Evaluation of "ventilation resilience" in mid-sized office buildings

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Abstract. In industrialized countries, people spend 80-90% of their times indoors, thus, providing them with clean spaces that preserve their wellbeing and productivity is critical. This can be done by delivering scheduled or demand-driven amounts of clean air that dilute the concentration of generated pollutants to adequate levels. However, the building and its ventilation system might be subjected to unpredictable shocks or disturbances (i.e., sudden failure in system components) that compromise the efficiency of the ventilation design, deteriorate indoor air quality and lead to acute exposure events. The ability of the building and its ventilation system to withstand and absorb the shock and maintain the IAQ design conditions is termed as "ventilation resilience". In this work, a typical open-plan office equipped with a balanced variable-air-volume mechanical ventilation system, is considered. Its ventilation resilience was assessed against power outage shocks and additional occupancy beyond expected peaks. Two types of pollutants were considered (exhaled CO_2 and formaldehyde from exhalation and office surfaces). To conduct this study, a Building simulation model was developed for the office and AHU in Modelica using Dymola. Results showed that for the considered shocks, no VOC violations were noted due to low emission rates. This was not the case for CO_2: For power outage shocks, the building/ventilation system were resilient for up to 15 minutes of shock and for 1 additional occupant in the space. Beyond those limits, the building/ventilation system are no longer resilient. For 60 minutes of power outage shock, CO_2 violations (>900 ppm) of 2 hours were noted with peaks of 1240 ppm while for 6 additional occupants, CO_2 violations of 2 hours were noted with peaks of 1150 ppm. A combined shock of these two cases caused 3 hours of violation and peak concentrations of 1747 ppm.

Keywords. Ventilation resilience, office buildings, indoor air quality, building simulation.
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1. Introduction

In today's generations, humans are mostly 'indoor dwellers', conducting their daily activities within enclosed workspaces, located in air-tight building envelopes (1). These spaces are characterized by a chemically diverse and complex indoor air quality (IAQ), due to the presence of multiple pollutants of either gaseous nature (volatile organic compounds (VOCs) (2), CO_2(3), bio-effluents (4)) or aerosol particulate matter (5). Pollutants can infiltrate indoors from the outside environment though the mechanical ventilation system (6) or are generated indoors due to endogenous sources (i.e., occupants' respiratory activities) (7) or exogenous sources (i.e., office equipment (8)).

With the lack of proper source control or inefficient IAQ management techniques, contaminants' concentrations can quickly build-up at the breathing level, increasing occupants' exposure. Acute exposure trends are either short-term (few minutes to few hours) to peak pollutants' concentrations, or long-term (years to decades) to upper-limit concentrations (9). These trends can cause adverse health effects from a lower life quality due to illnesses, and diseases (e.g., infections, pulmonary infections), to a decrease in life years' expectancy or mortality (10). To mitigate acute exposures in buildings, it is important to implement smart, energy-friendly ventilation strategies (i.e., scheduled, demand-controlled) with well-designed air distribution systems (11). These ventilation strategies are usually designed based on well-known indoor/outdoor conditions (i.e., outdoor, and indoor pollution sources, emission rates, occupancy schedules, etc.). In a field study, Merema et al. (12) monitored the performance of a demand-controlled ventilation system in educational buildings and landscape offices, driven by IAQ measurements (i.e., CO_2). Their results showed that demanded-controlled ventilation was able to maintain good IAQ levels even at reduced airflow rates. Additionally, it reduced energy use compared to a constant air volume system. Similar conclusions can be made for dynamic ventilation rates driven by pre-defined occupancy schedules (13).

Nevertheless, throughout a building's lifetime, there is a probability that indoor and outdoor conditions might shift unexpectedly from their pre-defined values (e.g., sudden increase in outdoor air pollution, unexpected rise in occupancy beyond expected peak)(6,14). Under such unprecedented and unavoidable circumstances – defined as "shocks" or "disturbances", the IAQ can shift quickly from its design conditions to unsatisfactory levels possibly causing instances of acute short-term exposures to harmful contaminants (e.g., VOCs, particles, CO_2). With the possible increase in shock occurrence (15), existing ventilation systems and strategies should be able to maintain good IAQ levels, not only under anticipated conditions but also in the case of extreme events. This characteristic is defined as "ventilation resilience". So far, in the literature, the resilience of current ventilation strategies in the non-residential sector has not been studied yet.

The aim of this work is to investigate the "ventilation resilience" of a scheduled ventilation strategy, a smart ventilation strategy considered as a simplified form of demand-controlled ventilation. supplying clean air to a multi-occupied office space. To reach this objective, a model of the office space and ventilation system will be developed using Modelica. The model will be simulated under normal operation (no shocks) and two types of shocks: a mechanical shock (power outage) shock and a spatial shock (increase in occupancy beyond peak values). The IAQ performance of the ventilation system will be assessed and compared between the cases.

2. Methodology

2.1 Office and system description

A typical single-zone medium-sized office based on the *medium office model of the commercial reference buildings* provided by the DOE, was considered (16,17). The office (16 m × 5.3 m × 2.7 m) location is in Brussels, Belgium (climate zone 4A) (18)(**Fig. 1**). The envelope consists of two external walls located on the south-west and north-eastern façades (U-value = 0.15 W/m².K) (passive house standard). Each wall has a triple-glazed window with a window to wall ratio of 0.48 and a U-value of 0.65 W/m².K). The rest of the boundaries (walls, floor, ceiling) were considered as internal or 'adiabatic' to represent a zone within a larger floor plan with other floors above and below. The envelope is air-tight with a rate of 0.3 h^{-1} (n-value). The space was conditioned by a mixing ventilation (MV) system, creating homogeneous conditions of temperature and IAQ (**Fig. 1**). The MV system is served by its own air handling unit (AHU) that supplies clean conditioned outdoor air to the space.

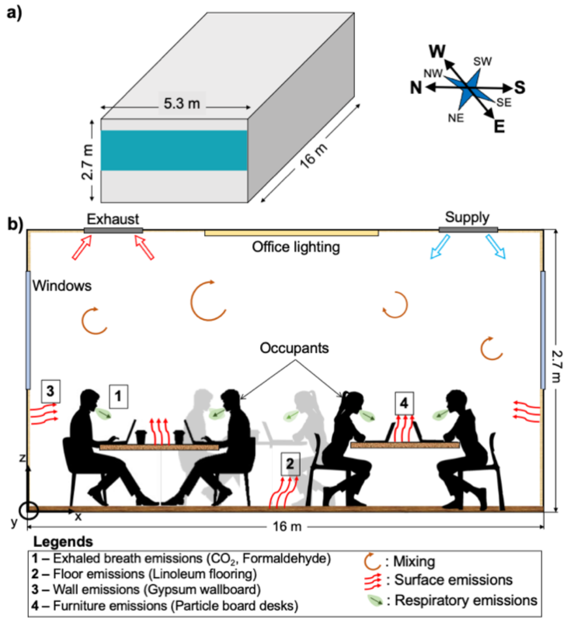


Fig. 1 – Schematic of occupied office space and associated sources of pollutants.

The ventilation rates Q (l/s) vary throughout the day depending on the occupancy schedule (**Fig. 2**). An occupant density of 0.07 person/m² was considered(20). According to ASHRAE standard 62.1 (21), Q (l/s) was determined by equation (1) below:

$$Q\ (t) = R_p P_z(t) + R_a A_z \qquad (1)$$

where R_p is the required airflow rate per person (7 l/s in the case of this study), P_z is the number of occupants at each time t (**Fig. 2**), R_a is the required outdoor airflow rate per unit area (0.3 l/s.m² recommended for offices) (21) and A_z(m²) is the floor area.

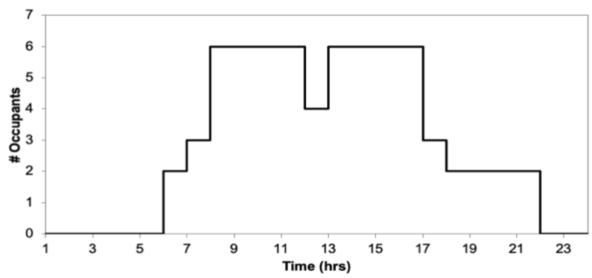


Fig. 2 – Occupancy schedule.

2.2 Pollution sources

Two sources of pollution were considered in the space. The first source is CO_2 resulting from occupants' exhalation flow (generation of 0.0048 l/s for adults at sedentary office activities, MET=1.2 (22)) (**Fig. 1**) and from outside air (400 ppm). According to a royal decree on indoor working conditions (21), a threshold of 900 ppm should be maintained for CO_2. Violations are allowed for 5% of the time over a maximum of 8 hours (24 minutes of violation). The second source of pollutants indoors is VOCs emissions, namely formaldehyde (CHOH), a common compound found in non-residential buildings (24). The sources of formaldehyde in the space are occupant exhalation (2.8 μg/h.person assuming an adult of 1.8 m high, 70 kg, body surface area of 1.89 m² and exhaled flow rate of 0.55 m³/h)

(25), linoleum flooring (0.01384 mg/h.m^2), gypsum wallboard walls and ceiling (0.001235 mg/h.m^2) and particle board tables (75 μg/h.m^2) (26) (**Fig. 1**). For simplification purposes, constant emission rates were assumed from surfaces. Outdoor formaldehyde concentrations of 0.002 ppm were considered (27). An intervention value of 0.08 ppm was recommended by the Flemish indoor environment decree (28).

2.3 Shocks and disturbances

Shocks and disturbances are unpredictable events that occur outside or inside the building envelope and that can compromise IAQ by causing it to shift from its design conditions. During such events, if the ventilation or source control strategies can maintain IAQ within the recommended levels of violation, then the building and associated systems can be characterized as resilient. Note that to be characterized as shocks, the events must occur suddenly; in a way that the occupants or building owner have no time to take preventive measures. To test the resilience of the current case, two types of shocks were considered:

- **Shock I:** A power outage shock due to an interruption of electricity supply from the grid. Interruption can be due to extreme weather conditions (i.e., heat waves, severe storms)(29) or equipment damage (30). Information on current and future trends of sudden power outages (in Belgium) are scarce. Hence, there is at this moment no typical duration to consider for power outage shocks. Thus, in this work, a power outage shock varying from few minutes to 1 hour was considered to cover a wide range of possible scenarios. The shock was considered to occur during peak occupancy at 9:00 AM.
- **Shock II:** An occupancy shock due to additional occupants (i.e., additional sources of pollution: CO_2 and CHOH) entering the office. The number of additional occupants varied from 1 to 6 (e.g., each occupant in the office had a visitor). The additional occupants were considered to enter the office at the same time during peak occupancy at 9:00 AM and stay there for 1 hour.

The effect of combined shocks on IAQ will be also assessed for an extreme case (maximum power outage and additional occupants).

2.4 Office space model

To assess the effects of shocks on IAQ (i.e., contaminants' concentrations in the space) and the ventilation resilience, a model was developed for the office space and the AHU. The building simulation tool Dymola (31) with the integrated District Energy Assessment by Simulation (IDEAS) library, was used due to its ability to accurately simulate models that combine the building environment and its envelope, the heating ventilation and air conditioning system as well as advanced controllers (32). The model assumes uniform thermal and IAQ conditions in the space (single node).

Figure 3 below illustrates the model as seen in the Dymola environment with its different components (1 to 8). Components (1) and (2) constitute the inputs to the model which consist of the typical meteorological year (TMY) weather data for Brussels (dry bulb temperature, solar radiation) embedded in Dymola (33) as well as outdoor species' concentrations (CHOH, CO_2, water vapor). Components (3) and (4) constitute the AHU and associated control. The AHU consists of a supply/exhaust fans with the ventilation schedule (equation (1)), a heat recovery unit with an efficiency of 75%, as well as a simplified ideal cooler/heater that conditions (according to a PID control), the outdoor clean air to supply temperatures that provide comfortable indoor setpoints of 23±0.5°C in the space. Component (5) illustrates the building envelope (walls, ceiling, floor, windows), and the air zone model. Component (6) is the occupancy schedule (**Fig. 2**) with associated sensible and latent heat and CO_2 gains. It also includes office equipment gains (30 W/person: each occupant has is considered to have a laptop) and lighting gains (LED) which are only active in the case of occupancy. Note that in the power outage shock, the lights were considered to turn off as well. Component (7) constitutes the VOC (CHOH) emission rates to the space and component (8) is a set of CO_2, CHOH sensors to monitor IAQ in the office.

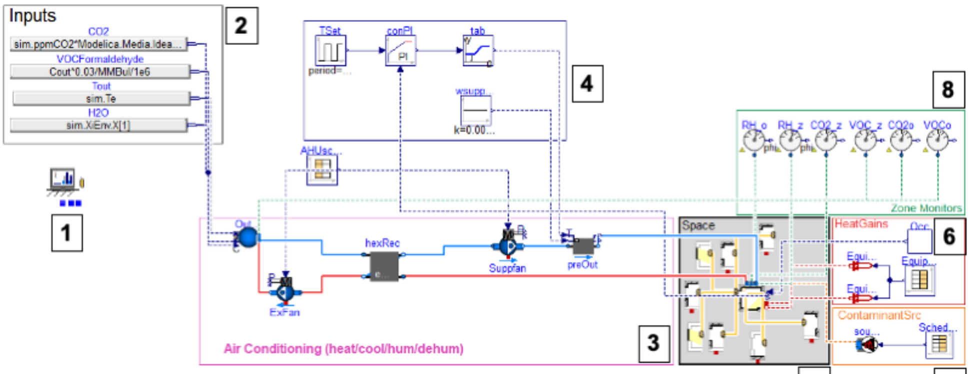
2.5 Simulation cases

The developed model will be simulated for a base case with no shock and for the case of the two shocks (**shock I** & **II**) and the combined shock (section 2.3). The simulations will be conducted for one representative day (August 1st). As the focus of this work is IAQ and ventilation resilience rather than thermal resilience, the choice of period of simulations is not critical to this study.

2.6 IAQ assessment

To assess ventilation resilience, and its effect on IAQ, the ppm.hours index will be used as seen in equation (2) below:

$$ppm.hours = \int C_s(t)dt \quad (2)$$



Legends

1 – Simulation and Information manager for handling time and climate data
2 – Model inputs: Weather data (T_{db}(°C), $\omega_a(kg/kg)$), outside pollutants (CO_2, Formaldehyde) concentrations (ppm)
3 – Simplified air handling unit (AHU) model
4 – AHU Control (Supply temperature, humidity)
5 – Office zone model (single-node lumped conditions) with envelope (walls, windows)
6 – Heat gains due to occupancy and office equipment (W) + CO_2 production due to exhalation
7 – Formaldehyde emission rates (kg/s) due to respiratory activities and surface emissions
8 – IAQ Sensors (RH(%), CO_2 (ppm), Formaldehyde (ppm))

Figure 3 Illustration of the office space model as seen in Dymola.

where C_s is the temporal variation of the concentration of either CO2 or CHOH. The ppm.hours will be calculated for concentrations above 900 ppm for CO2 and above 0.08 ppm for CHOH.

3. Results and discussion

3.1 Base Case (no shock)

For the base case scenario where no shocks occur (normal operation), the concentrations of CO_2 and CHOH are within the recommended guidelines (**Fig. 4, base case**). CO_2 concentrations increase during the day with increasing number of occupants and reach a maximum of 850 ppm at 12:00 during peak occupancy (<900 ppm threshold). Concentrations decrease during break hours (12:00-13:00) only to increase again when employees return to the office. After 17:00, concentrations start to decrease back to ambient concentrations (400 ppm) due to end of work shift and occupants gradually leaving the office.

As for CHOH concentrations, it is first noted that throughout the entire day, the threshold value (0.08 ppm) is never reached. Concentrations are higher during the early morning before occupancy starts. This is due to low ventilation rates and the constant CHOH surface emissions from flooring, walls and tables. When occupants start to come into the office, ventilation rates increase causing CHOH concentrations to decrease reaching minimum of 0.007 ppm at 12:00 when ventilation rates were the highest. This occurs despite the CHOH exhalation emissions from occupants. This is since the increment in CHOH concentration due to exhalation is not as significant as the dilution effect of the surface emissions by the increased amounts of clean air by the ventilation system. Subsequently, during break hours (12:00-13:00), an increase in CHOH concentration to 0.008 ppm is noted due to reduced ventilation rates. Concentrations reduce again during shift time at 13:00 and increase after the shift starts to end at 17:00 and occupants leave the office (**Fig. 4**). Note that during all times, the CHOH concentrations were well below the guideline value of 0.08 ppm.

3.2 Effect of Shocks

Figure 4 illustrates the temporal variation of CO_2 and CHOH concentrations from 6:00 – 17:00 for the base case scenario and the case of power outage shocks (5 min, 30 min and 60 min). **Figure 5** illustrates the temporal variation of CO_2 and CHOH concentrations from 6:00 – 17:00 for the base case scenario and the additional occupancy shocks (+2, +4 and +6) and **Figure 6** shows the cumulative ppm.hours for a) Power outage shock and b) Occupancy shock.

3.2.1 Shock I: Power outage

According to **Fig. 4**, when the power outage shock occurs, the ventilation system stops supplying air to the space. This causes CO_2 and CHOH concentrations to build up. For up to 10 minutes of power outage, the CO_2 concentrations remain below the guideline value of 900 ppm (ppm.hours = 0, **Fig. 6**). At 15 minutes of shock, concentrations increase beyond 900 ppm for 24 minutes reaching a maximum of 940 ppm (4% increase w.r.t threshold). Hence, for up to 15 minutes of power outage, the space remains within the allowed violation threshold of CO_2 (ppm.hours = 9.3, **Fig. 6**). However, for longer shocks (>15 minutes), violations become longer and more intense, deviating outside the allowed limits. For example, for a power outage of 60 minutes, concentrations remain above 900 ppm for 2 hours reaching a peak of 1240 ppm towards the end of the shock (27% increase w.r.t threshold) (**Fig. 4**) (ppm.hours = 381, **Fig. 6**). Such concentrations can cause sick building syndromes (lethargy, drowsiness, nausea, fatigue).

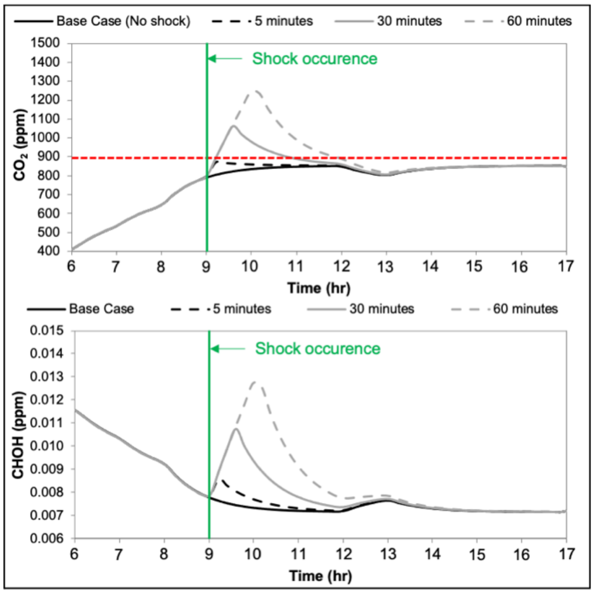


Fig. 4 – Illustration of the temporal variation of CO_2 and CHOH concentrations (ppm) for the base case and power outage shocks from 6:00 – 17:00.

As for CHOH, similarly during the power outage shocks, concentrations increase to reach peaks 0.013 ppm at 60 minutes. However, they remain way below the intervention value of 0.08 ppm and the thresholds of mild sensory irritation.

Consequently, during power outage shocks below 15 minutes, the building can be considered as resilient. However, this is not the case for longer shocks. The building is no longer resilient especially against high-emission pollutants like CO_2 (4% of exhaled air volume). Note that the building is always resilient against power outage shocks that cause peaks in VOC emissions. This is since VOC emission rates are much lower than CO_2 emission rates.

3.2.2 Shock II: Additional occupants

According to **Fig. 6**, for 1 additional occupant in the space, CO_2 concentrations remain well below 900 ppm (ppm.hours = 0). Therefore, an additional occupant is equivalent to [0-10] min power outage shock. For 2 additional occupants, concentrations increase beyond 900 ppm for 56 minutes reaching a peak of 940 ppm (4% increase w.r.t threshold) (**Fig. 5**) (ppm.hours = 17.5, **Fig. 6**). The violation duration and intensity increased with additional occupancy even long after the shock was over (additional occupants left the office after 1 hour). For example, for 6 additional occupants, violation duration increased to 2 hours with peak concentrations of 1150 ppm (ppm.hours = 251.5, **Fig. 6**).

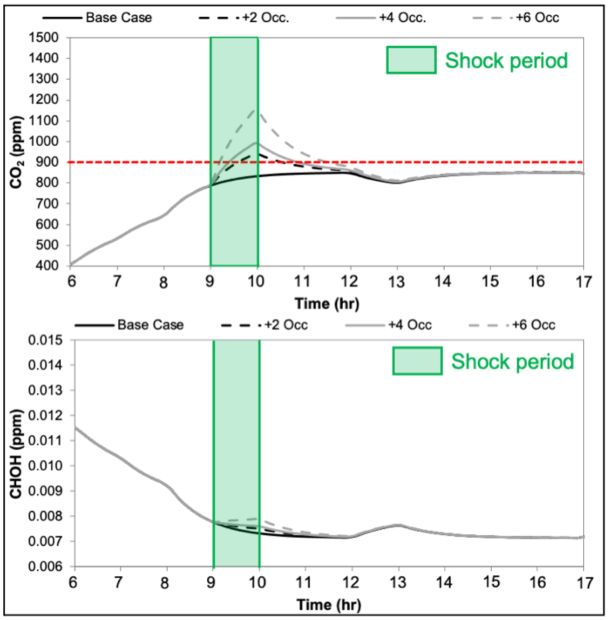


Fig. 5 – Illustration of the temporal variation of CO_2 and CHOH concentrations (ppm) for the base case and occupancy shocks from 6:00 – 17:00.

As for CHOH, concentrations increase during shocks, however much less than the power outage shock. For example, the peak concentration reached 0.0079 ppm during the maximum shock of 6 additional occupants. This is since the exhalation emission rates of CHOH from occupants are not that significant when compared to surface emissions especially from linoleum flooring (5 times lower), and particle board tables (27 times lower).

Consequently, the building remains resilient against CO_2 for 1 additional occupant. However, for more than 1 occupant, it is no longer resilient. Note that the building is always resilient against occupancy shocks that cause peaks in VOC emissions.

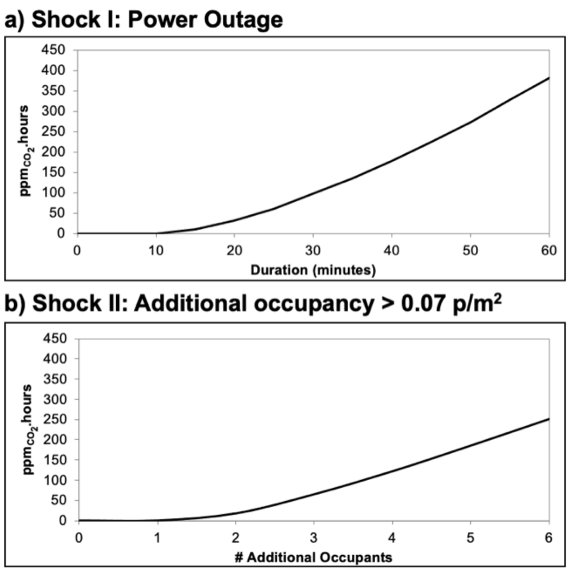


Fig. 6 – Illustration of CO_2 ppm.hours violations for the : a) Power outage and b) Occupancy shocks.

3.2.3 Combined shocks

For the case of combined power outage shock of 60 minutes and 6 additional occupants (extreme cases), as expected the building and system are not resilient. CO_2 violations lasted for 3 hours and concentrations reach peaks of 1747 ppm. The corresponding ppm.hours is 1061. No violations were noted for formaldehyde.

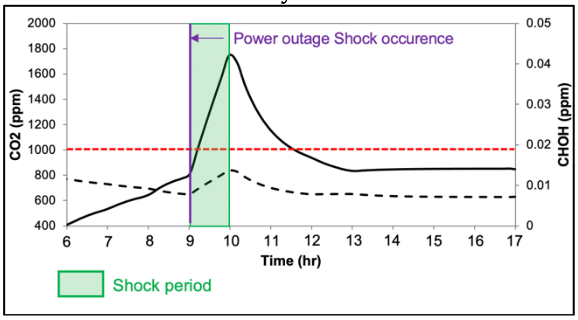


Fig. 7 – Illustration of the temporal variation of CO_2 and CHOH concentrations (ppm) for combined power outage (60 min) and additional occupancy (+6 occ) from 6:00 – 17:00.

4. Conclusion

In this work, the ventilation resilience of an office space equipped with scheduled ventilation was tested against power outage shocks and additional occupancy beyond expected peaks. Two types of pollutants were considered (exhaled CO_2 and formaldehyde from exhalation and surfaces to represent common indoor VOC). Simulation results showed that for power outage shocks, the building/ventilation system were resilient for up to 15 minutes of shock and for 1 additional occupant in the space. Beyond those limits, the building/ventilation system were no longer resilient (especially against high emission pollutants like CO_2) and additional interventions are needed (e.g., backup generator, battery-powered actuators to open windows, etc.). Therefore, as a standalone smart ventilation strategy, scheduled ventilation is not enough to withstand shocks of high intensity and duration.

Future work includes testing ventilation resilience against other types of shock (i.e., outdoor pollution), more critical contaminants like particulate matter, other types of spaces (i.e., educational buildings) and other ventilation strategies. Moreover, other aspects of ventilation resilience will be assessed and quantified along with shock impact (absorptivity and restorative capacity) as well as quantifying the shocks (degree of shock) by developing mathematical indicators.

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