Using co-simulation between EnergyPlus and CONTAM to develop IAQ and energy-centric demand-controlled ventilation systems

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ABSTRACT

Buildings account for approximately 40 % of energy use in the European Union, as well as in the United States. In light of the European Energy performance of buildings directive, efforts are underway to reduce this energy use by targeting zero or nearly zero energy buildings. In such low energy buildings in cold climates, ventilation to ensure suitable indoor air quality is responsible for half or more of their energy use. The use of heat recovery and demand-controlled ventilation are potential solutions to reduce ventilation-related energy consumption. Demand-controlled ventilation can be utilized to realize energy savings by maintaining the concentration of CO_2 below a control setpoint. This control approach can reduce ventilation airflows when possible to reduce energy use.

This paper presents a study of a corridor of offices ventilated with constant airflow in Norway over two weeks of normal occupancy. Measurements of temperature, relative humidity, carbon dioxide, particles and occupancy levels were used to calibrate a simulation model. These measurements were used to validate a coupled energy, airflow and indoor air quality model. Co-simulation between EnergyPlus and CONTAM was used to evaluate the baseline energy use and develop a CO_2-based demand-controlled ventilation strategy which took into account other pollutants and recirculation airflows. A parametric study was performed to evaluate energy use and occupant exposure. The main findings from the simulations reveal:

- Interactions between recirculation of air and increased ventilation rates to maintain low CO_2 levels are not always intuitive. In some cases, increased ventilation rates were unable to maintain acceptable CO_2 levels when using recirculation of exhaust air, and the increased fan power of the demand-controlled ventilation system prevented very large energy savings.
- DCV based on multiple pollutants must be carefully programmed to avoid control problems. For instance, reducing outdoor air intake when outdoor particle levels were high was effective so long as occupancy was below 100%.
- Occupant health and building energy use are strongly correlated, and the ventilation control needs to be programmed considering this interdependency. Here we propose to use reduced exposure to pollutants as a performance parameter for comparison to reduced energy use. The study presented herein serves as the initial phase of a project to study in greater detail how to reduce ventilation while ensuring indoor air quality using a comprehensive analysis method.

KEYWORDS

building simulation, CONTAM, demand-controlled ventilation, EnergyPlus, indoor air quality, energy use, recirculation

1 INTRODUCTION

Reducing energy consumption in buildings is fundamental to energy resource conservation and climate change mitigation, as well as addressing the Energy performance of buildings directive (EPBD) (European Commission 2010). While costs associated with building energy use can be significant, it has been estimated that for the commercial building sector that 1 % of the cost is related to energy, 9 % to building rental and 90 % to occupant payroll (Alker et al. 2014). This should justify health, well-being and productivity of occupants to be a higher priority (Parkinson et al. 2019a) than reduced energy use, which includes decisions about building ventilation rates. The most basic functions of ventilation are to ensure good indoor air quality by controlling indoor contaminant levels and thermal comfort. There are three general means to reduce indoor contaminant levels: reduce or remove the source, remove contaminants from the indoor air, i.e., via local exhaust and filtration, or dilute with air having lower or no contaminant levels. This paper addresses the latter. The ventilation rate should therefore be related to the indoor generation rate of pollutants and the resultant occupant exposure. Careful consideration of these concepts in applying demand-controlled ventilation (DCV) can yield energy savings.

Many different types of pollutants can be produced in an indoor environment. However, not all have hazardous health effects, nor do they have the same emission rates. Standards governing indoor air quality (IAQ) requirements are less specific than those related to thermal comfort (Parkinson et al. 2019b). Some regulations require good or satisfactory IAQ but do not provide specific threshold values for pollutants other than CO_2 (Standard Norge 2017). The requirements for the application of outdoor and recirculation ventilation also varies between countries; however, there does seem to be consensus on the need to reduce exposure to harmful pollutants. The WHO (2010) defines maximum threshold concentrations for various contaminants based on levels below which health effects occur, and many of the pollutant levels are based on perceived odour or general irritation.

Some studies have shown that CO_2 concentrations may be associated with cognitive performance and health issues, but other studies do not (Allen et al. 2016; Maddalena et al. 2015; Satish et al. 2011, 2012; Wargocki & Wyon 2013; Liu et al. 2017; Zhang et al. 2016; Zhang et al. 2017). Some standards recommend keeping CO_2 below 1000 ppm. However, Apte et al. (2006) and Erdmann et al. (2002) analysed data from 100 office buildings and concluded that increased prevalence of mucous membrane and lower respiratory sick building syndrome (SBS) symptoms occur when peak CO_2 concentrations are below 1000 ppm. However, those symptoms were not likely caused by CO_2 exposure but rather by other contaminants that increased in concentration due to lower ventilation rates. According to the literature review of Carrer et al. (2015), adverse effects (including respiratory and allergy symptoms, airborne and infectious diseases and sick leave, SBS, and performance and learning) can occur when ventilation rates fall below 7 L/s per person for residential buildings, 12 L/s per person in schools, and 25 L/s per person in offices. These values are mostly related to studies of SBS symptoms and are not consistent between studies. Most of these studies did not characterize sources either qualitatively or quantitatively, did not account for ventilation effectiveness, and considered air to be fully mixed within the zones. Further, it is often erroneously assumed that when ventilating at or above these rates and maintaining afore-mentioned CO_2 concentrations, that other pollutants will also be maintained at relatively low concentrations. This may be true for some occupant-related pollutants but does not necessarily correlate to all pollutant sources whether of indoor or outdoor origin.

Some authors indicate that CO_2 should only be used as an indication of occupant-related pollutants (Fisk 2018; Maddalena et al. 2015). Others propose that CO_2 should not only be regarded as an IAQ indicator but as a pollutant impacting health and cognitive functions (Allen et al. 2016; Satish et al. 2011). Ramalho et al. (2015) point out that the probability of exceeding pollutant health guideline values correlates with CO_2 concentration, but the probability of exceedance is still high even at low CO_2 levels. Chatzidiakou et al. (2015) concluded that indoor temperatures correlated with total volatile organic compound levels when potential indoor pollutant sources were limited and CO_2 levels were reduced by increased ventilation rates, and they also concluded that CO_2 levels correlated to indoor particulate levels when the influence of outdoor levels was small. However, CO_2 was not a good predictor of outdoor, traffic-related pollutants. Thus, they concluded that besides elimination of indoor sources, an average CO_2 level of 1000 ppm is recommended to meet WHO (2010) guidelines for particulate levels and reduce dissatisfaction with IAQ.

Jaakkola et al. (1994) carried out investigations into the effect of recirculating ventilation air on SBS symptoms. They investigated the differential impact of 0 % and 70 % recirculation rates and showed that reducing the outdoor air fraction to 30 %, assuming acceptable outdoor contaminant levels, does not have adverse health effects. However, they only looked at SBS symptoms and did not correlate it with building energy use.

In order to address these different issues related to indoor CO_2 concentrations, the case study herein presents the development of a ventilation strategy that considers both occupant exposure to indoor pollutants and energy use. Measurements were used to validate a building model that incorporated co-simulation between EnergyPlus and CONTAM. The model was validated against measurements and used to evaluate baseline energy use and develop a CO_2-based DCV strategy that considered other pollutants and recirculation airflows. Recirculation rates were based on the aforementioned results of Jaakkola et al. (1994). A combination of both quantitative and qualitative approaches was used to evaluate performance of the strategy.

2 MEASUREMENTS

Prior to performing measurements, information was gathered in the study building on the normal behaviour regarding ventilation air distribution and occupancy. Building operators and occupants agreed not to interfere with the equipment, not to open windows and to keep the door closed as much as possible. Samples of temperature, relative humidity (RH), CO_2, and $PM_{2.5}$ (particles of 2.5 μm in diameter or less) were taken every 5 minutes over a two-week period. Table 1 shows the specifics of the measurement equipment.

Measurements were conducted in a corridor located on the ground floor of a university office building in Trondheim, Norway as shown in Figure 1. The building is occupied by graduate students and administrative staff and is located next to a lightly-travelled road. However, during the measurement period, road work was taking place outside the windows leading to a brief period of elevated outdoor particle levels.

Table 1 Description of equipment and parameters measured

Parameter	Sensor type	Uncertainty
Relative humidity	Capacitive	±3 % RH at 25°C
CO_2	Non dispersive infrared (NDIR)	±10 % (500 ppm to 1500 ppm)
Temperature	10K NTC Thermistor	± 0.4 in the selected range
Particle concentration	Optical sensor	±10 %

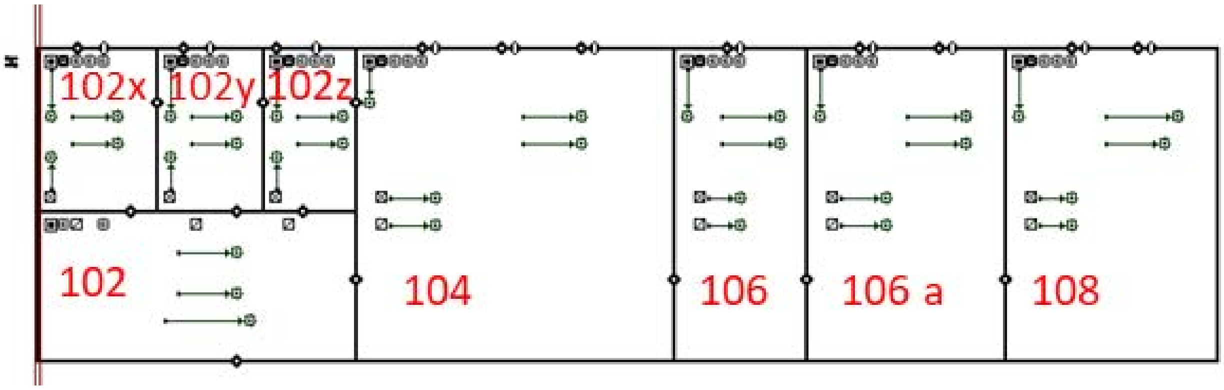

Figure 1: CONTAM sketch of the corridor measured and modelled with room numbers provided in red. Symbols indicated ventilation system supplies and returns, contaminant sources and sinks, occupants and CONTAM controls network.

3 CO-SIMULATIONS WITH ENERGYPLUS AND CONTAM

The corridor presented in Figure 1 is modelled via co-simulation between EnergyPlus and CONTAM (Dols et al. 2016), which enables simultaneous consideration of energy and pollutants to realize implementation of DCV algorithms that incorporate indoor concentrations provided by sensors. CONTAM performs multizone building airflow and contaminant transport calculations but does not perform heat transfer analysis (Dols & Polidoro 2015). EnergyPlus is a multizone energy analysis program that performs system sizing, loads analysis and calculates HVAC system airflow rates to meet thermal loads during runtime. EnergyPlus incorporates interzone and infiltration airflows, which it obtains from CONTAM during co-simulation run-time. In turn, CONTAM obtains indoor temperatures and system airflows from EnergyPlus.

While EnergyPlus provides for CO_2-based DCV, the built-in algorithms do not directly affect the terminal unit flow rate or the system flow rate. Zone occupancy is used by the outdoor air (OA) controller to increase the OA flow rates up to the current supply air flow 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 it does not directly respond to a CO_2 signal. This method works to control recirculated airflow, but it is not applicable to Norwegian systems that require continuous 100 % outdoor air intake. The models used in this study achieve variable system supply flow based on CO_2 sensors located within each occupied zone of the CONTAM model. Sensor values are then utilized within an EnergyPlus energy management system (EMS) program to adjust the terminal unit mass flow rates of respective zones.

A model was built in CONTAM and exported to EnergyPlus via the CONTAM3Dexport software tool. Thermal properties (U-value) of the building construction correspond to Norwegian Building Code, TEK 07 (Statens Bygningstekniske Etat 2007): external wall 0.18 W/m^{2}K, roof 0.13 W/m^{2}K, floor 0.15 W/m^{2}K, and windows 1.2 W/m^{2}K. The building was modelled in CONTAM with an air leakage of 10 cm^2/m^2 at 10 Pa. Indoor CO_2 sources are 18 L/h per person, based on an average sized adult engaged in office work (ASTM 2012), during occupied periods as described in Table 2. No indoor sources of $PM_{2.5}$ were modelled.

Table 2 Occupancy schedules for rooms shown in Figure 1. For rooms 104 and 108, one person arrives every 30 minutes and leaves every 30 minutes.

	102 (and x, y, z)	**104 (5 occupants)**	**106**	**106a**	**108 (4 occupants)**
Arrival	8:00	8:00-9:30	8:30	8:15	8:00-9:30
Lunch break	11:30-12:00	11:30-12:00	No vacancy	12:15-12:45	11:30-12:00
Departure	16:00	17:00-18:30	16:30	17:00	17:00-18:30
Weekends	Vacant	Vacant	Vacant	Vacant	Vacant

4 RESULTS

4.1 Measurements

Measurements were collected for two weeks, and the results were used to establish ventilation rates and emission sources in the simulation model. The ventilation rate was kept constant and measured at the supply and return, i.e., extract, air terminals using a volume flow hood. Figure 2 shows an example of measurement results for one of the rooms (104) over the course of a single day in mid-April. Room 104 is a 36 m^2 office that can accommodate up to six occupants and has a constant airflow rate of 350 m^3/h (100 % OA). Four to five occupants were in the office from 9:00 to 19:00. From 15:00 to 15:08, 16 people occupied the room.

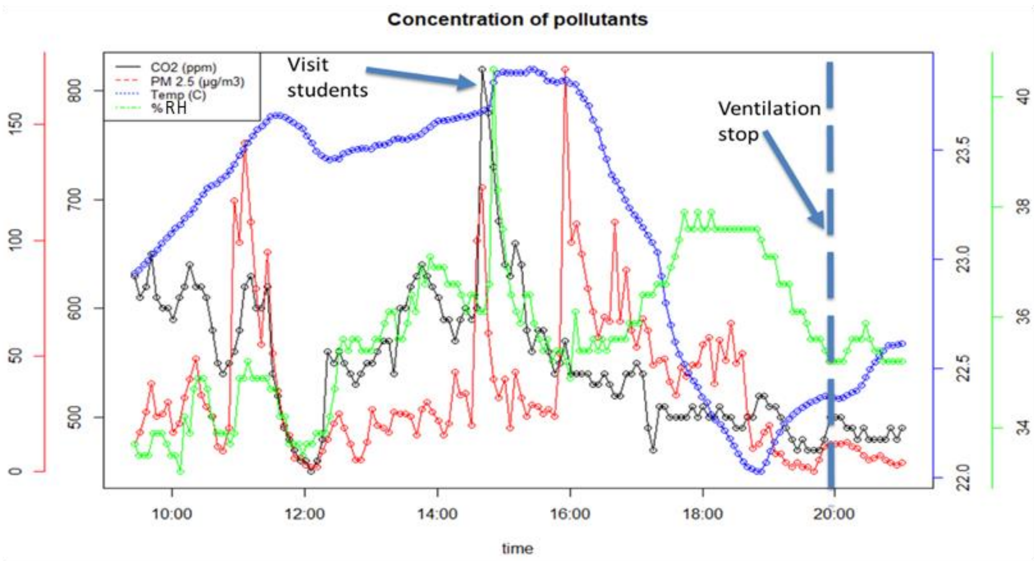

Figure 2: Pollutant concentrations in room 104 for one day

Figure 2 shows that the CO_2 levels remain below 750 ppm until the period when 16 students enter the room for a brief period of time, corresponding to a peak of about 850 ppm. The average $PM_{2.5}$ concentration over the measurement period was 36 µg/m^3 with a maximum value over 150 µg/m^3. Guidelines indicate a maximum concentration over a 24 hours period of 15µg/m^3 and 8 µg/m^3 over 8 hours (FHI 2013). Outdoor particle levels exceeded reference levels by up to 70 % during the measurement period. This is likely due to the measurements being taken during pollen season, and road work that was taking place adjacent to the building during this time. These high polluting sources were not introduced as sources in the simulations as they represent a momentary peak and are not representative of the whole year. Regardless, $PM_{2.5}$ concentrations do not track CO_2 concentrations, and the elevated concentrations may affect occupants in the short term related to allergy or asthma. If outdoor pollutants are introduced through the ventilation system, reducing supply airflow rates may be beneficial, but monitoring $PM_{2.5}$ and or other pollutants would require additional sensors and control logic.

Figure 2 shows that the indoor temperature is greater than 23 °C during most of the occupied period of the day. The Norwegian standard recommends a set point temperature of 22 °C in the winter (Statens Bygningstekniske Etat 2007), and Burroughs & Hansen (2011) recommends keeping temperatures below 22 °C to reduce SBS symptoms. Correlations between room temperatures over 23 °C and self-reported health effects have also been identified (van Loenhout et al. 2016). Seppänen et al. (2006) indicate that a drop in performance can be expected for temperatures over 23 °C. In this current study, occupants surveyed indicated that their ability to concentrate was reduced due to "heavy air" and high temperature. During this measurement period, outdoor temperatures were relatively low, so the radiators were at maximum output for this North-facing room. Given that supply air is delivered at 19 °C, reducing radiator output would allow for reducing room temperature. In this case, the humidity is kept above 32 %.

4.2 EnergyPlus and CONTAM Simulations

To validate the model, a one-year simulation was run with typical meteorological year weather data for Trondheim and normal activities as defined by the Norwegian design building codes NS 3031 and TEK 07 (Standard Norge 2014; Statens Bygningstekniske Etat 2007). The simulated annual energy was within 5 % of TEK 07 requirements. The outdoor CO_2 was not measured, but was assumed to be constant at 393 ppm. Outdoor $PM_{2.5}$ was modelled based on measurements made 400 m away from the office for an entire year (NILU 2018), and indoor particle removal was simulated in all zones with a deposition rate of 0.5 h^{-1}.

Simulated CO_2 differed from measurements by a maximum of 40 ppm and temperatures by less than 0.5 °C. Owing to the accuracy of the results, the model was considered to be validated both for energy use and IAQ simulations.

4.3 Simulated Cases

Four different ventilation strategies were simulated as summarized in Table 3. Cooling was not simulated as it is not used in Norwegian buildings of this construction period. The base case is modelled using the current strategy to provide a constant 100 % outdoor air and a constant volume of supply air from 8:00 to 16:00 allowing EnergyPlus to size the supply airflow based on winter design conditions. Two cases were based on Jaakkola et al. (1994) and consisted of recirculating extract air at constant rates corresponding to outdoor air intake rates of 70 % and 30 %, respectively. For these two cases, DCV consisted of setting the supply airflow rate to 100 % of the design airflow rate when the indoor CO_2 concentration was greater than or equal to 1000 ppm, and reducing the supply airflow rate to 50 % of the design air flow rate (DAFR) when the concentration is between 600 ppm and 1000 ppm and reducing to 20 % when below 600 ppm. In the fourth case both the supply and outdoor air (recirculation) rates were varied with the outdoor air fraction controlled based on the volume-weighted fraction of occupied zone CO_2 concentrations.

Table 3 Ventilation control methods (CO_2 in ppm)

Name	Outdoor Air Fraction Control	Supply Airflow Control
OA_100	Constant 100 % OA	$CO_2 \leq 400$ = 20% DAFR $400 < CO_2 \leq 1000$ = 50% DAFR $1000 < CO_2$ = 100% DAFR
OA_70	Constant 70 % OA	
OA_30	Constant 30 % OA	
Variable	$CO_2 \leq 750$ = 30 % OA; $750 < CO_2 \leq 900$ = 60 % OA; $900 < CO_2$ = 80 % OA	

In the EnergyPlus model, an electric resistance coil is located in the *AirLoopHVAC*, downstream of the Supply fan. The electric output is controlled via a thermostat located in

Room a102x and setpoint temperatures were 22 °C and 20 °C during and outside of working hours, respectively. An energy recovery ventilator was incorporated at the outdoor air mixing box having a heat wheel with a maximum sensible and latent effectiveness of 76 % and 68 %, respectively.

Particle filters were simulated in all cases and were specified according to their minimum efficiency reporting value (MERV). Filters were incorporated into the recirculation airstream and outdoor airstreams and were MERV 15 (equivalent to F9, e $PM_{2.5}$ > 95 %) and MERV 13 (equivalent to F7, e $PM_{2.5}$ 65 % - 80 %), respectively.

Figure 3 shows the results for the four simulated cases. Regarding CO_2, the higher the supply of OA, the lower the concentrations of CO_2. Conversely, the cases with higher outdoor air intake rates show higher $PM_{2.5}$ concentrations. Thus using 100 % OA, means higher entry of outdoor $PM_{2.5}$ as air is supplied via a coarser filter. Lower OA fractions mean higher recirculation rates through the recirculation air filter, which is approximately 15 % more efficient for $PM_{2.5}$ leading to lower indoor particle levels. This reveals the differences between indoor and outdoor sources, namely that increasing ventilation to control an indoor source can lead to increased levels of an outdoor source.

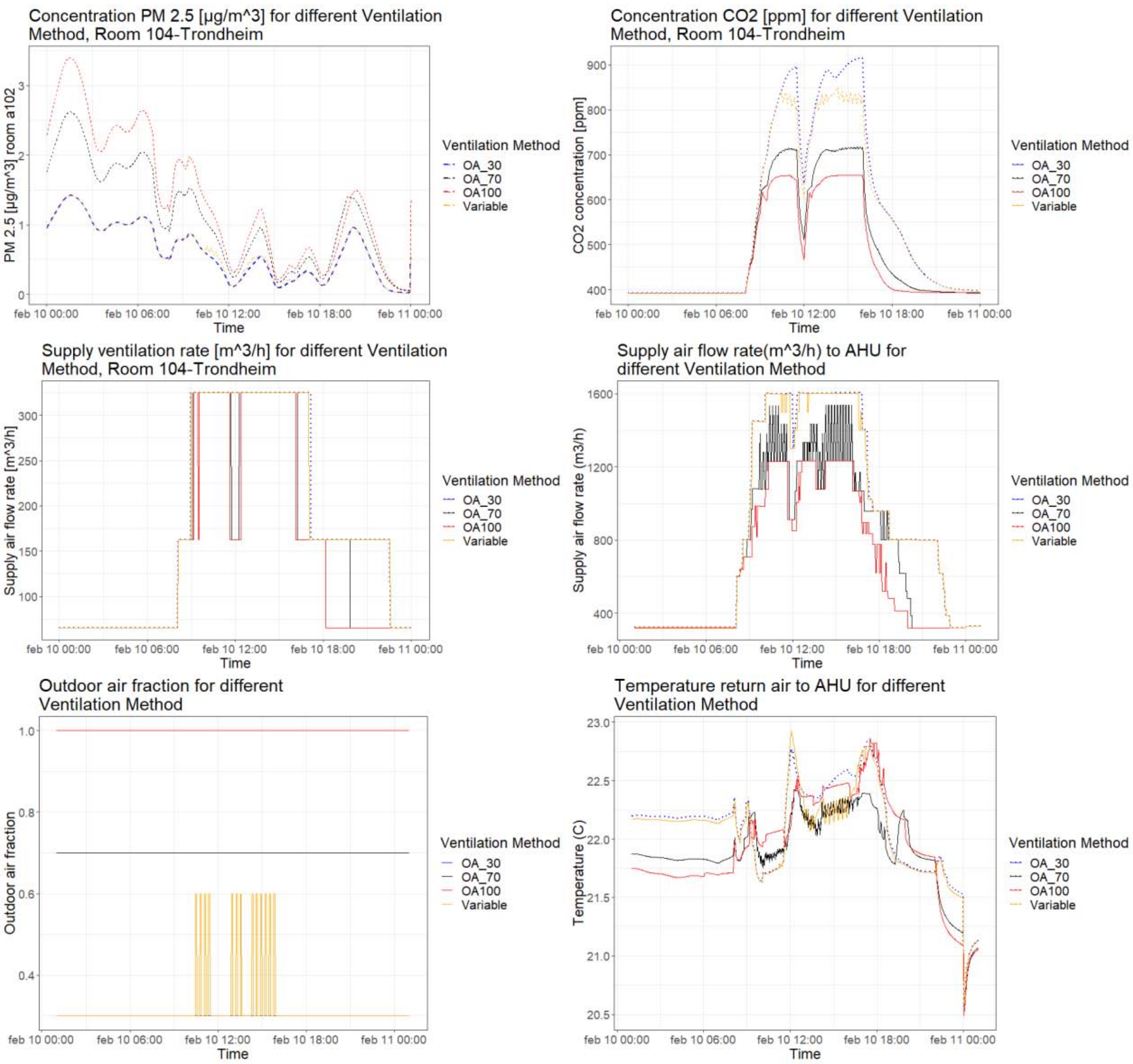

Figure 3: Simulation results for $PM_{2.5}$, CO_2, temperature, outdoor air fraction and supply airflow rates of room 104 for 10 February

Along with Figure 3, thermal comfort results in Table 4 shows that higher recirculation rates yielded higher indoor temperatures resulting in thermostatic setpoints being exceeded and unsatisfactory thermal comfort results provided by the EnergyPlus ASHRAE 55-2004 summary report. The values obtained regarding CO_2, temperature and particles are thus in agreement with the conclusions obtained by Jaakkola et al. (1994); that is, while recirculating extract air does lead to increased CO_2 levels, it did not adversely affect particle concentration levels for these cases.

Table 4: Thermal comfort-related results for all four cases

	100 % OA (h)	70 % OA (h)	30 % OA (h)	Variable (h)
Time setpoint not met during occupied heating	816	905	1263	1233
Time not comfortable based on simple ASHRAE 55-2004	1976	1990	1958	1966

Table 5 shows the annual energy use for all four cases. The cases with lower OA fractions have lower heating demands but have higher fan power demands, because when recirculating extract air, more air is needed to mitigate CO_2 levels.

Table 5: Annual energy use for all four cases

	100 % OA (kWh/m^2a)	70 % OA (kWh/m^2a)	30 % OA (kWh/m^2a)	Variable (kWh/m^2a)
Heating	188	137	67	73
Fans	28	30	37	36
Total	216	167	104	109

5 DISCUSSION

These results demonstrate the use of co-simulation of EnergyPlus and CONTAM as a tool for simultaneously simulating both energy use and IAQ. There is a clear interaction between energy use for heating and recirculation of extract air from the zone. In this study, higher recirculation rates yielded higher room temperatures and CO_2 levels. The energy use decreased while using recirculation due to reduction of the relatively high energy needs for heating in the 100 % OA case. For buildings located in other climates having lower heating demands, recirculation may pose an overheating challenge, so better temperature controls may be warranted in these cases.

The goal of all the strategies was to maintain CO_2 concentrations below 900 ppm, but the 30 % OA strategy does not achieve this goal despite the higher supply airflow rates. For the cases with higher recirculation of extract air, larger supply should be designed in order to maintain CO_2 levels and temperature. This may influence energy use, though in this case, due to the potential for reduced energy use associated with heating, this effect may not be significant.

When controlling CO_2 levels, the $PM_{2.5}$ levels varied independently as they depend on outdoor concentrations in this simulation, though they are reduced when larger recirculation rates are applied owing to the more efficient filter in the recirculation air stream. In Trondheim, outdoor air is considered to be relatively free of contaminants, but in the presence of elevated $PM_{2.5}$ levels the use of recirculation may warrant protection from particles of outdoor origin (even more in this case where the filter in the recirculated extract air was of higher efficiency for $PM_{2.5}$). The use of recirculation should be done with knowledge of $PM_{2.5}$ sources and monitoring of the supply and outdoor concentrations is recommended so that recirculation can be used as a protective measure.

6 CONCLUSIONS

- Recirculation of extract air and required ventilation airflow rates are correlated. In some cases, when using recirculation of exhaust air, increased ventilation rates were unable to maintain acceptable CO_2 levels. Thus, a minimum level of OA should always be maintained.
- DCV should be based on several pollutants, e.g. CO_2 and $PM_{2.5}$, as well as temperature, and must be carefully programmed to avoid control problems. For instance, reducing outdoor air intake when outdoor levels of $PM_{2.5}$ were high was effective so long as occupancy was below 100 % and there were no indoor sources of $PM_{2.5}$. This is normally not the case, and outdoor particle concentrations are not likely to be as low as simulated in this study.
- Pollutant levels and energy use are correlated, and the ventilation control needs to be programmed considering a hierarchy. Here we propose to use reduced exposure to pollutants as a more important parameter than reduced energy use. The study presented here serves as the initial phase of a project that will study, in detail, how to reduce energy use in ventilation while ensuring IAQ in a multidisciplinary way.

7 ACKNOWLEDGEMENTS

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