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Simulation of occupancy and CO_2-based demand-controlled mechanical ventilation strategies in an office room using *EnergyPlus*

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Abstract

Buildings are responsible for a large sharing of energy consumption worldwide. Among all energy services in buildings, heating, ventilation and air conditioning systems not only account for a significant part of energy consumption but they are also highly influential on indoor climate and occupants' satisfaction in consequence. In this paper, four demand-controlled ventilation strategies based on occupancy schedule period, occupancy level and indoor concentration of CO_2 in an office room have been studied. The indoor air quality as well as the energy consumption levels associated to each demand-controlled ventilation strategy were assessed through simulations performed using *EnergyPlus*. The results showed the best suited ventilation strategies for the office room that can provide acceptable level of indoor air quality with the least energy use. Furthermore, three sensitivity analyses were performed in order to assess the influence of changing different criteria on the energy consumption and indoor air quality.

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Keywords: demand-controlled ventilation; ventilation strategies; indoor air quality; energy consumption

1. Introduction

The role of Heating, Ventilation and Air-Conditioning (HVAC) systems is to provide favorable indoor climate condition for occupants in buildings, regarding the thermal environment and the indoor air quality (IAQ). HVAC

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accounts for almost 40 % of energy use in buildings in which ventilation plays a significant role [1]. Ventilation also interacts with health, productivity and comfort of the occupants [2]. Many energy-efficient and sustainable ventilation methods such as natural ventilation, hybrid ventilation, ventilation control strategies and Demand-Controlled Ventilation (DCV) have been reviewed by [3]. In DCV, a technology for energy saving in HVAC systems [4], the fan velocity is regulated according to the demanded fresh air flow rate. So that, DCV improves the energy-efficiency by supplying fresh air to and/or extracting stale air from the space only in the right time and the right amount. It results to reduce the cost and prevent energy waste while provides acceptable IAQ. Various studies [5–10] have shown the potential of DCV in saving energy in buildings.

In this paper, four Sensor-based Mechanical Demand-Controlled Ventilation (SBMDCV) strategies have been defined and simulated to assess the energy consumption and IAQ associated to each strategy. Moreover, three sensitivity analyses were performed to assess the influence of changing different criteria on the final results. SBMDCV strategies are based on occupancy schedule period, occupancy level and CO2 concentration in the office. This research has been developed under framework of Smart Window project at university of Coimbra [11, 12]. One of the tasks of this project is to develop and test DCV strategies for mechanical ventilation. These SBMDCV strategies can be used in spaces where occupants have difficulties in employing natural ventilation. Outdoor pollution and noise as well as security and privacy purposes are the main reasons to employ mechanical ventilation.

2. Material and methods

2.1. Case study overview

The Indoor Live Lab (I2L) [13], located in Mechanical Engineering Department (DEM) at university of Coimbra, with an area of 46.64 m^2 and 3 meters ceiling height, has been chosen as the test room to conduct simulations. The I2L is equipped with several instruments and sensors which monitor Indoor Environmental Quality (IEQ) indices. The I2L has been modelled in *OpenStudio*, a plug-in for *SketchUp* (a design software tool to create 2D and 3D models), which converts the 3D building model into an *EnergyPlus* file. There are five permanent and one guest working places in this office. Five occupants were considered as the maximum occupancy level in the room. Moreover, the activity level of occupants was assumed 1.2 met with an average Du Bois body surface area of 1.8 m^2. The windows and door are assumed to be closed during all simulations period. An infiltration rate of 0.2 h^{-1}, obtained from a CO_2 decay test, was considered for the simulations.

2.2. Ventilation systems

Constant Air Volume (CAV) fans as well as Variable Air Volume (VAV) fans with different airflow rates have been considered during simulation of ventilation strategies. The fans power is obtained from the following equation:

$$P = \frac{Q_{fan} \cdot \Delta p}{\eta} \quad (1)$$

where

P represents the fan power in watts;

Q_{fan} represents the fan airflow rate in m^3/s;

Δp represents the fan pressure rise in Pa (100 Pa is assumed);

η represents the fan efficiency (0.7 is assumed).

2.3. Ventilation strategies

Four occupancy and CO_2-based ventilation strategies have been defined and simulated:

- Control strategy 1 (Occupancy period based): In this strategy, regardless the number of occupants, a CAV fan is used that operates only during occupancy period;

- Control strategy 2 (Occupancy level based): Unlike the previous strategy, this is an occupancy-based DCV in which a VAV fan is used to provide a specific amount of airflow rate per occupant;
- Control strategy 3 (Single setpoint CO_2-based): A maximum setpoint for indoor CO_2 concentration (1000 ppm) is defined. In this case, a CAV fan that operates only if the CO_2 concentration goes above the setpoint and stops, when it is below the setpoint, is used;
- Control strategy 4 (Double setpoint CO_2-based): A maximum setpoint for indoor CO_2 concentration (1000 ppm) is defined as well as a minimum setpoint (500 ppm). Similar to the strategy 3, a CAV fan that operates when the CO_2 concentration is above the maximum setpoint is used. The fan only stops when CO_2 is below the minimum setpoint during occupancy time.

Fig. 1 demonstrates the flowcharts of the simulated ventilation strategies. It should also be mentioned that, all strategies have been simulated based on the main occupancy schedule represented in Table 1.

Table 1. Main occupancy schedule.

Weekdays occupancy schedule									
Time	00–09	09–10	10–13	13–14	14–18	18–19	19–20	20–21	21–24
Occupancy	0	2	5	0	5	3	2	1	0

2.4. Simulation software

After drawing the zone model in *OpenStudio*, the envelope (materials and constructions) and internal parameters (schedules, occupation, infiltration and CO_2 generation rates, mechanical ventilation components and control) were specified in *EnergyPlus* simulation software. *EnergyPlus* is one of the most-commonly used and versatile energy simulation programs [14] and perfectly suitable for the analysis [15], having the ability to compute CO_2 generation (based on human occupancy, 3.82E-8 m^3/s-W), predict its concentration evolution according to the generation rate or the decay caused either by external air infiltration or fresh air supply, while estimating the energy consumption involved in the complete process.

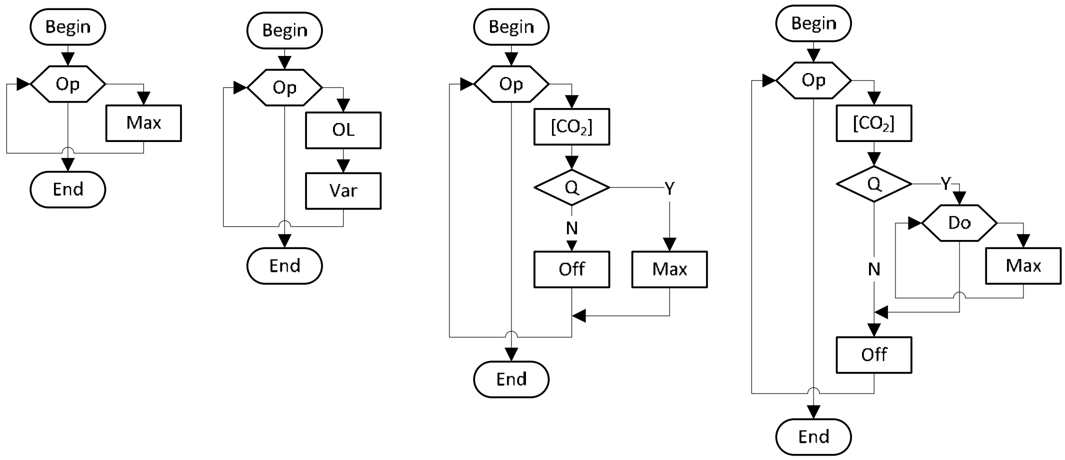

Fig. 1. Ventilation strategies flowcharts.

3. Simulation results and discussion

In this section the results from each strategy is being discussed. Moreover, comparisons between strategies considering the IAQ and energy consumption have been performed. Fig. 2 represents the zone CO_2 concentration during the day for all ventilation strategies.

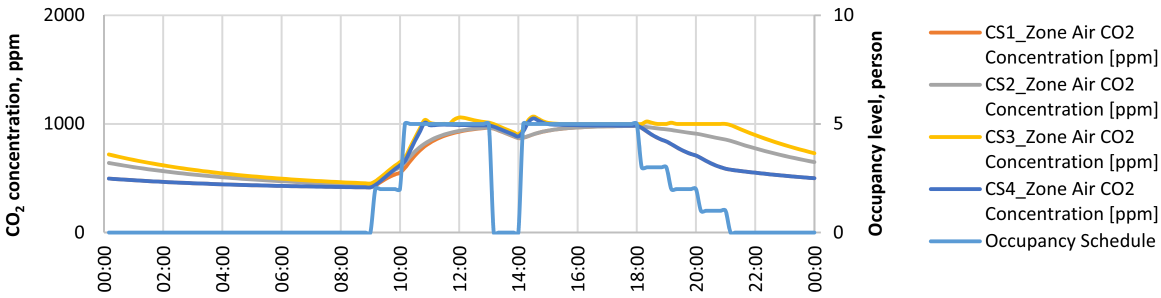

Fig. 2. Variation of CO_2 in the room associated to base ventilation strategies.

The chart above shows that using CS3, the occupants will be exposed to higher CO_2 concentration comparing with other strategies. Considering CS1 and CS2, the concentration in the room never reaches 1000 ppm in both of the strategies, while CS1 consumes 28 % more energy than CS2. CS4 shows a better performance in maintaining the room concentration below 1000 ppm comparing with CS3 but seems to have some unnecessary over ventilation during low density occupancy. Table 2 presents the results obtained from simulation such as maximum and average CO_2 concentration in the test office and the fan energy consumption associated to each strategy.

Table 2. The results from base ventilation strategies.

Control Strategy	Infiltration Rate, h^{-1}	Outdoor Airflow Rate, m^3/h.person	Zone Air Maximum CO_2 Concentration, ppm	Zone Air Average CO_2 Concentration, ppm	Fan Energy Consumption, kWh/day
CS1	0.2	24	981	833	0.0523
CS2	0.2	24	981	885	0.0408
CS3	0.2	24	1068	957	0.0387
CS4	0.2	24	1051	874	0.0419

The results from CS1 and CS2 presents the priority of real time occupancy-based strategy to the scheduled one with 22 % less energy consumption and providing almost the same IAQ level. Moreover, Fig. 3 presents a more practical view of these results in which CS3 can be indicated as the best suited strategy that provides acceptable IAQ for the occupants with lowest energy use.

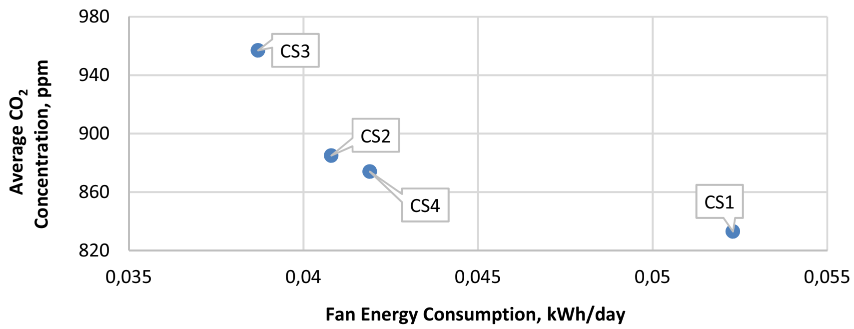

Fig. 3. Room average CO_2 Level and fan energy consumption for base ventilation strategies.

3.1. Sensitivity analyses

The first sensitivity analysis (SA1) considered in this research was changing the outdoor airflow rate from 24 to 20 m^3/h.person. All other parameters were maintained constant. This is to see how the energy consumption and IAQ are responding to these changes. Fig. 4 shows the variation of zone CO_2 concentration during the day. The concentrations in all strategies are slightly higher than those for the base situation. Although the time that occupants are exposed to concentrations higher than 1000 ppm is increased, still is not high enough to have negative influence on the occupants' comfort and productivity.

Table 3 shows the energy consumption, maximum and average CO_2 concentration level associated to each strategy as well as the energy savings and the IAQ drop. IAQ drop is the comparison between the average CO_2 concentration in sensitivity analysis strategies and the base strategies. The lowest IAQ drop and highest energy saving belong to CS3. In other strategies the IAQ drop is 7 % while the energy saving varies between 15–17 %.

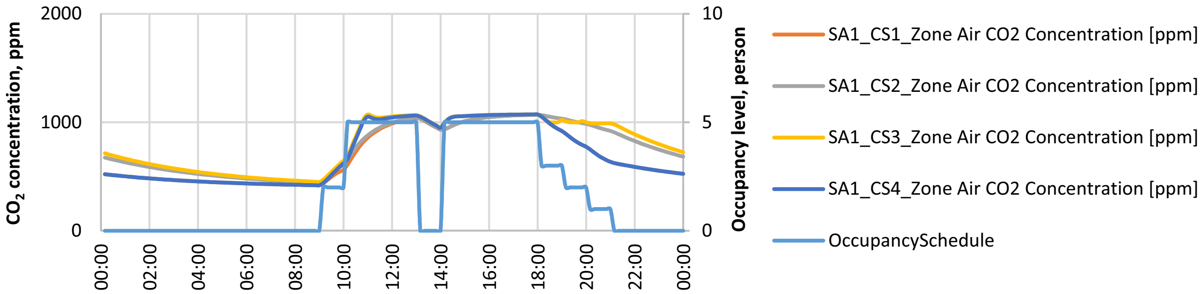

Fig. 4. Variation of CO_2 in the room associated to ventilation strategies after applying SA1.

Table 1. The results from ventilation strategies after applying SA1.

Control Strategy	Infiltration Rate, h^{-1}	Outdoor Airflow Rate, m^3/h.person	Zone Air Maximum CO_2 Concentration, ppm	Zone Air Average CO_2 Concentration, ppm	Fan Energy Consumption, kWh/day	Energy Saving Comparing with base strategies, %	IAQ Drop, %
SA1_CS1	0.2	20	1070	895	0.0435	17	7
SA1_CS2	0.2	20	1070	949	0.0340	17	7
SA1_CS3	0.2	20	1073	984	0.0310	20	3
SA1_CS4	0.2	20	1073	935	0.0356	15	7

In the second sensitivity analysis (SA2), besides changing the outdoor air flow from 24 to 20 m3/h.person, the infiltration rate was also modified, from 0.2 h^{-1} to 0.3 h^{-1}. All other parameters were maintained constant. Fig. 5 shows the variation of zone CO_2 concentration during the day which does not indicate a notable change in IAQ level comparing to the base strategies.

Table 4 shows the energy consumption, maximum and average CO_2 concentration level associated to each strategy as well as the energy savings and IAQ drop. SA2_CS2 and SA2_CS3 showed no changes in average CO_2 concentration while they had 17 % and 25 % lower energy consumption, respectively. The other two strategies also showed Energy savings up to 20 % and their IAQ drops are actually low and can be neglected. The results of SA2 revealed that increasing the infiltration rate will save fan energy while there would not be a noticeable change in IAQ.

Table 2. The results from ventilation strategies after applying SA2.

Control Strategy	Infiltration Rate, h^{-1}	Outdoor Airflow Rate, m^3/h.person	Zone Air Maximum CO_2 Concentration, ppm	Zone Air Average CO_2 Concentration, ppm	Fan Energy Consumption, kWh/day	Energy Saving Comparing with base strategies, %	IAQ Drop, %
SA2_CS1	0.3	20	1004	849	0.0435	17	2
SA2_CS2	0.3	20	1004	886	0.0340	17	0
SA2_CS3	0.3	20	1070	950	0.0290	25	0
SA2_CS4	0.3	20	1065	894	0.0336	20	2

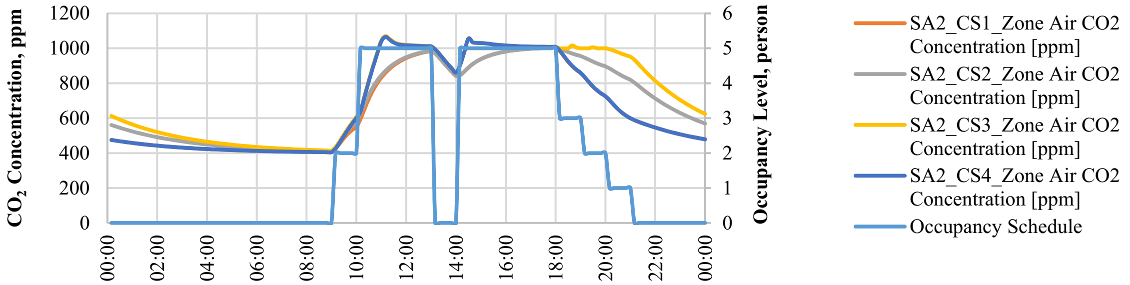

Fig. 5. Variation of CO_2 in the room associated to ventilation strategies after applying SA2.

Given to the CO_2 concentration graphs, there seemed to be some over ventilation during the low occupation density period in the evening. In the third Sensitivity analysis (SA3), the minimum setpoint in control strategy 4 has been modified to 800 pmm, to see how the results change with this modification.

Fig. 6 shows the CO_2 concentration and fan airflow rate in the zone during the day. As mentioned before, the over ventilation between 19:00 and 21:00 is observed. In the SA3_CS4, the fan stops almost two hours earlier than the CS4.

Moreover, table 5 exhibits the energy consumption and CO_2 concentration level associated to each strategy. The results show that increasing the minimum setpoint from 500 to 800 ppm leads to 15 % of energy saving and the daily average CO_2 concentration only increased 4 %. Also, by increasing the minimum setpoint to 900 ppm, the energy saving will increase up to 20 %.

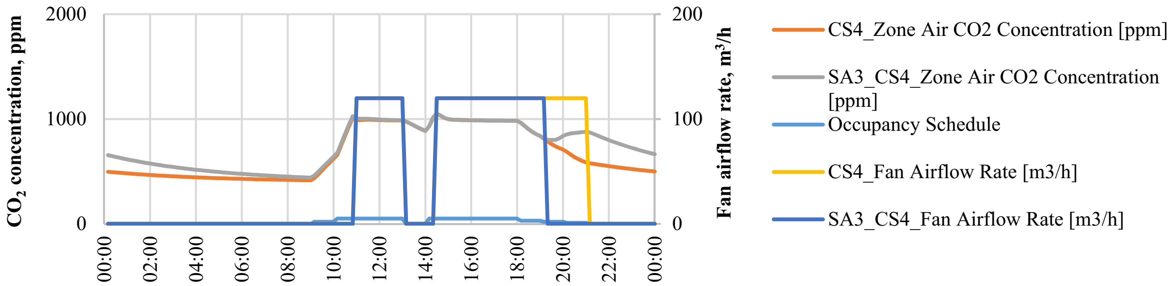

Fig. 6. Variation of CO_2 and fan airflow rate associated to CS4 before and after applying SA3.

Table 3. Comparison of the results from CS4 before and after applying SA3.

Control Strategy	Infiltration Rate, h^{-1}	Outdoor Airflow Rate, m^3/h.person	Zone Air Maximum CO_2 Concentration, ppm	Zone Air Average CO_2 Concentration, ppm	Fan Energy Consumption, kWh/day	Energy Saving, %	IAQ Drop, %
CS4	0.2	24	1051	874	0.0420	–	–
SA3_CS4	0.2	24	1052	906	0.0357	15	4

4. Conclusions

In this paper, four ventilation strategies have been defined based on occupancy schedule period, occupancy level and indoor concentration of CO_2 in an office room. The IAQ as well as the energy consumption levels associated to each strategy were evaluated through simulations performed using *EnergyPlus*. Three sensitivity analyses were also performed in order to assess the influence of different parameters on the energy consumption and IAQ. The main findings of the present study can be listed as following:

- A primary energy saving of 22 % was achieved from controlling the fan airflow rate based on the number of occupants instead of a fixed flow rate during occupancy period, while the IAQ level is kept acceptable;
- By decreasing the fan airflow rate per occupant, SA1_CS2 and SA1_CS4 showed the best integrated IAQ and energy performance, while SA1_CS3 presented the lowest consumption accompanying with an average CO_2 concentration, slightly over the setpoint, that could still be acceptable referring to some IAQ standards (e.g. Portuguese standard: Portaria n.º 353-A/2013 [16]);
- The third sensitivity analysis showed the importance of infiltration rate in providing acceptable IAQ with lower fan energy use (regardless the unforeseen influences on thermal comfort);
- Increasing the minimum setpoint for indoor CO_2 Concentration, made SA3_CS4 the best suited control strategy among all strategies in terms of both energy consumption and IAQ.

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