Experimental and simulation analysis of different natural ventilation scenarios and their relation with IAQ in office buildings

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ABSTRACT

Following the pandemic of Covid-19, the scientific interest in ventilation rate of buildings, and especially in spaces with high occupancy, has increased. The creation of a healthy and acceptable internal environment, especially at workplaces is considered necessary, both to deal with the sick building syndrome, or the spread of various diseases, as well as to improve the comfort of employees. In the proposed work, the experimental investigation of the indoor environment in naturally ventilated office buildings, located in Kozani, Western Macedonia, Greece, is presented; the investigation took place during the pandemic period of Covid-19. Measurements include thermal comfort parameters as well as Indoor Air Quality (IAQ) ones. As concern the ventilation of the buildings, the air exchange rates were determined according to the tracer gas decay and equilibrium analysis methods, using CO_2 as tracer gas; simulation analysis using appropriate computational approaches (CONTAM) was also applied. Different scenarios of ventilation, like natural ventilation with open or closed windows and mechanical ventilation, were applied; ventilation rates were assessed, as well as the concentration of chemical compounds like CO_2. The elaboration of results leads to the formulation of a daily practice concerning the opening of the windows or the operation of the mechanical ventilation system, in order to optimize IAQ, while energy consumption would also be potentially decreased. The proposed approach, combining experimental and computational tools, can be further elaborated, towards the formulation of an integrated methodology, contributing to healthier and more comfortable indoor environment, while energy aspects can also be considered.

KEYWORDS

IAQ; ventilation rate; office buildings; tracer gas method; CONTAM

1 INTRODUCTION

Covid-19 pandemic that we have been experiencing for the last years has led to the revision of the ventilation requirements for the residential buildings, especially as regards building units that show severe overcrowding like offices buildings (Sakellaris et., 2023) or educational facilities (Award et al., 2022). The ANSI/ASHRAE Standard 62.2 (ASHRAE, 2022), as well as the European CEN EN 16798-2 (CEN, 2018), are the most common standards which offer guidance on ventilation airflow rates. There are many factors that can affect indoor air quality (IAQ) like outdoor pollution sources, consumer products, building materials, human activities and ventilation (Baeza Romero et al., 2022). IAQ and generally the indoor environmental quality (IEQ) can influence health, comfort and productivity of the users. Building ventilation is an important parameter, in order to ensure adequate IAQ (WHO, 2010; Awbi, 1998). Ventilation can be provided by natural (passive) or mechanical supply and/or exhaust systems.

Air ventilation rate per hour is used to check the air renewal in a given place (ACH). The recommended minimum amount of fresh air at office buildings is about 8.5 l/s/person (ASHRAE, 2022) according to ASHRAE standard, while for the WHO is 10 l/s/person (WHO, 2010). The most common experimental methods to calculate ACH is the tracer gas and blower-door methods. The first method uses concentrations of gases like carbon dioxide (CO_2) as tracers to predict the ACH, while the blower door method is a steady-state method, which can be implemented by fan pressurization in a range of pressure differences, usually in steps of 10–60 Pa (ASTM, 2018). On the other hand, the numerical simulation models include multi-zone airflow model, regional model and computational fluid dynamics (CFD) model. Multi-zone airflow model is believed to be the best choice for predicting ventilation performance on the building scale, while CFD model is most widely used to describe the airflow in a zone part with high accuracy (Chen et al., 2010).

In the present work, a theoretical and experimental investigation of ventilation rates at office buildings located in Western Macedonia at the city of Kozani, is presented. The experimental measurements carried out included, among others, the recording of carbon dioxide (CO_2) concentrations of which can be used to calculate the ventilation rates of the spaces using tracer gas methods. At the same time, simulation of the ventilation was carried out in the multizone simulation program of CONTAM, investigating two natural ventilation scenarios, one with open windows at intervals and the other with closed ones. Then, CO_2 concentrations were calculated for the different simulated scenarios. The main objective of the work is to assess the effectiveness of the combination of experimental and theoretical methods, with an emphasis on naturally ventilated buildings, where the ventilation rate varies dynamically. The ability to accurately estimate indoor ventilation will contribute to formulating solutions to improve air quality, while avoiding uncontrolled energy consumption due to the consequent increase in heating and cooling loads brought by ventilation.

2 METHODOLOGY

2.1 Description of the investigated buildings

The buildings under investigation refer to three different natural ventilated office buildings, located at Kozani, Greece. The first is the building of the Research Committee of the University of Western Macedonia (Building I). The second one is the building of the Municipal Enterprise for Water Supply and Sewerage (Building II), while the third one is the building hosting the local tax authority (Building III). The climate of Kozani is characterized as the coldest one, regarding Greece (Kozani is ranked on D climate zone according to the Greek version of the EPBD (TEE, 2010)), because of its location and altitude (710m); rainfall is generally moderate, summers are mild and snowfall is frequent in the winter months. The occurring meteorological parameters during the campaign, have been obtained from a meteorological station installed for the scope of the research.

2.2 Experimental measurement set-up

The monitoring period took place during winter period of 2022, when the Pandemic Period of Covid-19 still existed. The investigation per building lasted five days, from Monday morning to Friday afternoon. The measurement campaign was based on ISO 7726 (ISO, 2001) and ANSI/ASHRAE Standard 55 (ANSI/ASHRAE, 2023). Sensors that can record air temperature, relative humidity and CO_2 were used. The above parameters were measured at a height of 1.1 m, based on the recommendations of ISO 7726 (ISO, 2001). Special care was taken in order to ensure that the instruments would not disturb any class activities. The time interval for all the environmental parameters are about 1-min (ISO, 2001). The characteristics of the installed instruments are presented in Table 1.

Table 1: Measuring quantity, instrument indication

Measuring Quantity	Instrument Type	Accuracy	Range
T-RH-C_{CO2}	Hobo Onset MX1102A	±0.21°C (T), ±2% (RH), ±50ppm (CO_2)	0-50 °C (T), 1-95% (RH), 0-5000ppm (C_{CO2})
T-RH-C_{CO2}	Hobo Onset U12-012	±0.5°C (T), ±5% (RH), ±50ppm (CO_2)	-20 to 70 °C (T), 5-95% (RH), 0-2500ppm (C_{CO2})
T-RH-C_{CO2}	Hobo Onset Talaire 7001	±0.5°C (T), ±5% (RH), ±50ppm (CO_2)	-20 to 70 °C (T), 5-95% (RH), 0-5000ppm (C_{CO2})
Wind Speed	Gill Instruments 3D Anemometer	±1.5% RMS	0-50m/s (u)
T-RH	DeltaOhm Hygrotransmitter HD9009TR	±0.5°C (T), ±5% (RH),	-40 to 80°C (T), 0-100% (RH)
Wind Speed	Thies CLIMA 4.3515.30.000	±0.5m/s (u)	0.5-40 m/s (u)
Wind Direction	Thies CLIMA 4.3127.40.000	±4°	0-360°

2.3 Tracer gas methods

For the estimation of the ventilation rate of the offices, the tracer gas approach is used (ASTM, 2018) as mentioned before. The steady-state or equilibrium method can be used when the concentration of the tracer gas becomes constant during the occupancy period. Since this method is a single zone method, it can only be used to estimate ventilation rate on a building with a uniform CO_2 concentration. On the other hand, decay or step-down methods can be used when a space is vacated after occupancy, or if there is a stepwise decrease in occupancy. The estimation of ventilation rate is made measuring the rate of the reduction of the tracer gas concentration over a certain period. Below are presented the equations of both models:

$$Q_S = \frac{10^6 G}{C_{in} - C_{out}} \quad (1)$$

where: Qs: Ventilation rate of the space [L/s], G: CO2 generation rate [L/s], C_{in}: Steady-state concentration CO_2 in the zone [ppm], Cout: Outdoor CO_2 concentration [ppm]

$$Q_D = \frac{V}{\Delta t} \ln \frac{(C_1 - C_{out})}{(C_0 - C_{out})} \quad (2)$$

where: Q_D: Ventilation rate of the space [L/s], V: Volume of the space [m^3], C_1: Maximum CO_2 concentration in decay period Δt [ppm], C_0: Minimum CO_2 concentration in decay period Δt [ppm], Cout: Outdoor CO_2 concentration [ppm], Δt: Time period [hours]

2.4 Simulation program

Contam is a multizone network software developed from the university of National Institute of Standards and Technology (Dolis and Polidoro, 2020). Contam can be used to calculate the ventilation rates of the building, taking advantage of the pressure differences observed between the zones of the building, as well as the external environment. In this way, it is possible to determine the air changes, but also the variation of the ventilation rate as a function of time. At the same time, the software can perform calculations regarding the concentration of pollutants inside the buildings, both due to external or internal sources. The steps of the simulation analysis are the following: firstly the design of the pseudo-geometry of the building with the inside zones is inserted; in figure 1 the case for Building I is presented. Then flow paths like windows, doors or cracks that connect each zone together or with the outdoor environment are created. Weather data are also necessary for the simulations, as CONTAM calculates the airflows between rooms (and outdoor), by taking into account the wind pressure on the building envelope through the use of pressure coefficients with wind velocity and direction; these are the air pathways (Picard et al., 2022). The needed meteorological data were taken from the meteorological station used in the measurement campaign, while the pressure coefficients were taken from the Air Infiltration and Ventilation Center (AIVC) database (Orme et al., 1998).

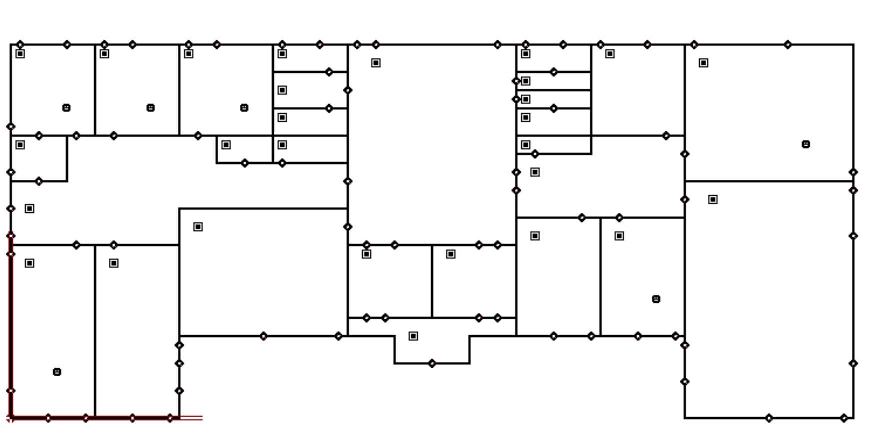

Figure 1: Pseudo-geometry of Building I

3 RESULTS/DISCUSSION

In this section, the ventilation rates determined using the experimental data with the tracer gas models, in comparison with the ventilation rates calculated by simulating them in the Contam computer program, for all three buildings, are presented. Following on, the CO_2 concentrations resulting from the experimental data, and from the CONTAM analysis, are presented.

3.1 Ventilation rates

In the following table (table 2), the measurement days per building are presented, as well as the number of offices for which CO_2 concentration was analysed. It is important to note that the ventilation frequency of the offices differed not only from building to building, but also from office to office. The users in all the examined buildings did not follow a specific program of ventilation, both in terms of time and ventilation method, i.e. number of open windows/percentage of opening), noting that this creates difficulties in the exact calculation of the ventilation rate using the experimental data. At the same time, the experimental method using tracer gas method applied for the assessment of ventilation is presented.

Table 2: Measurement campaign information

Column Title	Time of /measurement campaign	Number of offices	Tracer gas method
Building I	31/01/2022-03/02/2022	4	Decay
Building II	12/04/2022-19/04/2022	3	Decay/Steady-state
Building III	24/01/2022-27/01/2022	4	Decay

Figure 2 presents the ventilation rate (h^{-1}) for the first building (I), as it was determined according to the tracer gas methods (steady-state or decay), while also calculated on the basis of the simulation program (CONTAM). The decay method was implemented on a period when the users left from the offices. and CO_2 generation equals zero; the calculation of ventilation rate with Contam for this case was performed for the same time period.

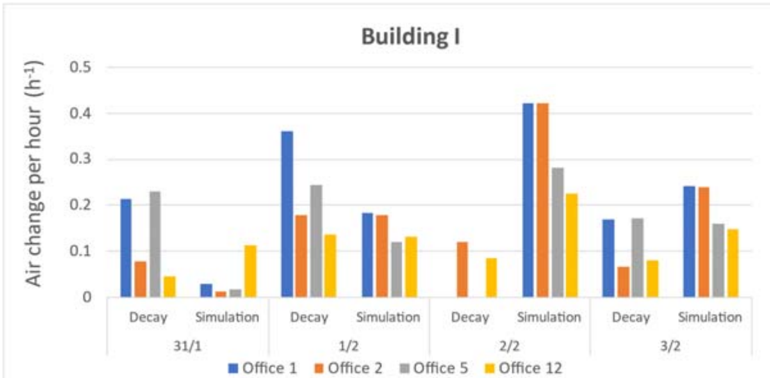

Figure 2: Ventilation rates of Building I

The absence of values at 2/2 for the decay method in Figure 2, is related to a problem in the measurement instrument. As it can be seen, in several cases the ventilation values of the decay method and the simulation present some deviation, , as for example on 1/31. This may be due to the meteorological data used to run the simulations or the selection of flowpaths and schedules entered into the software. From the results on 31/1 and 1/2, it is notable that the decay method gives higher ventilation rates compared to the simulation, in contrast to 2/2 & 3/2, where higher values of air changes per hour are observed according to Contam results. Nevertheless, on an overall assessment, the ventilation rate for each office is relatively small, i.e. less than $0.5h^{-1}$.

In the figures below (Figures 3 and 4), the ventilation rate calculated with the steady state model for the period 12/4 to 15/4 is presented, noting that conditions allowed the adoption of this model, while for the period 18/4 to 19/4, the decay method was implemented. Both results are compared with the simulation ones.

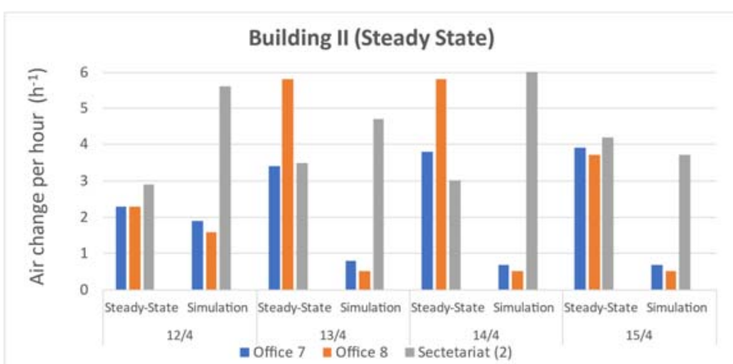

Figure 3: Ventilation rate for Building II (steady state method)

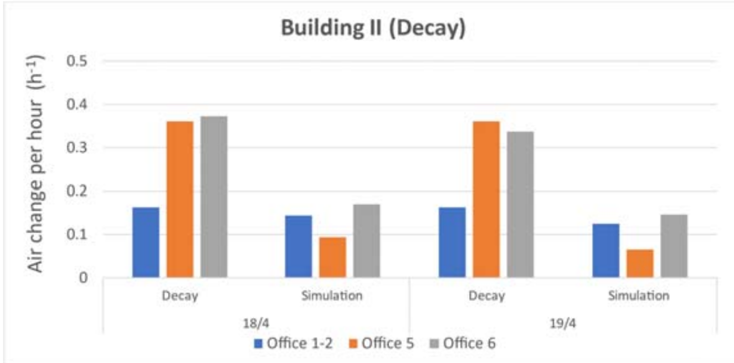

Figure 4: Ventilation rate for Building II (decay method)

The differences between the experimental and simulation results, regarding the ventilation rate estimation, are higher for the case of steady state, in comparison with the case of the decay method. This can be partly attributed to the fact that the time intervals selected for open windows, at the simulation runs, are different from the actual ones (referring to the steady-state method), as the good outdoor conditions give the opportunity to the users to open the windows for more time. On the other hand, during the measurement period of 18/4 and 19/4, the employees opened the windows of the offices for a shorter period of time as the external conditions were not very acceptable (low outside temperatures); this allowed the implementation of the decay method instead.

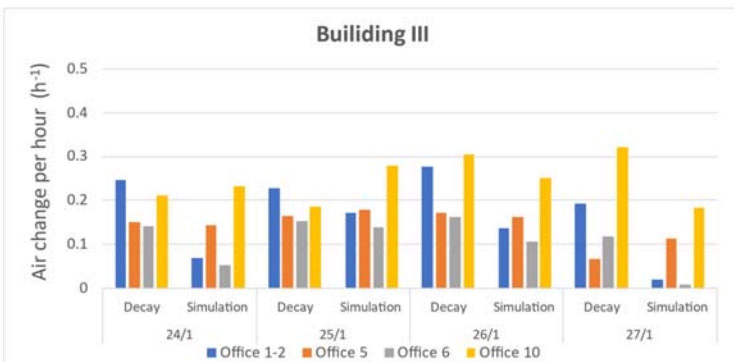

Figure 5: Ventilation rate for Building III (decay method)

Figure 5 presents the ventilation rates for Building III. The values are comparable between the simulation and experimental approach, with the main discrepancies to appear at offices 1&2, as well as office 6. On an overall assessment for all investigated buildings, the infiltration rates are similar and lower than 0.5 h^{-1}.

3.2 CO_2 concentration scenarios

Below are presented the CO_2 concentration diagrams for all buildings, as these are obtained from the experimental measurements, as well as from the simulation with the CONTAM software. The simulation scenarios included the business-as-usual scenario, referring to the conditions of the experimental analysis (scenario 1), an increased ventilation rate scenario, referring to the windows being opened at specific periods of the day (scenario 2), as well as a scenario with closed windows during the working hours (scenario 3); in table 3, specific characteristics of the experimental and simulation scenarios are summarized.

Table 3: Characteristics of experimental and simulation scenarios

Scenario 1	Experimental measurement of CO_2 using Hobo sensors (black color)
Scenario 2	Simulation results with open windows during some specific periods of working days: 9.00 – 9.15 a.m., 11.00 – 11.15 p.m. και 13.00 – 13.15 p.m. (green color)
Scenario 3	Simulation results with closed windows during working hours (yellow color)

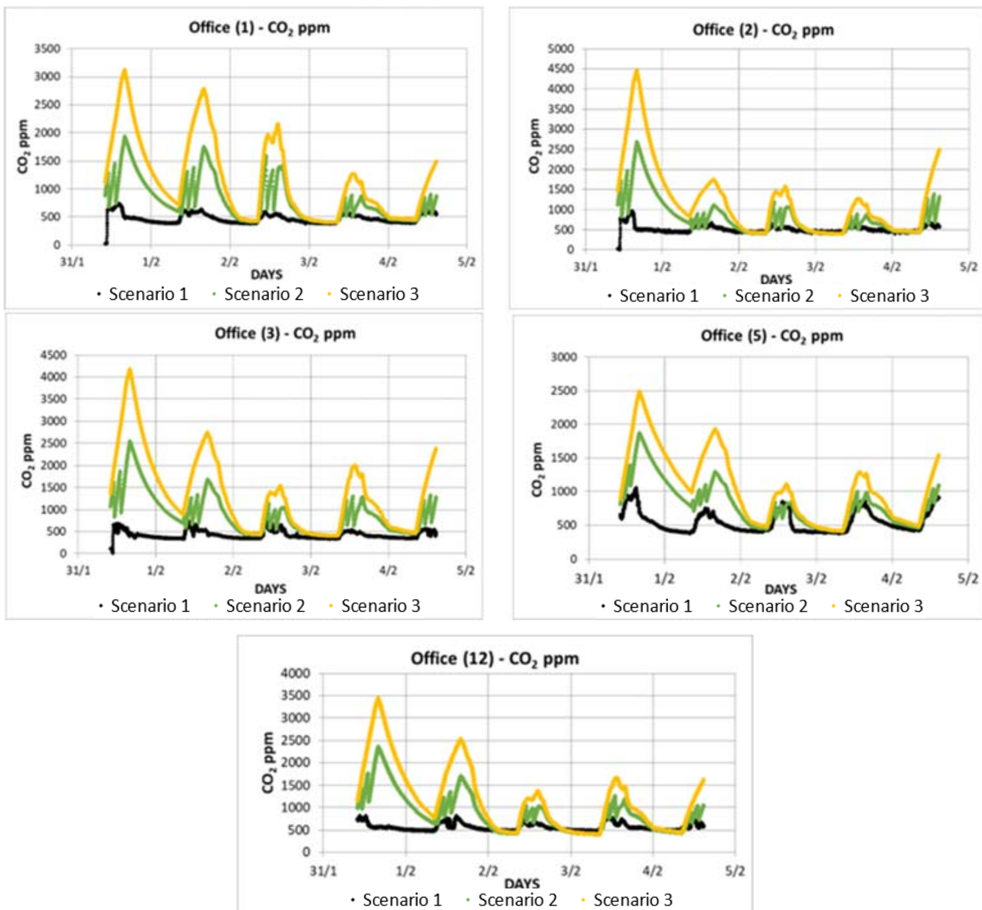

Figure 6: CO_2 concentration for experimental measurements and simulation scenarios for Building I

According to Figure 6, in all the offices of Building I it is notable that the actual CO_2 concentrations (scenario 1) are clearly lower than those obtained from the simulation (scenarios 2 & 3). The highest concentrations are shown in scenario 3, as the windows were closed, so CO_2 levels are expected to be considerably higher. Regarding scenario 2, the time program (schedule) for opening the windows that was selected was indicative, not representing the actual time that they were open. In general, the windows seem to open more hours for the actual case, as demonstrated by the results of scenario 1; this was also discussed above. In the time period 31/1 – 2/2 simulation included more people in the schedule of Contam, with regard to the actual case, leading to higher CO_2 concentration values for scenarios 2 and 3. Despite the discrepancies discussed above, one should note that for all scenarios the CO_2 concentration presets similar behavior; i.e. a gradual increase, after the users join their offices, accompanied by a decrease by the end of the working schedule.

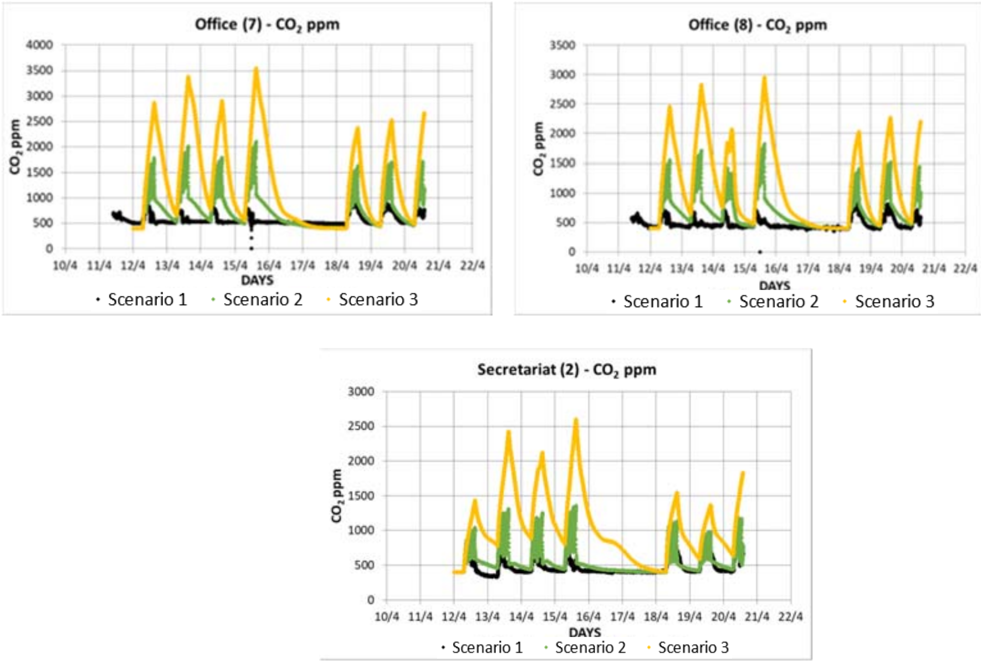

Figure 7: CO_2 concentration for experimental measurements and simulation scenarios for Building II

Similarly, in the case of Building II (figure 7), the CO_2 levels in scenario 1 are considerably lower than those in scenarios 2 and 3. The actual values of the experimental measurements are at low levels, as there was increased mobility of the employees during the day and many of them were absent from the workplaces. This mobility was difficult to be reflected at the schedule input of Contam, so the CO_2 concentration for scenarios 2 and 3 is higher. In addition, the open office spaces, as is the case of Building 2, lead to lower CO_2 concentrations (Sakellaris et al.,2023). Furthermore, the indicated differences in the CO_2 concentration, for scenarios 1 and 2, even on a qualitative basis, as indicated by the relevant curves in figure 7, can also be attibuted to the meteorological data used in the simulation, since these were rather incomplete. Despite the indicated differences, the gradual increase in concentration from the arrival to the departure of the employees, is also observed for Building 2 for all scenarios. By the end of the working schedule, CO_2 concentration seems to exceed the indicated limits (ASHRAE, 2022) for scenarios 2 and 3.

Regarding Building III, and similar to the other buildings, the CO_2 concentration is higher for the scenario 3 since the windows are closed (figure 8). In offices 1-2, 5 and 6 it is notable that scenarios 1 and 2 are generally identical, as people remained in their desks for longer period, and the opening of the windows seems to have taken place according to the prescribed schedule. Finally, especially regarding Office 10, the CO2 concentration is quite high, being in considerable agreement with scenario 3, demonstrating that the windows at this office are mostly closed.

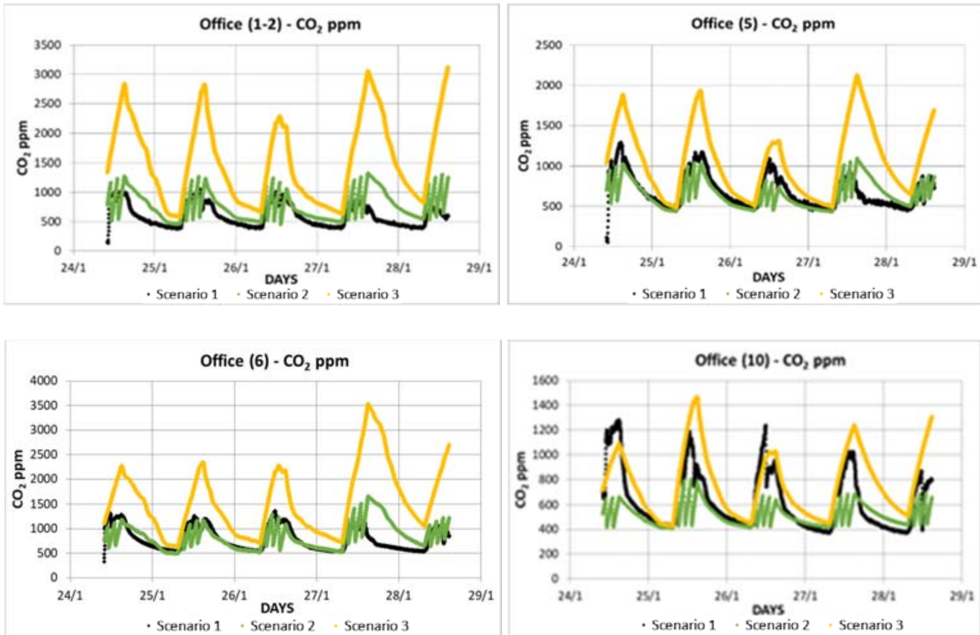

Figure 8: CO_2 concentration for experimental measurements and simulation scenarios for Building III

4 CONCLUSIONS

The proposed work aims at presenting the potential of combined use of experimental and simulation approaches, towards the assessment of IAQ and ventilation rates for burdened indoor air cases, as the offices ones, during the Covid-19 pandemic.

The results demonstrated that the current situation is satisfactory for all buildings, while at the same time there is intention for reducing the ventilation rate, which will lead to a potential reduction in energy consumption to maintain thermal comfort conditions. The application of the experimental methods showed that ventilation rate lies within expected levels, as far as infiltration is concerned, while CO_2 concentration is in line with the relevant limits. The uncertainties of experimental analysis are related to the accuracy of the measuring instruments, the estimation of the actual number of people inside the spaces and, mainly, the varying ventilation program of the spaces.

The results of the simulation investigation showed that the air exchanges fluctuate at normal levels and similar to the experimental results, while the CO_2 levels are proportional to the ventilation scenarios. As mentioned, the simulation method can be used for the approximate evaluation of the existing conditions during measurement campaign, but also for the investigation of different ventilation scenarios, so that interventions can be made to improve it. The uncertainties of this method are significant and varied, especially when investigating naturally ventilated buildings. Characteristics of the openings of the building, the meteorological data used for the simulations, the number of people inside the offices are critical parameters of uncertainties. The proposed analysis aimed at the demonstration and evaluation of experimental and simulation methods, towards the integration of the selected solutions into a single approach, in order to overcome any uncertainties arising from each method separately. Future work will systematically address the development of an integrated methodology for the assessment of IAQ and ventilation rates in buildings of various uses, utilizing the experience and results gained by this work, while also extending its applicability towards the consideration of energy aspects.

5 ACKNOWLEDGEMENTS

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