Building and Environment 211 (2022) 108737

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

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

M. Justo Alonso [a,*], W.S. Dols [b], H.M. Mathisen [a]

[a] *Norwegian Technical University (NTNU), Trondheim, Norway*
[b] *National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA*

ARTICLE INFO

Keywords:
Co-simulation
EnergyPlus
CONTAM
Recirculation of return air
Energy use
IAQ

ABSTRACT

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

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

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

1. Introduction

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

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

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

* Corresponding author.
E-mail addresses: Maria.j.alonso@ntnu.no (M. Justo Alonso), william.dols@nist.gov (W.S. Dols), Hans.m.mathisen@ntnu.no (H.M. Mathisen).

https://doi.org/10.1016/j.buildenv.2021.108737
Received 13 September 2021; Received in revised form 18 November 2021; Accepted 26 December 2021
Available online 28 December 2021
0360-1323/

Nomenclature

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

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

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

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

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

2. Methods

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

2.1. CONTAM- EnergyPlus simulation software

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

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

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

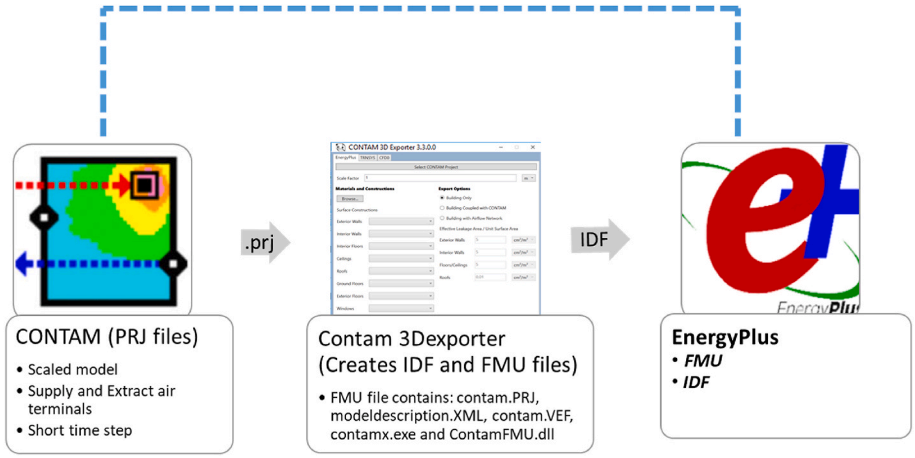

Fig. 1. Schematic of the coupled building model creation process.

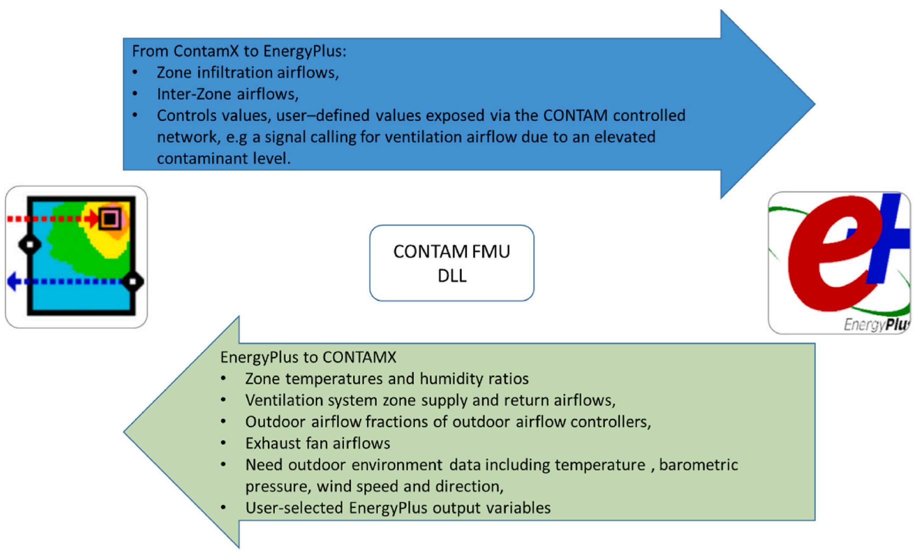

Fig. 2. Schematic of the information exchange during co-simulation between EnergyPlus and CONTAM.

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

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

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

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

2.2. Test case

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

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

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

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

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

2.3. Building model

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

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

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

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

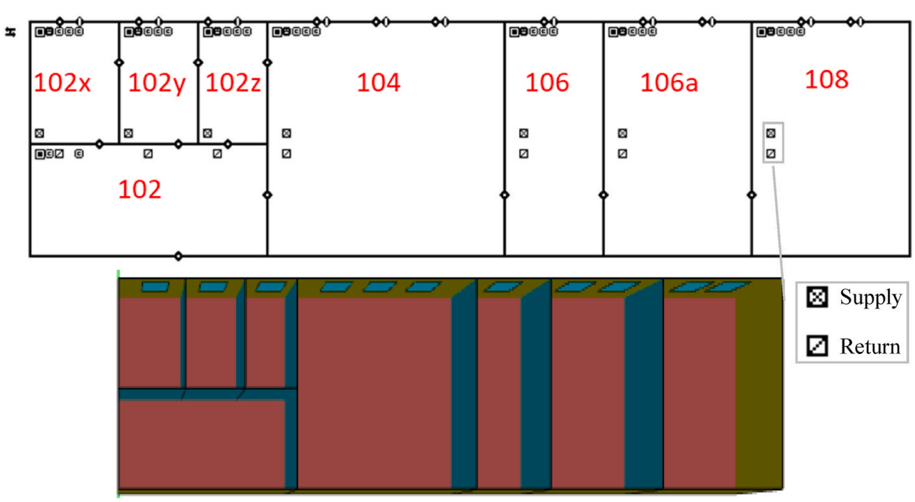

Fig. 3. *Upper: ContamW representation of the corridor. Lower: 3D rendering of IDF geometry generated by* CONTAM3DExporter.

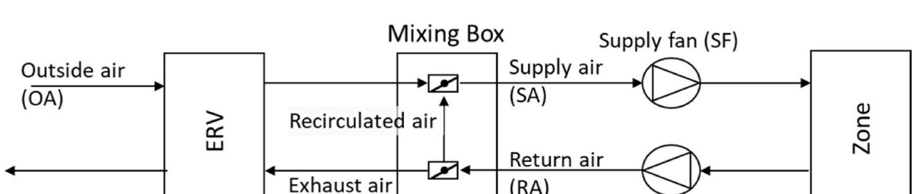

Fig. 4. Schematic of system airflows modeled in this analysis.

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

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

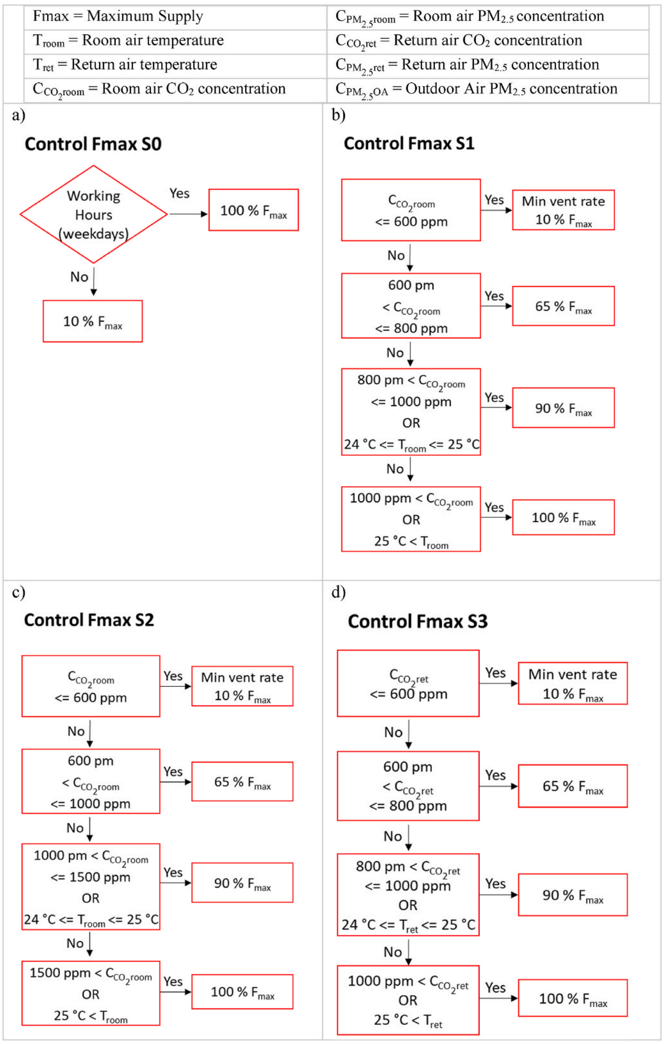

Fig. 5. Flowcharts for control of supply airflow rate.

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

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

2.3.1. HVAC system model

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

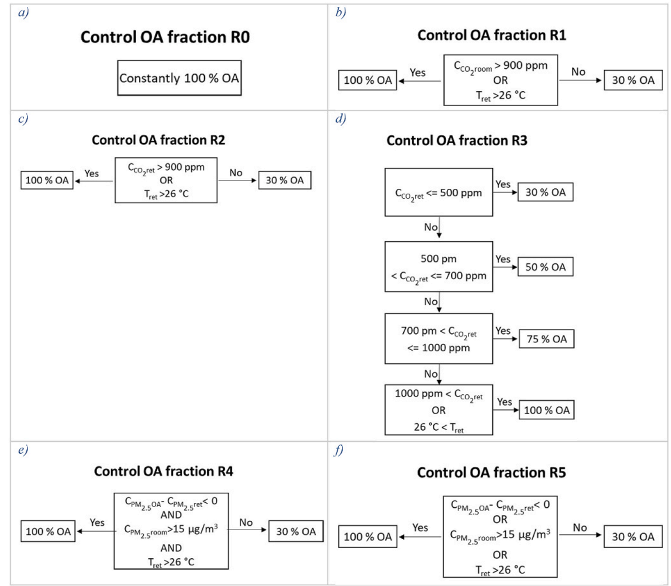

Fig. 6. Flowcharts for recirculation control (% Outdoor Air).

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

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

2.3.2. Ventilation control strategies

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

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

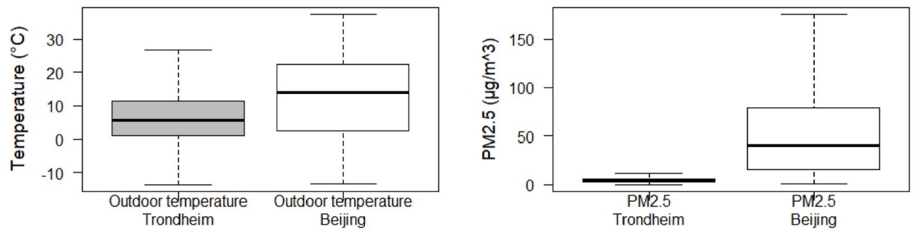

Fig. 7. Distribution outdoor temperature and $PM_{2.5}$ concentrations in the outdoor air in Trondheim and Beijing.

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

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

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

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

2.4. Parametric simulations

A parametric analysis was performed for the following simulation cases:

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

2.5. Supplementary considerations

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

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

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

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

3. Results

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

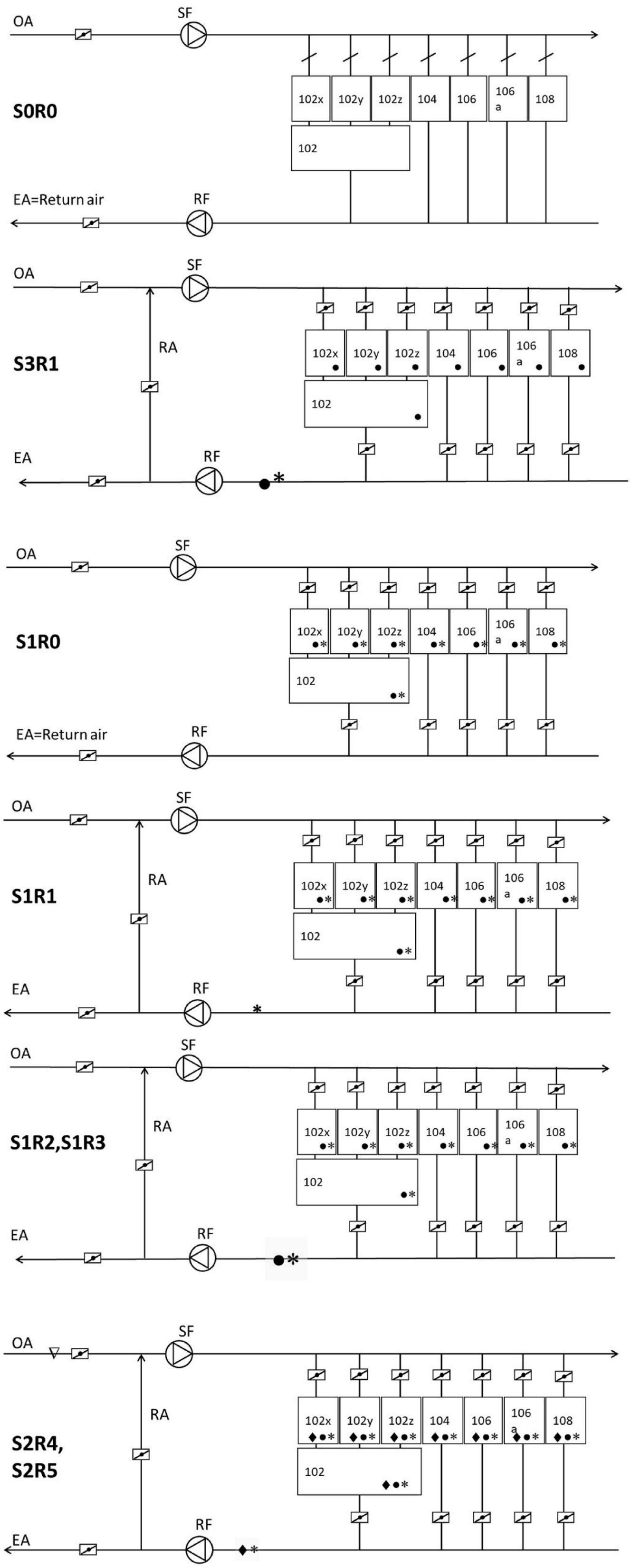

Fig. 8. Ventilation system schematics depicting the location of CO_2 sensors and $PM_{2.5}$ sensors and key for the symbols.

3.1. Annual performance evaluations

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

3.1.1. Energy usage

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

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

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

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

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

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

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

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

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

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

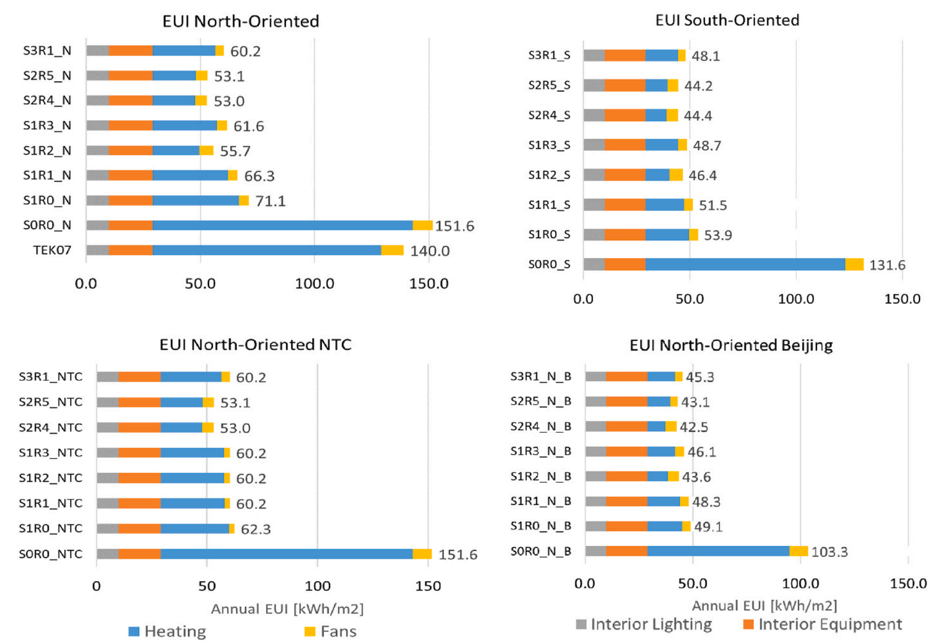

Fig. 9. Energy use for the different control strategies, including _NTC cases and for different orientations and locations.

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

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

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

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

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

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

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

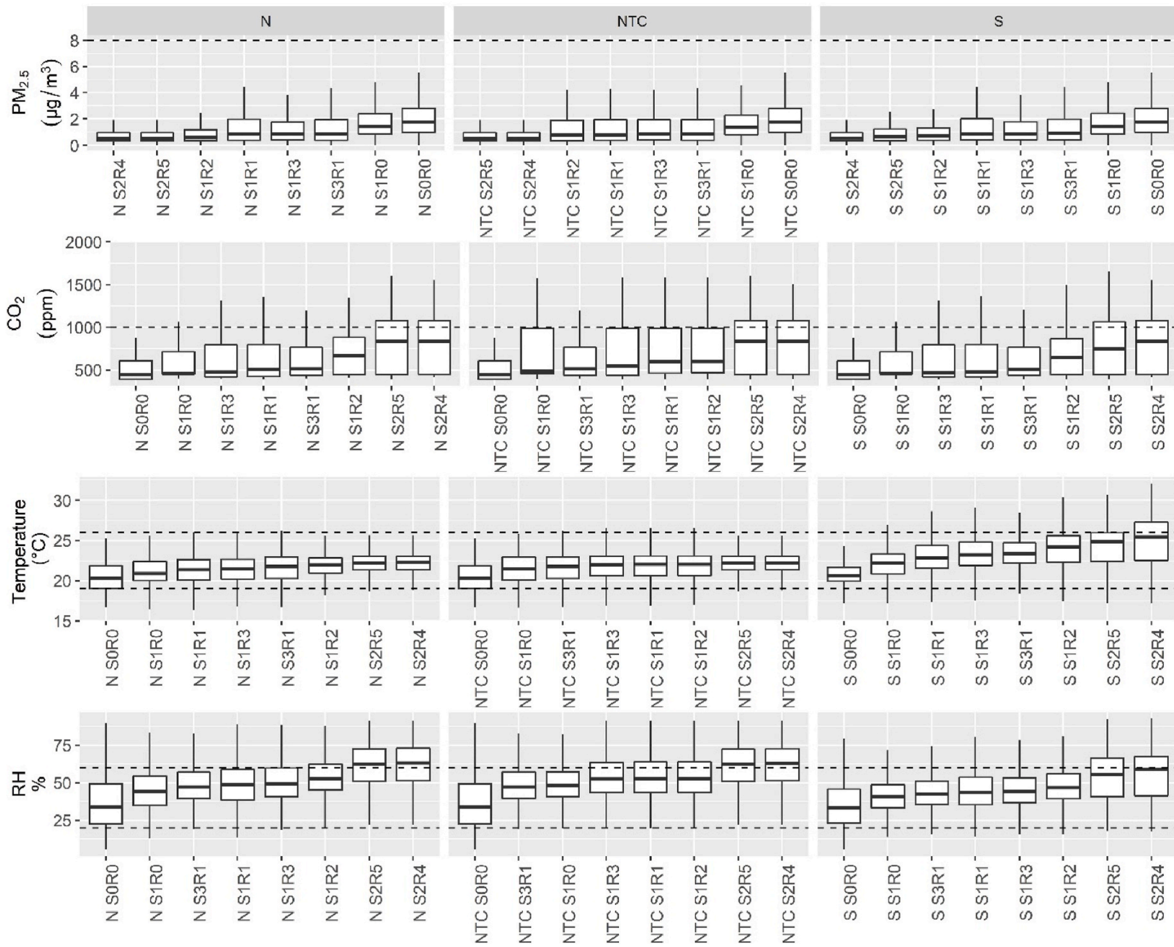

Fig. 10. *Distribution of $PM_{2.5}$, CO_2, temperature, and RH during working hours (Monday to Friday from 0800 to 1600) aggregating all simulated rooms. Dashed line in the $PM_{2.5}$ figure corresponds to the Norwegian annual threshold of* 8 μg/m^3 [53], *dashed line in the CO_2 figure shows the Norwegian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

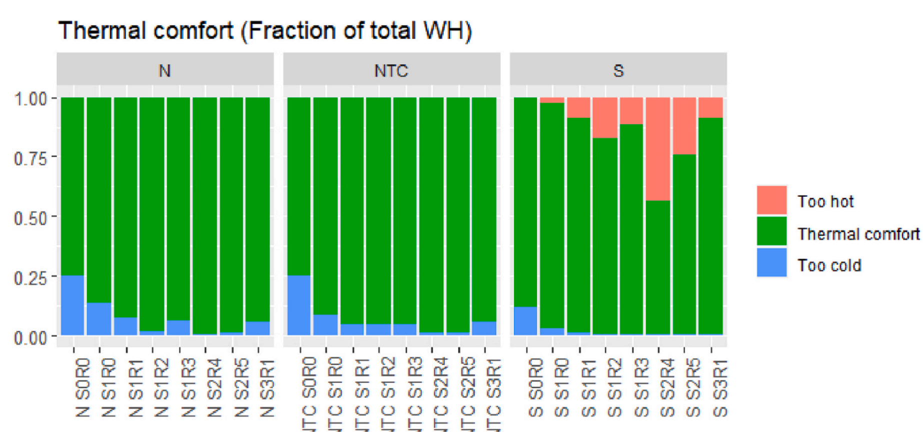

Fig. 11. *Fraction of WH of the temperatures relative to the thermal comfort range* [54].

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

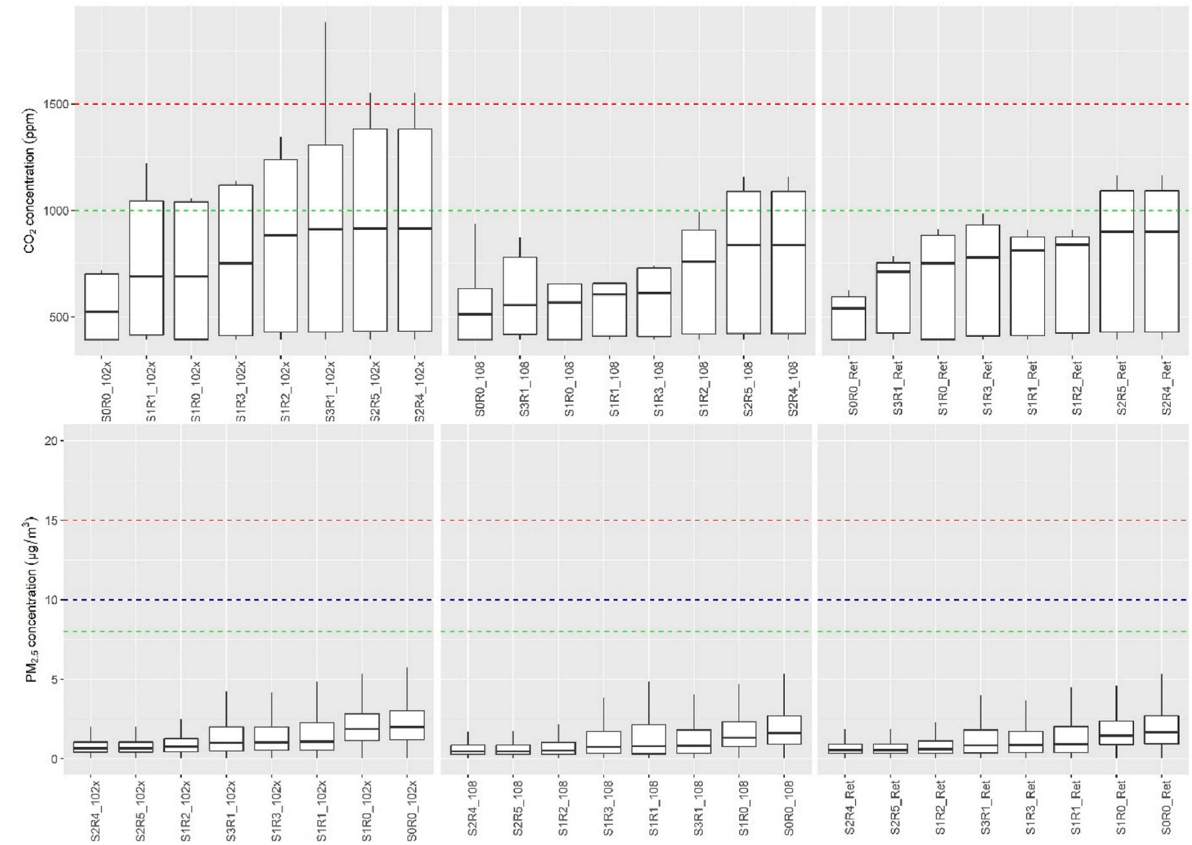

Fig. 12. *Distribution of concentration of CO_2 and $PM_{2.5}$ for the different control strategies during working hours for rooms 102x, 108 and return air. The green dashed line in the CO_2 graph shows the Norwegian recommendation of* 1000 ppm *and the red dashed line shows the REHVA recommendation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

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

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

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

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

3.1.3. Building in Beijing

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

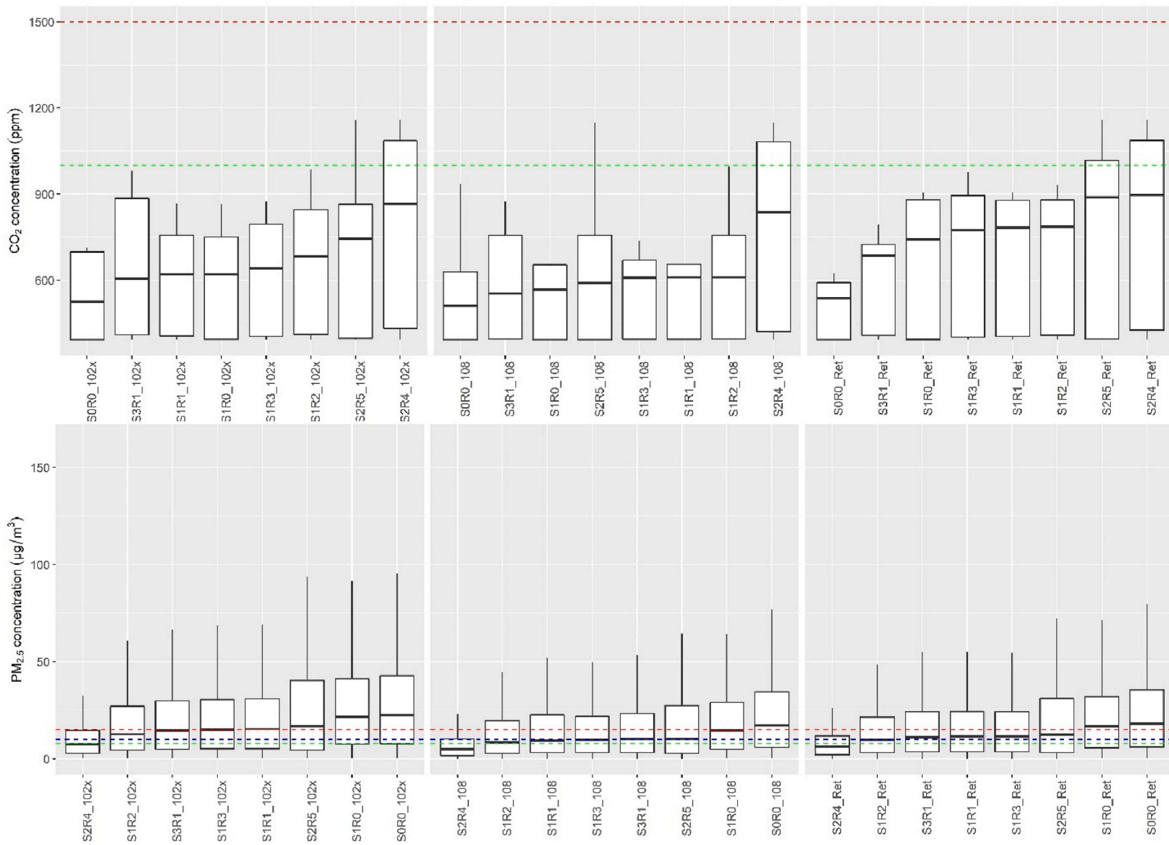

Fig. 13. *Distribution of CO_2 and $PM_{2.5}$ concentrations of for the different control strategies during working hours for rooms 102x and 108 and return air. The green dashed line in the CO_2 graph shows the Norwegian recommendation of* 1000 ppm *and the red line shows the REHVA recommendation of*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

Monitoring Centre.

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

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

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

3.2. One-day performance evaluations

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

3.2.1. Trondheim

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

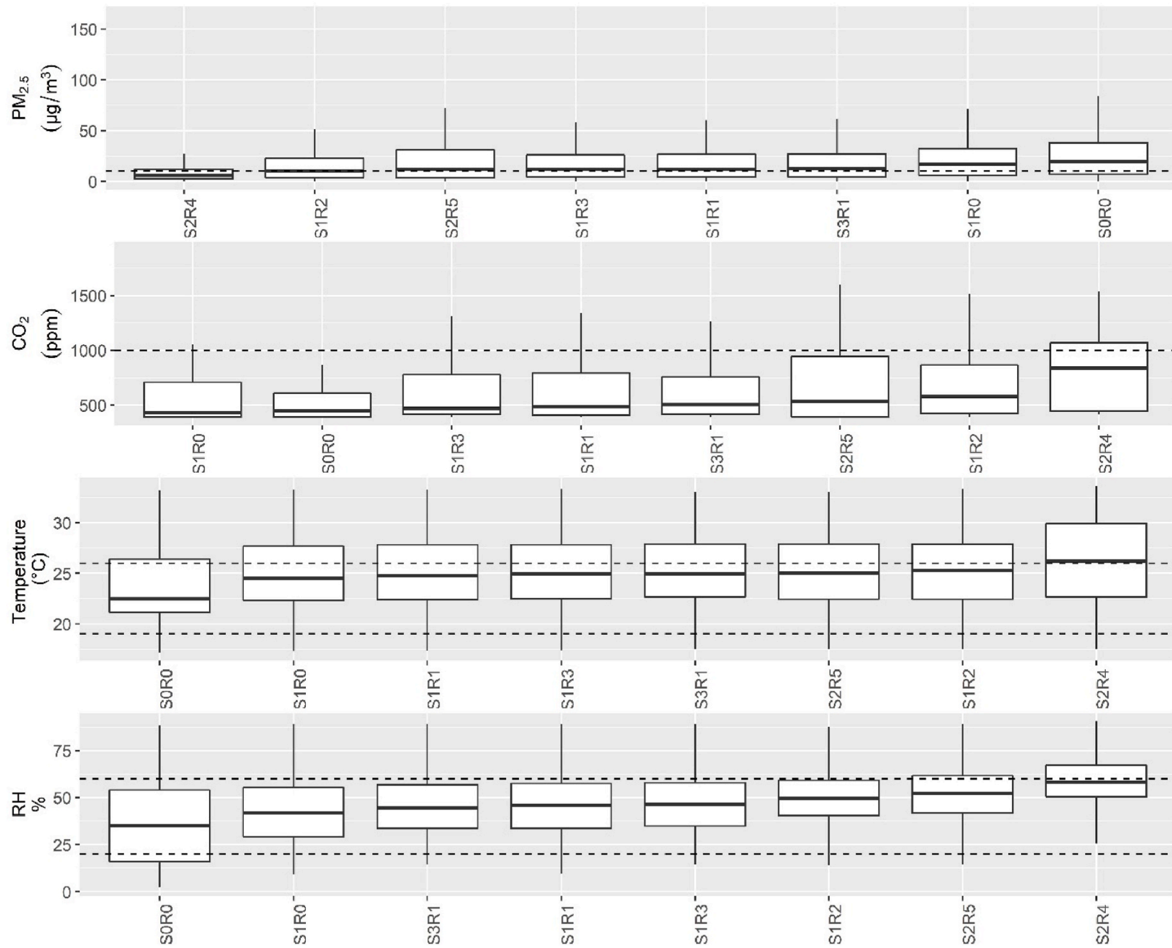

Fig. 14. *Distribution of $PM_{2.5}$, CO_2, temperature and RH during working hours (Monday to Friday from 0800 to 1600) aggregating all simulated rooms in Beijing. Dashed line in the $PM_{2.5}$ figure corresponds to the annual WHO's recommendation of $PM_{2.5}$ of* 10 μg/m^3 [57], *dashed line in the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

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

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

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

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

3.2.2. *Beijing*

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

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

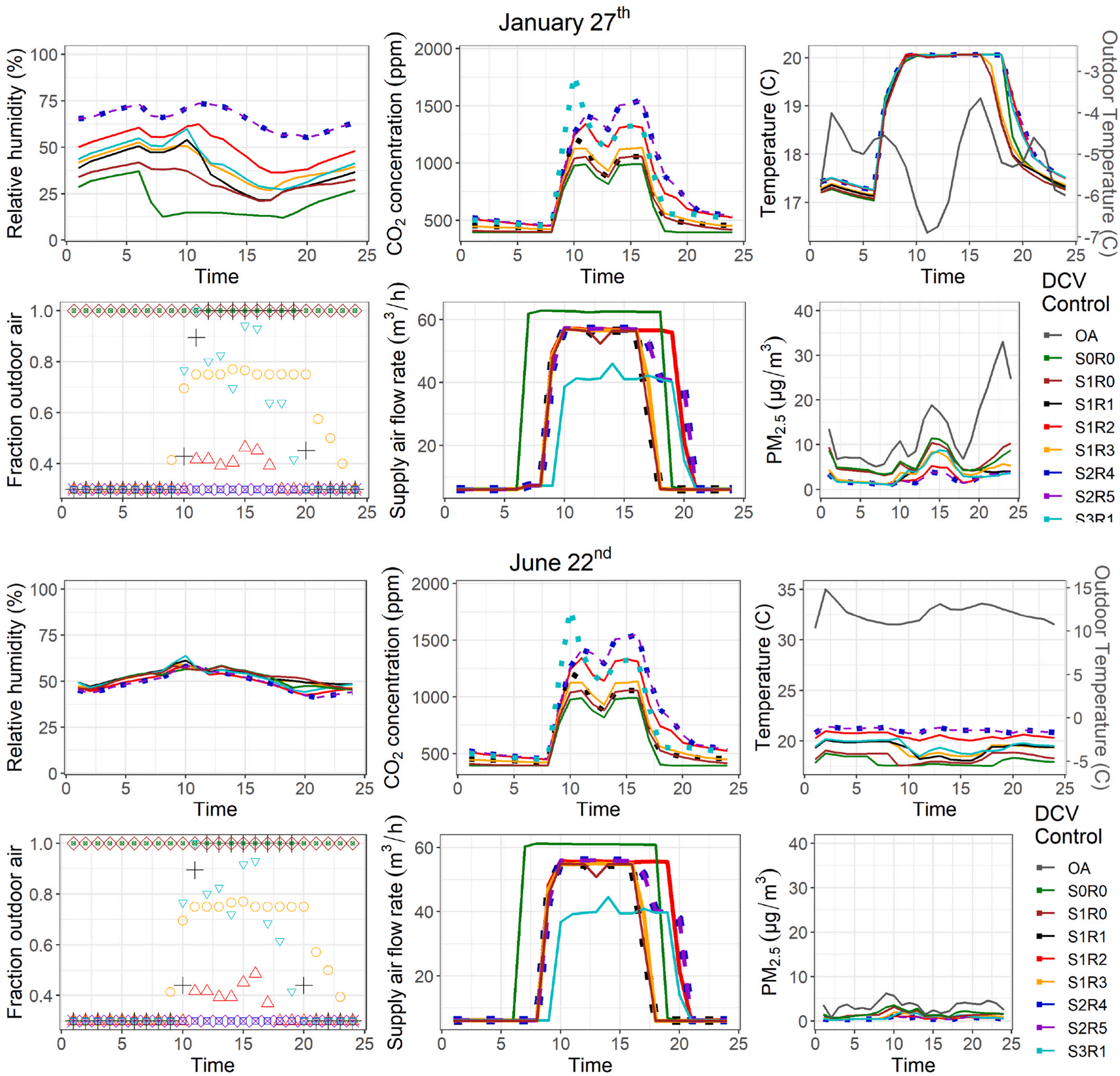

Fig. 15. Hourly averaged relative humidity, CO_2, temperature, OA fraction, supply airflow rate, and $PM_{2.5}$ for room 102x in Norway.

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

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

3.3. Ranking best control strategies in Norway

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

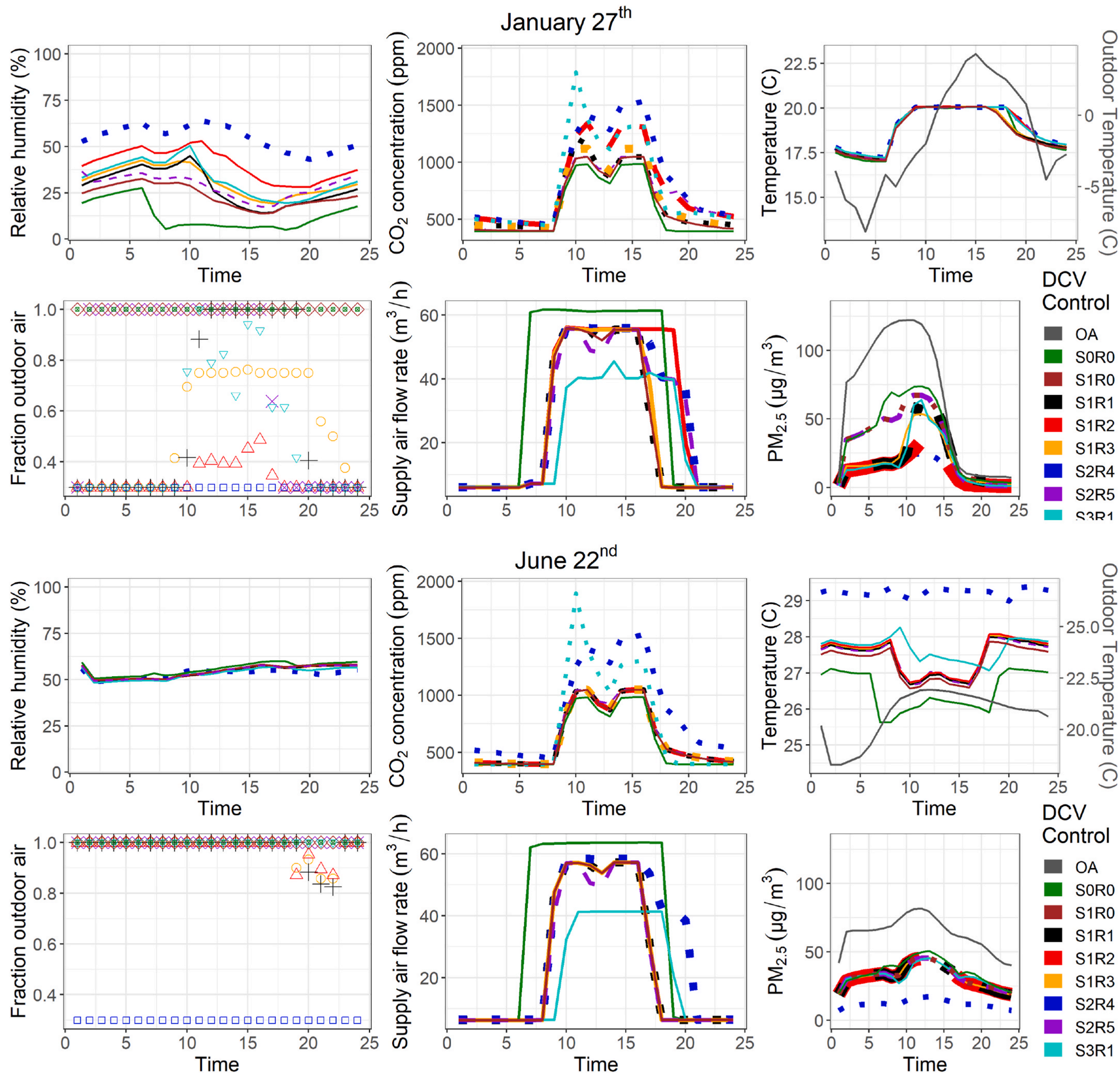

Fig. 16. Hourly averaged relative humidity, CO_2, temperature, OA fraction, supply airflow rate, and $PM_{2.5}$ for room 102x in Beijing.

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

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

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

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

4. Conclusions

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

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

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

CRediT authorship contribution statement

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

Declaration of competing interest

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

Acknowledgments

The NTNU authors gratefully acknowledge the support from the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighborhoods in Smart Cities (FME ZEN, project number 257660). The Indoor Air Quality and Ventilation Group at the National Institute for Standards and Technology is also hereby acknowledged.

References

[1] EPA, Energy Cost and IAQ Performance of Ventilation Systems and Controls - Executive Summary, 2000, p. 37, no. EPA-4-2-S-01-001.
[2] W.W. Nazaroff, Exploring the consequences of climate change for indoor air quality, Environ. Res. Lett. (2013).
[3] W.J. Fisk, D. Black, G. Brunner, Changing ventilation rates in U.S. offices: implications for health, work performance, energy, and associated economics, Build. Environ. (2012).
[4] D. Rim, S. Schiavon, W.W. Nazaroff, Energy and cost associated with ventilating office buildings in a tropical climate, PLoS One (2015).
[5] European Commission, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (Recast), 2010, pp. 13–35.
[6] Passive House Institute, Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, 2016.
[7] A. Houlihan Wiberg, et al., A net zero emission concept analysis of a single-family house, Energy Build. (2014).
[8] M. Justo Alonso, P. Liu, H.M. Mathisen, G. Ge, C. Simonson, Review of Heat/energy Recovery Exchangers for Use in ZEBs in Cold Climate Countries, 84, 2015, pp. 228–237.
[9] M.G. Apte, A review of demand control ventilation, Heal. Build (2006) 371–376. May.
[10] M. Schell, D. Inthout, Demand control ventilation using CO2, ASHRAE J 43 (2) (2001) 18–24.
[11] Y. Fan, K. Kameishi, S. Onishi, K. Ito, Field-based study on the energy-saving effects of CO2 demand controlled ventilation in an office with application of Energy recovery ventilators, Energy Build 68 (Jan. 2014) 412–422.
[12] M. Justo Alonso, P. Liu, H.M. Mathisen, G. Ge, C. Simonson, Review of heat/energy recovery exchangers for use in ZEBs in cold climate countries, Build. Environ. 84 (2015).
[13] S.J. Emmerich, A.K. Persily, State-of-the-Art Review of CO2 Demand Controlled Ventilation Technology and Application, NISTIR 6729. National Institute of Standards and Technology: Gaithersburg, MD (2001).
[14] P. Carrer, et al., What does the scientific literature tell us about the ventilation-health relationship in public and residential buildings? Build. Environ 94 (P1) (2015) 273–286.
[15] P. Wolkoff, Indoor air pollutants in office environments: assessment of comfort, health, and performance, Int. J. Hyg Environ. Health 216 (4) (2013) 371–394.
[16] K.-H.H. Kim, E. Kabir, S. Kabir, A review on the human health impact of airborne particulate matter, Environ. Int. 74 (2015) 136–143.
[17] W.J. Fisk, A.T. De Almeida, Sensor-based demand-controlled ventilation: a review, Energy Build 29 (1998) 35–45.
[18] C.A. Pope, et al., Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, JAMA 287 (9) (2002) 1132–1141.
[19] O. Ramalho, et al., Association of carbon dioxide with indoor air pollutants and exceedance of health guideline values, Build. Environ. (2015).
[20] J. Jaakkola, P. Tuomaala, O. Seppanen, Air recirculation and sick building syndrome: a blinded crossover trial, Am. J. Publ. Health (1994).
[21] M. Trčka, J.L.M. Hensen, M. Wetter, Co-simulation of innovative integrated HVAC systems in buildings, J. Build. Perform. Simul. (2009).
[22] M. Trčka, J.L.M. Hensen, M. Wetter, Co-simulation for performance prediction of integrated building and HVAC systems - an analysis of solution characteristics using a two-body system, Simulat. Model. Pract. Theor. (2010).
[23] W. Wang, I. Beausoleil-Morrison, Integrated simulation through the source-code coupling of component models from a modular simulation environment into a comprehensive building performance simulation tool, J. Build. Perform. Simul. (2009).
[24] W.S. Dols, S.J. Emmerich, B.J. Polidoro, Using coupled energy, airflow and indoor air quality software (TRNSYS/CONTAM) to evaluate building ventilation strategies, Build. Serv. Eng. Technol. (2016).
[25] M. Wetter, Co-simulation of building energy and control systems with the building controls virtual test bed, J. Build. Perform. Simul. (2011).
[26] W.S. Dols, B.J. Polidoro, Polidoro, CONTAM User Guide and Program Documentation Version 3.2, National Institute of Standards and Technology: Gaithersburg, MD (1887) (2015). Gaithersbu.
[27] U.S. Department of Energy, EnergyPlus Version 9.1, 2017. https://energyplus.net/.
[28] G.N. Walton, AIRNET - A Computer Program for Building Airflow Network Modeling. NISTIR 89-4072, National Institute of Standards and Technology: Gaithersburg, MD (1989).

[29] W.S. Dols, S.J. Emmerich, B.J. Polidoro, Coupling the multizone airflow and contaminant transport software CONTAM with EnergyPlus using co-simulation, Build. Simul. 9 (4) (2016) 469–479.
[30] B.J. Polidoro, CONTAM 3D Exporter version 3.2, 2015. https://www.nist.gov/el/energy-and-environment-division-73200/nist-multizone-modeling/software/contam-3d-exporter.
[31] D.M. Lorenzetti, Computational aspects of nodal multizone airflow systems, Build. Environ. (2002).
[32] A. Weber, M. Koschenz, V. Dorer, M. Hiller, S. Holst, TRNFLOW, a new tool for the modelling of heat, air and pollutant transport in buildings within TRNSYS, 8th Int. IBPSA Conf. (2003).
[33] T.S. Nouidui, M. Wetter, W. Zuo, L. Berkeley, Funtional mock-up unit import in EnergyPlus for co-simulation, Proc. BS2013 (2013) 3275–3282.
[34] DIBK, Veiledning 2007 Til Teknisk forskrift Til Plan- Og Bygningsloven 1997, 2007.
[35] ASHRAE, ANSI/ASHRAE Standard 62-2001: Ventilation for Acceptable, 2004.
[36] ASTM, D6245-18 Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation, American Society for Testing and Materials, West Conshohocken, PA, 2018.
[37] NILU. www.nilu.no, 2018.
[38] D.T. Tran, L.Y. Alleman, P. Coddeville, J.-C. Galloo, Indoor and Built Indoor particle dynamics in schools : determination of air exchange rate, size-resolved particle deposition rate and penetration factor in real-life conditions, Indoor Built Environ 26 (10) (2017) 1335–1350.
[39] ANSI/ASHRAE, Standard 52.2-2017. Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size, Am. Soc. Heat. Refrig. Air-Cond. Eng. (2017).
[40] B. Stephens, Evaluating the sensitivity of the mass-based particle removal calculations for HVAC filters in ISO 16890 to assumptions for aerosol distributions, Atmosphere 9 (3) (2018) 85.
[41] F.W.H. Yik, P.S.K. Sat, J.L. Niu, Moisture generation through Chinese household activities, Indoor Built Environ. (2004).
[42] K.M. Smith, S. Svendsen, The effect of a rotary heat exchanger in room-based ventilation on indoor humidity in existing apartments in temperate climates, Energy Build. 116 (Mar. 2016) 349–361.
[43] P. Johansson, S.B. Pallin, M. Shahriari, Risk Assessment Model Applied on Building Physics: Statistical Data Acquisition and Stochastic Modeling of Indoor Moisture Supply in Swedish Multi-Family Dwellings, 2010.
[44] DIBK, Veiledning TEK 2017 Byggeteknisk Forskrift, 2017.
[47] F.R. d'Ambrosio Alfano, et al., Indoor environment and energy efficiency in schools, REHVA (2010).
[48] A. Bang, Folkehelse – Støv Og Helseeffekter Av Luftforureining, 2017.
[49] DIBK, Byggteknisk Forskrift (TEK 07), 2007.
[50] Standard Norge, NS 3031:2007 Calculation of Energy Performance of Buildings - Method and Data, 2007.
[51] D. Crawley, L. Lawrie, Climate/weather data sources [Online]. Available, http://climate.onebuilding.org/sources/default.html, 2020.
[52] J. Halvarsson, Occupancy Pattern in Office Buildings: Consequences for HVAC System Design and Operation, Doctoral Thesis at Norwegian Institute of Science and Technology, Trondheim, 2012.
[53] T. Attramadal, P. Schwarze, B. Rune, Anbefalte faglige normer for inneklima, Revisjon av kunnskapsgrunnlag og normer - 2015 (2015).
[54] DIBK, Byggteknisk Forskrift (TEK17), 2017.
[55] FHI, Temperatur, Fukt Og Trekk Er Viktig for Kroppens Varmebalanse, 2015.
[56] M. Justo Alonso, R.B. Jørgensen, H.M. Mathisen, Short term measurements of indoor air quality when using the home office in Norway, E3S Web Conf 246 (2021).
[57] WHO, Guidelines for indoor air quality - selected Pollutants, WHO Guidel. 9 (2010) 454.
[58] A. Khan, Mulige strategier for avriming og deres konsekvenser for dimensjonerende varmeeffek, OsloMet (2020).
[59] S. Holøs, "Når inneklimaet blir for tørt,", Nasjonalt fuktseminar (2015).