the reduced size of the rooms (not applying for the canteen where the representativeness is more limited), we assume that the single measurement was representative for the occupied breathing zone as the ventilation was mixing air ventilation.

3. Results

3.1. Correlation between different variables in each room

Correlations were sought for the whole measured period.

The pre-whitening process and CCF described in section "Correlations Analysis" were carried out to find correlations between two time series as described in the methodology chapter. In the plots of CCF, the x-axis (lag) represented the offset between both series, its sign determined in which direction the series were shifted. The y-axis showed the Pearson correlation coefficient of the two respective time lags. The larger the y-value, the larger was the correlation. The lag i value returned by CCF (x, y) estimates the correlation between x [t + i] and y [t] [87]. A negative correlation value CCF (x, y) < 0 meant that if one parameter increased, the other decreased. The lag times showed how long it took for one perturbance to propagate in the other series. A positive time index between two pollutants at lag i (i > 0) represented that the current value of a pollutant (current meaning at time [t]) was correlated with the future value of the other pollutant at time [t + i]. Equally, a negative value at lag i (i < 0) meant that the previous value of

Table 2
Expected pollutants generated in the studied rooms based on the different activities.

Type of room	Type of activity	Expected indoor air quality sources				
		CO_2	Air temperature	Formaldehyde	$PM_{2.5}$	RH
Office	Sitting and PC working	Breathing	Heat gain from MET, sun and computers	Beauty products, papers, wall painting furniture	Infiltration	MET
Gym	Physical activity	Breathing: proportional to occupancy and activity: ↑ MET: ↑exhalation	Heat relative to occupancy and activity level: ↑ MET: ↑sweat and ↑exhalation	Apparels and carpets	Infiltration Friction treadmill Climbing wall dust	↑ MET: ↑sweat and ↑exhalation
Industrial kitchen	Cooking	Breathing limited to the chef	Heat gain from cooking, oven, dishwasher, sun	Trash and cleaning products	From cooking, oven	From cooking, oven, dishwasher
Canteen	Eating	Breathing: proportional to occupancy	Heat gain from ↑ occupancy short period, sun	Food wrapping?	↑ occupancy + food remaining	↑ occupancy + food vapor

Fig. 3. Installations of measurement equipment: (A) in the office; (B), (C) and (D): in the gym; (E) in the kitchen; (F) in the canteen.

Table 3
Properties of deployed sensors.

Parameter	Sensor type	Accuracy	Measurement range	Response time
Relative humidity	Capacitive	±3% at 25 °C	0–100%	8s
CO_2	Nondispersive infrared (NDIR)	±30 ppm ± 3% of reading (500–1500 ppm)	400–10000 ppm	20s
Temperature	10K NTC Thermistor	±0.4 °C + 0.023 (t [°C] - 25 °C)	−40 °C–70 °C	>10s
Particle concentration	Optical sensor	±10 μg/m^3 (0–100 μg/m^3) ±10% (100–1000 μg/m^3)	0–1000 μg/m^3	20 ms
Formaldehyde	Electrochemical sensor (MOS)	≤0.02 ppm formaldehyde equivalent < ± 2% repeatability	0.03–2 ppm	<40S

one pollutant at time [t + i] was correlated with the present value of the other pollutants at time [t]. This can be read as one pollutant was a predecessor for the current value of the other. The dashed blue line represented the 95% confidence bound (blue dashed lines) for a significant correlation.

3.1.1. *Correlations between pollutants from the gym*

As shown in Fig. 4, both supply and room levels of absolute humidity and temperature followed similar trends. CO_2 levels were mostly below 700 ppm for the presented period. Mostly, one person trained at the time, and no group training was presented in Fig. 4. In general, during training activities, the MET increased, the temperature rose quickly, and

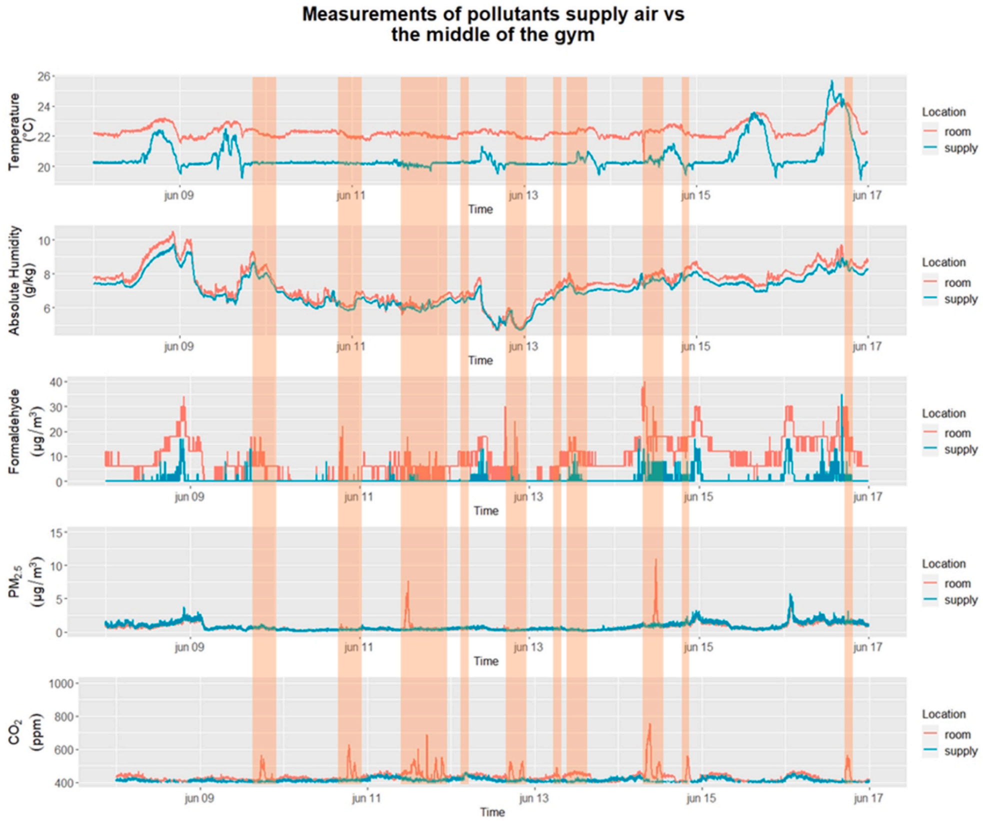

Fig. 4. Evolution of the concentration of different pollutants in the supply and room air in the gym. Training periods are shaded in orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the production of CO_2 was much higher. Formaldehyde concentrations rose towards the end of the day while ventilation was shut down and decreased every morning when ventilation started. Formaldehyde levels also seem to rise together with the periods of training read as peaks of CO_2. Regarding $PM_{2.5}$, the level of particles was continuously very low, the levels only rose during climbing activities (read from gym diary).

Fig. 5 shows the cross-correlation functions of the detrended time series of each two pollutants in the gym (room values). There were very few significant correlations between $PM_{2.5}$ and temperature or absolute humidity or formaldehyde, and those that were over the 95% confidence bands are very small in value. There is a significant correlation between $PM_{2.5}$ and CO_2 probably corresponding to the particle creation by gym users. However, judging by the module of the correlation and the few time lags with significant correlations, CO_2 does not seem to be describing $PM_{2.5}$ concentrations unquestionably. There was a weak correlation between CO_2 and temperature or absolute humidity in higher lags. The lags were related to the simultaneity, higher lags can be read as a delay in the effect. Occupants would come into the gym and CO_2 will rise faster than temperature and absolute humidity or $PM_{2.5}$. However, the absolute value of the correlation factors was still low, which meant a low effect. There was a strong correlation between temperature and absolute humidity at lag zero, i.e., simultaneously. Formaldehyde is correlated to CO_2 and absolute humidity. Many points were over the 95% confidence bands, and even if they were small, a large number of smaller values will add up to a large total effect. Even if we cannot conclude on a causal relationship, we can conclude that using these two parameters is important to describe formaldehyde. That is exactly another strength of this method that describes the effects of several parameters. Formaldehyde values were correlated positively to temperature in lag zero. When the temperature rose, the formaldehyde also rose.

The CCF when using non-detrended time series is presented in Fig. S1 in the appendix. In the trended analysis, the correlations appeared to be stronger than the detrended and all variables are significant (outside the 95% confidence interval). Mathematically, the assumptions to use covariance methods as Pearson's are: 1) that the cases should be independent to each other, 2) that the two variables should be linearly related to each other and 3) the residuals scatterplot should be roughly rectangular-shaped. This is not the case when using a non-de-trended time series.

3.1.2. Correlations between pollutants from the office

Occupants of the office reported that the door was only opened and closed to allow them to enter. They kept a diary of when they arrived and left the office, but they did not record short vacancies. Fig. 6 presents the room air and supply air concentrations of the five pollutants. The occupancy of the office was low, CO_2 stayed mostly below 650 ppm. The ventilation of the office was dimensioned to constantly deliver 100% design airflow rate for five persons from 06:00 to 20:00, but the maximum registered occupancy was 3 persons. CO_2 peaks seem to be simultaneous to formaldehyde and $PM_{2.5}$ peaks but not to the ones of temperature and absolute humidity.

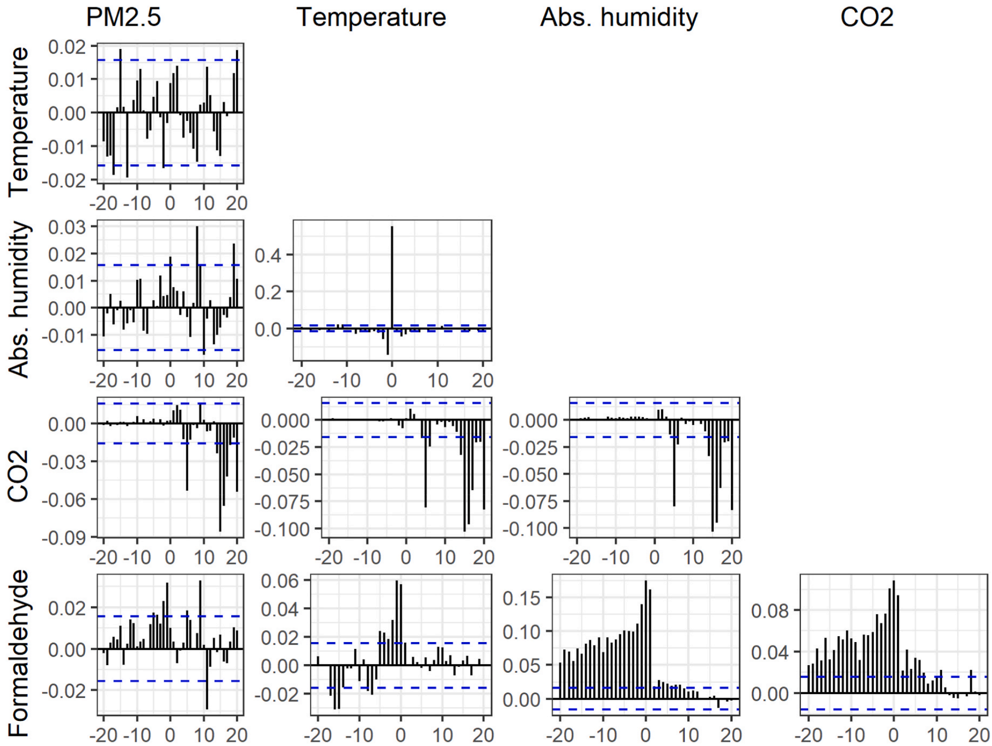

Fig. 5. Cross-correlation function between the different pollutants for the gym measurements (room measurements). The x-axis (lag) represents the offset between both series, its sign determines in which direction the series are shifted. The y-axis shows the Pearson correlation coefficient of the two respective time lags.

The levels of formaldehyde in supply air were almost always below indoor levels. Formaldehyde is produced continuously in small amounts by occupants, paper, and many other sources [48]. The emissions from the furniture and paintings were very low in this case as the university confirmed using low emitting materials and paintings and the renovation was done one year before the measurements. Most of the peaks happened while the ventilation was on, thus not necessarily because of the emission from materials but more related to occupants' activities. Therefore, a correlation with CO_2 could be justified. The same applies to $PM_{2.5}$ given that the outdoor air is very little polluted. Road construction works were happening, and the traffic was limited. The concentration of $PM_{2.5}$ in Trondheim's air is generally low in June. The spring cleaning of the roadway finished in May, and the studded snow tires are no longer used [88].

Fig. 7 shows the results for the cross-correlation function of the de-trended data series. Only temperature and absolute humidity correlate at a high value. There is also a correlation between CO_2 and temperature and CO_2 and absolute humidity that happened at low lags. However, the values were very small in the range (ca. 0.075) and had few occurrences. The absolute value of the function may depend on the number of observations, and probably a more extended sample should be analyzed to have stronger conclusions. Formaldehyde correlated significantly with absolute humidity, temperature and CO_2 at low lags, and these seem important as many different lags are significant.

3.1.3. Correlations between pollutants from the kitchen

Fig. 8 shows the development of the pollutants in the canteen and kitchen for three consecutive working days. In this case, due to the high temperature in the kitchen, the cook ran an additional personal air-cooling system. Besides, the kitchen had solar shading, which justifies the temperature difference with the canteen despite being both rooms connected.

The absolute humidity in both rooms depended mostly on the activities. During dishwashing, baking, or floor mopping, humidity levels rose. Regarding CO_2, both rooms followed each other as they were communicating through a large opening. During busy periods, up to fifty people can sit for lunch. These high occupancies are followed by peaks of CO_2. After 14:00, there was seldom anyone in the kitchen beside the cook that left around 15:00.

The high concentration levels of formaldehyde after the room was vacant were probably connected to the trash bin being left open in the room (emptied every third day). Thus, the first two days had high concentrations from probably the trash bin, and the third did not show the same pattern. The door separating the canteen and kitchen was left open during the first night and closed during the second.

$PM_{2.5}$ levels were generally low during the measurement period. During the food preparation and bread baking, some $PM_{2.5}$ spikes were recorded. Otherwise, the levels were almost consistently below 2.5 μg/m^3 despite the cooking activities. The kitchen was on the sixth floor thus, hardly exposed to traffic-related sources.

Fig. 9 shows the CCF for the de-trended time series. In this case, only the measurements inside the kitchen were analyzed. There was a higher correlation in the low lags between absolute humidity and $PM_{2.5}$ or formaldehyde. Formaldehyde and $PM_{2.5}$ are also correlated in low lags. Baking and cooking yielded formaldehyde, $PM_{2.5}$ and humidity. Absolute humidity and temperature were also correlated in low lags. CO_2 correlated temperature and absolute humidity in low lags, but not with $PM_{2.5}$ or formaldehyde.

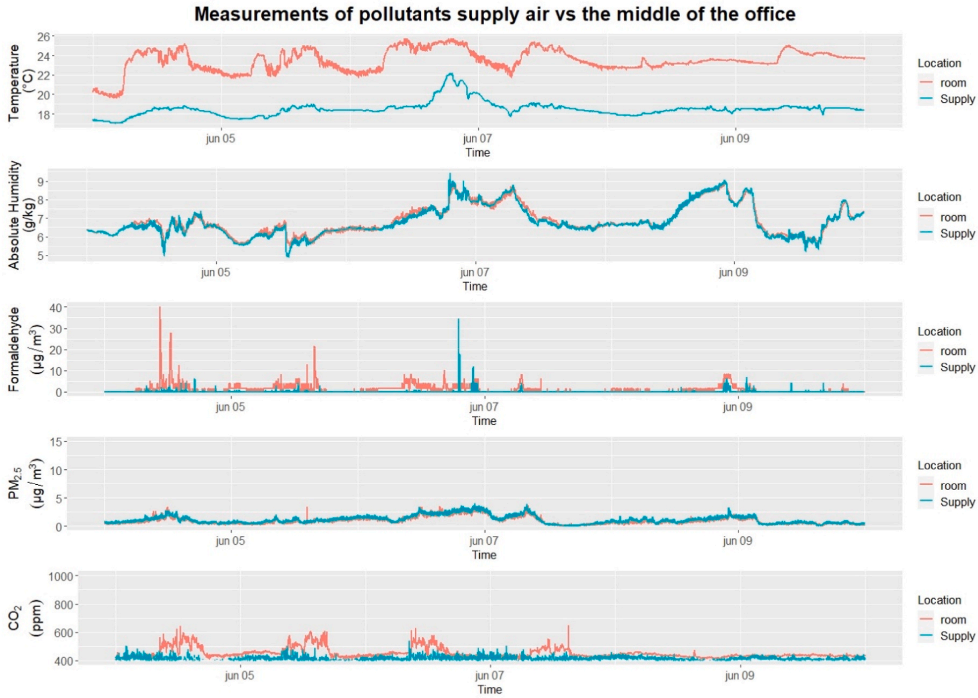

Fig. 6. Evolution of concentration of different pollutants in the office room.

3.1.4. Results using pearson correlations assessment

The widely used procedure for analyzing correlation in measurements of air pollutants is to use Pearson's correlation. The Pearson coefficients are indicators of a linear correlation between two sets of data. The Pearson correlation has two assumptions: i) the two variables are normally distributed and ii) the relationship between the two variables is linear.

However, if the time series show trends, it is crucial to remove these first to avoid autocorrelation interferences. A common way to de-trend is not to use the absolute values of the series but their relative changes over time. Hence, one applies Pearson's correlation coefficient on the differenced time series [89]. In this case, the de-trend of the values was done using ARIMA models as explained in steps 1 and 2 of the chapter of methodology for data analysis.

Fig. S2 to Fig. S7 presented in the Appendix show the correlation values for the pollutants in the three different rooms, first using the raw data and then using the de-trended time series. In the kitchen using the raw data would have induced us to conclude a correlation between absolute humidity and CO_2 that is not confirmed when using the de-trended data. Looking at the de-trended values in the kitchen there is only a correlation between the absolute humidity and the $PM_{2.5}$ or temperature. In the gym, there is a strong correlation between absolute humidity and temperature and a smaller correlation between absolute humidity and CO_2. In the office, there is only a correlation between absolute humidity and temperature. Using de-trended values is necessary to avoid overestimating correlations.

Pearson's correlations analyze correlation only the lag 0, whereas the cross-correlation functions analyze the whole time series. Thus, when using Pearson's correlations delays in response from different sensors would not be reflected in the result. For instance, the correlation in the kitchen between absolute humidity and formaldehyde or $PM_{2.5}$ are neglected when only looking at lag zero as these happen at lag −2 and −3.

3.2. Correlation of the different pollutants between supply and breathed air

This chapter presents the CCF between the same pollutants in the supplied air and breathed air and the I/O. No analysis of the kitchen/canteen is presented as the measurements were not at supply and breathing height but only at breathing height.

3.2.1. Correlation between room and supply air at the office

There was a high correlation between the room and the supply air in the variables $PM_{2.5}$, temperature, and absolute humidity in the office. Most of the particles in an office are derived from infiltrations from the outdoors. Thus, it was expected to see a correlation in $PM_{2.5}$. For absolute humidity and temperature, given that the measurements were taken under summer conditions for low occupancy periods, there were no large sources of moisture or heat, and correlation was expected. The CO_2 levels of supply and breathed air correlate weakly, which was plausible, given that indoors the largest source of CO_2 was human exhalation, but the ventilation rate is very high. Formaldehyde had a low correlation as most sources happened indoors. These findings agreed with the plots on Fig. S8 in the appendix.

From chapter 3.1.2 it was concluded that control to modify the supply airflow rates in this office should use CO_2 (representing temperature and absolute humidity indoors), formaldehyde and $PM_{2.5}$. Absolute humidity, temperature, formaldehyde and $PM_{2.5}$ correlate between indoor and outdoor, thus in this case measuring only indoor should be sufficient. Fig. 10 right shows the I/O. For all the presented pollutants, the I/O is larger than one meaning that increasing ventilation to remove these pollutants is an effective solution.

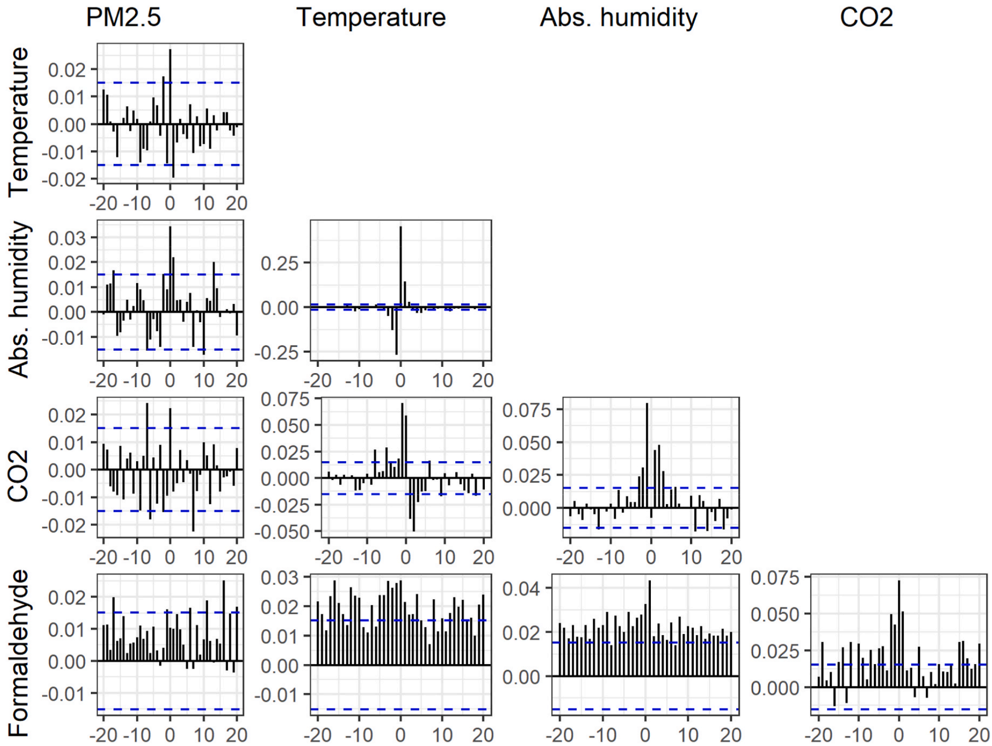

Fig. 7. Cross-correlation function between the different pollutants for the office measurements (room measurements).

3.2.2. Correlation between room and supply air at the gym

The gym had no window to the road that could let in $PM_{2.5}$ caused by traffic. $PM_{2.5}$ was mostly brought to the room via activities such as climbing. Hence, correlations for $PM_{2.5}$ deviate from the ones at the office as shown in Fig. S9 in the Appendix. Formaldehyde is brought to the room via the activities; thus, we do not see correlations with the supply air. The same applies to CO_2. For absolute humidity and temperature, as there is no heating of the air neither humidification there is a correlation between the supply and the room values.

In this case, most of the I/O ratios are over one for $PM_{2.5}$, formaldehyde and CO_2 as shown in Fig. 11. For $PM_{2.5}$, formaldehyde and CO_2 it is efficient to increase the airflow rates. For absolute humidity and temperature increasing the ventilation (given that there is no cooling nor dehumidification) may not be a good way of reducing over-temperature or too high absolute humidity.

For absolute humidity and temperature, the values are correlated between room and supply, but as the values can be below 1, both indoor and outdoor should be measured. As the I/O ratios are over 1 for formaldehyde, $PM_{2.5}$ and CO_2, increasing ventilation airflow rates to remove the pollutants is a good measure. Given the lack of correlation between indoor and outdoor and that the I/O is over one for CO_2, formaldehyde and $PM_{2.5}$ probably measuring only indoors is enough. However, for more conclusions regarding the removal of sensors longer measurement periods are recommended.

4. Discussion

CCF in de-trended time series is more accurate than CCF in non-detrended time series as autocorrelation could suggest stronger correlations [80,81]. The differences between Fig. 5 and Fig. S1 in the Appendix show the large effect of having trends in the data when analyzing with CCF. If only Fig. S1 in the Appendix was used for the analysis, overestimations of the correlations would be assumed. Using CCF instead of simple Pearson's correlation at lag zero studies both the contemporaneous relationship and delayed correlations. Fig. S2-Fig. S7 in the Appendix prove the need of expanding the analysis to CCF instead of only simultaneous correlations. When there is a risk for delayed effects, using Pearson would not suffice.

In this article, ARIMA models have been used to remove the autocorrelation. The assumption of linearity when using an ARIMA model has not been proven for these pollutants. However, in this work, we limit ourselves to linear models. With longer measurement periods the linearity could be tested as well.

In general, due to health hazards and possibilities for energy savings connected to reductions of VR, measuring several parameters, and using them for control of ventilation is recommended. Formaldehyde, $PM_{2.5}$, moisture and VOC were selected, additional to CO_2, because they represent the most plausible sources of pollutants in the measured indoor environment. Other pollutants, as ozone, bioaerosols, bacteria, NO_x, or SO_x could have been additionally measured but no available/reliable low-cost sensors were found for them.

The robustness of the conclusions from the measurements is limited, as the measurement campaign was too short and only in one season. Seasonal variations of outdoor-generated pollutants such as PM are expected. These are not reflected when measuring only for such a short period. For this methodology, the larger the data sample, the more robust conclusions. A one-week measurement period was sufficient only to demonstrate the methodology and this is how these results should be read. For the data presented for the rooms considered, the following can be concluded.

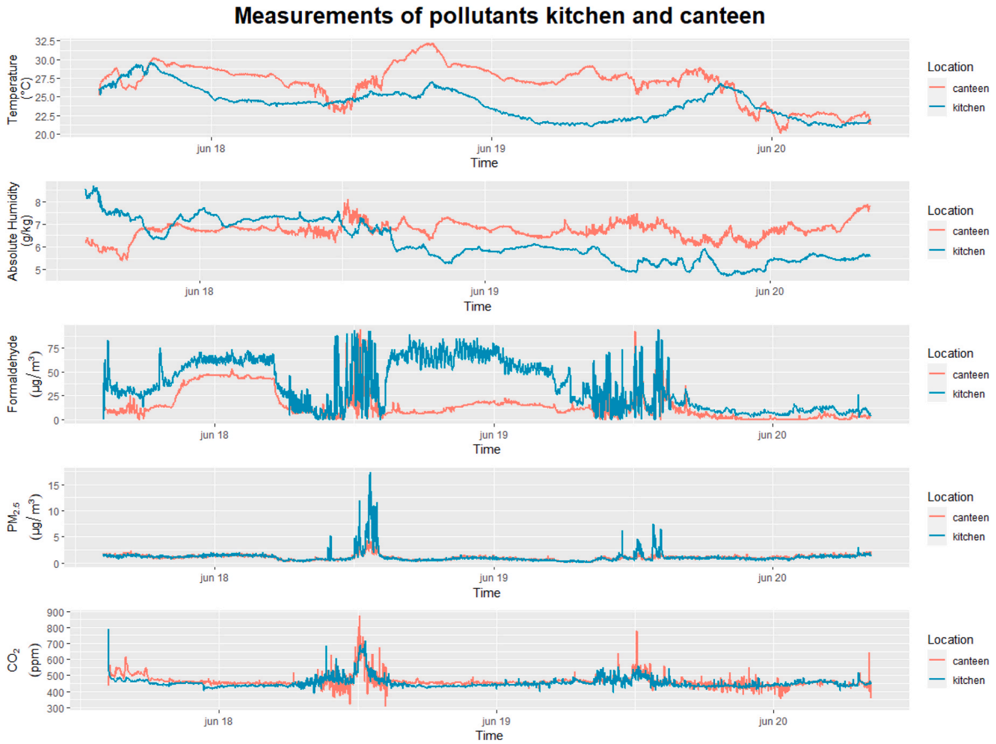

Fig. 8. Evolution of the concentration of various pollutants in the industrial kitchen and canteen.

- For most of the measured cases, the absolute humidity and room temperature were correlated (see Fig. 5, Figs. 7 and 9). Consequently, using only one to be representative of the other may be sufficient. Note that in these measurements, there were no large sources of humidity as it may happen in a bathroom.
- CO_2 did not capture most of the peaks in $PM_{2.5}$ (Fig. 4, Figs. 6 and 8), for the three measured spaces CO_2 and $PM_{2.5}$ did not correlate (see Fig. 5, Figs. 7 and 9), thus using CO_2 would not have been a good proxy to control $PM_{2.5}$. $PM_{2.5}$ was not strongly correlated to any of the other pollutants and should, therefore, be measured both in supply and room air. However, in the measurement period, the concentrations of $PM_{2.5}$ were very low indoors and outdoors. More data would be required representing a period with higher occupancy and higher outdoor $PM_{2.5}$ to have a better background. If the values were to be high and still not represented by the measurements of CO_2 as in the measurement period, they should be included in the ventilation control.
- Formaldehyde measurements may be exacerbated due to cross sensitivities. However, in some rooms such as the kitchen or gym where sources were available, it should at least be monitored to avoid surpassing safe limits. In the measured office and gym, formaldehyde was correlated to relative humidity, temperature, and CO_2.

These three cases show the need to measure $PM_{2.5}$ additionally to temperature and CO_2 to map all the different sources of pollutants. During the measurements in this article, the risk of exceedance of health guidelines was low as most of the rooms were ventilated with very high airflow rates. But the correlation between CO_2 and $PM_{2.5}$ was weak as for Ramalho et al. [19] measurements.

The proposed methodology provides a reliable way to select which parameters to use in the ventilation control. Correlation between the parameters does not induce causation. Causal relationships between the parameters are not subject of this study. In this study, correlation is used to determine which parameters can serve as a proxy for others. In practice, the correlations between parameters should be considered in the logic of IAQ control, either by monitoring all the parameters or by developing correlation equations that would ensure maintaining non-measured pollutants within a satisfactory range. Even if parameters are correlated, their absolute values are still important. For instance, formaldehyde should be at least measured to develop correlation equations. Formaldehyde peaks may be described by measurements of CO_2, temperature and absolute humidity. This is justified as in the measured cases; people and their activities are the largest reason for formaldehyde emissions. If we compare this methodology to the one proposed by Sun et al. [28], in their case, using weighting factors, would not allow for developing descriptive relations for the pollutants that are correlated. However, more measurements are needed as the ones presented here do not represent the design occupancy of the rooms or different seasons. The development of the control strategy must be case-and-space-dependent. An example of the protocol to formulate VR and a ventilation control based on the parameters that are not correlated in an office can be seen in the article from the authors [90] where a traffic pollutant and CO_2 are used for control.

Several reviews have studied existing knowledge about low-cost sensors. Coulby et al. [91] concluded on several sensor having varying accuracy compared to reference devices, but most of them responding similarly to environmental changes. Thus, several sensors were deemed to have high precision but reduced accuracy. In such cases, calibration can increase the accuracy [91]. However, Giordano et al. concluded that low cost sensors are subjected to the biases and calibration dependencies and the correction of such can range from simple linear regressions to very complex machine learning algorithms [92]. Therefore, low-cost

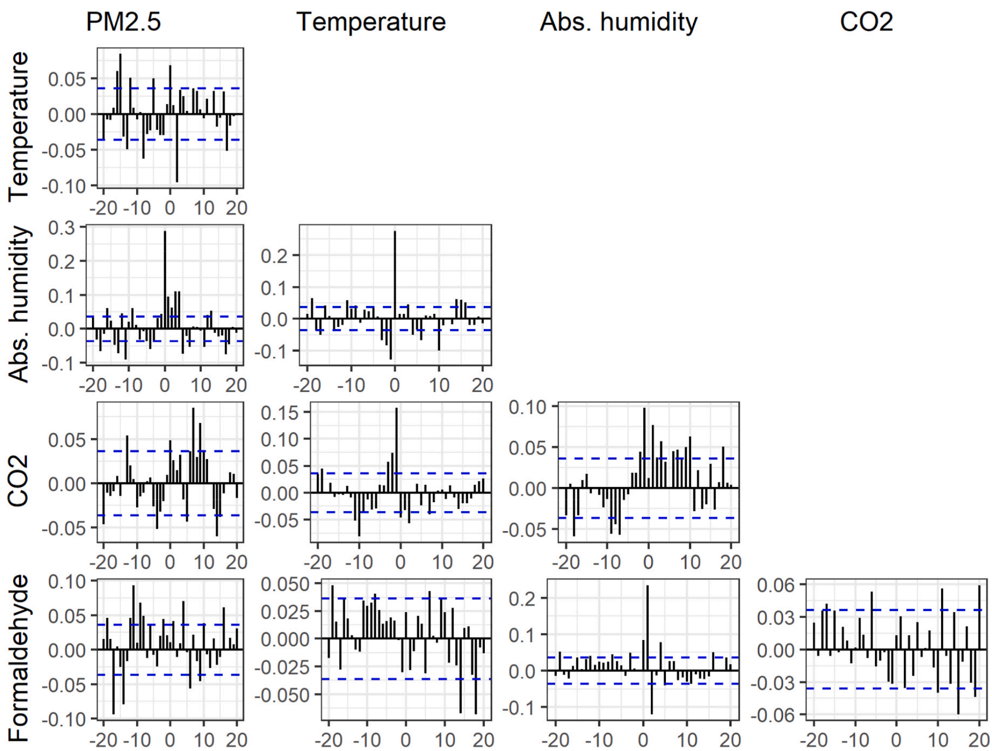

Fig. 9. Cross-correlation function between the different pollutants for the kitchen measurements.

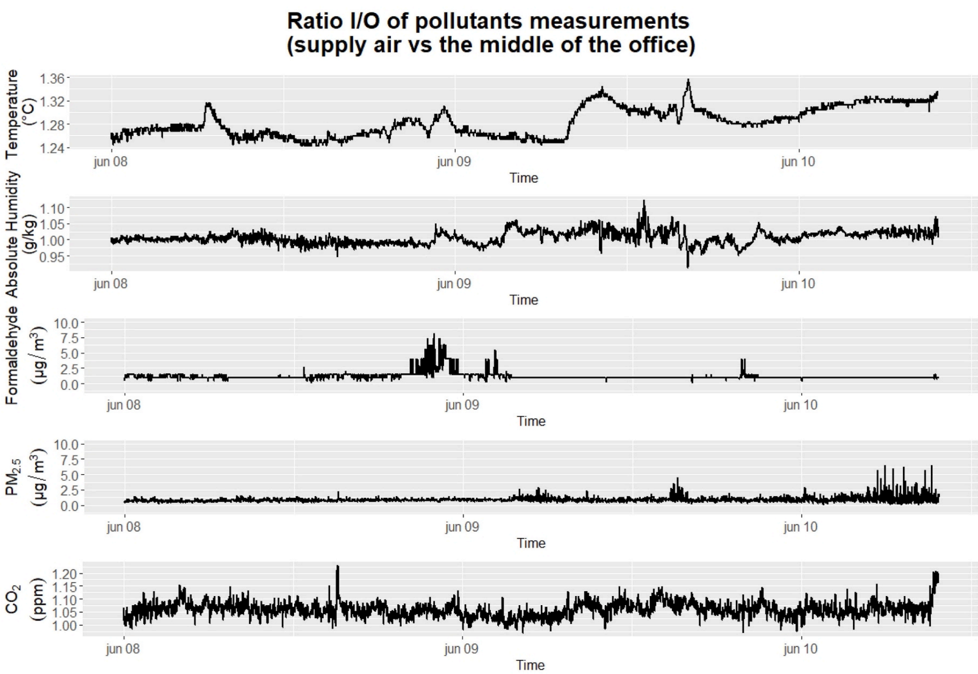

Fig. 10. I/O of pollutants measured in supply and room air at the office.

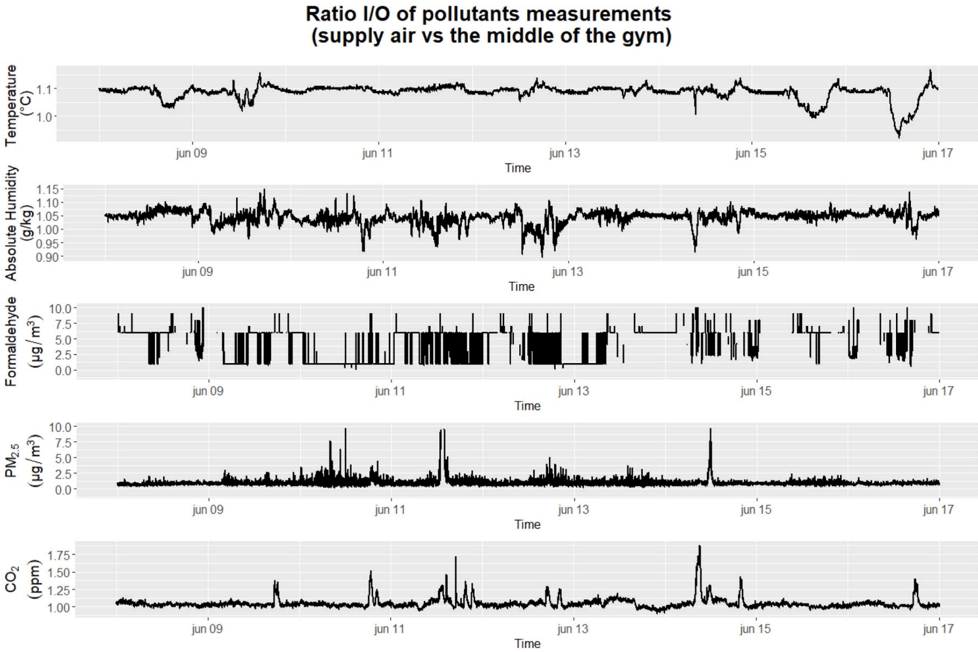

Fig. 11. Left: CCF of supply and room air concentrations of pollutants at the gym, Right I/O of pollutants measured in supply and room air at the gym.

sensors seem to be acceptable for this kind of study, but they must be calibrated always. When used for control of air quality using changes in concentration may be more suitable than using absolute values. Uncertainty of the measurements may jeopardize the selection of the main pollutants.

4.1. Limitations

- Short time measurements: The measurements in this study have been taken to map correlations between pollutants in different spaces. In observational studies like this, there is a potential for bias based on the representativeness and the short duration of the measurements. The difference in sampling duration is owed to the accessibility of the rooms. The presented measurements are in this case proof of concept of the methodology. Due to the small sample size and having only one room of each type, the representability of the results is limited. If these measurements would be used to develop a ventilation control, a longer measurement period would be needed to draw more robust conclusions. We would recommend having at least one week of measurements in every season at different occupancy levels so that the results are more representative. The results in this article should be read as the validation of the methodology. A generalization from the conclusions is not recommended.
- In practice, the deployment of this methodology would be very labor-intensive as first many sensors would need to be installed leaving the building "free float" with constant ventilation, and then the ventilation control strategy would need to be developed. However, with the development of deep learning algorithms and with a collection of data from different buildings, it is expected that the load of work to migrate to such a more holistic control strategy would be mitigated.
- Use of low-cost sensors: Manufacturers have started marketing low-cost air quality sensors to measure air pollution. The availability of such sensors will likely continue to grow [98]. Provided that they could produce reliable data, they could improve current ambient air monitoring. The providers of many of these sensors report limited information about sensor reliability and accuracy. Yet, due to their "low cost" and ease of use, they are used more and more. However, preliminary tests performed in the U.S. [99], [100] and in Europe [101], [102] suggest uncertain reliability, some do not perform well under ambient conditions, and do not correlate with data from "standard" measurement methods employed by regulatory agencies. They may also stop communicating with the system or may just have a shorter lifetime or show incorrect measurements Therefore, it is urgent to characterize the actual performance of IAQ sensors and to educate the public and users about the potential and limitations of these devices [98]. Drift was not followed up as calibration was done before the measurements, and the sampling duration was short. However, when using this methodology in practice, if low-cost sensors are used, their correct performance should be followed up. Several authors recommend using differential rather than absolute values in control [92,93].

Placement of the sensor and using single point: With the universalization of the use of low-cost sensors, better recommendations regarding placement should be delivered together with the sensor datasheets as the users are less expert on IAQ measurements. In this article, the placement of the sensor is the same as for the customarily CO_2 - temperature sensors. However, this affects, among others, the measurement of $PM_{2.5}$, which depending on the size, may distribute differently, or the formaldehyde that is heavier than air. The discussion of the optimal placement of sensors in the different types of rooms (e.g., with different functions, areas, height, and sources) is not taken in this article. However, to follow "standard control strategies", the sensor prototype measuring the five parameters at the same time is placed in breathing height (1.2 or 1.8 m high depending on the normal tasks of the occupants). The location of the sensor, low-cost or "standard", is very important as this measurement must be representative of the room. In the measured cases the air is provided via terminals that encourage full mixing. The placement of the sensor was protected from direct disturbances such as sunlight, heat from radiators, close to a trash bin, etc.

Using a single point to represent the whole occupied volume is a bold assumption. Even more in this case where we have not proven that the air is fully mixed. This is a practical and technical limitation related to the cost of sensors and the limitations on the disturbance to the users of the sampled rooms. We acknowledge that using one single point is an imperfect indicator of exposures and that it cannot provide high-resolution spatiotemporal data that would be important for an accurate evaluation of a dynamic indoor environment. However, this is standard practice when measuring temperature and CO_2 in DCV-systems and we have decided to follow it for practical reasons.

- The formaldehyde sensor has known cross-sensitivity issues with methanol, ethanol, isopropanol, carbon monoxide, phenol, acetaldehyde H_2, H_2S, and SO_2 [94]. Many low-cost $PM_{2.5}$ sensors are affected by RH and temperature [95]. Additionally, converting the light spreading to concentrations of PM depends on chemical and physical properties, size, and shape of particles and others that are not measured. Also, the air intake affects the particles entering the equipment by entraining smaller particles along. In general, these sensors are recommended for cases where the particle types are known and remain unchanged [96] what may not be the case here.
- Low concentration of pollutants: This building had very high ventilation rates per person during the measured period (due to vacancies as some measurements were done in summer periods). It would be very interesting to repeat the measurements when lower ventilation rates per person would be supplied. However, once again the measurements here are to be seen as an illustration of the methodology.

5. Conclusions

This paper presented a methodology to select the pollutants that should be used to control ventilation.

1. A methodology for the selection of pollutants *to use as control parameters* for supply flow rates and to control the share of outdoor air in the supplied air was developed. This is based on the study of CCF in pre-whitened data series. Additionally, an I/O -study approach was used to allow a deeper insight into the origin of the pollutants (indoor or outdoor). This methodology sets to study (i) Where to measure, supply, or/and breathing height and (ii) Which parameters to measure. The methodology should be used to give answers that are case-and-space-dependent.
2. Time series were detrended and correlations due to autocorrelation were removed. Studying correlations in detrended (pre-whitened) time series instead of Pearson's coefficients is superior as autocorrelation on the time series could imply stronger correlations and using CCF allows for studying the correlations at different time lags.
3. The methodology was studied with three case studies, an office, a gym and a kitchen. Measuring the five selected parameters (CO_2, $PM_{2.5}$, temperature, RH and formaldehyde) seems to give a more complete picture of the IAQ in the studied rooms than using only CO_2 and temperature. For most of the measured cases, the absolute humidity and temperature were correlated; CO_2 or temperature did not capture most of the peaks in $PM_{2.5.}$ and formaldehyde was correlated to temperature and CO_2.
4. From the measurements we can conclude on the need to measure at least one parameter representing: 1) pollutants related to human activities 2) pollutants that infiltrate from processes like combustion or traffic outdoors, 3) pollutants related to combustion indoors, 4) pollutants related to degassing from building materials, 5) pollutants related to other "non-combustion-related activities" indoors and moisture loads. These are not undoubtedly covered using only CO_2 and temperature.
5. In conclusion, this is a promising methodology that should be used further.

CRediT authorship contribution statement

Maria Justo Alonso: Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sebastian Wolf:** Formal analysis, Methodology, Software, Visualization, Writing – review & editing. **Rikke Bramming Jørgensen:** Writing – review & editing, Formal analysis. **Henrik Madsen:** Formal analysis. **Hans Martin Mathisen:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.108668.

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PAPER 2

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Using Co-simulation between EnergyPlus and CONTAM to evaluate recirculation-based, demand-controlled ventilation strategies in an office building

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A B S T R A C T

A coupled energy, airflow, and contaminant transport building model was developed using co-simulation between EnergyPlus and CONTAM. The model was used to analyze different strategies to control supply air delivery and return air recirculation rates including the use of demand-controlled ventilation (DCV) strategies. Strategies were evaluated for their effects on indoor pollutant concentrations and energy use of an office building in Trondheim, Norway. Typically, office buildings in Norway employ 100% outdoor air ventilation systems. Measurements in the office building served as the basis to develop the coupled model. The same building was also simulated with the outdoor conditions of Beijing.

The results showed that all the simulated DCV strategies yielded reductions in energy use compared to a baseline, schedule-based strategy. Using recirculation of return air was also an energy efficient measure which increased the otherwise low indoor humidity levels in Trondheim. Using CO_2-based DCV may result in increased levels of indoor particulate ($PM_{2.5}$) from outdoors but using $PM_{2.5}$ monitoring in the ventilation control strategies reduced indoor concentration of $PM_{2.5}$ and energy usage. However, the low outdoor $PM_{2.5}$ levels in Trondheim may not justify its use in this location. The Beijing case revealed that the indoor levels of $PM_{2.5}$ can be reduced below the World Health Organization requirement of annual average of 10 μg/m^3 using $PM_{2.5}$ control.

Co-simulation results revealed that it is possible to both reduce energy use and improve IAQ by controlling the outdoor air fraction based on multiple pollutants while also considering local outdoor environments.

1. Introduction

Systematically reducing outdoor airflow rates to buildings is a common strategy to limit energy use [1]. While reducing outdoor airflow rates may yield energy savings and lower operational costs, it can also lead to increased indoor contaminant levels for contaminants generated indoors. Low outdoor air intake rates, especially in airtight buildings, can degrade indoor air quality (IAQ) and increase sick building syndrome (SBS) symptoms [2,3]. There is a growing body of literature that recognizes the importance of ventilation in working and living environments, and minimum outdoor air (OA) intake rates are required by building standards and regulations to promote occupant health, well-being, and productivity. However, there are often trade-offs between increased amounts of outdoor air and increased energy consumption and costs [4].

Reduced energy consumption is the prime motivation in developing the latest European regulations and standards [5]. Highly efficient buildings, such as Passive houses [6] or zero-emission buildings [7], require a significant decrease in energy use compared to current construction. Heat/energy recovery and demand-controlled ventilation (DCV) are usually proposed to reduce energy use [8–11] as they reduce fan energy and ventilation air heating needs. In cold climates, the temperature difference between indoors and outdoors may be over 40 °C [12]. When ventilating with 100% OA, a common practice in Norway, the heating of this outdoor air may represent a considerable energy demand that can be reduced by heat recovery [8]. In warmer climates when using 100% OA, heating needs would increase in wintertime and in summer, cooling demand or dehumidification demands may appear.

With DCV, the ventilation airflow rates depend on the concentration of one or more airborne contaminants or some other indicator of building occupancy. Typical strategies involve maximizing ventilation

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Nomenclature

AFR	Air Flow Rate
AHU	Air Handling Unit
C	Concentration
CAV	Constant Air Volume
CO_2	Carbon dioxide
DCV	Demand Controlled Ventilation
EMS	Energy Management System
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
HVAC	Heating, Ventilation and Air- Conditioning
IAQ	Indoor Air Quality
IDF	Input data file (for EnergyPlus)
MERV	Minimum efficiency reporting value
OA	Outdoor Air
PM	Particulate matter
PRJ	CONTAM project file
Ret	Return air
RH	Relative humidity
SBS	Sick Building Syndrome
T	Temperature
VOC	Volatile Organic Compounds
WH	Working hours (Monday-Friday 0800-1600)

rates at room/zone level when there is full occupancy and reducing them to minimum levels when the room/zone is vacant. Carbon dioxide (CO_2) is used as a marker for occupancy in CO_2-based DCV [13]. Under occupied conditions, OA has a lower CO_2 concentration than indoor air [14]. However, not all indoor pollutants are associated with occupancy levels. For instance, outdoor levels of particulate matter of 2.5 μm diameter or less ($PM_{2.5}$) are often higher than those indoors, and may not necessarily track occupancy [15,16]. Using CO_2 as a proxy for pollutants that do not originate from occupants may not be effective for ventilation and IAQ control [17]. Thus, controlling ventilation based solely on CO_2, may not support healthy indoor environments as long-term exposure still occurs to other important indoor pollutants at levels high enough to cause serious health effects including cancer and cardiopulmonary disease [18,19].

Another way to reduce heating energy use is to use recirculation of room return air. In this case, a fraction of the otherwise exhausted return air is recirculated to the supply. Jaakkola et al. [20] investigated the effect of recirculation on SBS symptoms. They showed that reducing the outdoor air fraction to 30%, thus recirculating 70% of the return air, assuming acceptable outdoor contaminant levels, does not have adverse health effects. Their research investigated the differential impact of 0% and 70% recirculation rates. However, they only looked at the SBS symptoms and did not investigate energy use. Others have looked at the relation between airflow rates and health [14]. When compared to 100% OA systems, the use of recirculated air requires increased OA to maintain CO_2 concentrations at the same concentration. Recirculated air could also lead to higher indoor temperatures and relative humidity (RH) if no air conditioning is used, as is typical in Norway.

This study investigated energy use and indoor environmental quality (indoor air temperature and RH, $PM_{2.5}$ and CO_2) as a result of variable amounts of room air supply and recirculation to help develop ventilation control strategies. The main objectives of this paper include:

a) Investigating the relationship between indoor pollutant levels and energy savings associated with DCV and air recirculation strategies,
b) Demonstrating ventilation control schemes that account for both IAQ and energy savings, and
c) Demonstrating the applicability of co-simulation between EnergyPlus and CONTAM to highlight the importance of a multi-domain approach to ventilation control.

2. Methods

The use of recirculation of return air affects both energy use and IAQ. Therefore, a comprehensive approach is needed to simultaneously address both domains of building analysis. This section presents the methods used in this study to address these domains of whole-building analysis using co-simulation between the multizone airflow and IAQ and energy modeling software programs, CONTAM and EnergyPlus, respectively.

2.1. CONTAM- EnergyPlus simulation software

A wide variety of building simulation programs have been developed. However, no single tool has the ability to analyze all aspects of building performance or to address innovative building technologies [21]. Co-simulation provides an integrated approach to combine different building simulation tools to address multiple areas of building analysis, e.g., energy, airflow, IAQ, and HVAC control. Some simulation tools address multiple areas of analysis including ESP-r, EnergyPlus, IES VE, IDA ICE, and TRNSYS [22]. Some of these tools also provide the ability to communicate with other programs during simulation. Examples of such run-time coupling have been demonstrated between ESP-r and TRNSYS [23], CONTAM and TRNSYS [24], and EnergyPlus with Matlab/Simulink or Modelica [25]. This article utilizes co-simulation between CONTAM and EnergyPlus to capture the simulation goals of evaluating whole-building energy, airflow and IAQ, and both tools are available free of cost.

CONTAM is a widely-used, free software program developed by the U.S. National Institute of Standards and Technology (NIST) that can be used to simulate multizone whole-building airflow and contaminant transport [26]. EnergyPlus is a well-known, free software program developed by the U.S. Department of Energy that can be used to perform whole-building energy analysis [27].

CONTAM can perform interzone and infiltration airflow calculations given driving forces including ambient temperature, wind speed and direction, and HVAC system airflows. CONTAM also provides a rich set of contaminant transport analysis capabilities that allow it to simultaneously account for a wide variety and number of contaminants, both indoor and outdoor pollutant sources, and contaminant removal mechanisms including particle filtration and deposition. However, CONTAM does not perform heat transfer calculations, so it requires indoor temperature schedules to be user-defined. EnergyPlus can perform system sizing to determine HVAC system requirements including system airflow rates required to meet thermal loads during runtime and calculate indoor zone temperatures required by CONTAM. EnergyPlus does implement an airflow network model based on a predecessor to CONTAM [28], but it is relatively difficult to define the detailed models as compared with the ContamW graphical user interface. EnergyPlus can also simulate two contaminants: CO_2 and a generic contaminant. However, it cannot implement filters within the HVAC system or simulate particle penetration through the building envelope, which are critical to particle transport analysis within buildings. Using co-simulation between CONTAM with EnergyPlus captures the interdependencies between airflow and heat transfer and allows for the sharing of these data between the two simulation tools during runtime [29]. At each simulation time step, EnergyPlus obtains interzone and infiltration airflows from CONTAM. In turn, CONTAM obtains indoor temperatures and system airflows from EnergyPlus and performs the contaminant transport calculations. This co-simulation is performed using the Functional Mock-up Interface capabilities incorporated into

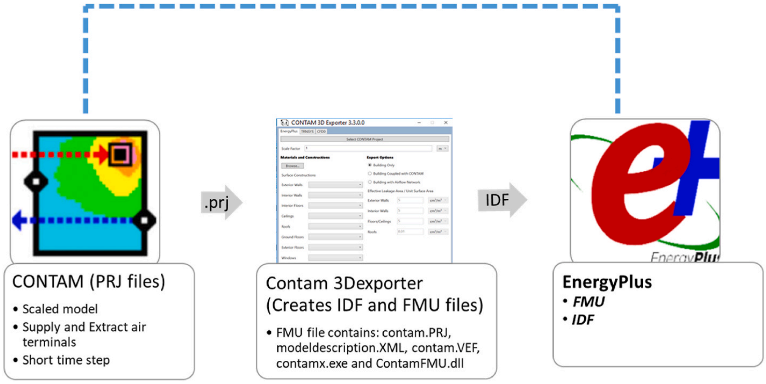

Fig. 1. Schematic of the coupled building model creation process.

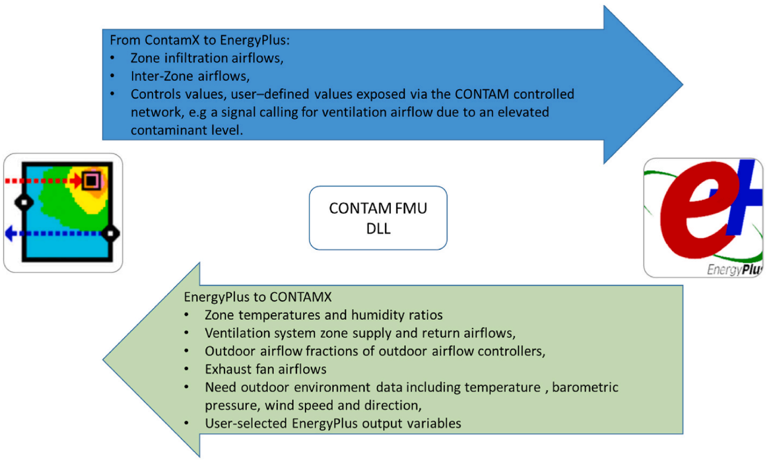

Fig. 2. Schematic of the information exchange during co-simulation between EnergyPlus and CONTAM.

EnergyPlus as described by Dols et al., 2016 [29].

Fig. 1 summarizes the process of developing a coupled building model between EnergyPlus and CONTAM. A CONTAM project file (PRJ) containing a scaled building representation is created using the CONTAM user interface, ContamW. The NIST-developed CONTAM3DExporter tool [30] reads in the PRJ file and creates an EnergyPlus input data file (IDF) along with a compressed functional mock-up unit (FMU) file that contains the PRJ; the CONTAM simulation engine, ContamX; a dynamic link library that facilitates the exchange of data between EnergyPlus and ContamX, ContamFMU.dll; and two files that provide data exchange parameters to be used during co-simulation by both EnergyPlus and ContamFMU (XML and VEF files, respectively) [29].

ContamX provides a set of execution control and data transfer messages to enable compatibility with the EnergyPlus heat balance model. Before running a co-simulation, the time steps must be the same in both the IDF and PRJ of EnergyPlus and CONTAM, respectively. Existing literature [29,31–33] presents convergence and stability issues due to the sequential nature of the execution of the separate programs and the lagging in time of the state variables exchanged between the programs during co-simulation. The quasi-dynamic method requires relatively short time steps to avoid instabilities; therefore, a 1-minute time step (the minimum allowed by EnergyPlus) was used for this project.

Fig. 2 shows the data exchange between the programs. The CONTAM3DExporter generates an IDF that contains building geometry, user-selected materials and constructions, zone infiltration and mixing objects, HVAC air loop related objects, and external interface-related objects. This IDF can be modified as needed, e.g., to add or modify thermal energy systems to the air loops, set HVAC system sizing properties, and define control logic using the energy management system (EMS). Detailed mappings between CONTAM and EnergyPlus entities are provided in the CONTAM documentation [26,29].

2.2. Test case

A co-simulation case was developed between CONTAM and EnergyPlus consisting of an eight-room corridor of an office building located in Trondheim, Norway. Measurements of energy use for the year 2018, as well as two weeks (April 16 −30, 2018) of pollutant concentrations, were available.

Thermal properties (U-value) of the building construction correspond to Norwegian Building Code, TEK 07 [34]: external wall 0.18 W/m^2K, roof 0.13 W/m^2K, floor 0.15 W/m^2K, windows 1.2 W/m^2K and envelope leakage rate of 1.5 h^{-1} at 50 Pa. The case has a gross wall area of 145.6 m^2, 57.85 m^2 oriented towards the North and south and 14.95 oriented towards the East and West. The windows are in the North face

Table 1
Weekday Occupancy Schedules (Vacant on Weekends). Values based on the two-weeks measurements.

Room (occupants)	102x (1)	102y (1)	102z (1)	104 (5)	106 (1)	106a (1)	108 (4)
Arrival	0800	0800	0800	0800 to 0930	0800	0800	**1000 to 1030**
Lunch break	1130 to 1200	1130 to 1200	1130 to 1200	1130 to 1230	1130 to 1200	1130 to 1200	**1130 to 1230**
Departure	1600	1600	1600	1730 to 1835	1600	1600	**1730 to 1835**
Floor area (m^2)	8	6	5	36	14	22	**23**
Supply airflow rate (m^3/h·person)	**60**	60	60	**66**	**126**	**224**	**76.5**

having a total window area of 11.88 m^2 and a gross window-wall ratio of 8.16%. All occupants followed the schedules defined in Table 1 that are based on the two-week field measurements. Airflow rates were simulated following the measured values summarized in Table 1. Note that these supply airflow rate values (under 100% OA) are larger than the minimum OA rates required by ASHRAE Standard 62.1 [35]. All rooms had only one occupant, except for rooms 104 and 108, which had five and four occupants, respectively. Rooms having multiple occupants also had staggered arrival and lunch times. Room 102 is a 17 m^2 hall adjoining rooms 102 x, y and z and contains no occupants.

2.3. Building model

As shown in Fig. 3, the four zones on the right (104, 106, 106a and 108) contain both supply and return air terminals, but zones 102x, 102y and 102z have only supply terminals with associated return air terminals in zone 102. Thus, room 102 acts as a plenum for the other three zones. This requires manual modifications to the IDF and VEF files after generation by CONTAM3DExporter.The building envelope and internal airflow paths are defined as CONTAM leakage area elements of 5 cm^2 per m^2 of exterior wall surface area and 10 cm^2 per m^2 of interior wall surface area, respectively, with a 10 Pa reference pressure, a discharge coefficient of 0.6, and an exponent of 0.65 for the pressure difference.

The outdoor CO_2 was not measured but was assumed to be constant at 719 mg/m^3 (393 ppm). Indoor CO_2 sources are 18 L/h per person during occupied periods based on an average-sized adult engaged in office work [36]. Occupants also acted as heat sources. Outdoor $PM_{2.5}$ was measured 400 m away from the office for an entire year [37] and incorporated into a CONTAM contaminant (CTM) file. Indoor particle removal was simulated in CONTAM in all zones using a deposition rate sink model with a deposition rate of 0.5 h^{-1} [38]. It was assumed that there were no indoor sources of $PM_{2.5}$. Particle filters were simulated in the outdoor air intake and recirculation airflow paths of the CONTAM air handling system. The filters were specified according to minimum efficiency reporting values (MERV) of MERV-13 (equivalent to F7, e $PM_{2.5}$ 65%–80%) and MERV-15 (equivalent to F9, e $PM_{2.5} > 95\%$) [39, 40], respectively. Outdoor conditions (temperature, RH, and wind) were obtained from Meteonorm 7, EPW (EnergyPlus weather) files.

Moisture transport was modeled using EnergyPlus, because moisture coupling between CONTAM and EnergyPlus has not been fully implemented (CONTAM only uses humidity ratios provided by EnergyPlus to convert volumetric units of flow to mass flow units required by CONTAM). The moisture production schedules were defined in EnergyPlus as schedules connected to “Other Equipment” to account for occupant-generated moisture. The moisture generation profiles were calculated based on the two weeks of field measurements and values from [41–43].

An electric resistance heating coil was located downstream of the supply fan in the EnergyPlus AirLoopHVAC system. The average supply temperature was controlled based on the heating load requirements of

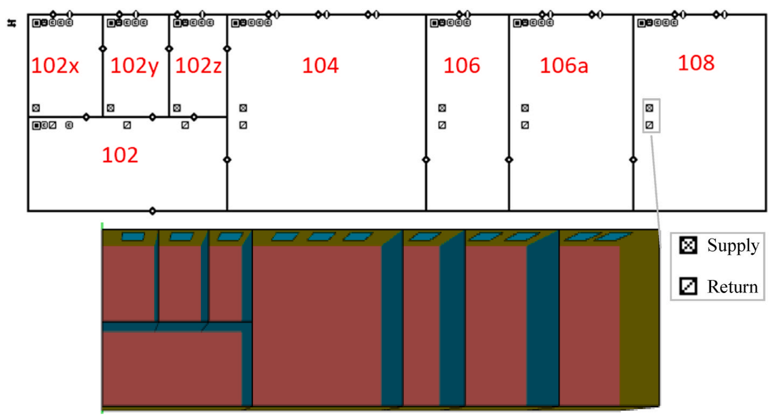

Fig. 3. *Upper: ContamW representation of the corridor. Lower: 3D rendering of IDF geometry generated by* CONTAM3DExporter.

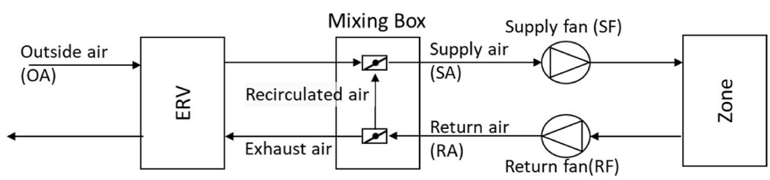

Fig. 4. Schematic of system airflows modeled in this analysis.

Table 2
Simulated latent and sensible effectiveness at 100 and 75% heating airflow.

	100% heating airflow	75% heating airflow
Sensible effectiveness	80%	85%
Latent effectiveness	68%	73%

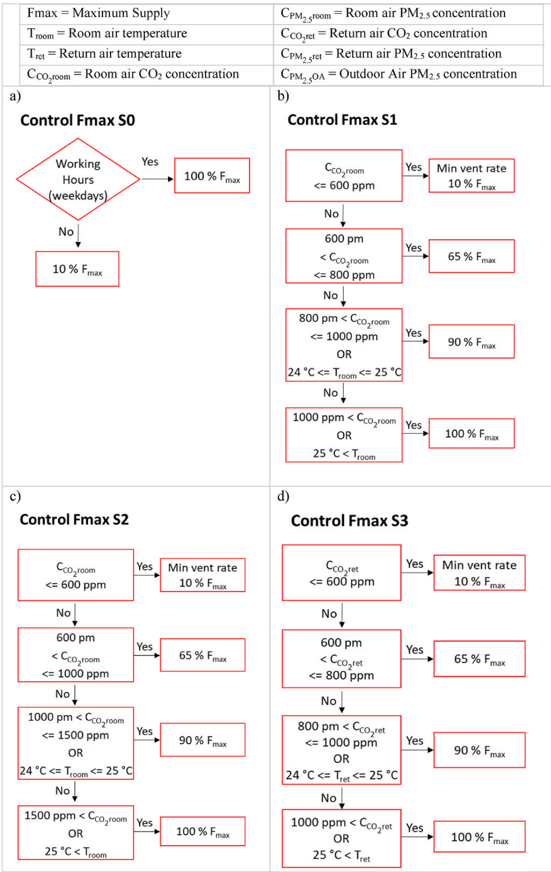

Fig. 5. Flowcharts for control of supply airflow rate.

all controlled zones in the air loop. The supply air temperatures during winter and shoulder seasons were 18 °C from 0600 to 1800 and 15 °C during the rest of the day and 16 °C all day during the summer. The building does not have mechanical cooling, so none was included in the model. All the zones were modeled to have an electric heater thermostatically controlled at 20 °C and 17 °C during and outside of working hours, respectively, except during summer months when the setpoint was always 17 °C.

In the model, the energy recovery ventilator (heat wheel) was incorporated at the outdoor air side of the mixing box in Fig. 4 with the maximum sensible and latent effectiveness stated in Table 2 at 100% and 75% heating airflow.

2.3.1. *HVAC system model*

To minimize the distribution of contaminants, Norwegian building code TEK17 (guidebook), advises against using recirculated air unless rooms are unoccupied [44]. The goal of this restriction was to maintain satisfactory IAQ, defined as maintaining CO_2 concentrations below

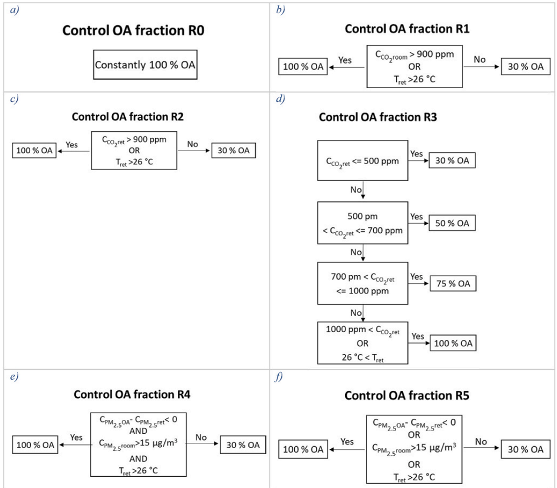

Fig. 6. Flowcharts for recirculation control (% Outdoor Air).

1830 mg/m^3 (1000 ppm). The validity of this threshold value has been discussed in several studies [12,15]. Therefore, it was assumed in this study that, beyond maintaining CO_2 concentrations under a given level, recirculation of return air can also reduce occupant exposure to outdoor pollutants. Thus, recirculation was implemented during occupied hours in opposition to the guidance of the Norwegian building code TEK17.

Fig. 4 shows a schematic of the HVAC system airflows modeled in this analysis. While EnergyPlus provides for CO_2-based DCV, the built-in algorithms do not directly affect the terminal unit flow rate or the system supply airflow rate. In the EnergyPlus algorithms, zone occupancy was used by the OA controller to increase the OA flow rates up to the current supply airflow rate. Thus, using the *AirTerminal:SingleDuct:Uncontrolled* and *DesignSpecification:OutdoorAir* objects, EnergyPlus will vary the terminal unit flow request based on the current occupancy, but this does not incorporate a direct response to a CO_2 signal. This method works to control recirculated airflow, but it does not apply to Norwegian systems that require a continuous 100% OA intake fraction. In addition to modeling 100% OA intake systems, models were developed in this study to implement variable system supply and OA intake rates based on CO_2 and $PM_{2.5}$ sensors located within the CONTAM model and temperature sensors located in the EnergyPlus model. Sensor values were then utilized within EMS programs to control the supply airflow rates to each room and the OA intake fraction delivered by the HVAC system. The maximum total supply airflow rate of the HVAC system was 0.32 m^3/s.

2.3.2. *Ventilation control strategies*

In this article, multiple DCV strategies were simulated. Some strategies were meant to maintain CO_2 below 1830 mg/m^3 (1000 ppm). For the other strategies, CO_2 was allowed to surpass 1830 mg/m^3, but it was assumed that IAQ would be maintained by keeping CO_2 below 2744 mg/m^3 (1500 ppm) (e.g., in schools as proposed by REHVA [47]) and $PM_{2.5}$ below 15 µg/m^3 which corresponds to the Norwegian Public Health guideline for one-day exposures [48]. In Norway, low RH can be a challenge that can be addressed by recirculation of return air. However, for simplicity in this study, controls were only based on temperature, CO_2 and $PM_{2.5}$.

Fig. 5 and Fig. 6 provide the logic associated with each of the supply and outdoor airflow control strategies, respectively. These strategies incorporate various combinations of strategies to control supply airflow rates (S0 – S3) and to control recirculation or fraction of OA intake (R0 – R5). Supply and recirculation control strategies were based on air temperature and concentrations of CO_2 and $PM_{2.5}$ within individual rooms

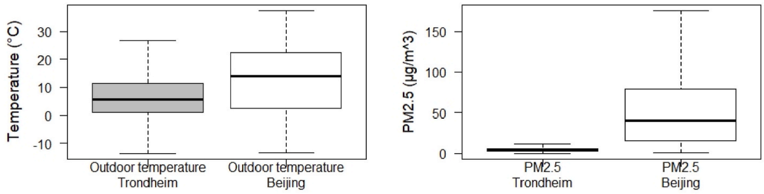

Fig. 7. Distribution outdoor temperature and $PM_{2.5}$ concentrations in the outdoor air in Trondheim and Beijing.

or within the ventilation system return. The threshold and setpoint values in the rule-based control sequences were determined by the authors based on parametric trials (not presented in this article) that targeted the solution that produced the largest energy savings and lowest room air pollutant concentrations. In all these strategies, once the amount of supply air required for all the rooms was determined, then the fraction of OA (and total OA intake rate) required at the air handler was determined. The S0 case provides the maximum supply airflow rate to every room (F_{max}) during the scheduled period (0600–1800); otherwise, the airflow rate is reduced to the minimum (0.10 F_{max}). S1 and S2 control the supply airflow rate to each room based on the CO_2 concentrations and temperatures, and S3 utilizes the CO_2 and temperature in the HVAC system return. S1 and S2 are very similar, but S2 allows for higher CO_2 concentrations than S1. For cases, S1 and S3, the goal is to maintain CO_2 below 1830 mg/m^3 (1000 ppm) and temperature below 25 °C. For case S2, the goal is to maintain CO_2 below 2744 mg/m^3 (1500 ppm) and temperature below 25 °C.

R0 provides for a constant 100% OA intake rate, i.e., there is no recirculation of return air. R1 provides 30% OA unless any CO_2 room air concentration or the return air temperature exceed the indicated threshold values in which case it provides 100% OA. Note, an OA fraction of 30% represents double the minimum per person outdoor air intake rate of 8.5 L/s (0.0085 m3/s) required by ASHRAE Standard 62.1 [35] for office spaces. R2 is the same as R1 except it utilizes the return air CO_2 concentration. R3 sets the OA fraction in a stepwise fashion based on the concentration of CO_2 or the temperature in the return air. R4 and R5 utilize $PM_{2.5}$ instead of CO_2. R4 provides 30% OA unless any room air $PM_{2.5}$ concentration is above the threshold value and the outdoor air $PM_{2.5}$ concentration is less than the return air concentration and the return air temperature exceeds the indicated threshold value in which case it provides 100% OA. R5 is the same as R4 except for 30% OA is provided if any of the three conditions are met, i.e., using the logical OR operator instead of AND.

Eight different combinations of control strategies were simulated: S0R0, S1R0, S1R1, S1R2, S1R3, S3R1 S2R4, and S2R5. S0R0 and S1R0 are typical of Norwegian CAV and DCV systems, respectively, and they do not include recirculation of return air.

The case TEK 07 was developed to compare the simulated energy use to the energy use that should be obtained following the TEK 07 standard definition [49] and specific details as described in NS 3031 [50]. In this case, ventilation system airflow was constant from 0600 to 1800 at 7 m^3/h per m^2 and outside this period 2 m^3/h per m^2 (100% outdoor air), and thermal loads were based on NS 3031:2007 [50]: occupant-based to be 4 W/m^2 and 15 m^2 of floor area per person, lighting 8W/m^2, and appliances 11 W/m^2.

2.4. Parametric simulations

A parametric analysis was performed for the following simulation cases:

1. The building was rotated 180° so that the north-facing façade pointed south for the eight previously defined combinations of control strategies. These cases are referred to in the results as having the same identifiers but with "_S" appended.
2. The north-oriented building models were modified to not include temperature in the eight control strategies. The same temperature setpoints in S1, S2 and S3 were used to control zone temperatures with the electric heaters. These cases are referred to in the results with the "_NTC" suffix.
3. The north-oriented building models were simulated using Beijing weather and outdoor air quality files using the eight, original control strategies. These cases are referred to in the results with the suffix "_N_B". Beijing was simulated because it has similar winter temperatures to Trondheim, but it has much higher outdoor levels of $PM_{2.5}$ as Fig. 7 shows.

2.5. Supplementary considerations

The more complex the control method, i.e., a larger number of parameters used for control, the greater the cost of the system. More advanced systems require the installation of more dampers, sensors, and control circuitry.

The eight strategies are presented here in order of increasing number of sensors required. S0R0 is schedule-based, so it does not require sensors. S3R1 requires CO_2 sensors in every room and both temperature and CO_2 sensors in the return. S1R0 requires temperature and CO_2 sensors in every room. S1R1 requires a temperature sensor in the return in addition to the CO_2 and temperature sensors in every room. S1R2 and S1R3 require both temperature and CO_2 sensors in the return in addition to the CO_2 and temperature sensors in every room. S2R4 and S2R5 require three sensors in each room (temperature, CO_2, and $PM_{2.5}$) as well as temperature and $PM_{2.5}$ in the return.

Fig. 8 provides schematics of the simulated ventilation systems and associated sensors.

Table 3 provides a summary of the associated pollutants, sensors, and additional dampers required for each system type. The number of sensors and dampers were in addition to those that would be required by the S0R0 system. The S2R4 and S2R5 strategies required the most sensors as these controls were based on temperature, CO_2 and $PM_{2.5}$. Additionally, there is a cost of dampers, wiring the sensors and programming the controls. These costs could have a significant effect on the payback period of implementing such systems. Typical DCV systems utilize only temperature and CO_2 for control, so the added sensors of the more complex systems will increase the cost. It can also lead to more sources of error regarding malfunction or miscalibration.

3. Results

Before testing the different control strategies, the co-simulation model was compared to standardized values. The building model was used to simulate the same corridor with the values for ventilation airflow rates, occupancy, and plug loads, etc., from the Norwegian building code TEK 07 [34] which corresponds to the building. The simulated annual energy use and that required by TEK 07 were within 5% of each other. Thus, the model was considered to be valid concerning energy.

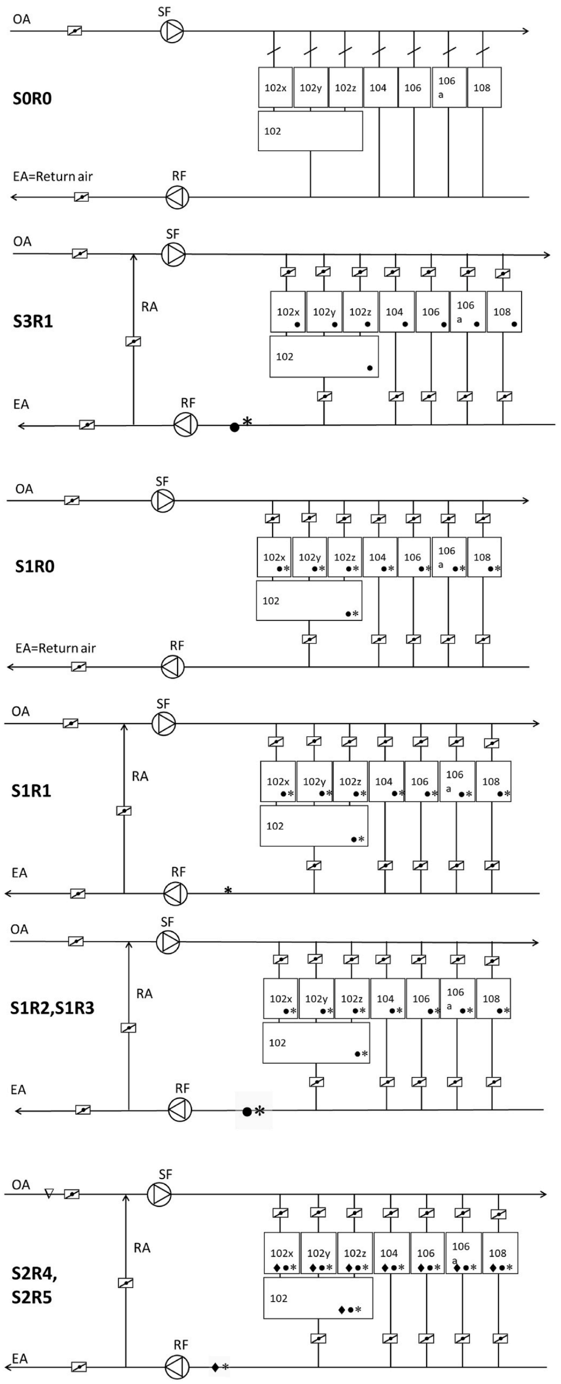

Fig. 8. Ventilation system schematics depicting the location of CO_2 sensors and $PM_{2.5}$ sensors and key for the symbols.

3.1. Annual performance evaluations

The results were analyzed concerning the overall energy usage on an annual basis. These results were further broken down into heating and fan energy usage which can be affected by the various control strategies. Results were then compared to national recommendations and thresholds with respect to total, thermal comfort, and CO_2 and $PM_{2.5}$ concentrations.

3.1.1. Energy usage

Fig. 9 shows the results for all the parametric cases introduced previously in terms of the annual energy usage index (EUI) in kWh/m^2. The results are presented for one-year simulations of a TMYx 2003–2017 normal year [51]. As previously mentioned, no cooling systems were simulated, because the real building is not provided with cooling. Temperature control was maintained by varying the supply and outdoor airflow rates. In climates like Beijing, a cooling system would normally be incorporated, but it was not simulated in this study to reduce the sources of disparity. Domestic hot water use was not simulated either.

In typical Norwegian offices, the occupancy is about 35% of design capacity [52]. In this simulation, the occupancy was much higher, about 66% from 0600 to 1800. Most occupants were Ph.D. students or administrative personnel and therefore, they barely abandon the working station throughout the day. In a typical office, DCV systems can lead to significant reductions in energy use due to reduced airflow rates during periods of reduced occupancy.

For the eight control strategies implemented in the north-oriented building in Norway, rotating the building 180° (_S cases) resulted in annual energy savings between 13% and 24%. This is a result of the increased solar gains that reduced the heating demands. North-oriented cases with systems that did not implement temperature control (_NTC cases) yielded energy reductions of 0%–12%, only S1R2 increased 8%. For the buildings located in Beijing, annual energy savings were between 19% and 32%. The average outdoor temperature in Beijing was approximately 18 °C, whereas in Trondheim, it was approximately 5.2 °C. The number of heating degree days with base 15 °C was 2470 in Beijing vs. 3606 in Trondheim. Thus, this change of location lead to a significant reduction of energy usage.

In all cases, the S0R0 systems used the most energy as they do not regulate airflow rates during working hours relative to occupancy levels, so the maximum airflow rate was supplied every working day from 0600 to 1800. For the S0R0 simulations, rotating the building 180° yielded a total energy reduction of 13%. The S0R0 and S0R0_NTC were the same as neither strategy implemented temperature control. The S0R0 system in Beijing (S0R0_B) used 32% less energy than that in Norway.

S1R2 was the same as S1R0 with the addition of CO_2-based DCV used to control the OA fraction. The S1R0 consumed more energy because the OA must be heated as it enters the system. In fact, for all the building variations simulated, the S1R0 strategy consumed the most energy when compared to all other DCV strategies. When compared to the S1R0 strategy, S1R2 reduced the EUI by 22% for the north-oriented building, 14% for the south-oriented (due to more limited heating needs), 3% for the NTC strategies, and 30% for Beijing.

The S2R4 and S2R5 strategies were within 0.5% of each other and resulted in the lowest annual energy consumption for all cases analyzed. These two methods implement recirculation control based on particle concentrations and result in the largest recirculation flow rates. In heating-dominated countries, such as Norway, the use of recirculation and the resultant reduction in heating requirements lead to these relatively large energy savings.

S1R2, S2R4 and S2R5 strategies used the least amount of energy for all the Norwegian cases. The following presents the relative differences in energy reduction between these strategies.

- For the north-oriented case, S2R4 used 5% less energy than S1R2 (25% less than S1R0).

Table 3
Summary of pollutants, sensors and dampers required for each system type.

	S0R0	S1R0	S1R1	S1R2	S1R3	S3R1	S2R4	S2R5
Supply air control pollutants	–	Temperature and CO_2						
OA fraction control pollutants	–	–	Temperature and CO_2				Temperature and $PM_{2.5}$	
Sensors required	1 timer	1 Temperature and 1 CO_2 per room	1 Temperature and 1 CO_2 per room +1 Temperature in return	1 Temperature and 1 CO_2 per room +1 Temperature and 1 CO_2 in return		1 CO_2 per room +1 Temperature and 1 CO_2 in return	1 Temperature, 1 CO_2, and 1 $PM_{2.5}$ per room +2 $PM_{2.5}$ (OA and return)	
Additional dampers S1R0	–	–	1 Recirculation damper					

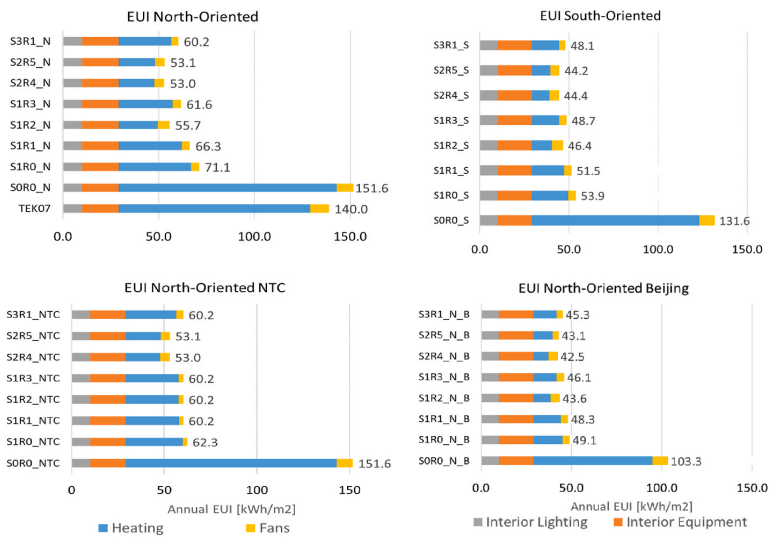

Fig. 9. Energy use for the different control strategies, including _NTC cases and for different orientations and locations.

- For the south-oriented case, S2R4 used 4% less energy than S1R2 (18% less than S1R0).
- For the north oriented NTC case, S2R4 used 12% less energy than S1R2 (15% less than S1R0).

The energy usage for the building located in Beijing was lower for all cases. However, the relative amounts of energy usage among the different control strategies were remarkably similar. S2R4_B consumed the least amount of energy which was 3% less than S1R2_B and 13% less than S1R0_B.

3.1.2. Performance relative to national recommendations and thresholds (Thermal comfort and contaminant control)

The performance of the different control strategies was compared with the recommendations and thresholds of the different pollutants. The boxplots in Fig. 10 show the median, first and third quartile and the 95% confidence interval of the median. Plots include all the simulated rooms during working hours (WH) which are Monday to Friday from 0800 to 1600 unless otherwise pointed out. The boxplots are ordered by increasing median value and dashed lines are provided that represent relevant national standards and recommendations as presented in the caption.

The first graph in Fig. 10 shows the distributions of $PM_{2.5}$ for all the cases simulated with Norwegian weather during WH. The concentrations of $PM_{2.5}$ are well below the Norwegian maximum annual concentration of 8 μg/m^3 for all cases. $PM_{2.5}$ was simulated as an outdoor source, and there were no indoor sources. The recirculation air filter was modeled to have a higher removal efficiency than the outdoor air filter. Thus, the solutions resulting in lower fractions of OA yielded lower concentrations of $PM_{2.5}$. The two typical Norwegian control strategies, namely S0R0 and S1R0 resulted on the highest concentration of $PM_{2.5}$.

The second graph in Fig. 10 depicts the boxplots of CO_2 concentration during WH of all the strategies, and the dashed line the recommended threshold of 1830 mg/m^3 (1000 ppm). The cases for which the building was ventilated with consistently higher OA airflow rates resulted in the lowest CO_2 concentrations. S1R1, S1R2, S2R4, S2R5 and S3R1 presented higher concentrations of CO_2 due to the use of recirculation of return air.

Thermal comfort can also be affected by the various control strategies. In relatively cold climates, the recirculated air is warmer than the OA, especially in buildings such as this that do not implement cooling. Thus, there is a greater potential for overheating if the setpoints are not modified as in these control strategies. The dashed lines in the temperature graph in Fig. 10 show the thermal comfort criteria range (19 °C and 26 °C) as recommended by Norwegian standard [54]. When using 100% OA, there are more hours in the lower range of temperatures. As

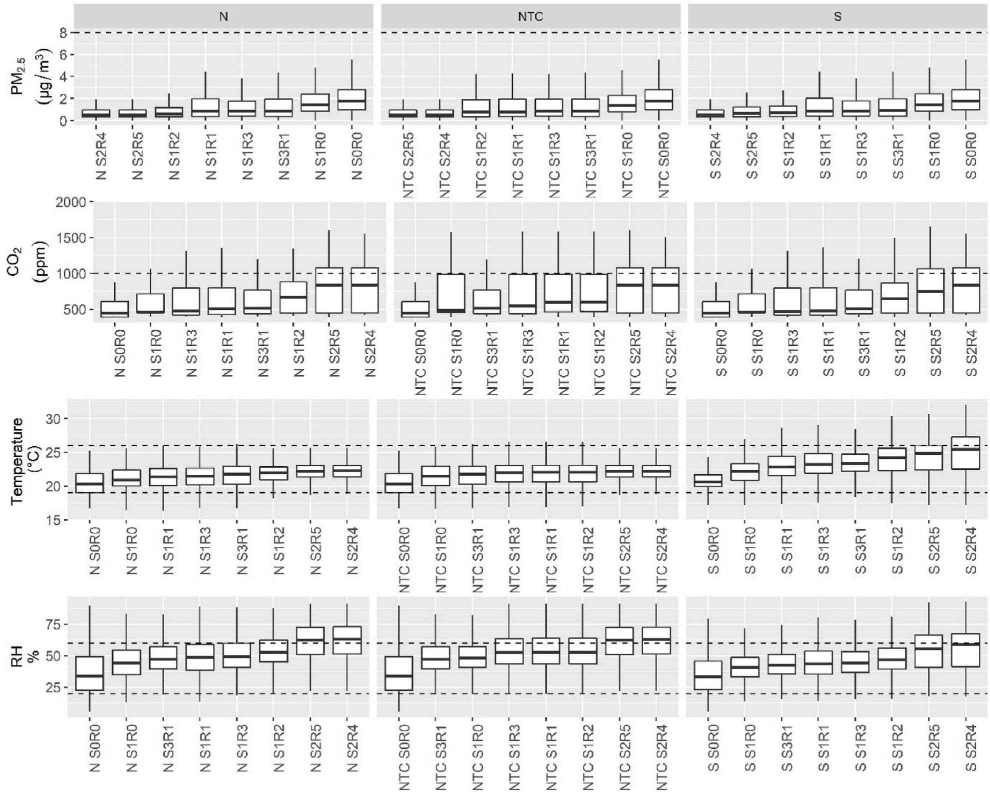

Fig. 10. *Distribution of $PM_{2.5}$, CO_2, temperature, and RH during working hours (Monday to Friday from 0800 to 1600) aggregating all simulated rooms. Dashed line in the $PM_{2.5}$ figure corresponds to the Norwegian annual threshold of* 8 μg/m^3 [53], *dashed line in the CO_2 figure shows the Norwegian threshold of* 1000 ppm, *the dashed lines regarding temperature correspond to the Norwegian standard 19 °C and 26 °C for thermal comfort* [54] *and the dashed lines in the RH figure correspond to the 20% to 60% range recommended by the institute of public health* [55].

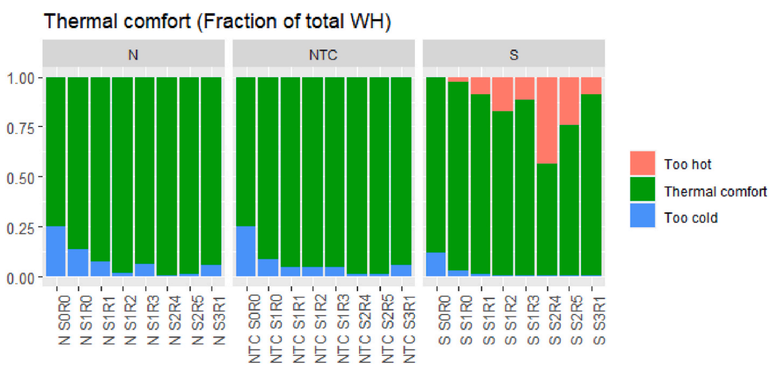

Fig. 11. *Fraction of WH of the temperatures relative to the thermal comfort range* [54].

shown in Fig. 10, the cases with the largest recirculation rates, e.g., S2R4 and S2R5, yielded higher median temperatures. For example, the S_S2R4 case resulted in the threshold being exceeded about 45% of WH. In the S cases, the heaters rarely ran, but the temperatures are consistently higher than in the other cases. The outdoor temperature in Norway is relatively low throughout the year, and temperature control is typically designed for the heating season. These setpoints were chosen for the North-oriented case considering that recirculation would lead to warmer indoor temperatures. In the summer, the supply air temperature was 16 °C and the heating setpoint was 17 °C to avoid running the heating system in Trondheim. Due to larger solar heat gains, overheating may happen more often in the shoulder season when the supply air temperature setpoints have not yet been reduced for the summer. For all the cases, Fig. 11 depicts the fraction of WH when temperatures are

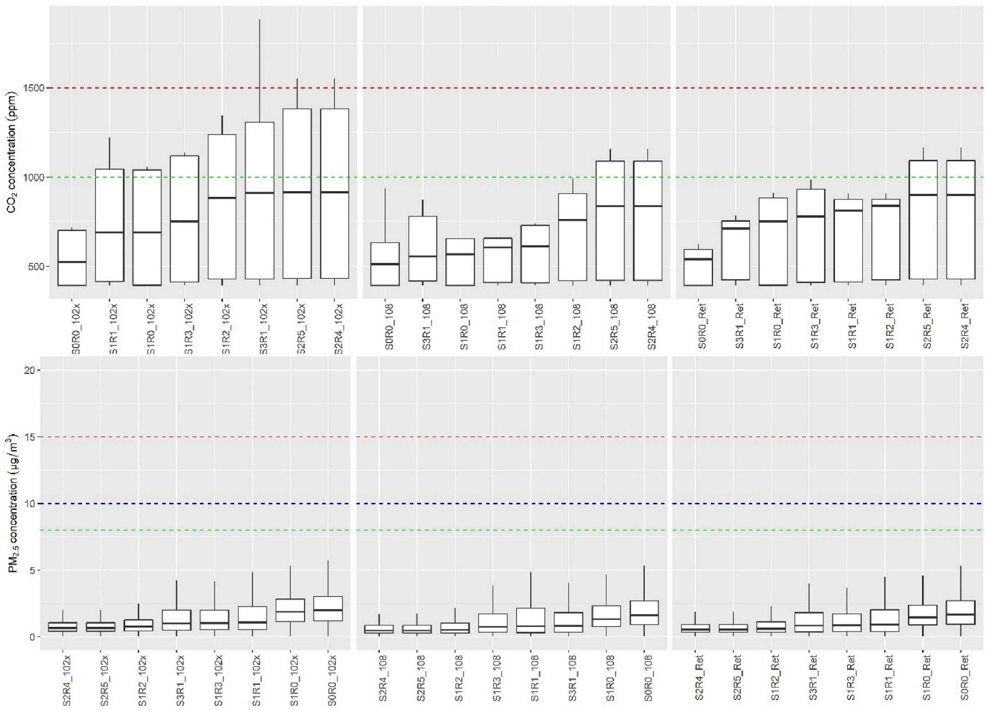

Fig. 12. *Distribution of concentration of CO_2 and $PM_{2.5}$ for the different control strategies during working hours for rooms 102x, 108 and return air. The green dashed line in the CO_2 graph shows the Norwegian recommendation of* 1000 ppm *and the red dashed line shows the REHVA recommendation of* 1500 ppm [47]. *In the $PM_{2.5}$ graph, the red, blue, and green dashed lines show the $PM_{2.5}$ recommendations: Norwegian daily of* 15μg/m^3 [44], *the WHO annual of* 10 μg/m^3 [57], *and Norwegian annual of* 8 μg/m^3 [44]. *(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)*

below, within, or above the thermal comfort range (i.e., Too cold, Thermal comfort, or Too hot, respectively). None of the North-oriented cases exhibited temperatures that were "Too hot." However, some South-oriented cases did exhibit overheating during WH. During weekends or outside working hours (not included in these figures the temperatures were higher due to the reduced supply airflow.

The fourth graph in Fig. 10 shows the distribution of RH for all WH. In Norway it is very common that during winter months RH drops below 20% during the coldest weeks of the year [56] because the supply air consists of 100% dry OA. Low relative humidity is correlated with discomfort. Using more recirculation of extract air yielded improvements in the RH both because of supplying moister air and because of the higher temperature. However, in the S2R4 and S2R5 cases where recirculation was used more often, RH should be introduced in the control strategy to avoid possible challenges with mold growth.

Fig. 12 shows the distribution of the CO_2 and $PM_{2.5}$ during extended working hours (from 0800 to 1900) for room 102x with a single occupant, room 108, which had four occupants, and in the return of the AHU for the north-oriented cases. The median values for all the cases and all zones shown in Fig. 12 were below 1830 mg/m^3 (1000 ppm). The S0R0 strategy yielded lower CO_2 concentrations in all rooms as it provided the highest outdoor airflow rates. S1R0 yielded lower median CO_2 values than S1R2, which used the same control for room supply but varied the OA fraction. The S2R4 and S2R5 (controlled the recirculation based on $PM_{2.5}$ and had a threshold of 2744 mg/m^3 (1500 ppm)) and S3R1 (controlled the supply based on the return air temperature and CO_2 concentration and the OA based on CO_2 in the rooms) had higher CO_2 concentrations in room 102x but were mostly below 2744 mg/m^3 (1500 ppm). For S2R4 and S2R5 the threshold in this room was not met and thus ventilation was not increased. For S3R1, the threshold 1830 mg/m^3 (1000 ppm) was surpassed in room 102x mostly early in the morning, but this room had little weight in the return air. Until the concentration in the return rose, no response was given to the local rise in the small room. Room 108 was larger, had more occupants and got more sun. Thus, this room had higher airflow rate per person and more weight in the return. Therefore, the delay in room 102x did not affect room 108.

While higher recirculation rates may lead to higher CO_2 concentrations, they can also result in lower $PM_{2.5}$ concentrations. In these simulations, $PM_{2.5}$ only originated from the outdoors and the filter for recirculated return air removed $PM_{2.5}$ 15% more efficiently than the outdoor air filter. S0R0 resulted in the highest $PM_{2.5}$ concentrations but were still below the annual Norwegian Public Health threshold of 8 μg/m^3 [48]. S1R0 resulted in the second-highest concentration of $PM_{2.5}$. S2R4 and S2R5 resulted in the lowest concentrations closely followed by S1R2. The S2R4 strategy resulted in an annual median $PM_{2.5}$ concentration that was half that when using the S0R0 strategy. However, S0R0 had an annual concentration of 2.3μg/m^3 which was almost four times below the recommended threshold. Using $PM_{2.5}$ in the control scheme would likely increase cost and system complexity that are difficult to justify, especially in Trondheim which has very low outdoor $PM_{2.5}$ (and no indoor sources were present in the model).

3.1.3. Building in Beijing

The previous results showed the indoor pollutant development in a city with low outdoor $PM_{2.5}$ concentrations and RH. In Beijing the outdoor air is more polluted and has higher RH than in Trondheim, which will affect the resulting IAQ attainable by the ventilation control strategies. The north-oriented building was simulated with the following outdoor conditions: weather files from Meteonorm 7 and pollutant concentrations obtained from the China National Environmental

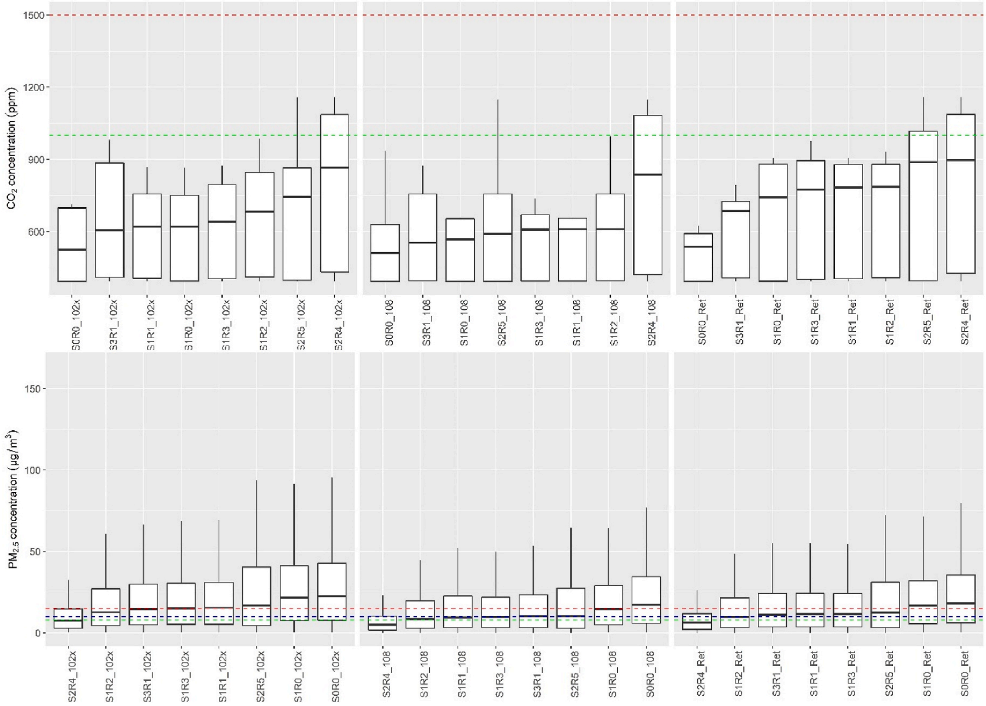

Fig. 13. *Distribution of CO_2 and $PM_{2.5}$ concentrations of for the different control strategies during working hours for rooms 102x and 108 and return air. The green dashed line in the CO_2 graph shows the Norwegian recommendation of* 1000 ppm *and the red line shows the REHVA recommendation of* 1500 ppm*. In the $PM_{2.5}$ graph, the red dashed line shows the Norwegian daily recommendation of $PM_{2.5}$* 15μg/m^3 [44]. *the blue, the annual WHO's recommendation of $PM_{2.5}$ of* 10 μg/m^3 [57] *and the green the Norwegian annual recommendation of $PM_{2.5}$ of* 8 μg/m^3 [44]. *(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)*

Monitoring Centre.

Fig. 13 shows the concentrations of CO_2 in rooms 102x, 108 and the return air. The CO_2 concentrations were lower than for the respective cases in Trondheim (Fig. 12). For most cases, the temperature control via supply airflow resulted in increased flow rates to the rooms to reduce overheating. S2R4 yielded the highest CO_2 concentration due to higher recirculation rates to control the $PM_{2.5}$ concentration. S2R5 controlled the OA fraction based on the difference between outdoor and indoor $PM_{2.5}$ levels OR the $PM_{2.5}$ being below 15 μg/m^3 in every room. As the mean concentration in the rooms were so high, this condition was fulfilled most of the time. Thus, 100% OA fractions were used, and the $PM_{2.5}$ concentrations were not reduced compared to S0R0 or S1R0. For S2R4, lower levels of $PM_{2.5}$ were attained in exchange for higher CO_2. S2R4 used an AND function for the difference between indoor and outdoor and room concentration. The AND condition was seldom met. Thus, there was a relatively lower amount of OA delivered, and the $PM_{2.5}$ levels did not increase as much. Only S2R4 managed to have an annual average concentration of $PM_{2.5}$ during the working hours below 10 μg/m^3. S0R0 and S1R0 showed the downside of using 100% OA in cities with lower outdoor air quality, namely the highest $PM_{2.5}$ concentrations. S1R2 was the second-best control strategy regarding $PM_{2.5}$.

Fig. 14 shows the distributions of results for the Beijing simulations. These results show that S2R4 was the most efficient strategy to reduce the concentration of $PM_{2.5}$ during working hours. The annual average $PM_{2.5}$ concentration for S2R4 was 8.1 μg/m^3, which was below the maximum recommended by the WHO of 10 μg/m^3 [57]. All the other control strategies resulted in median values above this threshold, and S0R0 resulted in the highest annual average of 23.4 μg/m^3.

Regarding CO_2, as for Trondheim, the cases using more recirculation of extract air presented higher CO_2 concentrations, but all the strategies yielded an annual average CO_2 concentration below 1830 mg/m^3 (1000 ppm). Regarding temperatures, using too much recirculation, as in S2R4, yielded more working hours with temperatures outside the thermal comfort range of 19 °C–26 °C. In Beijing, the control strategies should be modified to achieve this temperature range along with solar shading, higher supply airflow rates, a lower temperature supply air and lower heating setpoints. Finally, it is usual practice in Beijing to use a cooling system which was not considered in these simulations. However, as in the Trondheim cases, controlling for RH should also be incorporated but to reduce indoor RH as opposed to increasing it.

3.2. One-day performance evaluations

Two summer and winter days: January 27th to 28th and June 22nd to 23rd were used for an in-depth evaluation of the effects of the different control strategies for the north-oriented building in both Trondheim and Beijing as shown in Fig. 15 and Fig. 16, respectively. Each set of charts includes hourly averaged values of RH, CO_2, temperature, OA fraction, supply airflow rate, and $PM_{2.5}$ for room 102x for all the control strategies. Although not shown, the other rooms showed similar pollutant time histories as room 102x.

3.2.1. Trondheim

The rise of $PM_{2.5}$ by the end of the day was related to exceptionally high outdoor $PM_{2.5}$ concentrations due to road cleaning in January. The corresponding indoor peak was especially visible for the cases delivering the largest amount of OA. The strategies using $PM_{2.5}$ for control of OA fractions, S2R4 and S2R5 yield the lowest $PM_{2.5}$ concentrations. Higher recirculation fractions had a protective effect regarding $PM_{2.5}$ concentrations, even in Trondheim, where the outdoor concentrations were

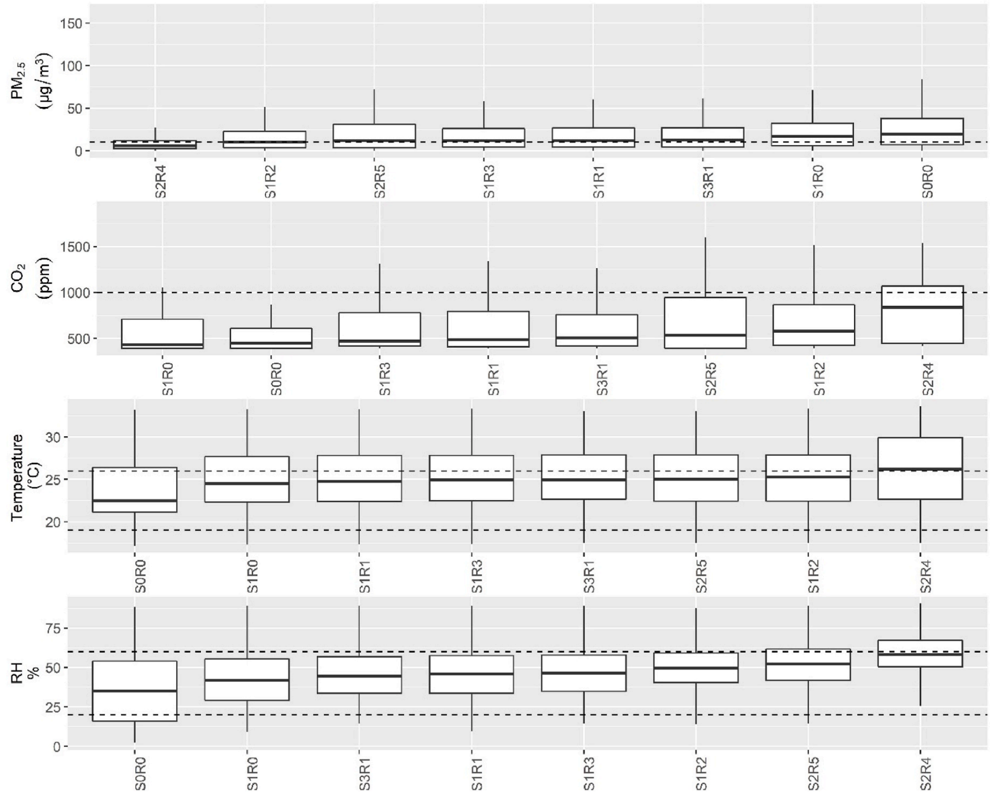

Fig. 14. *Distribution of $PM_{2.5}$, CO_2, temperature and RH during working hours (Monday to Friday from 0800 to 1600) aggregating all simulated rooms in Beijing. Dashed line in the $PM_{2.5}$ figure corresponds to the annual WHO's recommendation of $PM_{2.5}$ of* 10 µg/m^3 [57]*, dashed line in the CO_2 figure of shows the Norwegian threshold of* 1000 ppm*, the dashed lines regarding temperature correspond to the Norwegian standard 19 °C and 26 °C for thermal comfort* [48] *and the dashed lines in the RH figure correspond to the 20% to 60% range recommended by the institute of public health* [49].

low. In this case, increasing ventilation to control an indoor source (CO_2, in this case) can lead to increased levels of an outside source ($PM_{2.5}$).

The S0R0 strategy resulted in the lowest CO_2 concentration because it utilized 100% OA and the supply was at the maximum level during occupied hours. S1R0 also provided 100% OA, but the supply airflow rates were reduced according to occupancy to save energy. The strategies that did not use $PM_{2.5}$ as the control parameter (S1R0, S1R1, S1R2 and S1R3) proved to be effective at maintaining the CO_2 levels below 1830 mg/m^3 (1000 ppm). CO_2 levels in room 102x peaked in the morning for S3R1 after the occupants of this room entered at 0800. S3R1 controlled the supply airflow to room 102x based on the return air CO_2 concentration, so the control system did not react until enough rooms were occupied to raise the return air concentration to the control setpoint value. Thus, controlling CO_2 based only on the return air concentration resulted in a delayed response when compared to strategies that controlled based on individual room air concentrations. As shown in Fig. 15, S1R3 (individual room control) reacted faster than S1R2 (return air control). The control of the OA fraction of R3 was finer than for R2, so CO_2 did not increase as much in S1R3 as it did in S1R2. Increasing the supply airflow did not dilute the CO_2 concentration because return air had higher levels of CO_2 than did the OA. The strategies S2R4 and S2R5 using $PM_{2.5}$ to control the fraction of OA kept CO_2 below 2744 mg/m^3 (1500 ppm).

Regarding the temperature, all the strategies managed to maintain 20 °C ± 2 °C during working hours in winter. In summer, the heaters were run with a setpoint of 17 °C ± 2 °C and the outdoor air preheating was off. Thus, the temperatures were higher when recirculation was used.

In Norway, due to low outdoor temperatures, the RH indoors may drop to 10% or lower in winter. Some would argue that the best method to increase RH in such climates would be to reduce supply airflow rates [58,59]. These simulation results show that reducing the supply airflow rate increased RH. However, using a reduced OA fraction had an even more significant effect (even though, in this study, RH was not part of the control strategies).

3.2.2. Beijing

Single-day plots for Beijing are presented in Fig. 16. Outdoor $PM_{2.5}$ levels in Beijing were about 20–50 times those used in the Trondheim simulations, leading to higher indoor $PM_{2.5}$ results compared to Trondheim. S0R0 resulted in the highest levels of $PM_{2.5}$ as previously noted in the annual distributions. The trends of $PM_{2.5}$ concentration for S1R1, S1R3, S3R1 were similar to each other as they did not use $PM_{2.5}$ for control. S2R4 was most effective at controlling $PM_{2.5}$. For June 22nd S2R4 had an average $PM_{2.5}$ concentration of 11.8 µg/m^3 versus (33.5, 32.0, 31.1, 31.0, 31.1, 32.0, and 32.1) µg/m^3 for S0R0, S1R0, S1R1, S1R2, S1R3, S2R5, and S3R1, respectively. For January 27th, S2R4 had an average of 11.7 µg/m^3 vs. (34.2, 32.8, 20.5, 13.1, 19.5, 31.7, and 18.9) µg/m^3 for S0R0, S1R0, S1R1, S1R2, S1R3, S2R5, and S3R1 respectively.

The CO_2 levels were similar to those obtained in the Norwegian case except for S2R5 where Beijing exhibited lower CO_2 concentrations due

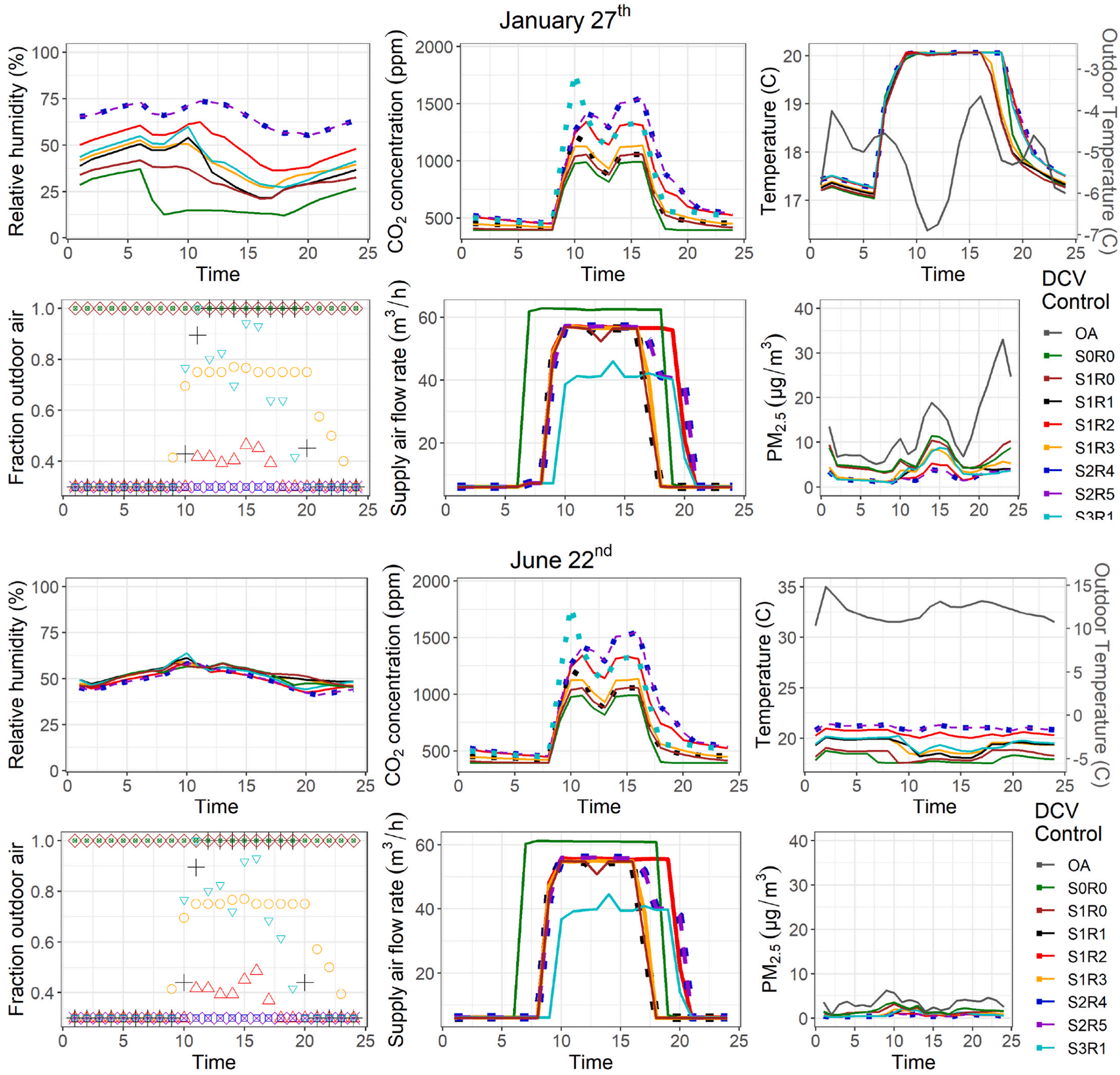

Fig. 15. Hourly averaged relative humidity, CO_2, temperature, OA fraction, supply airflow rate, and $PM_{2.5}$ for room 102x in Norway.

to larger OA fractions. The OA fraction was controlled by the difference between outdoor and indoor $PM_{2.5}$ levels OR the $PM_{2.5}$ being below 15 μg/m^3 in every room OR return temperature larger than 26 °C. As the room $PM_{2.5}$ levels were so high and the return temperatures were often over 26 °C, this condition was fulfilled most of the time. The relatively high recirculation rates of S2R4, resulted in a significant reduction of $PM_{2.5}$ concentrations throughout the day in both winter and summer compared to the cases without recirculation. Regarding temperature, as explained before, the setpoints of the heating control were not modified and no cooling system was simulated for Beijing. Therefore, none of the strategies maintained the temperature within the defined comfort range during the summer day, i.e., the lack of cooling often resulted in overheating. S2R4 yielded the highest temperatures during the summer day due to the high recirculation rate revealing the potential tradeoffs between elevated contaminant levels and thermal comfort. On the winter day, when the outdoor temperatures were like those in Trondheim, the graphs of temperatures were similar. The RH in the summer would likely be different if cooling was introduced.

Although it's difficult to discern from the plots, all the cases were plotted on each graph. In the summer, several strategies yielded the same results for RH temperature, CO_2 and $PM_{2.5}$ as the control parameters induced the same supply air and OA fraction. To optimize the control strategies, the setpoints should be varied at least for the summer in Beijing as the weather conditions were very different.

3.3. Ranking best control strategies in Norway

Regarding $PM_{2.5}$, lower values mean less exposure of building occupants. Thus, the three best strategies were S2R4, S2R5, S1R2 for the N and S cases and S2R5, S2R4, S1R2, for the NTC case. However, in all the

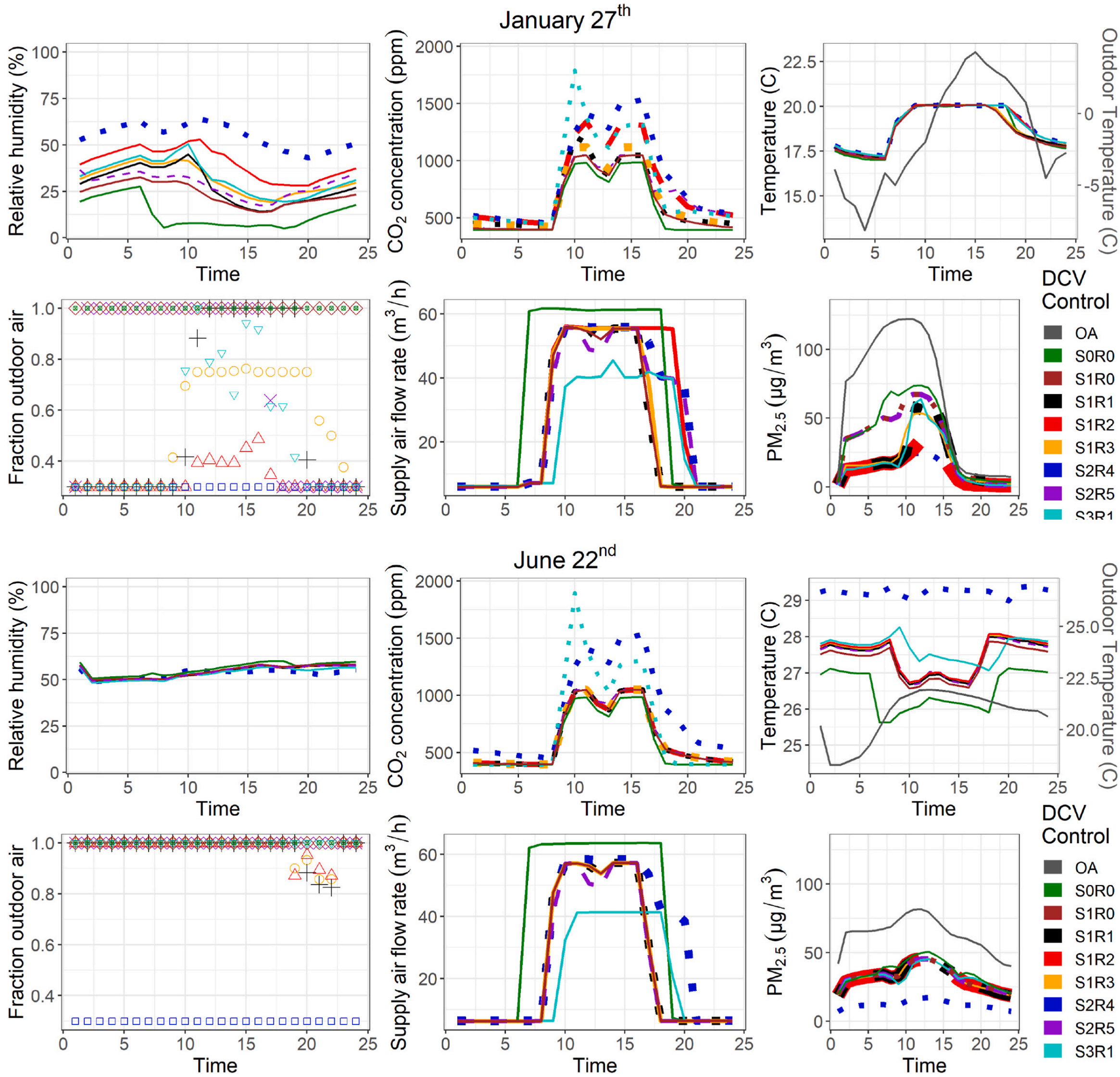

Fig. 16. Hourly averaged relative humidity, CO_2, temperature, OA fraction, supply airflow rate, and $PM_{2.5}$ for room 102x in Beijing.

simulated cases in Norway the $PM_{2.5}$ concentration was so low that controls using $PM_{2.5}$ may not be justified, due to increased complexity and cost of associated sensors. However, in locations with elevated outdoor $PM_{2.5}$ concentrations, such as Beijing, the increased complexity and cost may be easily justified.

Regarding CO_2, the three best strategies were S0R0, S1R0 and S1R3 for N and S strategies and S0R0, S1R0 and S3R1 for the NTC strategy. The strategies using more recirculation (S2R4 and S2R5) resulted in the highest concentrations; however, in all cases the median and the third quartile were well below the recommended threshold.

Regarding temperature, the cases using less recirculation resulted in larger fraction of WH within the prescribed 19 °C to 26 °C temperature range. S0R0, S1R0 and S1R1 were the best performing strategies for both the N and S variations. For the south-oriented variation the recirculation strategies S2R4 and S2R5 resulted in the highest temperatures indicating that setpoints for heating could be reduced to account for the larger solar gains.

RH was not controlled, but it is affected by the use of recirculation. Over the whole year the N and S cases with more recirculation, S2R4 and S2R5, resulted in higher indoor humidity with RH being greater than 60% for about half the working hours. S0R0 presented the lowest RH. However, RH was highly dependent on the time of the year. While not shown, during the winter months S2R4 and S2R5 can increase indoor humidity in Norway. Ventilation strategy S0R0 yielded a mean RH of 15% during the winter months, whereas S2R4 resulted in a mean RH of 52% during the same period (note that the previous graphs showed the boxplots of the whole year).

4. Conclusions

A partial building model was developed to utilize co-simulation between EnergyPlus and CONTAM to evaluate control strategies that utilize recirculation of return air for a Norwegian office building. The use of these two software tools together was shown to be beneficial in analyzing building control strategies with respect to energy use and IAQ. Though it can be somewhat more complicated to create building models for co-simulation, instead of using either EnergyPlus or CONTAM alone, the benefits of co-simulation in providing a more comprehensive analysis seem to outweigh the initial efforts of developing the combined building models.

The results presented for Trondheim showed that reducing airflow rates as a response to occupancy reduced energy use. All the simulated DCV control strategies yielded reductions in energy use compared to the typical ventilation control strategy for Norway (S0R0). When room CO_2 concentrations were used in the ventilation control strategy, the room level CO_2 was maintained below the selected threshold. The control strategy that utilized only the return air CO_2 concentration (S3R1) proved disadvantageous because using only one return air sensor as a proxy for all the rooms served by the system did not capture room to room variations leading to some rooms having higher concentrations than others. Recirculation of return air also influenced thermal comfort and IAQ, for example reducing $PM_{2.5}$ concentrations or increasing RH in Norway during the dry winter months. On the other hand, using a contaminant of indoor origin, e.g., CO_2, to control supply airflow and OA fraction may result in increased indoor levels of $PM_{2.5}$ or other pollutants of outdoor origin. When the outdoor air concentrations of $PM_{2.5}$ were as low as in Trondheim (the annual simulated average was 6.2 $\mu g/m^3$), it was more difficult to justify the added complexity of that slightly more effective control strategy. However, in other locations such as Beijing where the outdoor particle concentrations were higher than in Trondheim, the increased cost and complexity of incorporating $PM_{2.5}$-based control schemes might be justified. In this study, such control schemes reduced the annual average indoor $PM_{2.5}$ concentration from 23.4 $\mu g/m^3$ to 8.1 $\mu g/m^3$, which was just below the WHO recommendation of 10 $\mu g/m^3$. Limiting criterion for evaluation to energy use may not justify the added cost in complexity and system components, e.g., sensors, and more comprehensive analysis that includes consideration of IAQ in addition to energy use would be necessary.

In this paper, no internal sources of $PM_{2.5}$ were considered. Other pollutants of indoor origin, e.g., bacteria, viruses, or formaldehyde, should also be considered. Such internally generated contaminants may not exhibit the same emission profiles as occupant-generated CO_2, so control schemes may not lead to improved levels of such non-controlled contaminants. Some pollutants might also benefit from the use of other reduction methods, e.g., filtration technologies including ultraviolet or activated carbon. CONTAM can handle a wide range and number of sources within a single simulation, so co-simulation would be quite useful for these analyses. However, existing co-simulation capabilities could be improved to account for interactions related to these capabilities as they relate across simulation domains, e.g., filter loading and related fan energy usage due to increased pressure drops across particle filters.

CRediT authorship contribution statement

M. Justo Alonso: Conceptualization, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.**William Stuart Dols** conceptualization, investiagation, methodology, software, visualization and writing of original and reviwed draftHans Martin Mathisen Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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PAPER 3

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Evaluation of low-cost formaldehyde sensors calibration

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ABSTRACT

Low-cost sensors (LCS) are becoming ubiquitous in the market; however, calibration is needed before reliable use. An evaluation of the calibration of eight identical pre-calibrated formaldehyde LCS is presented here. The LCS and a reference instrument were exposed to a pollutant source(s) for the calibration measurements. After one year, some tests were repeated to check the drift and stability of calibration.

This paper presents methodologies for calibration using data with significant autocorrelations. Autocorrelation in sensor measurements might be present when performing a frequent sampling. To obtain reliable results, sensor calibration methodologies must consider autocorrelation or serial correlation between subsequent measurements. Experimental design can be used to reduce the risk of highly autocorrelated measurement.

Ordinary Least Squares Estimations should not be used when measurements are autocorrelated, as their central assumption is that the residuals are independent and identically distributed. Two alternative methods considering autocorrelation using a first-order Markov scaling are proposed: Maximum Likelihood and Restricted Maximum Likelihood Estimation (REML). REML has better compensations for the estimated parameters and the scaling parameters. Akaike information criterion was used to select the most significant parameters resulting in formaldehyde and temperature.

The results were presented for only one of the eight sensors. According to EPA's recommendations, the tested formaldehyde LCSs were Tier III, supplementary monitoring. The LCS over-and under-estimated the values obtained by the reference sensor, but they presented very similar dynamic responses, indicating that LCS could be used to detect concentration changes after calibration.

1. Introduction

Tightening building envelopes and using demand-controlled ventilation are commercial buildings' most applied energy-saving strategies [1]. When reducing supply airflow or infiltration rates, pollutants that otherwise would be ventilated away may be present at higher and even harmful concentrations [2]. Without correct implementation, retrofits targeting energy efficiency can adversely affect health due to the lower air change rates [3,4].

Formaldehyde is one compound widely found in household materials [5]. It is also produced in cooking, wood burning, other domestic activities [5], and waterproofing coatings [6]. However, it is associated with health risks such as mucous irritation [7] and is carcinogenic (group 1) to humans, according to the International Agency of Research on Cancer (IARC) [8]. Wolkoff [9] concluded that formaldehyde and benzene are generally reported as sensory irritation even before being smelled.

Norwegian indoor air quality should meet the air quality criteria based on health impacts defined in the building codes [10], the occupational health codes [11], and the public health legislation [12]. However, several defined pollutants are rarely measured due to the high cost of reliable sensors. Traditionally, air pollutants were measured with complex, expensive, and massive equipment at fixed locations. Thus,

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Nomenclature

CO_2	Carbon Dioxide
CH_2O	Formaldehyde
CV	Coefficient of variation
HVAC	Heating, ventilation, and air-conditioning
IAQ	Indoor Air Quality
LCS	Low-cost sensor
MAE	Mean absolute error
ML	Maximum likelihood
MV	Measured value
NMB	Mean Normalized Bias
OLS	Ordinary Least Squares
PCC	Pearson Correlation Coefficient
PM	Particulate matter
RH	Relative humidity
REML	Residual maximum likelihood estimates
RMSE	Root mean squared error
TVOC	Total volatile organic compound

manufacturers have developed low-cost air quality sensors to measure air parameters and airborne pollutants. Technological advances in metal oxide semiconductors, for the detection of gaseous compounds [13] allowed the development of sensors with a much lower cost than the certified reference instruments. Typically, they are less accurate and suffer from cross-sensitivities with other pollutants. They are usually smaller sensors, measure constantly, provide real-time monitoring, and are easily deployed. They can send the information to IoT servers or record data in loggers. Thus, the availability of such sensors will likely continue to grow [14].

Current ambient air monitoring could be improved if LCS could produce reliable data under typical ambient conditions. However, preliminary tests [15–20] suggest poor to uncertain reliability. Some do not perform well under typical ambient conditions or do not correlate with data from regulatory measurement equipment [20]. A recent analysis of 112 studies on LCS [21] concluded that only a few studies followed US EPA guidelines [22] to examine performance. LCSs often suffer from errors due to internal causes (such as cross-sensitivities with other pollutants, drift, bias …) and external causes (such as temperature and relative humidity) [23]. Therefore, it is urgent to characterize the actual performance of LCS and educate the users about the potential and limitations of these sensors [14]. Understanding the sensors' limitations is needed to interpret the data output and its weakness [24]. A poor understanding of flaws (problems with experimental design) and limitations (factors that constrain the applicability of study findings) can lead to undesirable outcomes such as alarmistic behaviors. For some gaseous measurements, cross sensitivities to confounding compounds overpredict the measured pollutant [25] precisely as drift may [26].

With the universalization of the use of LCSs, better recommendations regarding placement should be delivered together with the sensor datasheets as the users know less about IAQ measurements. This knowledge is even more critical when using these sensors to control ventilation.

To compensate for their lower accuracy, dealing with the error is crucial no matter the accuracy required by the application of the sensor. Giordano et al. [27] revised the needs and challenges of achieving reliable data from particulate matter LCS. They summarized their knowledge on best practices in calibration considering data collection and model analysis, but they did not address the autocorrelation in the measurements.

1.1. Objectives

This study has two main objectives:

1-Testing the performance of eight formaldehyde sensors in comparison to laboratory-grade equipment. The evaluation uses measurements at the beginning of the sensors' lives and after one year.

2- Support that non-mathematician IAQ researchers can do a good calibration of LCS and that they are able to evaluate the results within the calibration range. The results of only one of these eight sensors are presented as the goal is to focus on the calibration procedure. For that, the article will address the following:

- The challenge of having frequent sampling yielding autocorrelated measurements and tests taken with very heterogeneous data collection periods
- Establish the best calibration estimation method that considers the autocorrelation of the calibration measurements and that the number of samples in the tests is not equal. The method must do a correct estimate of parameters and the uncertainties.

Contrarily to most of the existing articles evaluating LCS, this article focuses on the evaluation of the calibration process, which would also apply to other sensors when the data sampling results are autocorrelated. In this article, the experimental design is thoroughly described, discussed, and evaluated. The common application of R^2 evaluations to study correlations is confronted. It is mathematically wrong to use OLS when the residuals are not independent and identically distributed (iid). Thus, this article demonstrates an alternative methodology for this situation.

2. Methodology

In this study, eight identical Dart formaldehyde WZ-S LCS were calibrated using measurements in a laboratory's small chamber. The sensors were exposed to the same formaldehyde sources as laboratory-grade equipment. Some of the experiments were repeated after one year. The data obtained by low-cost and professional-grade sensors were compared to establish a model representing the sensor behavior and then estimate the residuals, i.e., the error in the model-based predictions. This article has created a procedure for estimating a weighting according to the autocorrelation based on the first-order Markov. Then a simple method using this weighting was created. To the authors' knowledge, the method presented here considering and weighting the autocorrelation using a first-order Markov scaling has not been used in the sensor calibration field.

2.1. Measurement equipment

2.1.1. Indoor air sensing stations and LSC sensors

Eight equal in-house mounted IAQ stations were assembled comprising LCSs to measure formaldehyde, TVOC, temperature, and RH. The LCSs were selected based on user-friendliness (these sensors had available information on the internet regarding mounting) and pre-calibrated from the factory (according to the producers, they should not need any pre-use calibration). Table 1 summarizes the LCS's model, type, and technical specifications. More information about the kit, the LCS not discussed in this article (commercial Sension LCS to measure particle matter SPS30, CO_2 SCD30) and their calibration can be found in Ref. [30].

The Dart Sensor WZ-S is a micro fuel cell formaldehyde sensor. In addition to formaldehyde, the other parameters were studied to see if they were confounding parameters. Air temperature and RH were measured with SHTC1 from Sensirion and TVOC with SGP30 from Sensirion. Sensors SGP30 and SHTC1 were integrated into the Arduino Shield SGP30_SHTC1 from Sensirion.

All the sensors were connected to an Arduino via a customized shield

Table 1
Technical specification LCSs data retrieved from, SVM30 [33], Dart WZ-S [35].

Sensor name	Parameter	Sensor type	Measurement range/size range	Accuracy collected from datasheets	Single unit price when bought in NOK
Dart Sensors WZ-S	Formaldehyde	MOS	0,03 - 2 ppm	≤0.001 ppm	148
Sensirion Arduino Shield SGP30_SHTC1[a]	TVOC	MOx	0–60′000 ppb	1 ppb or 6 ppb[b]	190
	Air Temperature Relative humidity	CMOS	−30 °C–100 °C 0%–100% RH	±0.3 °C ±3% RH	

[a] This sensor uses SHTC1 for measuring T/RH and SGP30 for measuring TVOC. Sensirion does not recommend the use of this sensor for new designs anymore: https://www.sensirion.com/en/environmental-sensors/gas-sensors/multi-gas-humidity-temperature-module-svm30/.
[b] 1 ppb from 0 ppb to 2008 ppb, and 6 ppb from 2008 ppb to 11110 ppb.

card. The logged values were sent to a Raspberry Pi via USB cable. The Dart Sensors WZ-S were connected using a custom-written code. The complete code for Arduino and Raspberry Pi was available on GitHub. LCS collected data every 5 min, and measurements were converted to 30 min averages. The Arduino Shield SGP30_SHTC1 was connected using code from Adafruit [31] and Sensirion AG [32], available on GitHub. This sensor needs a pre-calibration file based on 12 h of calibration in the air. This pre-calibration is done because when the sensor is exposed (measuring or not) to conditions (RH and temperature) outside the recommendations, the RH signal may offset. After being in normal temperature and humidity, the sensor will slowly return to standard specifications [33] (removing the offset). The resulting calibration files to standard specifications were stored in the Raspberry Pi. This calibration to standard specifications was done previously to the one explained in the remaining of the article and should be done each time the sensors are used so that the following calibration makes sense. The data processing and further analysis were done with R software [34].

2.1.2. Reference monitoring equipment

Graywolf FM-801 was deployed as the reference instrument for formaldehyde measurements, and it was calibrated before the experiments. The Graywolf sensor uses photoelectric absorptiometry to read the sensor's absorbance change that formaldehyde induces. A small colorimetric sensor cartridge is used for passive diffusion sampling. Graywolf FM-801 measures the absorption change between each 30-min interval and then calculates the difference. The value reported by the unit represents the average of over 30 min. The sensor has a detection range from 25 μg/m^3 to 1230 μg/m^3 and an accuracy of ±10% for readings larger than 48 μg/m^3 [28]. The sensor suffers from cross-sensitivity to methanol, ethanol, isopropanol, carbon monoxide, phenol, acetaldehyde H_2, chloroform, limonene, styrene, acetaldehyde, ozone, H_2S, and SO_2, among others [28]. Pegasor AQTM Indoor was deployed for measuring RH and temperature [29]. RH range: 0–100%; producer-reported accuracy ±1.5% within 0–90%. Temperature range: 40 - 80 °C; producer-reported accuracy ±0.2 °C in the range 0–40 °C.

2.2. The chamber setup

The calibration evaluation of the formaldehyde LCS was conducted in the 1.5 m^3 plexiglas mini environmental chamber in Trondheim, Norway showed in Fig. 1. The chamber is equipped with dedicated ventilation, heating, and humidification systems run as the tests required. The HVAC system consists of extract and supply fans to control the ventilation rate and a small computer fan for mixing the chamber's air, a radiator, and a humidifier.

The sensors were launched at least 2 h before introducing the air pollution source. All the ventilation supply was turned off at the beginning of each experiment, right before the start of pollutant generation and monitoring. The background concentrations of formaldehyde were negligible at the start of the experiments. The air exchange was reduced to infiltration, which was minimized by blocking the openings with duct tape. Each experiment was monitored with both the LCS and the reference sensor continuously. In some cases, the sensors measured at least 1 h after the pollutant source was stopped/removed.

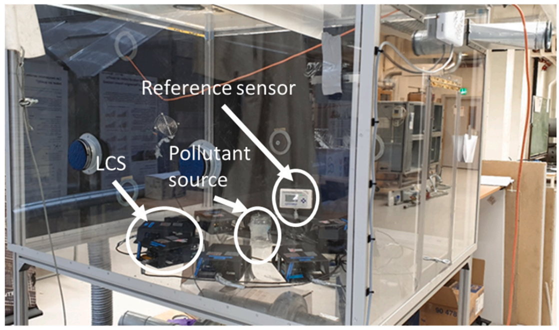

Fig. 1. Picture of the experimental setup with the formalin source in the center. The eight equal IAQ stations and the reference sensor in a circle equidistantly to the source.

The eight IAQ stations and the reference sensor stood in a circle around the pollutant source during the experiments, as shown in Fig. 1. For the experiments with chipboards, these were placed along the walls of the mini chamber.

2.3. Experiment description

The performance evaluation was done by comparing formaldehyde measurements with the eight equal LCSs and the reference sensor.

The calibration-tests details are summarized in Table 2. Test A was conducted under uncontrolled ambient temperature and RH in the chamber, thus, representing typical temperatures and RH in the laboratory in a Norwegian winter. In tests B, C, D, E, and F, a heater and a humidifier were run to control the temperatures and relative humidity. Tests with wood chipboards were repeated after one year, as Table 2 specifies, to study the repeatability of the results and drift of the equipment.

When wet, wood chipboards produce formaldehyde and TVOC at a higher range than under normal conditions. Formalin is a source of formaldehyde and methanol.

It was expected that in one year, the aging of the LCS would be negligible [27]; however, at the same time, problems with drift or problems with singular defective units would be identified. In-between calibrations, the sensors were used for routine measurements in schools. Effects of a differential exposure history during this period were considered by studying the recorded measurements. The recorded measurements were compared. In this case, the maximum measured concentrations did not differ by more than 9 %, and the effect of differential exposure history was assumed negligible.

2.4. Use of correlated data in calibrations

A calibration model is a regression model developed from the response of a sensor to known sources (customarily measured with a

Table 2
Description of calibration activities and resulting formaldehyde concentration reported as the highest 30-min average concentration with the reference sensor. TVOC is reported as the highest measured 5-min concentration by the 8 LCS. Conditions of temperature and relative humidity are shown as the average ± the standard deviation.

ID	Source	Test duration in minutes	Temperature and RH	Date	Activity description	Formaldehyde µg/m3	TVOC ppb
A	Formalin	150 min	20.2 ± 0.2 °C 28 ± 0.41%	Feb 2020	Beaker with (liquid 37%) formalin. Radiator and Humidifier off	336	1695
B	Wet wood chipboard	780 min	19.9 ± 0.1 °C 48.8 ± 13.7%	Feb 2020	1 wet board size $1m^2$. Humidifier on	224	1802
C	Wet wood chipboard	180 min	21.1 ± 0.5 °C 26.8 ± 0.25%	March 2021	4 wet boards size $1m^2$. Humidifier off	606	55
D	Wet wood chipboard	120 min	27.7 ± 0.8 °C 64.7 ± 9.7%	March 2021	3 wet boards size $1m^2$. Radiator on, Humidifier on	451	105
E	Wet wood chipboard	90 min	23.5 ± 0.9 °C 72.6 ± 8.4%	March 2021	1 wet board size $1m^2$ Radiator off, Humidifier on	41	214
F	Wet wood chipboard + wet glass wool insulation	180 min	21.2 ± 0.5 °C 35 ± 3.7%	March 2021	2 wet boards size $1m^2$, $0.7m^2$ wet insulation. Radiator and Humidifier off	22	278

reference sensor). To have a good calibration model is not so important to have a good fit of the measurements fed but to precisely predict/estimate new/unseen measurements within the calibration range.

Measurements have to be taken carefully to do a good calibration. For instance, if an additional measurement were taken only 1 s after the previous measurement, then the additional information of this new measurement would be limited. These two measurements are said to be serially correlated using statistical terminology, and such correlation in time for the same phenomena is often called autocorrelation.

Most often, standard OLS is used for analyzing data from calibration studies. OLS techniques assume that the measurements are independent and identically distributed (iid). Often this can be assured by an experimental design where the time distance between samples is large and constant.

However, the measurements might have been obtained in a more heterogeneous setting in some cases. An example could be that for some tests, several measurements might have been obtained during a few hours at that test, whereas sometimes, just a single measurement is conducted on other tests. Measurements within a single test can often be highly correlated in time. A high autocorrelation must be considered in a proper data analysis to obtain reliable conclusions.

The validity of using simple linear models or the effects of the experimental design are seldom discussed. Calibration quality is usually addressed as the coefficient of determination (R^2) between the evaluated and the reference instruments [21]. However, R^2 should only be used if the measurements are independent (not correlated) and evenly distributed. In the actual study, the lag-1 autocorrelation is 0.972, which is a high autocorrelation; thus, it has to be taken into account. This paper describes methodologies for conducting proper calibration analysis given such highly correlated data.

To understand the problem, let an extreme case be considered. It is assumed that the correlation between measurements taken on the same day was 1, whereas the correlation between measurements taken on two different days was 0. For simplicity, it will be assumed that 1000 measurements were obtained for one day, whereas for nine days, a single measurement was obtained for each day. Since the correlation was 1 within the same day, a single measurement contains all relevant information, and the 999 remaining measurements do not provide further information.

Using OLS, all measurements will have the same weight. The calibration line would be very close to the perfectly correlated observations on the day with 1000 measurements, and the influence from the nine other measurements will be minor. The resulting calibration line will thus be highly biased towards the line through the 1000 measurements. Using OLS, it is (wrongly) assumed that there are N = 1009 observations, and consequently, the uncertainty of the parameter estimates will be very low (proportionally to 1/N = 1/1009). Finally, R^2 will be very high (close to 1), and the Residual Standard Error will be very low, which does not reflect reality.

A proper weighting of the measurements is needed to do the correct analysis. Since the correlation was one within the same day, the 1000 measurements should effectively count only as one measurement. Since the correlation was assumed to be zero between days, the best calibration can be found using a weighting where the 1000 measurements were treated as a single measurement, and consequently, there are effectively only N = 10 observations. The uncertainty of the parameter estimates of the best calibration will be much higher (proportional to 1/10), and the Residual Standard Error will be much higher, but it would reflect the true calibration error needed if the calibrated sensor is expected to be used on a day in future.

This paper describes methods for calibration which take the actual autocorrelation into account and provide proper calibration curves and uncertainty estimates no matter how the measurements are taken. To the authors' knowledge, the suggested approach for handling autocorrelated measurements using a first-order Markov scaling has not been used to calibrate LCS.

2.4.1. Regression models used for calibration

The classical regression model is a statical relationship between a dependent variable Y_t and p independent variables X_{1t}, X_{2t}, …, X_{pt}. For these sensor calibration experiments, the observations occur successively in time; therefore, an index t is introduced to denote the measurements at time t. In the calibration, the p independent (or explanatory) variables imply that adjusting for experimental conditions, like temperature and moisture, is possible.

A nonlinear function for the calibration curve can be used if a linear calibration curve does not fit the experimental data well for some calibration experiments. Thus, the general regression model will be introduced

$$Y_t = f(X_t, t; \theta) + \varepsilon_t \quad (1)$$

where $\theta = (\theta_1\theta_2, \ldots\theta_m)^T$ is a vector of the m unknown parameters, f is a known function of the $p + 1$ independent variables $X_t = (X_{1t}, X_{2t}, \ldots, X_{pt})^T$ and t.

The error term ε_t is assumed to be a random variable with a mean zero ($E[\varepsilon_t] = 0$), and the variance $Var[\varepsilon_t] = \sigma_t^2$, is assumed to depend on the time t. Furthermore, it is assumed that the residuals are correlated in time:

$$Cov\left[\varepsilon_{ti}, \varepsilon_{tj}\right] = \sigma^2 \Sigma_{ij} \quad (2)$$

where Σ_{ij} is a weight. In the following, it is assumed that the independent variable is known, i.e., $X_t = x_t$.

The central assumption in linear regression is that the sequence of error terms is a sequence of independent and identically distributed

(IID) random variables [37]. The above formulation contains a generalization that allows for varying uncertainty (variances) and a heterogeneous time sequence of autocorrelated error terms. Readers are referred to Madsen [37] for more details on how this is considered in the general nonlinear setting.

2.4.1.1. The general linear model. The calibration curve is often assumed to be linear, which allows using the general linear model or multiple linear regression model:

$$Y_t = X_t^T\theta + \varepsilon_t \tag{3}$$

where $X_t = (X_{1t}, X_{2t}, ..., X_{pt})^T$ is a known (non-random) vector and $\theta = (\theta_1, \theta_2, \ldots, \theta_m)^T$. The error term εt has zero mean and covariance $Cov[\varepsilon_{ti}, \varepsilon_{tj}] = \sigma^2\Sigma_{ij}$

N observations of the dependent and independent variables are assumed:

$$(Y_{t1}, x_{t1}), (Y_{t2}, x_{t2}), \ldots, (Y_{tN}, x_{tN}) \tag{4}$$

These observations occur successively in time, but observations at any given point in time, e.g. at non-equidistant time points, are allowed. This implies that very flexible experimental design and sampling times are allowed.

The total model for the N observations can be written

$$Y = x\theta + \varepsilon \tag{5}$$

where the design matrix x has dimension N × p. Following the definitions given in Eq. (3), $E[\varepsilon_t] = 0$, and the covariance matrix for the residuals ε is $Var[\varepsilon] = \sigma^2\Sigma$ where $\Sigma = [\Sigma_{ij}]$.

Linear regressions assume that the residuals are independent and identically distributed (IID). This is described using the above formulation by putting $\Sigma = I$, being I the identity matrix leading to Ordinary Least Squares Estimation (OLS). However, this assumption is often violated in calibration problems and cannot be used.

2.4.1.2. Covariance and correlation structure. The covariance matrix Σ has to be specified appropriately to get reasonable estimates. Hence, both the variance and the correlation structure of the residuals ε_t have to be described.

The general formulation of the covariance matrix for the residuals is given by Eq. (2). By inspection of the data from these calibration experiments, it is seen that consecutive time residuals within a single test appear to be dependent. Similarly, it seems reasonable to assume that the variance is the same for all the residuals; thus, only the correlation structure must be specified.

In this case, it seems reasonable to assume that the correlation structure is an exponentially decaying function of the time distance between two observations, i.e.,

$$Cor[\varepsilon_{t_i}, \varepsilon_{t_j}] = \rho^{|t_i - t_j|} \tag{6}$$

where ρ is the correlation between two observations one-time unit apart. For hourly data, this is the hour-to-hour correlation. This corresponds to assuming a first-order Markov structure, or an Autoregressive first-order model, for the residuals [37]. Higher values of ρ coefficients denote a stronger correlation.

The assumption in linear regression is that Σ is known, but this is seldom the case in practice. In Ref. [37] a relaxation procedure is described, but for the above-mentioned problem, the likelihood function can be written assuming that the residuals are Gaussian.

2.4.1.3. Maximum likelihood estimates. The maximum likelihood method aims to describe the variation in the data by assuming a probability density and accounting for the autocorrelation. The consideration of autocorrelation will be advantageous in both forecasting and control.

As before equation (5) is considered for all N observationsand the residuals are assumed Gaussian, i.e., the measurements follow the Gaussian distribution

$$Y \in N(x\theta, \sigma^2\Sigma) \tag{7}$$

and contrarily to other authors, a first-order Markov correlation for the residuals Σ is assumed so that the correlation structure can be modeled and specified by

$$\Sigma_{ij} = Cor[\varepsilon_{t_i}, \varepsilon_{t_j}] = \rho^{|t_i - t_j|} \tag{8}$$

The above assumptions imply that the joint density for all observations, Y, is

$$f_y(y) = \frac{1}{\sqrt{(2\pi\sigma^2)^N det\Sigma}} \exp\left[-\frac{1}{2\sigma^2}(Y - x\widehat{\theta})^T\Sigma^{-1}(Y - x\widehat{\theta})\right] \tag{9}$$

Which implies that apart from a constant, the log-likelihood function for the unknown parameters is defined with equation (10):

$$\log L(\theta, \rho; Y) = -\frac{1}{2}\log\det(\Sigma) - \frac{N}{2}\log\sigma^2 - \frac{1}{2\sigma^2}(Y - x\theta)^T\Sigma^{-1}(Y - x\theta) \tag{10}$$

The maximum likelihood estimates are found using numerical methods by maximizing equation (10). Estimates of the uncertainty of the parameter estimates are found using the observed Fisher Information Matrix; see Ref. [38] for details. In this article, the problem was implemented in R, and the GLS function was used in the NLME package. The Maximum Likelihood (ML) method and the residual maximum likelihood method (REML) were used. The ML method has the weakness that the variance estimates are biased, but this problem is handled by the REML method. The REML estimator corrects the estimated variance components for the degrees of freedom lost in estimating the fixed effect parameters; hence, the REML estimates the random effects more accurately. In practice, ML and REML give similar results and converge for large samples. Readers are referred to Ref. [38] for details.

2.5. Error determination

The idea of the error determination is to evaluate:

1) the accuracy that refers to how close the sensor reports to the true value or reference measurement,
2) the precision that responds to how consistently is the sensor reacting,
3) the bias that looks for systematic errors in reporting a value.

As already proven, it is impossible to demonstrate in this case that the residuals are independent and identically distributed. Therefore, using R^2 that quantifies the strength of the association (information about the goodness of a fit of a model) by equation (11) is not relevant for ML and REML. The ML or REML methods will "weight" the data, considering its information to consider it more reasonably. Thus, the fit will never be as good as when using the regression line considering all the data.

$$R^2 = 1 - \frac{\sum\left(C_{Lcs,i} - \widehat{C_{LCS,i}}\right)^2}{\sum\left(C_{Lcs,i} - \overline{C_{LCS,i}}\right)^2} \tag{11}$$

$$MAE = \frac{\sum_{i=1}^{N}\left|\widehat{C_{LCS,i}} - C_{ref,i}\right|}{N} \tag{12}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(\widehat{C_{LCS,i}} - C_{ref,i}\right)^2}{N}} \tag{13}$$

For precision metrics, mean absolute error (MAE; eq. (12)) and root mean squared error (RMSE; eq. (13)) will often be used. For equations (11)–(13) C_{ref} and C_{LCS} are formaldehyde concentrations measured by the reference monitor and LCS, respectively, $\widehat{C_{LCS,i}}$ is the predicted value and $\overline{C_{LCS,i}}$ the mean value.

MAE and RMSE calculate the average model prediction error, and their value can range from zero to values as high as the measured concentrations themselves. These parameters are useful to evaluate the fitted models' accuracy.

As these calibration models are built on different scales of formaldehyde concentrations, normalizing the accuracy metric is important so that models can be compared. Reporting normalized and absolute metrics is necessary when reporting errors. Normalizing performance metrics allows models to be appropriately compared between environments where concentration ranges are different [27]. The Coefficient of Variation (CV) and Mean Normalized Bias (MNB) are recommended guidelines by the United States Environmental Protection Agency (US EPA) for the evaluation of sensors [22] and thus, introduced in this article.

$$MNB = \frac{1}{N}\sum_{i=1}^{N}\frac{\left(C_{LCS,i} - C_{ref,i}\right)}{C_{ref,i}} \tag{14}$$

$$CV = \frac{\sigma}{\mu} = \frac{\sqrt{\frac{\sum\left(C_{Lcs,i} - \overline{C_{LCS}}\right)^2}{N}}}{\overline{C_{LCS}}} \tag{15}$$

However, R^2, MAE, and RMSE do not account for autocorrelations. These performance indicators are created with the basic assumption that measurements are independent, which they are not in our case. They are nevertheless reported in this article to compare to other existing literature.

The Akaike information criterion (AIC) is a measure of the model's fit. AIC measures the quality of one model relative to the other as long as the models are constructed with the same estimate principle. For example, it will compare two different OLS models or two different REML models with different parameters, but not one OLS and one REML model. AIC provides a means for model parameter selection [39]. It is calculated using formula (16), where k is the number of estimated parameters in the model and $\widehat{L}$ the maximum value of the likelihood function for the model. As the Log-likelihood is a measure of model fit. The lower the number, the better the fit.

$$AIC = 2k - 2\ln\left(\widehat{L}\right) \tag{16}$$

For evaluation of the ML or the REML models, no error formulation is recommended as the evaluation would be very much dependent on the use of the sensor and other statistical parameters out of the scope of this article. In the case of ML and REML, a numerical method is often needed for finding the parameters which maximize the likelihood function.

2.6. Calibration procedure

The procedure for calibration followed the steps described below:

1 Check that all sensors react similarly to the exposure to the reference source. Before corrections can be studied, it should be controlled that all the units respond similarly to the same event [27]. Malings [40] defined intra-unit consistency when the variability is less than 20 % between equal units.
2 Log transformation of the data. To make it more normally distributed.
3 Study the calibration model most suitable to the available data, in this case, considering autocorrelated measurements and heterogeneous sampling lengths. The model sought was fitted using all the measured variables.
4 Repeat the fitting of the model only with the most significant variables chosen using the Akaike information criterion.
5 Evaluate the results based on the EPA suggested performance goals by application for MNB and CV according to Ref. [15]. This evaluation is done according to the values described in Table 3

3. Results and discussion

3.1. Raw measurements

Fig. 2 shows the raw measurements (out of the box) of all the eight sensors, and in black, the reference equipment (not for TVOC as a reference instrument was not available). For most of the measurements, all sensors react similarly. For temperature, the LCS overestimates the values compared to the reference sensor. For RH, the LCS over and underpredict the RH. For formaldehyde, LCS mostly overpredicts, being especially wrong in test A where the overprediction is especially high due to cross sensitivities with other gases. For TVOC, all LCS sensors predict similarly.

The sensors react similarly to the events to which they are exposed. The average difference among the LCS is 14%, 1%, 3%, and 18% for formaldehyde, temperature, RH, and TVOC, respectively. In the following, only the measurements and the models for calibrating sensor station S1 will be reported.

3.2. Calibration using formaldehyde, RH, temperature, and TVOC

The log transformation was done to have data that are more normally distributed.

The results for only one sensor are presented to exemplify the calibration methodology, but the results for all the other sensors were very similar.

Firstly, all the measured parameters were used to fit the calibration. Table 4 shows the parameters for OLS, ML, and REML after taking the logarithm of the data for sensor station 1.

OLS is just shown here for comparison to other literature, but given the performed experimental design (autocorrelation of the data and heterogenous sampling), its use is not recommended for the collected data. Given that not all the tests were equally long, with OLS, the longer ones will significantly affect the estimation. OLS is based on minimizing the sum of squares of the difference between the observed dependent variables in the dataset. Thus, when having autocorrelations, the fitting using OLS will be very good for the dataset fed-in. However, when using the calibration estimates to predict other "unseen" datasets, OLS estimates will perform poorly because they are "overfitted for the calibration dataset."

A practical example is given for clarity. If measurements of the size of a river are mostly taken after the snow-melting period, a huge river will

Table 3
EPA suggested performance goals by application for MNB and CV according to [15].

	MNB range	CV range
Tier I: Education and Information	$-0.5 < MNB < 0.5$	$CV < 0.5$ for all pollutants
Tier II: Hotspot Identification and Characterisation	$-0.3 < MNB < 0.3$	$CV < 0.3$ for all pollutants
Tier III: Supplemental Monitoring	$-0.2 < MNB < 0.2$	$CV < 0.2$ for all pollutants
Tier IV: Personal Exposure	$-0.3 < MNB < 0.3$	$CV < 0.3$ for all pollutants
Tier V: Regulatory Monitoring	$-0.07 < MNB < 0.07$	$CV < 0.07$ forO_3
	$-0.1 < MNB < 0.1$	$CV < 0.1$ for CO and $PM_{2.5}$
	$-0.15 < MNB < 0.15$	$CV < 0.15$ for NO_2

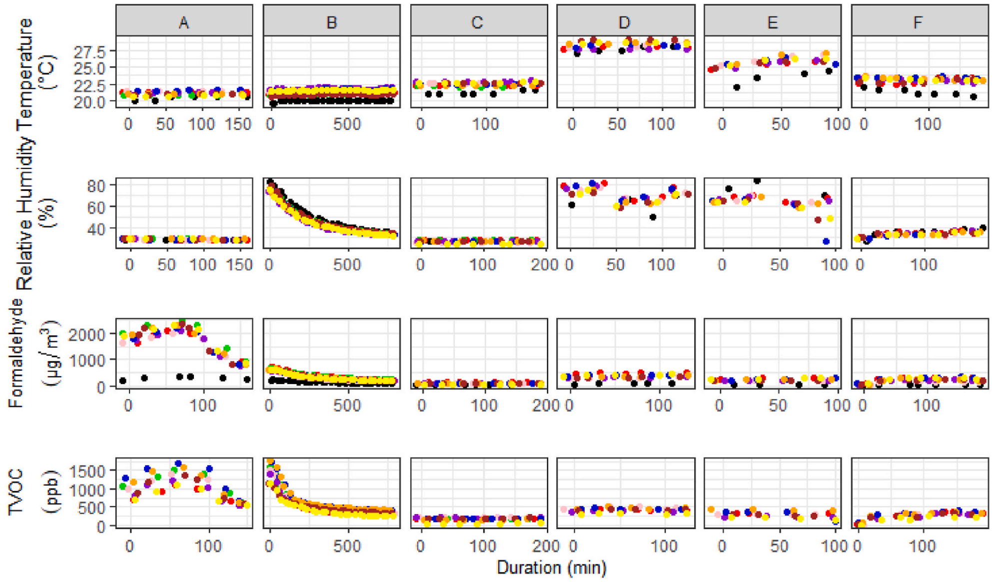

Fig. 2. Out-of-the-box response of the eight sensors to the six exposure tests. Every facet plots the results of each test, and the points are colored based on the sensor. Dots in black represent the reference instrument.

Table 4
Fitting of parameters using the different estimations. A p-value less than 0.05 was considered statistically significant. The middle part of the table shows the errors with typical formulations, and the lower part shows the evaluation according to EPA recommendations. OLS is just shown here as a comparison point, but its use is not recommended for calibration given the experimental design.

	OLS	p-value	ML	p-value	REML	p-value
Intercept	4.934	0.000	−7.83029	0	−7.958	0
FA	0.748	4.73E-05	0.176965	0.423	0.152	0.491
Temperature	−4.976	3.74E-06	6.721079	0	6.870	0
RH	0.661	0.015	−0.37359	0.078	−0.377	0.072
TVOC	2.576	0.190	2.227658	0.019	2.303	0.016
Residual standard error	0.211		0.48		0.63	
R-squared	0.7751					
AIC	−5.76		−128.9467		−127.0673	
RMSE	0.203		0.543		0.540	
MAE	0.146		0.509		0.512	
ρ	0.65		0.972		0.972	
CV	0.20	Tier II/IV	0.1486	Tier III	0.1482	Tier III
MNB	4.29e-18		0.112		0.099	

be predicted and may be perfectly predicted. However, its size will be overpredicted when the corrections are used to predict the same river in summer. Therefore, even though in Table 4, Fig. 4, and Fig. 5 the OLS predicts the measurements by the reference equipment with the smallest errors, the model is not recommended. Calibration is needed so that the sensors can be used to predict unseen data, and if the model is overfitted to the calibration dataset, each time that a measurement is taken outside of the dataset conditions, the sensor will not be reliable. ML and REML, as they consider autocorrelations, will not produce the best fitting of the measured data but will be the models that estimate best the calibration so that the sensor works best when used with new data.

Considering the OLS, based on p-values, TVOC is not a significant parameter, but formaldehyde, RH, and temperature are significant. However, when considering ML and REML, TVOC becomes significant instead of formaldehyde. In the last cases, some VOCs causing cross-sensitivities are produced, e.g., the test with wooden materials, making cross sensitivities so important that TVOC becomes an explanatory variable. According to their manufacturers, the reference formaldehyde sensor has known cross-sensitivity with possible-present VOC such as limonene, styrene, propionaldehyde, n-Nonyaldehyde, benzaldehyde, and acetaldehyde, among others, while the Dart formaldehyde sensor has cross sensitivities with ethanol phenol, ethylene among others and all these could have been degassed from our test. ML and REML weight the data based on the autocorrelations; therefore, TVOC cross-sensitivities with formaldehyde gain importance.

Most published works use temperature and relative humidity in linear fits to increase the fitting (e.g., Crilley et al., [41]). However, for ML and REML, RH is not a significant parameter as these sensors are already compensated for it in the out-the-box measurements [33].

Fig. 3 shows the autocorrelation of the residuals of the ML model. The model's residuals are highly autocorrelated, and this figure shows the importance of considering and describing autocorrelation as it may affect the reliability of the models if not accounted for. By using autocorrelation, the one-step forecast error of ML and REML will be much smaller. The variance of the one-step forecast error is proportional to 1 minus the squared value of the autocorrelation in lag 1 [37]. When lag1 autocorrelation is high, the uncertainty of short-term predictions is highly reduced.

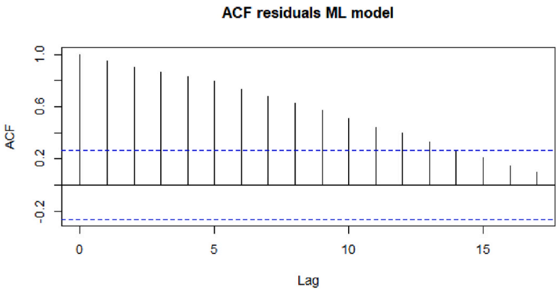

Fig. 3. ACF of the residuals for the ML model.

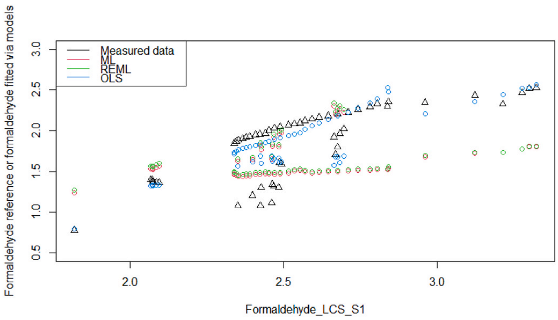

Fig. 4. Fitting of LCS measurements using all measured variables as explanatory variables.

Fig. 4 shows the fitting results when using all the measured parameters. The OLS fitting follows the values on the top part of the graph very well. Most of these values correspond to the same test, test B (defined in Table 2). OLS will not consider the autocorrelation of the values, and as this test is the test with more points, it has a larger effect on the fitting parameters. The suggested ML and REML will account for the autocorrelation, and thus the fitting of these points is much worse. When using REML or ML, the model considers only the "new information" from a test, and thus it predicts individual points in test B poorly, but it predicts much better the ones in the lower part of the graph as they have new information. Overall, the ML and REML show a more balance fit to the data.

Fig. 5 shows the predictions facetted by the test. Tests A, B, and C are the longest tests and thus very well predicted by OLS; however, tests D-F have a similar error for all three methods (test defined in Table 2). ML and REML overpredict results for tests C–F and underpredict in A and B. OLS under and overpredicts in tests A and B, underpredicts in tests C and D, and overpredicts in tests E and F. The fact that results are under and over-predicted makes the calibration more unreliable due to randomness.

Using stepwise regression, a regression model was built that minimizes the AIC value for ML and REML models. A simpler model was developed using the AIC to measure the loss of information while removing variables. The model considering only formaldehyde and temperature as the explanatory variables is selected in this case. The AIC penalizes adding more variables; thus, only the variables that are better predictors are maintained. In this case, TVOC has the lowest AIC value, and it is the parameter where less information will be lost when being removed.

Additionally, multicollinearity is checked. Multicollinearity happens when two or more predictor variables are highly correlated. TVOC and formaldehyde are strongly correlated. Hence when removing multicollinear predictors, the remaining predictor will still contain most of the information [42]. Keep in mind that resulting AIC values with different estimates should not be compared.

3.3. Calibration using formaldehyde and temperature

Table 5 shows the results for the model considering only formaldehyde and temperature. Formaldehyde and temperature are significant for all three types of models. OLS results are included in Table 5 to compare to other existing literature but will not be further discussed.

According to EPA's recommendations, the sensors are evaluated as Tier III, supplementary monitoring for all the sensors with these models. Fig. 6 is not substantially different from Fig. 4. The prediction of the larger values is better with these models. This is probably a consequence of removing TVOC from the model, which gives formaldehyde measurements more weight. The same can be concluded by looking at the smaller MAE and RMSE with fewer parameters.

Both Figs. 6 and 7 show that the LCS predicts the trends of formaldehyde concentration reliably. However, Fig. 7 shows that despite being the error smaller in REML and ML, the models still have a systematic bias. Tests A and B were underpredicted, test C was very well predicted, and D, E, and F were overpredicted. Measurements A and B were performed with no heater and only a humidifier for the latter. During the D and E, the radiator was on, and in F, none was on. Therewas a second difference; these measurements were taken one year apart. In the midtime, the sensors were exposed to different concentrations of formaldehyde during several measurements, and what we see may be drift due to the loss of baseline or accumulation of material on the oxidizing membrane. The measurement principle relies on a two-electrode electrochemical type, operating by the diffusion principle. Clogging of the membrane may incur wrong measurements or over predictions.

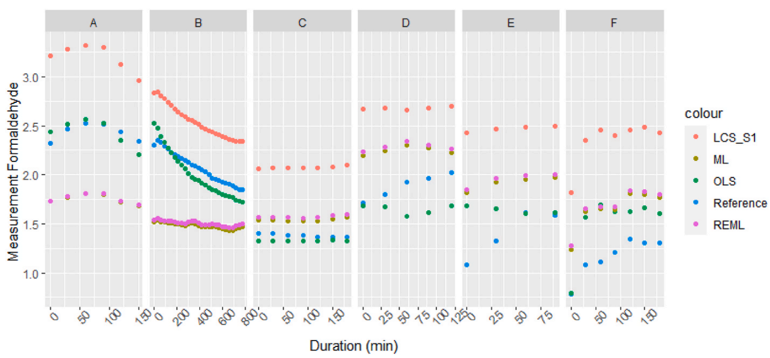

Fig. 5. Prediction of calibrated values using OLS, ML, and REML methods. Results facetted by test.

Table 5
Estimation of parameters using the different estimations.

	OLS	p-value	ML	p-value	REML	p-value
Intercept	4.21	5.7E-04	−6.18	1.0E-04	−6.33	1.00E-04
FA	1.03	1.8E-14	0.63	0	0.62	0
Temperature	−3.69	3.7E-05	4.62	2.0E-04	4.77	1.00E-04
Residual standard error	0.25		0.42		0.53	
R-squared	0.70					
AIC	−159.7		−125.9		−123.7	
RMSE	0.245		0.37		0.37	
MAE	0.193		0.32		0.33	
CV	0.19	Tier III	0.15	Tier III	0.15	Tier III
MNB	9.66e-17		−0.11		−0.09	

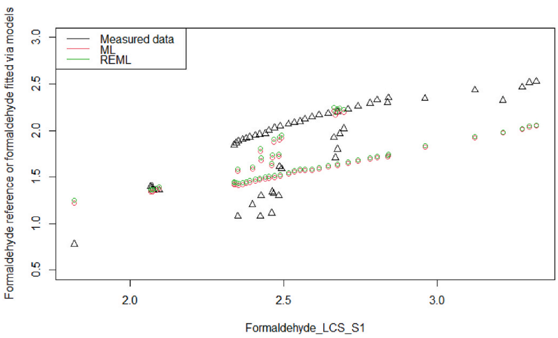

Fig. 6. Fitting of LCS measurements using formaldehyde and temperature as explanatory variables.

It is also important to note that three years after using the sensors, two of the eight sensors stopped working, two years before the sensor's five-year expected lifetime [35]. According to EPA's recommendations, these sensors should only be used for supplementary and not for regulatory monitoring. However, as they respond well to the changes in trends, they can be used to control personal exposure.

3.4. Summary of the essential parameters to make a good calibration

To evaluate sensors, it is common in the literature to develop linear models that correlate measurements with a laboratory-grade sensor and an LCS, and by evaluating the R^2, the goodness of the fit or the sensor is concluded.

However, at least three elements should be considered before developing such correlations, 1) the experimental design, 2) the autocorrelations, and 3) the selection of the best model.

3.4.1. Experimental design and limitations of the presented tests

It is essential to make an experimental design that ensures causal and proper dependencies in the data [43]. The following facts affected the selection of the model that could be used for calibration:

- The length of the measurements was not equal for all the tests. Some tests went overnight, and others lasted only a couple of hours. Difference test lengths would affect a linear model by giving overweight to the longer test. For test B, the idea behind having so long measurements was to see if, after exposure, the sensors returned to the initial baseline or if they suffered from drift.
- The same tests were run at slightly different humidity and temperatures, but these were not constant during the test or from test to test. We intended to test at "dry-wet" and "cold-warm" conditions as Demanega did [36]. Neither the radiator nor the humidifier maintained constant conditions, and conditions averaged around the set points. Having constant factors would help establish or not the effect of a single factor. Dependent variables could be measured at different levels, intervals, or ratios, affecting the level of precision attainable here; these variables could only be measured and not controlled [43].
- The selected tests were known from the literature to produce formaldehyde [44]; however, too little attention was set to the different TVOCs that were simultaneously produced, resulting in cross-sensitivities for both formaldehyde and the TVOC sensors. For example, formaline is a known source of formaldehyde, but it contains methanol, to which the WZ modules and the Graywolf sensor have a strong cross-sensitivity. Cross-sensitivity is a prevailing challenge for sensors that measure gaseous pollutants [21].
- If a high autocorrelation is seen for the measurements, then this autocorrelation has to be taken into account to give reliable estimates for highly correlated measurements. As a rule of thumb, conventional OLS methodologies can be used if the autocorrelation is less than, say, 0.3.

3.4.2. Importance of describing the correlation

OLS assumes independent observations, and if this is not fulfilled, then the outlined measures that describe the systematic variation in the data should be used.

In general, LCSs measure with a high sampling rate, i.e., with a small-time distance between the individual data points. In such cases, the calibration error at two consecutive measurements is often highly correlated. Using measurement campaigns with more frequent sampling than needed would often yield overestimated R^2 [40] due to autocorrelations in the time series. In the case of frequent sampling, the errors

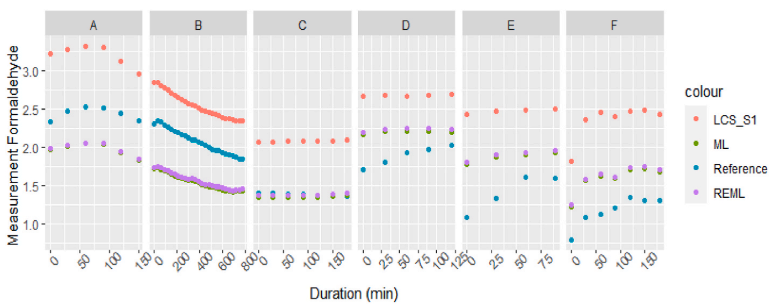

Fig. 7. Prediction of calibrated values using ML and REML methods. Results facetted by test.

from the one-time point are often highly correlated with the sampling error at a neighboring time point. Compared to more scarcely sampling points, the extra points arising from the frequent sampling over a long time do not provide extra information proportional to the relative number of samples. Using several test exposures at different environmental conditions and with different sources rather than very frequently sampled measurements are recommended to develop calibration models.The LCS collected data every 5 min, and the measurements were averaged every 30 min to be compared to the laboratory-grade sensor. Measurements taken continuously will almost always be autocorrelated and result in models with autocorrelated residuals.

One condition of linear regression is that the residuals are independent and identically distributed. However, in calibration, when the sampling is done as here, continuously, this assumption is then often violated. Measurements are taken often with little variations of the source, thus with measurements very correlated to the previous. Consequently, generalized least squares estimation must be considered so that the explanatory variables fully describe the autocorrelation. ML considers the autocorrelation, but REML has better compensations for the estimated and scaling parameters (related to the variance).

3.4.3. Selection of best model

In our analysis, the best model is selected based on a test for significant parameters and a comparison between different model candidates using the AIC criterion. In general, the ML approach provides a robust framework for model selection even in the case of autocorrelated errors. However, the REML approach is preferred for the final parameter estimation since it provides more unbiased estimates of the variances.

3.4.4. Performance of the tested formaldehyde LCS

Both LCS and the reference sensor present very similar dynamic responses, which means that LCS could be used to detect concentration changes. However, there were quantitative discrepancies even after the calibration. These discrepancies over-and under-estimated the values obtained by the reference sensor. The LCS and the reference sensor suffer from cross-sensitivities to some VOC released by the tested sources. However, the cross-sensitivity reaction is different for the different chemical compounds and sensors, making the evaluation of the precise values more complicated.

The present study suggests that these sensors have the potential to be used in indoor environments as Supplemental Monitoring. According to EPA's recommendation as Tier III, a sensor can be used to improve the characterization of concentration gradients [22]. This would mean triggering the proper responses for the control, but this control would need to focus on trends better than values.

4. Conclusions

LCSs use is becoming widespread in the market. However, these sensors are often delivered from the provider with limited information regarding use and performance, reliability, and response to aging or drift. This article analyzes the performance of eight IAQ stations with the same formaldehyde sensor type via comparison with reference equipment. Tested sensors were pre-calibrated from the factory at purchase, and the drift is removed via a 12 h calibration before the experiments.

The tests were run in a mini chamber as a collection of measurements of formaldehyde. The lengths of the tests were heterogeneous based on the estimated duration of the exposure. Some tests were run in cold, warm, dry, and wet conditions controlled with a domestic radiator and humidifier. The experimental design did not ensure that tests data were not autocorrelated.

Given the autocorrelation of the measurements, Ordinary Least Squares Estimations should not be used. In this article, there are two alternative methods for evaluating the calibration: Maximum Likelihood and Restricted Maximum Likelihood Estimation. ML considers the autocorrelation, but REML has better compensations for the estimated and scaling parameters (related to the variance). This article has created a procedure for estimating a weighting according to the autocorrelation based on the first-order Markov. Then a simple method using this weighting was created. Finally, the AIC criterion was used to select the most significant parameters, and for the calibration of the formaldehyde sensor, formaldehyde and temperature were estimated as significant parameters.

According to EPA's recommendations, these models evaluate the sensors as Tier III supplementary monitoring. These results are presented for only one of the eight sensors. Out of the eight, one sensor stopped working during the calibration tests (a second one stopped recently after continuous use), and the remaining six presented similar performance.

The main message is that when sensors collect data continuously with a very high-frequency interval, there is often little difference between measurements, which are often highly autocorrelated. OLS cannot be used in this case and different models considering the autocorrelation are necessary. This paper exactly presents such new methods that can use data that are autocorrelated. The practical implication is that these models allow handling heterogeneous test sampling. This means they can use data where in some tests, many samples are taken on the same day, and some tests where much fewer tests are taken, and then measurements after some days without data sampling.

The LCS and the reference sensor suffer from cross-sensitivities to some VOC released by the tested sources. Even if there were discrepancies where the LCS over-and under-estimated the values obtained by the reference sensor, they both presented very similar dynamic responses, indicating that LCS could be used to detect concentration changes. The present study suggests that these sensors have the potential to be used in indoor environments as Tier III supplemental Monitoring (according to EPA's recommendation), especially for triggering appropriate controls.

CRediT authorship contribution statement

Maria Justo Alonso: Writing – original and reviewed draft, Conceptualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Henrik Madsen:** Writing original and reviewed draft, Methodology, Formal analysis, Conceptualization. **Peng Liu:** Writing – original and reviewed draft, Formal analysis. **Rikke Bramming Jørgensen:** Writing – original and reviewed draft, Formal analysis, Supervision. **Thomas Berg Jørgensen:** Investigation. **Even Johan Christiansen:** Software, Resources, Investigation. **Olav Aleksander Myrvang:** Software, Resources, Investigation. **Diane Bastien:** Writing –original draft, Resources. **Hans Martin Mathisen:** Writing – original and reviewed draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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PAPER 4

Justo Alonso, Maria; Moazami, Therese Nitter; Liu, Peng; Jørgensen, Rikke Bramming; Mathisen, Hans Martin. Assessing the Indoor air quality in 21 home offices in Trondheim, Norway – *accepted in Building and Environment journal*

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Assessing the indoor air quality and their predictor variable in 21 home offices during the Covid-19 pandemic in Norway

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ABSTRACT

In this study, concentrations of pollutants: formaldehyde, carbon dioxide (CO_2), and total volatile organic compounds (TVOC) and parameters: indoor room temperature and relative humidity (RH) were measured in 21 home offices for at least one week in winter in Trondheim, Norway. Eleven of these were measured again for the same duration in summer. Potentially explanatory variables of these parameters were collected, including building and renovation year, house type, building location, trickle vent status, occupancy, wood stove, floor material, pets, RH, and air temperature.

The association between indoor air pollutants and their potential predictor variables was analyzed using generalized estimation equations to determine the significant parameters to control pollutants. Significantly seasonal differences in concentrations were observed for CO_2 and formaldehyde, while no significant seasonal difference was observed for TVOC. For TVOC and formaldehyde, trickle vent, RH, and air temperature were among the most important predictor variables. Although higher concentrations of CO_2 were measured in cases where the trickle vent was closed, the most important predictor variables for CO_2 were season, RH, and indoor air temperature.

The formaldehyde concentrations were higher outside working hours but mostly below health thresholds recommendations; for CO_2, 11 of the measured cases had indoor concentrations exceeding 1000 ppm in 10% of the measured time. For TVOC, the concentrations were above the recommended values by WHO in 73% of the cases. RH was generally low in winter. The temperature was generally kept over the recommended level of 22–24 °C during working hours.

1. Introduction

On March 11th, 2020, the coronavirus disease 2019 (COVID-19) pandemic was declared [1]. Among others, exposure to COVID-19 may lead to severe acute respiratory syndrome and death. Social distancing has been considered one of the most effective measures against the spread of COVID-19, and many workers were asked to work remotely from home when possible. This situation was expected to last for a short period but finally extended from March 2020 to January 2022, with short periods of restrictions relief varying from country to country. Suddenly, working from home became the new normal, and rooms designed or not as home offices were taken into this use.

Shortly after the implementation of the home office, the Federation of European Heating, Ventilation, and Air Conditioning Associations (REHVA), the American Society of Heating and Air-Conditioning Engineers (ASHRAE), the Centre for Disease Control, and the World Health Organization (WHO) released guidelines explaining how to handle the COVID-19 situation [2–6]. However, none of these entities focused on what happened to the workers when they started working from home. Although working from home reduced the spread of COVID-19, the indoor air quality (IAQ) at the home offices was seldom questioned.

According to the Norwegian Labor Inspection Authority, the employer must ensure that the employee's safety, health, and welfare are safeguarded and, as far as practicable, ensure that the working conditions are entirely justifiable, which translates to the documentation of the minimum ventilation rates. Rules apply to the workplace, work equipment, and the indoor environment [7]. However, it is complicated for employers to follow up on IAQ in the home offices, and the codes are laxer in practice. For the home office, the Norwegian Labor

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Nomenclature

AR(1)	first-order autoregressive
ASHRAE	American Society of Heating and Air-Conditioning Engineers
β	Estimates for the most important predictor variables
CH_2O	Formaldehyde
CO	Carbon monoxide
CO_2	Carbon dioxide
COVID-19	Coronavirus Disease 2019
GEE	Generalized estimation equation
IAQ	Indoor air quality
IRT	Indoor room temperatures
LCS	Low-cost sensors
MOS	Electrochemical sensor
MT	Whole measured time in one household
NO_x	Nitrogen oxides
n_{50}	Infiltration air changes at 50 Pa
NDIR	Nondispersive infrared
OEL	Occupational exposure limit values
O_3	Ozone
PM	Particulate matter
QIC	Quasi-likelihood under Independence Model Criterion
QICC	corrected QIC
REHVA	Federation of European Heating, Ventilation, and Air Conditioning Associations
RH	Relative humidity
SBS	Sick building syndrome
TEK	Norwegian regulations on requirements for construction works and products for construction works
TVOC	total volatile organic compounds
WH	Working hours: defined in base to subject's feedback
WHO	World Health Organization

Inspection Authority focused its recommendations [7] on parameters the employer can follow, such as ergonomics.

New buildings are commonly equipped with mechanical ventilation systems. However, 40% of Norwegian dwellings are built before 1970 and 65% before 1990 [8]. According to Mjønes et al. [9], apartment blocks built before 1970 utilized natural ventilation; after this year, mechanical ventilation became more common. Mechanical ventilation with heat recovery of at least 70% efficiency was introduced in TEK97 [10].

Generally, the ventilation criteria are based on comfort levels, but the thresholds and recommendations regarding indoor air pollutants exposure are based on epidemiological studies. The health related pollutant recommendations set limits based on the maximum value of exposure to a pollutant before there is a correlation with increases in mortality or sicknesses [11]. Kampa and Castana [12] concluded that the hazardous effect of a chemical causing adverse effects on human health must be the same, disregarding where exposure occurs. Occupational exposure limit values (OEL) represent the maximum concentration of a chemical substance in the worker's breathing zone during a reference period of 8 h. OELs are based on toxicological and medical evaluations (health-based) and what is technically and financially possible to achieve in a workplace [13]. For this reason, workers may not be fully protected from hazardous exposure, although the OELs are respected. Additionally, OELs are assigned to protect healthy adults with normal pulmonary ventilation and are usually considerably higher than the limit values set to protect public health. During the COVID-19 pandemic, workers worked from home regardless of having a devoted room for that. Vulnerable people such as children, the elderly, or pregnant women were present. Thus, not all OELs may be a suitable reference limit; instead, the national standards set to protect vulnerable people also are considered more relevant. Thus, the standards for indoor air quality, as defined by WHO, were used to assess the air contaminants measured in the present study. In this article, it was assumed that the home office should meet the same criteria as defined in the building codes for offices [14] and occupational health and public health legislation [15,16].

Roth et al. [17] showed that working from home may cause health effects due to poor home IAQ and a higher prevalence of reported Sick building syndrome (SBS). Yang et al. studied 169 energy-efficient dwellings, reporting that 90% and 50% of dwellings exceeded the chronic exposure limits for formaldehyde and total volatile organic compounds (TVOC) [18]. Additionally, Birimoglu Okuyan et al. found that home offices significantly adversely affect physical and mental wellbeing [19]. However, despite home office side effects, it is expected to continue after the pandemic, and the results of this study would still be valid even after the COVID-19 restrictions are lifted.

1.1. *Threshold and recommendation for pollutant concentrations*

Common outdoor air pollution, such as PM, TVOCs, carbon monoxide (CO), ozone (O_3), and nitrogen oxides (NO_x) can infiltrate into the indoor environment and affect the IAQ. In addition, indoors, pollutants related to building materials, formaldehyde (CH_2O), cleaning agents, paints, adhesives cooking fumes, wood smoke, biological pollutants, and many others may be found [20–22]. Short-term and long-term exposures to various indoor air pollutants have been linked with multiple health outcomes, such as minor upper respiratory irritations, chronic respiratory and heart disease, acute respiratory infections in children and chronic bronchitis in adults, aggravating pre-existing heart and lung disease, or asthmatic attacks [12] premature mortality and reduced life expectancy [23]. The concentration and composition of indoor air pollution vary with determinants such as building airtightness, outdoor air quality, the share of outdoor air if recirculation of extract air is allowed (not used in dwellings in Norway), the supplied airflow rates, the quality and status of filters, building materials, occupancy, cooking and cleaning habits, carpets, use of a wood stove, pets, and many others [24,25]. Limited by the availability of low-cost sensors (LCS) described in Refs. [26,27], this article focuses on pollutant measurements of formaldehyde, TVOC, and CO_2 and measurements of the parameters temperature and RH.

1.1.1. *Formaldehyde*

The International Agency for Research on Cancer (IARC) characterizes formaldehyde as being carcinogenic (group 1) to humans [28]. The indoor air quality guideline, defined by WHO, for short- and long-term exposure to formaldehyde is 100 μg/m^3 for all 30-min periods at lifelong exposure (see Table 1) [29].

1.1.2. *TVOC*

Few guidelines exist for TVOCs, although several TVOCs may impact

Table 1
Evaluation levels for formaldehyde.

Exposure duration	Threshold value [μg/m^3]	Rationale
4 h	600	Accounts for sensory effect [30]
30 min	100	Conservative assessment of sensory irritation and the carcinogenic effects [29]
1 min	110	Accounts for odors [31]

our health. To evaluate the concentration of TVOC in the present article, the air quality guidelines from the WHO (see Table 2) [32] were used.

1.1.3. CO_2

CO_2 concentrations are related to the perception of human bioeffluents and the level of human-related odors [33,34]. The CO_2 concentrations in outdoor air typically range from 400 to 430 ppm depending on the season but can be as high as 600–900 ppm in metropolitan areas [35]. The OEL for CO_2 is 5000 ppm [35]. The European standard EN 16798–1:2019 defined the thresholds in Table 3 based on categories that reflect expectations. Pettenkofer, in 1858, defined 1000 ppm for naturally ventilated houses as a guideline [36].

1.2. Other parameters affecting health and perception of IAQ and typical confounding variables

1.2.1. Relative humidity

A joint agreement on thresholds for RH is missing. According to Lin and Marr, the viability, transmission, and infectivity of influenza were promoted by RH< 40% and RH > 90% [37]. Indoor RH below 50% has been associated with asthma and allergies [38]. Building dampness has also been associated with an increased risk of wheezing and daytime breathlessness [39]. Additionally, the expectations for RH vary depending on the season and the climate.

RH may also affect human perception of stress. In a study by Razjouyan et al. [40], office workers exposed to RH between 30% and 60% were more likely to experience 25% less stress than those exposed to lower RH. As Wu et al. [41] proved in their experimental studies, elevated RH generally improved work performance positively. RH below 30–40% and above 60–70% may lead to physical discomfort, as RH impacts the perception of comfort [42]. Other research studies and guidelines recommend the low RH comfort and health-related limit to be 20–30% [38,43,44].

1.2.2. Temperature

Low and high indoor room temperatures (IRT) can be risk factors for human health [45]. The WHO [46] provided the evidence-based recommendation for housing a threshold of 18 °C to prevent cardiovascular and respiratory morbidity and mortality during cold seasons for regions with temperate or cold climates. However, the WHO's text [46] does not provide recommendations for the direct effect of high IRT on human health due to the limited number of studies.

An association between high IRT and acute upper respiratory symptoms has been suggested [47]. Air temperature above 26 °C increased the risk of acute symptoms, including thinking difficulty, poor concentration, fatigue, and depression. The risk of respiratory symptoms increased above 30 °C [48]. Respiratory diseases, asthma, and chronic airway obstruction were associated with long-term exposures to lower average temperature, but respiratory disorders and chronic airway obstruction in the elderly were related to long-term exposure to higher average IRT [45].

22 °C was found to promote the highest performance in the accuracy of brain executive functions compared to 18 °C, 26 °C, and 30 °C [49]. Optimal productivity was observed from 20 °C to 26 °C, especially 22 °C-24 °C [50]. This article defined the optimal performance range as 22 °C-24 °C.

In NS-EN 16798–1: 2019, four different categories (I–IV) for the thermal environment have been defined based on different criteria for the predicted percentage of dissatisfied people (PPD) and predicted mean vote (PMV). For living spaces in residential buildings, including bedrooms, kitchens, and living rooms, the guidelines for air temperature during heating seasons, with normal clothing levels (1.0 clo), range from 21 to 25 °C for category I to 17–25 °C for category IV. During cooling seasons (0.5 clo), the temperature range for category I is 23.5–25.5 °C, and for category IV, it is 21.0–28 °C [51].

Table 2
Levels and recommendations for TVOC according to recommendations from WHO [32].

Level	Recommendation	TVOC [ppm]
Outside quality classes	Not acceptable	>0.61
4	Only temporary exposure	0.2–0.61
3	Harmless	0.1–0.2
2		0.05–0.1
1	Target value	0–0.05

Table 3
EN 16798–1:2019 recommendations for CO_2 concentrations above the outdoor level.

Level	Category I	Category II	Category III	Remark
School (classroom)	550 ppm	800 ppm	1350 ppm	Allowable ppm levels above outdoor levels
Office (landscape layout)	550 ppm	800 ppm	1350 ppm	
Residential building (bedroom)	380 ppm	550 ppm	950 ppm	

1.3. Objectives

The objectives of this study were to: i) visualize the IAQ measured during at least one week in winter in twenty-one home offices and eleven in summer, ii) to quantify the fraction of time when health-based recommendations of different parameters and pollutants are not met, iii) associate the distribution of the real-time readings with the individual house characteristics to explain which parameters are better explanatory variables.

To the authors' knowledge, no previous research has assessed the indoor environment in residential buildings used as home offices regarding the concentration of formaldehyde, TVOC, CO_2, indoor humidity, and IRT.

2. Methods

This chapter summarizes the details of the measured home offices (cases), the placement and details of the sensors, and the statistical analysis done of the data.

2.1. Measurement methodology

2.1.1. Measured houses

This study collected formaldehyde, TVOC, CO_2, RH, and IRT measurements from 21 houses for one to two weeks during the winter season, from December the 8th, 2020, to February the 28th, 2021, and then again in 11 of these 21 houses during the summer season, from May the 21st, 2021, to June the 21st, 2021. The specific details for each house are described in Table 4.

This study's eligibility criteria required individuals to work from home at least four days during measurement. The participants were recruited from the academic environment.

Employees were asked to behave as normally as possible and not change their window opening practices to characterize their normal IAQ. Table 4 summarizes the self-responded details about the house and the normal status of windows and trickle vents. Habits about working hours were collected individually for each household. They are not reported in the text but are considered in the data analysis.

The subjects reported that in average during the measurement period, they worked 8 h: 40% of their time in writing activities, 7% in simulations, 6% in data analysis, 18% studying or reviewing literature, and 29% in video meetings.

Table 4
Summary of self-responded details of measured cases. The nomenclature corresponds to Type: Type of building where the measurements were performed, SDH: Semi-detached house, SFH: single-family house, A: Apartment, Floor: B: Basement, Room main use, Ba: Bathroom, K: Kitchen, S: Staircase, B: Bedroom, LR: Living room, HO: Home office, OK = open kitchen, K= Kitchen, Bdg. Loc: Building location in the city, CC: City centre, SNF: Suburban non-forested area, SF: suburban forested area, NV natural ventilation, EV: Exhaust ventilation, MV: Mechanical ventilation. Floor material: W-wooden flooring or cork; P-Parquets; C-carpet. Values in parentheses show summer status.

ID	Construction year (renovation)	Type	Floor	Area (m^2)	Maximum occupant density (m^2/pers)	Room main use	Linked rooms	Bdg. loc	Ventilation	Wood Stove	Pets	Floor material	Trickle vent open?
A1	1952 (2007)	SFH	2nd	15	15	HO	LR, B	CC	NV	Yes	Yes	P + C	No
A2	1900 (1995)	A	3rd	9.8	9.8	HO	Ba	CC	NV + EV	No	No	W	No
A3	1900 (1995)	A	2nd	48	48 (24)	LR	K	CC	NV + EV	No	No	P + C	No
A4	2019	SDH	3rd	15	15	LR	S	SNF	MV	No	Yes	P + C	No
B5	1972	SDH	2nd	5	5	HO	B	SNF	NV	No	No	P	Yes
B6	1960(2000)	SFH	B	4.5	4.5	HO	LR, OK	SF	NV + EV	No	No	W	Yes
B7	1972 (2015)	A	2nd	40	40(8)	LR	OK	SNF	NV	Yes	No	W	No
B8	1890 (2019)	A	1st	15	15(5)	LR, B, OK		CC	NV	No	No	W	No
C9	1970 (1997)	SDH	B	32	32	LR, K	B	SNF	NV	No	No	P	No
C10	1960(2000)	SFH	B	4.5	4.5	HO	LR, B	SF	NV + EV	No	No	P + C	Yes
C11	1964(2013)	SDH	1st	10.5	10.5	B	Ba	SF	NV	No	No	W	Yes
D12	1947 (2013)	A	1st	38	38(9.5)	LR	OK	CC	NV	No	No	P	No
D13	1946 (2007)	MFH	2nd	18	18 (4.5)	LR	OK	SNF	NV + EV	Yes	No	P + C	No (Yes)
D14	1946 (2007)	MFH	3rd	8	8	HO	B	SNF	NV	No	No	P	No
E15	1952 (2010)	SFH	1st	20	20	HO		SF	MV	No	Yes	P	Yes
E16	1989	SHF	1st	23	23 (11.5)	B		SF	MV	No	No	W + C	Yes
E17	1967	SFH	1st	47	47(16)	LR	OK	SNF	NV	Yes	No	P	No
E18	1967	SFH	1st	14	14	B		SNF	NV	No	No	W	No
F19	2019	A	3rd	25	25	LR, HO, OK		CC	MV	No	No	P	No
F20	2019	A	3rd	10	10	B	LR	CC	MV	No	No	P	No
F21	1964 (2013)	SDH	1st	10.5	10.5	B		SF	NV	No	No	P + C	Yes

They were given feedback after the winter measurements about how to improve their IAQ.

They were asked to keep a log of their activities such as cooking, cleaning, visits. However, most of the participants filled out this questionnaire loosely and it was not requested after the first two weeks of measurements. A second anonymized questionnaire was sent to all participants asking about their habits regarding working hours and house parameters. This was filled out by all the participants and the information was deemed as reliable. At least three houses were measured simultaneously in the same city area to control bias regarding outdoor air. Data management and analysis were performed using R studio Version 1.3.959 [52] and SPSS Version 28.0.1.0.

2.1.2. Measuring equipment

Data were collected using the LCS (see Table 5) at a single point per office. The sensors were placed on the desk next to the computer's keyboard to represent the breathing zone of the occupants but protected from exhaled air (checked by looking at peaks in CO_2 concentrations during exhalation periods). The data were collected every 5 min and logged into the internal memory of the Raspberry Pi to avoid sending the information to the cloud. More information about the sensor's calibration and intra-unit consistency can be found in Refs. [26,27]. The average difference among the LCS is when all are exposed to the same source is 14%, 1%, 3%, 2% and 18% for formaldehyde, temperature, RH, CO_2 and TVOC respectively [26,27].

Ventilation rates were not measured. Airflow rates in naturally ventilated buildings highly depend on weather, including outdoor air temperature, wind speed and direction, building characteristics, and windows and doors opening depending. Thus, measurements in different weather conditions would be necessary to develop a model for each household. This would have been necessary to study the effects of external leakages and the window and internal door opening degrees on airflow rates. Since the occupancy reporting was not thorough, using black-box models to characterize air changes as defined by Wolf et al. in Ref. [53] would not be accurate. Using any tracer gas measurement to map average air changes would also be affected by weather dependencies, so it would be necessary to repeat the process several times to get the dynamic ventilation rates. Using an average for the whole measurement period is deemed inaccurate Such measurement campaigns would have been disturbing to the subjects. In addition, during these visits, there would be a health risk of contracting COVID 19. Therefore, ventilation measurements were dropped to have a big enough sample that could be statistically representative and have enough households measured. As measurements for the naturally ventilated households were unavailable, no measurements were collected for the mechanically ventilated cases either for having comparable samples/weakness. Design values for the measured cases could have been added, but these are very theoretical. Mechanical ventilation users reported changing the settings of the openings to their comfort, closing the terminals because of noise, or opening more elsewhere in the house to

Table 5
Properties of the low-cost sensors used.

Sensor name	Parameter	Sensor type	Accuracy	Measurement range	Response time
Sensirion SCD30 [54]	Relative humidity	Capacitive	±3%RH at 25 °C	0–100%	8 s
Sensirion SCD30 [54]	CO_2	Nondispersive infrared (NDIR)	±30 ppm ± 3% (500–1500 ppm)	400–10000 ppm	20 s
Sensirion SCD30 [54]	Temperature	10 K NTC Thermistor	± (0.4 °C + 0.023 x (T [°C] - 25 °C))	−40 °C – 70 °C	>10 s
DART WZ-S formaldehyde module [55]	Formaldehyde	Electrochemical sensor (MOS)	≤0.02 ppm formaldehyde equivalent < ±2% repeatability	0.03–2 ppm	<40 s
Sensirion SVM30 [56]	TVOC	Multi-pixel metal-oxide	15% of MV[a]	0–60′000 ppb	

[a] typ 1.3% accuracy drift per year.

increase the feeling of "fresh air." In addition, for natural or mechanical ventilation, airtightness would play a significant role, and provided that most of the households have undergone building envelope/window renovations, the current state of the airtightness from construction time to today's status is probably changed.

For this work, the focuses lie on 1) mapping the IAQ, which is the result of the balance between supplied air and emission sources, to characterize the IAQ that subjects were breathing and 2) analysis of the predictor variables for the pollutants. For 1), the analysis can be done straightforwardly even without the ventilation rates as the interest lies in the resulting pollutant concentration breathed. For 2), more research is needed, including the airflow rates, to characterize the ventilation, which is supposed to be the primary predictor variable in the dilution of pollutants. Lacking the ventilation rates makes it challenging to analyze ventilation as predictor variable, as will be further discussed in the Result and Limitations chapter.

2.2. Statistical analysis

Models were developed to analyze the building characteristics' influence on CO2, formaldehyde, and TVOC concentrations using the statistical software IBM® SPSS® (Ver. 28.0).

Model selection is a prominent issue in practical data analysis [57]. Data collected from the same household is likely to be correlated. The generalized estimation equation (GEE) method was used to account for the correlations of samples collected from the same households (clusters). GEEs are an extension of generalized linear models, which facilitate regression analyses also when the dependent variable does not follow a normal distribution. GEE is a population-level approach based on a quasi-likelihood function and allows to account for correlations within clusters of responses on the dependent variable while assuming no between-cluster correlations exist [58,59]. TVOC, formaldehyde, and CO_2 were selected as continuous dependent variables and analyzed in separate models to identify each pollutant's specific determinants (independent variable). In our model, building ID was used as a cluster variable. Judged by the Shapiro Wilk test and histograms, the continuous dependent variables were skewed towards larger positive values. They were log-transformed before analysis to normalize the dependent variables and fitted using the standard gamma distribution with an identity link.

Continuous predictors included in the models were: RH (in %) and air temperature (°C). Categorical predictors were seasons (winter/summer), trickle vent status (open/closed), ventilation strategy (natural/hybrid/mechanical), pets (yes/no), wood stove (yes/no), floor material (carpet/wooden flooring or cork/parquet/carpets and wooden flooring), building location (city Centre/suburban non-forested area/suburban forested area), house type (single-family houses/semi-detached house/apartment/multifamily house), and main room (home office/bedroom/living room/open kitchen).

Considering the GEE is non-likelihood-based, no test for model fit exists [58]. However, the GEE model provides the Quasi-likelihood under Independence Model Criterion (QIC). QIC and corrected QIC (QICC) were used to select the correlation matrix and between different subsets of model terms. The model giving the smallest QIC gives the best model fit for the data, and the subset of predictor variables with the smallest QIC value is the preferred model [57]. Under the first-order autoregressive (AR (1)) correlation structure, each independent variable was first fitted stepwise. Different subsets of covariates were then fitted together to find the combination of variables that provided the smallest QICC chosen as the model fit for our data [60]. Furthermore, pairwise comparisons were conducted with Bonferroni correction to compare means within the same category.

In general, the GEE can be expressed using formula (1).

$$\sum_{i=1}^{k} \frac{\partial \mu_i}{\partial \beta} V_i^{-1} (Y_i - \mu_i(\beta)) = 0 \quad (1)$$

where Y_i represents the responses from cluster i, μ_i is the model mean for cluster i, β is the model parameters, and V_i is the estimated covariance matrix of Y_i.

A p-value less than 0.05 was considered statistically significant. It is important to point out that a correlation is a statistical indicator of the relationship between variables, but this is not necessarily due to a causal link.

3. Results and discussion

This section presents and discusses the analysis of the measured data.

3.1. Analysis of indoor air parameters against the health limit values

3.1.1. Relative humidity

In general, the houses with mechanical ventilation had a lower median RH (22.9%) compared to houses with natural ventilation (RH = 33.3%) and hybrid ventilation (RH = 29.6%).

Fig. 1 presents the distribution of the measured RH in the different cases during the whole measured time (MT). MT represents the whole period where measurements were collected in each case. Working hours (WH) were defined based on the subject's feedback. During the wintertime, with low outdoor temperature, only three cases were measured to have more than 2% of the WH between 40 and 60%, which is the range that may not lead to physical discomfort related to RH [42]. Five houses had more than 50% of the WH in winter between 30 and 60%, which reduces stress [40]. Only home office B8 had an RH above 60% during 37% of the WH. An RH above 60% is associated with an increased risk of mold growth [45] on cold and poorly ventilated surfaces. Roughly half of the home offices presented RH below 30% for more than 47% of the WH during wintertime. The users commonly complained about dry skin and eyes in households with dry air. When considering summer measurements, the problem with low RH was improved.

3.1.2. Temperature

Fig. 2 shows the fraction of the MT at the different ranges of temperature. In most cases, the air temperature was kept above 18 °C. Most periods where the temperature was below this threshold corresponded to the airing of the rooms or while sleeping. Sleeping with windows open during summer and winter is common in Norway [61]. Additionally, it is worth mentioning that users were not always present in the home office, and in cases E17 and E18, the heating was only on while working; thus, when users were not at the home office, the air temperature decreased.

For the cases measured, only an average of 20% of the WH were within the range of 22–24 °C, which has been found to provide optimal productivity and learning conditions [49,50], considering both measured periods and only 13% considering only winter. When asked, the users stated that they actively controlled the air temperature to their best comfort. A temperature above 26 °C is correlated with risks of thinking difficulty, poor concentration, fatigue, and depression. In four of the 21 cases measured during the winter, the temperature exceeded 26 °C for more than 30% of the WH.

In many cases, local heaters were started at maximum power when using the home office. In these cases, the heaters were not temperature-controlled, and thus the temperature peaked. However, when asked, the users claimed to be very satisfied with the temperature in the home offices. Temperatures above 30 °C were only measured in four cases. B8 surpasses 30 °C in 98% of the MT. Air temperatures above 30 °C have previously been linked to an increased risk of respiratory symptoms. In this study, none of the occupants reported having respiratory symptoms.

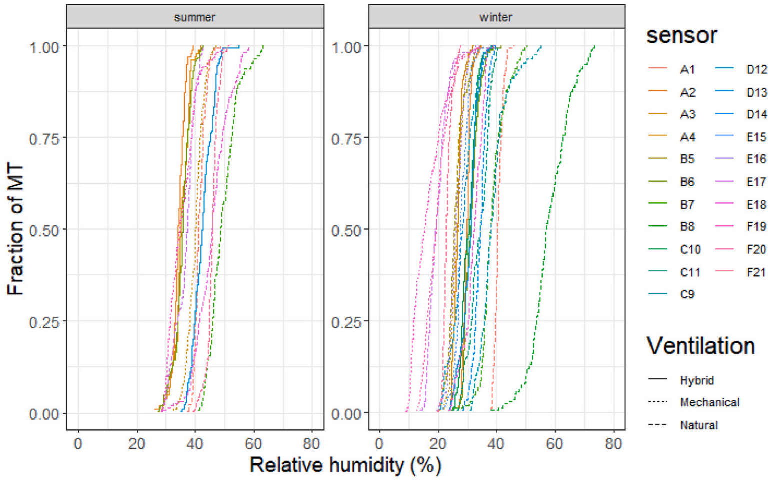

Fig. 1. Distribution of the RH during the measured time for each case, distinguishing summer and winter measurements. The color of the lines corresponds to the different cases and the line type to the ventilation strategy. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

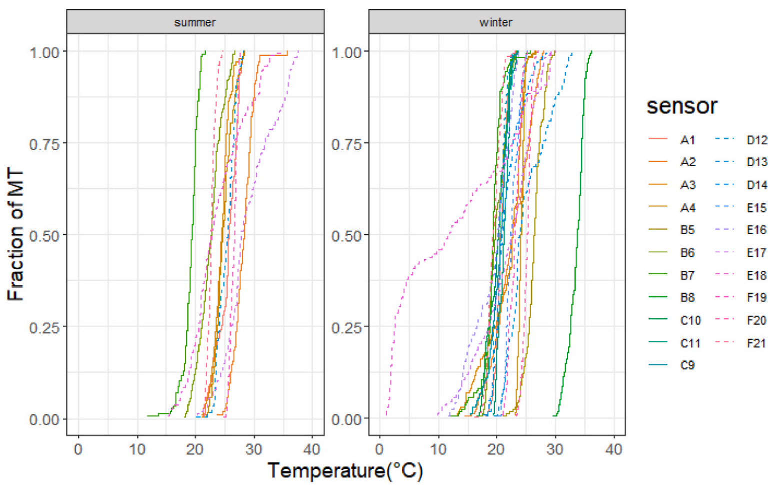

Fig. 2. Distribution of the temperature during the measured time for each case (summer and winter are included where two rounds of measurements were performed).

3.2. Analysis of pollutants against the health limit values and using the building parameters as explanatory variables

Overall, the highest median concentrations of formaldehyde, CO_2, and TVOC were measured in multi-family houses, while the lowest concentrations were in semi-detached houses. The highest concentrations of formaldehyde, CO_2, and TVOC were measured in B8, a combined living room, kitchen, and bedroom. The lowest median concentrations were measured in the bedrooms, followed by the living rooms.

3.2.1. Formaldehyde

Table 6 shows the fraction of the MT where the formaldehyde thresholds defined in Table 1 were surpassed. In this evaluation, the times are evaluated using moving averages during the limit-selected times. B8 was the only case exceeding the threshold for sensory irritation for 7% of the MT, but when focusing only on WH, none of the cases surpassed this threshold. Formaldehyde sensory irritation of the eyes and nasal cavities is an objective effect [62]. Sensory irritation is concentration-dependent with a ready onset, and there is no indication of an accumulative effect [62]. However, it has some latency and is not perceived immediately [63]. When asked, the occupants in B8 reported problems with eczema but no sensory irritation.

The WHO's threshold of 100 μg/m^3 for 30 min was generally surpassed during a limited share of the time, as shown in the second column in Table 6. The formaldehyde concentrations were generally lower during WH than considering the whole MT. When sitting in front of the computer, formaldehyde production is lower than during cooking, burning candles, or using the wood stove, and most of these activities happen outside WH. The results regarding the odor thresholds presented

Table 6
Fraction of the time where measured formaldehyde surpasses the indicated limit on the specified duration. Results in parentheses show values considering only winter.

ID	% Hours formaldehyde over 600 μg/m^3 4 h [30]		% Hours formaldehyde over 100 μg/m^3 30 min [29]		% Hours formaldehyde 110 μg/m^3 1 min [31]	
	% MT	% WH	%MT	%WH	%MT	%WH
A1	0%	0%	10 %-(17%)	0 %-(0%)	8 %-(12%)	0 %-(0%)
A2	0%	0%	2 %-(3%)	2 %-(4%)	1 %-(2%)	0 %-(1%)
A3	0%	0%	6 %-(10%)	1 %-(1%)	2 %-(6%)	0 %-(1%)
A4	0%	0%	5 %-(9%)	1 %-(3%)	4 %-(7%)	1 %-(3%)
B5	0%	0%	14%	29%	12%	25%
B6	0%	0%	3 %-(6%)	4 %-(7%)	1 %-(4%)	1 %-(7%)
B7	0%	0%	10 %-(19%)	10 %-(22%)	9 %-(17%)	7 %-(14%)
B8	7%	0%	87%	77%	76%	61%
C9	0%	0%	20%	17%	15%	14%
C10	0%	0%	2%	3%	2%	4%
C11	0%	0%	7%	6%	5%	5%
D12	0%	0%	8%	0%	7%	0%
D13	0%	0%	27 %-(25%)	7 %-(0%)	17 %-(25%)	7 %-(2%)
D14	0%	0%	25%	1%	21%	0%
E15	0%	0%	0%	0%	0%	0%
E16	0%	0%	0%	0%	0%	0%
E17	0%	0%	11 %-(13%)	11 %-(17%)	8 %-(11%)	10 %-(16%)
E18	0%	0%	4 %-(3%)	6 %-(7%)	3 %-(2%)	2 %-(5%)
F19	0%	0%	3 %-(5%)	2 %-(4%)	3 %-(4%)	2 %-(3%)
F20	0%	0%	6%	4%	5%	4%
F21	0%	0%	1% (2%)	2% (4%)	1%(2%)	1% (3%)

in the third column were very similar. to the ones using the WHO's threshold.

In GEE, the subset of variables with the smallest QIC was considered the preferred model. Table 7 shows the combination of variables giving the smallest QIC for formaldehyde. The model used summer, trickle ventilation closed, and wood stove "yes" as reference values. As shown, higher concentrations of formaldehyde ($\beta = 0.32$) were measured during the winter compared to the summer ($\beta = 0$), a statistically significant result ($p = 0.01$). The median concentrations of formaldehyde were 50.7 μg/m^3 and 36.9 μg/m^3 for winter and summer, respectively. This finding corresponds to a previous study in which season was a significant predictor variable for the formaldehyde concentrations measured indoors [64]. Other important predictor variables were trickle vent status and wood stove (See Fig. 3). As shown in Table 7, significantly higher (<0.001) formaldehyde concentrations were measured in houses where the trickle vent was closed compared to houses where the trickle vent was open. The median concentrations of formaldehyde in houses where the trickle vent was closed was 57.9 μg/m^3 compared to houses where the trickle vent was open, 36.7 μg/m^3. Significantly higher concentrations were also measured in houses with woodstoves (70.5 μg/m^3) than those without woodstoves (43.0 μg/m^3). These results may be explained by increased dilution by ventilation (controlled or uncontrolled) and less use of candle burning, wood storage, and wood-burning, during the summer season, compared to the winter season.

As shown in Table 7, air temperature and RH were significant positive predictor variables for the formaldehyde concentration measured indoors. This finding is in line with previous studies in which a significant positive relationship has been established between air temperature, RH, and various gases found in the indoor environment [65–67].

In a previous study, the median formaldehyde concentrations measured in apartments and single-family houses were 22 μg/m^3 and 13 μg/m^3, respectively, and air change rate was found to be a significant predictor variable for the concentrations of NO_2, TVOC, and formaldehyde measured indoors [68]. Although this study measured significantly lower concentrations in houses with mechanical ventilation than in houses with natural ventilation ($p = 0.01$), the ventilation strategy was not a significant predictor variable for the formaldehyde concentration. The reader must remember that the ventilation rates were not measured, and the comparison was made between different ventilation strategies but not ventilation airflow rates. However, ventilation rates may be connected to the high concentrations of formaldehyde, considering that 1) the lower concentrations of formaldehyde were measured in houses with mechanical ventilation and 2) that trickle vent status was one of the most important predictor variables for the formaldehyde concentrations measured indoors.

Sakai et al. [69] measured the concentration of VOC and formaldehyde in 37 and 27 dwellings in Japan and Sweden. The formaldehyde concentrations were found to be higher in new buildings (age <10 years) and modern concrete houses [69]. Contrarily, in our study, the four houses with the highest median formaldehyde concentrations were older than 60 years, and the year of the building was significantly negatively correlated with the formaldehyde concentration. The formaldehyde emission from building materials and furniture decays exponentially with time [70]. One of these cases was renovated in 2019, two in 2007, and one was never renovated.

In Norway, airtightness requirements have increased in the more recent building codes. The required infiltration air changes at 50 Pa (n_{50}) were reduced from 2.5 h^{-1} in TEK10 [45] to 0.6 h^{-1} in TEK17 [46], and thus, stricter ventilation airflow rate requirements were introduced. This energy-saving/air-tightening trend has been transferred to renovation projects, and many renovations focus on tightening the envelopes while neglecting the need for ventilation [71,72], as no requirements are enforced in renovation projects. For example, B8 was retrofitted with envelope tightened and no mechanical ventilation in 2015 and painted in 2019. This may explain part of the high concentrations observed in this case.

One of the recommendations to reduce formaldehyde in households is to increase the ventilation rates via mechanical ventilation or the opening of windows, trickle vents, and doors unless the outdoor air quality is harmful. According to this and our measurements and analysis, to ensure lower levels of formaldehyde, the important actions are to keep the trickle vents open, to keep IRT low, and to keep wood away when having wood stoves. A general ventilation increase during activities that can be sources of formaldehyde, such as cooking, burning candles, etc., is recommended.

Table 7
The estimates for the most important predictor variables (β) for formaldehyde using GEE.

Predictors Log formaldehyde	Season*		Trickle ventilation		Woodstove		Indoor air temperature	Relative humidity
	Winter	Summer	Closed	Open	Yes	No		
β	0.32	0**	0.31	0**	0**	−0.28	0.05	0.03
p-value	0.01		<0.001			0.01	<0.001	<0.001

A p-value less than 0.05 was considered statistically significant.
*Estimated based on houses measured both during the summer and winter (n = 11).
** This variable was used as a reference variable.

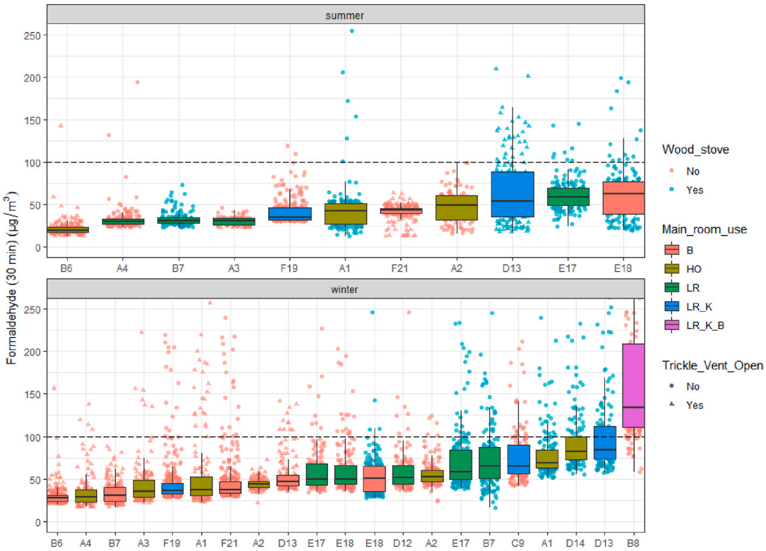

Fig. 3. Distribution of formaldehyde measurements for each house colored by the room's primary use. The dots or triangles in this figure show the single measurements aggregated by hour featured by the status of the trickle vent, and their coloring refers to the existence or not of the wood stove in the house.

3.2.2. TVOC

The fraction of time in the various TVOC-WHO categories [32] during the MT is presented in Table 8. Seventy-three percent of the MT, considering all the 21 cases, belong to "greatly" and "significantly" increased TVOC levels. These levels were maintained consecutively for 68 h on average and constantly in the worst measured case. Case B7 had a significant fraction of measured hours with elevated levels, but it did not have as many consecutive hours as its users were "shock ventilating" and opening windows.

In our study, the variables providing the best model fit for TVOC, interpreting data from the 21 houses measured in the winter only, were trickle ventilation, air temperature, and RH, as shown in Table 9. Thus, these variables are considered the most important predictor variables for the TVOC concentration. Significantly higher ($p = 0.05$) concentrations of TVOC were measured in houses where the trickle vent was closed

Table 9
The estimates for the most important predictor variables (β) for TVOCusing generalized estimating equations (GEE).

Log TVOC	Predictors			
	Trickle ventilation		Indoor air temperature	Relative humidity
	Closed	Open		
β	0.32	0**	0.10	0.06
p-value	0.05		<0.001	<0.001

A p-value less than 0.05 was considered statistically significant.
** This variable was used as a reference variable.

Table 8
Fraction of the MT in the different levels is defined by the WHO [32], presented in Table 2, and maximum consecutive hours in the worst levels (aggregated by 30 min). Parentheses show results considering only winter measurements.

ID	Outside quality classes MT %	Level 4 MT %	Level 3 MT %	Level 2 MT %	Level 1 MT %	Maximum consecutive hours outside or level 4
A1	6 %-(12%)	74 %-(88%)	9 %-(0%)	6 %-(17%)	5 %-(0%)	163
A2	2 %-(6%)	77 %-(90%)	11 %-(3%)	5% -(17%)	5 %-(1%)	93
A3	5 %-(2%)	54 %-(52%)	25 %-(39%)	10 %-(17%)	6 %-(1%)	23
A4	8 %-(14%)	78 %-(86%)	9 %-(0%)	4 %-(17%)	1 %-(0%)	143
B5	11%	56%	18%	7%	8%	21
B6	1 %-(3%)	22 %-(33%)	39 %-(29%)	26 %-(18%)	12 %-(17%)	23
B7	15 %-(20%)	69 %-(70%)	9 %-(5%)	3 %-(1%)	4 %-(4%)	27
B8	86%	13%	1%	0%	0%	90
C9	19%	72%	9%	0%	0%	123
C10	1%	32%	32%	11%	24%	16
C11	7%	89%	4%	0%	0%	47
D12	4%	48%	20%	15%	13%	20
D13	20 %-(43%)	62 %-(57%)	11 %-(0%)	5 %-(0%)	2 %-(0%)	169
D14	43%	57%	0%	0%	0%	169
E15	3%	96%	1%	0%	0%	171
E16	0%	54%	33%	8%	5%	22
E17	6 %-(8%)	56 %-(44%)	19 %-(28%)	9 %-(9%)	10 %-(11%)	21
E18	10 %-(0%)	80 %-(48%)	5 %-(28%)	2 %-(14%)	3 %-(10%)	23
F19	13 %-(8%)	63 %-(53%)	15 %-(24%)	5 %-(9%)	4 %-(6%)	19
F20	6%	56%	25%	7%	6%	21
F21	0%	41%	32%	11%	16%	19

(median 355.0 μg/m^3) compared to houses where the trickle vent was open (median 244.2 μg/m^3). Although higher median concentrations of TVOC were measured in houses with a wood stove (429.5 μg/m^3) than in houses without a wood stove (284.6 μg/m^3), the wood stove was not a significant predictor variable for the TVOC concentrations observed, see Fig. 4.

As shown in Table 9, season were not included as one of the most important predictor variables for TVOC, and no significant difference was observed in TVOC concentrations between summer and the winter ($p = 0.85$). This corresponds with the findings of a previous population-based study, in which no significant difference was observed in 18 VOCs measured across seasons [73].

Exposure to elevated levels of certain TVOCs in households has been linked to deleterious health effects. The immediate perception of IAQ is very much affected by odorous VOCs and particles [74]. Users may suffer from sensory irritation when a single VOC is over the threshold and from combined effects of sensory irritants [74] or a weak sensory irritation combined with much higher levels of olfactory stimulation [75].

RH should not be disregarded because it may also affect perception [74]. Dry mucous membranes may exacerbate the effects of sensory irritants and other pollutants [62]. Odors are easily detected at the lowest exposure levels, but individuals may confuse odors with sensory irritation symptoms. Thus, due to the cofounding effects of odor and RH, the threshold values for sensory irritation may be too low [74]. During winter periods, the RH levels were low in many cases, affecting the perception. However, no further analysis was done regarding the composition of the TVOC or possible health effects. The general recommendation would be to increase ventilation as outdoor air in Trondheim typically has lower TVOC values than indoors.

In a recent study from Switzerland, in which TVOC and formaldehyde were measured in 169 energy-efficient dwellings, it was found that retrofitted dwellings without mechanical ventilation were associated with elevated indoor concentrations of formaldehyde, toluene, and butane and that measures to reduce the energy use of the buildings should be accompanied by measures to mitigate the exposure concentrations [18]. These findings correspond to the findings in our study, in which lower concentrations of formaldehyde, TVOC, and CO_2 were measured in houses where the trickle vent was open.

3.2.3. Carbon dioxide

7 of 21 cases had more than 5% of the MT above 1000 ppm, and 11 of 21 cases had more than 10% of the MT above 1000 ppm during winter. Due to infiltration and the ventilation via windows, trickle vents, and mechanical ventilation, CO_2 levels were primarily below 1000 ppm. However, for cases B8 and E15, the 1000 ppm threshold was surpassed. Case B8 was a very small apartment, with a high occupancy density, and the windows and trickle vents were continuously closed to avoid thermal discomfort. Case E15 consisted of a large room at the end of the mechanical ventilation branch, with a very low supplied airflow rate. The user claimed that the air regularly felt too heavy.

Tsai et al. [76] showed with GEE models that workers exposed to indoor CO_2 levels greater than 800 ppm were likely to report more eye irritation or upper respiratory symptoms [76]. CO_2 impairs cognitive performance already at exposures over 1000 ppm over 1 h [77,78]. CO_2 retention may also happen after exposures below 4 h to CO_2 concentrations below 1000 ppm [78]. Therefore, it is very positive that this value is not surpassed, and CO_2 measurements during home office are recommended.

As shown in Table 10, the differences observed in CO_2 between summer and winter reached statical significance ($p = 0.01$), with median concentrations of CO_2 of 637 ppm and 514 ppm, for winter and summer, respectively. This is probably due to reduced ventilation in

Table 10
The estimates for the most important predictor variables (β) for CO_2 using GEE.

Log CO_2	Predictors			
	Season*		Indoor air temperature	Relative humidity
	Winter	Summer		
β	0.18	0**	0.03	0.03
p-value	0.01		<0.001	<0.001

A p-value less than 0.05 was considered statistically significant.
*Estimated based on houses measured both during the summer and winter (n = 11).
** This variable was used as a reference variable.

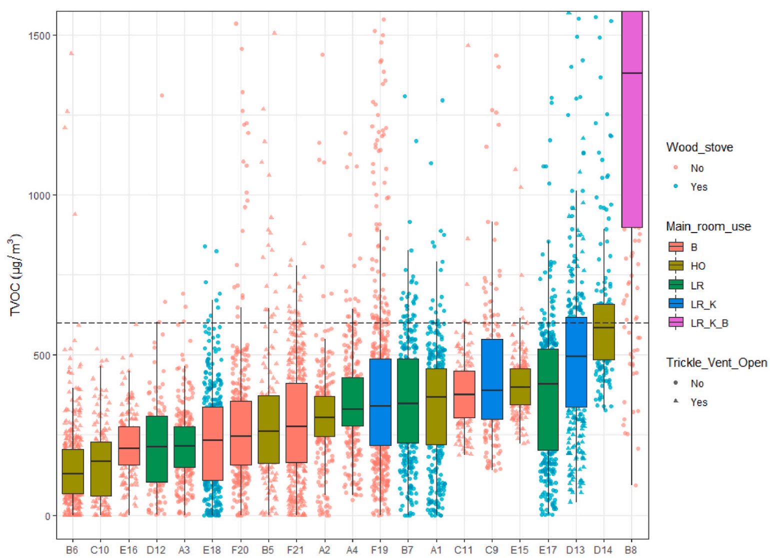

Fig. 4. Distribution of TVOC measurements for each house colored by the room's primary use. The dots or triangles in this figure show the single measurements aggregated by hour featured by the status of the trickle vent, and their coloring refers to the existence or not of the wood stove in the house.

winter to avoid the draft. This finding aligns with a previous study, where higher concentrations of CO_2, CO, PM_{10}, and $PM_{2.5}$ were measured during the winter compared to the summer [79]. Significantly higher concentrations of CO_2 were also measured during the winter in another study [80].

No difference in CO_2 concentration was observed between the cases with natural, mechanical, or hybrid ventilation. In this case, the correlations are not sought among ventilation rates and CO_2 but ventilation strategies and CO_2 disregarding actual airflow rates as these were unknown. This may be counterintuitive and is a big weakness of not measuring the airflow rates. However, in this text, it is not stated that ventilation airflow rates are not a relevant predictor but that the ventilation strategy without further consideration of airflows is not a significant predictor. Although the median CO_2 concentration was 49 ppm lower in homes with the trickle vents open, the only two variables improving the model fit for CO_2 were RH and air temperature, see Table 10. This is in line with a recent study [80], where the multivariate linear regression model was used to analyze the most important predictor variables of CO_2. After adjusting for seasonal differences, the most important predictor variables for the measured CO_2 concentration were background concentration, RH, flooring material, heating, and age of the occupants. These variables explained 64% of the variability observed in CO_2 [80].

Several previous studies have investigated if CO_2 could be used as a surrogate for other indoor air quality parameters and pollutants [81]. In one study [82], the weekly average CO_2 concentrations measured in dwellings were positively and significantly correlated with formaldehyde, acetaldehyde acrolein, benzene, $PM_{2.5}$, and PM_{10}. However, low CO_2 concentrations did not correspond to satisfactory indoor air quality [82]. In another study [79], the measured concentrations of $PM_{2.5}$ and PM_{10} exceeded the WHO guidelines, while the concentration of CO_2 was below the WHO guidelines. In the measurements hereby presented, simultaneously with CO_2 concentrations below 1000 ppm, there were many occurrences of high concentrations of TVOC and formaldehyde.

3.3. Limitations of the study

- Air changes, airflow rates, or air leakages were not measured. It is a weakness of this article not to have measured the supplied/exhausted airflow rates or at least the air changes in a representative condition or to have calculated them with a black box model. This was not done due to the difficulty of continuous measurements of airflows for natural ventilation and the general challenges of measuring during a period with COVID-19 restrictions. In literature, CO_2 is commonly used as a surrogate to calculate ventilation rates [53,83], and numerous studies are concluding on correlations between ventilation rates and RH, CO_2, and temperature [84,85]. The present article cannot corroborate or contradict these.
- Occupancy was not measured. Another weakness of the experimental design was not automatically measuring occupancy. Users were asked to keep a log of their presence in the room. Most subjects had a general knowledge of their working hours, but they did not keep reliable recordings after the first or second day, and thus the correlations between the real number of occupants and pollutants could not be studied.
- Short time measurements. The measurements of this study have been collected for one to two weeks. In observational studies, there is a potential for bias from the users over opening the windows, changing radiator setpoints, or other behavior divergent from their normal as they feel “observed by the sensors.” Being all the users from the same engineering population may also affect the results. A more extended measurement period would have been better to reduce this bias.
- These measurements would not be sufficient to represent the whole room as the mixing of the air or any other considerations about air distribution in the room have not been studied. These measurements only intend to represent the air breathed by the home office user.
- Though the CO_2, formaldehyde, temperature, and RH were measured with calibrated low-cost sensors, TVOC sensors were not calibrated, and their quality was not assessed beforehand more than the intra-unit consistency. However, the sensors have been exposed to different sources of TVOC reacting similarly. The average intra-unit consistency of all the TVOC sensors was 18%, as stated in the article [27]. Therefore, the TVOC sensor should be considered valid for analyzing trends, but further calibrations of the sensor should be done to evaluate their accuracy.

4. Conclusions

In this study, the concentrations of formaldehyde, CO_2, TVOC, and the levels of indoor room temperature and relative humidity were measured in 21 home offices for at least one week in winter in Trondheim, Norway. Eleven of these were measured again for the same duration in summer. Parameters that could be explanatory variables such as building and renovation year, house type, building location, trickle vent status, occupancy, wood stove, floor material, and pets were simultaneously collected. A statistical data analysis using generalized estimation equations was done to determine the significant parameters to control pollutants.

Relative humidity was generally too low in winter. During working hours, the temperatures were generally kept over the recommended level of 22–24 °C.

In general, formaldehyde concentrations were higher outside working hours than during working hours but mostly below health thresholds. They were higher in winter than summer, with median concentrations of 50.7 $\mu g/m^3$ and 36.9 $\mu g/m^3$ for winter and summer, respectively. Additionally, the status of the trickle vent, the air temperature, and the RH were important predictor variables for the formaldehyde concentrations.

Measurements of TVOC showed generally elevated levels, higher than recommended in 73% of the measured cases. Trickle vent status, air temperature, and RH were considered the most important predictor variables for the TVOC concentration. The median winter concentration of TVOC was about 100 $\mu g/m^3$ higher when the trickle vent was closed. Although higher median concentrations of TVOC were measured in houses with a wood stove (429.5 $\mu g/m^3$) than in houses without a wood stove (284.6 $\mu g/m^3$), the wood stove was not a significant predictor variable for the TVOC concentrations. Neither the season gave a significant difference.

Regarding CO_2, roughly half of the measured cases had more than ten percent of the measured time above 1000 ppm during winter. The difference among seasons was statical significant, with median concentrations of CO_2 of 637 ppm and 514 ppm, for winter and summer, respectively. No difference in CO_2 concentration was observed between the different ventilation strategies. RH and air temperature were the only two variables improving the model fit for CO_2.

Our findings suggest that RH and air temperature significantly predict formaldehyde, TVOC, and CO_2 indoor concentration. This is probably due to the changes in ventilation. Trickle vent is a significant predictor of formaldehyde and TVOC, and thought is not significant to predict CO_2; higher levels were measured while this vent was closed. Having a wood stove is significant and positively related to formaldehyde concentrations, and though TVOC was also measured on average higher in cases with a wood stove, it was not a significant predictor. Finally, measurements in winter seasons resulted in higher for the three pollutants, but the season is only a significant predictor of CO_2 and formaldehyde.

These results also show that controlling the concentration of CO_2 may not be sufficient to provide for healthy indoor air quality as occurrences of high TVOC or formaldehyde happen simultaneously to concentrations of CO_2 below 1000 ppm.

CRediT authorship contribution statement

M. Justo Alonso: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **T.N. Moazami:** Writing – original draft, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **P. Liu:** Writing – original draft, Formal analysis. **R.B. Jørgensen:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **H.M. Mathisen:** Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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PAPER 5

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Holistic methodology to reduce energy use and improve indoor air quality for demand-controlled ventilation

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Abstract

Ventilation control logics are usually based on the control indicators of occupancy. However, strategies including control of contaminants not linked to occupancy are requested and more feasible with the introduction in the market of low-cost sensors (LCS).

In this work, a methodology for the improvement of demand-controlled ventilation (DCV) including different parameters measured with LCS, correlation analysis, and co-simulation EnergyPlus/CONTAM to reduce annual energy use and the fraction of time with room air concentration of IAQ parameters outside the selected guidelines is presented.

The ventilation control sequences focused on the significant parameters chosen by cross-correlation functions in the de-trended measurements to control supply airflow rates and recirculation of return air.

The results revealed that the model successfully developed control sequences that simultaneously reduced annual energy use and the number of hours outside the recommended IAQ guidelines compared to the baselines. In cold cities with excellent outdoor air quality, recirculation could reduce energy use and increase the RH in winter. Further simulations demonstrated that the use of recirculation had a protective effect on the indoor concentrations of $PM_{2.5}$, assuming low outdoor air quality. However, when using recirculation, it is essential to control the IAQ to avoid excessive pollutants, RH, and temperatures.

Keywords

Annual energy use, indoor air quality, low-cost sensors, airborne pollutants, correlations

Nomenclature

AHU Air handling unit

CAV Constant air volume

CCF Cross-correlation function

CV-RMSE Coefficient of variance of the root-mean-squared error

DCV Demand-controlled ventilation

EUI Annual energy usage index (kWh/m^2)

HVAC Heating, ventilation, and air-conditioning

IAQ Indoor air quality

I/O Ratio between indoor and outdoor pollutant concentrations

KPI Key performance factor

LCS Low-cost sensor

NMBE Normalized mean bias error (

NDIR Nondispersive infrared

OA Outdoor air

PM Particulate matter

RH Relative humidity

TVOC Total volatile organic compound

VAV Variable air volume

WH Working hours: Monday-Friday 0800-1700. All moths included

WHO World Health Organization

Introduction

In the past several decades, Norwegian and several countries' building envelopes have become more airtight and insulated to reduce the energy used for space heating [1,2]. In the pursuit of reducing uncontrolled air leakage, it has become apparent that ventilation systems using demand control are needed to improve energy efficiency [3]. In countries such as China, Canada, and the USA, the recirculation of return air is a state-of-the-art practice. In these cases, the minimum outdoor air (OA) fraction is influenced by two factors: the requirements to meet indoor air quality (IAQ) standards and the desire to reduce heating, cooling, and dehumidification demands from air handling unit (AHU) coils [4]. However, insufficient OA fractions and airtight buildings may degrade the IAQ [5,6]. Therefore, in Norway, building codes do not recommend the recirculation of return air when the room is in use [7]. However, simulations have proven that a well-controlled recirculation of a fraction of the return air can produce a protective effect against outdoor pollutants and reduce annual energy use [8]. This is mainly because the ratio between indoor and outdoor pollutant concentrations is dependent on the OA supply and the filters [9].

Most countries' IAQ criteria are based on health impacts and perceptions of the IAQ [10,11]. However, several of the pollutants defined in these documents, such as nitrogen oxides, sulfur oxides, ozone, particulate matter, and formaldehyde, are rarely measured because airborne pollutant concentration measurement by traditional measurement equipment is costly. Therefore, until recently [12], the literature often refers to IAQ measurements as CO_2, temperature, and sometimes relative humidity (RH) [13]. Manufacturers have tried to bridge the gap, enabling measurements of health-related pollutants and standard measurements by supporting extended IAQ measurements with low-cost sensors (LCSs), defined in this article as a sensor costing less than EUR 50.

The newest LCSs are becoming more reliable, and many can produce continuous measurements [14]. They allow measurement at a reasonable price but often have lower accuracy than reference equipment [14]. LCSs allow the monitoring of several IAQ parameters, but they need to be calibrated [15]. In

2010, an experimental evaluation of 45 nondispersive infrared (NDIR) CO_2 sensors (three from each of the 15 models tested) revealed wide variability in sensor performance among various manufacturers and, in some cases, among sensors of the same model [16]. Since then, NDIR technology for CO_2 measurements has shown major development.These devices have better accuracy and repeatability [17].

The communication between LCSs and conventional ventilation control systems is not standardized. Although this may currently result in more complicated systems, improvements are expected [18]. LCSs may also reduce embodied CO_2 emissions [19,20], as many of these sensors can communicate wirelessly, facilitating reduced emissions.

CO_2 is an accurate marker for bioeffluents [21]. Therefore, together with temperature, it is often used to control demand-controlled ventilation (DCV). However, more than 50 % of the pollutants in offices are not emitted by humans [22], and in homes, NO_2, CO, PM_{10}, and $PM_{2.5}$ may be highly relevant [23]. Moreover, CO_2 is not necessarily correlated with other frequent IAQ pollutants [24] and thus, using CO_2 as proxy for them may be misleading. The correlations between airborne pollutants or pollutants and environmental parameters, such as RH, and temperature are not necessarily constant between buildings [24], and they are not necessarily correlated between buildings of the same type [25]. Finally, the ratios between indoor and outdoor pollutant concentrations (I/O ratios) depend on the season [26], building tightness, installed filters, and considered pollutants. Several studies have measured elevated levels of "other" pollutants and low CO_2 concentrations simultaneously[27,28]. Therefore, some researchers recommend using CO_2 to signal occupant-related pollutants [29,30], but others recommend controlling other additional parameters [25,30–33] given that CO_2 and temperature may not detect other airborne pollutants with more concerning health, comfort, and productivity effects. Thus, a selection protocol of required airborne pollutants is needed because of the limited knowledge of controlling ventilation on the basis of several IAQ parameters.

Some attempts have been done to introduce several control parameters. A study in the residential sector used CO_2 in bedrooms and volatile organic compounds (VOCs) in toilets [34]. Guyot [35] reviewed the existing smart residential ventilation and found that the most advanced ventilation control used CO_2, temperature, RH, and total volatile organic compounds (TVOCs) (mostly in bathrooms). In industrial ventilation, some research has used indicators other than CO_2 to control ventilation; for example, PM was used to control ventilation in melting factories [36]. Although DCV and economizers have been commonly used in offices, we did not identify noteworthy literature on the use of economizers and heat recovery systems. Furthermore, no literature was found regarding the optimization of DCV or the recirculation of return air, considering energy use and IAQ from a broader perspective than CO_2 and temperature. The HVAC control sequences in Guideline 36 [37] focus on occupancy, CO_2, and temperature. Using the sequences provided in Guideline 36, energy savings have been calculated to be 31% [38] but these sequences are deterministic and do not consider the effects of modulating OA on airborne pollutants other than the preselected. Other studies have focused on different parts of the control; for example, these studies have evaluated: real-life performance [39], forecasted pollutants [40], optimized ventilation control[41,42], and assessed simulation strategies [8,43–46].

A recent ASHRAE position paper [33] requested *"Strategies for DCV using CO_2 and other indicators of occupancy that overcome limitations of current approaches and control contaminants that are not linked to occupancy"*. However, the paper did not elaborate on how to select these other indicators not linked to occupancy or how to use them in DCV sequences.

In order to choose which of the measurable contaminants not linked to occupancy are necessary to control ventilation, correlation analysis can be used. Correlation analyses are practical as using one of the correlated parameters in the control logic would be enough to represent the correlated parameters and control the supplied airflow rate [47]. In the literature, Pearson and Spearman correlation coefficients are often used to analyze correlations [48–52]. However, these analyses focus on simultaneous correlation and not on the effect of one variable on another over time. Cross-correlation functions (CCFs) can address this challenge [47] and unveil correlations even if they are shifted in time. CCFs calculate the Pearson correlations in simultaneous and time-shifted lags.

Introducing the new/additional parameters in ventilation control strategies can be cumbersome and complicated. Given that parameters with different origins have different emission profiles and strengths they may send contradictory control feedback. Validated simulations can improve the trial-and-error for ventilation controls. Many programs are used to simulate control strategies for DCV, such as EnergyPlus [43], IDA ICE [45], TRNSYS [53], CONTAM [54], and Modelica [46]. However, most of these simulation programs cannot simultaneously simulate all aspects of energy, airflow, IAQ, pollutants sources, and heating, ventilation, and air conditioning (HVAC) controls. Therefore, available simulation literature has focused on energy or IAQ but not both simultaneously. Emmerich and Persily [55] focused on several IAQ pollutants but did not consider energy use. Hua *et al.* [56] developed a method for obtaining the necessary OA fraction based on the indoor CO_2 concentrations and then examined the OA damper static pressure to optimize the OA volume setpoint according to the total volume demand of terminals. This work assessed energy and CO_2 but no other IAQ parameters. Zhao *et al.* [57] developed a control method for determining the OA volume flow setpoints based on differential pressure control strategies to optimize energy, but they too did not assess other IAQ parameters. Zhao, Wang, *et al.* [58] compared the performance of different OA fractions concerning CO_2 and energy savings. Although the tools for IAQ and energy simulation are available, no previous work has focused on the simultaneous effects of extended IAQ (referring to CO_2, temperature, and several other airborne pollutants) and energy use while using DCV and recirculating return air. Co-simulation can solve this weakness. EnergyPlus/CONTAM [8] or CONTAM/TRNSYS [44] can be used when all the above mentioned parameters must be evaluated. Co-simulation between EnergyPlus and CONTAM can be used to evaluate whole-building energy, airflow, and IAQ, and both tools are available free of cost [8].

The research gap addressed in this article involves the development and testing of a holistic method for improving DCV control using (or not) the recirculation of return air. The improvements of the ventilation control logic aim to reduce annual energy use and number of hours where CO_2, temperature, and several other airborne pollutants and RH are outside the guidelines. In the methodology developed in this article, the selection of the pollutants is probabilistic and nondeterministic because pollutant selection is part of the method. A holistic methodology is needed to harmonize the trade-off between energy use and IAQ. This methodology is demonstrated in a full-scale office case study using measurements and simulations. This work represents an instrumental step toward a paradigm shift in ventilation control. In addition, it contributes to accommodating the future use of several pollutants' measurements with the spread of LCSs into the market.

2 Methods

This section summarizes the details of the data collection, the selection of the significant parameters, the simulation environment, and the stepwise tuning of the ventilation control. The methodology developed for tuning the ventilation control logic to simultaneously reduce annual energy use and improve IAQ followed the steps defined below and summarized in Fig. *1*.

Step 1. Pollutants in three full-scale cell office rooms were measured (bubbles 1-3 in Fig. *1*) to characterize and validate an EnergyPlus/CONTAM simulation model (bubbles 5, 6, 8 in Fig. *1*). For this purpose, calibrated LCSs [15,59] were used. The measured pollutants were CO_2, formaldehyde, TVOCs, and $PM_{2.5}$, and the environmental parameters were RH and temperature (in this text, all these measurements are often referred to as parameters).

Step 2. According to the method described in [47], CCF in de-trended time series were used to determine which parameters should be used to control the ventilation airflow rates. Correlations between different parameters at room level were used to control the supply airflow rates to the room. Correlations between the same parameters at room and supply air were evaluated to control the recirculation airflow rates (bubbles 4, 7 in Fig. *1*). Significant correlations were sought to select the appropriate parameters for tuning the control of the supply airflow rate and the recirculation of return air in a probabilistic way.

Step 3. The control sequences of the selected parameters were tuned by studying the results of the validated EnergyPlus/CONTAM co-simulation (bubbles 9-14 in Fig. *1*). Improvements focused on increasing the number of hours in which the guidelines of the parameters were maintained and reducing the energy use. The sequences were kept simple to focus on the methodology.

Fig. *1* summarizes the above steps carried out for this methodology. This comprehensive methodology to improve ventilation control and thus reduce annual energy use and improve IAQ offers a procedure that operation personnel can use to map and react to problems with IAQ or energy use. The methodology can be improved by using more advanced control optimization methods, but this was outside of the scope of this article.

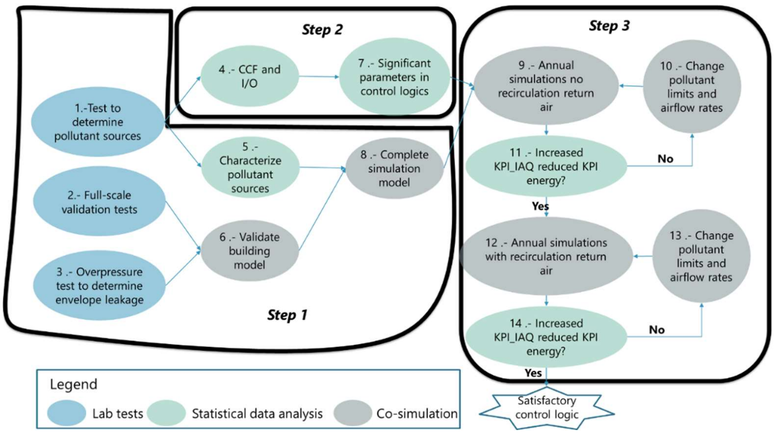

Fig. 1. Framework of the methodology in this study. *Note for abbreviations for the Fig. CCF= cross-correlation factors, I/O= indoor outdoor ratio, KPI = Key performance indicator, IAQ= Indoor Air Quality.*

2.1Case study: measurements in the laboratory

A setup consisting of three equal offices was built inside a climate chamber in the laboratory of the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU). The dimensions of the three equal offices are marked in

Fig. 2. All rooms had equal ventilation and were equipped with a supply terminal (Orion-Løv from TROX Auranor) [60] and an exhaust terminal (LVC from TROX Auranor) [61]. Volume flow controllers (LEO VAV from TROX Auranor) [62] were placed in the main supply, main exhaust, and recirculation duct branches. The damper positions were provided as a 0–10 V signal via a Belimo Modbus register [63]. The fan speed needed in the AHU UNI 3 from Flexit [64] was sent via a Modbus

adapter CI66, both from Flexit [65]. The damper throttling was modulated to achieve the expected airflow rates, and the exhaust dampers were controlled to extract air at the same rate. The rotary heat recovery of the UNI 3 was run at constant rotational speed. The control signal was calculated and sent from a Raspberry Pi, which evaluated the LCS measurements. Room 1 was positioned nearest to the commercially available AHU UNI 3.

Fig. 3 shows the control architecture.

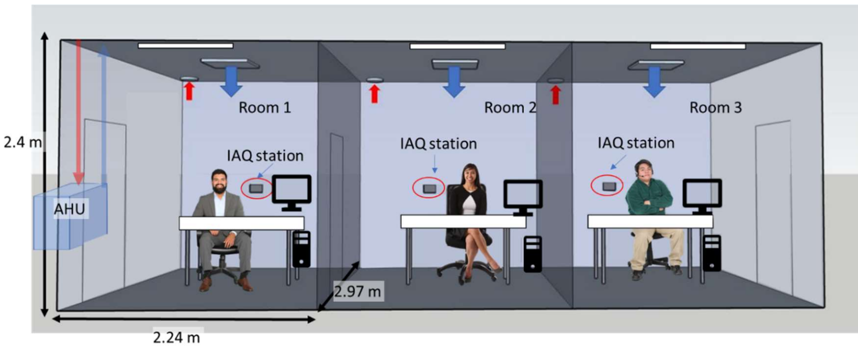

Fig. 2. Sketch of the three cell offices showing their dimensions and the placement of the LCS and ventilation.

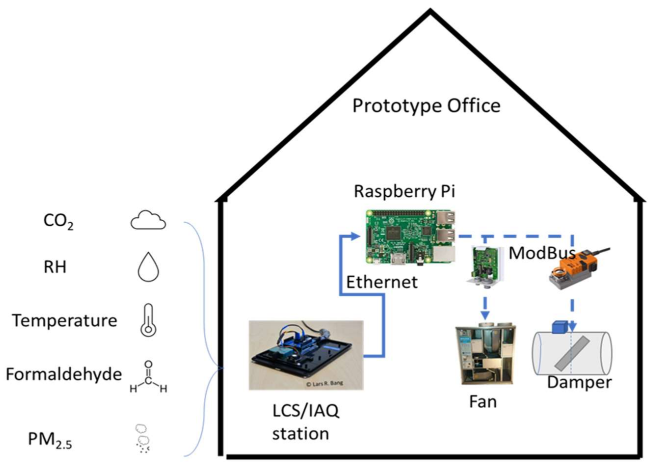

Fig. 3. Overview of the developed control system. The Arduino based sensors send measurements feedback to the Raspberry Pi that calculates the fan and damper settings

Every room was equipped with an in-house mounted IAQ station each with five LCSs. Table 1 shows the main details of the LCSs used. More information about these sensors and their calibration can be found in [15,59]. The total cost of the LCS station with all the sensors described in Table 1 and the Raspberry Pi was below EUR 200. The individual prices of the sensors in 2018 were as follows: EUR 47 for the SCD30, EUR 29 for the Arduino Shield SGP30_SHT1, EUR 39 for the SPS30, EUR 15 for the Dart WZ-S formaldehyde module, and EUR 72 for the Raspberry Pi. The IAQ stations were placed in the center of the wall (1.12 m from each sidewall) behind the occupants at a height of 1.2 m, as shown in Fig. 2.

Table 1: Properties of the low-cost sensors.

Sensor name	Parameter	Sensor type	Accuracy	Measurement range	Response time
Sensirion SCD30 [66]	Relative humidity	Capacitive	±3% RH at 25 °C	0–100%	8 s
Sensirion SCD30 [66]	CO_2	Nondispersive infrared (NDIR)	± 30 ppm, ± 3 % (500–1500 ppm)	400–10000 ppm	20 s
Sensirion SCD30 [66]	Temperature	10K NTC Thermistor	± (0.4 °C + 0.023 × (T [°C] −25 °C)	−40 to 70 °C	>10 s
DART WZ-S formaldehyde module [67]	Formaldehyde	Electrochemical sensor (MOS)	≤0.02 ppm formaldehyde equivalent <± 2% repeatability	0.03–2 ppm	<40 s
Sensirion SVM30 [68]	TVOCs	Multi-pixel metal-oxide	15% of MV	0–60000 ppb	8 s
Sensirion SPS30 [69]	Particle concentration	Optical sensor	0–100 μg/m^3 ≥ ±10 μg/m^3 100–1000 μg/m^3 ≥ ±10%	Resolution 1 μg/m^3	20 ms

The rooms were constructed in a climate chamber where the U-values of walls, roof, and floor were estimated to 0.1 W/(m^{2}K). The external doors were also very tight and insulated, with a U-value of ≤0.8 W/(m^{2}K). The rooms had no windows, and the internal walls were constructed of polystyrene panel insulation with a U-value of 0.15 W/(m^{2}K). The internal door was a standard door with a U-value of ≤1.2 W/(m^{2}K). The leakages between rooms were minimized by covering the wall with a polyethylene film. The ventilation filters were F7 $ePM_{2.5}$ 65% to 80% for the supply air and F9 $ePM_{2.5}$ >95 % for the recirculated air.

2.1.1 Conducted tests in the rooms

Three types of tests were conducted in the rooms.

- *Test with students (*Bubble 1 and 5 in Fig. *1*): These tests were used to determine occupants' production of CO_2, formaldehyde, $PM_{2.5}$, TVOCs, heat, and moisture while they performed standard office work on the computer. A maximum of one student was present in each office room, and all the students entered their rooms simultaneously and did not leave the room until the CO_2 was at steady state concentration. During most of the tests, the three offices were occupied simultaneously; when only two students were in the three rooms, the room in the middle was vacant. The occupants were 11 males and 13 females aged between 20 and 50 years old. They had an average height of 165 cm (standard deviation: 10 cm) and an average weight of 71.8 kg (standard deviation: 13.6 kg). The ventilation rate was continuously kept in balance at 26 m^3/h between supply and extract, as recommended by [7].
- *Test with mannequins (*Bubble 2 in Fig. *1*): This test was conducted to evaluate the simulation models of the DCV. The occupants were mimicked by a simplified mannequin in the form of a metallic cylinder breathing out CO_2 through a hole at mouth height (1.2 m for a sitting person) at the average rate calculated from the student tests. The CO_2 exhalation (occupation of the room) followed the patterns described in Table 2, but the heat production did not. The cylinders contained a lightbulb that produced 120 W, which had to be run constantly throughout the tests to ensure that the cylinders were warm enough to represent the convection flow caused by a person.
- *Pressurization test (*Bubble 3 in Fig. *1*): This test was performed to quantify envelope and internal leakages. First, all the offices were pressurized at 50 Pa relative to the ambient lab. Subsequently, three tests were run in which the pressure in one room was 5 Pa higher than that of the contiguous office and the lab.

Table 2: Number of persons in the different rooms at the different times in the Test with mannequins

Time	Room 1	Room 2	Room 3
00:00–00:15	1	0	0
00:15–00:30	1	0	1
00:30–01:30	1	1	1
01:30–01:45	2	1	0
01:45–02:00	1	1	1
02:00–02:15	0	1	1
02:15–02:30	0	0	1

2.2 Simulation environment

Simulations were performed in an EnergyPlus/CONTAM co-simulation model. The co-simulation followed the steps described by [8]. Using a co-simulation allowed the interdependencies between airflows and heat transfer to be captured. EnergyPlus obtained interzone infiltration airflows at each simulation timestep from CONTAM. CONTAM obtained indoor temperatures and system airflows from EnergyPlus and performed the contaminant transport calculations [8]. The co-simulation was performed using the functional mock-up interface capabilities incorporated into EnergyPlus, as described by [70]. The first step for the co-simulation was to build the two models and the data exchange. The bridge between both programs was accomplished using the NIST-developed CONTAM 3D Exporter tool [71]. The principles and procedure of the co-simulation are not discussed further in this article, but [8] provides further details.

The simulated offices consisted of the three office rooms described in Section 2.1. The with students described in Section 2.1.1 was used to model the pollutant production from the occupants, and the pressurization tests were used to model air leakages. The test with mannequins was used to validate the DCV model with regard to pollutants and energy. The heat recovery of ventilation was simulated with a sensible efficiency of 78% and a 40% latent efficiency. Airflow rates were simulated to vary according to the CO_2 concentrations, as shown in Fig. 4.

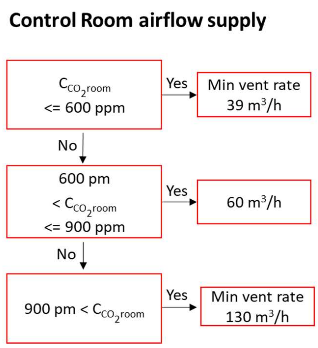

Fig. 4. Flowchart for control of supply airflow rate to every room.

In this case rule-based control is chosen as it is a standard approach in commercial building automated systems to reduce the energy and operating costs. It can provide significant savings when applied correctly. In rule-based control; the operator has to constantly monitor and adjust the HVAC operation to meet the objectives of reducing energy consumption while maintaining thermal comfort [72]. For simplicity, no recirculation of the return air was run for the test with mannequins. The measured conditions in the laboratory were used as boundary conditions in the simulation.

2.3Simulation validation

For precision metrics, the normalized mean bias error (NMBE), given by Eq. (1), and the coefficient of variance of the root-mean-squared error (CV-RMSE), given by Eq. (2), are often used [73,74]. The NMBE provides a normalization of the average error of a sample space, which can be compared with other cases [74]. The CV-RMSE measures the variability of the errors between the measured and simulated values [74]. In the equations, C_{sim} and C_{LCS} are the concentrations simulated and measured by LCS, respectively. $C_{LCS,av}$ is the average of the monitored data for N observations.

$$NMBE = \frac{\sum_{i=1}^{N}(C_{sim} - C_{LCs})}{N} * \left(\frac{100}{C_{LCS,av}}\right)(\%) \quad (1)$$

$$CV - RMSE = \left(\frac{100}{C_{LCS,av}}\right) * \sqrt{\frac{\sum_{i=1}^{N}(C_{sim} - C_{LCs})^2}{N}} \quad (2)$$

The NMBE and CV-RMSE calculate the average model prediction error to help evaluate the accuracy of the fitted models. To calibrate a model, ASHRAE 14 [75] recommends an NMBE below ±10 % and a CV-RMSE of ±30 % for hourly calibrations and ±5 % and ±15 % for monthly measurements.

This work corresponds with Bubble 6 in Fig. *1*

2.4 Methodology for the analysis of pollutant selection

This study included measurements of CO_2, TVOCs, formaldehyde, $PM_{2.5}$, RH, and temperature. Introducing all these parameters in a control logic may be complicated and sometimes contradictory. Moreover, considering that they may be derived from the same source or activity, using all the parameters may outweigh the activity's importance. Therefore, the first step in this work was to assess the significant parameters for ventilation control. The methodology proposed in this article for selecting the significant parameters for control is based on cross-correlation functions. This was described in detail by [47] and will only be summarized in this article. This methodology used CCFs in de-trended time series instead of the standard Pearson or Spearman coefficients. If two time series of measurements followed similar trends, they could appear more strongly correlated. This higher correlation stems from the autocorrelations more than from the pure correlation because the underlying trends and time series structures affect the correlation patterns. Therefore, this methodology recommends de-trending by pre-whitening the time series to remove the underlying correlations. CCFs were used to calculate the Pearson correlations in simultaneous and time-shifted lags. Thus, both simultaneous and time-shifted correlations were mapped. The following consecutive steps are recommended for the CCF methodology:

1. Determine a time series model that describes the variable to residuals that are white noise.
2. Filter the second time series using the model created for the first variable.
3. Calculate the CCF between the residuals from step 1 and the filtered values for the second variable.

The obtained CCF is proportional to both variables' impulse response rather than their autocorrelations.

In the analysis of supply airflows, two highly and significantly correlated parameters indicate that one can be removed because the remaining parameter(s) would serve as an adequate proxy for the removed one. Contrarily, in the analysis of recirculation, if the same pollutant is correlated between the supply and room air, the OA quality affects the concentration of the pollutant in the room. In this case, it makes sense to use correlated parameters in the control logic of the recirculation. If pollutants are not correlated, they are probably either collected by the filters or produced indoors, in which case recirculation would not remove them. Finally, to define the best ventilation procedure to reduce pollutants, the I/O was evaluated. An I/O below 1 indicates that the main source of the pollutant is outside of the room. In this case, it would not be useful to increase OA ventilation rates to dilute the outdoor-generated pollutant.

For the CCF and I/O analysis, the measurements of the test with students were analyzed in section 3.3. This work corresponds with Bubbles 4 and 7 in Fig. *1*

2.5 Ventilation control strategies

The ventilation control was improved on the basis of simulations. This work corresponds to Step 3, bubbles 9- 14 in Fig. *1*. In this case, two objectives were pursued: a) the reduction of the annual energy use index (EUI) (kWh/m^2/year) and b) the reduction of the key performance indicators (KPIs) for IAQ (KPI_IAQ) or the fraction of time with a room air concentration of pollutants or a temperature and RH outside the guidelines defined in Table *3*.

Table 3: Summary of the guidelines for CO_2, formaldehyde, $PM_{2.5}$, temperature, and RH.

Parameter	Limit	Reference
CO_2	1000 ppm	[76]
Formaldehyde	110 µg/m^3 in 1 min	[77]
$PM_{2.5}$	15 µg/m^3 in 1 min	[10] defined 24 hours, but 1 minute is used
Temperature	22–24 ° C	[78]
Relative humidity	30–60 %	[79,80]

The KPI_IAQ was defined according to Eq. (3) by adding all the timesteps when all the guidelines from Table *3* were met simultaneously in the three rooms and dividing by the total number of timesteps. The parentheses in Eq. (3) show a logical evaluation of the three rooms simultaneously; if the conditions were met simultaneously for all the rooms, the result for the current timestep was one. If one of the rooms did not satisfy a single criterion, the solution to the equation was zero. The value of the KPI ranged between 0 and 100%. These simulations consisted of 525,960 timesteps (1-year simulation). When defining working hour (WH) KPIs, the number of timesteps was reduced to 124,800. The subindex R indicates that the evaluation was performed simultaneously for the three rooms, and WSP in the sum represents the whole simulated period.

$$KPI_{IAQ} = \frac{\sum_1^{WSP} \left(CO_{2\_R}<100 \ \ \& \ Temp_R<24 \ \& Temp_R>22 \ \& \ Formaldehyde\_R<110 \ \ \& \ RH_R<60 \ \& \ RH_R>30 \ \& \ PM_{2.5\_R}<15 \right)}{Number\ of\ simulated\ time\ steps} * 100 \quad (3)$$

The remaining KPIs were calculated following Eqs. 4–8 for each timestep using the same logic as the IAQ KPI. KPI_CO_2 divides the timesteps with CO_2 concentrations below 1000 ppm in the three rooms by the total number of timesteps. The same reasoning was applied to calculate the KPI of formaldehyde, $PM_{2.5}$, temperature, and RH. The KPIs defined in Eqs. 4–8 represent compliance with the selected guidelines from Table *3*. A perfect control will achieve 100% in all these KPIs.

$$KPI_{CO2} = \frac{\sum_1^{\mathrm{WSP}} \left(CO_{2\_R}<1000 \right)}{Number\ of\ simulated\ time\ steps} * 100 \quad (4)$$

$$KPI_{formaldehyde} = \frac{\sum_{1}^{\mathrm{WSP}} (Formaldehyd\ _{R}<110\ )}{Number\ of\ simulated\ time\ steps} * 100 \tag{5}$$

$$KPI_{PM2.5} = \frac{\sum_{1}^{WSP} (PM_{2.5\_R}<15\ )}{Number\ of\ simulated\ time\ steps} * 100 \tag{6}$$

$$KPI_{temp} = \frac{\sum_{1}^{WSP} (Average\ room\ air\ temperature_{R} < 24\ \&\ Average\ room\ air\ temperature>\ \ )}{Number\ of\ simulated\ time\ steps} * 100 \tag{7}$$

$$KPI_{RH} = \frac{\sum_{1}^{WSP} (Average\ room\ air\ RH_{R} < 60\ \&\ Average\ room\ air\ RH>30\ )}{Number\ of\ simulated\ time\ steps} *100 \tag{8}$$

The developed sequences in section 3.4 are the result of several attempts (not presented here) that looked at how different limits for pollutants and corresponding airflow rates affected the KPIs in eq 3-8 and energy use during WH.

The ventilation logic was tuned as follows:

1. To focus on the supply airflow rate to the room without recirculating return air, the supply airflow rate was changed on the basis of rule-based sequences using one uncorrelated parameter/pollutant. Then, the “combined” rules included all the uncorrelated parameters simultaneously. Table *6* shows the simulated control logic. To have a comparison point, the results were compared with the scheduled constant air volume strategy, as shown in the results (section 3.4.1).

2. The best-performing strategy for the supply airflow was tested with different logic to control the OA fraction. In this case, the rule-based strategies were based on the correlations between the supply and room air concentrations and the I/O ratios. The simulated cases are described in Table *7*.

The controlled pollutants were selected by the strategy described in section 2.4, and the selected pollutants are summarized in section 3.3. The simulations were run for Trondheim and then repeated with Trondheim’s weather and Beijing’s OA pollution to study the effect of outdoor pollution.

3 Results and discussion

3.1 Measurements in the laboratory: tests with students

The tests with students were carried out as described in section 2.1. The grey dots in Fig. *5* represent the measured concentrations of pollutants for all the cases. The blue lines indicate the local polynomial regression fitting (fitted by weighted least squares) with time in minutes for each parameter.

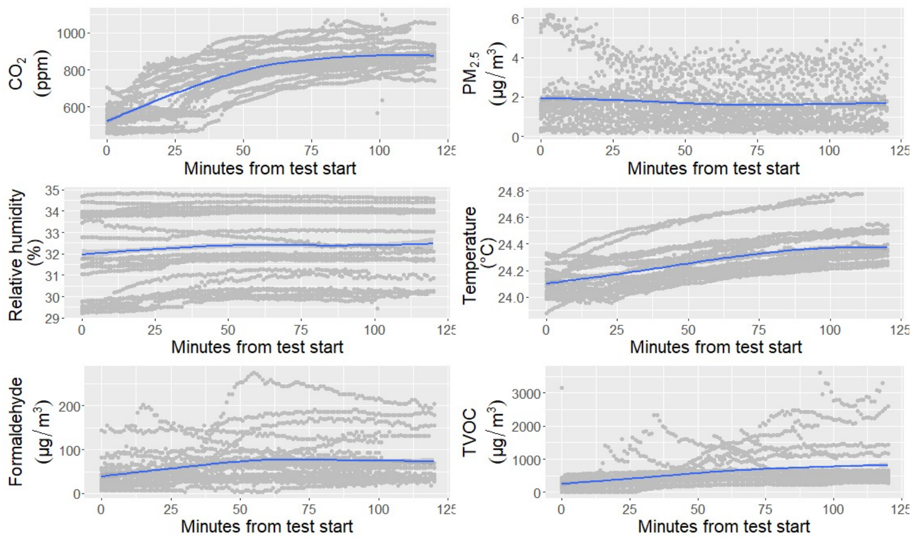

Fig. 5. Concentration of pollutants (CO_2, $PM_{2.5}$, formaldehyde, and TVOCs) and the parameters RH and temperature for the 24 measured cases.

The CO_2 measurements agreed with the theoretical production described in [81]. The trends for $PM_{2.5}$ were similar in most of the tests. When occupants entered the rooms, they brought in variable amounts of $PM_{2.5}$, which decayed with time. However, five tests were slightly different. These tests corresponded to measurements taken on a day when renovation work was carried out in the lab. The concentration of the $PM_{2.5}$ rose before the tests when all doors were open to ventilate between two consecutive tests. These measurements were not considered in the model fitting. The same happened for formaldehyde and TVOCs; the divergent tests also corresponded to the day of construction/painting work in the laboratory building. Temperature and RH measurements were very similar for all the tests because the conditions in the laboratory surrounding the tested offices were very constant during the week that measurements were taken.

3.2 Model validation

The pressurization tests were performed to map the air leakages of the three offices using mass balances of pollutants [82]. The test with 50 Pa pressurization was used to calculate the envelope leakages of the three rooms. The pressurization tests with the pressurization higher in one room were used to calculate the leakages across the internal walls. The calculated air leakages based on the pressurization tests were simulated in CONTAM as flow path elements described as one-way overflow using the power law, a method inspired by [83]. More information about the characterization of the leakages can be found in Marman's thesis [84]. The individual values for CO_2 production for each person, considering a constant MET and the particular body mass and height [81], were used to validate the calculated leakage rates in each room using mass balances in the pressurization tests. These leakages were included in the calculation of the strength of the sources used to evaluate improvements in the ventilation control strategy.

The simulated CO_2 sources corresponded to the CO_2 production based on the average CO_2 production presented in Fig. 5 (0.0053 L/s). This production was in line with the production based on 1.3 MET for occupants aged 20–30 years [81]. Humidity was simulated according to measurements (Fig. *5*) at 0.06 kg/h and in line with the results from [85]. $PM_{2.5}$ was simulated as the combination of a burst source of 0.6 µg when the occupants entered the room and an exponential decay with a first-order decay constant of 0.0001 min^{-1} according to the results shown in Figure 5. Formaldehyde was simulated according to the rate calculated in Fig. *5* of 17 $µg/m^3$ h. The simulated heat loads were 120 W/mannequin, the lights were simulated to produce 8 W/m^2, and the plug-in loads were 11 W/m^2, according to the Norwegina guidelines [86]. TVOCs was not introduced as a source in the simulation, as the sensor calibration was unavailable.

Fig. *6* compares the measured data and the simulation results of the test with mannequins. For this test, the occupants entered and exited the three rooms as summarized in Table 2, and the OA supply varied, as shown in Fig. *4*. The background colors of Fig. *6* correspond to the number of occupants.

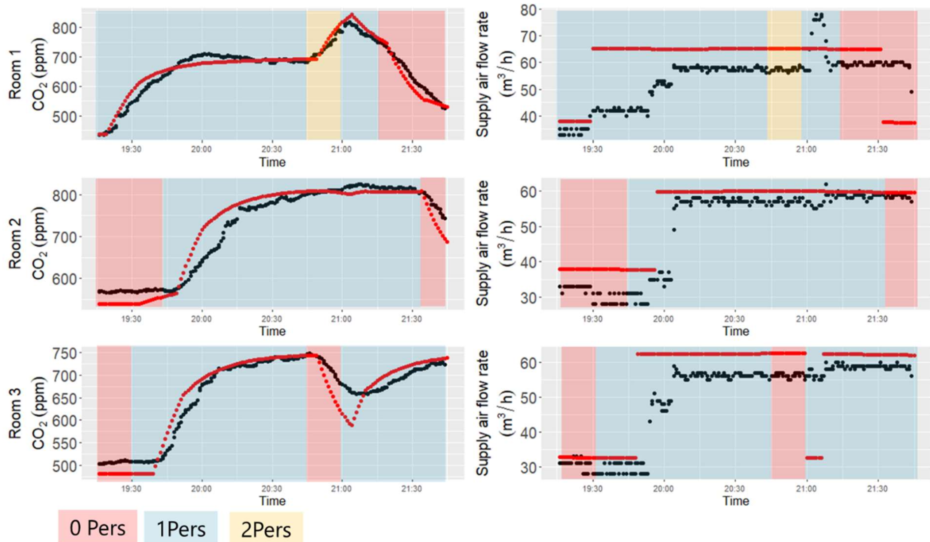

Fig. 6. Measured (black) and simulated (red) results in the three rooms. The red, blue, and yellow shading shows whether the room was used by zero, one, or two person(s), respectively.

In general, the simulation represented the measured response of the CO_2 levels in the rooms very well. However, from 19:30 to 20:00, the airflow rates in Room 1 did not react as the control strategy required, as shown in Fig. *6*. The LEO VAV units dynamically measured the volume flows and controlled the damper positions to maintain the airflow rate required. In this case, on the basis of the measurements of the LCS, the Raspberry Pi sent information about the desired airflow rate to a VAV damper, which adjusted the damper's opening. Therefore, when the room controllers further down in the branch opened or closed, the pressure in the branch varied, and the damper was regulated until the correct volume flow was restored. Thus, variations in the flow were observed (Fig. *6*), which the control strategy could not explain, and the simulation results did not reflect. When occupants arrived in Rooms 2 and 3, the simulated CO_2 concentrations rose faster than in reality, although the ventilation rates were higher in the model. This is most likely the result of the CO_2 supply from the mannequins. The CO_2 was supplied from the bottle and distributed to each room. The CO_2 supplied to the room may have been poorly distributed in the three-way valve. In addition, once the flow was opened, the CO_2 filled the pipes leading to the mouth of the mannequins and then mixed with the air in the room before arriving at the sensor. The lack of perfect mixing could have caused a delay in the measurement compared with the ideal mixing simulation. These hypotheses could have been studied in detail to add a delay to the model, but because the error corresponded to very local points that would not have changed the general results of this study, this small difference was disregarded.

Measurements and simulations had a 1-minute resolution, and they were calibrated according to ASHRAE recommendations. Table 4 shows the NMBE and CV-RMSE values that are below ASHRAE 14 [75] calibration recommendations (NMBE below ±10 % and a CV-RMSE of ±30 % for hourly calibrations). Thus, the model is considered validated. The energy use was validated using the results from the test with mannequins. The energy use NMBE of the validated simulation was 2 %, and the CV-RMSE was 1.7 %; thus, the energy simulation was also considered validated.

Table 4: Summary of NMBE and CV-RMSE of the validation simulation.

	Temperature			RH			$PM_{2.5}$			CO_2			Formaldehyde		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
NMBE (%)	0.13	−0.09	0.05	0.9	1.15	2.4	−0.52	−0.8	1.3	−0.09	−0.19	0.07	1.94	2.10	0.57
CV-RMSE (%)	0.310	0.257	0.244	1.19	1.41	3.47	28.3	20.3	25.6	24.2	29.36	28.9	3.36	3.96	2.99

3.3 Pollutant selection

Correlations between parameters were assessed according to the methodology explained in section 2.4. Then, the supply air ventilation logic focused on the uncorrelated parameters, and the control of the return air recirculation was based on the correlated parameters.

Using the data collected in the test with students, the correlation coefficients obtained between pollutants and indoor climate parameters were determined and are presented in Fig. *7*. To understand this figure, the following information is essential: the blue dashed lines represent the 95 % confidence bound for a significant correlation; the x-axis represents the lag that indicates the offset between both series, and its sign determines the direction in which the series were shifted; and the y-axis shows the value of the Pearson correlation coefficient of the two respective time lags, with larger values indicating stronger correlations. According to these results, the measured temperature represented the room's RH and $PM_{2.5}$. The correlation between temperature and $PM_{2.5}$ was not obvious, likely because of the sample size and the small variations in $PM_{2.5}$ and temperature during the tests, though more measurements with larger variations would be needed to draw a conclusion. According to Fig. *5*, most of the $PM_{2.5}$ and heat was brought to the room by the occupants. It is important to keep in mind that the correlations between the parameters may indicate a common reason for the rise in the parameters, although this is not necessarily a causal link. Formaldehyde was strongly correlated with TVOCs. CO_2 and formaldehyde were significantly but not strongly correlated; thus, in this study, the control strategies for optimizing the rules focused on using formaldehyde, CO_2, and temperature.

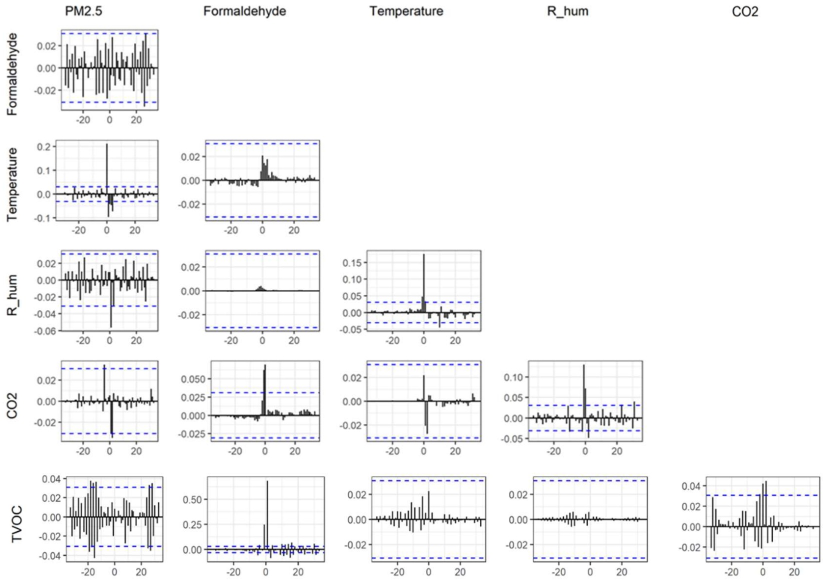

Fig. 7. Cross-correlation function between the different pollutants and parameters measured in the test with students.

Regarding the parameters to control the recirculation, the correlations of interest were between the same parameter in the supply air and room air. Some pollutants were generated in the offices, and some infiltrated from outdoors. For example, in a room with a high concentration of $PM_{2.5}$ infiltrating from the lab, increasing the airflow rate would not be beneficial for diluting $PM_{2.5}$ concentrations (supposing that these PMs were not filtered, filter efficiency is essential here); however, reducing the OA fraction may have a protective effect against $PM_{2.5}$. The I/O ratios focused on the ratio between parameters in the supply and the room to provide information about their origin.

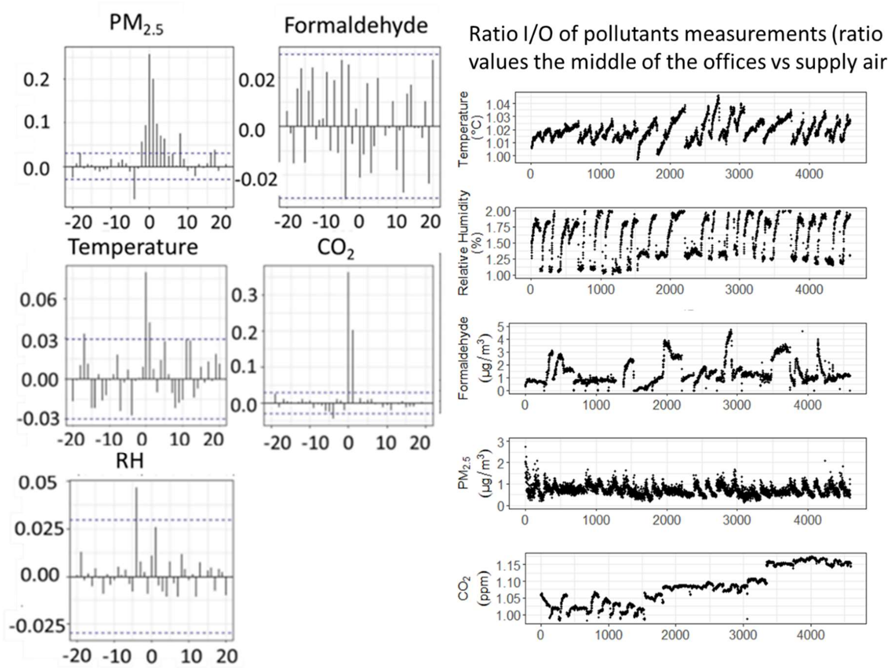

Fig. 8. Left: CCF of supply and room air concentrations; right: I/O ratio of pollutants where all the test are plotted consecutively. The x-axis shows the ID of the measurements ordered by consecutive time.

According to Fig. 8 (left), CO_2 and $PM_{2.5}$ showed significant correlations between the room and supply concentrations. Thus, $PM_{2.5}$ and CO_2 should be controlled in recirculation. Notably, the PM measured in this lab had a considerable share of $PM_{1.0}$, which would have been able to pass through the filters used in this AHU.

All the pollutants, RH, and temperature had I/O ratios of more than 1, as shown in Fig. 8 (right). This means that the sources were the students inside the office. Thus, increasing OA ratios was an efficient method to reduce concentrations indoors. Formaldehyde and $PM_{2.5}$ had very high values and ratios greater than 1 because the divergent tests (from the period when there were renovations in the lab) were removed from the analysis.

The TVOCs sensors were not calibrated. The correlation between TVOCs and formaldehyde was expected because their sensors were based on very similar measuring principles. However, because these sensors were not calibrated, the results could have been coincidental. Thus, TVOCs was not simulated in the co-simulation model and was not further analyzed in this article.

3.4Tuning of the ventilation control strategy by simulations

Table *5* describes the schedules of the three offices. The schedules were repeated Monday to Friday throughout the year, except for the summer holidays (July 1 to 31), when the offices were empty.

Ventilation control tuning focused on reducing the EUI and increasing the KPI_IAQ during WHs. The remaining simulation building parameters, pollutant sources, and ventilation systems followed the protocols described in sections 2.1, 2.2, and 2.3 for the validated model in section 3.2.

Table 5: Number of people in the different rooms at different times.

Time	Room 1	Room2	Room 3
00:00–08:00	0	0	0
08:00–08:35	1	0	0
08:35–09:00	1	0	1
09:00–10:30	1	1	1
10:30–11:45	2	1	0
11:45–12:15	0	0	0
12:15–15:30	1	1	1
15:30–15:45	0	1	1
15:45–16:15	0	0	1
16:15–00:00	0	0	0

3.4.1 Simulated cases

As described in section 3.3, the selected parameters for controlling the airflow supply to the room were CO_2, formaldehyde, and temperature. Table *6* shows the short name of the strategies used in the graphs, the logic behind the control, and the airflow rate supplied to each room. The limits and setpoint values for the supply and recirculation airflow rates in the rule-based control sequences were determined by parametric analysis. This targeted the solution that produced the largest annual energy savings and lowest room air pollutant concentrations. For simplicity, most of the trials are not presented in this article; only a few cases of CO_2 and temperature are included to show that a single parameter could affect the various KPIs differently. As the control logic introduced more parameters, the "easy" tuning became more complicated because of the effects of controlling one parameter on several others. In this work, the control sequences were kept very simple so that the steps of the methodology could be clearly seen and understood, although more complicated strategies could have been developed.

The KPI_IAQ and the individual KPIs needed to be checked to improve the control. The KPI_IAQ gave a general overview of the performance of the control, and the individual KPIs revealed factors that were not controlled correctly and needed to be improved by modifications to the rules. For instance, if a control resulted in a KPI_IAQ of 0% because the KPI_CO_2 equaled 0%, but all other KPIs were satisfactory, then changing the logic of the control of CO_2 would be the best way to improve the performance of the control logic; no other changes would improve the system's performance as much.

Table 6: Summary of simulated supply air control strategies with 100% OA.

Name	Control logic	AFR (m^3/h)

CAV	IF ((Saturday) OR (Sunday)),
	ELSE IF ((Hour < 8) OR (Hour ≥ 17)),
	ELSE
		8
		8
		72

CO_2-1	IF (CO_2_Room_ppm ≤ 600), ELSE IF (CO_2_Room_ppm ≤ 900), ELSE IF (CO_2_Room_ppm > 900)	26 46 72

CO_2-2	IF (CO_2_Room_ppm ≤ 800), ELSE IF (CO_2_Room_ppm ≤ 1000), ELSE IF (CO_2_Room_ppm > 1000)	26 46 72
CO_2-3	IF (CO_2_Room_ppm ≤ 800), ELSE IF (CO_2_Room_ppm ≤ 1000), ELSE IF (CO_2_Room_ppm > 1000)	26 33 59
CO_2-4	IF (CO_2_Room_ppm ≤ 660), ELSE IF (CO_2_Room_ppm ≤ 900), ELSE IF (CO_2_Room_ppm ≤ 1000), ELSE IF (CO_2_Room_ppm > 1000)	26 46 72 98
CO_2-5	IF (CO_2_Room_ppm ≤ 700), ELSE IF (CO_2_Room_ppm ≤ 850), ELSE IF (CO_2_Room_ppm ≤ 1000), ELSE IF (CO_2_Room_ppm > 1000)	26 46 72 98
FA-1	IF (FA_Room_µg/m^3 ≤ 50), ELSE IF (FA_Room_µg/m^3 ≤ 110), ELSE IF (FA_Room_µg/m^3 > 110)	26 46 72
T-1	IF (T_Room_°C ≤ 22), ELSE IF (T_Room_°C ≤ 23), ELSE IF (T_Room_°C ≤ 25), ELSE IF (T_Room_°C > 25)	8 46 72 98
T-2	IF (T_Room_°C ≤ 22), ELSE IF (T_Room_°C ≤ 23), ELSE IF (T_Room_°C > 23)	8 46 98
T-3	IF (T_Room_°C ≤ 23), ELSE IF (T_Room_°C ≤ 24), ELSE IF (T_Room_°C > 24)	8 46 72
C-1	IF ((T_Room_°C ≤ 23) OR (FA_Room_µg/m^3 ≤ 50)), ELSE IF ((CO_2_Room_ppm ≤ 600), ELSE IF ((CO_2_Room_ppm ≤ 700) OR (T_Room_°C ≤ 24)), ELSE IF ((CO_2_Room_ppm ≤ 800) OR (T_Room_°C ≤ 25)), ELSE IF ((CO_2_Room_ppm > 800) OR (FA_Room_µg/m^3 > 110))	8 33 98 111 130

The airflow rates in the constant air volume (CAV) strategy, presented in *Table 6*, were based on the Norwegian building code TEK 17 [87]. The airflow rates and limits for the other strategies were chosen to increase the KPI_IAQ and reduce the annual EUI by stepwise tuning.

The best-performing supply air strategy for Trondheim was combined with the control strategies of the return air summarized in Table *7*.

Table 7: Summary of simulated logic for control of the recirculation of return air (outdoor air (OA) fraction).

Name	Control logic	Fraction OA (%)
No_rec	Always	100
PM_OR	IF (($PM_{2.5}$_Amb − $PM_{2.5}$ return < 0) OR ($PM_{2.5}$_Room_µg/m^3 > 15)), ELSE	100 25
PM_AND	IF (($PM_{2.5}$_Amb − $PM_{2.5}$ return < 0) AND ($PM_{2.5}$_Room_µg/m^3 > 15), ELSE	100 25
PM_CO_2_OR	IF (($PM_{2.5}$_Amb − $PM_{2.5}$ return < 0) OR ($PM_{2.5}$_Room_µg/m^3 > 15) OR (CO_2_Return_ppm > 700)), ELSE	100 25
PM_CO_2_AND	IF (($PM_{2.5}$_Amb − $PM_{2.5}$ return < 0) AND ($PM_{2.5}$_Room_µg/m^3 > 15) AND (CO_2_Return_ppm > 700)), ELSE	100 25

3.4.2 Results without recirculation of return air in Trondheim

Fig. *9* shows the simulated control strategies with a 100% OA fraction. The KPI_IAQ considered that the three rooms simultaneously presented concentrations of pollutants below the defined threshold, and RH and temperature within the defined range. Table *8* breaks down the KPI_IAQ into the KPIs for all the parameters defined according to Eqs. 3–8 to make concrete improvements to the control logic if needed. EUI considered the annual energy use in kWh/m^2, including heating and ventilation. In the simulated cases, no direct cooling was considered apart from increasing the air supplied to the room.

As can be seen in *Fig. 9,* the control logic that used the least energy and provided the best IAQ was the strategy that controlled CO_2, temperature, and formaldehyde (C-1, explained in Table 6. This strategy reduced airflow rates mainly during the evening, night, and early morning. The sources of formaldehyde were small in the rooms (Fig. *5*), and thus throughout the winter, when the indoor temperatures were not very high, the supply rates could be minimized after the occupants left the room. Then, when the occupants started their working day, CO_2 rose, and airflow rates rose simultaneously. Airflow rates increased progressively with CO_2 or temperature. The maximum airflow rate in the room was achieved when CO_2 surpassed 800 ppm or when the formaldehyde was too high. As in the simulation, both sources for CO_2 and formaldehyde were indoors; increasing ventilation helped to dilute these pollutants.

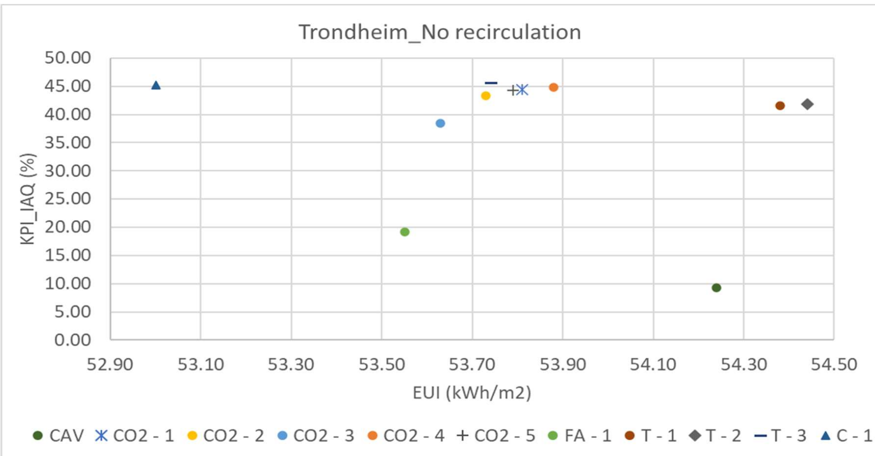

Fig. 9. Percent of working hours (WHs) in which all the KPIs related to IAQ were satisfied versus the annual energy use index (kWh/m^2) for different control logics.

The DCV solutions did not represent a considerable improvement in energy use compared with the CAV solution. This was primarily due to the high occupancy of the rooms. The Norwegian standard NS3031 [86] recommends simulating occupancies between 30 % and 70 %, whereas here, the simulated occupancy was almost always 100 %, except when people arrived at or left work and during lunchtime when it dropped to 0 %. Therefore, the possibility to reduce annual energy use from the differential occupancy was smaller.

The reference system CAV used more energy than most other control sequences. However, because the airflow was not controlled from pollutant concentrations, it resulted in too low RH and temperature and thus, the KPI_IAQ was the lowest. The formaldehyde-based control did not perform well either. It did not control parameters that rose above the thresholds or those that were not correlated with formaldehyde but were more present than the latter (e.g., CO_2 and temperature).

Table *8* breaks down the KPI_IAQ into all the parameters' KPIs. The CAV control logic was especially poor for temperature, which was typically outside the range of 22–24 °C. RH was not controlled, and for all the cases, the RH values were too high in summer and too low in winter. The range of 30–60 % was used throughout the year, although keeping the RH below 60% is more important in the winter to avoid condensation problems, which can cause mold. With the simulated outdoor conditions, increasing the ventilation rate would reduce the RH in the winter but not in the summer. To control the RH more tightly without introducing it into the control strategies or introducing dehumidification or humidification, a potential solution is tightening the limits of the temperatures and making them different between summer and winter. Allowing lower temperatures in the winter and higher temperatures in the summer would mean higher RH levels in the winter and lower levels in the summer. The general recommendations for thermal comfort [88] allow for a wider range than what was used in this simulations. The limits of temperature here are mostly performance-based, but if the energy-saving dimension is included, these limits should have a seasonal dimension differentiating between summer and winter. This change would have a larger effect on the KPI _RH than changing the airflow rates. $PM_{2.5}$ concentrations were generally low because the indoor simulated sources were low, and the outdoor concentrations were also low.

Table 8: Individual KPI values for the different parameters and the ventilation control strategies for WHs, defined as Monday to Friday from 08:00–17:00.

KPI WH	CAV	CO_2-1	CO_2-2	CO_2-3	CO_2-4	CO_2-5	FA-1	T-1	T-2	T-3	C-1
KPI_IAQ (%)	9.3	44.3	43.3	44.4	44.8	38.5	19.2	41.5	41.8	45.6	45.2
CO_2_KPI (%)	100	100	96.4	100	100	90.8	45.8	93.5	94.0	89.0	72.5

Temp _KPI (%)	18.7	83.4	83.4	83.1	81.7	72.8	60.0	81.5	81.2	97.0	97.5
Formaldehyde_KPI (%)	100	100	100	100	100	100	100	100	100.0	100.0	99.3
RH_KPI (%)	46.0	50.8	50.2	51.2	52.3	46.4	40.7	52.9	53.0	53.0	57.0
$PM_{2.5}$_KPI (%)	99.8	99.7	99.7	99.7	99.8	99.7	99.7	99.8	99.8	100.0	99.3
T > 24 °C (%)	27.9	0.5	0.6	0.5	0.5	4.1	11.24	0.3	0.4	0.5	0.0
T < 22 °C (%)	41.5	3.0	2.6	3.3	3.8	1.2	1.0	3.1	3.2	0.0	0.0
Energy (kWh/m^2)	54.2	53.8	53.7	53.8	53.9	53.6	53.7	54.4	53.6	54.4	53.0

3.4.3 Results without recirculation of return air in Trondheim with the outdoor air pollutants of Beijing

Fig. 10 shows that when the OA quality in Trondheim was replaced with that in Beijing, the KPI_$PM_{2.5}$ worsened for all the cases because the supply air was more polluted than it was in Trondheim. The decrease in the KPI_$PM_{2.5}$ was not proportional to the increase in the PM levels because of the filters' effect, and the leakages were limited in this case. Because $PM_{2.5}$ was not part of the control strategies for the supply air, most of them performed very similarly to the ones for Trondheim regarding energy, CO_2, temperature, RH, and formaldehyde, but the KPI_IAQs were generally lower.

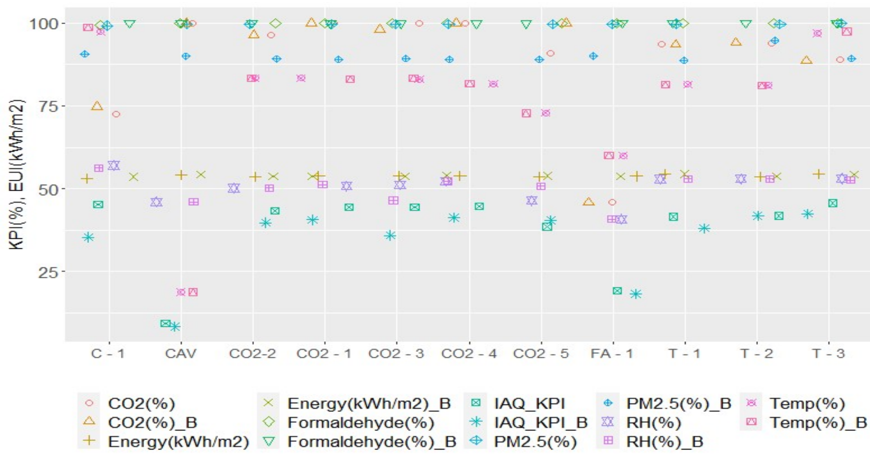

Fig. 10. KPIs for the different ventilation logics. Comparison between the simulations in Trondheim and the simulations in Trondheim with the outdoor air quality in Beijing (indicated by _B) during WHs.

3.4.4 Results with recirculation of return air in Trondheim

Table *9* compares the best solution with 100% OA and the recirculation strategies based on only $PM_{2.5}$ and $PM_{2.5}$ AND CO_2. Using recirculation of return air in Trondheim based on $PM_{2.5}$ did not yield significant changes because the $PM_{2.5}$ concentrations indoors were mainly within the guidelines. The recirculation strategies $PM_{2.5}$_OR and $PM_{2.5}$_AND cases consumed more energy because more air had to be supplied to reduce the CO_2 and temperature in the room during the periods in which the rooms were in use. The indicator of the fraction of time when the temperature was over 24 °C rose from 0 to 2.4%. In addition, because the recirculated air had higher concentrations of CO_2, the KPI_CO_2 worsened when using $PM_{2.5}$-based recirculation. Using recirculation resulted generally higher RH.

Using the reasoning of the correlations, as CO_2, temperature, and RH were related to the occupancy, changing one of them (CO_2) sufficed to improve the KPIs of RH and temperature, as shown by the controls with $PM_{2.5}$ and CO_2 in Table *9*. Adding CO_2 to the recirculation control positively affected the CO_2, temperature, and RH, whose KPIs were improved. The general KPI_IAQs also improved compared with the non-recirculation or the strategies considering only $PM_{2.5}$. This was mainly attributed to an improvement of almost 30 % between the KPI_CO_2 of the logic $PM_{2.5}$ and the logic $PM_{2.5}$ OR CO_2. The energy use was reduced because less energy was needed for heating. During occupied periods, less recirculation was used because an increase in fan power increased the energy consumption, whereas using $PM_{2.5}$ to control recirculation did not have the same effect. The $PM_{2.5}$_CO_2_OR logic resulted in slightly better results for energy and general IAQ than $PM_{2.5}$_CO_2_AND.

Table 9: KPIs for the different parameters when considering the weather and OA quality in Trondheim during working hours (WHs).

KPI WH	C-1	$PM_{2.5}$_OR	$PM_{2.5}$_AND	$PM_{2.5}$_CO_2_OR	$PM_{2.5}$_CO_2 AND
IAQ_KPI(%)	45.2	26	26	54.9	53.6
CO_2_KPI (%)	72.5	55.2	55.2	84.2	81.6
Temp_KPI (%)	97.5	84.7	84.7	97.6	99.2

Formaldehyde_KPI (%)	99.3	100	100	100	100
RH_KPI (%)	57.0	56.2	56.2	62.6	59.9
$PM_{2.5}$_KPI (%)	99.3	99.7	99.7	99.7	99.7
T > 24 °C (%)	0.0	2.4	2.4	0.9	0.6
T < 22 °C(%)	0.0	0	0	0	0
Energy (kWh/m^2)	53.0	54.71	54.71	46.6	48.1

3.4.5 Results with recirculation of return air in Trondheim and outdoor air pollutants in Beijing

Fig. 11 compares the results with the recirculation of return air for the simulated case in Trondheim and the case simulated in Trondheim with the OA quality of Beijing. In general, the sequences reducing the fractions of OA yielded lower concentrations of $PM_{2.5}$. This is because the recirculation air filters were superior to the OA filters and the very small production of $PM_{2.5}$ indoors. By contrast, increasing the recirculation rates may increase the concentration of CO_2 but reduce that of $PM_{2.5}$. In places such as Beijing, where the outdoor $PM_{2.5}$ concentrations are much higher, this has a large effect on the results and thus the control sequences including $PM_{2.5}$ and CO_2 could result in better KPIs (IAQ, $PM_{2.5}$, and CO_2). Compared with the control logic C-1 with Beijing's OA, using recirculation positively affected the cases controlled using $PM_{2.5}$ and CO_2; not much improvement was observed in the case of only using $PM_{2.5}$. In the reference case, the IAQ KPI was lower because of the low KPIs for CO_2, RH, and $PM_{2.5}$. These were improved using the recirculation of return air based on $PM_{2.5}$ and CO_2. The combined control of recirculation also resulted in decreased energy use. Reducing the OA fraction increased the RH in the winter without increasing the $PM_{2.5}$ concentration. With dual control (CO_2–$PM_{2.5}$), because of the rise in CO_2 during periods with occupants, recirculation could not be used to reduce the CO_2; thus, more OA was supplied during periods with higher CO_2 indoors, which resulted in a higher $PM_{2.5}$ KPI. However, the CO_2 KPIs in the dual controls were not as high as those in the cases without recirculation; this is because to keep the $PM_{2.5}$ low, the OA fraction had to be reduced in some periods to account for the PM increase.

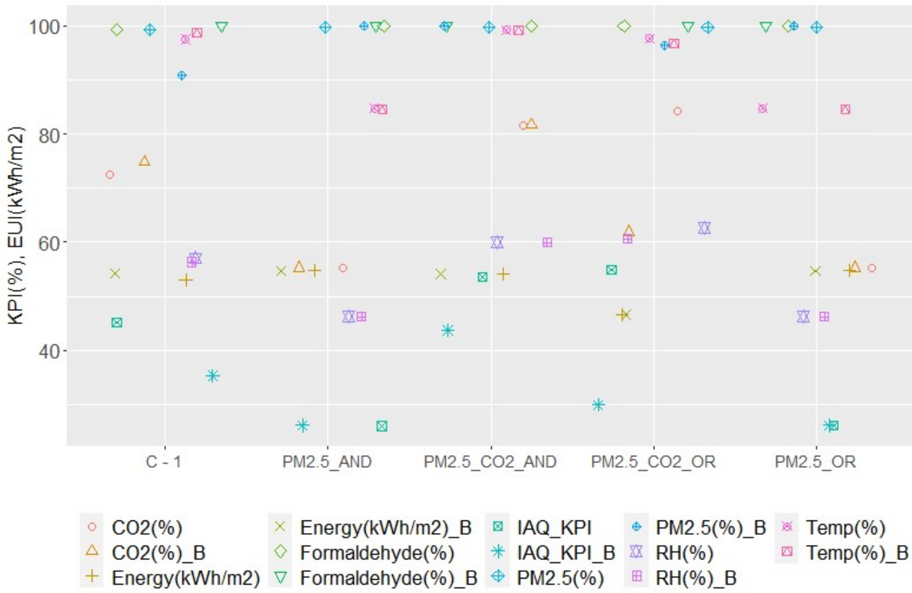

Fig. 11. KPIs for the different ventilation logics with recirculation of return air. Comparison between the simulations in Trondheim and the simulations in Trondheim with the outdoor air quality in Beijing (indicated by _B) during WHs.

3.5 Discussion

There is a clear need to introduce several parameters to the control of ventilation additionally to occupancy [33]. However, how to introduce them and which ones to introduce is unclear and will depend on the use of the considered building. In this case, the aim was to improve ventilation in offices. For that, measurements were first collected to map the parameters that need to be controlled. The "need" was evaluated based on CCF in the de-trended time series. This allows for a more probabilistic choice of the parameters in the control that, despite making the analysis more complicated, gives it the flexibility to adapt to different uses of the building or sources of pollutants.

The co-simulation EnergyPlus/CONTAM allowed to test many different control strategies thoroughly and is recommended for its flexibility and free software cost. In order to evaluate the resulting ventilation control logic fairly, KPIs were developed. These are simple to use and are based on current knowledge. New KPIs equations should be developed if the guidelines in Table *3* are updated. Additionally, as new LCS become more precise in measuring other parameters, more KPIs should be developed.

Multiple DCV strategies were simulated in this study, but only the most satisfactory control logics according to IAQ and EUI are presented. The tested sequences are kept simple to focus on the methodology. Although this study did not use advanced methodologies for control optimization, it achieved reductions in energy use and the number of hours outside the IAQ guidelines. More complicated strategies could be used in future research with a broader scope; for example, machine learning could be used to develop more advanced controls.

The $PM_{2.5}$ guideline [10] in *Table 3* is based on 24-hour averages. In all these calculations (Sections 3.4.2-3.4.5), 1-minute averages were used because this was the timestep in the ventilation control. Using a 24-hour moving average every minute could have been another option instead of just reducing the exposure time to 1 minute, but 1 minute was used for simplicity. Changing the time from 24 hours to 1 minute removes the night period, in which the concentrations normally drop, leading to overweighting of the $PM_{2.5}$ effect. However, using 24 hours for a control strategy is not practical. This $PM_{2.5}$ limit is health-based, derived from studies on long- and short-term effects. The updated guidelines from the WHO [10] state that the $PM_{2.5}$ 24-hour average should not exceed 15 $\mu g/m^3$ more than 3–4 days per year. If $PM_{2.5}$ evolves as a standard control parameter for ventilation, different guidelines based on much shorter timesteps should be developed. In such a case, these guidelines should be updated in the control strategies. The ones used in this article are a proof of concept that must be updated considering both health effects and ventilation control needs.

4 Conclusions

A holistic methodology was developed in this study to improve ventilation control logic. This methodology addressed energy efficiency and reduced the number of hours during which the selected IAQ parameters were outside the selected guidelines. Many previous studies investigated CO_2 but not other pollutants. CO_2 is a good indicator of occupancy, but it may be inferior for predicting pollutants from other sources. The methodology required measurements of pollutants and simulations to improve the control logic.

This methodology was demonstrated and used in a case study of three full-scale cell office rooms built in a lab at the Norwegian University of Science and Technology. The ventilation control of these rooms was based on measurements taken with LCSs connected to a Raspberry Pi.

Three tests were run in this set-up: the first test measured the occupants' production of pollutants by studying 24 students' individual measurements; the second test mimicked CO_2-controlled ventilation with thermal mannequins to validate the simulation model; and the third consisted of pressurization tests used to calculate envelope and room leakages.

For the three office rooms, we developed a model based on a co-simulation between EnergyPlus and CONTAM. This model was validated with results from the test with mannequins. A validated model is essential because it can evaluate different control logics on the basis of energy use and KPIs of IAQ.

An investigation of the CCF in the prewhitened measurement data series was performed together with I/O ratios to select the most suitable control parameters for ventilation. On the basis of these results, the ventilation control was tuned by studying the best supply control strategies and the recirculation of return air.

The results showed it is possible to reduce the annual energy use and the number of hours when some pollutants are outside the recommended guidelines. Recirculation positively affected the otherwise very dry winter (low RH) indoor conditions in Trondheim.

In Trondheim, the OA quality is excellent, so to test the effect of the outdoor conditions, the same simulations were repeated with the OA quality in Beijing to compare the recirculation effect. In this case, using recirculation of return air also had a protective effect on the indoor concentrations of $PM_{2.5}$. When recirculating the return air, a holistic approach to control the different IAQ parameters is recommended for a safe system that avoids excessive values of the uncontrolled parameters. When the control strategy has more parameters, it is essential to use simulation tools to determine how controlling one parameter can affect several others.

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PAPER i

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Measurements of indoor air quality in four Norwegian schools

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ABSTRACT

Children spend a minimum of six hours per day in Norwegian schools. Their exposure to different indoor air quality it is known to affect their performance. It is very common to use demand-controlled ventilation (DCV) in schools as is estimated to save about 50 % of the conventionally used energy for ventilation. CO_2 and temperature are the preferred control parameters. Usually, it was expected that these human-centric controls resulted in high indoor air quality as occupants are the largest source of contaminants. This study presents measurements for two months to up to one year in the supply and room air in the four classrooms whose ventilation is CO_2-based DCV. Using low-cost sensors formaldehyde, PM_1, $PM_{2.5}$, relative humidity CO_2 and temperature were monitored.
Even when the CO_2 concentration lied below 1000 ppm 1) the concentration of formaldehyde surpassed the recommended WHO thresholds in 30 % of the time and 2) RH is below 20 % during 56 % of the time.

INTRODUCTION

Children spend one quarter of their day in schools. Over the past decades, most research in indoor air quality (IAQ) in schools has emphasized the need of measuring CO_2 and temperature and use these parameters for control of ventilation (Clausen et al., 2016; Heebøll et al., 2018). Historically, research investigating the factors associated with IAQ and performance has focused on CO_2 (Coley et al., 2007; Wargocki et al., 2020). CO_2 is a good proxy for occupancy as about 50 % of the pollutants emitted in offices are emitted by humans (Fanger, 1988).
However, there is a growing body of literature proving that there are other pollutants that should be controlled and ventilated away. Erdmann and Apte et al. (Apte, 2006; Erdmann et al., 2002) concluded from the data analysis of 100 office buildings that there is prevalence of mucous membrane and lower respiratory sick building syndrome symptoms already at CO_2 concentrations below the customary 1000 ppm threshold.

Particulate Matter

PM affects more people's health than any other source of pollution (Kim et al., 2015). The data demonstrate a dose-dependent relationship between PM and human disease, and that removal from a PM-rich environment decreases the prevalence of these diseases (Anderson et al.2012). Chronic $PM_{2.5}$ exposure affects the respiratory and cardiovascular systems (Martinelli et al. 2013). Chronic bronchitis, stroke, heart disease, and thickening of arterial walls, diabetes, and reduced lung function are also connected to $PM_{2.5}$ exposures (Burnett et al. 1999; Kunzli et al. 2005; Pope et al. 2002). The low end at which health effects have been demonstrated is not much above the background concentration and has been estimated to be 3-5μg/m^3 (WHO 2005)

Formaldehyde

Formaldehyde is widely used in the manufacture of building materials and numerous household products, it is also a by-product of combustion and other natural processes (LBNL 2019) and a preservative in some food packing (NHI 2019). Wood-based products, cleaning products produced in ozone-initiated alkene reactions, and combustion emit formaldehyde (Wolkoff, 2013). Formaldehyde has been classified as a potential human carcinogen by the US EPA and International Agency for Research on Cancer as a Class 2A carcinogen. It irritates humans mostly in the upper airways, mucosae, and eyes (Norliana et al. 2009). Abdollahi et al. (2014) claim that it is a powerful cross-linking agent, even at low concentrations. Formaldehyde is a sensitizing agent that can cause an immune system response and sensory irritation (Wolkoff 2013). Moreover, formaldehyde is supposed responsible agent in the development of neurobehavioral disorders such as, but not limited to, insomnia, memory loss, lack of concentration, and mood and balance alterations, as well as a loss of appetite (Abdollahi et al.2014)

Relative Humidity (RH)

A common complaint in perceived IAQ questionnaires in office environments is perceived dry air. Some questionnaires have shown relations between low RH (5–30%), typical in cold climate offices during winter, and increased prevalence of complaints about perceived dry and stuffy air and sensory irritation of the eyes and upper airways (Wolkoff, 2018). Fewer tears are produced, and precorneal and epithelial damage has been observed at low RH (Wolkoff, 2018). Thus, the studies show that low RH aggravates the stability of the eye tear film, which initiates a cascade of adverse inflammatory reactions (Wolkoff & Kjærgaard, 2007) Interventional studies have shown that increasing RH may reduce the perception of dry air and symptoms of dry eyes and upper airways (Hashiguchi et al., 2008). Note that in most of these intervention studies, the humidity was kept below 50% because higher percentages of RH may affect moulds and mite's growth.

Therefore, though CO_2 has a proven effect on performance, maintenance of at least these three parameters below recommended guidelines (and over in the case of RH) should be controlled at least as much as CO_2 and temperature. In this article measurements over two months to one year in four classrooms in different schools in Trondheim, Norway have been used to study the prevalence of high concentration of pollutants. All the studied schools have mechanical ventilation CO_2-based and are new or renovated latest 5 years prior to the measurements. Correlations between different pollutants have also been studied.

METHODS

In this section, the measuring equipment is described and the classrooms where measurements were done, are presented.

Measuring equipment

Low-cost sensors were used to monitor the concentration of pollutants. Carbon dioxide was measured by a Sensirion SCD30 which uses CMOSens® Technology for NDIR measurement (Sensirion, 2020). The same sensor was used to monitor relative humidity and temperature. Particles in the fractions $PM_{2.5}$ and PM_1 were measured by a Sensirion SPS30 based on real-time optical particle counters. Formaldehyde was measured by a Dart Sensor WZ-S. This sensor is based on the measurement of the oxidization on the working electrode to generate an electric signal (Dart, n.d.).

All the sensors are pre-calibrated, and according to the producers they should not need any calibration prior to use. More information about the employed sensor and their calibration can be found in (Justo Alonso et al., n.d.)(under publication).

Classrooms

Four schools were selected in Trondheim, Norway to be analysed. The schools were selected so that they represented: one new school close to the road, one new away from the road, one older close to the road and one older away from the road. The selected schools have CO_2-based DCV. A single classroom was selected in each school. In the selected classrooms general teaching was performed. All the classrooms were placed on the first floor on the direction of the closest road. The classrooms were selected based on availability and no special IAQ concerns were expressed connected to these classrooms.

Table 1 summarizes the characteristic of the measured classrooms. Ld is a school constructed with massive wood. Due to access restrictions, in this room the "supply" air is measured next to the air terminal. Thus, this sensor measured the concentration of pollutants in the supplied air only when there is airflow supply, otherwise it measured room air. The same problem will happen in Brdln and Sgp.

Br has supply via two textile supply diffusors, Br and Ld have two supply terminals and Spg has eight supply terminals. All the rooms have a single return terminal.

Ld classroom hosts the general teaching of students of 2nd grade, Brdln 3rd grade, Br 7th grade and Spg 1st grade. Students of the first and second grade may use playdough or perform drawing cutting and gluing activities. Students on the 7th grade sit on their desks and receive normal teaching. The four classrooms have whiteboards.

Table 1. Summary of the measured classrooms (one per school)

Room	Ventilation	Year of facility improvements	Proximity to roads
LD 60m² / 25 pp	CO_2-based DCV 48 m³/h person	One-year old school.	200 m away from high traffic road.
BRDLN 110m²/ 36 pp	CO_2-based DCV 50 m³/h person	Renovated three years prior to measurement	700m away from High traffic road, 600 m away from medium traffic road in the south and in the west.
BR 60m² / 26 pp	CO_2-based DCV 58 m³/h person	Renovated two years prior to measurement	200 m to a medium traffic road.
SPG 60m² / 20 pp	CO_2-based DCV 60 m³/h person	Five-years old school by measurement period	100 m to a medium traffic road.

During occupancy, the room's airflow rate is controlled based on CO_2 and temperature. Outside schools' hours Br and Spg schools would turn off the ventilation. Ventilation would be turned on to the maximum one to two hours before the school start to remove the pollutants from the materials and insulation, i.e., those that do not originate from the human body. The time during which the ventilation is run to maximum is calculated so that the average of ventilation during unoccupied period is 0.5 ach. Ld and Brdln schools would reduce ventilation to the minimum during the periods when the school is not in use. In these four schools no recirculation of return air is used. 100 % of the supply air to the room is outdoor air.

In each of the classrooms two sensors were installed, one in the supply terminal and one in the breathing zone. Measurements lasted for at least two months from April to June and in the case of Br school, the measurement period is a whole year in two consecutive years. Data is collected at least every five minutes.

RESULT AND DISCUSSION

This chapter summarizes the measured results in the four classrooms and analyses correlations between pollutants.

Summary of measurements in the four classrooms

Figure 1 and Figure 2 show the boxplots summarizing the data for the whole measurement period. The results are presented as follows:

- Thirty minutes averages of formaldehyde in µg/m³.
- Daily averages of $PM_{2.5}$ in µg/m³.
- Temperatures in °C.
- Relative humidity in %.
- CO_2 concentration in ppm.
- RH in %.
- Supply airflow rate in m³/h.

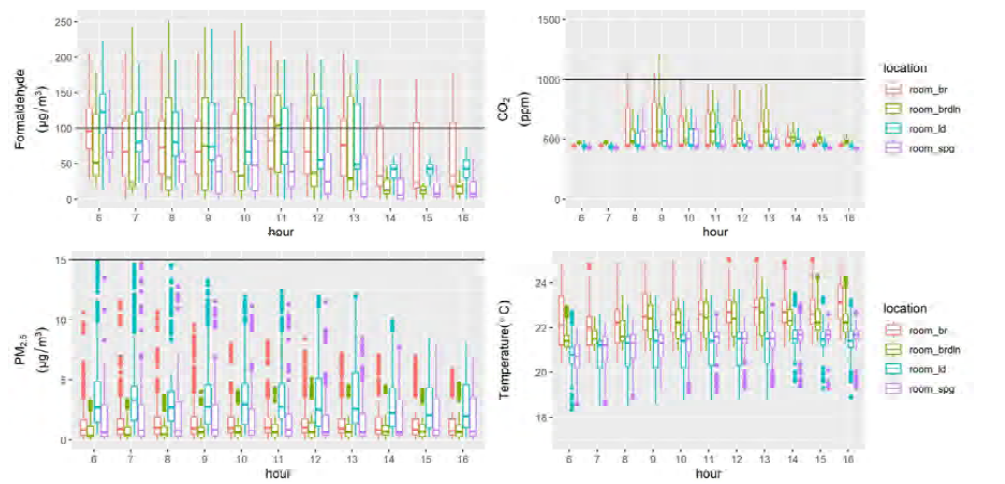

Figure 1. Boxplot summarizing measurements of formaldehyde, CO_2, $PM_{2.5}$ and temperature. The black horizontal lines represent recommended thresholds

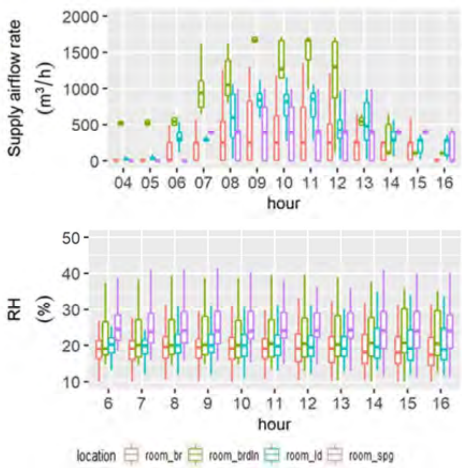

Figure 2. Boxplot summarizing measurements of the supply airflow rate and RH in the room

The classroom Ld presented the highest concentration of formaldehyde. This building was the newest and it was built in massive wood. In addition, the ventilation is stopped outside school hours. The materials used in the construction of this school followed the standard

NS-EN 15251(Standard Norge, 2014) of low emitting materials. However, solid wood can emit from an average of 4µg/(m² h) to GM=80 µg/(m² h) if considering MDF(Salthammer, 2019). These emissions depend as well on ambient RH and temperatures. Thus, when the ventilation stops the formaldehyde concentration rose over what the World Health Organization's (WHO) recommends as 30-minutes threshold: 100 µg/m³ (WHO, 2010). The most prominent concentrations of formaldehyde happened at 6 am in this room. At this time, the ventilation was started increasing the mixing in the room. However, no separated study was done of the wood materials in this room. Additionally, it is known that the formaldehyde sensor has cross-sensitivities with methanol, ethanol, CO, phenol, isopropanol, acetaldehyde, H_2, H_2S, and SO_2. The measurements of formaldehyde may appear higher than they are due to these cross sensitivities. It was observed one day that formaldehyde values rose when students were eating lunch in the classroom. But as the largest values of formaldehyde in Ld classroom happen at 6 am we are more prone to guess they derive

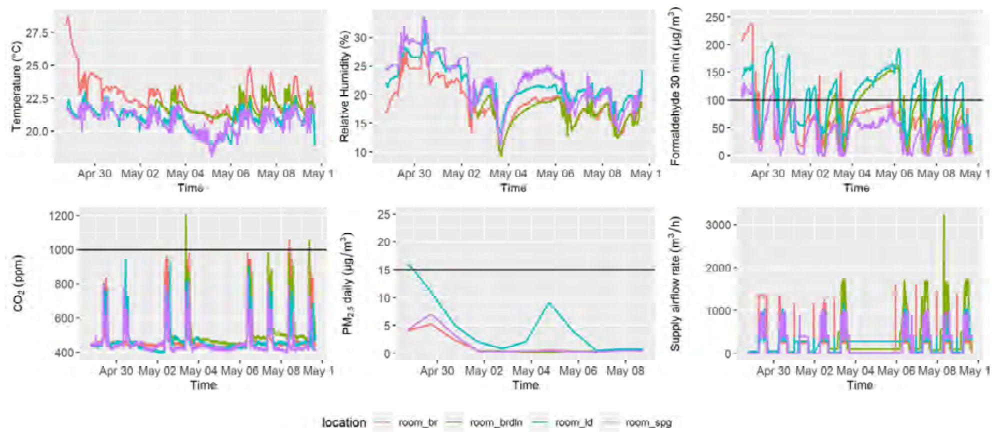

Figure 3. Evolution of pollutant measurements of temperature, RH, formaldehyde, CO2, PM2.5 and Supply airflow rates. The black horizontal lines represent recommended thresholds

from wooden materials in the classroom. Further controlled measurements should be done to study these high values in detail and then propose specific measures to minimize these emissions.

Room Brdln had the highest concentration around eleven, when many students eat in the class (in other classrooms students do not eat in the classroom). The most plausible explanations for this peak were 1) that the formaldehyde sensor had cross-sensitivities to some conserving VOC and 2) that the students were eating fruits such as pear and banana which have naturally high concentrations of formaldehyde. Students confirmed this second hypothesis.

Classroom Spg which was placed in the oldest building presented the lowest concentration of formaldehyde.

Regarding $PM_{2.5}$, all the classrooms show values below the Norwegian threshold of daily averages of 15 µg/m^3 (Bang, 2017), note that the graph shows averages per hour in Figure 1 Classroom Ld presented a very constant profile of concentrations. This room is 100 m away from a medium traffic road which may be the source of this pollution. The presented values were still very low, in many cases below the normal background concentration 3-5µg/m^3

RH was often below 20 % in classrooms Br, Brdln and Ld. In Spg, RH was mostly over 20 % with an average value of 25 %. In the boxplots in Figure 2, it was barely noticeable the increase of RH due to room occupancy. However, there was a small rise at 15 pm after students left the room at 14 pm and the ventilation was stopped

CO_2 and temperature were the control parameters and all four classrooms presented results below the established threshold.

Figure 3 shows the evolutions of the pollutants during two weeks in May. Here, formaldehyde rose every day when the ventilation was turned off and Ld classroom presented the highest values. The ventilation for this period followed the concentration of CO_2 increasing everyday as occupants enter the room and dropping to the selected minimun or turned off when the occupants left the room. The 29th of April roads where cleaned for the season in the area of Ld classroom. The measured peak probably results from this action. RH fluctuated everyday with occupancy and temperatue and only in classroom Ld and Spg its value was always over 20 %.

The RH was below 20 %, during 56 % of the time that the CO_2 was below 1000 ppm. The formaldehyde was over 100µg/m^3 during 30 % of the time that the CO_2 was below 1000 ppm and the $PM_{2.5}$ were over 15 µg/m^3 during 2 % of the time (Note that for this comparison it is used the Norwegian threshold of 15 µg/m^3 (Bang, 2017)). However, when referring to the periods from school hours between 8 am and 16 pm, the occurrence of RH being below 20 % happens in 69 % of the time, the formaldehyde is over 100 µg/m^3 during 19 % of the time and $PM_{2.5}$ is never over 15µg/m^3. During occupancy period, all rooms are ventilated with 100 % outdoor air making that when there is large occupancy, the volume of air is changed often, reducing the concentration of formladehyde but also reducing the concentration of RH that drops below recommended levels(FHI, 2015). It is important to increase the RH leves as the dry air perception can be connected to mucous membrane irritation of eyes and upper airways in the presence of sensory irritants (Doty et al., 2004). In this case formaldehyde could be such irritant. Additionally, low indoor temperatures and low RH are associated with increased occurrence of respiratory tract infections. This could be seen as a result of increased survival and transmission efficiency of influenza virus, e.g., from coughing (Derby et al., 2017; Wolkoff, 2018). Increasing the RH> 40 % dramatically reduces the infectivity of some virus (Myatt et al., 2010).

Correlation between pollutants were analysed as well. For this analysis only the occupied periods are considered. Data is analysed from the four rooms together and no difference is done between classrooms. In total there is data of about one year for room Br and about 2-3 months from the other classrooms.

Formaldehyde levels are too high, and they do not follow the occupancy measured as the increased CO_2. The Pearson correlation factor of the detrended CO_2 and formaldehyde is 8 % meaning that the correlation is weak. This justifies the prevalence of high concentrations of formaldehyde independently of the concentration of CO_2. Also, this may be related to the different origins of formaldehyde and CO_2. The same can be concluded when looking at $PM_{2.5}$. In this case the values are very low due to the low concentration of particles in the outdoor air and low sources of $PM_{2.5}$ indoor as well. The Pearson value in this case is 14 %. In classroom_ld it was deemed interesting to look at correlation between formaldehyde and temperature and RH as this building is constructed in massive wood. For this classroom the correlation between formaldehyde and temperature is of the 41 % and with RH and formaldehyde is only 8 %.

If correlation between temperature and CO_2 is studied the Pearson value rises to 56 % which means that these are correlated. And when looking at the correlation between temperature and RH the correlation factor resulted on 50 %. CO_2 and temperature correlate 56 %.

When focusing on the origin of the pollutants, a correlation analysis of de-trended time series between supply and room air was done. Note that as some sensors (supply sensors) could not be installed inside the supply terminal and only on it, the analysis is only done for classroom Br only. For this classroom, data of about one year is analysed. In this case there is a significant corelation, 82 % between supply and room RH. This could be also be expected as there is a large supply of outdoor air. Temperatures do not correlate so strongly, 69 %, probably due to the solar heat gains and the use of radiators in the room that affect the correlation with the supply air. CO_2 in the room correlates 63 % with the supply air. Formaldehyde is also mostly produced indoors, thus, the correlation drops at 46 %. PM1.0 and $PM_{2.5}$ are very much provided via ventilation and the correlation is respectively 82 % and 75 %. (Note that the supply air has already passed through a filter as the measurements are done in the air terminal).

CONCLUSIONS

This article present measurements in four Norwegian schools placed in Trondheim. Measurements were collected for two months to up to one year in the supply and room air in the schools whose ventilation is CO_2-based DCV. Usually, it was expected that when controlling these mainly human-produced pollutants high indoor air quality is preserved.

This study uses low-cost sensors to monitor the concentration of formaldehyde, PM_1, $PM_{2.5}$ and relative humidity additionally to CO_2 and temperature.

The measurements prove that even when the CO_2 concentration lies below 1000 ppm 1) the concentration of formaldehyde surpasses the recommended by the WHO in 30 % of the time and 2) RH is below 20 % during 56 % of the time.

Controlling CO_2 and temperature results in overseeing peaks of formaldehyde and maintaining RH levels are lower than 20 %. This work proves the need to control these parameters additionally to the customary CO_2 and temperature.

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PAPER ii

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Short term measurements of indoor air quality when using the home office in Norway

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Abstract. In 2020, due to the outbreak of COVID-19 many workers have been sent home to avoid the sickness spread. As a result, rooms that otherwise had domestic use, living rooms or bedrooms, have become offices. This change has happened in many houses without improving the ventilation systems. In many cases, the rooms were overcrowded, and no attention was paid to ventilation. Thus, this study collects measurements of one to two weeks in different home offices. Measurements were taken in home offices used by one or more occupants. These home offices were designed as bedrooms and living rooms with and without separation from the kitchen. During the pandemic they are used as offices during working hours and as designed otherwise. One or more occupants shared the rooms. Natural and mechanically ventilated and older and newer home offices were studied. Winter measurements of CO_2, temperature, relative humidity, particulate matter, formaldehyde and TVOC were collected via low-cost sensors. The sensors were placed on the working space in front of the user to map the exposure to pollutants. The results show an analysis of the concentration of pollutants close to the breathed air. Some users were smart, remembering the aeration, whereas others were exposed to high concentrations of CO_2 and other pollutants sometimes higher than the health-based thresholds.

1 Introduction

The coronavirus disease 2019 (COVID-19) is caused by the transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). On the auspices of the outbreak of the COVID-19 pandemic in March 2020 workers were requested to work from home from one day to the other. Rooms that were designed for domestic use were suddenly transformed into home offices. Some people used the kitchen bench, some people the living room and some bedrooms. Some people had at least the reglementary area per office workplace of 6 m^2[1], some did not. Anyhow, there was too much risk for COVID contamination and people had to work from home whenever possible. However, now is December 2020 and many of us keep on working from home as the risk of contamination is still high.

The Norwegian authorities published a guide that provides advice on how workplaces should be arranged to reduce the risk of infection in May [2]. This document does not specify any further information about ventilation. The Norwegian Labour Inspection Authority specifies that *"To ensure that the employee's safety, health and welfare are safeguarded, the employer must, as far as practicable, ensure that the working conditions are fully justifiable. This applies, among other things, to the workplace, work equipment and the indoor environment not causing unfortunate physical strain"*[3]. This rule of behavior is not very specific. For this article, we assume that the home office should meet the criteria defined in the building codes [4] and in the occupational health and public health legislation [5], [6] as humans are the same and the effect of pollutants on health is the same at home or the office.

Owing to recommendations in [3], it was a general move in many companies to provide computers, screens and chairs to satisfy the ergonomic challenge of moving to the home office. However, ventilation or indoor air quality (IAQ) was not followed up as closely. This article intends to map the indoor air quality that a sample of users is exposed to when working from home. Measurements taken during one to two weeks show that more attention should be drawn towards the IAQ and probably employers should give some recommendations and requirements to the home office users.

2 Methods

This study is a field study realized in December 2020 when home office use was still recommended in Norway. Eligibility criteria required individuals to be working from home at least four of the seven days of the week. The participants of this study were recruited from the academic environment of Trondheim, Norway. A sample of eleven houses has been selected for collecting the measurements. Such a small sample was chosen because of the restricted number of available sensors. There are several instruments with different accuracy

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for measuring the IAQ. We used low-cost sensors as these could be used to monitor the IAQ and not represent a huge economic investment. More information about the employed sensor and their calibration can be found in [7] (under publication).

The sensor was placed in the working table next to the keyboard to represent as much as possible the breathed air (note that these measurements would not be sufficient to represent the whole room as the mixing of the air or any other considerations about air distribution in the room have not been studied. These measurements only intend to represent the air breathed by the home office user).

To quantify the normal IAQ that the employees were breathing, the participants were asked to behave as normally as possible and not to change their practices regarding window opening. To know their habits regarding ventilation, all participants were sent an anonymized questionnaire. To control for bias regarding outdoor air, at least three houses were measured simultaneously in the same area of the city. Data management and analysis were performed using R studio Version 1.3.959.

Once the samples were extracted, the feedback was given to the users in the form of recommendations regarding window opening.

In observational studies, there is a potential for bias from the users over opening the windows as they feel “observed by the sensors”. A longer measurement period would have been better to reduce this bias. The small size of the dataset with all the users coming from the same population of engineering may be affecting the results as well. Thus, further data collection is required to determine exactly the IAQ representative for Norwegian home offices. Table 1 presents the home offices where the results were collected results.

Table 1. Shows the sample where measurements are collected. The nomenclature used is described below. Type: Type of building where the measurements are performed, Bdg. Loc: Building location the city, SDH: Semi-detached house, SFH: single-family house, A: Apartment, B: Basement, Ba: Bathroom, K: Kitchen, S: Staircase, B: Bedroom, LR: Living room, CC: City center, SNF: Suburban non-forested area, SF: suburban forested area, NV natural ventilation, EV: Exhaust ventilation, MBV: Mechanical balanced ventilation.

ID	Type	Floor	Area (m^2)	Linked room	Bdg. loc	Ventilation
1a	SFH	2nd	12	LR, B	CC	NV
1b	A	3rd	9.8	Ba	CC	NV+EV
1c	A	2nd	48	LR	CC	NV+EV
1d	SDH	3rd	15	S	SNF	MBV
2a	SDH	2nd	5	B	SNF	NV
2b	SFH	B	4.5	LR,B,K	SF	NV+EV
2c	A	2nd	40.4	LR,K	SNF	NV
2d	A	1st	15	LR,B,K	CC	NV
3a	SDH	B	32	LR,B,K	SNF	NV
3b	SFH	B	4.5	LR,B	SF	NV+EV
3c	SDH	1st	10.5	B	SF	NV

36 % of the measurements are done in single-family houses, 36 % in apartments and 28 % in semi-detached houses. 28 % of the rooms are in basements, 18 % on the first floor, 36 % on the second floor and 18 % on the third floor. 54 % of the rooms are used for at least two functions in addition to the home office, indeed only 45 % were designed as domestic offices. There is only one building that has mechanical balanced ventilation. 36 % of the offices are placed so close to the bathroom that their ventilation is affected by its extraction. Other 36 % have an opening to the kitchen and the extraction via the kitchen hood would influence the pollutants. However, in these cases, the kitchen activities will as well affect the pollutant concentration.

Measurements are done in one house of 1900, one house from 2018 and the rest of the houses are constructed in the period from 1950 to 1970. Among the latter, 45 % have undergone renovations such as newer windows and/or tighter envelope.

2.1 Outdoor conditions during measurements

Measurements were performed from the eighth of December to the 31st. During this period, the wind velocity was on average 2 m/s with a maximum of 9.4 m/s blowing mostly from the South. A summary of the measurements is shown in Figure 1.

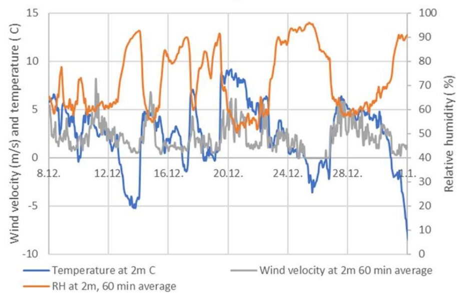

Figure 1. Summary of outdoor conditions during the measurements

3 Results

The results are presented as weekly graphs of the measurements:

- Thirty minutes averages of formaldehyde in µg/m^3.
- Continuous measurements of Total Volatile Organic Compounds (TVOC) in µg/m^3.
- Daily averages of $PM_{2.5}$ in µg/m^3.
- Temperatures in °C.
- Relative humidity in %.
- CO_2 concentration in ppm.

The horizontal green lines in **Figures 2, 3 and 4** represent existing maximum thresholds defined by the national or international authorities and the purple represent the recommendations by the Norwegian authorities. Following this:

- The threshold for Formaldehyde is 100 µg/m^3 according to [8]

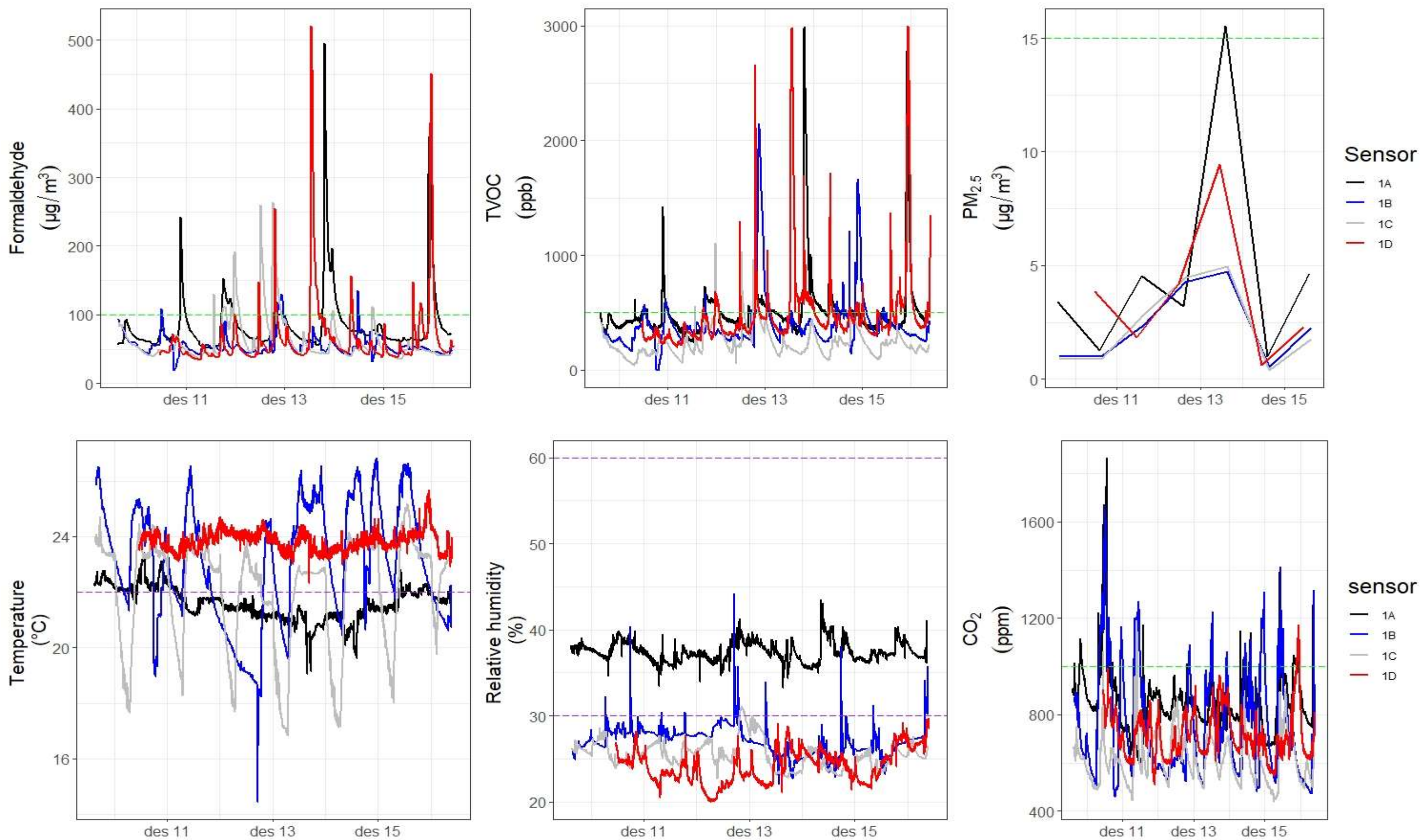

Figure 2. Measurement results during the first week.Formaldehyde in 30 minutes averages, $PM_{2.5}$ in 24-hours averages. Green dashed lines show the health thresholds and purple the recommendations

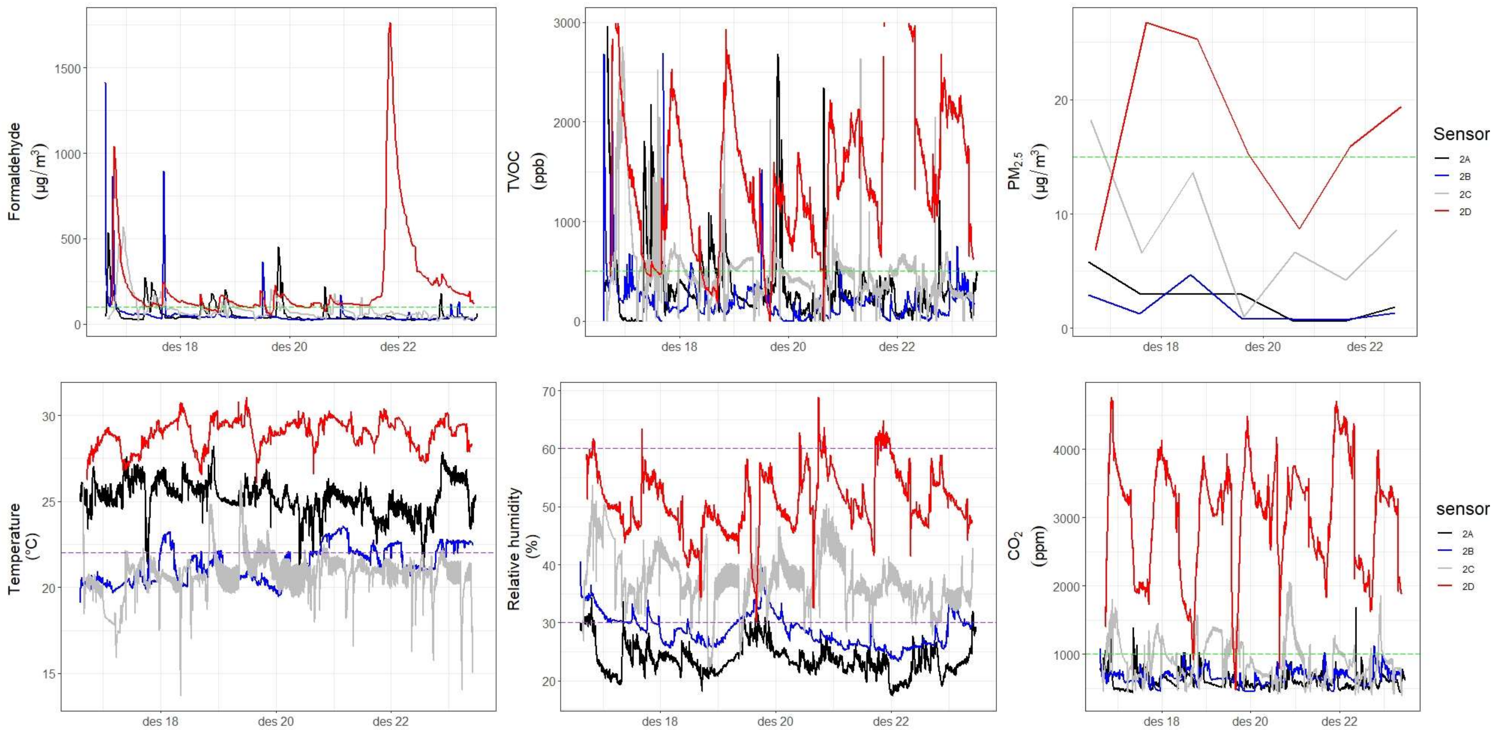

Figure 3. Measurement results during the second week. Formaldehyde in 30 minutes averages, $PM_{2.5}$ in 24-hours averages. Green dashed lines show the health thresholds and purple the recommendations

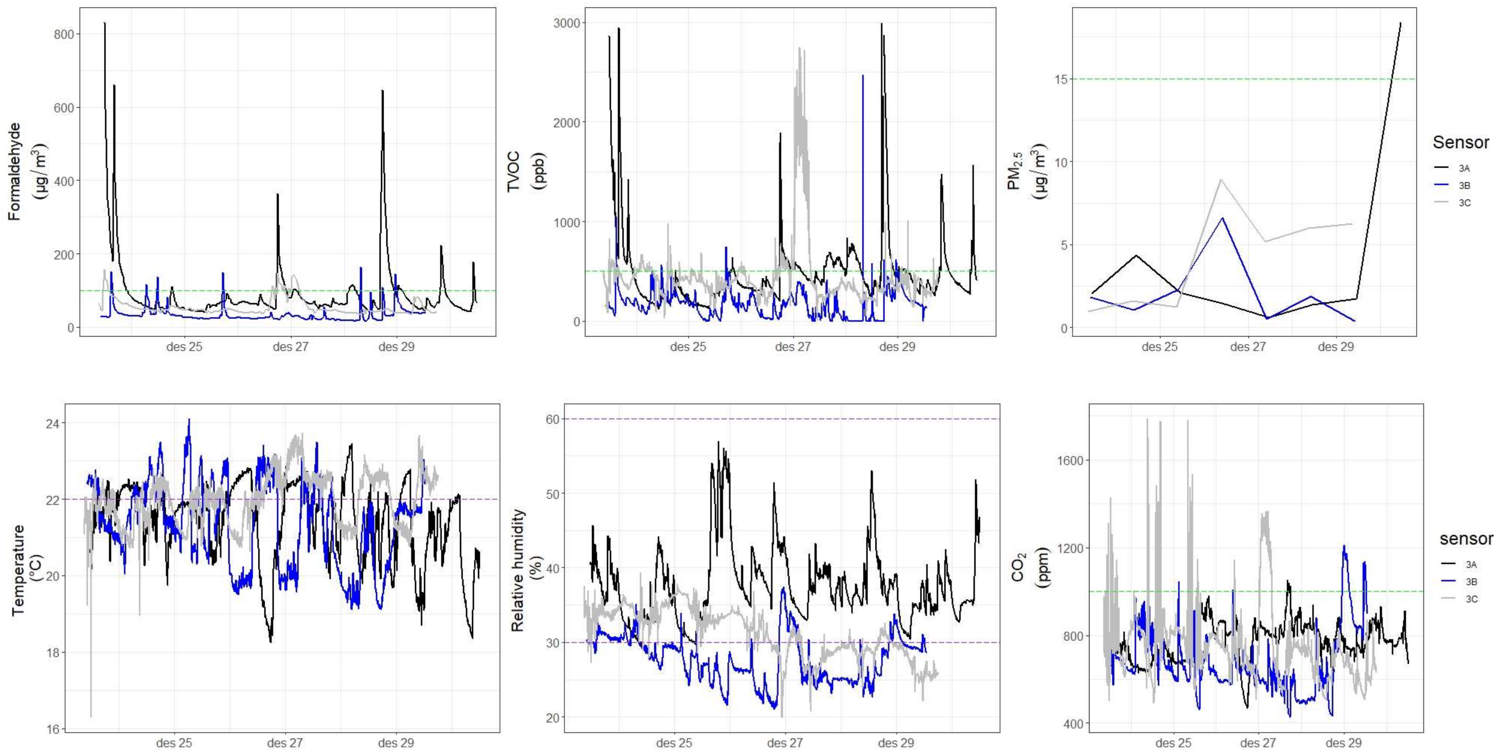

Figure 4. Measurement results during the third week. Formaldehyde in 30 minutes averages, $PM_{2.5}$ in 24-hours averages. Green dashed lines show the health thresholds and purple the recommendations

- According to the WELL Building Standard, the limit for TVOC is <500 µg / m^3 [9].
- For $PM_{2.5}$ according to the NPHI, the maximum is 15 µg/m^3 in daily averages [5].
- For temperature, the advised value that should not be overpass in heating season is 22 °C [4].
- For moisture, the advised range is 20-60 % according to [10].
- For CO_2 the advised limit is 1000 ppm according to TEK10 [11].

Figure 2 shows the measurements in offices 1 A-D from December the 8th to 16th. House 1D represents the newest and tightest envelope of all the measured home offices. In this house, there is mechanical ventilation supplying constant air. In this house the concentration of CO_2 is mostly below 800 ppm except for the evening of December 15th when 8 people were using a lower room and thus, we see a peak in CO_2 concentration. At the same time, this is the house with the highest supply of outdoor air and thus, the relative humidity is among the lowest. This house counts with heat recovery, electric heaters and a highly insulated envelope that keep the temperature constantly at 24 °C that the user has defined as comfort temperature. This house is also painted with low emitting materials and the concentrations of TVOC or formaldehyde are comparable with the other houses although the other houses have been painted several years before. It is very interesting to see that both 1A and 1D had meetings when several people joined to cook Christmas cookies on the evening of December 13th (also on 15th of December) and both home offices present similar concentrations of formaldehyde and TVOC. However, the PM concentration differs much more. 1A is placed very close to the kitchen and 1D is two floors away from the kitchen. Thus, the volatile and gaseous components dissolve in every room of the house but not the $PM_{2.5}$ that has a much more local effect. 1B and 1C are situated in the same building on the third and second floor. In 1B the user has an oil radiator that is turned on when the user is working, thus, the large variations during and outside working hours. In this room, there is a window in the roof and the user feels colder than when going to room 1C that is normally at a lower temperature. 1C is separated from the kitchen by a door that is normally closed. However, we can see the variations in the volatile compounds connected to cooking.

Figure 3 shows the measurements in home offices 2 (A-D) from 16th to 23rd of December. Here the measurements for home office 2D stand out. This is a 15 m^2 sleeping room, office and kitchen where two adults and one baby live. During working hours one parent goes to work, the baby goes to kindergarten and the other parent stays at the home office. These users do not open the windows to ventilate to avoid the entrance of cold air (though the average temperature of the room is 28 °C). This affects the concentration of CO_2 that in the worst moments is close to 5000 ppm. The users do not feel headaches but sometimes need to go for a walk *"to get some air"*. These users are exposed to health affecting levels of formaldehyde, TVOC, $PM_{2.5}$ and CO_2 owing to surpassing the threshold levels defined by the World health organization and all national standards. Home office 2B is placed in a basement at the top of a hill. This user always has the window closed and the 4.5 m^2 room has no mechanical ventilation. However, the room's CO_2 concentration is maintained below 1000 ppm. On windy days such as December 21st , the concentration of CO_2 is lower. The building envelope has not been tightened though the windows were changed. During construction, the requirement of tightness for such a house was 4 m^3/m^3 h [12]. This may justify the low levels of CO_2 together with a strong extraction in the bathroom. Home office 2C uses a wood stove additionally to an electric radiator, on the evening of the 16th of December. On this day formaldehyde, TVOC and $PM_{2.5}$ levels are much higher than for the other days probably related to wood firing. The users also report daily burning of candles in the evenings and this is reflected as peaks of TVOC and $PM_{2.5}$ (though $PM_{2.5}$ peaks are not visualized in Figure 3 as this graph represents 24-hours averages).

Figure 4 shows the measurements of home offices 3 (A-C) from 23rd to 30th December 2020 (none of the users celebrated Christmas). 3A is an office, living room, bedroom and kitchen space. As in all the other cases where there is a kitchen (2b, 2c, 2d, 3a), we see an effect of cooking on the formaldehyde, TVOC and $PM_{2.5}$ levels. Home office 3C is used also as a bedroom. On the 27th of December, two people sleep and this influences CO_2, relative humidity, temperature and TVOC that rise simultaneously. The user of this room also reports that on the first three days, the sensor was placed close to its face and this may justify the peaks in CO_2, probably due to direct breathing on the sensor.

Figure 5 agglomerates the values for all the measured offices during working hours. Working hours are defined as between 8:00 at 16:00 and from Monday to Friday. In summary, the employees are exposed to the following concentrations:

Formaldehyde is over 100 µg/m^3 more than 9 % of the measured time. For the worst-case scenario, this value is surpassed 45 % of the measured time.

For $PM_{2.5}$ the cases where the measurements are over 15 µg/m^3 represent only 4 % of the time, though in the cases where there is an open kitchen in the same room, these values may rise to up to 26 % of the time (note that we are looking at the 24-hours averages, large instantaneous peak happen frequently).

For the temperature, we have evaluated the hours outside the range from 20 to 24 °C. When considering all the offices, the measured temperature is outside this range for 81 % of the time, being the temperatures mostly over 24 °C. In the worst case, the temperature is outside this range for 100 % of the time. This proves that these users don't agree with the defined thermal comfort by the Norwegian TEK and regulate their heaters to feel comfortable.

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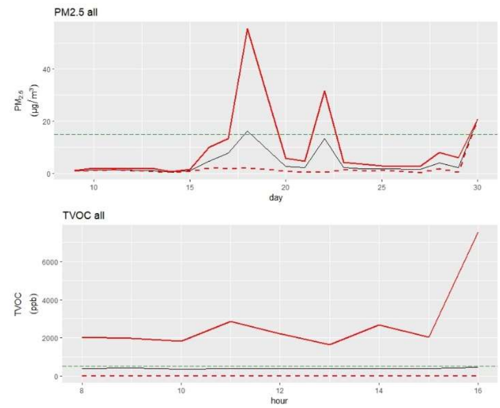

Figure 5. Aggregated values for all the home offices during working hours defined from 8-16 from Monday to Friday. $PM_{2.5}$, formaldehyde and TVOC in µg/m³ and CO_2 in ppm The solid black line represents the average of all the measurements, the solid red line the maximum measured in that hour (or day for $PM_{2.5}$), the dashed red represents the minimum measured in that hour (or day) and the green dashed line the health recommendation. For formaldehyde, the graph represents the 30 minutes averages and for $PM_{2.5}$ the comparison is on daily basis.

For the relative humidity, the measured values are outside the range 30-60 % during 69 % of the time, being the humidity below 20 % during 8 % of the time. This is a typical problem in Norwegian offices during winter as being the outdoor temperatures so low the indoor humidity is also very low. In the worst-case, the office 1D is below a humidity of 30 % 100 % of the time and below 20 % 25 % of the time. This user complains that since not working at the office, the contact lenses are stickier to the eyes.

Regarding TVOC, considering all the home offices, the value 500 µg/m³ is surpassed 18 % of the time. The worst measured office this value is overpassed for 69 % of the measured period.

Finally, the CO_2 threshold of 1000 ppm is surpassed 10 % of the time considering all the home offices. However, for the worst measured home office, this value is never gone under.

We do not know how the home office affects their performance or health as this was not questioned.

4 Discussion

The levels of $PM_{2.5}$ are generally very low in these measurements. Most of the sources for $PM_{2.5}$ in these home offices are candle burning, wood stoves, oven cooking, the toasting of bread or outdoors. We did not measure the outdoor concentration of $PM_{2.5}$ in each house, but Trondheim Municipality, the Norwegian Public Roads Administration and the Norwegian Institute for Air Research have installed measurement equipment not so far from the measured home offices. As Figure 6 shows with data from these sensors, during the measurements the average concentrations of $PM_{2.5}$ are 3.4 and 5.4 µg/m³. Given that only 1A and 2C use the wood stoves actively, most of the pollutants must derive from activities such as cooking and a candle burning. Still, the average values are generally lower than the 15 µg/m³ recommended.

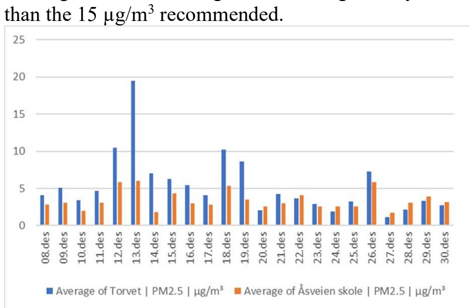

Figure 6. Hourly measurements of outdoor concentrations of PM2.5 in the vicinity of the home offices

The average value of formaldehyde is 60 µg/m³ for all the sensors during the measured period, but many home offices present peaks that should be addressed. Formaldehyde is probably emitted by furniture, wooden products, textiles, paints, glues, household cleaning products, beauty products, computers and electronic equipment and of course cooking, heating and candle and incense burning [8]. For many of these sources, the high temperature and high relative humidity affect the emissions [13], [14]. Some of the peaks of formaldehyde happen simultaneously to peaks in TVOC. The used sensors have known cross sensitivities with methanol, ethanol, isopropanol, carbon monoxide, phenol, acetaldehyde H_2, H_2S, and SO_2. These may also affect the results. When asked many of the users responded that they had the habit to burn candles. Additionally, many of the home offices are close by or in the same room as the kitchen and temperatures are relatively high in many of the measured houses. Many users also report frequent use of antibacterial gels. Thus, high values can be sustained.

The TVOC average value is around 400 µg/m³ for all the home offices. However, the threshold value of 500 is often surpassed in many home offices. The sources for TVOC are many and it is difficult to remove them as TVOC are ubiquitous. For some wooden flooring, the emissions at 35 °C were more than double at 25 °C [15].

Given that the home office has been for the last nine months and may continue in the future, more attention should be paid towards ventilating the formaldehyde and TVOC. The general advice for these pollutants would be to keep the temperatures low to remove emission from furniture, wooden products, textiles, etc and ventilate more.

For CO_2 most of the users manage to keep its value below 1000 ppm, even when no employee had any indicator of its value, thus, for most of the home offices the ventilation was satisfactory regarding this parameter. However, for some home offices, the value was almost three to four times the threshold limit. When asked, most of the users claim to have the windows always closed and they rely on infiltration to ventilate away all pollutants. In cold periods like the measured, the infiltration levels must be high or very high. These house are not very airtight, thus these houses may be "very ventilated" but the ventilation is irregular and unpredictable.

Temperatures are regulated by the users to their comfort which is slightly higher than what is normally maintained in offices. The relative humidity is not controlled and just varies based on the occupant's activities. In general, most houses show RH close from the lowest advised threshold of RH and the outdoor temperatures are not even in the lowest of the year.

In general, while some parameters are generally kept below the thresholds for most of the offices, for some other parameters or in other offices, all the parameters, the measured values are dangerously high. The standard from the Norwegian Labour Inspection Authority should be updated to address the new needs that the home office is requiring, and the employers should remind employees to open windows more frequently to avoid health problems. Further measurements and correlations to health challenges are also recommended considering the results from this sample.

5 Conclusions

Measurements have been collected in eleven houses for at least one week in the last month of 2020. For many of the measured offices, thanks to the large infiltration rates, the general levels of CO_2 are maintained below the threshold of 1000 ppm and given the low outdoor pollution levels of Trondheim the $PM_{2.5}$ levels are also quite low. However, for other pollutants such as TVOC or formaldehyde more ventilation would be advised as the lower the concentration of these, the better.

Comfort temperature when users can change it freely is higher than what is standard in offices. This should be further studied.

It is recommended that additionally to the ergonomic facilities, more recommendations of increasing the ventilation and/or open windows should be given from the employers to remember to keep the pollutants levels low.

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PAPER iii

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PAPER iv

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