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

M. Justo Alonso [a,c,*], P. Liu [b], S.F. Marman [a], R.B. Jørgensen [b], H.M. Mathisen [a]

[a] Department of Energy and Process Engineering, NTNU, Kolbjørn Hejes v 1B, Trondheim, Norway
[b] Department: Architecture, Materials and Structures SINTEF Community, Høgskoleringen 13, Trondheim, Norway
[c] Department of Industrial Economics and Technology Management, NTNU, Sem Sælands vei 5, Trondheim, Norway

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ABSTRACT

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

In this work, a methodology for the improvement of demand-controlled ventilation (DCV) using measurements of IAQ parameters with LCS, correlation analysis, and co-simulation EnergyPlus/CONTAM is presented. Its goal was reduced annual energy use and the fraction of time with room air concentration of IAQ parameters outside thresholds.

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

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

1. Introduction

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

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

* Corresponding author at: Department of Energy and Process Engineering, NTNU, Kolbjørn Hejes v 1B, Trondheim, Norway.
E-mail address: maria.j.alonso@ntnu.no (M. Justo Alonso).

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Nomenclature

AHU	Air handling unit
CAV	Constant air volume
CCF	Cross-correlation function
CV-RMSE	Coefficient of variance of the root-mean-squared error
DCV	Demand-controlled ventilation
EUI	Annual energy usage index (kWh/m^2a)
HVAC	Heating, ventilation, and air-conditioning
IAQ	Indoor air quality
I/O	Ratio between indoor and outdoor pollutant concentrations
KPI	Key performance Indicator
LCS	Low-cost sensor
NMBE	Normalized mean bias error
NDIR	Nondispersive infrared
OA	Outdoor air
PM	Particulate matter
RH	Relative humidity
TVOC	Total volatile organic compound
VAV	Variable air volume
WH	Working hours: Monday-Friday 0800–1700. All months included
WHO	World Health Organization

The newest LCSs are becoming more reliable, and many can produce continuous measurements [14]. They allow measurement at a reasonable price but often have lower accuracy than reference equipment [14]. LCSs allow the monitoring of several IAQ parameters, but they need to be calibrated [15]. In 2010, an experimental evaluation of 45 nondispersive infrared (NDIR) CO_2 sensors (three from each of the 15 models tested) revealed wide variability in sensor performance among various manufacturers and, in some cases, among sensors of the same model [16]. Since then, NDIR technology for CO_2 measurements has shown major development. These devices have better accuracy and repeatability today [17].

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

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

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

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

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

Introducing the new/additional parameters in ventilation control strategies can be cumbersome and complicated. Given that parameters with different origins have different emission profiles and strengths they may send contradictory control feedback. Validated simulations can improve the trial-and-error for ventilation controls. Many programs are used to simulate control strategies for DCV, such as EnergyPlus [43], IDA ICE [45], TRNSYS [53], CONTAM [54], and Modelica [46]. However, most of these simulation programs cannot simultaneously simulate all aspects of energy, airflow, IAQ, pollutants sources, and heating, ventilation, and air conditioning (HVAC) controls. Therefore, available simulation literature focused on energy or IAQ but not both simultaneously.

Emmerich and Persily [55] focused on several IAQ pollutants but did not consider energy use. Hua *et al.* [56] developed a method for obtaining the necessary OA fraction based on the indoor CO_2 concentrations and then examined the OA damper static pressure to optimize the OA volume setpoint according to the total volume demand of terminals. This work assessed energy and CO_2 but no other IAQ parameters. Zhao *et al.* [57] developed a control method for determining the OA volume flow setpoints based on differential pressure control strategies to optimize energy, but they too did not assess other IAQ parameters. Zhao, Wang, *et al.* [58] compared the performance of different OA fractions concerning CO_2 and energy savings. Although the tools for IAQ and energy simulation are available, no previous work focused on the simultaneous effects of extended IAQ (referring to CO_2, temperature, and several other airborne pollutants) and energy use while using DCV and recirculating return air. Co-simulation can solve this weakness. EnergyPlus/CONTAM [8] or CONTAM/TRNSYS [44] can be used when all the above mentioned parameters must be evaluated. Co-simulation between EnergyPlus and CONTAM can be used to evaluate whole-building energy, airflow, and IAQ, and both tools are available free of cost [8].

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

2. Methods

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

Step 1. Pollutants in three full-scale cell office rooms were measured (bubbles 1–3 in Fig. 1) to characterize and validate an EnergyPlus/CONTAM simulation model (bubbles 4, 5, 6 in Fig. 1). For this purpose, calibrated LCSs [15,59] were used. The measured airborne pollutants were CO_2, formaldehyde, TVOCs, and $PM_{2.5,}$ and the measured environmental parameters were RH and temperature. These six items are referred as "IAQ parameters" in the text.

Step 2. According to the method described in [47], CCF in detrended time series were used to determine which IAQ parameters should be used to control the ventilation airflow rates. Correlations between different IAQ parameters at room level were used to control the supply airflow rates to the room. Correlations between the same IAQ parameters at room and supply air were evaluated to control the recirculation airflow rates (bubbles 7,8 in Fig. 1). Significant correlations were sought to select the appropriate IAQ parameters for tuning the control of the supply airflow rate and the recirculation of return air in a probabilistic way.

Step 3. The control sequences of the selected IAQ parameters were tuned by studying the results of the validated EnergyPlus/CONTAM co-simulation (bubbles 9–14 in Fig. 1). Improvements focused on increasing the number of hours in which the concentrations of airborne pollutants were maintained below the thresholds defined in Table 4, the environmental parameters were kept within the rages defined in Table 4 and the energy use was reduced. The sequences were kept simple to focus on the methodology.

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

2.1. Case study: Measurements in the laboratory

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

Fig. 2. All rooms had equal ventilation and were equipped with a supply terminal (Orion-Løv from TROX Auranor) [60] and an exhaust terminal (LVC from TROX Auranor) [61]. Volume flow controllers (LEO VAV from TROX Auranor) [62] were placed in the main supply, main exhaust, and recirculation duct branches. The damper positions were provided as a 0–10 V signal via a Belimo Modbus register [63]. The fan speed needed in the AHU UNI 3 from Flexit [64] was sent via a Modbus adapter CI66, both from Flexit [65]. The damper throttling was modulated to achieve the expected airflow rates, and the exhaust dampers were controlled to extract air at the same rate. The producer states an accuracy of the VAV controls ± 25 % when regulating 10–20 % of nominal flow, < ± 10 % at 20–40 % of nominal flow and < ± 4 % for 40–100 % of nominal flow [60–62]. The rotary heat recovery of the UNI 3 was run at constant rotational speed. The control signal was calculated and sent from a Raspberry Pi, which evaluated the LCS measurements. Room 1 was positioned nearest to the commercially available AHU UNI 3.

Every room was equipped with an in-house mounted IAQ station each with five LCSs. The IAQ stations were placed in the center of the wall (1.12 m from each sidewall) behind the occupants at a height of 1.2 m, as shown in Fig. 2.

Fig. 3 shows the control architecture of the ventilation. Table 1 shows the main details of the LCSs used. More information about these sensors and their calibration can be found in [15,59]. The total cost of the LCS station with all the sensors described in Table 1 and the Raspberry Pi was below EUR 200. The individual prices of the sensors in 2018 were as follows: EUR 47 for the SCD30, EUR 29 for the Arduino Shield SGP30_SHT1, EUR 39 for the SPS30, EUR 15 for the Dart WZ-S formaldehyde module, and EUR 72 for the Raspberry Pi.

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

2.1.1. Conducted tests in the rooms

Three types of tests were conducted in the rooms.

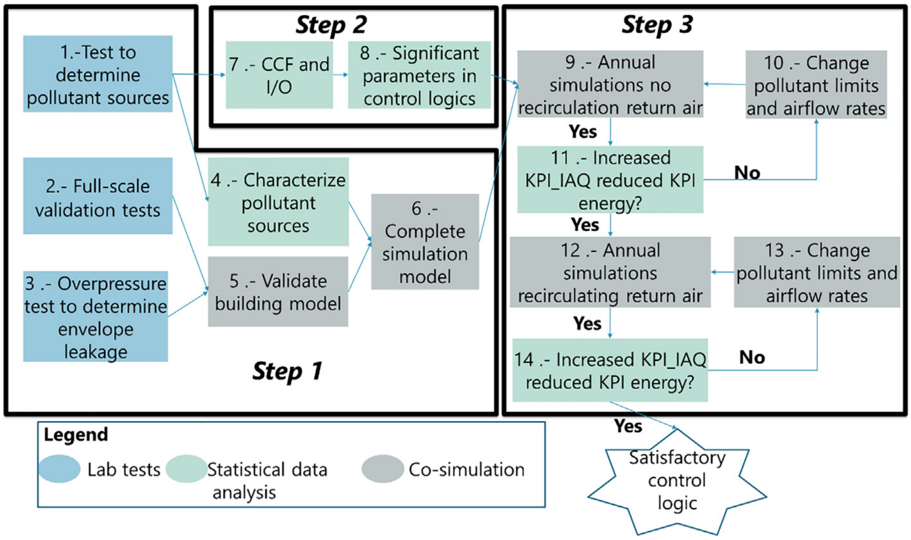

Fig. 1. Framework of the methodology in this study. Note for abbreviations for the Fig. CCF = cross-correlation factors, I/O = indoor outdoor ratio, KPI = Key performance indicator, IAQ = Indoor Air Quality.

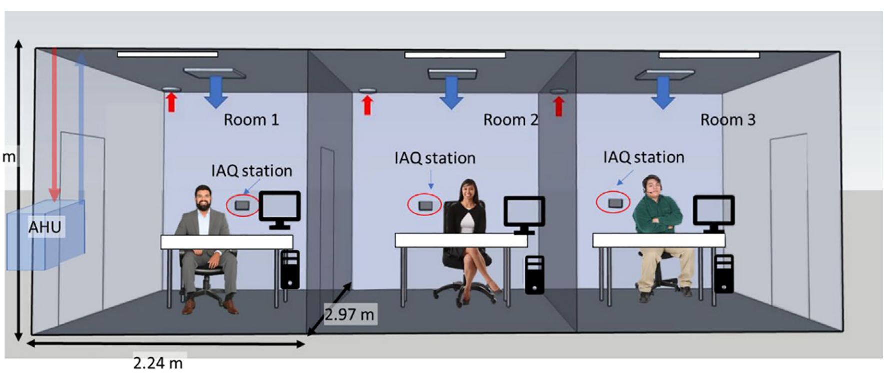

Fig. 2. Sketch of the three cell offices showing their dimensions and the placement of the LCS and ventilation.

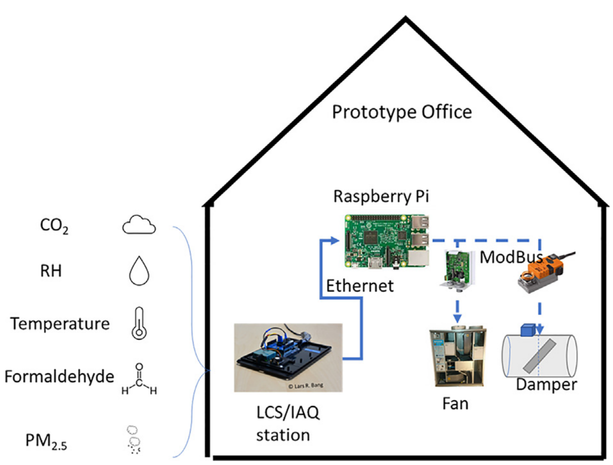

Fig. 3. Overview of the developed control system. The Arduino based sensors send measurements feedback to the Raspberry Pi that calculates the fan and damper settings.

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

Table 1
Properties of the low-cost sensors.

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

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

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

quantified. First, all the offices were pressurized at 50 Pa relative to the ambient lab to quantify the envelope leakages. Subsequently, three tests were run in which the pressure in one room was 5 Pa higher than that of the contiguous office and the lab to quantify the internal leakages.

2.2. Simulation environment

Simulations were performed in an EnergyPlus/CONTAM co-simulation model. The co-simulation followed the steps described by [8]. Using a co-simulation allowed the interdependencies between airflows and heat transfer to be captured as Fig. 4 shows. EnergyPlus obtained interzone infiltration airflows at each simulation timestep from CONTAM. CONTAM obtained indoor temperatures and system airflows from EnergyPlus and performed the contaminant transport calculations [8]. The co-simulation was performed using the functional mock-up interface capabilities incorporated into EnergyPlus, as described by [70]. The first step for the co-simulation was to build the two models and the data exchange. The bridge between both programs was accomplished using the NIST-developed CONTAM 3D Exporter tool [71]. The principles and procedure of the co-simulation are not discussed further in this article, but [8] provides further details.

The simulated offices consisted of the three office rooms described in Section 2.1. The tests with students described in Section 2.1.1 were used to model the pollutant production from the occupants, and the pressurization tests were used to model air leakages. The test with mannequins was used to validate the DCV model with regard to pollutants and energy. The heat recovery of ventilation was simulated with the maximum sensible and latent effectiveness stated in Table 3 at 100 % and 75 % heating airflow.

Airflow rates were simulated to vary according to the CO_2 concentrations, as shown in Fig. 5.

In this case, the three step control in Fig. 5 was chosen as rule-based control or proportional versions of it are standard approach in commercial building automated systems to reduce the energy and operating costs. Such controls can provide significant savings when applied correctly. In rule-based control; the operator has to constantly monitor and adjust the HVAC operation to meet the objectives of reducing energy consumption while maintaining thermal comfort [73]. For simplicity, no recirculation of the return air was run for the test with mannequins. The measured conditions in the laboratory were used as boundary conditions in the simulation.

2.3. Simulation validation

For precision metrics, the normalized mean bias error (NMBE), given by Eq. (1), and the coefficient of variance of the root-mean-squared error (CV-RMSE), given by Eq. (2), are often used [74,75]. The NMBE provides a normalization of the average error of a sample space, which can be compared with other cases [75]. The CV-RMSE measures the variability of the errors between the measured and simulated values [75]. In the equations, C_{sim} and C_{LCS} are the concentrations simulated and measured by LCS, respectively. $C_{LCS,av}$ is the average of the monitored data for N observations.

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

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

The NMBE and CV-RMSE calculate the average model prediction error to help evaluate the accuracy of the fitted models. To calibrate a model, ASHRAE 14 [76] recommends an NMBE below ± 10 % and a CV-RMSE of ± 30 % for hourly calibrations and ± 5 % and ± 15 % for monthly measurements.

This work corresponds with Bubble 6 in Fig. 1.

2.4. Methodology for the analysis of pollutant selection

This study included measurements of CO_2, TVOCs, formaldehyde, $PM_{2.5}$, RH, and temperature. Introducing all these IAQ parameters in a control logic may be complicated and sometimes contradictory. Moreover, considering that they may be derived from the same source or activity, using all the IAQ parameters may outweigh the activity's importance. Therefore, the first step in this work was to assess the significant IAQ parameters for ventilation control. The methodology proposed in this article for selecting the significant IAQ parameters for control is based on analysis of correlation by cross-correlation functions. This was described in detail by [47] and will only be summarized in this article. This methodology used CCFs in de-trended time series instead of the standard Pearson or Spearman coefficients. If two time series of measurements follow similar trends, they can appear to be strongly correlated. This higher correlation may stem from the autocorrelations more than from the pure correlation. Underlying trends and time series structures affect the correlation patterns and thus, de-trending is needed to analyze correlations. De-trending can be done in many ways such as using first differences or linear regressions with time as a predictor. In this case, de-trending is done by pre-whitening. Pre-whitening reduces the presence of not relevant systematic information and the obtained

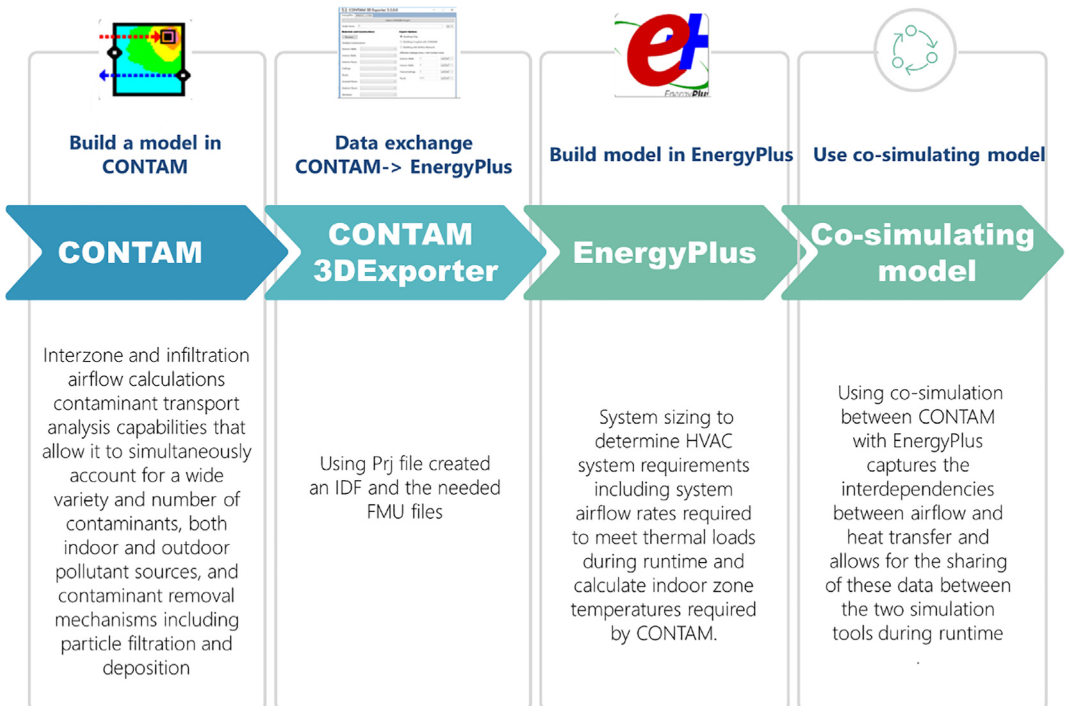

Fig. 4. Schematic of the co-simulation architecture.

Table 3
Simulated latent and sensible effectiveness at 100 and 75% heating airflow [72].

	100 % nominal heating airflow	75 % nominal heating airflow
Sensible effectiveness	78 %	75 %
Latent effectiveness	40 %	45 %

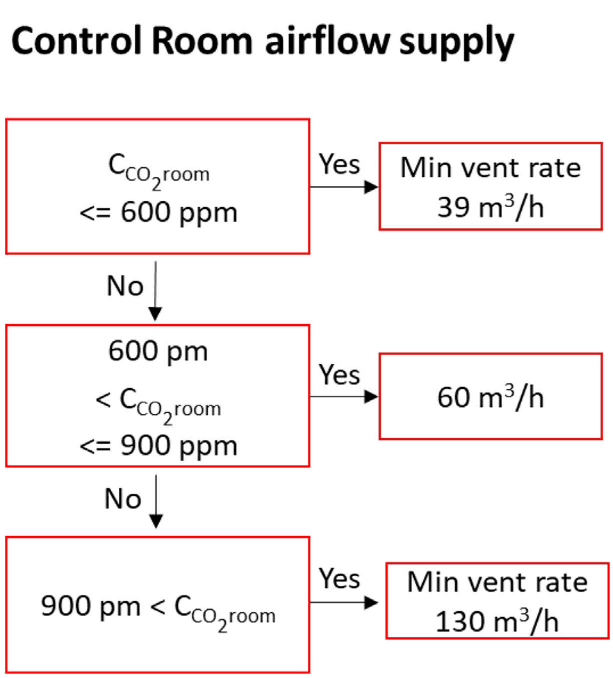

Fig. 5. Flowchart for control of supply airflow rate to every room.

CCF is proportional to both variables' impulse response rather than their autocorrelations. CCFs were used to calculate the Pearson correlations in simultaneous and time-shifted lags. Thus, both simultaneous and time-shifted correlations were mapped. The following consecutive steps are recommended for the CCF methodology with pre-whitened time series:

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

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

For the CCF and I/O analysis, the measurements of the test with students were analyzed in Section 3.3. This work corresponds with Bubbles 7 and 8 in Fig. 1.

2.5. Ventilation control strategies

The ventilation control was improved on the basis of simulations. This work corresponds to Step 3, bubbles 9–14 in Fig. 1. In this case, two objectives were pursued: a) the reduction of the annual energy use index (EUI) (kWh/m^2/year) and b) the reduction of the key performance indicators (KPIs) for IAQ (KPI_IAQ) or the fraction of time with a room air concentration of pollutants or a temperature and RH outside the guidelines defined in Table 4.

The KPI_IAQ was defined according to Eq. (3) by adding all the timesteps when all the guidelines from Table 4 were met simultaneously in the three rooms and dividing by the total number of timesteps. The parentheses in Eq. (3) show a logical evaluation of the three rooms simultaneously; if the conditions were met simultaneously for all the rooms, the result for the current timestep was one. If one of the rooms did not satisfy a single criterion, the solution to the equation was zero. The value of the KPI ranged between 0 and 100 %. These simulations consisted of 525,960 timesteps (1-year simulation). When defining working hour (WH) KPIs, the number of timesteps was reduced to 124,800. The subindex R indicates that the evaluation was performed simultaneously for the three rooms, and WSP in the sum represents the whole simulated period.

The developed sequences in Section 3.4 are the result of several attempts (not presented here) that looked at how different limits for pollutants and corresponding airflow rates affected the KPIs in eq 3–8 and energy use during WH.

The ventilation logic was tuned as follows:

1. To focus on the supply airflow rate to the room without recirculating return air, the supply airflow rate was changed on the basis of rule-based sequences using a single uncorrelated IAQ parameter. Then, the "combined" rules included all the uncorrelated IAQ parameters simultaneously. Table 7 shows the simulated control logic. To have a comparison point, the results were compared with the scheduled constant air volume strategy, as shown in the results (Section 3.4.1).
2. The best-performing strategy for the supply airflow was tested with different logic to control the OA fraction. In this case, the rule-based strategies were based on the correlations between the supply and room air concentrations and the I/O ratios. The simulated cases are described in Table 8.

$$KPI_{IAQ} = \frac{\sum_{1}^{WSP}(CO_{2\_R} < 1000\,\&\,Temp_R < 24\,\&Temp_R > 22\,\&\,Formaldehyde\_R < 110\,\&\,RH_R < 60\,\&\,RH_R > 30\,\&\,PM_{2.5\_R} < 15)}{Number\ of\ simulated\ time\ steps} * 100 \quad (3)$$

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

$$KPI_{CO2} = \frac{\sum_{1}^{WSP}(CO_{2\_R} < 1000)}{Number\ of\ simulated\ time\ steps} * 100 \quad (4)$$

$$KPI_{formaldehyde} = \frac{\sum_{1}^{WSP}(Formaldehyde_R < 110)}{Number\ of\ simulated\ time\ steps} * 100 \quad (5)$$

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

$$KPI_{temp} = \frac{\sum_{1}^{WSP}(Average\ room\ air\ temperature_R < 24\,\&\,Average\ room\ air\ temperature > 22)}{Number\ of\ simulated\ time\ steps} * 100 \quad (7)$$

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

Table 4
Summary of the guidelines for CO_2, formaldehyde, $PM_{2.5}$, temperature, and RH.

Parameter	Limit	Reference
CO_2	1000 ppm	[77]
Formaldehyde	110 µg/m^3 in 1 min	[78]
$PM_{2.5}$	15 µg/m^3 in 1 min	[10] defined 24 h, but 1 min is used
Temperature	22–24° C	[79]
Relative humidity	30–60 %	[80,81]

The controlled pollutants were selected by the strategy described in Section 2.4, and the selected pollutants are summarized in Section 3.3. The simulations were run for Trondheim and then repeated with Trondheim's weather and Beijing's OA pollution to study the effect of outdoor pollution.

3. Results and discussion

3.1. Measurements in the laboratory: Tests with students

The tests with students were carried out as described in Section 2.1. The grey dots in Fig. 6 represent the measured concentrations of IAQ parameters for all the cases. The blue lines indicate the local polynomial regression fitting (fitted by weighted least squares) with time in minutes for each parameter.

The CO_2 measurements agreed with the theoretical production described in [82]. The trends for $PM_{2.5}$ were similar in most of the tests. When occupants entered the rooms, they brought in variable amounts of $PM_{2.5}$, which decayed with time. However, five tests were slightly different. These tests corresponded to measurements taken on a day when renovation work was carried out in the lab. The concentration of the $PM_{2.5}$ rose before the tests when all doors were open to ventilate between two consecutive tests. These measurements were not considered in the model fitting. The same happened for formaldehyde and TVOCs; the divergent tests also corresponded to the day of construction/painting work in the laboratory building. Temperature and RH measurements were very similar for all the tests because the conditions in the laboratory surrounding the tested offices were very constant during the week that measurements were taken.

3.2. Model validation

The pressurization tests were performed to map the air leakages of the three offices using mass balances of pollutants [83]. The test with 50 Pa pressurization was used to calculate the envelope leakage. The three tests in which the pressure in one room was 5 Pa higher than that of the contiguous office and the lab were used

Table 5
Summary of NMBE and CV-RMSE of the validation simulation.

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

Table 6
Number of people in the different rooms at different times.

Time	Room 1	Room2	Room 3
00:00–08:00	0	0	0
08:00–08:35	1	0	0
08:35–09:00	1	0	1
09:00–10:30	1	1	1
10:30–11:45	2	1	0
11:45–12:15	0	0	0
12:15–15:30	1	1	1
15:30–15:45	0	1	1
15:45–16:15	0	0	1
16:15–00:00	0	0	0

Table 7
Summary of simulated supply air control strategies with 100% OA.

Name	Control logic	AFR (m^3/h)
CAV	IF ((Saturday) OR (Sunday)),	8
	ELSE IF ((Hour < 8) OR (Hour ≥ 17)),	8
	ELSE	72
CO_2-1	IF (CO_2_Room_ppm ≤ 600),	26
	ELSE IF (CO_2_Room_ppm ≤ 900),	46
	ELSE IF (CO_2_Room_ppm > 900)	72
CO_2-2	IF (CO_2_Room_ppm ≤ 800),	26
	ELSE IF (CO_2_Room_ppm ≤ 1000),	46
	ELSE IF (CO_2_Room_ppm > 1000)	72
CO_2-3	IF (CO_2_Room_ppm ≤ 800),	26
	ELSE IF (CO_2_Room_ppm ≤ 1000),	33
	ELSE IF (CO_2_Room_ppm > 1000)	59
CO_2-4	IF (CO_2_Room_ppm ≤ 660),	26
	ELSE IF (CO_2_Room_ppm ≤ 900),	46
	ELSE IF (CO_2_Room_ppm ≤ 1000),	72
	ELSE IF (CO_2_Room_ppm > 1000)	98
CO_2-5	IF (CO_2_Room_ppm ≤ 700),	26
	ELSE IF (CO_2_Room_ppm ≤ 850),	46
	ELSE IF (CO_2_Room_ppm ≤ 1000),	72
	ELSE IF (CO_2_Room_ppm > 1000)	98
FA-1	IF (FA_Room_µg/m^3 ≤ 50),	26
	ELSE IF (FA_Room_µg/m^3 ≤ 110),	46
	ELSE IF (FA_Room_µg/m^3 > 110)	72
T-1	IF (T_Room_°C ≤ 22),	8
	ELSE IF (T_Room_°C ≤ 23),	46
	ELSE IF (T_Room_°C ≤ 25),	72
	ELSE IF (T_Room_°C > 25)	98
T-2	IF (T_Room_°C ≤ 22),	8
	ELSE IF (T_Room_°C ≤ 23),	46
	ELSE IF (T_Room_°C > 23)	98
T-3	IF (T_Room_°C ≤ 23),	8
	ELSE IF (T_Room_°C ≤ 24),	46
	ELSE IF (T_Room_°C > 24)	72
C-1	IF ((T_Room_°C ≤ 23) OR (FA_Room_µg/m^3 ≤ 50)),	8
	ELSE IF ((CO_2_Room_ppm ≤ 600),	33
	ELSE IF ((CO_2_Room_ppm ≤ 700) OR (T_Room_°C ≤ 24)),	98
	ELSE IF ((CO_2_Room_ppm ≤ 800) OR (T_Room_°C ≤ 25)),	111
	ELSE IF ((CO_2_Room_ppm > 800) OR (FA_Room_µg/m^3 > 110))	130

Table 8
Summary of simulated logic for control of the recirculation of return air (outdoor air (OA) fraction).

Name	Control logic	Fraction OA (%)
No_rec	Always	100
PM_OR	IF (($PM_{2.5}$_Amb − $PM_{2.5}$ return < 0) OR ($PM_{2.5}$_Room_µg/m^3 > 15)),	100
	ELSE	25
PM_AND	IF (($PM_{2.5}$_Amb − $PM_{2.5}$ return < 0) AND ($PM_{2.5}$_Room_µg/m^3 > 15),	100
	ELSE	25
PM_CO_2_OR	IF (($PM_{2.5}$_Amb − $PM_{2.5}$ return < 0) OR ($PM_{2.5}$_Room_µg/m^3 > 15) OR (CO_2_Return_ppm > 700)),	100
	ELSE	25
PM_CO_2_AND	IF (($PM_{2.5}$_Amb − $PM_{2.5}$ return < 0) AND ($PM_{2.5}$_Room_µg/m^3 > 15) AND (CO_2_Return_ppm > 700)),	100
	ELSE	25

to calculate the leakages across the internal walls. The calculated air leakages based on the pressurization tests were simulated in CONTAM as flow path elements described as one-way overflow using the power law, a method inspired by [84]. More information about the characterization of the leakages can be found in Marman's Master thesis [85]. The individual values for CO_2 production for each person, considering a constant MET and the particular body mass and height [82], were used to validate the calculated leakage rates in each room using mass balances in the pressurization tests. These leakages were included in the calculation of the strength of the sources used to evaluate improvements in the ventilation control strategy.

The simulated CO_2 sources corresponded to the CO_2 production based on the average CO_2 production presented in Fig. 6 (0.0053 L/s). This production was in line with the production based on 1.3 MET for occupants aged 20–30 years [82]. Humidity was simulated according to measurements (Fig. 6) at 0.06 kg/h and in line with the results from [86]. $PM_{2.5}$ was simulated as the combination of a burst source of 0.6 µg when the occupants entered the room and an exponential decay with a first-order decay constant of 0.0001 min^{-1} according to the results shown in Fig. 6. Formaldehyde was simulated according to the rate calculated in Fig. 6 of 17 µg/m^3 h. The simulated heat loads were 120 W/mannequin, the lights were simulated to produce 8 W/m^2, and the plug-in loads were 11 W/m^2, according to the Norwegian guidelines [87]. TVOCs was not simulated, since the sensor calibration was unavailable.

Fig. 7 compares the measured data and the simulation results of the test with mannequins. For this test, the occupants entered and exited the three rooms as summarized in Table 2, and the OA supply varied, as shown in Fig. 5. The background colors of Fig. 7 correspond to the number of occupants.

In general, the simulation represented the measured response of the CO_2 levels in the rooms very well. However, from 19:30 to 20:00, the airflow rates in Room 1 did not react as the control strategy required, as shown in Fig. 7. The LEO VAV units dynamically measured the volume flows and controlled the damper positions to maintain the airflow rates required. In this case, on the basis of the measurements of the LCS, the Raspberry Pi sent information about the desired airflow rate to a VAV damper, which adjusted the damper's opening. Therefore, when the room controllers further down in the branch opened or closed, the pressure in the branch varied, and the damper was regulated until the correct volume flow was restored. Thus, variations in the flow were observed

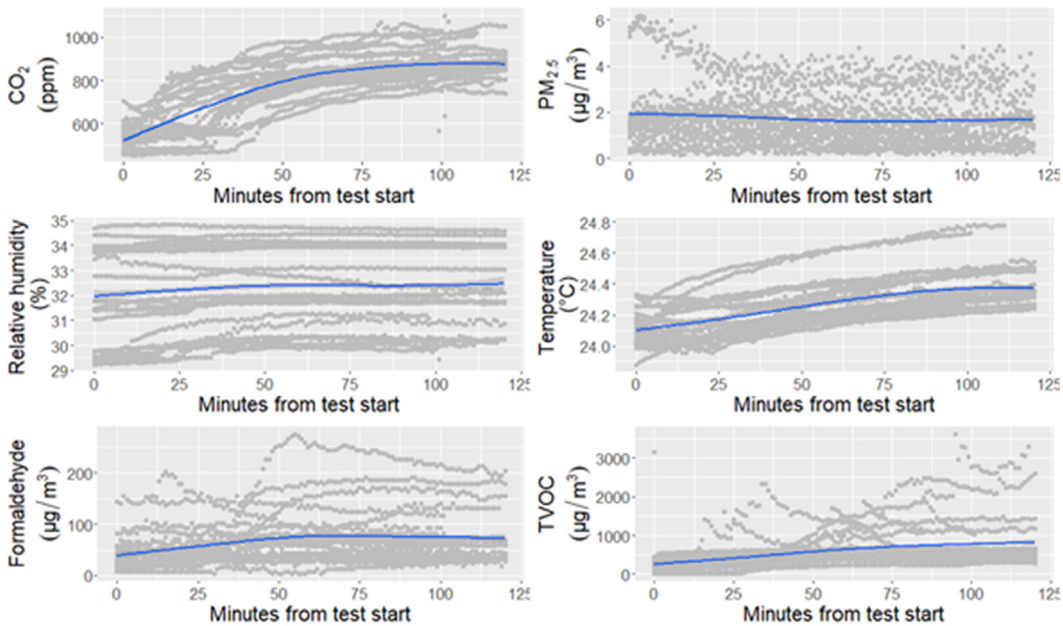

Fig. 6. Concentration of pollutants (CO_2, $PM_{2.5}$, formaldehyde, and TVOCs) and the environmental parameters RH and temperature for the 24 measured cases.

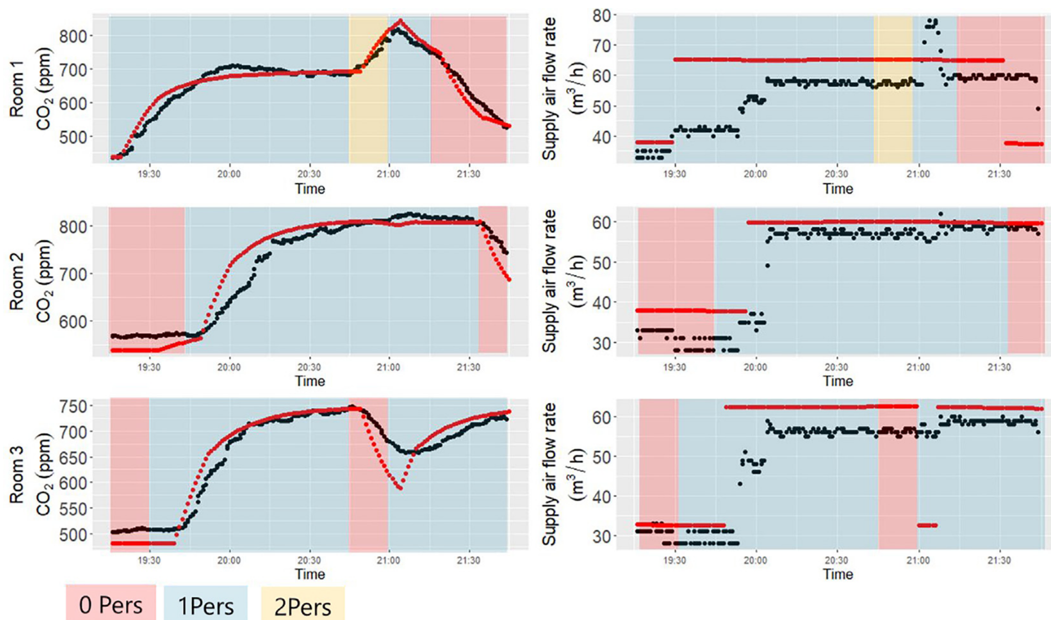

Fig. 7. Measured (black) and simulated (red) results in the three rooms. The red, blue, and yellow shading shows whether the room was used by zero, one, or two person(s), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 7), which the control strategy could not explain, and the simulation results did not reflect. When occupants arrived in Rooms 2 and 3, the simulated CO_2 concentrations rose faster than in reality, although the ventilation rates were higher in the model. This is most likely the result of the CO_2 supply from the mannequins. The CO_2 was supplied from the bottle and distributed to each room. The CO_2 supplied to the room may have been poorly distributed in the three-way valve. In addition, once the flow was opened, the CO_2 filled the pipes leading to the mouth of the mannequins and then mixed with the air in the room before arriving at the sensor. The lack of perfect mixing could have caused a delay in the measurement compared with the ideal mixing simulation. These hypotheses could have been studied in detail to add a delay to the model, but because the error corresponded to very local points that would not have changed the general results of this study, this small difference was disregarded.

Measurements and simulations had a 1-minute resolution, and they were calibrated according to ASHRAE recommendations. Table 5 shows the NMBE and CV-RMSE values that are below ASHRAE 14 [76] calibration recommendations (NMBE below ± 10 % and a CV-RMSE of ± 30 % for hourly calibrations). Thus, the model is considered validated. The energy use was validated using the results from the test with mannequins. The energy use NMBE of the validated simulation was 2 %, and the CV-RMSE was 1.7 %; thus, the energy simulation was also considered validated.

3.3. Pollutant selection

Correlations between IAQ parameters were assessed according to the methodology explained in Section 2.4. Then, the supply air ventilation logic focused on the uncorrelated IAQ parameters, and the control of the return air recirculation was based on the correlated IAQ parameters.

Using the data collected in the test with students, the correlation coefficients obtained between IAQ parameters were determined and are presented in Fig. 8. To understand this figure, the following information is essential: the blue dashed lines represent the 95 % confidence bound for a significant correlation; the *x*-axis represents the lag that indicates the offset between both series, and its sign determines the direction in which the series were shifted; and the *y*-axis shows the value of the Pearson correlation coefficient of the two respective time lags, with larger values indicating stronger correlations.

According to Fig. 8, the measured temperature represented the room's RH and $PM_{2.5}$. The correlation between temperature and $PM_{2.5}$ was not obvious, likely because of the sample size and the small variations in $PM_{2.5}$ and temperature during the tests, thus more measurements with larger variations would be needed to draw a conclusion. According to Fig. 6, most of the $PM_{2.5}$ and heat was brought to the room by the occupants. It is important to keep in mind that the correlations between the IAQ parameters may indicate a common reason for the change in the values, although this is not necessarily a causal link. Formaldehyde was strongly correlated with TVOCs. CO_2 and formaldehyde were significantly but not strongly correlated; thus, in this study, the control strategies for optimizing the rules focused on using formaldehyde, CO_2, and temperature.

Regarding the IAQ parameters to control the recirculation, the correlations of interest were between the same parameter in the supply air and room air. Some pollutants were generated in the offices, and some infiltrated from outdoors. For example, in a room with a high concentration of $PM_{2.5}$ infiltrating from the lab, increasing the airflow rate would not be beneficial for diluting $PM_{2.5}$ concentrations (supposing that these PMs were not filtered, filter efficiency is essential here); however, reducing the OA fraction may have a protective effect against $PM_{2.5}$. The I/O ratios focused on the ratio between IAQ parameters in the supply and the room to provide information about their origin.

According to Fig. 9 (left), CO_2 and $PM_{2.5}$ showed significant correlations between the room and supply concentrations. Thus, $PM_{2.5}$ and CO_2 should be controlled in recirculation. Notably, the PM measured in this lab had a considerable share of $PM_{1.0}$, which would have been able to pass through the filters used in this AHU.

All the pollutants, RH, and temperature had I/O ratios of >1, as shown in Fig. 9 (right). This means that the sources were the students inside the office. Thus, increasing OA ratios was an efficient method to reduce concentrations indoors. Formaldehyde and $PM_{2.5}$ had very high values and ratios >1 because the divergent tests (from the period when there were renovations in the lab) were removed from the analysis.

The TVOCs sensors were not calibrated. The correlation between TVOCs and formaldehyde was expected because their sensors were based on very similar measuring principles. However, because these sensors were not calibrated, the results could have been coincidental. Thus, TVOCs was not simulated in the co-simulation model and was not further analyzed in this article.

3.4. Tuning of the ventilation control strategy by simulations

Table 6 describes the schedules of the three offices. The schedules were repeated Monday to Friday throughout the year, except

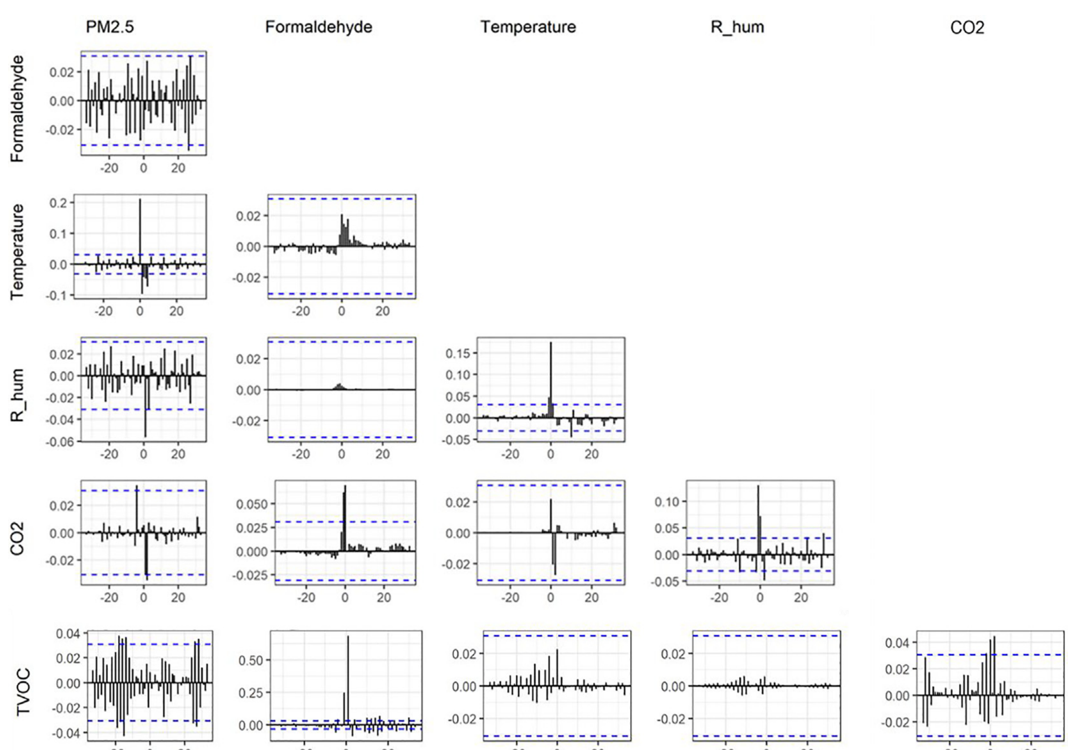

Fig. 8. Cross-correlation function between the different pollutants and environmental parameters measured in the test with students.

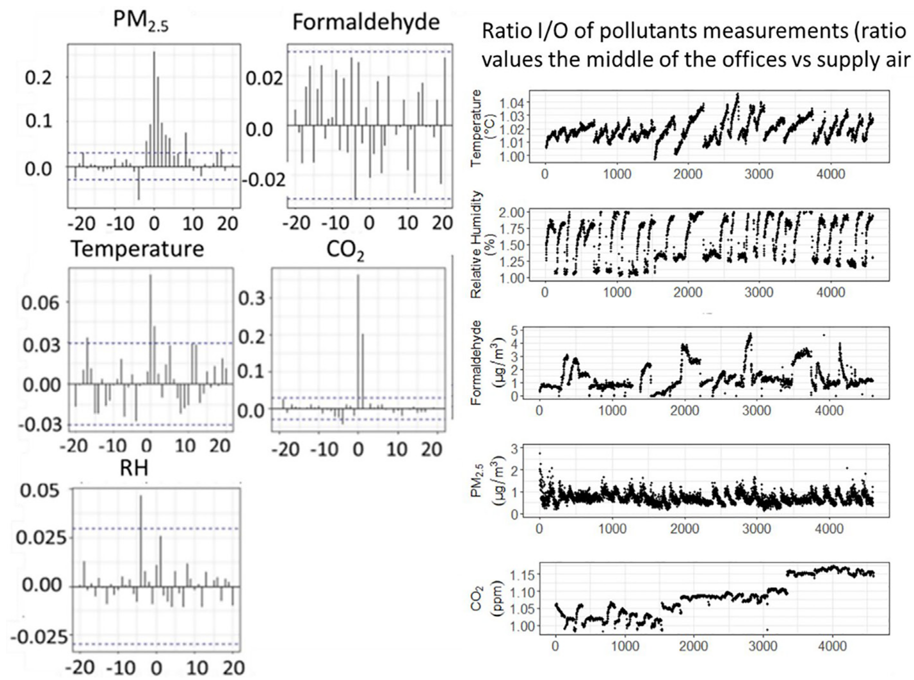

Fig. 9. Left: CCF of supply and room air concentrations; right: I/O ratio of pollutants where all the test are plotted consecutively. The x-axis shows the ID of the measurements ordered by consecutive time.

for the summer holidays (July 1 to 31), when the offices were empty.

Ventilation control tuning focused on reducing the EUI and increasing the KPI_IAQ during WHs. The remaining simulation building parameters, pollutant sources, and ventilation systems followed the protocols described in Sections 2.1–2.3 for the validated model in Section 3.2.

3.4.1. Simulated cases

As described in Section 3.3, the selected IAQ parameters for controlling the airflow supply to the room were CO_2, formaldehyde, and temperature. Table 7 shows the short name of the strategies used in the graphs, the logic behind the control, and the airflow rate supplied to each room. The limits and setpoint values for the supply and recirculation airflow rates in the rule-based control sequences were determined by parametric analysis. This targeted the solution that produced the largest annual energy savings and lowest room air pollutant concentrations. For simplicity, most of the trials are not presented in this article; only a few cases of CO_2 and temperature are included to show that a single parameter could affect the various KPIs differently. As the control logic introduced more IAQ parameters, the ''easy'' tuning became more complicated because of the effects of controlling one parameter on several others. In this work, the control sequences were kept very simple so that the steps of the methodology could be clearly seen and understood, although more complicated strategies could have been developed.

The KPI_IAQ and the individual KPIs were checked to improve the controls. The KPI_IAQ gave a general overview of the performance of the control, and the individual KPIs revealed factors that were not controlled correctly and needed to be improved by modifications to the rules. For instance, if a control resulted in a KPI_IAQ of 0 % because the KPI_CO_2 equaled 0 %, but all other KPIs were satisfactory, then changing the logic of the control of CO_2 would be the best way to improve the performance of the control logic; no other changes would improve the system's performance as much.

The airflow rates in the constant air volume (CAV) strategy, presented in Table 6, were based on the Norwegian building code TEK 17 [88]. The airflow rates and limits for the other strategies were chosen to increase the KPI_IAQ and reduce the annual EUI by stepwise tuning.

The best-performing supply air strategy for Trondheim was combined with the control strategies of the return air summarized in Table 8.

3.4.2. Results without recirculation of return air in Trondheim

Fig. 10 shows the simulated control strategies with a 100 % OA fraction. The KPI_IAQ considered that the three rooms simultaneously presented concentrations of the airborne pollutants below the defined threshold, and RH and temperature within the defined range. Table 9 breaks down the KPI_IAQ into the KPIs for all the IAQ parameters defined according to Eqs. (3)–(8) to make concrete improvements to the control logic if needed. EUI considered the annual energy use in kWh/m^2, including heating and ventilation. In the simulated cases, no direct cooling was considered apart from increasing the air supplied to the room.

As can be seen in Fig. 9, the control logic that used the least energy and provided the best IAQ was the strategy that controlled CO_2, temperature, and formaldehyde (C-1, explained in Table 6). This strategy reduced airflow rates mainly during the evening, night, and early morning. The sources of formaldehyde were small in the rooms (Fig. 6), and thus throughout the winter, when the indoor temperatures were not very high, the supply rates could be minimized after the occupants left the room. Then, when the occupants started their working day, CO_2 rose, and airflow rates rose simultaneously. Airflow rates increased progressively with CO_2 or temperature. The maximum airflow rate in the room was achieved when CO_2 surpassed 800 ppm or when the formaldehyde was too high. As in the simulation, both sources for CO_2 and formaldehyde were indoors; increasing ventilation helped to dilute these pollutants.

The DCV solutions did not represent a considerable improvement in energy use compared with the CAV solution. This was pri-

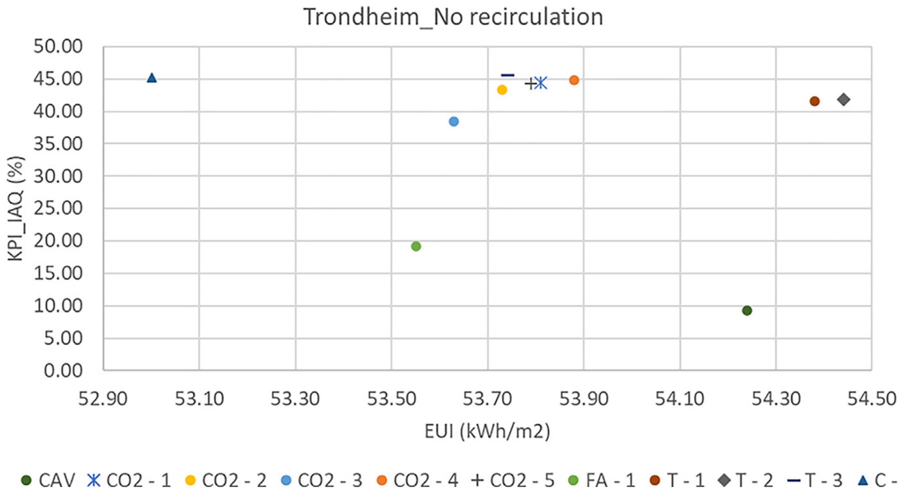

Fig. 10. Percent of working hours (WHs) in which all the KPIs related to IAQ were satisfied versus the annual energy use index (kWh/m^2) for different control logics.

Table 9
Individual KPI values for the different IAQ parameters and the ventilation control strategies for WHs, defined as Monday to Friday from 08:00 to 17:00.

KPI WH	CAV	CO_2-1	CO_2-2	CO_2-3	CO_2-4	CO_2-5	FA-1	T-1	T-2	T-3	C-1
KPI_IAQ (%)	9.3	44.3	43.3	44.4	44.8	38.5	19.2	41.5	41.8	45.6	45.2
CO_2_KPI (%)	100	100	96.4	100	100	90.8	45.8	93.5	94.0	89.0	72.5
Temp _KPI (%)	18.7	83.4	83.4	83.1	81.7	72.8	60.0	81.5	81.2	97.0	97.5
Formaldehyde_KPI (%)	100	100	100	100	100	100	100	100	100.0	100.0	99.3
RH_KPI (%)	46.0	50.8	50.2	51.2	52.3	46.4	40.7	52.9	53.0	53.0	57.0
$PM_{2.5}$_KPI (%)	99.8	99.7	99.7	99.7	99.8	99.7	99.7	99.8	99.8	100.0	99.3
T > 24 °C (%)	27.9	0.5	0.6	0.5	0.5	4.1	11.24	0.3	0.4	0.5	0.0
T < 22 °C (%)	41.5	3.0	2.6	3.3	3.8	1.2	1.0	3.1	3.2	0.0	0.0
Energy (kWh/m^2)	54.2	53.8	53.7	53.8	53.9	53.6	53.7	54.4	53.6	54.4	53.0

marily due to the high occupancy of the rooms. The Norwegian standard NS3031 [87] recommends simulating occupancies between 30 % and 70 %, whereas here, the simulated occupancy was almost always 100 %, except when people arrived at or left work and during lunchtime when it dropped to 0 %. Therefore, the possibility to reduce annual energy use from the differential occupancy was smaller.

The reference system CAV used more energy than most other control sequences. However, because the airflow was not controlled from IAQ parameters values, it resulted in too low RH and temperature and thus, the KPI_IAQ was the lowest. The formaldehyde-based control did not perform well either. It did not control IAQ parameters that rose above the thresholds or those that were not correlated with formaldehyde but were more present than the latter (e.g., CO_2 and temperature).

Table 9 breaks down the KPI_IAQ into all the IAQ parameters' KPIs. The CAV control logic was especially poor for temperature, which was typically outside the range of 22–24 °C. RH was not controlled, and for all the cases, the RH values were too high in summer and too low in winter. The range of 30–60 % was used throughout the year, although keeping the RH below 60 % is more important in the winter to avoid condensation problems, which can cause mold. With the simulated outdoor conditions, increasing the ventilation rate would reduce the RH in the winter but not in the summer. To control the RH more tightly without introducing it into the control strategies or introducing dehumidification or humidification, a potential solution is to tighten the limits of the temperatures and make them different between summer and winter. Allowing lower temperatures in the winter and higher temperatures in the summer would mean higher RH levels in the winter and lower levels in the summer. The general recommendations for thermal comfort [89] allow for a wider range than what was used in these simulations. The limits of temperature here are mostly performance-based, but if the energy-saving dimension was encouraged, these limits should have a seasonal dimension differentiating between summer and winter. This change would have a larger effect on the KPI _RH than changing the airflow rates. $PM_{2.5}$ concentrations were generally low because the indoor simulated sources were low, and the outdoor concentrations were also low.

3.4.3. Results without recirculation of return air in Trondheim with the outdoor air pollutants of Beijing

Fig. 11 shows that when the OA quality in Trondheim was replaced with that in Beijing, the KPI_$PM_{2.5}$ worsened for all the cases because the supply air was more polluted than it was in Trondheim. The decrease in the KPI_$PM_{2.5}$ was not proportional to the increase in the PM levels because of the filters' effect, and the leakages were limited in this case. Because $PM_{2.5}$ was not part of the control strategies for the supply air, most of them performed very similarly to the ones for Trondheim regarding energy, CO_2, temperature, RH, and formaldehyde, but the KPI_IAQs were generally lower.

3.4.4. Results with recirculation of return air in Trondheim

Table 10 compares the best solution with 100 % OA and the recirculation strategies based on only $PM_{2.5}$ and $PM_{2.5}$ AND CO_2. Using recirculation of return air in Trondheim based on $PM_{2.5}$ did not yield significant changes because the $PM_{2.5}$ concentrations indoors were mainly within the guidelines. The recirculation strategies $PM_{2.5}$_OR and $PM_{2.5}$_AND cases consumed more energy because more air had to be supplied to reduce the CO_2 and temperature in the room during the periods in which the rooms were in use. The indicator of the fraction of time when the temperature

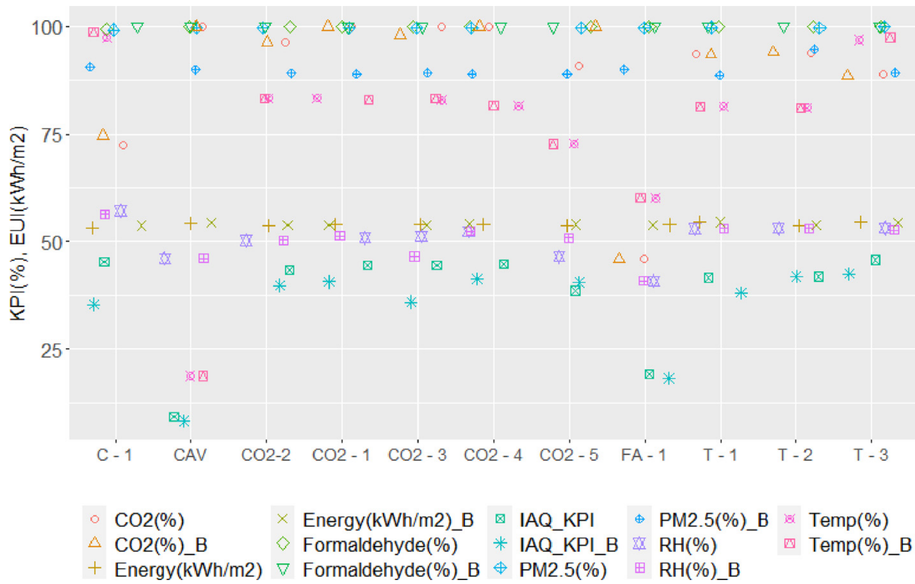

Fig. 11. KPIs for the different ventilation logics. Comparison between the simulations in Trondheim and the simulations in Trondheim with the outdoor air quality in Beijing (indicated by _B) during WHs.

Table 10
KPIs for the different IAQ parameters when considering the weather and OA quality in Trondheim during working hours (WHs).

KPI WH	C-1	$PM_{2.5}$_OR	$PM_{2.5}$_AND	$PM_{2.5}$_CO_2_OR	$PM_{2.5}$_CO_2_AND
IAQ_KPI(%)	45.2	26	26	54.9	53.6
CO_2_KPI (%)	72.5	55.2	55.2	84.2	81.6
Temp_KPI (%)	97.5	84.7	84.7	97.6	99.2
Formaldehyde_KPI (%)	99.3	100	100	100	100
RH_KPI (%)	57.0	56.2	56.2	62.6	59.9
$PM_{2.5}$_KPI (%)	99.3	99.7	99.7	99.7	99.7
T > 24 °C (%)	0.0	2.4	2.4	0.9	0.6
T < 22 °C(%)	0.0	0	0	0	0
Energy (kWh/m^2)	53.0	54.71	54.71	46.6	48.1

was over 24 °C rose from 0 to 2.4 %. In addition, because the recirculated air had higher concentrations of CO_2, the KPI_CO_2 worsened when using $PM_{2.5}$-based recirculation. Using recirculation resulted generally higher RH.

Using the reasoning of the correlations, as CO_2, temperature, and RH were related to the occupancy, changing one of them (CO_2) sufficed to improve the KPIs of RH and temperature, as shown by the controls with $PM_{2.5}$ and CO_2 in Table 10. Adding CO_2 to the recirculation control positively affected the CO_2, temperature, and RH, whose KPIs were improved. The general KPI_IAQs also improved compared with the non-recirculation or the strategies considering only $PM_{2.5}$. This was mainly attributed to an improvement of almost 30 % between the KPI_CO_2 of the logic $PM_{2.5}$ and the logic $PM_{2.5}$ OR CO_2. The energy use was reduced because less energy was needed for heating. During occupied periods, less recirculation was used because an increase in fan power increased the energy consumption, whereas using $PM_{2.5}$ to control recirculation did not have the same effect. The $PM_{2.5}$_CO_2_OR logic resulted in slightly better results for energy and general IAQ than $PM_{2.5}$_CO_2_AND.

3.4.5. Results with recirculation of return air in Trondheim and outdoor air pollutants in Beijing

Fig. 12 compares the results with the recirculation of return air for the simulated case in Trondheim and the case simulated in Trondheim with the OA quality of Beijing. In general, the sequences reducing the fractions of OA yielded lower concentrations of $PM_{2.5}$. This is because the recirculation air filters were superior to the OA filters and the very small production of $PM_{2.5}$ indoors. By contrast, increasing the recirculation rates may increase the concentration of CO_2 but reduce that of $PM_{2.5}$. In places such as Beijing, where the outdoor $PM_{2.5}$ concentrations are much higher, this has a large effect on the results and thus the control sequences including $PM_{2.5}$ and CO_2 could result in better KPIs (IAQ, $PM_{2.5}$, and CO_2). Compared with the control logic C-1 with Beijing's OA, using recirculation positively affected the cases controlled using $PM_{2.5}$ and CO_2; not much improvement was observed in the case of only using $PM_{2.5}$. In the reference case, the IAQ KPI was lower because of the low KPIs for CO_2, RH, and $PM_{2.5}$. These were improved using the recirculation of return air based on $PM_{2.5}$ and CO_2. The combined control of recirculation also resulted in decreased energy use. Reducing the OA fraction increased the RH in the winter without increasing the $PM_{2.5}$ concentration. With dual control (CO_2–$PM_{2.5}$), because of the rise in CO_2 during periods with occupants, recirculation could not be used to reduce the CO_2; thus, more OA was supplied during periods with higher CO_2 indoors, which resulted in a higher $PM_{2.5}$ KPI. However, the CO_2 KPIs in the dual controls were not as high as those in the cases without recirculation; this is because to keep the $PM_{2.5}$ low, the OA fraction had to be reduced in some periods to account for the PM increase.

4. Discussion

There is a clear need to introduce several IAQ parameters to the control of ventilation, additionally to occupancy [33]. However, it is still unclear how to introduce them and which ones to introduce,

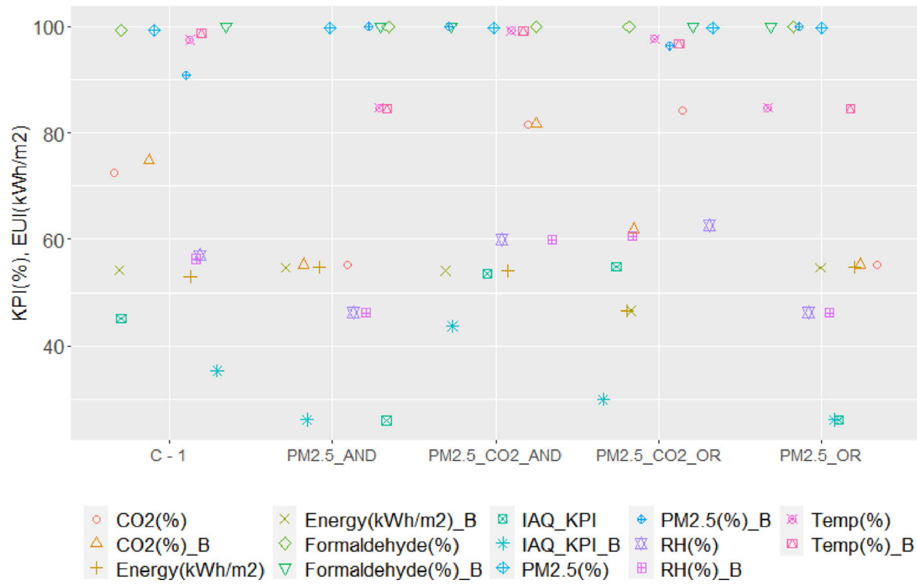

Fig. 12. KPIs for the different ventilation logics with recirculation of return air. Comparison between the simulations in Trondheim and the simulations in Trondheim with the outdoor air quality in Beijing (indicated by _B) during WHs.

since this will depend on the use of the considered building. In the present case, the aim was to improve ventilation in offices. In that respect, measurements were first collected to map the IAQ parameters which required to be controlled. This requirement was evaluated based on CCF in the de-trended time series. Despite making the analysis more complex, this method allows for a more probabilistic choice of the IAQ parameters in the control and add up the flexibility to adapt to different uses of the building or sources of pollutants.

The co-simulation EnergyPlus/CONTAM allowed to test many different control strategies thoroughly and is recommended for its flexibility and accessibility (license-free software). In order to evaluate the resulting ventilation control logic fairly, KPIs were developed. These are simple to use and are based on current knowledge. New KPIs equations should be developed if the guidelines in Table 4 are updated. Additionally, as new LCS become more precise in measuring other IAQ parameters, additional KPIs should be developed.

Multiple DCV strategies were simulated in this study, but only the most satisfactory control logics according to IAQ and EUI are presented. The tested sequences are kept simple to focus on the methodology. Although this study did not use advanced methodologies for control optimization, it achieved reductions in energy use and the number of hours outside the IAQ guidelines. More advanced strategies could be used in future research with a broader scope; for example, machine learning could be used to develop more predictive controls.

The $PM_{2.5}$ guideline [10] in Table 4 is based on 24-hour averages. In all of these calculations (Sections 3.4.2–3.4.5), 1-minute averages were used because this was the timestep in the ventilation control. Using a 24-hour moving average every minute could have been another option instead of simply reducing the exposure time to 1 min, but 1 min was assumed to be sufficient. Changing the time from 24 h to 1 min removes the night period, in which the concentrations normally drop, leading to overweighting of the $PM_{2.5}$ effect. However, using 24 h for a control strategy is not practical. This $PM_{2.5}$ limit is health-based, derived from studies on long- and short-term effects. The updated guidelines from the WHO [10] state that the $PM_{2.5}$ 24-hour average should not exceed 15 $\mu g/m^3$>3–4 days per year. If $PM_{2.5}$ evolves as a standard control parameter for ventilation, different guidelines based on much shorter timesteps should be developed. In such a case, these guidelines should be updated in the control strategies. The ones used in this article are a proof of concept that must be updated considering both health effects and ventilation control needs.

5. Conclusions

A holistic methodology was developed in this study to improve ventilation control logic. This methodology addressed energy efficiency and reduced the number of hours during which the selected IAQ parameters were outside the selected guidelines. Many previous studies investigated CO_2 but not other pollutants. Though CO_2 is a proper indicator of occupancy, it may be inferior for predicting pollutants from other sources. The methodology required measurements of pollutants and simulations to improve the control logic.

This methodology was demonstrated and used in a case study of three full-scale cell office rooms built in a lab at the Norwegian University of Science and Technology (NTNU) in Trondheim (Norway). The ventilation control of these rooms was based on measurements taken with LCSs connected to a Raspberry Pi.

Three tests were run in this set-up: the first test measured the occupants' production of pollutants by studying 24 students' individual measurements; the second test mimicked CO_2-controlled ventilation with thermal mannequins to validate the simulation model; and the third consisted of pressurization tests used to calculate envelope and room leakages.

For the three office rooms, a dedicated model was developed based on a co-simulation between EnergyPlus and CONTAM. This model was validated with results from the test with mannequins. A validated model is essential because it can evaluate different control logics on the basis of energy use and KPIs of IAQ.

An investigation of the CCF in the pre-whitened measurement data series was performed together with I/O ratios to select the most suitable control IAQ parameters for ventilation. On the basis of these results, the ventilation control was tuned by studying the best supply control strategies and the recirculation of return air.

The results showed that it is possible to reduce the annual energy use and the number of hours when given pollutants are outside the recommended guidelines. Recirculation positively affected the otherwise very dry winter (low RH) indoor conditions in Trondheim.

In Trondheim, the OA quality is excellent. Therefore, to test the effect of the outdoor conditions, the same simulations were repeated with the OA quality in Beijing to compare the recirculation effect. In this case, using recirculation of return air also had a protective effect on the indoor concentrations of $PM_{2.5}$. When recirculating the return air, a holistic approach to control the different IAQ parameters is recommended for a safe system that avoids excessive values of the uncontrolled IAQ parameters. When the control strategy has additional parameters, it is essential to use simulation tools to determine how controlling one parameter can affect several others.

Data availability

Data will be made available on request.

Declaration of Competing Interest

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

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