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 3-5$\mu g/m^3$ (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.

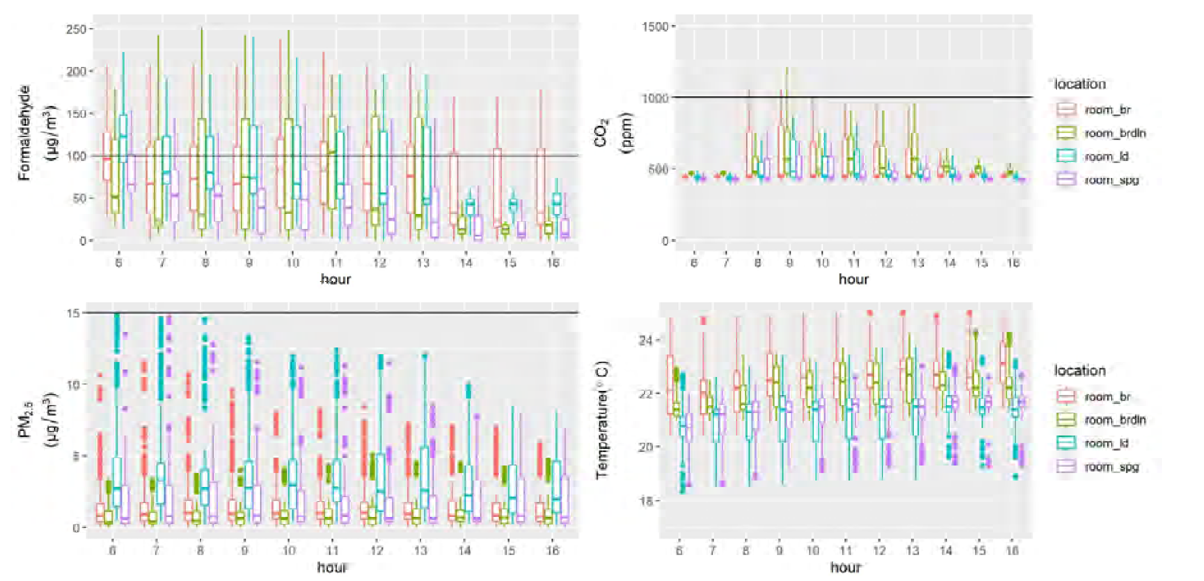

Figure 1. Boxplot summarizing measurements of formaldehyde, CO_2, $PM_{2.5}$ and temperature. The black horizontal lines represent recommended thresholds

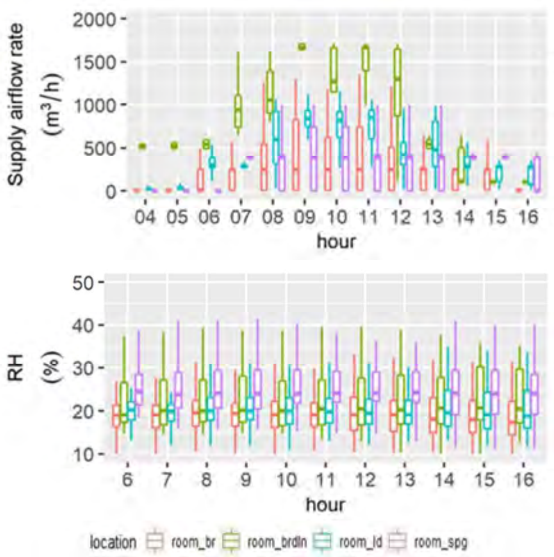

Figure 2. Boxplot summarizing measurements of the supply airflow rate and RH in the room

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

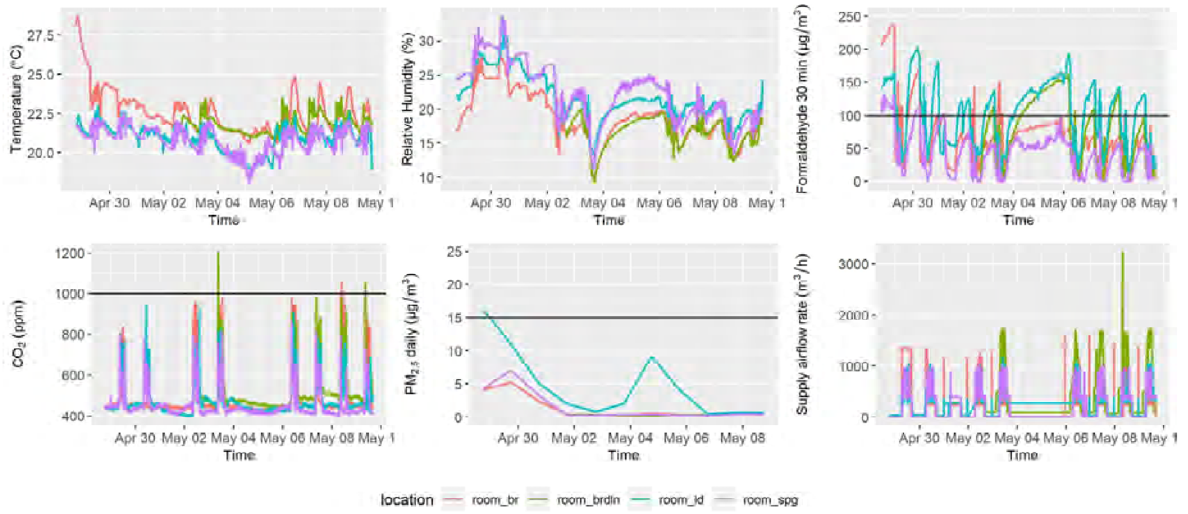

Figure 3. Evolution of pollutant measurements of temperature, RH, formaldehyde, CO2, PM2.5 and Supply airflow rates. The black horizontal lines represent recommended thresholds

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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