Covid Risk^{airborne}, a tool to test the risk of aerosol transmission of SARS-CoV-2 under different scenarios: a pre-school classroom case study

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Abstract: The COVID-19 emergency has shown that airborne transmission of SARS-CoV-2 is especially relevant in poorly bad ventilated spaces with high occupancy density, like non-university classrooms, a widespread space typology with very sensitive occupants. Of these, pre-school classrooms stand out, due to the vulnerability of children. Thus, this study has estimated the existing transmission risk of SARS-CoV-2 in a pre-school classroom, due to the especial vulnerability of the children, regarding to different indoor CO_2 excess levels. This statistical evaluation has been performed through 68 calculation hypotheses, grouped into 4 cases, according to who is the primary infected occupant (one of the children or the teacher) and depending on whether the teacher wears a mask or not. It can be concluded that, to have acceptable risk conditions for airborne disease transmission (with one infected occupant) in pre-school classrooms, it is necessary to maintain sufficient ventilation conditions to reach a maximum average excess CO_2 level exhaled of 150 ppm, while teachers should wear well-fitting N95 respirators. In this way, infection risk is much higher when the primary infected occupant is the teacher and is wearing no mask or a surgical one —5 or 6 times more.

Keywords: CO_2 concentration; School buildings; SARS-CoV-2; Airborne transmission; COVID-19 infection risk

1. Introduction

The airborne transmission of SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2) is widely proven by scientific community (Morawska and Cao, 2020; Greenhalgh *et al.*, 2021; Miller *et al.*, 2021; Tang *et al.*, 2021; Wang *et al.*, 2021; World Health Organization, 2021; Burgos-Ramos, Urbieta and Rodríguez, 2022), with the main COVID-19 outbreaks occurring indoors (Qian *et al.*, 2021; Randall *et al.*, 2021; Wang *et al.*, 2022). In this way, medium and long-range transmission —beyond 1.5 m— is especially relevant in poorly bad ventilated spaces (Li, 2021; Peng *et al.*, 2022).

In this way, one of the most widespread space typologies are non-university classrooms, in which children —considered as sensitive and vulnerable population— spend an average of 5-6 hours a day, from Monday to Friday during nine months a year, focused on winter and mid-seasons. In this way, classrooms are high occupancy density spaces with usually poor ventilation conditions, as several studies have pointed out in southern Spain (Fernández-Agüera *et al.*, 2019; Villanueva *et al.*, 2021), France (Annesi-Maesano *et al.*, 2012), Italy (De Giuli, Da Pos and De Carli, 2012; Annesi-Maesano *et al.*, 2013; De Giuli *et al.*, 2014) and Portugal (Almeida *et al.*, 2011; Campano *et al.*, 2017), among others, due a lack of ventilation. Given that there have also been several documented COVID-19 outbreaks in educational buildings (Fontanet *et al.*, 2021; Lorthe *et al.*, 2022), it is necessary to promote healthy classrooms through self-protection practices and adequate indoor air quality (IAQ). Thus, the removal of the virus-containing aerosols from indoor air —by ventilation, air filtration or UV radiation— is an essential part of the prevention strategy.

One of the main ways to assess the degradation of the IAQ in occupied spaces —with no other significant sources or sinks of indoor carbon dioxide (CO_2) — is monitoring the indoor CO_2 level, which can be a good proxy to evaluate and control the aforementioned ventilation rates, especially in spaces with high occupancy density such as non-university classrooms (Persily and de Jonge, 2017; American National Standards Institute and American Society of Heating Refrigerating and Air-Conditioning Engineers, 2019; Zhu *et al.*, 2020; Pavilonis *et al.*, 2021; Peng and Jimenez, 2021; Peng *et al.*, 2022). As it was mentioned already, the measurement of the excess CO_2 level exhaled (ΔCO_2) can also be used to estimate the airborne transmission risk of respiratory diseases such SARS-CoV-2, tuberculosis, or measles, given that virus-containing aerosols are emitted during the respiratory process as CO_2 does. Thus, the infection risk of SARS-CoV-2 can be estimated using the indoor CO_2 excess as a proxy through adaptations (Jiménez Palacios and Peng, 2021; Peng and Jimenez, 2021; Peng *et al.*, 2022; Rowe *et al.*, 2022) of the Wells-Riley model (Rudnick and Milton, 2003).

In this way, it is possible to estimate the COVID-19 infection risk indoors —strictly via aerosols— is to use the online tool COVID Risk [airborne] (https://www.covidairbornerisk.com/), non-profit developed by Campano et al. (Campano-Laborda et al., 2021) and based on the adaptation of the Wells-Riley model performed by Peng and Jiménez (Jiménez Palacios and Peng, 2021; Peng and Jimenez, 2021).

The main aim of this work is to estimate and analyse the existing transmission risk of SARS-CoV-2 in a pre-school classroom, due to the especial vulnerability of the children and the lack of proper use of masks due to their age, regarding to different indoor CO_2 excess levels. With the results of this theoretical study, it is possible to optimize the ventilation and self-protection strategies of the occupants.

2. Materials and Methods

The following phases have been established to develop this study:

- Sample
- Boundary conditions
- Hypotheses under study
- Infection risk indicators

2.1. Sample

An Andalusian pre-school classroom was chosen as the study case. Its shape, dimensions, HVAC systems, furniture and theoretical occupation are standardized according to the design standards established for non-university educational institutions (Junta de Andalucía, 2003). The premise is 50 m² and 3 meters high, designed for a maximum capacity of 24 children (Campano, 2015). It has its own bathroom, with a direct access from inside the classroom, as well as an associated schoolyard, accessible from a door on the façade of the premise (Figure 1).

The classroom has no suspended ceiling or perforations in the inner partitions with the adjacent classroom nor the corridor. The external vertical wall is composed by a half-brick wall with rendering, an air chamber, projected polyurethane as thermal insulation and a plasterboard. The internal partitions are composed of two layers of plasterboard with mineral wool between them.

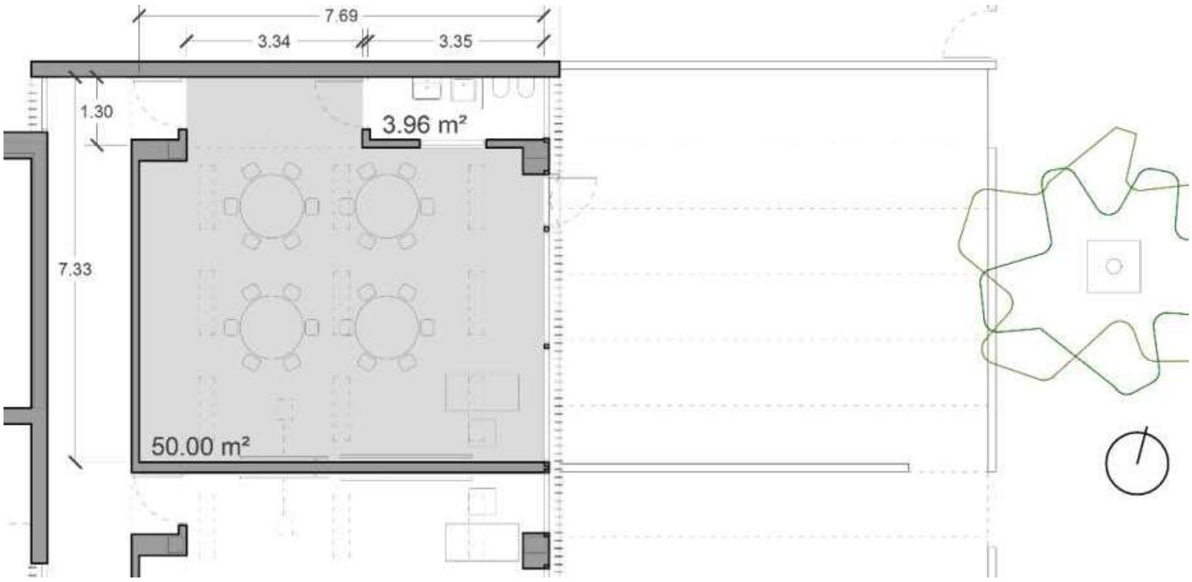

Figure 1. Ground plan of the pre-school classroom under study, following design standards for regional educational institutions.

Heating system is composed by hot water (HW) radiators, with no provision for cooling systems (Campano, Sendra and Domínguez, 2011; Campano *et al.*, 2019).

Ventilation is traditionally relied by windows operation and uncontrolled infiltrations, despite the Spanish Standard on thermal installations in Buildings (RITE) (Ministerio de la Presidencia del Gobierno de España, 2021) establishes the controlled mechanical ventilation as the only option for non-residential buildings. In winter conditions, the lower limit for operative temperature set by Spanish RITE is 21 ºC, while the maximum operative temperature in summer conditions is 25 ºC.

The school day in pre-school and primary public schools of Andalusia is 5 hours, usually from 9:00 a.m. to 2:00 p.m., with a half-hour break in between. Each centre can establish the starting point of said break, although it is usually in the middle of the school day (from 11:15 to 11:45).

2.2. Boundary conditions

The calculation conditions required to estimate the existing infection in the pre-school classroom under study are listed in Table 1 (Campano-Laborda *et al.*, 2020).

The exposure time (event duration) is established in 135 minutes, given that it can be considered the average period between the lunch break and the start/end of the school day. The pre-school classroom under study is also considered to be in winter environmental conditions, with the existing HW radiator system operating to achieve compliance with the hygrothermal conditions of the RITE (T_a 21ºC and *HR* 40%).

It has been estimated that there is always an infected occupant with a high viral load in the classroom, as a realistic hypothesis for the airborne transmission risk simulations.

Table 1. Boundary conditions of the case of study for the statistical study of infection risk

Dimensions			
Area (m²)	50.0	Heigh (m)	3.0
Environmental conditions (winter season)			
Indoor air temperature (ºC)	21.0	Relative indoor air humidity (%)	40
Atmospheric pressure (atm)	1.0	Indoor atmosphere	Still air
Variant of SARS-CoV-2			
Variant of SARS-CoV-2	Omicron BA.2	Percentile of viral exhalation rate (%)	85
Occupancy parameters and type of activity			
No. of infectious occupants	1	No. of people present	25
Mean age of occupants (years)	5	Event duration (min)	135
Intensity of activity of the children	Sitting – Oral respiration	Intensity of activity of the teacher	Standing – Speaking

2.3. Hypotheses under study

Four scenarios were considered for this study, using the average excess CO_2 level exhaled (ΔCO_2) during 135 minutes of a regular educational day (exposure period) as a proxy to calculate how many 'quanta' inhaled each occupant (a 'quanta' can be considered as the minimum infectious dose of the aerosol pathogen whose inhalation leads to infection in 63% of vulnerable people). They are grouped in two categories, according to the occupant who was initially infected (child or teacher).

- CASE 1: One infected child by SARS-CoV-2 (sitting – oral respiration) and no one wearing a mask in the classroom.
- CASE 2a: Teacher infected (standing – speaking) and no one wearing a mask in the classroom.
- CASE 2b: Teacher infected (standing – speaking), wearing a surgical mask (non-fitted) and the rest of occupants with no masks.
- CASE 2c: Teacher infected (standing – speaking), wearing a well-fitting N95 respirator and the rest of occupants with no masks.

The risk calculations defined above were performed considering increases in the average indoor-outdoor CO_2 differential of 100 ppm, with an excess range of 100 to 1600 ppm, as previously measured in this type of premises (Fernández-Agüera *et al.*, 2019).

This procedure also allows to consider the following thresholds:

- The Spanish RITE CO_2 limit value for classrooms (indoor air quality of IDA 2), which can be expressed as an increase of 500 ppm of CO_2 above the outside level for spaces with high occupancy density (Ministerio de la Presidencia del Gobierno de España, 2021).
- The recommendations developed for schools during the COVID-19 emergency situation, which establishes a CO_2 threshold of 300 ppm above the outside level (Jones et al., 2020; Minguillón et al., 2020; Plataforma Aireamos, 2021). This limit is close to the IDA 1 CO_2 threshold of the Spanish RITE (350 ppm), applicable to hospitals, nurseries and nursing homes.
- The recommendation developed for indoor educational spaces, both for classrooms with vulnerable occupants or with no masks, and for corridors (spillway spaces), which

establishes a CO_2 threshold of 150 ppm above the outside level (Plataforma Aireamos, 2021).

2.4. Infection Risk Indicators

This statistical study is developed through two risk indicators, adapted to airborne disease transmission (Peng and Jimenez, 2021; Peng *et al.*, 2022):

- Attack rate (*AR*): The proportion of occupants in the event who could have inhaled the necessary infectious dose of the aerosol pathogen whose inhalation leads to infection in 63% of vulnerable people ('quanta').
- Relative risk of infection (H_r): Number of 'quanta' emitted by a single infected person which are inhaled by a single person for a given exposure time and premises of the volume specified.

The main point of both indicators is that they are not referred to the number of vulnerable occupants (those who are liable to contract the disease), so they can be used regardless of the number of people vaccinated or the effectiveness of the different vaccines.

There are three categories of risk (low, medium, and high) for these indicators, according to previous studies of different indoor scenarios and existing documented outbreaks, as it can be seen in Table 2 (Peng and Jimenez, 2021; Peng *et al.*, 2022).

For the Wild-type SARS-CoV-2, it can be considered that there are no documented outbreaks when *AR* was under 0.5% (Peng et al., 2022), which can be correlated with a value of $Hr<0.001$.

Table 2. Limits for relative risk (*Hr*) and attack rate (*AR*) indicators (Peng and Jimenez, 2021) corrected for SARS-CoV-2 Omicron variant BA.2 sublineage.

	Low	**Medium**	**High**
AR (%)	< 0.5	< 5.0	≥ 5.0
H_r (h^2/m^3) for wild-type SARS-CoV-2	< 0.00100	< 0.01000	≥ 0.01000
Corrected H_r (h^2/m^3) for Omicron variant BA.2	< 0.00035	< 0.00294	≥ 0.00294

2.5. Calculation tool

The simulation software used to evaluate the aforementioned infection risk indicators (*AR* and H_r) is COVID Risk^{airborne} (https://www.covidairbornerisk.com/), developed by Campano et al. (Campano-Laborda et al., 2021). This tool (Figure 2) estimates the SARS-CoV-2 propagation —strictly via medium and long-range aerosols— using the adaptation (Jiménez Palacios and Peng, 2021; Peng and Jimenez, 2021; Peng *et al.*, 2022) of the Wells-Riley model for simulating disease propagation (Rudnick and Milton, 2003).

Figure 2. Landing page of Covid Risk[airborne] tool.

This methodology has been validated by comparison with existing COVID-19 outbreaks (Peng *et al.*, 2022), as it can be seen in Figure 3.

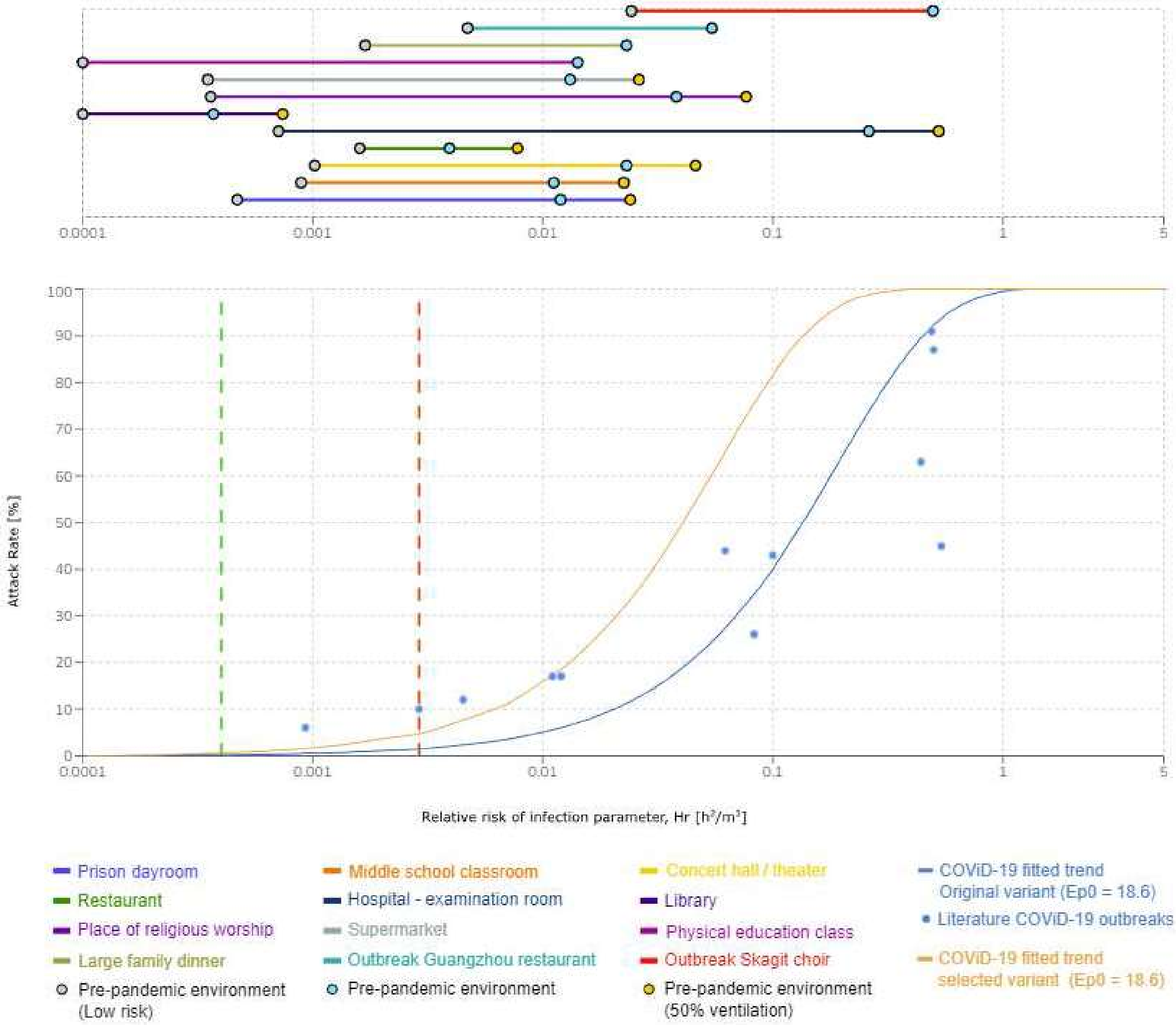

Figure 3. Graphic analysis of the Attack Rate (AR) versus the Relative risk of infection (H_r), calculated via COVID Risk[ariborne] using the methodology of Peng *et al.* (Peng *et al.*, 2022).

Among the various considerations made by this tool, it should be noted that:

- The increased transmissibility of the SARS-CoV-2 variants is obtained from the reports of the European and North American Centres for Disease Control and Prevention (Campbell *et al.*, 2021; Centers for Disease Control and Prevention, 2022).
- The estimation of the airborne viral emission is performed through the expiratory activity, which depends on the metabolic and vocalization activities (Morawska *et al.*, 2009; Buonanno, Stabile and Morawska, 2020).
- The evaluation of the average ventilation rate and the recommended short-term exposure values for inhalation, in m^3/h per occupant, are calculated through the metabolic rate, which depends on activity, age and gender (Wang *et al.*, 2011; Peng *et al.*, 2022), as well as the CO_2 emission (Persily and de Jonge, 2017).
- The decay rate of the virus infectivity in aerosols depends on the Air Temperature (T_a), Relative Humidity of the air (*HR*), the UV index and the deposition of virus-containing aerosols to surfaces (Schuit *et al.*, 2020; Smither *et al.*, 2020; van Doremalen *et al.*, 2020).
- The theoretical aerosol retention efficiency of masks, respirators and face shields (Davies *et al.*, 2013; Milton *et al.*, 2013; Melikov, 2015) is considered as:
  - Surgical mask (non-fitted): 32.5%
  - Well-fitting N95 respirator: 90.0%

3. Results and discussion

3.1. Results

The graphical evolution of H_r with respect to *AR* can be seen in Figure 4.

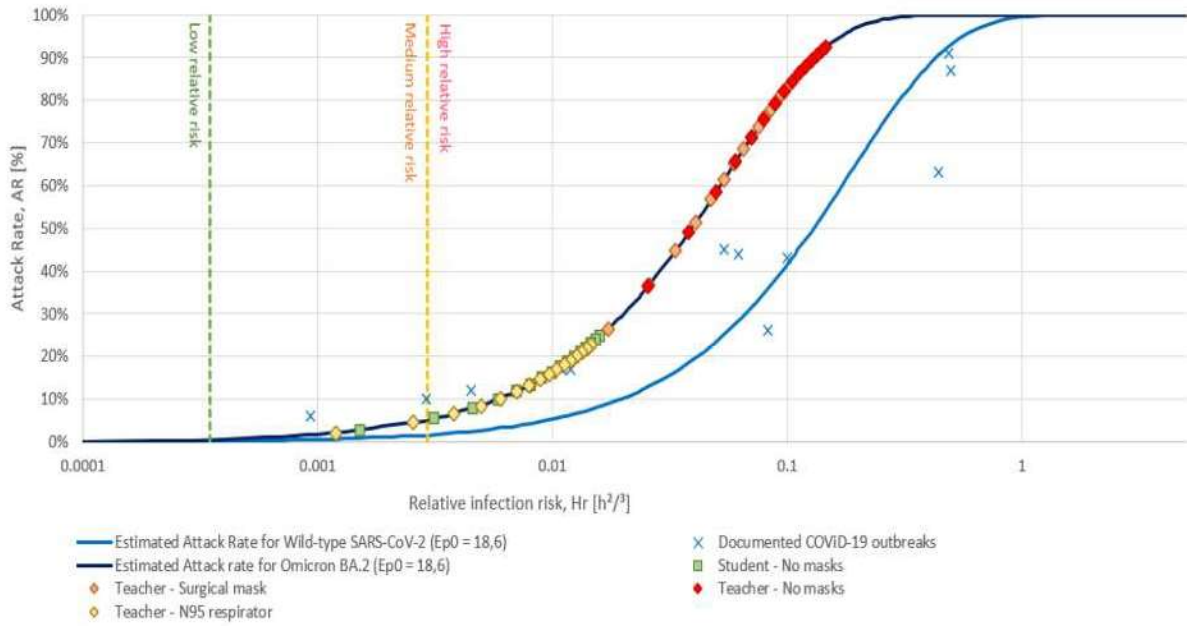

Figure 4. Graphical analysis of the Attack Rate (AR) with respect to the Relative risk of infection (H_r) for the 4 case studies of the pre-school classroom. Exposure time of 135 minutes.

The mean values of H_r and *AR* parameters are listed in Table 3 for the four cases under analysis, with respect to ΔCO_2.

Table 3. Mean values of Attack Rate (*AR*) and Relative Risk of infection (*Hr*) of SARS-CoV-2 (Omicron BA.2) per case, based on indoor boundary conditions

	Case 1		Case 2a		Case 2b		Case 2c	
Average CO_2 value	**Child - no masks**		**Teacher - no masks**		**Teacher - surgical mask**		**Teacher – well-fitting N95 respirator**	
	Oral breathing		**Talking**		**Speaking**		**Speaking**	
ΔCO_2 (ppm)	**AR (%)**	**H_r (h^2/m^3)**	**AR (%)**	**H_r (h^2/m^3)**	**AR (%)**	**H_r (h^2/m^3)**	**AR (%)**	**H_r (h^2/m^3)**
1600	24.7	0.0160	92.5	0.1463	82.6	0.0988	22.8	0.0146
1500	23.8	0.0153	91.6	0.1399	81.2	0.0945	21.9	0.0140
1400	22.8	0.0147	90.5	0.1334	79.6	0.0900	21.0	0.0133
1300	21.8	0.0139	89.3	0.1266	77.9	0.0855	20.1	0.0127
1200	20.8	0.0132	87.9	0.1196	76.0	0.0807	19.1	0.0120
1100	19.8	0.0124	86.3	0.1123	73.8	0.0758	18.0	0.0112
1000	18.6	0.0117	84.3	0.1047	71.3	0.0707	16.9	0.0105
900	17.4	0.0108	82.0	0.0969	68.5	0.0654	15.7	0.0097
800	16.2	0.0100	79.1	0.0885	65.2	0.0598	14.5	0.0089
700	14.8	0.0091	75.6	0.0797	61.4	0.0538	13.1	0.0080
600	13.3	0.0081	71.2	0.0704	56.8	0.0475	11.7	0.0070
500 (IDA 2)	**11.7**	**0.0070**	**65.7**	**0.0605**	**51.4**	**0.0408**	**10.1**	**0.0060**
400	9.9	0.0059	58.5	0.0497	44.8	0.0336	8.4	0.0050
300	**7.8**	**0.0046**	**49.1**	**0.0382**	**36.6**	**0.0258**	**6.5**	**0.0038**
200	5.4	0.0032	36.4	0.0256	26.4	0.0173	4.4	0.0026
150	**4.1**	**0.0024**	**28.5**	**0.0190**	**20.2**	**0.0128**	**3.3**	**0.0019**
100	2.6	0.0015	19.1	0.0120	13.3	0.0081	2.1	0.0012

As can be seen both in Table 3 and in Figure 4, the relative infection risk (H_r) of almost all the situations studied is high. There are no situations with low risk, existing two categories:

- High risk (<25%): The primary infected occupant is a child, or is the teacher, who is wearing a well-fitting N95 respirator.
- Very high risk (>25%): The primary infected occupant is the teacher, who is wearing no mask or a surgical one (non-fitted).

The graphical evolution of ΔCO_2 with respect to *AR* can be seen in Figure 5.

On the one hand, the hypotheses studied which have *AR* under 5% (threshold for high risk of outbreaks) are:

- One of the children is the infectious occupant —which is sedentary, silent, and breathing orally— and there is a low interior CO_2 excess (ΔCO_2 ≤150 ppm).
- The teacher is infectious occupant —which is standing and speaking, being the only one wearing a well-fitting N95 respirator— and there is a low interior CO_2 excess (ΔCO_2 ≤200 ppm).

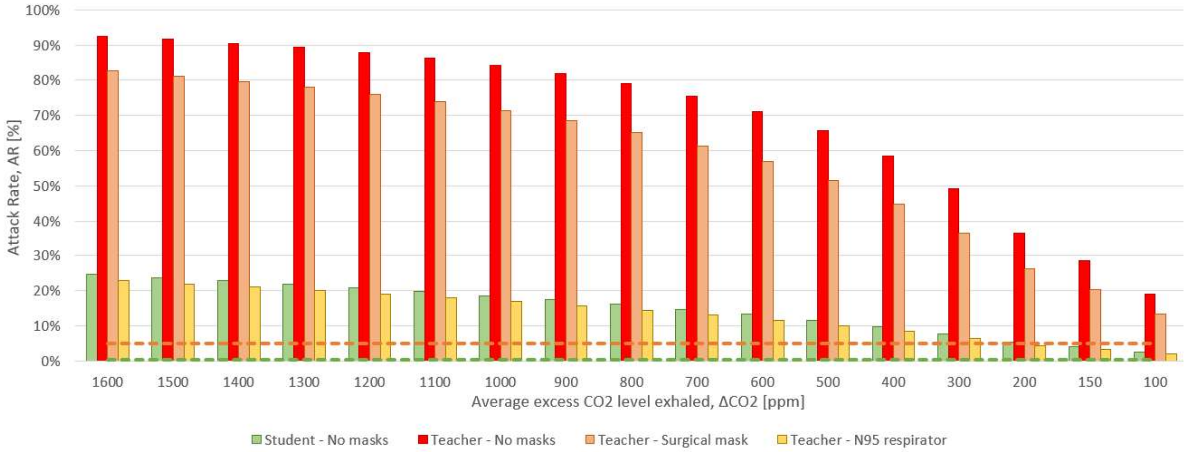

Figure 5. Graphical analysis of the Attack Rate (AR) with respect to the average excess CO_2 level exhaled (ΔCO_2) for the 4 case studies of the pre-school classroom. Exposure time of 135 minutes.

This ΔCO_2 value of 150 ppm agrees with the recommendations developed by Aireamos for indoor spaces with vulnerable occupants or with no masks.

On the other hand, the proportion of occupants who can inhale a sufficient viral dose (*AR*) rises much more markedly with respect to ΔCO_2 when the primary infected occupant is the teacher. This is due to a higher to a greater emission of potentially virus-laden aerosols, both their increased vocalization activity and their increased metabolic rate (because of their age and weight). In this way, when the teacher was the primary infected occupant and was not wearing a well-fitting N95 respirator, there was no situation with AR under 20% but with $\Delta CO_2 \leq 100$ ppm.

When AR is analysed according to RITE threshold (ΔCO_2 of 500 ppm), it can be seen that:

- If the infectious occupant is either one of the children, or the teacher (wearing a well-fitting N95 respirator): *AR* is 10-11%, doubling the admissible threshold.
- The teacher is infectious occupant, who either is wearing no mask or a non-fitted surgical one: AR is over 50-65%, 10-12 times the admissible threshold.

3.2. Study limitations

The present study has the following limitations:

- It was developed through a set of simulations, despite the method was previously validated by comparison with existing COVID-19 outbreaks.
    - Whilst it is not an epidemiological model, it can be used as a component of such approaches to estimate variations in aerosol propagation across a range of inputs.
    - The model excludes droplet and contact/fomite transmission and assumes that 2 m (6 ft) social distancing is honoured. Otherwise, the infection rates calculated would be higher.
    - Several parameters used in the model are uncertain, as they were estimated based on current knowledge.
- These simulations, of a statistical nature, simplify the existing problem by considering that the atmosphere in the classroom is uniformly distributed, so the results may differ slightly from real cases.
- The hypotheses proposed are conservative, since they are based on a maximum occupancy of the enclosure, in which there is also an infected person with a high viral

load (85% percentile of viral exhalation rate). Thus, transmissibility may be lower in many carriers.

3.3. Future lines of research

Given these limitations, future studies are suggested. They can be focused on increasing the types of classes under study to have a broader characterization of the risk of transmission in educational centres, as well as on expanding occupancy level, schedules, and prevention measures —like HEPA filters, UV radiation or HVAC systems with filters. In addition, more types of premises in another building typologies can be analysed.

4. Conclusions

A study has been performed to estimate the existing transmission risk of SARS-CoV-2 in a pre-school classroom, due to the especial vulnerability of the children and the lack of proper use of masks due to their age, regarding to different indoor CO_2 excess levels. The statistical evaluation of the infection risk has been performed through 68 calculation hypotheses, grouped into 4 cases, according to who is the primary infected occupant (one of the children or the teacher) and depending on whether the teacher wears a mask or not.

It can be concluded that, to have acceptable risk conditions for airborne disease transmission (with one infected occupant) in pre-school classrooms, it is necessary to maintain sufficient ventilation conditions to reach at least an average excess CO_2 level exhaled of 150 ppm, as well as teachers should wear well-fitting N95 respirators. In this way, infection risk is much higher when the primary infected occupant is the teacher and is wearing no mask or a surgical one —5 or 6 times more.

Thus, the use of a CO_2-controlled mechanical ventilation system is necessary in pre-schools classrooms to ensure adequate indoor air quality, especially during emergency situations due to high risk of airborne disease transmission.

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