ENERGY PERFORMANCE AND INFECTION RISK EVALUATION OF RETROFITTED VENTILATION SYSTEMS IN TIMES OF COVID

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Abstract

The rapid escalation of the COVID-19 pandemic has highlighted the importance of efficient ventilation systems in reducing the risk of airborne transmission of the SARS-CoV-2 virus. This study evaluates the energetic performance and viral transmission characteristics of a low-cost mechanical extract ventilation system in comparison to alternative strategies in an educational context. The results show a significant improvement in indoor air quality combined with energy savings relative to natural ventilation strategies.

Introduction

The COVID-19 pandemic has underscored the importance of sufficient ventilation. In enclosed spaces with dense occupancy efficient ventilation strategies have become a vital criterion to reduce the risk of airborne transmission of the SARS-CoV-2 virus and to ensure a healthy indoor environment. Adequate ventilation can be realized either naturally, using window openings, or by mechanically driven fans. A report by the German TÜV association found that of 17,9 thousand mechanical ventilation systems tested in buildings such as schools, clinics and skyscrapers 34% of those had a serious deficiency (TÜV, 2021). The German Environment Agency (UBA) estimates that 90% of German schools are naturally ventilated (i.e. via windows) (UBA, 2021a). However, an ongoing study conducted by Munich University of Applied Sciences shows that less than 8% of naturally ventilated classrooms are aired regularly, i.e. every 20 minutes. On the contrary, most classrooms are only ventilated during breaks (i.e. once every 45-60 minutes) (Schwarzbauer, 2021). Hence, the number of educational buildings with defective mechanical ventilation systems and poor natural ventilation strategies shows a need for efficient technical measures to improve indoor air quality. Energy efficiency is also of vital importance when designing a ventilation system. The European Commission reports that ventilation units consume 2% of all electricity in the EU (EU Commission, 2022). As a result, the design and commissioning of mechanical ventilation systems should be adapted to the actual demand of the space; to meet both the requirements for energy efficiency as well as indoor air quality. This paper examines a number of widely used natural and mechanical ventilation strategies in comparison to a novel retrofitted mechanical extract ventilation (MEV) system (see Figure 1) developed by the Max Planck Institute for Chemistry (MPIC); as a way to minimize the risk of airborne transmission of the SARS-CoV-2 virus in naturally ventilated classrooms (Klimach et al., 2021). The MPIC-MEV system (Figure1) consists of an axial fan positioned in a window box that removes the stale indoor air, through extract hoods and ductwork, to the outside. The extract hoods are positioned above the occupants' desks to directly capture and remove respiratory aerosols before they are mixed into the ambient air. The ductwork consists of a main central duct (connected to the fan) from which smaller diameter ducts branch off to the extract hoods. In the process of this study four experimental rooms with different variants of the MPIC-MEV system were set up at the University of Technology in Graz. One room with a system almost identical to the system developed by the MPIC, is used as the primary focus of this study. The aim of this research is to examine the functionality of the MPIC-MEV system and to draw comparisons between various alternative ventilation approaches in relation to key performance characteristics, including energetic performance, thermal comfort, indoor air quality and airborne viral transmission infection risks. A decentralised air handling unit with heat recovery (AHU-HRV) and two natural ventilation strategies, using tilted windows (NV-T) and purge ventilation (NV-P), were used for comparison.

Figure 1: MPIC-MEV system installed in a TU Graz lecture room

Methodology

The energetic and thermal performance of the ventilation systems are evaluated using IDA ICE 4.8, 2020. Five different ventilation scenarios are examined based on a model of the same lecture room in which the original MPIC MEV system is installed.

The indoor CO$_2$ concentration is widely used as an indicator for indoor air quality (IAQ) (ASHRAE, 2018). In the context of the pandemic values in the range of 800 to 1000 ppm are considered to reflect good IAQ (CIBSE, 2021; REHVA, 2020).

Scenarios

Table 1 lists the five scenarios examined in this paper. Scenario 1 assumes an occupied classroom with infiltration and exfiltration but no active ventilation (base case). The second and third scenario look at mechanically ventilated rooms. Scenario 2 examines the MPIC MEV as installed in the experimental room. Scenario 3 investigates a decentralised air handling unit with heat recovery (AHU-HRV), with approximately the same nominal flow rate as in scenario 2. Technical data for scenarios 2 and 3 are taken from manufacturer specifications. The fan in scenario 2 has a maximum power consumption of 68 W and an air flow rate of 1100 m^3/h at maximum speed. The air handling (AHU) unit in scenario 3 has a recuperative heat exchanger with a thermal efficiency (EN 308) of 81 %. Supply air and exhaust air fans have a power consumption of 520 W each. The relatively high power input of the AHU fans is required to overcome the internal pressure drops (275 Pa each for supply and exhaust sides). The nominal flow rate is given by the manufacturer as 0,2 m^3/s (720 m^3/h) at a nominal external pressure of 200 Pa. For comparative purposes, both mechanically ventilated scenarios are operated under the same air flow rate depending on the ventilation demand (see section “*Ventilation rates*”).

Table 1: Scenarios and associated simulated air flow rates

Scenarios	Abbreviation	Explanation	Air flow rates (per unit internal floor area) Min [L/s/m²]	Max [L/s/m²]	Mean winter [L/s/m²]	Mean summer [L/s/m²]
1	BC	base case (infiltration only)	0,17 [d]	0,17	0,17	0,17
2	MPIC-MEV	mechanical extract ventilation [a]	2,90	4,45	4,43	4,43
3	AHU-HRV	air handling unit - heat recovery [b]	2,90	4,45	4,35	4,36
4	NV-T	natural ventilation - tilted windows	2,60	8,28	7,35	2,95
5	NV-P	natural ventilation - purge ventilation [c]	10,18	43,30	37,67	13,05

a) HV-300 AE (SOLER & PALAU 2022)
b) Topvex FC02 HWH-L-CAV WRG (Systemair GmbH 2022)
c) During purge period (4 - 15 min)
d) n$_{inf}$ = 0,17 L/s/m²

Scenarios 4 and 5 examine natural ventilation strategies. In case of scenario 4 all windows were tilted during the entire occupation period. Scenario 5 provided purge ventilation in 20 minutes intervals through fully opened windows as suggested by the German environment agency (UBA, 2021b). In winter, the windows were opened every 20 minutes for 4 minutes and in summer, for 15 minutes respectively. The room was occupied from 8 a.m. till 12 a.m. and from 1 p.m. till 5 p.m. (in all scenarios). Lighting and equipment followed the same schedule. As the MPIC-MEV was controlled by occupants with an electronic speed controller, the ventilation system was only operating in occupied periods. For scenario 3 the air change rate was set to 0,5 h^{-1} 2 hours prior to occupation from 6 a.m. to 8 a.m. (EN 16798-1, 2019). This set-back rate was also set for unoccupied periods during lunch breaks from 12 a.m. to 1 p.m.

Simulation model

An IDA ICE (version 4.8) dynamic simulation model of the lecture room with a floor area of 48,3 m^2, a height of 3,05 m and a volume of 147,3 m^3 was created. In order to reflect the long-term mean climatic conditions (1991-2019) in this location a reference year weather file was generated using the Meteonorm (version 7.2) software. This enabled an assessment of the typical long-term energetic performance of the lecture-room. Information about dimensions, construction components and building services were taken from construction drawings and checked on site. The building was heated by means of district heating. The heating set point was specified as 20 °C. The external wall with an area of 23,9 m^2 facing southwest had a heat transfer coefficient of 0,33 W/(m^{2}K). 32% of the external wall area consisted of windows with a heat transfer coefficient of 2,00 W/(m^{2}K) and a solar heat gain coefficient of 0,6. The infiltration rate is set to a constant value of 0,22 air changes per hour (ach), which corresponds to a building airtightness of approximately $n_{50} = 3\ h^{-1}$.

The energy produced by metabolic activity due to occupancy was defined as 70 W/m^2 per person (ISO, 2005). Assuming an adult body surface area of 1,8m^2 the total sensible heat gains due to occupancy resulted in 126 W per person. The energy consumption for the lighting was set to 400 W, based on the lamps used in the lecture room. In addition the room was equipped with a projector with a power consumption of 150 W.

Measurements from a thermal and rotating vane anemometer (with measuring cone) were used (respectively) as boundary conditions in the simulation for air speed and volumetric flow rates. The latter confirmed an air flow rate of 780 m^3/h at the highest fan speed.

Ventilation rates

The MEV system's ventilation rates are designed in accordance with EN 16798-1:2019 (CEN). Assuming a standard CO_2 emission rate of 20 L/(h per person) for sedentary activity, the default design CO_2 concentrations (above outdoor concentration) of 550 m^3/h for category 1 and 800 m^3/h for category 2 are used (CEN, 2019). These values correspond to a total indoor CO_2 concentration of less than approximately 950 ppm for category 1 and 1200 ppm for category 2. Using these indoor CO_2 concentrations as limits, the required air exchange rate to reach an equilibrium concentration could be determined according to the standard ISO 16000-26:2012 (ISO, 2012). A desired air flow rate of 750 m^3/h is used for 20 occupants (i.e. 10 L/(s per person), thus fulfilling the criteria for category 1. For 30 occupants the design air flow rate matches the category 2 limit (CEN, 2019). For 10 occupants the ventilation rate was reduced to 500 m^3/h to maintain energy efficiency while still ensuring a sufficient per capita air flow of 14 L/(s per person).

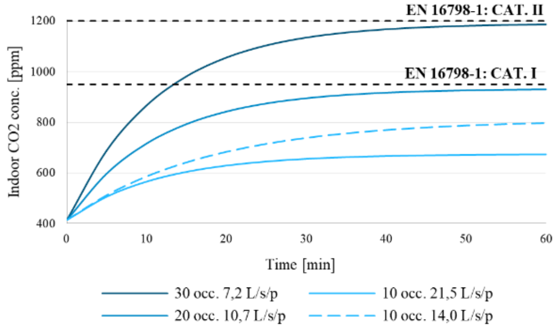

Figure 2: CO_2 *increase over time for ventilation rate of 780*m^3*/h and reduced rate (dashed line) of 500*m^3*/h*

To ensure comparable IAQ, air flow rates of 780 m^3/h for 20 and 30 occupants as well as 500 m^3/h for 10 occupants were implemented in the simulation models for both mechanically ventilated scenarios (2 and 3). Figure 2 shows the increase in indoor CO_2 concentration over time for the obtained and the reduced ventilation rates and compares these concentrations to the EN 16798-1:2019 (CEN) threshold limiting values.

Risk assessment

The infection risk for the SARS-Cov-2 virus was calculated with an analytical model (Lelieveld et al., 2020) using the number of infectious respiratory aerosol particles inhaled to derive a personal infection risk for each individual in the room. The time depending airborne virus concentration in the room and the corresponding number of virus particles inhaled per person was calculated conservatively for an example day under summer conditions (30th of June). This date was chosen due to the fact that natural ventilation air exchange rates are typically lowest during this time. Assuming that (for the Delta variant of the SARS-CoV-2 virus) around 230 inhaled virus particles corresponds to an infection probability of 50% (Max-Planck-Institut für Chemie, 2021) the individual infection risk for each susceptible person could be determined. To determine the viral emission intensity, a viral concentration of 6,72 particles per litre of exhaled air with a respiration rate of 10 L/min was assumed (Lelieveld et al., 2020). Using an aerosol measuring device (Helleis et al., 2022) showed that under winter conditions the MPIC-MEV system removed between 30% to 60% of potentially infectious aerosols by the means of extract hoods before they were mixed into the room air, thus significantly decreasing the emission intensity. Under summer conditions this value is reduced to around 25% (due to weaker stratification effects). In accordance with Helleis et al. (2022), this effect is taken into account in the effective emission rate. Therefore, in scenario 2 it was, assumed that the effective emission rate is reduced by 25%. Since the use of hoods is unique to the MPIC system the effective emission rates of the other ventilation strategies were not modified. It should be noted here that the 'hood-capture effect' described here is not the same as the vertical displacement effect (which occurs as a result of buoyancy driven air-flows in the room). Since the buoyancy effects were not quantified in this study they were omitted from the infection models of all systems. The calculations were performed for classroom conditions assuming no usage of face masks using the volumetric flow rates determined by IDA ICE.

Results and discussion

Energy consumption

The annual final energy consumption (for heating, lighting, projection equipment and ventilation) was calculated for all scenarios as a function of the occupancy rate. Final energy is an important metric in the context of educational buildings since it directly reflects the metered energy consumption which the end-user pays for and forms part of the operational energy rating used in Display Energy Certificates (DECs), mandated under the EPBD. As expected, increasing occupancy resulted in a proportionate decrease in final energy consumption for each scenario (Figure 3). The results showed an average final energy consumption of 33 kWh/(m^2a) (Scenario 1); 71 kWh/(m^2a) (Scenario 2); 51 kWh/(m^2a) (Scenario 3). In the two naturally ventilated scenarios, the final energy consumption was significantly higher at 82 kWh/(m^2a) (Scenario 4) and 70 kWh/(m^2a) (Scenario 5) respectively.

Lighting and projector equipment contributed to an electrical energy demand of 13,3 kWh/(m^2a) for all scenarios. The electrical energy demand of the fans resulted in 1,0-1,5 kWh/(m^2a) for scenario 2 and 5,3-11,0 kWh/(m^2a) for scenario 3. The increased consumption in scenario 3 resulted from the higher fan power of the air handling unit.

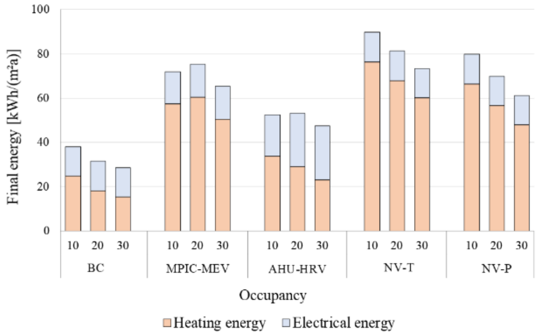

Figure 3: Final energy (heating and electrical) consumption [kWh/m^2a] for the five scenarios with three different occupancy levels (n=10, 20, 30)

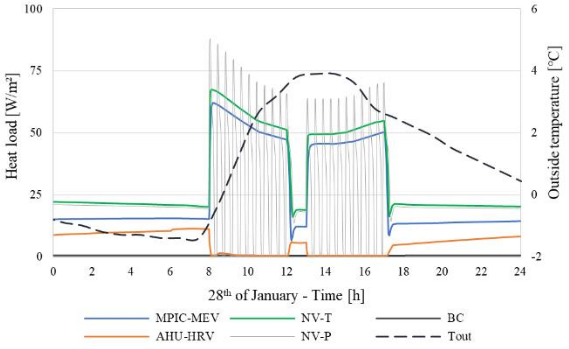

Figure 4: Heating load density [W/m^2] for 20 occupants on the 28th of January

Figure 4 shows the heating load for a typical day in January. Scenario 1 shows that transmission heat losses were completely compensated for by internal heat gains when no ventilation measures were taken. Furthermore, it was found that the heating load (during the occupied period) despite higher internal heat gains, increased significantly for all scenarios without heat recovery (2,4,5). In scenario 3, there was also no heating demand during occupied periods due to the heat recovery.

Indoor climate

Figure 5 shows the operative temperature of the room for 20 occupants over the coldest occupied day of the year. In the base case (scenario 1) the operative temperatures increased up to 24 °C during occupation as there were no ventilation heat losses. For the mechanically ventilated cases (scenarios 2 and 3) the operative temperatures showed steady values throughout the whole day. With an operative temperature of 19°C scenario 2 maintained acceptable thermal conditions. This was due to the demand-oriented ventilation rates combined with the high internal heat gains from the 20 occupants. In scenario 3, the temperatures rose to a constant value of 21°C during the coldest day of the year and thus ensured a comfortable thermal state. The natural ventilation scenarios (4 and 5) showed colder temperatures overall, indicating a loss of thermal comfort (Eibinger et al., 2022). For scenario 4, the operative temperatures ranged from 16°C-17°C. Scenario 5 displayed very high fluctuations with temperature amplitudes ranging from 11°C-22°C, as a result of the purge-vent cycles.

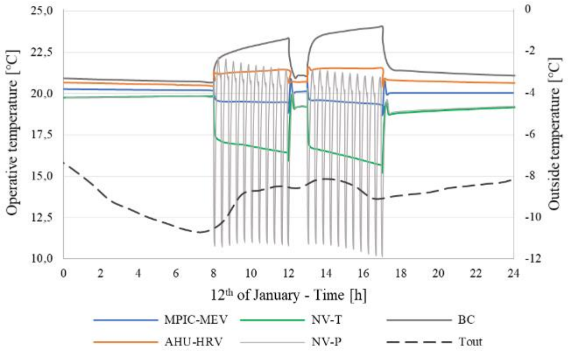

Figure 5: Operative temperature [°C] for 20 occupants on the 12th of January (coldest day)

Figure 6 shows the development of the indoor CO_2 concentrations over the coldest and warmest occupied days of the year. Scenario 1 showed that the CO_2 concentration would increase to over 10000 ppm during an 8-hour period without active ventilation. As scenarios 2 and 3 are mechanically driven by fans, the indoor CO_2 concentrations displayed consistent values of about 950 ppm over the whole year. It should be noted however, that the DSM model and the CO_2 outputs do not include the direct extraction (hood effect) nor the displacement effects of the MPIC-MEV system. Scenario 3 showed a decrease in indoor CO_2 concentration during the lunch break in comparison to scenario 2. This is because the AHU ventilation in scenario 3 continued to run in set-back mode (at 0,5 air exchanges per hour) during the breaks. Due to the high temperature differences between outside and inside on winter days, higher natural ventilation rates were achieved. However, this effect was reduced in warmer months. Hence, the indoor CO_2 concentrations for scenario 4 ranged from 700 ppm in January to values of 1350 ppm in June, and therefore, did not comply with category 2 of EN 16798-1:2019 during the summer months (CEN, 2019) Scenario 5 showed high variations for the indoor CO_2 concentrations, as a result of the purge-vent cycles, with values ranging from 600 to 1600 ppm.

Although, the inside/outside temperature difference was smaller in summer, the maximum CO_2 concentration for 30th June did not increase significantly in comparison to the 12th January. The reason for this was the longer purge ventilation duration of 15 minutes every 20 minutes in summer.

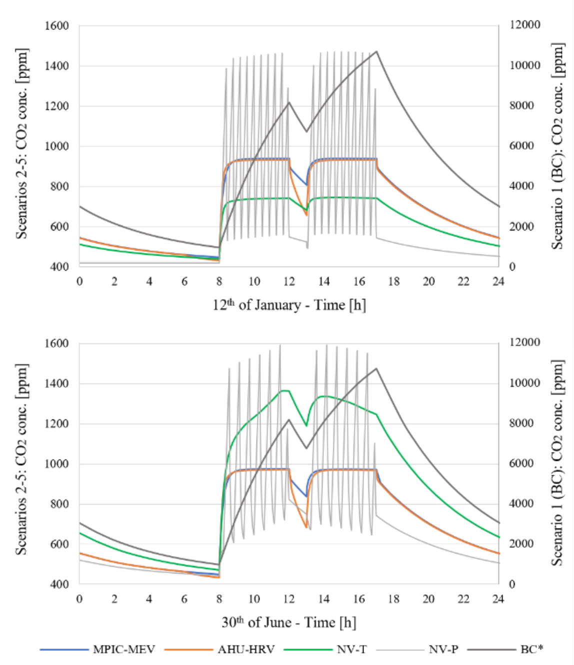

*Figure 6: Indoor CO_2 concentration† [ppm] for 20 occupants on 12th January (coldest day) and 30th June (warmest day). †NB the CO_2 values shown ignore displacement and hood capture effects. * NB Base Case (Scenario 1) shown on the secondary axis.*

Infection risk

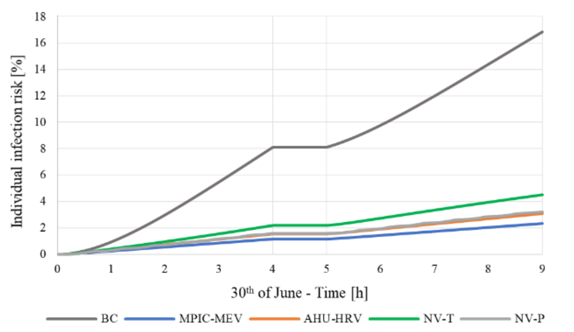

Figure 7: Individual infection risk over the duration of one operational day in June

Table 2: Infection risk [%] after 8 hours' exposure

Infection risk	BC	MPIC-MEV	AHU-HRV	NV-T	NV-P
Individual	17	2	3	4	3
20 occupants	97	36	45	58	46
30 occupants	100	49	59	74	61

Figure 7 and Table 2 show how the different ventilation strategies affect the probability of infection during summertime, depending on the exposure time and the various air exchange rates. The risk of a COVID-19 infection risk for any one individual in the room over an exposure duration of 8 hours with a one-hour break in between can be seen in Figure 7. In addition to the individual infection risk, Table 2 illustrates the combined probability of at least one susceptible person becoming infected in a group of n=20 or n=30 people. In the calculation it was assumed that only one person was infectious, and the other occupants were all susceptible and unmasked.

The results show the highest individual risk of infection for scenario 1 with 17 %, as there is no active ventilation in the base case. Based on an occupancy of 30 persons in the room there is a risk of 100 % that one person would get infected. Scenario 2 showed the lowest individual infection risk with 2 %. This corresponded to a risk of 49 % that one out of 30 people present in the room would become infected. Despite the same air exchange rate, the AHU-HRV (scenario 3) had a higher individual infection risk of 3 % and a consequential risk of 59 % that one among 30 occupants would be infected. This was due to the reduced emission intensity caused by the distributed extraction of potentially infectious aerosols by the MPIC-MEV system extract hoods.

On the other hand, natural ventilation with tilted windows (scenario 4) displayed an individual infection risk of 4 % resulting in a combined risk of 74% that one out of 30 people would become infected (during an 8-hour period) and thus showed the highest infection risk among the ventilated scenarios in summer conditions. Purge ventilation (scenario 5) showed an individual daily infection risk of 3%. This corresponded to a combined risk of 61 % that one in 30 occupants would get infected.

Summary

As expected, scenario 1 (without any ventilation system) has the lowest energy consumption but does not provide sufficient air flow for adequate IAQ and to ensure protection against COVID-19 infections.

In scenario 2 the (MPIC-MEV) system performs well with respect to energy consumption particularly in comparison to the two naturally ventilated scenarios. This is due to the targeted control of the ventilation according to the actual demand rather than by means of natural driving forces. In addition, scenario 2 performs well with respect to IAQ, maintaining constant CO_2 values over the whole year. Moreover this scenario shows the lowest risk of infection under summer conditions, as a result of the enhanced aerosol extraction capability of the extraction hoods. It should be noted that under winter conditions the aerosol removal capacity of the hoods is significantly higher (circa 50%). Moreover, the infection risk model used here excludes the room air displacement effects which will be most pronounced in the case of the MPIC-MEV system and can improve the system performance by up to approximately 50% (Helleis, 2022).

In scenario 3 the (AHU_HRV) system results in a comparatively small heating demand due to the use of air-to-air heat recovery but consumes more electrical energy in the process. The overall final energy consumption is, nevertheless, smaller than with the other ventilation strategies. Due to the demand based regulation of the air flow rates of the AHU-HRV (scenario 3), satisfactory IAQ and a low risk of infection are observed here as well. However from a capital expenditure perspective this type of system is significantly more expensive than the alternatives.

In scenario 4 the (tilted window) system achieves the lowest CO_2 concentrations in colder periods at the expense of the highest energy consumption and a loss of thermal comfort due to higher air exchange rates. During the summer months, when the temperature difference and the resulting air exchange rate is smaller, it is not possible to achieve sufficient indoor air quality with tilted windows alone. Therefore, scenario 4 shows a comparatively higher probability of COVID-19 infection in the warmer months.

In scenario 5 the (purge ventilation) system results in operative temperatures and indoor CO_2 concentrations that are quite unstable throughout the year, indicating a loss of thermal comfort and variable IAQ. However, the use of shorter purge-ventilation times in winter can save a considerable amount of energy in comparison to using tilted windows (scenario 4).

Conclusion

This paper presents the impact of different ventilation strategies on energy performance, thermal comfort, indoor air quality and viral transmission.

The results of this study show that the MPIC-MEV system provides a viable low-cost solution for retrofitted spaces using natural ventilation. The system achieves a significant improvement in indoor air quality whilst enhancing the removal of aerosol particles. However mean indoor temperatures during winter are likely to be lower than an AHU-HRV system unless additional heating is used.

The findings of this study support recommendations for promoting the use of purge ventilation for natural ventilated spaces (UBA, 2021b) to help improve indoor air quality. However, maximum indoor CO_2 concentrations of up to 1600 ppm are reached several times a day. Likewise ventilation with tilted windows displays a comparatively high CO_2 concentration in warmer conditions. Thus, both natural ventilation strategies examined here do not fulfil the target limiting values of 1000 ppm proposed by international directives (CIBSE, 2021; REHVA, 2020).

The application of dynamic simulations using building data together with empirical infection models opened up a comprehensive way to assess information on energy, thermal comfort, and infection risks under the realistic assumption of transient boundary conditions.

Future work

Future work will investigate the environmental impacts and primary energy usage of the natural and mechanical ventilation systems over all life cycle stages. Computational fluid dynamics (CFD) simulations will also be used to gain a better insight into local airflow and infection risk characteristics.

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