Mitigation of airborne contaminants dispersion in an educational building and investigate its impacts on indoor air quality and energy performance

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Abstract. In today's modern world, people spend most of their time inside buildings, highlighting the importance of indoor air quality (IAQ) and providing clean air to the occupants. In this regard, a simple educational building is modeled using CONTAM-EnergyPlus co-simulation to investigate IAQ enhancement strategies and their role in the building's energy performance. Three contaminants, including CO_2, PM2.5, and SARS-CoV-2, are considered to be generated from various sources. The occupants generate CO_2, a source of PM2.5 is assumed in the lunchroom to represent cooking activities, and a person who sheds SARS-CoV-2 moves around the zones. The main goal of this study is to apply various pollutant mitigation methods to the model, such as increasing ventilation rate and outdoor air (OA) percentage, natural ventilation, installing filters and air cleaners, and UVGI lights. Then, their performance and impact on the defined contaminants are studied individually and in combination.

In this regard, a scenario with 80% outdoor air (OA) and 100% ventilation rate has been shown to be effective in reducing all three contaminants' concentrations to acceptable levels in most zones, but this results in 50% higher energy consumption compared to the model with no outdoor air. However, to achieve a safe level of PM2.5 in the lunchroom, a combination of all the strategies presented in the (0.8OA+1Vent+NatVent+all) scenario is required. Furthermore, HEPA air cleaners are more effective in diluting contaminants in all zones than UVGI lights and MERV 13 filters. Additionally, this study has shown that HVAC systems operating with little or no outside air can increase the risk of pollutants being transmitted between adjacent zones through the ducts, making it necessary to install in-duct filters.

Keywords: Indoor air quality; CONTAM-EnergyPlus; Contaminants controlling strategies; Energy performance; Educational building

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1. Introduction

Nowadays, the improvement of indoor air quality (IAQ) and energy performance in buildings has become one of the most important factors in refurbishment and construction projects. This is especially true after the recent outbreak of the Coronavirus, where providing a clean and healthy environment inside various types of buildings has been put in the spotlight to protect occupants from airborne diseases and prevent the buildings from shutting down during the pandemic.

Educational buildings, in particular, require a high-quality indoor environment due to their high occupancy. This, in turn, can put everyone in danger of serious health problems. In other words, the lack of indoor fresh air in educational buildings can exacerbate different respiratory (M. Simoni et al., 2010; Mentese et al., 2020) and cardiovascular diseases (Brook et al., 2010), especially in the younger generation, as they spend most of their time at schools and universities.

Several strategies have been proposed to maintain high levels of IAQ in enclosed environments, including educational buildings. Ventilation is one of the most critical factors that affect a place's safety in terms of IAQ and preventing the spread of airborne contaminants. Bhagat et al. (2020) investigated the impact of ventilation on the spread of contaminants, particularly the SARS-CoV-2 virus, in indoor

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environments.

Ventilation can be provided through natural, mechanical, or hybrid methods (a combination of natural and mechanical ventilation). Therefore, some of the suggested methods for controlling the dispersion of contaminants inside a building depend on the type of ventilation in that place. For example, in a naturally or hybrid ventilated room, occupants must improve IAQ by opening windows to keep CO_2 levels below 1000 ppm, which is an indicator of acceptable ventilation. In mechanical ventilation, supply and return airflows can be precisely measured to maintain the required IAQ level without requiring any action from the occupants (Mentese et al., 2020).

However, this does not mean that in a mechanically ventilated place, occupants cannot affect their level of safety with their actions. In other words, if the ventilation rate is insufficient, the occupants can protect themselves from various diseases by wearing masks or maintaining social distance, as was done during the COVID-19 pandemic.Furthermore, providing adequate mechanical ventilation in the buildings becomes more significant, especially during winter. Natural ventilation would be very minute due to the cold weather, keeping thermal comfort and heating costs. Therefore, all the pressure of renewing the air would be on mechanical ventilation (Di Gilio *et al.*, 2021).

In this regard, several organizations, such as the Federation of European Heating, Ventilation, and Air Conditioning Associations (REHVA) and the American Society of Heating, Ventilating, and Air-Conditioning Engineers (ASHRAE), have presented guidelines and recommendations concerning the ventilation of public places to improve the health level inside them (Aguilar et al., 2022). For instance, REHVA suggested installing sensors to warn of CO_2 concentration levels inside classrooms equipped with natural or hybrid ventilation systems, to help occupants recognize the right time to open doors and windows constantly for fresh air. In closed spaces, most of the CO_2 in the air is generated by people's exhalation, and its increase in comparison to outdoor CO_2 levels leads to an increased probability of airborne disease transmission due to inhaling infected occupants' exhaled particles (Rudnick and Milton, 2003; Peng and Jimenez, 2020). In addition to CO_2 levels, methods to measure ventilation metrics, such as Air Changes per Hour (ACH) and Ventilation Rate (VR), include airflow measurement (Fenner et al., 2018) and comparison of indoor-outdoor gas concentration (Kibert, 2013), which are used to analyze the ventilation inside the building to determine whether it is adequate.

In recent years, the number of research studies focused on the ventilation of buildings and enhancing the Indoor Air Quality (IAQ) to mitigate the dispersion of contaminants has dramatically increased. This increase is not surprising, considering the hard times all human beings have experienced during the coronavirus pandemic. In this context, many researchers have particularly investigated the safety of educational buildings, where many juveniles gather together for hours in relatively limited spaces such as classrooms, and are prone to several health problems due to the spread of airborne contaminants. Aguilar et al. (2022) assessed the ventilation systems inside educational buildings in Spain and Portugal by applying various ventilation methods and estimating CO_2 concentration and VR. This research mentioned that many educational buildings in Europe are not equipped with mechanical ventilation; thus, natural ventilation is the predominant solution to keep the air clean. Finally, they concluded that the CO_2 level could significantly vary by implementing different ventilation methods and proposed acceptable amounts of CO_2 for various ventilation configurations to maintain a low risk of infection.

In another project, Di Gilio et al. (2021) conducted an experimental study in nine schools in Italy to investigate the role of air ventilation in preventing COVID-19 transmission by real-time monitoring of the CO_2 level. They reported this method as an effective way to achieve the study's goal. Another real-case study concerning the refurbishment of an Italian university building was conducted by Ascione et al. (2021) to enhance the quality and safety of classrooms during the pandemic. They proposed various scenarios to improve HVAC and air distribution systems and utilize specific equipment. Furthermore, Burridge et al. (2022) presented a method to assess the risk of infection in places where the same people gather daily, such as open-plan offices or school classrooms. Their study calculates the number of infected people in the presence of one infected occupant and is applicable to data obtained either by modeling or monitoring the CO_2 level.

Various building simulation tools have recently been developed to assist engineers in analyzing and designing energy-efficient, comfortable, and safe buildings or finding the best method to retrofit existing buildings. Some tools provide the building's geometric and graphical design, known as Building Information Modeling (BIM) tools, such as SketchUp and Revit. Others are used for energy simulation and analysis, known as Building Energy Simulation (BES) tools, such as EnergyPlus and eQUEST (Del, Gonzalo, and Ferrandiz, 2019).

This study uses three simulation tools, including EnergyPlus, SketchUp, and OpenStudio, to simulate and analyze an educational building in the UK to enhance its Indoor Air Quality (IAQ) and energy performance. EnergyPlus was developed by the Department of Energy (DOE), USA, as a console-based program that reads and writes only text files. EnergyPlus does not have a visual interface for graphical design; therefore, SketchUp is used as the interface to provide 3D models of buildings. OpenStudio is another interface for EnergyPlus that is utilized as a SketchUp plug-in.

Furthermore, this study uses a multi-zone indoor air quality and ventilation analysis computer program called CONTAM 3.2 to model the airborne contaminants inside the building. CONTAM can be coupled with EnergyPlus, and various data, such as schedules, ventilation/infiltration airflow rate, output variables, zone temperatures, and outdoor environmental data, can be exchanged. This coupling is performed using CONTAM's previously developed inter-process communication application programming interface (API) (Dols and Polidoro, 2015). In the new version of this software, the gradient concentration of the contaminant within a given zone under steady, transient, or cyclic states can be simulated using the "short time step method" (Dols and Polidoro, 2015).

Moreover, a single part of the case study can be considered a Computational Fluid Dynamics (CFD) zone in CONTAM to calculate the three-dimensional pressure, airflow, and contaminant concentration fields within the CFD zone (Dols and Polidoro, 2015). However, performing multi-zonal modeling by assuming the zones are well-mixed would be more efficient as it takes less time for simulation and computing (H.E. Feustel, 1992; Feustel, 1999; Gao, 2002; Villi, Pasut, and Carli, 2009; Trocme et al., 2011; Jose, Pérez, and Gonzalez-Barras, 2021). Also, different contaminant transmission mitigation strategies, such as mask-wearing, portable High-Efficiency Particulate Air (HEPA) air cleaners in high-occupancy zones, Minimum Efficiency Reporting Value (MERV) filters, ultraviolet germicidal irradiation (UVGI), and increasing the outdoor air (OA) percentage of the air delivered by the HVAC system (Shrestha et al., 2021), can be modeled in the simulation procedure by CONTAM.

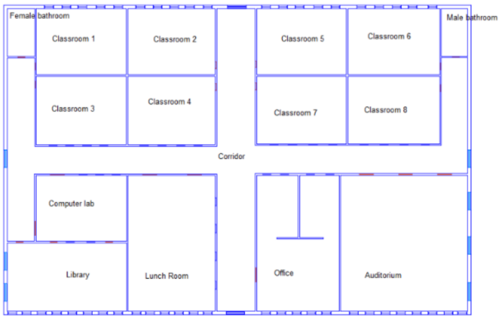
In this context, Shrestha et al. (2021) and Yan et al. (2022) conducted research using CONTAM to study SARS-CoV-2 aerosol transmission inside office buildings. In these studies, they assumed all zones to be well-mixed. They compared various infection risk mitigation strategies that could be applied in the building and finally selected the best options based on their impact on contaminant dispersion control. A similar study using CONTAM was conducted by Emmerich et al. (2013) to reduce the infectious risk in a healthcare center. In this project, the current guidelines to control the transmission of contaminant pathogens in hospitals were investigated, and better solutions were presented to meet this goal. In another study, Pease et al. (2021) investigated the impact of indoor and outdoor infection sources by conducting multi-zonal well-mixed modeling and concluded that air handling units with no filtration could increase infection in connected rooms.

The objective of this paper is to evaluate various contaminant dispersion scenarios inside a mechanically ventilated educational building in the UK and apply some transmission control strategies to determine the most effective solution for mitigating the spread of contaminants and minimizing energy consumption. Three contaminants are selected for the study: CO_2, SARS-CoV-2, and PM2.5. To create a more realistic scenario, it is assumed that all occupants generate CO_2. Additionally, a source of PM2.5 is assumed in the lunchroom as a representation of cooking activities, and a person shedding SARS-CoV-2 moves around the zones.

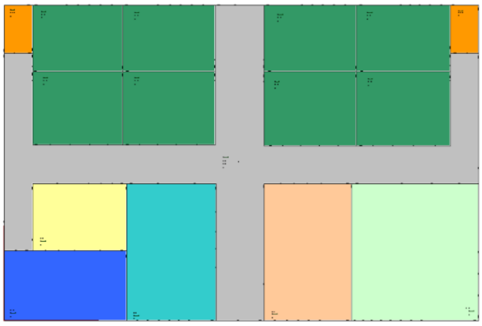
2. Methodology

2.1 Case study

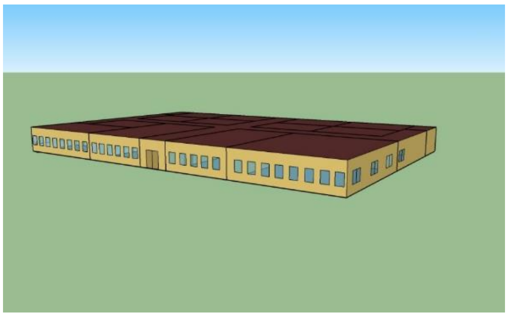
In the current study, a single-floor school is considered as the case study. Fig. 1 shows the floor plan and the model of the building in CONTAM and Sketchup. As illustrated in Fig. 1 (a), this building consists of eight classrooms, a computer lab, a lunchroom, an auditorium, an office, a library, a corridor, and two bathrooms, all located on the ground floor. The total floor area of the building is 1572 m^2, and the ceiling height is 3.4 m. An Air Handling Unit (AHU) with supply and return diffusers operates as mechanical ventilation to provide clean air in all zones. Moreover, two exhaust fans are implemented in the bathrooms to provide additional ventilation to these spaces.



(a) Floor plan of the building



(b) Building model in CONTAM



(c) Schematic of the building in Sketchup

(d) Inside view of the building in Sketchup

Fig. 1 floor plan and the model of the building in CONTAM and Sketchup

2.2 Simulation and inputs

As previously mentioned, at the initial stage of this study, EnergyPlus was used to simulate the building and analyze its thermal performance in order to create a reference model for further comparison and provide input data for CONTAM modeling. The building's simulation using EnergyPlus involves three steps, as shown in Fig. 2. According to Fig. 2, a 3D model of the building is created in Sketchup, which is then exported to OpenStudio to specify the building's materials and construction (Abbaspour et al., 2022). Fig. 1(c) and 1(d) depict the schematic of the school modeled in Sketchup. Finally, the building's spatial information modeled in OpenStudio is exported to EnergyPlus as an "IDF" file. As a result, EnergyPlus can calculate the building's energy consumption due to heating, lighting, ventilation, and other factors.

It should be noted that EnergyPlus has an "internal network" feature for calculating building loads due to ventilation. However, this feature is not suitable for multi-zone modeling of contaminants spread inside the building (Yan et al., 2022). Three types of internal gain sources are defined in EnergyPlus: people, light, and electric equipment. Table 1 shows the input parameters for the electric equipment of the building. Additionally, Table 2 depicts the lighting levels for each zone per square meter. All the lighting is considered to be LED lights.

Table 1 Input parameters for the electric equipment

Equipment	Power (W)	Quantity	Zone
Computer	130	35	Computer lab- classrooms- office- library- auditorium
Printer	45	5	Office
Photocopy	180	4	Office- library
Telephone	20	5	Office
Video Projector	280	10	Classroom- computer lab- auditorium
CCTV	125	18	All zones except bathrooms
WiFi router	10	14	All zones except bathrooms
WiFi server	180	1	Computer lab
Finger print	10	1	Corridor
Refrigerator	200	1	Lunchroom
Microwave	600	1	Lunchroom
Oven	4000	1	Lunchroom

After simulating the school's energy performance using EnergyPlus, the next stage involves conducting multi-zonal modeling in CONTAM to analyze indoor air quality (IAQ) and investigate the spread of contaminants inside each zone. Fig. 1(b) shows the school's model in CONTAM. In this modeling, all zones are assumed to be well-mixed, so the concentration of contaminants, temperature, and airflows are constant in every part of the rooms.

The HVAC system modeled in CONTAM contains an air handling unit (AHU), which is defined as the mechanical ventilation of the zones and operates at a constant rate during working hours (from 8 am to 5 pm). For the worst-case scenario (baseline model), the AHU operates at 10% of its calculated capacity, and the percentage of outdoor air (OA) is considered to be 0% to investigate and analyze the impact of ventilation rate and OA increase on mitigating the spread of contaminants.

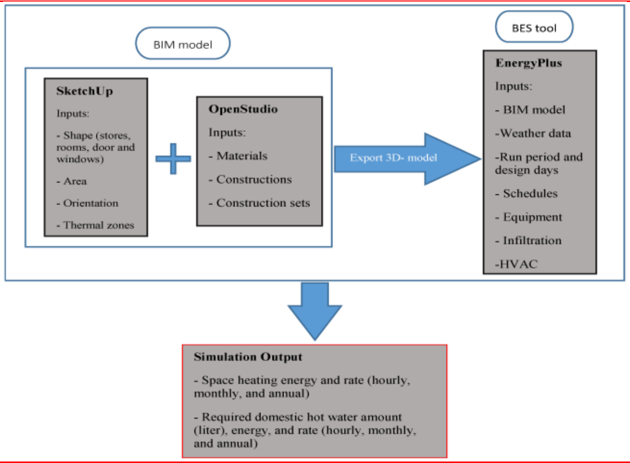


Fig. 2 Three main stages of building modeling in EnergyPlus (Abbaspour et al. 2022)

In addition, infiltration through interior and exterior walls via leakages is defined in CONTAM as airflow paths in three elevations (divided into three portions) in order to accurately capture the stack effect (Ng et al., 2019). The infiltration and exfiltration flow rates (Q) due to these leakages are calculated in CONTAM using a power law equation.

$$Q = \frac{C_D A_L}{10000} \sqrt{\frac{2}{\rho}} (\Delta P_r)^{0.5-n} \Delta P^n \qquad (1)$$

Where C_D is flow discharge coefficient, A_L is leakage area, ρ is the air density, ΔP_r is the reference pressure difference, ΔP is the indoor-outdoor pressure difference, and n is the flow exponent. Fig. 3 depicts part of the CONTAM model drawn on its graphical interface (ContamW), and some of the parameters used in the modeling are described in the figure.

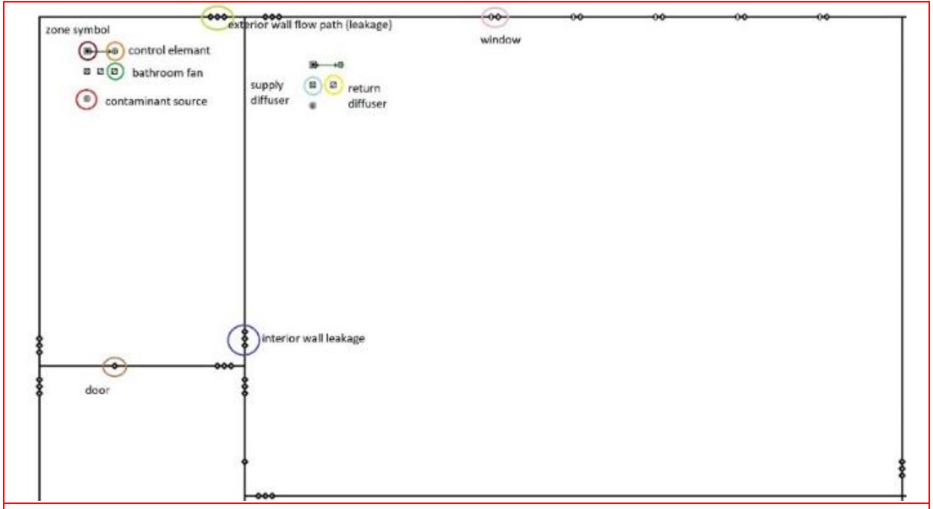


Fig. 3 Parameters defined in CONTAM modeling

During the EnergyPlus-CONTAM co-simulation, some of the results of the EnergyPlus simulation, such as hourly temperatures, occupancy and operation schedules, and ventilation rates of the zones, are passed to CONTAM using a Continuous Values File (CVF). Fig. 4 illustrates the occupancy schedules of all the zones used in the simulation. Additionally, Table 2 shows the maximum number of occupants and area of each zone.

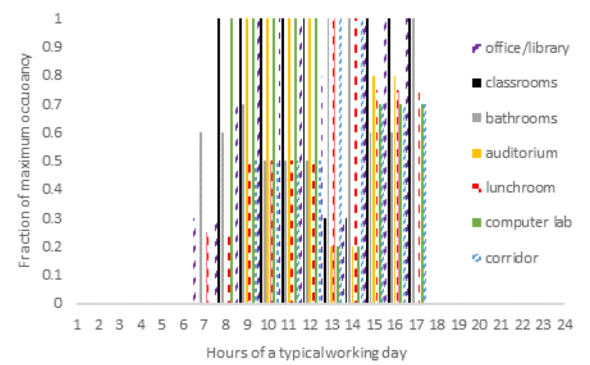


Fig. 4 Occupancy schedules of all the zones

This research considers three contaminants: a gaseous contaminant (CO_2), a particle pollutant (PM 2.5), and a biological contaminant (SARS-CoV-2 virus). The rationale for choosing these contaminants is based on their significance in affecting indoor air quality and their potential impact on the health of the occupants. CO_2 is a commonly used indicator for indoor air quality, and its concentration can provide an estimation of the ventilation effectiveness in a space. PM2.5 is a harmful airborne particulate matter, which can lead to respiratory problems and other health issues. SARS-CoV-2 virus is a highly infectious pathogen that has been identified as the cause of the COVID-19 pandemic.

To provide more details on the selection of these contaminants, it should be noted that CO_2 and PM2.5 are two of the most commonly measured indoor air pollutants in IAQ studies (Heo et al. 2015; Han et al. 2022). Furthermore, the COVID-19 pandemic has highlighted the importance of indoor air quality in public health, and the study of SARS-CoV-2 virus dispersion in indoor spaces has received increasing attention from the scientific community (Buonanno et al. 2020; Aguilar et al. 2022).Therefore, the study of these three contaminants in the context of indoor environments is of great significance.

Taking these into account, a source of CO_2 with a generation rate of 0.3 liters per minute is defined separately for each zone as representative of its occupants. A PM 2.5 source is defined in the lunchroom, active from 9 am to 5 pm.

To compare the virus's concentration in each zone while having a source in it, an infector is introduced, who is a person with a generation rate of 65 quanta per hour (Buonanno, Stabile and Morawska, 2020). The infector moves around the zones until 4 pm while staying 1 hour in each zone. A quantum is defined as a dose of virus that can infect a susceptible person (Wells, 1955; Buonanno, Stabile and Morawska, 2020; Dai and Zhao, 2020). Table 3 shows the infector's schedule and location during their presence in the building.

The actual rate of pathogen generation of an infected person may vary based on the activity that produces the virus, such as coughing, sneezing, speaking, and so forth, and is also dependent on the person's age (Gregson et al., 2020; Feng et al., 2021; Mürbe et al., 2021). However, for the sake of simplicity, a constant value of 65 quanta per hour is assumed based on previous studies' assumptions (Buonanno, Stabile and Morawska, 2020; Yan et al., 2022).

Furthermore, the deposition rate and deactivation rate of SARS-CoV-2 are assumed to be 0.24 h^{-1} (Moreno et al., 2021) and 0.63 h^{-1} (Doremalen et al., 2020), respectively, to provide more details.

In the previous studies (Rudnick and Milton 2003; Moreno et al. 2021; Yan et al. 2022), basic reproductive number (R0) was used as the limit for acceptable SARS-CoV-2 level in the zones, which is defined hereunder:

$$R_0 = \frac{N_C}{I} \tag{2}$$

Table 2 Characteristics of the zones defined in the simulation

Zones	Total area (m2)	Volume (m3)	No of occupants (max)	Density of people (person/m2)	Lighting (W/m2)
Classrooms	75	255	35	0.47	8
Auditorium	196	665	40	0.20	5.24
Office	135	459	13	0.10	7.3
Library	96	327	10	0.10	7.3
Corridor	435	1480	39	0.09	3.22
Computer lab	71	241	16	0.23	7.3
Lunchroom	138	468	25	0.18	3.89
Bathrooms	15	52	4	0.27	9.27

Table 3 Schedule of the infector's location during his presence in the building

Time	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00
Location	corridor	Computer lab	auditorium	library	office	lunchroom	Classroom6	female bathroom

Where N_C is the expected number of infections, and I is the number of infectors. R0 should be lower than 1, so the virus cannot spread in the zone. Generally, minimizing the R0 means the transmission risk has decreased among a certain population. In order to calculate the infection risk of the occupants, the Wells-Riley equation (Dols et al. 2020; Yan et al. 2022), which has been used before in most of the previous researches has been considered:

$$P_I = \frac{N_C}{N_S} = 1 - exp\left(-\frac{Iqpt}{Q}\right) = 1 - exp(-n_q) \tag{3}$$

$$n_q = p(1 - M_{inh} \times F_m) \int_{t_1}^{t_2} C(t)dt \tag{4}$$

Where P_I is the probability (or risk) of infection, N_C is the infection cases, N_S is the number of susceptibles, I is the number of infectious sources (infectors), p is the pulmonary ventilation rate of a person (breathing rate) per hour, q is the quanta generation rate per hour, t is the exposure time to the certain microorganism (in hours), Q is the room ventilation rate, and n_q is the number of quanta that have been inhaled. In equation (4), M_{inh} is the mask inhale efficiency, F_m is the percentage of mask-wearing, and C is the quanta's concentration (quanta/m^3). In this study, considering a light activity (whispering and speaking) level for occupants, p is assumed to be 0.75 m^3/h (Bazant and Bush 2021).

2.3 Contaminants transmission control strategies

The objective of this study is to reduce the dispersion of contaminants inside the school, and various mitigating strategies are investigated to compare their effectiveness on the IAQ and energy performance in the next stage. The methods of minimizing the building's energy consumption often conflict with enhancing the IAQ. For instance, while natural ventilation (opening doors and windows) is encouraged to keep the indoor air clean and healthy, it can lead to energy loss, and therefore, more energy should be consumed to compensate and keep the room warm and comfortable.

Another example is the plan to increase biomass usage for heating purposes in the building to reduce energy consumption, which can negatively impact the outdoor and indoor air quality of the building (Settimo and Avino, 2021). Moreover, increasing the percentage of recirculated air in the ventilation system will enhance energy performance, but it also escalates the risk of contaminants' dispersion between different zones.

Taking these into account, it is challenging to keep both factors at an acceptable level and achieve a healthy and energy-efficient environment. In a properly designed building, these two parameters should not conflict but should be harmonious (Settimo and Avino, 2021) because both are equally important and cannot be neglected.

The first step in reducing contamination in a building is to identify the sources. There are different kinds of sources for each contaminant, which could be inside or outside the building. The most important action to mitigate outside sources should be taken before construction, and the pivotal role of urban structure is highlighted (Settimo and Avino, 2021). In other words, the building, based on its type, should be built in a safe location regarding pollutants and air quality. Other procedures should also be considered to mitigate indoor sources of particles, gases, and pathogens, such as activities and equipment operating inside the buildings.

In the current study, decreasing the number of sources as one of the pollutant mitigation strategies is not considered, and for each pollutant, one type of source is considered. However, several other strategies will be applied to the model to determine their impact on energy consumption and prevent contamination dispersion. It should be noted that some strategies can only be effective on certain types of pollutants. For example, UVGI lights, HEPA filters, and MERV filters are effective in mitigating liquid or solid particles but cannot decrease the amount of CO_2 in the room (Settimo and Avino, 2021).

In this study, various strategies are applied individually to the model, and in the final case, they are combined to form a pack of solutions to decrease three contaminants: CO_2, SARS-CoV-2, and PM2.5. The first strategy is to increase the OA percentage from 0% in the baseline case to 80% in all zones. Then, to highlight the key role of ventilation in mitigating contaminants, 10% and then 100% of the designed ventilation rates are applied to the model. OA percentage and ventilation rate are the key factors in decreasing the CO_2 level inside the building.

It should be noted that to capture the performance of each strategy separately in mitigating contaminants, each scenario investigates the effect of only one method on the model, except for the final case, which combines all of them. Therefore, as increasing the OA percentage in the HVAC system is a pivotal action in mitigating pollutants, its role is studied in a scenario with 80% OA, and in the other scenarios, it is considered 0% to determine the performance of other strategies without OA percentage's impact on the system. This work has been done in previous studies (Shrestha et al., 2021; Yan et al., 2022), which also considered the OA percentage as 0% or less than 20% for their baseline and worst-case scenarios.

As one of the most conventional methods of removing pollutants in most buildings, opening windows is considered in the model to investigate the impact of natural ventilation on cleaning indoor air. Table 4 presents the schedule of opening windows in two different cases. In the schedule of Case 1 recommendation of The Education and Skills Funding Agency (ESFA) (Daniels 2018) regarding opening of windows in schools is taken into account. In the first case, external windows of all zones except the corridor are opened. In the second case (last scenario), only the lunchroom's windows are opened because it is the source zone of PM 2.5 generation, and other controlling strategies will be considered in the rest of the areas. This has been done to mitigate the significant impact of natural ventilation on the surging of energy consumption.

Table 4 Schedule and fraction of windows' opening in case 1 and case 2

Time	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**
Case 1	0.5	0	0.5	0	1	1	0.5	0	0.5	0
Case 2	0.2	0.5	0.5	0.5	1	1	1	0.5	0.5	0

The other strategy is using MERV 13 (Minimum Efficiency Reporting Value) filters in the recirculation and outdoor air ducts of the AHU. Generally, MERV filter efficiency varies based on the target contaminant's dimension. In this regard, there is a standard provided by ANSI/ASHRAE (ANSI/ASHRAE, 2017) that presents all the MERV filters (from MERV 1 to MERV 16) efficiencies depending on the particle sizes. In the current study, two particles could be cleaned by MERV filters: PM2.5 and droplets containing SARS-CoV-2. Considering that airborne SARS-CoV-2 aerosols are mainly transmitted as particles containing the virus, an investigation of previous studies reveals that these particles' sizes could vary between 0.25 µm to 5 µm (Lee, 2020; Santarpia et al., 2020, 2021; Lednicky et al., 2021; Mallach et al., 2021). Taking this into account, range 2 of the particle sizes (1.0 µm to 3.0 µm) in the ANSI/ASHRAE standard (ANSI/ASHRAE, 2017) is considered for the PM2.5 and SARS-CoV-2 particles, which in this case, MERV 13 filter has a minimum efficiency of 85%.

Furthermore, HEPA air purifiers, which are effective in diluting SARS-CoV-2 and PM2.5, are considered in each zone with a removal rate of 0.003 s^{-1} (Kogan et al., 2008) and 2.4 h^{-1} (Macintosh et al., 2008), respectively. The last control method investigated in this study is using ultraviolet germicidal irradiation (UVGI) light in the rooms to dilute the virus with a removal rate of 4 h^{-1} (Miller and MacHer, 2000). It should also be noted that UVGI is not effective on particles.

In the baseline case, the OA is 0%, the ventilation rate is 10% of the design capacity of the HVAC, and no filters are used in the HVAC system. For the rest of the cases, the aforementioned methods are applied to the model in various scenarios as different sets of combinations, which are described in Table 5.

Table 5 Scenarios applied to the model to investigate their impact on contaminants concentration and energy performance

Scenarios	OA (%)		Ventilation rate (%)		MERV 13 filter	HEPA air cleaner	UVGI	Natural Ventilation	
	0	80	10	100				All rooms	Lunchroom
1- (0OA+ 0.1Vent) (Baseline)	▨		▨						

2- (0OA+ 1Vent)	▨			▨					
3- (0.8OA+1Vent)		▨		▨					
4- (0OA+ 0.1Vent+NatVent)	▨			▨				▨	
5- (2)+ MERV 13	▨			▨	▨				
6- (2)+ HEPA	▨			▨		▨	▨		
7- (2)+ UVGI	▨			▨			▨		
8- (3)+ NatVent+ all (MERV13+ HEPA+ UVGI)		▨		▨	▨	▨	▨		▨

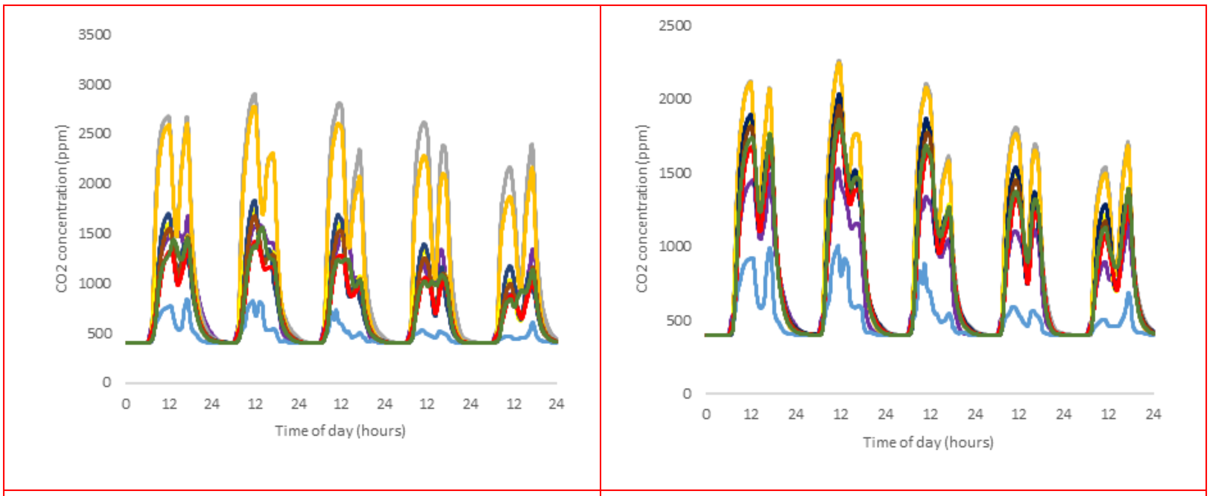
3. Results and discussion

3.1. Contaminant's simulation results

The model consists of 16 total zones, and 8 different scenarios were applied to the model. To better understand the impact of the applied strategies on the model, the results for the 5 working days from 20th to 24th February are presented. Moreover, among the 8 classrooms with similar conditions, classroom 1 and classroom 8, along with the rest of the zones, were chosen to display the concentration of CO_2 and PM2.5. Since the source of SARS-CoV-2 moves around the 8 zones, the peak concentration of this contaminant in each zone occurs when the source stays in that particular zone. Therefore, only the locations where the infector is present are selected to display the concentration of SARS-CoV-2 under various scenarios.

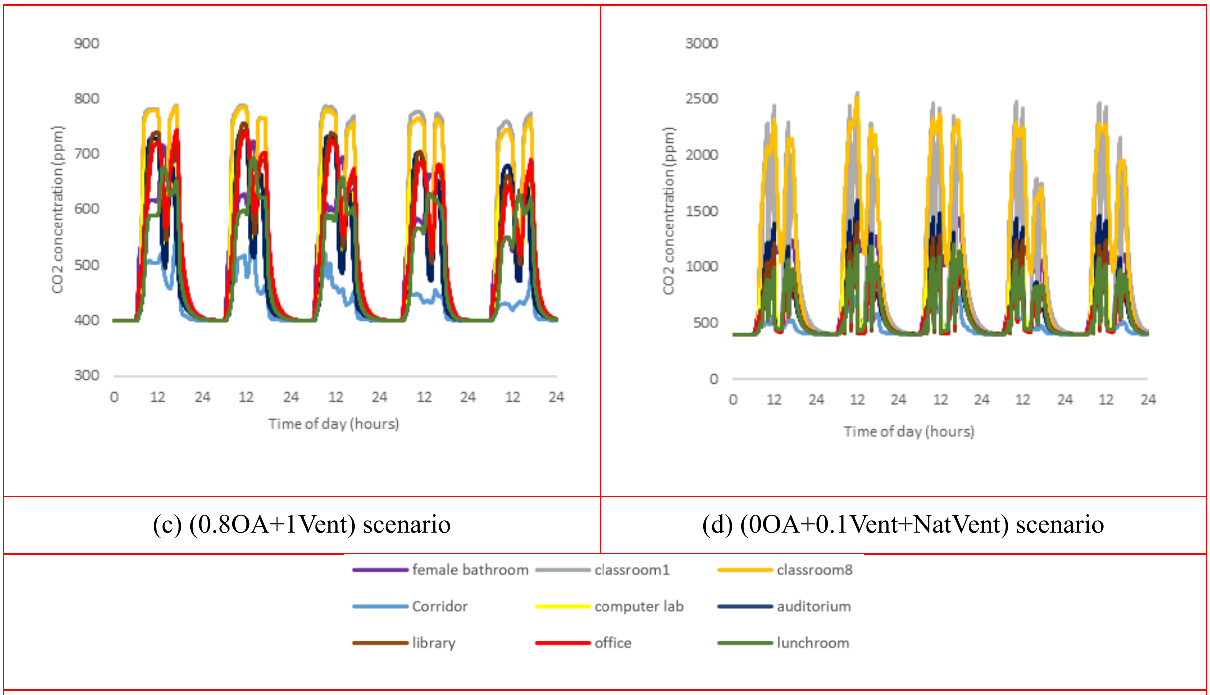
3.1.1. Carbon dioxide concentration

The main source of CO_2 generation in the building is the occupants in all zones, each with different maximum numbers and occupancy schedules (Fig. 4). According to the latest United Kingdom national guidelines from 2018 (Building Bulletin 101, BB101) (Daniels, 2018) for ventilation of educational buildings, the CO_2 level should be below 1000 ppm during occupancy. Therefore, in this study, the limit for CO_2 concentration is based on the BB101. Additionally, the outdoor CO_2 level is assumed to be 400 ppm. Fig. 5 (a) shows the CO_2 concentration in selected zones in the baseline scenario. As expected, the classrooms, being the most densely occupied rooms in the school, have the highest CO_2 levels, reaching nearly 3000 ppm during peak occupancy.



(a) (0OA+0.1Vent) scenario

(b) (0OA+1Vent) scenario



(c) (0.8OA+1Vent) scenario

(d) (0OA+0.1Vent+NatVent) scenario

Fig. 5 CO_2 concentrations during 20-24th February

In contrast, the corridor has an acceptable amount of CO_2 even in the baseline scenario, which has almost no ventilation. The main reason for this is that most of the time, only around 50% of the total number of occupants considered for the corridor spend their time there. In this case, the density of people drops to 0.045 person/m^2 from the peak density of 0.09 person/m, which is very low compared to the classrooms' density (0.47 person/m2). Moreover, the entrance doors provide natural ventilation for the corridor and decrease the CO_2 and other contaminant levels in this zone. Therefore, it could be concluded that the corridor is a safe place for occupants even without ventilation. Consequently, omitting the corridor's ventilation could be considered as one of the solutions to enhance the school's energy efficiency.

In the next steps, the rest of the scenarios are applied to the school's CONTAM model, and the results are illustrated in Fig.5 (b), (c), and (d). As aforementioned, UVGI lights, air purifiers with HEPA filters, and MERV filters are ineffective on CO_2 levels. Therefore, the only scenarios that can affect the CO_2 concentration in the school are those related to ventilation (mechanical/natural) and outdoor air percentage. As can be seen from Fig. 5 (c), applying the (0.8OA+1Vent) scenario leads to achieving an acceptable level of CO_2 (below 1000 ppm) in all zones, which is compatible with the BB101 standard. On the other hand, Fig. 5 (b) depicts that increasing the ventilation rate without outdoor air is not effective enough, proving the importance of having a level of outdoor air in the ventilation system. Moreover, as can be seen from Fig. 5 (d), natural ventilation is also not enough to achieve a safe level of CO_2 in all zones because if a room does not have an external window, natural ventilation would be ineffective in that space. Therefore, this approach should be combined with other controlling strategies.

3.1.2. SARS-CoV-2 concentration

In this study, the individual shedding SARS-CoV-2 quanta does not remain in only one zone and can move between zones to investigate the differences in their impact on the SARS-CoV-2 concentration of each room. To be clear, the SARS-CoV-2 level reaches its peak at the time of the infector's presence in the room, and the rest of the time, the area is recovering and diluting the virus through the controlling strategies applied to the model, resulting in a low and negligible level of the virus because it has an acceptable level of exposure risk or probability of infection for the occupants of the school. Therefore, the results are a combination of the peak level of SARS-CoV-2 in the total of 8 zones, and the goal is to decrease the maximum concentration during a 1-hour exposure of occupants to the SARS-CoV-2 pathogen to an amount considered safe in terms of virus transmission. It should be noted that in all cases, the outdoor level of the virus is considered to be 0 quanta/ m^3.

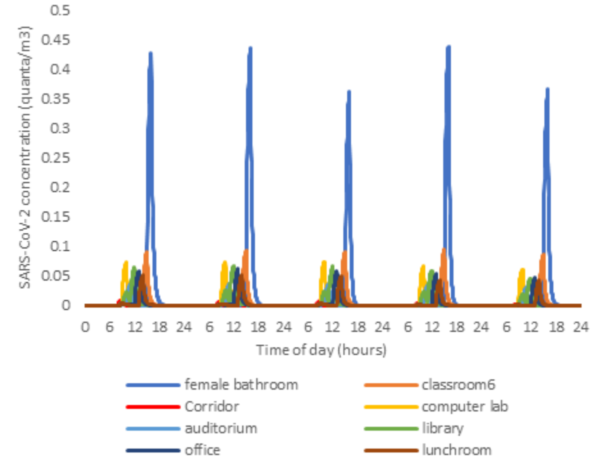


Fig. 6 SARS-CoV-2 concentration in selected zones in the baseline scenario (20-24th February)

In the baseline case, with no outdoor air circulating in the ducts and a low ventilation rate, it is expected to have a high concentration of SARS-CoV-2 in the zones. As shown in Fig. 6, among the eight zones where the infector visits, the female bathroom has the highest concentration, and the corridor has the lowest quanta per m^3. As the female bathroom is relatively small compared to the other zones, it has less infiltration and ventilation, although an extra exhaust fan is considered for bathrooms to provide more ventilation. As a result, most of the generated virus in 1 hour accumulates until it reaches the highest concentration among all zones. Taking this into account, it can be concluded that the same source of the virus with a constant quanta generation rate and the same deposition and removal rates could lead to different concentrations in the rooms due to the particular conditions of each zone, such as its ventilation rate, airflow paths, and infiltration.

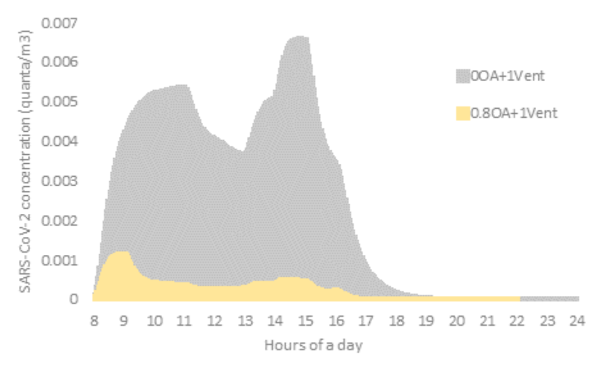


Fig. 7 Comparison of the SARS-CoV-2 level in classroom 5 in two scenarios with different OA percentage

In the next two scenarios, the AHU works with its full capacity (100% ventilation rate) with 0% and 80% of OA and no filters. 0% OA means that recirculated air in the ducts transfers the virus from where the source is located to the connected rooms. Therefore, under the same ventilation rate, the concentration of SARS-CoV-2 in neighbouring zones with 0% OA would be higher than in the case with a higher OA percentage, in which mostly clean air is delivered to the rooms. In this regard, classroom 5 has been selected as one of the connected rooms to the classroom 6 with the infector inside. Fig. 7 compares the virus concentration in scenarios 2 and 3, in which OA percentage is the only variable parameter to show its impact on neighbouring zones. As shown in Fig.7, adding 80% outdoor air can significantly reduce the quanta concentration in neighbouring zones. However, in this case, the in-duct installed filters become less effective in reducing contamination, as the outdoor air is assumed to be clean and only 20% of the ventilation air is recirculated, which contains the contaminants.

Increasing the ventilation rate leads to a notable dilution of the virus in the source zones. Fig. 8 illustrates the SARS-CoV-2 concentration in scenario 2 with a full capacity of ventilation operating. In this case, the contamination level in the female bathroom shows a 53% decrease compared to the first scenario. Similarly, the amount of quanta concentration reduction in the zones due to increased ventilation in the second scenario is as follows: classroom 6, 44%; auditorium, 6%; computer lab, 31%; office, 13%; library, 24%; and lunchroom, 15%. Moreover, Fig. 9 (a) compares the difference in the virus level in the scenarios related to ventilation. Accordingly, the (0.8OA+1Vent) scenario is the best option when considering only ventilation-related mitigation methods. Although the difference between (0OA+1Vent) and (0.8OA+1Vent) is not as significant as the reduction made by switching from the baseline case to scenario 2 (increasing the ventilation rate), it is still one of the important strategies that should be considered in controlling contaminants, especially as it is more effective in reducing the CO_2 level.

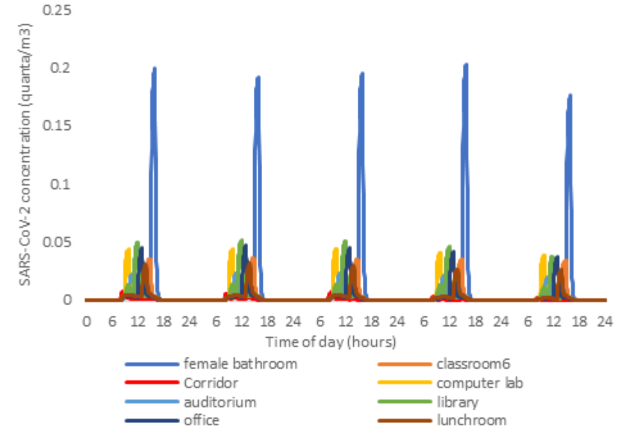
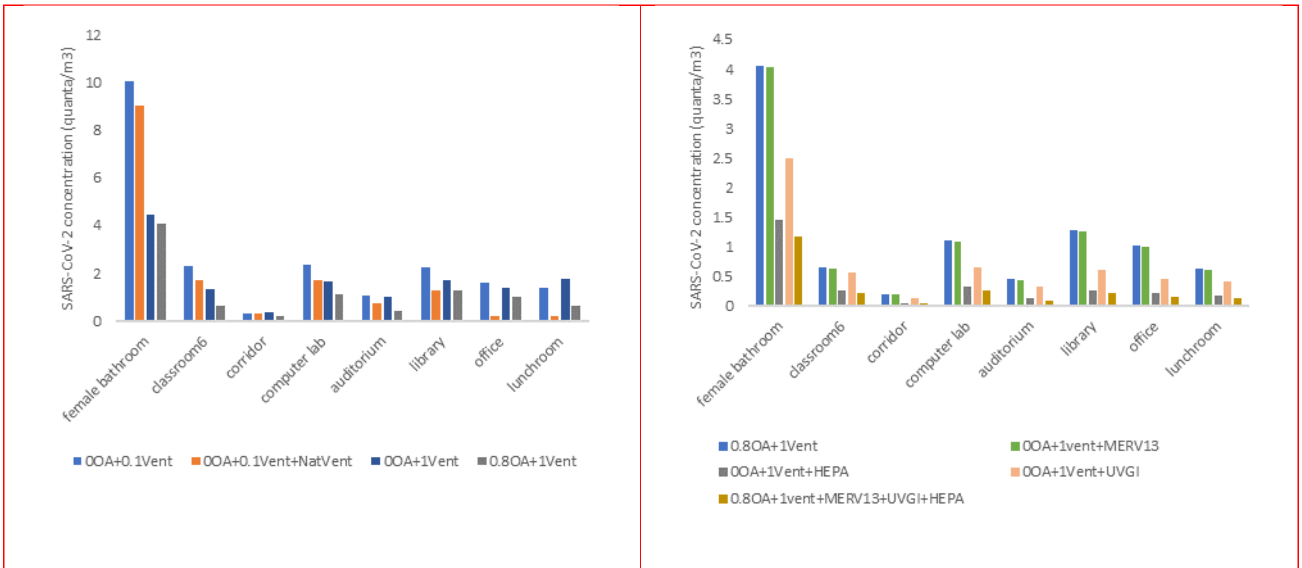


Fig. 8 SARS-CoV-2 concentration in selected zones in (0OA+1Vent) scenario (20-24th February)



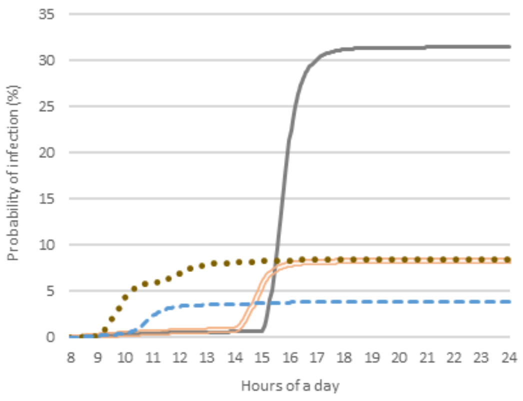
(a) In the scenarios related to ventilation

(b) In the scenarios related to installing extra devices

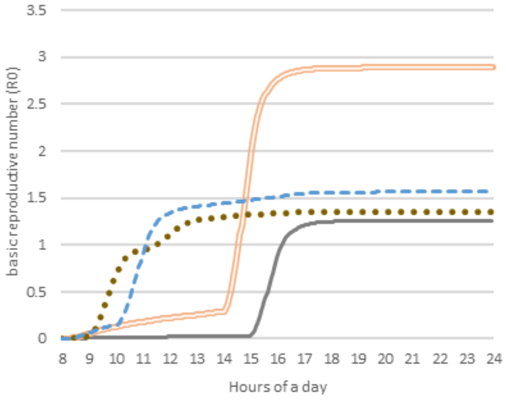
Fig. 9 Comparison of the total amount of SARS-CoV-2 level in various scenarios during 20th of February

Installation of a MERV13 filter in the inlet duct of recirculation air, usage of portable air purifiers with HEPA filters in the zones, and in-room UVGI light are other disinfection methods used separately and in combination. Fig. 9 (b) compares the effectiveness of these cases in cleansing the air from the virus during February 20th. As per Fig. 9 (b), using HEPA filters in air cleaners can remove viruses more than other methods. It is also effective on both SARS-CoV-2 and PM2.5, while UVGI is only suitable for removing the virus, not the particles. On the other hand, although using MERV13 filters in the duct has a lower impact than the other two methods, it can still decrease the contaminants in the zones to an acceptable level. In the last scenario, all the controlling strategies are combined to achieve the best case in which all three contaminants are at a safe level.

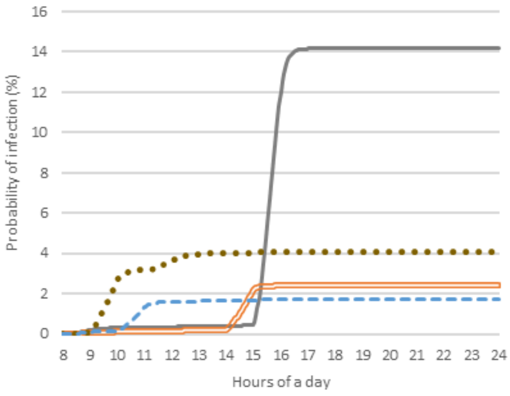
The probability of infection or individual exposure risk and basic reproductive number (R_0) are important terms that should be considered in the analysis of SARS-CoV-2. Four zones are selected to compare these terms in four different cases during February 20th from 8:00-24:00 hours, which are illustrated in Fig. 10. Fig. 10 (a-1) shows that the probability of infection in the female bathroom in all cases is very high. However, R_0 is relatively low for this zone with an average of 0.65, 0.3, 0.33, and 0.11 in (0OA+1Vent), (0.8OA+1Vent), (0OA+1Vent+NatVent), and (0OA+1Vent+HEPA) scenarios respectively due to its fewer number of occupants and therefore fewer susceptibles. On the other hand, although in the first case (Fig. 10 (a-1)), the probability of infection in the auditorium is less than 5%, the average R0 is 1.25, and from around 11 am onwards, it becomes more than 1, which means the virus could be dispersed among the occupants, and the place is not safe. Among the four selected scenarios, (0.8OA+1Vent) and (0OA+1Vent+HEPA) are the most effective, as the R_0 is less than 1 in all the zones. The efficacy of natural ventilation, as per (Fig. 10 (c-2)), is acceptable in the computer lab but not in auditorium, classroom 6 and the female bathroom because there are no external windows in these rooms or fraction and schedule of opening of the windows are not enough. Therefore, other mitigation methods should be adopted for the zones.



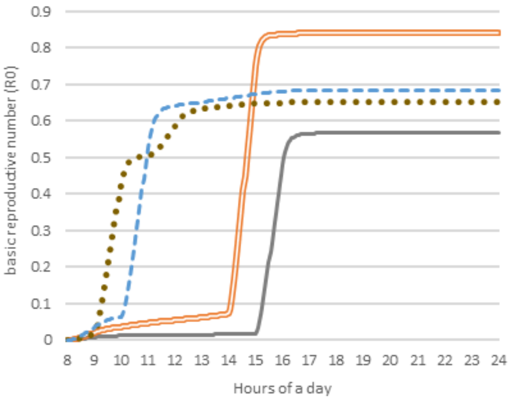
(a-1) Probability of infection in (0OA+0.1Vent) scenario



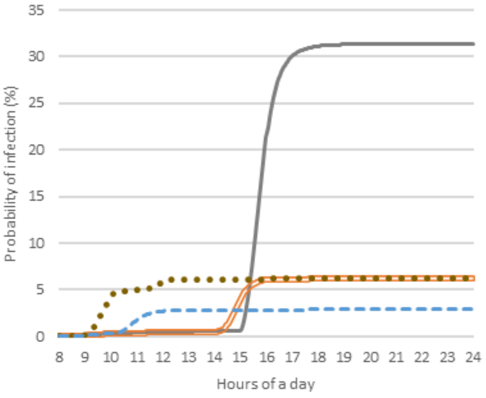
(a-2) Basic reproductive number (R_0) in (0OA+0.1Vent) scenario



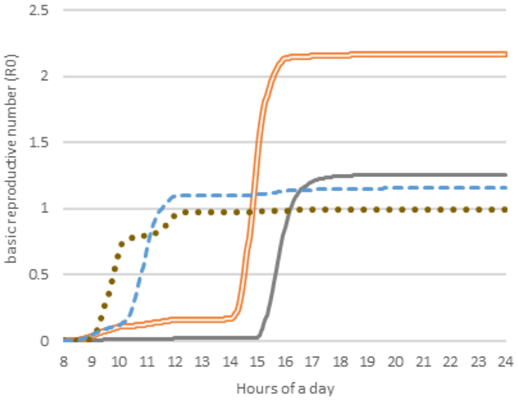
(b-1) Probability of infection in (0.8OA+1Vent) scenario



(b-2) Basic reproductive number (R0) in (0.8OA+1Vent) scenario



(c-1) Probability of infection in (0OA+0.1Vent+NatVent) scenario



(c-2) Basic reproductive number (R0) in (0OA+0.1Vent+NatVent) scenario

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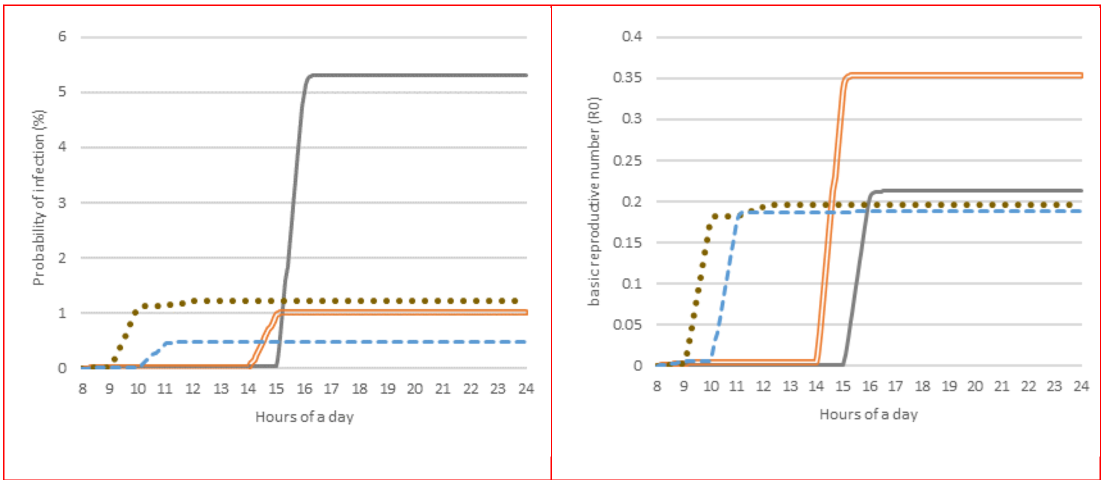


(d-1) Probability of infection in (0OA+1Vent+HEPA) scenario

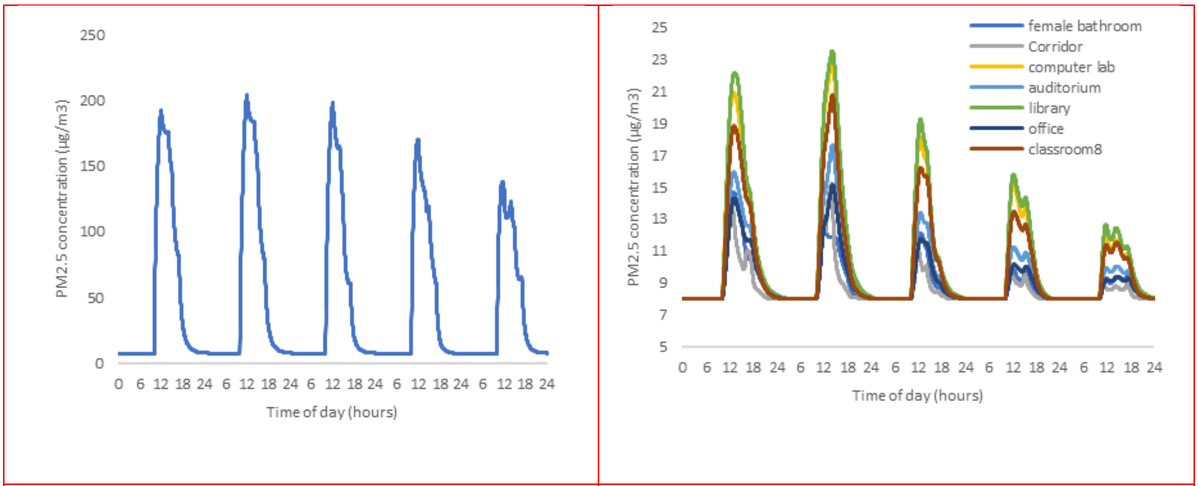
(d-2) Basic reproductive number (R0) in (0OA+1Vent+HEPA) scenario

Fig. 10 Probability of infection and basic reproductive number during the 20th of February

3.1.3. *PM2.5 concentration*

Various indoor sources of PM2.5 include smoking, cooking, and human activities. In this study, a source of PM2.5 in the lunchroom is assumed, where there are cooking activities. Furthermore, the acceptable level for the indoor amount of PM2.5 is considered 15 µg/ m^3 based on the ASHRAE/ANSI textbook "Ventilation for Acceptable Indoor Air Quality" (ANSI/ASHRAE, 2022). Fig. 11 (a) illustrates the PM2.5 concentration in the lunchroom, the source zone. The cooking in this zone runs from 10:00 to 17:00 with different intensities of generating PM2.5. The rest of the zones receive PM2.5 from the lunchroom through infiltrations via airflow paths and AHU ducts, which is very low compared to the lunchroom's level. However, it is possible that the amount of PM2.5 gets more than the acceptable level, and hence, mitigation strategies should be applied in those zones as well. In this regard, Fig. 11 (b) shows the PM2.5 level in nine selected zones in the baseline case from February 20-24th. As expected, the zones with a shared wall with the lunchroom, i.e., the computer lab and library, have more particles than the other rooms and have exceeded the PM2.5 limit.

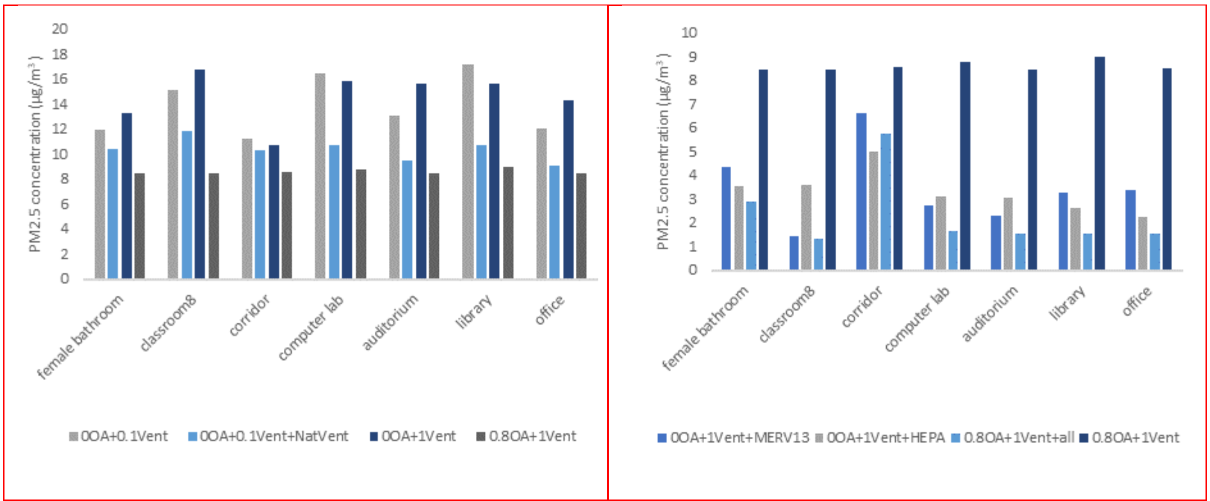
Similar to the other contaminants, the impact of mitigation methods on PM2.5 concentration has been investigated. In order to have a better insight into particle level and compare various strategies' effects on different zones, the average concentration of the particles on the 20th of February from 10:00-18:00 hours is illustrated in Fig. 12. Fig. 12 (a) compares the methods related to OA percentage, natural ventilation, and ventilation rate, while Fig. 12 (b) compares the effect of different filters and opening the windows of just the lunchroom rather than opening the windows of all zones (0OA+0.1Vent+NatVent scenario). In other words, in the last scenario, which includes all the strategies, natural ventilation has been provided by opening the lunchroom windows with the highest opening ratio (100%) between 12 to 15 hours to compensate for the fact that UVGI lights could not remove PM2.5. As shown in Fig. 12(a), increasing the ventilation rate alone has a reverse impact in most of the rooms because enhancing the ventilation with no outdoor air leads to the contribution of the HVAC ducts in transmitting the particles between the rooms. However, when the OA has been increased to 80% as well, it turns out to be the most effective strategy (among the cases in Fig. 12(a)) in removing the particles. On the other hand, comparing this scenario (0.8OA+1Vent) with the cases in Fig.2(b) shows that other solutions, such as the MERV13 filter and HEPA air purifier, are more effective even with no outdoor air. MERV filters are installed in the ducts and, therefore, they are more effective in reducing the particles in the zones with higher ventilation rates, such as classrooms and auditorium, compared to the female bathroom with less ventilation rate. The final method (0.8OA+1Vent+all) makes all the rooms, including the lunchroom, safe in terms of PM2.5 level. In this case, the average particle concentration in the corridor becomes 5.74 µg/ m^3, which is the highest among the zones (except lunchroom), and in classroom 8, it is 1.31 µg/ m^3 with the minimum level.



(a) In the lunchroom

(b) In other selected zones

Fig. 11 PM2.5 concentration during the 20-24th of February in the baseline scenario

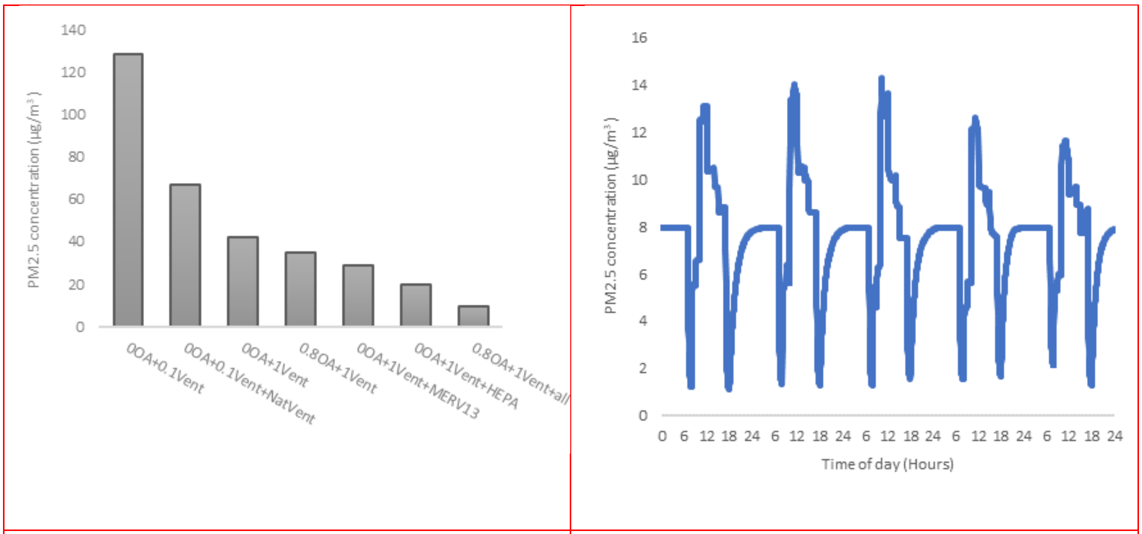


(a) In the scenarios related to ventilation

(b) In the scenarios related to installing extra devices

Fig. 12 Comparison of the average concentration of PM2.5 on the 20th of February in various scenarios from 10:00-18:00

Furthermore, diluting the PM2.5 level in the lunchroom is the main goal of applying controlling strategies as it has the highest density of particles, and when this zone is considered safe, all the other zones will be safe as well. In this regard, Fig. 13(a) compares the impact of all methods on the average concentration of PM2.5 in the lunchroom. Considering the acceptable level of 15 µg/ m^3, only the last scenario (0.8OA+1Vent+NatVent+all) meets this limit. Fig. 13(b) illustrates the PM2.5 level in the last case during the 20th-24th of February, where the PM2.5 level is below the limit all day long



(a) Comparison of various scenarios' impact on decreasing the PM2.5 level

(b) Final concentration of PM2.5 in the (0.8OA+1Vent+NatVent+all) scenario

Fig. 13 PM2.5 concentration in the lunchroom during 20-24th of February

3.2. Building energy performance

The CONTAM models for all scenarios were exported to EnergyPlus to perform a co-simulation and analyze the building's energy consumption under various conditions. Fig. 14 shows the energy performance results for all scenarios from 20-24th February. The total energy usage is divided into heating, interior lighting, equipment, fans, and pumps. Heating is provided by a gas-fired boiler and a pump that circulates hot water in the heating loop to deliver the required heat through radiators. The characteristics of the interior equipment are presented in Table 1. In the AHU, fans consume electric energy to condition the zones. There is a constant volume fan in the AHU and two exhaust fans operating in bathrooms to provide excess ventilation. As the ventilation rate increases in the second scenario, the fans work more; therefore, the share of electricity consumption increases by 3%. However, having no outdoor air in the system results in a 12% decrease in heating energy usage.

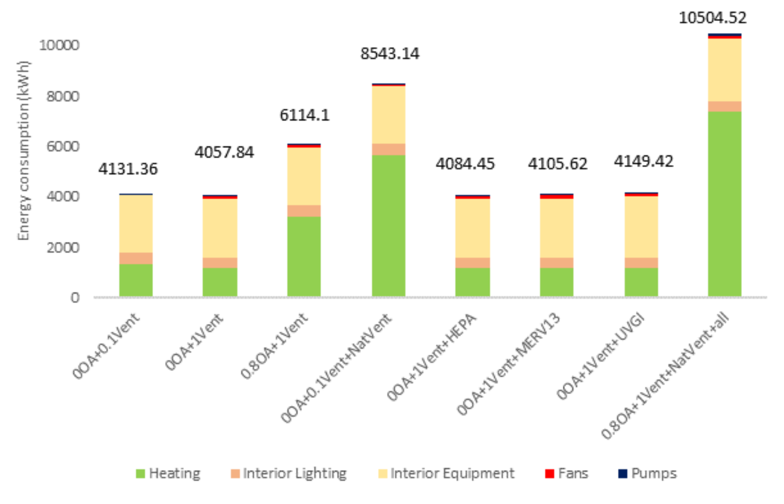


Fig. 14 Energy consumption of the building in the case of various scenarios from 20-24th February

On the other hand, in the 3rd case when the OA percentage becomes 80%, more heating energy is required to heat up the air coming from outside, resulting in a 50% increase in energy consumption. However, keeping the OA at zero percent to capture the effect of natural ventilation on energy performance reveals that the impact of opening windows on the surge of heating demand and the pump's electricity usage is much more noticeable. In other words, mitigating the contaminants by natural ventilation leads to a 39% increase in energy consumption compared to the increase of the share of OA in AHU.

Air purifiers are assumed to have 50W power each, which increases the interior equipment's electricity usage by 1.7%. Similarly, 160W UVGI lights are operating for 15 minutes per hour in the room to provide the desired removal rate, resulting in a total equipment energy consumption increase of 4.7%. Furthermore, as MERV 13 filters are installed in the ducts and act as a barrier against airflow, they lead to a pressure drop and therefore a pressure rise in the fan's operation. In this case, the fan will require 49% more electric energy, and overall, 1.17% more energy is consumed compared to the second scenario. Combining all strategies in the last scenario results in an increase in energy consumption compared to the baseline scenario in all categories except for lighting, which remains constant. Heating increases by 450%, equipment by 6.4%, fans by 1311%, and pumps by 167%.

4. Conclusion

A multi-zonal analysis of contaminant dispersion was conducted in the current research to enhance the IAQ of a simple educational building. Furthermore, the energy performance of the whole building was simulated using CONTAM-EnergyPlus co-simulation to study the building's energy consumption under different pollutant mitigation strategies. In this regard, the efficacy of each strategy in improving IAQ and the excess energy consumption posed by that specific method was investigated. Each method for controlling the contaminants was applied to the model individually to understand their sole performance on the model.

In the first scenario, the worst-case scenario was presented, with a very low ventilation rate (10% of the designed rate) with no OA in the system, no natural ventilation, and no filters. It showed that the CO_2 level could rise to nearly 3000 ppm in some classrooms, proving the importance of having at least one controlling method in the building to enhance the IAQ. In this case, SARS-CoV-2 and PM2.5 also had critical concentrations in most of the zones, which were then diluted in further scenarios.

The high amount of CO_2 was treated by increasing the OA percentage and ventilation rate and adding natural ventilation. The scenario with both 80% OA and 100% ventilation rate proved to be the most effective, as the CO_2 level in all zones reached the acceptable level. Therefore, a 100% ventilation rate without OA or natural ventilation alone is not effective enough in removing the contaminants.

In the case of SARS-CoV-2, zones with external windows and doors reached a safe level by providing natural ventilation; however, for the rest of the zones, adding other mitigation methods is still necessary. The most effective options for reducing the virus's concentration in all zones are air purifiers with HEPA filters, UVGI lights, in-duct MERV 13 filters, and 80% outdoor air, respectively.

As the lunchroom was the source zone of PM2.5, it had the highest concentration of PM2.5. Most of the mitigation methods, except for the last one (0.8 OA + 1Vent + NatVent + all), were not effective in reducing its concentration to a safe level. However, for the rest of the zones that receive particles through infiltration, the (0.8 OA + 1Vent) scenario was sufficient to achieve an acceptable level of 15 $\mu g/m^3$. Additionally, adding air purifiers, MERV 13 filters, and UVGI lights does not significantly increase the building's energy consumption compared to the 80% OA and natural ventilation. However, in this particular case, installing MERV 13 filters for recirculating air consumes less energy than adding 50 W air purifiers. In the last scenario, despite its excellent performance in improving the IAQ from all contaminants, it increases energy consumption to the highest level among all the scenarios.

The main goal of this research was to study the performance of each of these contaminants separately rather than selecting one of the scenarios as the best method. Because there are other possibilities for mixing these strategies to achieve an effective as well as an energy-efficient combination, which requires further analysis to find the most efficient one. However, it should be noted that some of the methods are not effective on all of the contaminants, such as UVGI, which is only effective on the virus and not PM2.5 and CO_2. Also, some of them are in conflict with each other. For instance, increasing the OA percentage in a place where OA is considered clean and has none or little of a particular pollutant (just an indoor source) limits the usage of MERV 13 filters because, in this case, only recirculation air with a brief share of total ventilation air contains the contaminants and the filter can be effective on this part of the system.

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