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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 bio-effluents 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.

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	

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].

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).

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

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.

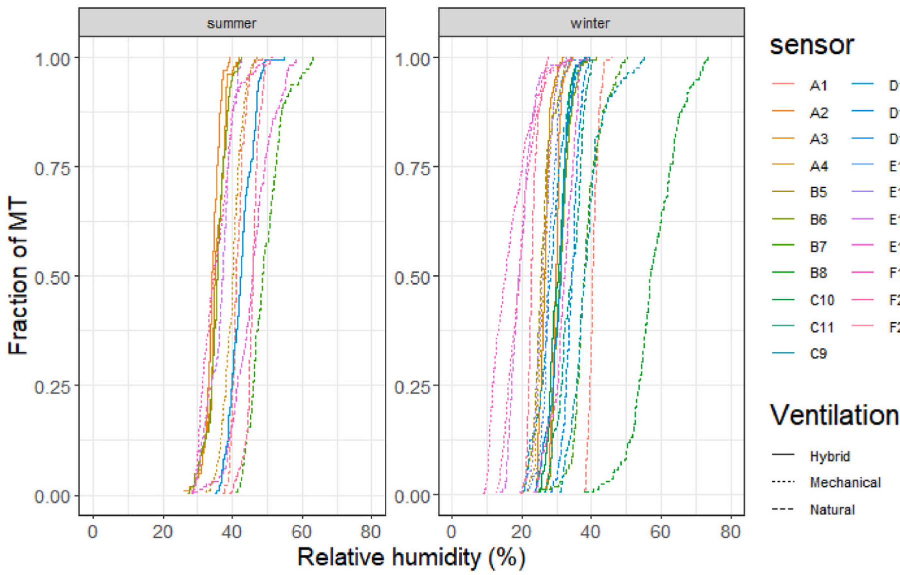

Fig. 1. Distribution of the RH during the measured time for each case, distinguishing summer and winter measurements. The color of the lines corresponds to the different cases and the line type to the ventilation strategy. (For interpretation of the references to color in this figure legend, the reader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

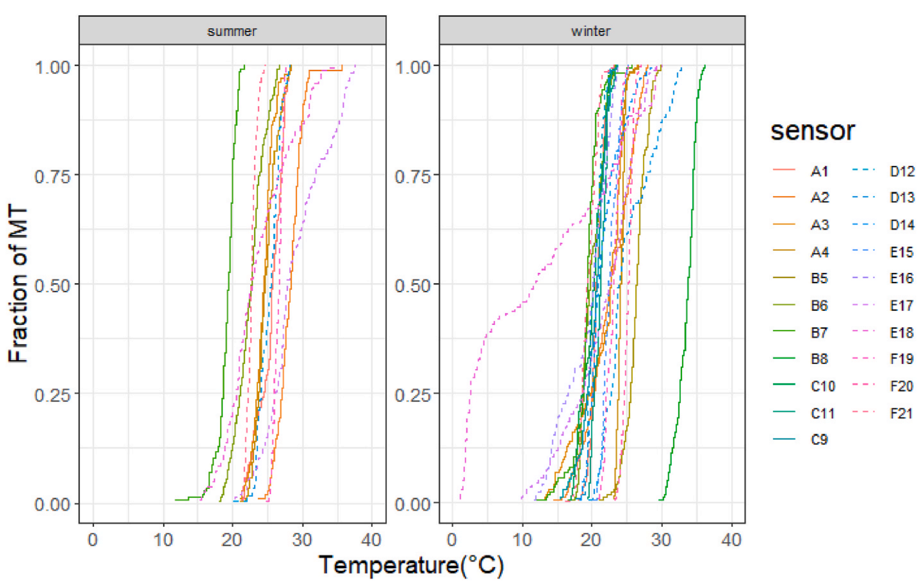

Fig. 2. Distribution of the temperature during the measured time for each case (summer and winter are included where two rounds of measurements were performed).

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.

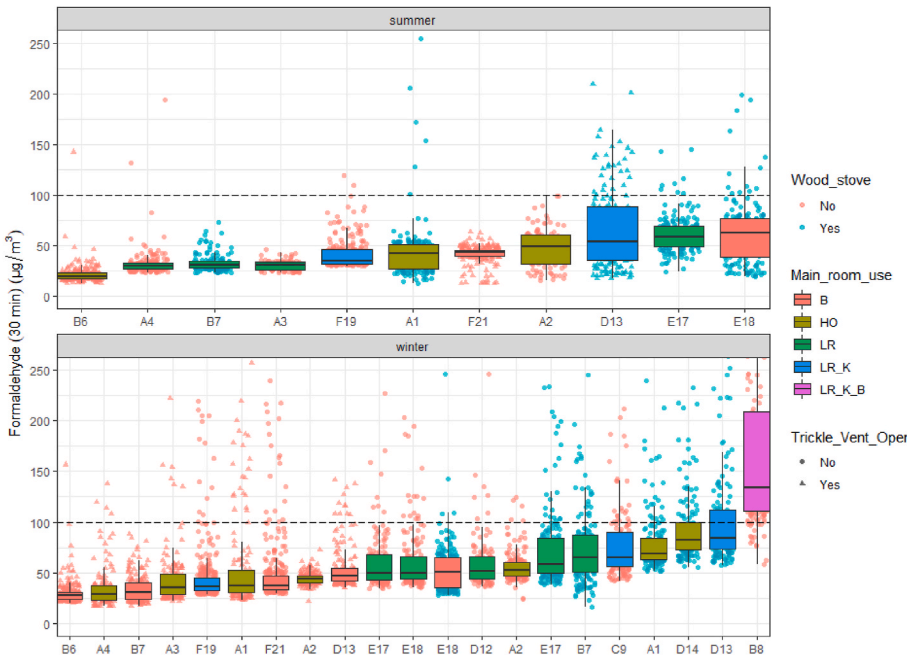

Fig. 3. Distribution of formaldehyde measurements for each house colored by the room's primary use. The dots or triangles in this figure show the single measurements aggregated by hour featured by the status of the trickle vent, and their coloring refers to the existence or not of the wood stove in the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

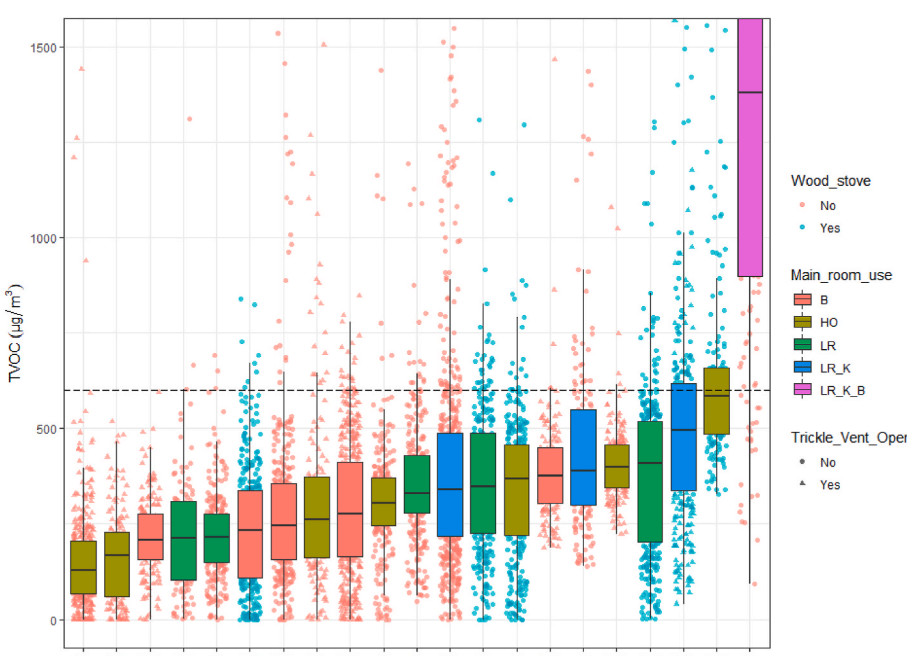

Fig. 4. Distribution of TVOC measurements for each house colored by the room's primary use. The dots or triangles in this figure show the single measurements aggregated by hour featured by the status of the trickle vent, and their coloring refers to the existence or not of the wood stove in the house.

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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