Experimental analysis of the ventilation rate in an amphitheater operating under the COVID-19 pandemic constraints

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Abstract. In the context of the Covid-19 pandemic (officially declared by the WHO on March 11th, 2020), indoor air quality (IAQ) has resurged as a renewed paradigm, demanding enhanced attention, especially in spaces with high occupancy density, as is the case of school buildings. To minimize the risk of contamination indoors, it is needed to assure low concentrations of the biological pollutant load eventually resulting from the exhalation of the microorganism SARS-COV-2, through the dilution capacity of the ventilation systems. One way of checking the risk reduction is through the spatially comprehensive assessment of the air exchange rate (AER) in the indoor space. The present study was motivated by a request from the Faculty of Sciences and Technology of the University of Coimbra (FCTUC) in Portugal, whose spaces have been used under restrictive conditions derived from the recommendations on the operation of buildings during the pandemic. Two onsite experiments were carried out in an Amphitheater with only the exhaust component on, due to technical issues with the HVAC system in that period. The tests comprised measurements in ten different locations for representative monitoring of the occupied zone of the space. The estimation of the AER in the amphitheater in both tests was based on the analysis of the time evolution of the tracer gas (CO_2) concentration measured by each sensor/equipment. The results showed that the analyzed space presented an adequate rate of air renewal to ensure an effective dilution of indoor pollutants, and likewise of the biological pollutant load possibly resulting from the exhalation of microorganisms by an infected occupant.

Keywords. Ventilation rate, Fresh air flow rate, built environment, multisensory, Tracer Gas Method, COVID-19.
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1. Introduction

In the context of the recent pandemic, Covid-19 (officially declared by the WHO on March 11th, 2020), indoor air quality (IAQ) has resurged as a renewed paradigm, demanding specific attention.

To minimize the risk of contamination indoors, it is needed to assure low concentrations of the biological pollutant load eventually resulting from the exhalation of the microorganism SARS-COV-2, through the dilution and exhaust capacity of the ventilation system. To assess the risk contamination reduction, the spatial broad value determination of the air exchange rate (AER) of an indoor space is one possibility.

In fact, Covid-19 has stressed the reprioritization of indoor air quality (IAQ) [1]. Concerning IAQ, the need to inspect HVAC systems before spaces return to their "normal" occupancy has been strongly advocated [2], starting from the early positioning of ASHRAE relating to SARS-COV-2 microorganism air transmission, in April 2020: "Transmission of SARS-CoV-2 through the air is sufficiently likely that airborne exposure to the virus should be controlled" [3].

The present study was motivated by a request from the Faculty of Sciences and Technology of the University of Coimbra (FCTUC) in Portugal, whose classrooms and amphitheaters have been used under restrictive conditions derived from the recommendations on the operation of buildings during the Covid-19 pandemic [4], namely reduced occupancy and all possible measures for ventilation enhancement. The methodology adopted is multiuse and replicable to many other case studies such as concert halls, cinema rooms, or meetings rooms, for example.

To assess the current ventilation performance of the Amphitheater C.1 of the building of the Department of Physics of FCTUC, an experimental assessment of the air exchange rate (AER) was carried out. The amphitheater's fresh airflow rate (Q) was determined using the tracer gas method (TGM), in its concentration decay variant, as it is the best-suited one for a quick analysis. Besides the COVID-19 inherent restrictions – occupancy reduced to about one third, this amphitheater has presently a further limitation: its central heating, ventilation and air conditioning (HVAC) system cannot be fully operated because the air supply ducts are thermally insulated from the inside and the insulation material (rock wool) is degraded. Therefore, during the current academic activities, only the exhaust network of the HVAC system is active and the access doors (at the top level of this space) are kept frankly open. As stated in [5], "the prevention of indoor pollution is essential, especially considering the purpose of disease transmission resistance". The Amphitheater's current operation condition – just the extraction system is on – works also as a precaution manner against COVID-19 since no use of air recirculation is done [6], assuring one very important aspect: occupants' health [7].

In November 2020, two onsite experiments were carried out with the exhaust system on and: a) only the upper, main access doors open (at ground level); b) with all doors of the amphitheater open (i.e., two additional doors at the lower level). It should be remarked that this amphitheater is accessed through a big hall and a long corridor on the ground floor of the building, whose main entrance is kept open during the working day periods. As such, the ventilation air (infiltrated through the access doors) is not strictly outdoor fresh air; it is rather air transferred from the inner spaces of the building.

The tests comprised measurements in ten different locations for representative monitoring of the occupied space. The estimation of the AER in the amphitheater in both tests was based on the analysis of the time evolution of the tracer gas (CO_2) concentration measured by each sensor/equipment.

2. CO_2 concentration measurement in the indoor air

2.1 Method and object of study

The Amphitheater under study is located in the building of the Department of Physics of the University of Coimbra (b. 1969-75), in Portugal. Following the purpose of this study, the Amphitheater's fresh air flow rate (Q) was determined using the Tracer Gas Method (TGM), in its variant based on the concentration decay, as it is the one that best suited the aimed objective. This method consists essentially of the supply and homogenization of tracer gas in the compartment object of study and in the subsequent analysis of the time evolution (decay) of its concentration, by the action of the ventilation system operating in a steady-state regime.

Considering that this gas must be colorless, odorless, and tasteless, with a density close to that of air, and non-toxic, carbon dioxide (CO_2) was used as a tracer gas, since it is easily available and the respective monitoring sensors are nowadays affordable to be simultaneously used in multiple measuring locations. This gas is inherently present and associated with the human occupancy of indoor spaces (metabolic CO_2), but it can also be proposedly emitted through some equipment such as fire extinguishers (where the extinguishing agent is carbon dioxide, a liquefied gas stored under high pressure). The latter was the option in this study, since the amphitheater was not, nor had just been, occupied – only the authors were present. As such, after vigorous CO_2 spraying and a 5-minute homogenization period, using a movable long-range fan, the ventilation system (exhaust only) was turned on and the time evolutions of the CO_2 concentration measured at ten different locations were recorded for further analysis, aiming at the estimation of the AER λ [h^{-1}] in the amphitheater, in both tests.

Deriving from a steady-state mass balance, the time evolution of a pollutant concentration inside a uni-zone indoor space, during a period in which the emission rate of that pollutant and the fresh air flow rate remain constant, after a step variation of any of these parameters that can affect the concentration value, can be modeled by the exponential equation (1):

$$C(t) = C_{equi} + (C_0 - C_{equi}) \times e^{-\lambda t} \qquad (1)$$

where:
- $C(t)$ is the pollutant concentration at the instant t, [ppm] or [mg/m^3];
- C_{equi} is the asymptotic value of the concentration reached at equilibrium ($t \rightarrow \infty$);
- C_0 is the initial concentration value ($t = 0$), [ppm] or [mg/m^3];
- λ is the infiltration rate / AER in the compartment, [h^{-1}] or [n. º of air changes per hour].

Equation (1) can be written as follows*:*

$$C(t) - C_{equi} = (C_0 - C_{equi}) \times e^{-\lambda t} \qquad (2)$$

which suggests fitting to the experimental data an exponential function, in the form:

$$y = k \times e^{-\lambda x} \qquad (3)$$

To perform this type of adjustment (*e.g.*, using MS Excel), it is necessary to create the column of instantaneous values of y, corresponding to the difference $C(t) - C_{equi}$ (excess concentration), where $C(t)$ represents the measured values. In the case of the CO_2 concentration decay in an indoor space, after the emission suppression from internal sources, the value of the equilibrium concentration C_{equi} usually corresponds to the CO_2 concentration of the ambient outdoor air (approximately 400 ppm, in a low-polluted area). To obtain the air exchange rate λ (number of air changes per hour, h^{-1}), the values of the independent variable (time instants t) must be expressed in hours, taking $t = 0$ as the instant corresponding to the initial concentration C_0.

As an example, **Fig. 1** shows the time evolution of the concentration values $C(t)$ measured with one of the sensors during one of the decay tests, and of the corresponding excess concentration, $C(t){-}C_{equi}$, considering C_{equi} = 500 ppm (1). The exponential regression fitted to the values of $C(t){-}C_{equi}$ (dashed line) allows one to conclude that λ = 4.53 h^{-1}, *i.e.*, the ventilation rate would be 4.53 air changes per hour. The 1549 ppm value corresponds to the "fitted" estimate of the excess concentration $C_0{-}C_{equi}$ at the beginning of the test.

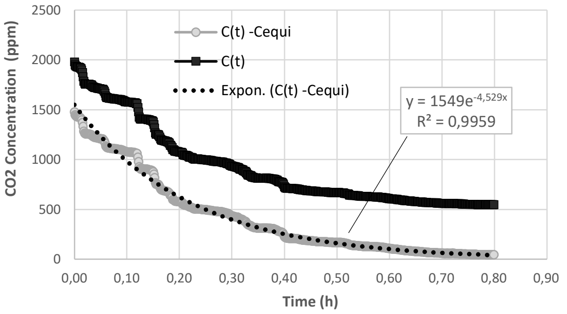

Fig. 1 - "Typical" time evolution of the CO_2 concentration $C(t)$ during a decay test. The AER λ corresponds to the symmetrical of the exponent coefficient of the fitting equation, Eq. (3).

2.2 The monitoring campaign

On November 9th, 2020 afternoon, for approximately three hours, two tests were carried out,–under the following conditions: a) only the two upper doors open (just one of the two-door leaves); b) with all doors open (2).

The CO_2 concentration measurements were made simultaneously in ten different locations inside the amphitheater. **Fig. 2** shows the spatial distribution of the measurement points, over a plan drawing. **Fig. 3** also shows the interior of the amphitheater, with images of the spatial distribution of the various equipment and sensors. The sampling and measurement strategy is summarized in **Tab. 1**.

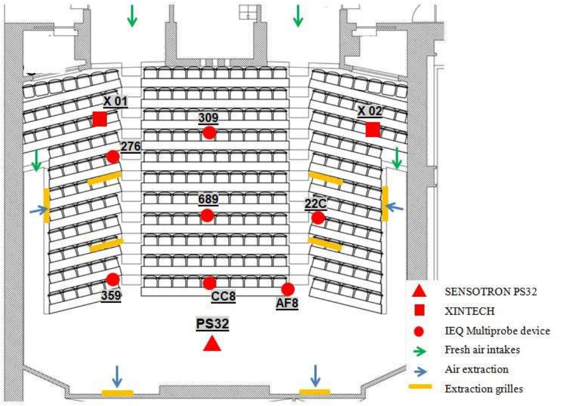

Fig. 2 - Amphitheater plan drawing with the location of the sensors, as well as the infiltration air intakes and the extraction grilles.

Tab. 1 - Sampling and measurement strategy.

Volume (m^3)	Nº points	Nº technologies	Nº tests
1200	10	3	2

Fig. 3 - Interior view of the amphitheater: images at various moments of the tests and of the spatial distribution of sensors and equipment.

2.3 Equipment

Information on the measurement equipment used and the respective metrological characteristics (accuracy and resolution) is shown in **Tab. 2**. The measurement methodology was the same in all devices (**Fig. 4**): non-dispersive infrared (NDIR) sensors and 5/10 s-time step data acquisition.

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[1] This C_{equi} value is higher than the typical CO_2 concentration value in ambient air (~ 400 ppm) because, in this case, the ventilation intake air was not real outdoor air, but transferred air, from other spaces in the building (entrance hall and corridors).

[2] For the second test, two additional doors at the amphitheater's ground level were also opened. The upper two-leaf doors (at the building's ground level) are the usual access to the amphitheater; under the COVID-19 health security restrictions, these doors are kept frankly open (both leaves) before and during academic activities, while the occupancy capacity has been reduced from 206 to 64 (teacher included).

Tab. 2. Equipment used in measurements for the assessment of IAQ in the building and respective measurement methods

Pollutant	Equipment	Accuracy	Quantity	Sampling frequency
CO_2	SENSOTRON PS32	±10 + 3% rdg* ±50 ppm	1	10 s
	XINTEST data logger	±5% rdg ±50 ppm	2	
	IEQ Multiprobe device	±3% rdg ±30 ppm	7	5 s

**% rdg= % reading*

Fig. 4 - Monitoring equipment (*[8]).

2.4 Legal framework

The Portuguese legal framework, originally presented in M. C. Gameiro da Silva 2020, is cited as follows:

"In Portugal, the legal regime for indoor air quality in buildings is established by Decree-Law nº. 118/2013 of 20 August and other complementary and subsequent legislation (Decree-Law no. 68A / 2015, Decree-Law no. 194/2015, Decree-Law no. 251/2015, Decree-Law no. 28/2016, Decree-Law no. 52/2018 and Decree-Law no. 95/2019) and by Ordinance no. 349B / 2013 of 29 November, specifically for residential buildings and Ordinance No. 353-A / 2013 of 4 December and Law No. 52/2018 of 20 August for commerce and services buildings.

RECS (3) *establishes also the need to comply with minimum fresh air flow rates, to guarantee, under normal conditions, the dilution of contaminants to concentration values below the respective protection thresholds.*

For the calculation of the fresh air flow rate requirements, it is necessary to consider the pollutant load occupant-originated, two methods are proposed, both based on the CO_2 *concentrations, inside the space in question, as this bio-effluent is most abundant and its evolution has a high correlation with occupancy rates:*

- *The Analytical Method, in which the criterion to be verified is the average concentration of* CO_2 *during the occupancy period inside the space under analysis, is prescribed a protection threshold that should not be exceeded (2500* mg/m^3 *or 1250 ppm);*

- *The Prescriptive Method, in which the criterion is that the* CO_2 *equilibrium concentration does not exceed the prescribed value for the protection threshold (2500* mg/m^3 *or 1250 ppm). The values prescribed in the RECS resulted from the application of the expression*:

$$Q = G/(C_{equi} - C_{ext}) \tag{4}$$

Where:
- Q is the fresh air flow rate (m^3/h*);*
- G is the generation of pollutants inside the room (mg/h);
- C_{equi} *is the equilibrium concentration of the pollutant in the indoor air (*mg/m^3*);*
- C_{ext} *is the concentration of the pollutant in the outside air (*mg/m^3*).*

In a simplified way, the required fresh air flow rates, per person, suggested by the prescriptive method in RECS (which takes into account human occupancy, can be calculated from the expression Q = 20 x M, where M represents the metabolic rate of occupants expected for the space/activity in question, expressed in the "met" unit defined in ISO 7730: 2015 [10]*".*

The studied Amphitheater has an approximate volume of 1200 m^3. According to the terminology of the SCE (4), this building is considered a service

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[3] RECS - Regulation of Energy Performance of Commercial and Service Buildings (In Portuguese, *Regulamento de Desempenho Energético dos Edifícios de Comércio e Serviços*).

[4] SCE - Building Energy Certification System (In Portuguese: *Sistema de Certificação Energética dos Edifícios*). Decree-Law no. 118/2013, of 20 August

building, therefore framed by the RECS [5].

In this context, according to Ordinance 353-A / 2013, *"the value of fresh air flow rate to be introduced into the spaces must be corrected by the efficiency of pollutant removal (...).",* which defines that the minimum fresh air flow rates (Q) to be considered for a space can be determined using the two above-mentioned methods.

Herein, Q was determined through the *Prescriptive Method.* According to Ordinance No. 353-A / 2013, Table I.04, the metabolic rate (M) of the occupants in an amphitheater corresponds to 1 Met, prescribing 20 m^3/(hour. person). For this purpose, Q is estimated using the following expression:

$$Q = \mathrm{M}_{\mathrm{med}} \cdot Q_{1met} \quad \text{expressed in } m^3/(\text{h.person}). \qquad (5)$$

As an example, in an amphitheater with a capacity for 100 people, Q = 2000 m^3/h would be necessary (4080 or 1280 m^3/h, in the cases of 204 or 64 occupants, respectively.

3. Results and Data analysis

3.1 Experimental data

As previously described, to determine the ventilation rates in the amphitheater under the COVID-19 restrictive conditions, two tests were carried out: a) first, only the two upper access doors were opened (only one leaf); b) afterward, all doors (upper and lower) open. In both tests, only the exhaust air part of the HVAC system was turned on.

The results of the measurements for all the sampling points considered (Figure 2) are shown in the following figures and tables.

As an example, in **Fig. 5**, the overall continuous monitoring of sensor SN_309 along the two tests is presented. The measurements by the other probes/equipment showed similar trends. Then, the CO_2 concentration decay periods were analyzed in the two tests (indicated in red in this figure).

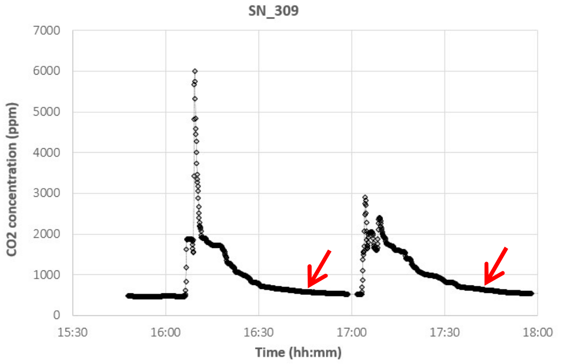

Fig. 5 - Graphical representation of CO_2 decay in the Amphitheater (measured in sensor SN_309). The red arrows indicate the analyzed decay periods.

The graphical representation of the decay period during the second test is shown in **Fig. 6**, showing the values measured with all the sensors/equipment. The interpretation of this graph can be followed by **Tab. 3**, regarding the first test. The results of the second test are shown in **Tab. 4**.

Based on the averages of the monitoring with the different sensors/equipment, in the different locations for representative distribution of the occupied zone of the space, the following average values of the air renewal rate and fresh air flow rate were obtained:

- 5.62 h^{-1} and 6744 m^3/h, first test;
- 4.77 h^{-1} and 5728 m^3/h, second test.

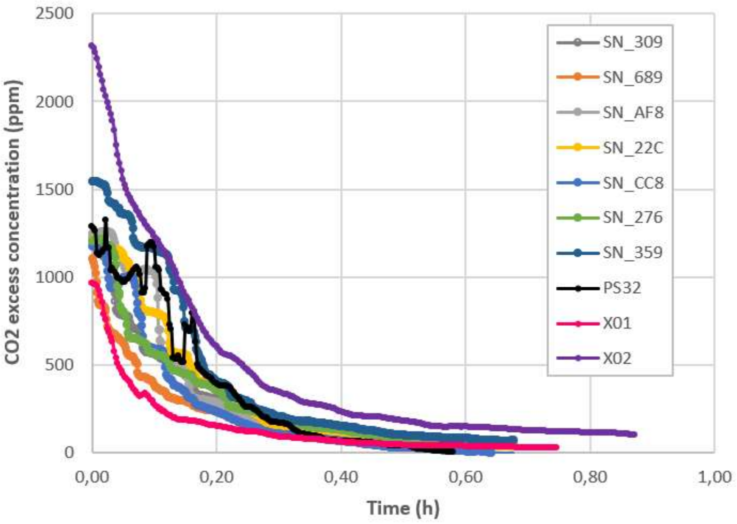

Fig. 6 - Graphical representation of CO_2 decay in Amphitheater C.1 during the second test (as in Fig.2).

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[5] Ordinance No. 353-A / 2013 of 4 December.

Tab. 3. Results of the first test

Equipment	Sampling point reference	AER (λ, h^{-1})	Fresh Air Flow Rate ($Q = V \times \lambda$, m^3/h)
SENSOTRON	PS32	8.93	10716
XINTEST	X 01	4.69	5628
	X 02	3.46	4152
IEQ Multiprobe	SN_309	4.92	5904
	SN_689	5.13	6156
	SN_AF8	5.21	6252
	SN_22C	5.67	6804
	SN_CC8	7.95	9540
	SN_276	4.89	5868
	SN_359	5.35	6420

Tab. 4. Results of the second test

Equipment	Sampling point reference	AER (λ, h^{-1})	Fresh Air Flow Rate ($Q = V \times \lambda$, m^3/h)
SENSOTRON	PS32	7.58	9096
XINTEST	X 01	6.28	7536
	X 02	3.30	3960
IEQ Multiprobe	SN_309	4.53	5436
	SN_689	4.39	5268
	SN_AF8	4.27	5124
	SN_22C	4.92	5904
	SN_CC8	4.17	5004
	SN_276	4.48	5376
	SN_359	3.81	4572

Figure 7 shows the AER, λ (h^{-1}), values obtained in the two tests with each of the different sensors/equipment, together with the respective location in the amphitheater. This figure suggests the following essential conclusions:

1. There is no advantage in opening the lower-level doors in addition to the main access doors (2nd test). On the contrary, the air exchange rate is lower than keeping only the upper doors open (1st test).
2. With greater evidence in the 1st test, the flow of fresh air intaken through the two (upper) access doors tends to converge to the lower central zone, which presents a clearly higher ventilation rate than the average of the entire amphitheater.

3.2 Simulation results

Using a computational tool that allows modeling the time evolution of CO_2 concentration in an interior compartment [11], simulations were made for two different conditions of use of the studied amphitheater (see **Fig. s 8** and **9**). The current situation of the auditorium in the pandemic scenario was simulated, with the restriction of the total of 206 existing seats to a maximum of 64 occupied seats (63 students and 1 teacher).

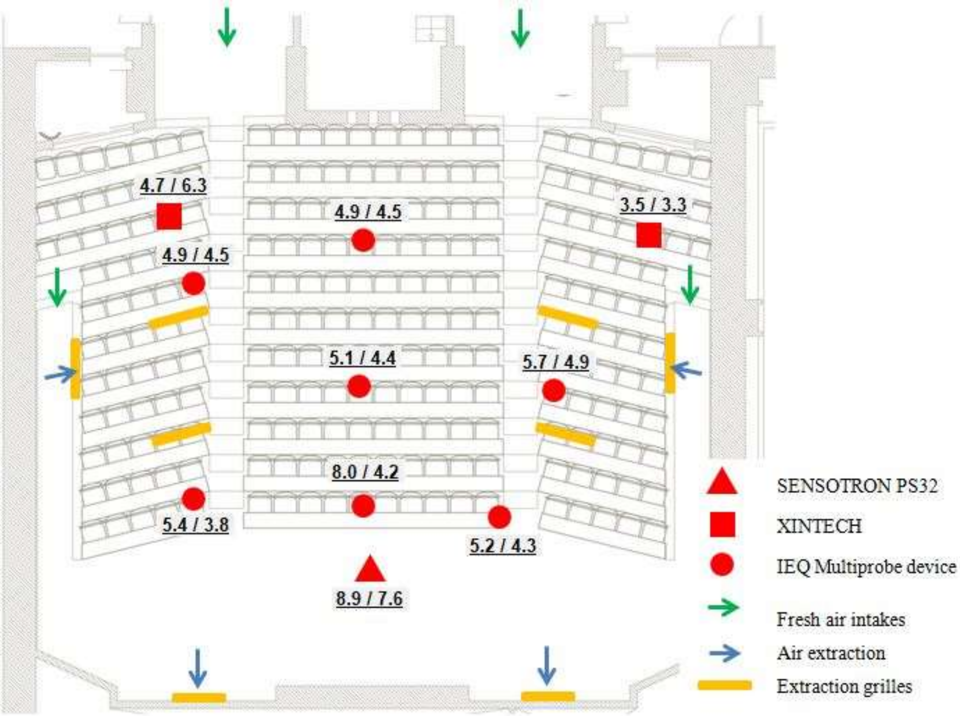

Fig. 7 - Air Exchange Rate values, λ (h^{-1}) obtained in the different locations in the two tests performed (1^{st} / 2^{nd}).

In this case, a typical value of 5.15 air changes per hour was considered, similar to what was determined in the experimental tests, which, for a room volume of 1200 m^3, indicates a total of 6080 m^3/h of fresh air, corresponding to 95 m^3/h per person.

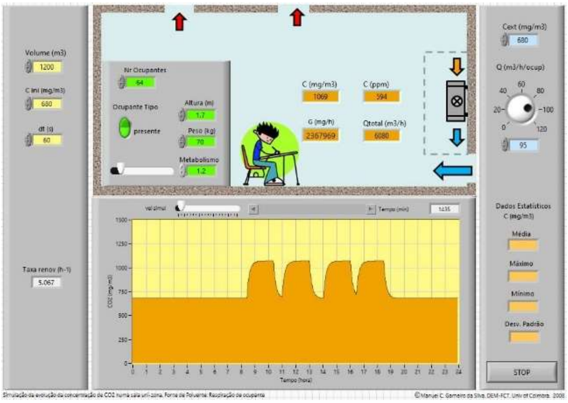
Volume (m3) 1200
C ini (mg/m3) 680
dt (s) 60
Taxa renov (h-1) 5.067
Nr Ocupantes 64
Ocupante Tipo presente
Altura (m) 1.7
Peso (kg) 70
Metabolismo 1.2
C (mg/m3) 1069
C (ppm) 594
G (mg/h) 2367969
Qtotal (m3/h) 6080
Cext (mg/m3) 680
Q (m3/h/ocup) 95
Tempo (min) 1435
Dados Estatísticos C (mg/m3)
Média
Máximo
Mínimo
Desv. Padrão
Simulação da evolução da concentração de CO2 numa sala uni-zona. Fonte de Poluente: Respiração do ocupante
©Manuel C. Gameiro da Silva, DEM-FCT, Univ of Coimbra 2008

Fig. 8 - Simulation of the temporal evolution of CO_2 concentration in the Amphitheater in the current use (64 seated people).

In the simulation carried out, it was assumed that the Amphitheater would have 64 seats occupied, during a typical school day, comprising four 2h-classes. It was also considered that students would leave the space in the 15-min intervals between consecutive classes, as well as during the 1h-break for lunch. The value of the equilibrium/maximum CO_2 concentration reached during each of the classes, under the conditions mentioned above, is 1089 mg/m^3 (594 ppm), which indicates an excellent level of indoor air quality, particularly remarkable because the assumed value of ventilation rate (5.15 h^{-1}) is achieved by operating only the exhaust network of the HVAC system.

A second simulation was performed for the conditions that would certainly have been the design parameters of the ventilation system (maximum occupancy of the room with 206 people and a fresh air flow rate of 30 m^3/h/person). A room operation routine similar to the previous case was considered. A value of 1913 mg/m^3 (1063 ppm) was obtained for the CO_2 equilibrium concentrations, which shows to be frankly satisfactory.

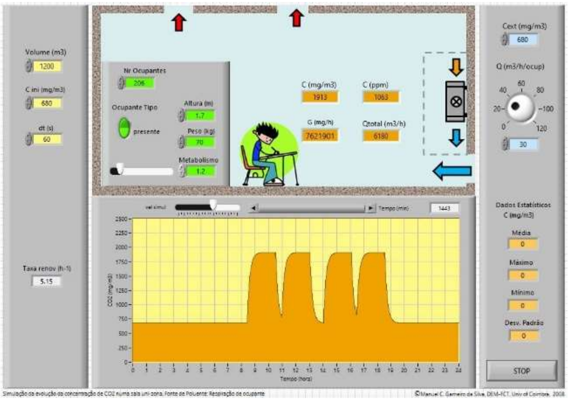
Volume (m3) 1200
C ini (mg/m3) 680
dt (s) 60
Taxa renov (h-1) 5.15
Nr Ocupantes 206
Ocupante Tipo presente
Altura (m) 1.7
Peso (kg) 70
Metabolismo 1.2
C (mg/m3) 1913
C (ppm) 1063
G (mg/h) 7621901
Qtotal (m3/h) 6180
Cext (mg/m3) 680
Q (m3/h/ocup) 30
Tempo (min) 1443
Dados Estatísticos C (mg/m3)
Média 0
Máximo 0
Mínimo 0
Desv. Padrão 0
Simulação da evolução da concentração de CO2 numa sala uni-zona. Fonte de Poluente: Respiração do ocupante
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Fig. 9 - Simulation of the time evolution of CO_2 concentration in the Amphitheater with the normal, pre-pandemic use (206 seated people).

4. Conclusions

The present study allows concluding that the analyzed space presents an adequate rate of air renewal to ensure that there is an effective dilution of the biological pollutant load that might result from the exhalation of this microorganism (SARS-COV-2) by an infected occupant. The values of fresh air flow rate guaranteed by the existing conditions, in this scenario of reducing the maximum number of occupied places from 206 to 64, are around 95 m^3/h per occupant, which is more than thrice the values recommended by the national legislation and international standards for the pre-pandemic scenario.

However, considering that the "fresh air" is not directly intaken from the outdoors, but is rather transferred from interior spaces of the building itself – mainly from the access hall and the ground floor corridor –, it is important to ensure that the entrance door of the building remains open during operating hours, having all underlying health safety rules currently in effect at the UC, in the current COVID-19 pandemic context.

The proposed methodology that allows obtaining a spatial distribution of the air exchange rate in a large room is multiuse and replicable to other case studies such as concert halls, cinemas, or meeting rooms.

5. Acknowledgement

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Data Statement

The datasets generated during and/or analysed during the current study are not available but the authors will make every reasonable effort to publish them in near future.