A Novel Methodology for Risk Assessment of Airborne Transmission due to Covid-19 in University Classrooms

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Abstract

The Covid-19 pandemic revolutionized the way of designing buildings, which should be created to improve health conditions and limit the spread of contagion. Among these, schools certainly need special attention. To improve indoor conditions, the first step of this study was conducted by simulating three classrooms having different ventilation strategies, using a CFD analysis. Then the infection probability was calculated using the Gammaitoni-Nucci model to analyse the risk in the classrooms according to different ventilation and building characteristics. The study showed the need for providing adequate ventilation to ensure healthy conditions for the students. Furthermore, the infection probability was calculated considering non-uniform environments, which can result from various air distributions in the classroom due to local non-uniformities. The configuration obtained from the CFD analysis was then compared to the standard condition. which considers the classrooms as uniform environments. This allows an understanding of the effective conditions to which students are exposed and to comprehend whether the classical models do not risk underestimating the infection probability. This study provides a new methodology for airborne transmission risk assessment in non-homogeneous environments and supports designers with a new tool to evaluate HVAC systems layout and classroom operation.

1. Introduction

The importance of providing Indoor Environmental Quality (IEQ) in buildings has been always a necessity for enhancing people's health and well-being (Lamberti, 2020), especially in educational buildings, where students can improve their learning abilities (Bluyssen, 2016; Lamberti et al., 2021). This issue became even more evident after the Covid-19 outbreak, when improving IEQ to guarantee occupants' health became a priority, both during normal and critical operations (Awada et al., 2021). This new awareness led building practitioners to focus on the aspect of Indoor Air Quality (IAQ) (Awada et al., 2022). Overall, there was a tendency to rethink building design strategies (Megahed & Ghoneim, 2021) to prepare buildings for post-pandemic architecture.

Since airborne transmission was recognized as a possible route of infection (Morawska et al., 2020), researchers focused on the relationship between ventilation rate and infection risk. Indeed, ventilation can be an important preventive measure to reduce infection probability, even if most existing ventilation standards are comfort-based and not sufficient to control the risk (Ding et al., 2022). For this reason, studies that relate the ventilation rate and infection probability have been carried out considering diverse building types (Dai & Zhao, 2020). The most used models for assessing these relationships are the well-established Wells-Riley (Riley & Nardell, 1989) and the Gammaitoni-Nucci (Gammaitoni & Nucci, 1997) models. In this scenario, educational buildings present particularly critical situations, as students spend a consistent amount of time indoors (Lamberti et al., 2020) and are in close contact with other occupants. Thus, the infection risk was often analyzed in these types of buildings (Pavilonis et al., 2021; Fantozzi et al., 2022) to ensure healthy conditions for students.

However, these models assume that the air in the indoor environment is uniformly distributed, which is not necessarily true. Indeed, there is the possibility of underestimating infection risk if, in some locations of the room, the ventilation rate is below the assumed uniform value. This fact may

Part of
Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2023. Building simulation applications BSA 2022. bu,press.
https://doi.org/10.13124/9788860461919

have negative consequences on students' health, especially if the infection probability is underestimated in the positions occupied by their desks. Building simulation and CFD analysis, which have often been used to evaluate various aspects of IEQ (Rugani et al., 2021) and validated on the real conditions encountered in classrooms (Fantozzi et al., 2021), are valid tools for analyzing the distribution patterns of the air in the rooms. In fact, CFD simulations were recently used to minimize Covid-19 spread (Ascione et al., 2021).
The aim of this paper is, then, to analyze the air patterns through a CFD analysis using university classrooms with different room characteristics, occupancy, and operation mode as a case study. This analysis will provide important information regarding the estimation of infection risk considering the classrooms as non-uniform spaces and validation of the models predicting infection risk. Furthermore, an innovative methodology for enhancing classroom management and improving the health conditions of the students is proposed.

2. Methodology

2.1 The Case Study

In this study, the classroom environments were studied as a non-homogeneous space, investigating the infection probability from an individual-oriented perspective. Three different classrooms at the School of Engineering of the University of Pisa were simulated, which present three different HVAC configurations. The three classrooms are located in different buildings: the first is under construction and will be equipped with a VRF system with a mechanical air exchange ventilation system (Class A), the second was built in 2006 and is air-conditioned by an air-to-air heat pump with ceiling fan coil distribution (Class B); the latter was built in 1930 and has a traditional hydronic radiator system (Class C).
Table 1 shows the characteristics of the three classrooms studied. Ideal manikins were placed in the stalls to study the infection risk that the users are actually exposed to.
Several points mainly corresponding to students' positions were identified.

Table 1 – Characteristics of the classrooms

Class	Surface [m^2]	Volume [m^3]	Occupancy	Ventilation rate [m^3/h]
Class A	130	390	129	3250
Class B	131	468	130	1000
Class C	70	182	49	370

2.2 Simulation of the Classrooms and Infection Probability

The three classrooms were analyzed by means of a 3D CFD analysis, using Autocad CFD. CFD decomposes the environment of a zone into a large number of control volumes and can provide a detailed description of the airflow by solving the Navier-Stroke's equations. CFD was used with the Finite Volume Method (FMV) approach, as it can perform detailed computation on heat transfer and air-flow simulation. The standard k-ε turbulence model was used for air turbulence due to its accuracy in predicting indoor airflows (Hughes et al., 2012).
Classes A, B, and C were modeled and simulated in two different scenarios: one lesson on a summer day and on a winter day. The boundary conditions were set as the output of a Building Energy Simulation (BES) campaign carried out using the well-known EnergyPlus software with a Typical Mean Year weather file. The room investigated and all adjacent classrooms were modeled as different thermal zones. An airflow network was used to simulate internal air movements, aimed at assessing the effective boundary conditions, i.e., mainly wall surface temperatures, for CFD analysis. The aim was to obtain the local value of the Local Mean Age (LMA) and the air velocity at the previously identified points of the environment.
The infection probability in the classroom was calculated using the well-established Gammaitoni-Nucci model (Gammaitoni & Nucci, 1997), which relates the ventilation rate to the infection probability. First, P was calculated considering the air distribution in the classroom uniform using the values from Table 1, then the infection probability was evaluated for the different zones that were established in the different classrooms, obtaining the Air

Changes per Hour for each zone from the simulated local mean age. The ACH for each zone corresponded to the position occupied by the students to assess their actual condition. The number of infectors was considered equal to 2 % of the total number of occupants.

3. Results

3.1 Local Mean Age

From the LMA, obtained from the CFD simulation, it was possible to derive the ventilation rate, so the Air Changes per Hour (ACH) were assumed for each zone, considering summer (yellow) and the winter (light blue) conditions (Fig. 1). The dashed line represents the ACH assumed for the simulations, which was considered uniform in the entire classroom ($ACH_{uniform}$), and is calculated from the ventilation rate given in Table 1.

Fig. 1 shows that the most favorable conditions can be encountered in Class A, which presents the highest ACH, both considering the $ACH_{uniform}$ and the single zones. On the other hand, the most critical conditions are in Class C, which is the naturally ventilated classroom, and whose ventilation was poorer both during summer and winter conditions. From the simulation of summer and winter conditions, it can be noticed that, for Class A, the winter scenario was generally less critical than the summer one, while, for Class B, the trend was the opposite. In general, mechanically ventilated classrooms present better indoor conditions, with higher values of ACH. It can be immediately noticed that the $ACH_{uniform}$ remains lower in each case than the ACH obtained in the different zones, which is a good indicator that assuming this parameter for the calculation of the infection probability does not lead to underestimation of the risk. The ventilation rate in the different zones of the classroom tends to be higher than the one assumed if the air distribution of the room is considered uniform. This tendency is particularly evident in the mechanically ventilated classrooms (Class A and B), while it is less clear for the naturally ventilated ones (Class C). This fact shows that, in the naturally ventilated classroom, the air distribution tended to be more uniform and closer to the value assumed for $ACH_{uniform}$, probably also due to the reduced volumetric dimensions of Class C.

3.2 Calculation of the Infection Probability for the Different Classrooms

The infection probability for five hours of exposure was then calculated using the Gammaitoni-Nucci model for Classes A, B, and C (Fig. 2). Five hours of exposure were considered, as they are the most critical representative period in which students may remain in a classroom. Two typical activities that can be performed in classrooms were reported: the infector breathing and the infector speaking while the occupants are resting. The winter scenario was chosen for the analysis and Fig. 2 reports the infection probability calculated in the case that the air distribution in the classroom is considered uniform (continuous line), for the zone with the lowest ACH ("worst condition", dashed line) and the zone with the highest ACH ("best condition", dotted line). This allows a comparison of the results of the different conditions in classrooms, as all the other zones will be included between the best and the worst conditions for each class.

It can be noticed that, for all the classrooms, the in-

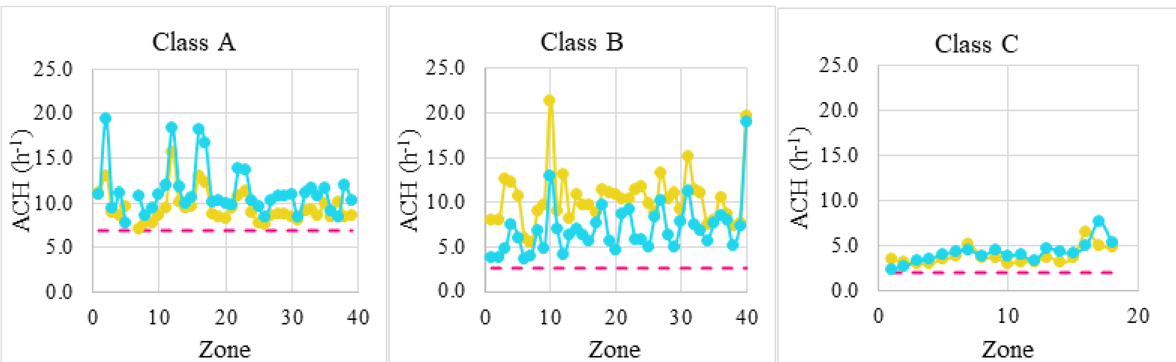

Fig. 1 – ACH obtained for each zone in the three classrooms for summer (yellow) and winter (light blue) conditions. The dashed line represents the ACH assumed for the entire classroom.

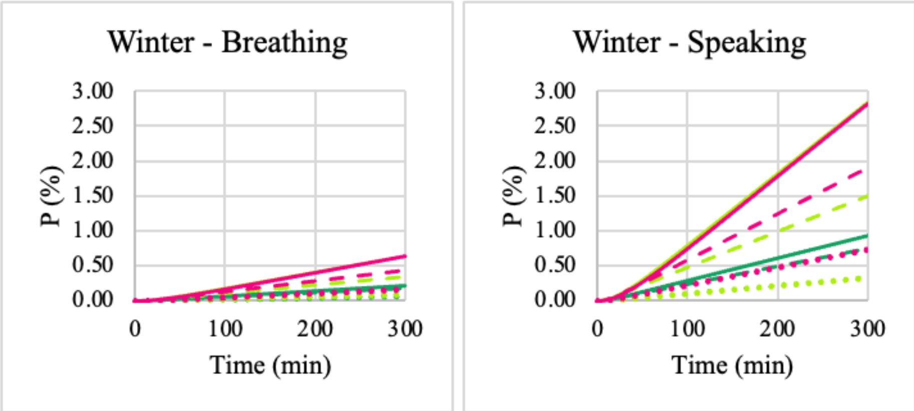

Fig. 2 – Infection probability for 5 hours of exposure in the three classrooms considered. Classes A, B, C are represented by the green, yellow, and red colors, respectively. The continuous line shows the uniform case, the dashed line the worst, and the dotted line the best condition

fection probability for the worst and the best conditions remained below the one calculated considering the $ACH_{uniform}$. This means that using the typical conditions assumed in infection risk models, namely the hypothesis of well-mixed air distribution, there is no risk of underestimating infection probability. On the contrary, the ventilation required to reduce infection probability can lead to an increased demand for ventilation, which may affect energy costs.

Fig. 2 shows that the most critical cases are represented by Classes B and C, due to the reduced ventilation. Furthermore, results show a high influence of the infector's activity on the infection probability. Indeed, the infection probability remains below 1 % for all the classrooms if the infector is only breathing, considering the five hours of exposure. On the contrary, if the infector is speaking, P exceeds 1 % after about 140 minutes in Class C and 200 minutes in Class B, considering the most critical zone (dashed line). On the contrary, Class A reports the most favorable conditions, where the critical infection probability of 1 % is never exceeded for all the scenarios and in five hours of exposure, showing the importance of providing adequate ventilation in educational buildings. Indeed, correct ventilation design can have a consistent influence on the maintenance of healthy indoor conditions. The infection probability calculated for the best condition (dotted line) shows that some positions are particularly favorable for maintaining the health of the occupants, which suggests that the students should favor certain locations in the class over more risky ones.

Since the real challenge is to design buildings that are healthy and comfortable for everyone, in the design phase it is necessary to consider the most critical scenario, which is represented by the activity of speaking. In this case, for Classes B and C, the threshold infection probability is soon exceeded, and preventive measures, such as increasing the ventilation rate, reducing the number of occupants, or including breaks during the duration of the lecture, are needed.

3.2.1 Relation between the ACH and infection probability in different classrooms

The relation between ventilation rate, expressed by the ACH, and infection probability was analyzed for different classrooms for the activity of speaking, as shown in Fig. 3. The exposures of one and five hours were considered, as they represent the minimum and the maximum time that students usually spend in university classrooms. The activity of speaking was chosen, as it represents the most critical scenario that can be probably encountered in university classrooms.

Regarding ventilation, Class A presents the most uniform conditions, as can be noticed by the range in which the ACH was varying. Classes B and C are less uniform, as they present Air Changes per Hour varying between about 5 h^{-1} and 25 h^{-1}. Non-uniformity in classroom ventilation can lead to different exposures to the infection risk, which means that some locations are less favorable than others. There is then the need for avoiding students being exposed to unhealthy conditions and, therefore, for providing indications on the correct management of university classrooms.

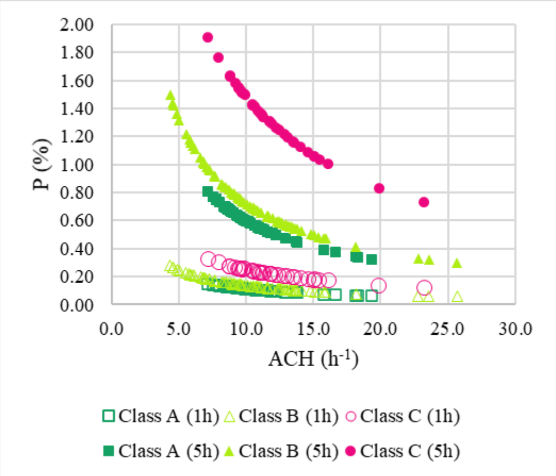

Fig. 3 – Relation between the infection probability for 1 and 5 hours of exposure and the ACH in the three classrooms considered with an infector speaking.

Concerning exposure time, for one hour of exposure, infection probability remains below the threshold value of 1 % for all the classrooms, while, for five hours, only Class A remains below this limit. This implies that, for long exposures, not all the locations should be occupied, but only the ones with acceptable risk values, or that breaks should be guaranteed to reduce infection probability.
Also noteworthy is the fact that there are some differences in the relationship between the ACH and infection probability considering the characteristics of different classrooms. Indeed, despite Class A and B presenting a higher occupation and therefore a higher number of possible infectors, the reduced room volume of Class C largely influences infection probability, as the curve of this class is much higher. The difference between the classrooms is particularly evident for long exposures, as can be noticed in Fig. 3.

4. Discussion

To assess the relationship between ventilation rate and infection probability, the models that are commonly used adopt the hypothesis that ventilation is uniformly distributed in all the locations in the room. However, from the previous results obtained from CFD simulations, it can be noticed that the local mean age of the air, and therefore the ventilation rate, may vary greatly between different positions. In this paper, mechanically and naturally ventilated university classrooms were analyzed to understand how different ventilation strategies, building characteristics, and occupancy can influence indoor infection probability. The crucial point is that the risk must not be underestimated by considering the air in the space to be uniformly distributed.
For this reason, the deviation between infection probability in the different zones (P_{zone}) and infection probability calculated considering ventilation uniform in all the classrooms ($P_{uniform}$) was calculated. Table 2 reports the minimum and maximum deviation for the three classes for the activity of speaking. The choice of infection probability for speaking is related to the fact that it is the most critical and common condition that can be encountered in university classrooms.
The deviation was calculated as the maximum difference between the effective infection probability in the zone and the one calculated considering the ventilation uniformly distributed in the environment. The negative sign in the deviation is associated with the fact that the $P_{uniform}$ was higher than the P_{zone} for all the zones of the classrooms, even in the case of the ventilation rate being the lowest, thus their difference is negative. This means that there is no risk of underestimating the infection probability by using uniform air distribution in the classroom, which is a fundamental issue if the health and the safety of the students are to be guaranteed.

Table 2 – Minimum and maximum deviation for the three classes for the activity of speaking

Class	Season	Minimum deviation	Maximum deviation
Class A	Summer	-0.11	-0.53
	Winter	-0.17	-0.58
Class B	Summer	-1.79	-2.55
	Winter	-1.35	-2.51
Class C	Summer	-1.20	-2.00
	Winter	-0.92	-2.10

This result shows that, in certain cases, the effective infection probability P_{zone} was much lower than the $P_{uniform}$, especially for Classes B and C. Therefore, even if some differences occur, these results demonstrate that assuming the air to be uniformly distributed in the classroom is an acceptable hypothesis, which benefits student safety. However, from the previous results, it can be noticed that, in several cases, infection probability exceeded the threshold value of 1 % for five hours of exposure. This implies more responsible management of the classrooms to ensure healthy conditions for the students. For this reason, the classrooms used as a case study were divided into homogeneous-risk zones, as can be noticed from Fig. 4. As expected, the lowest infection probability can be found in Class A, while the worst conditions for Class C also present the most homogenous ventilation pattern. This subdivision provides homogeneous risk zones, which permit the identification of the conditions of higher risk for students. In this case, an exposure time of five hours was considered the most critical condition, but similar trends

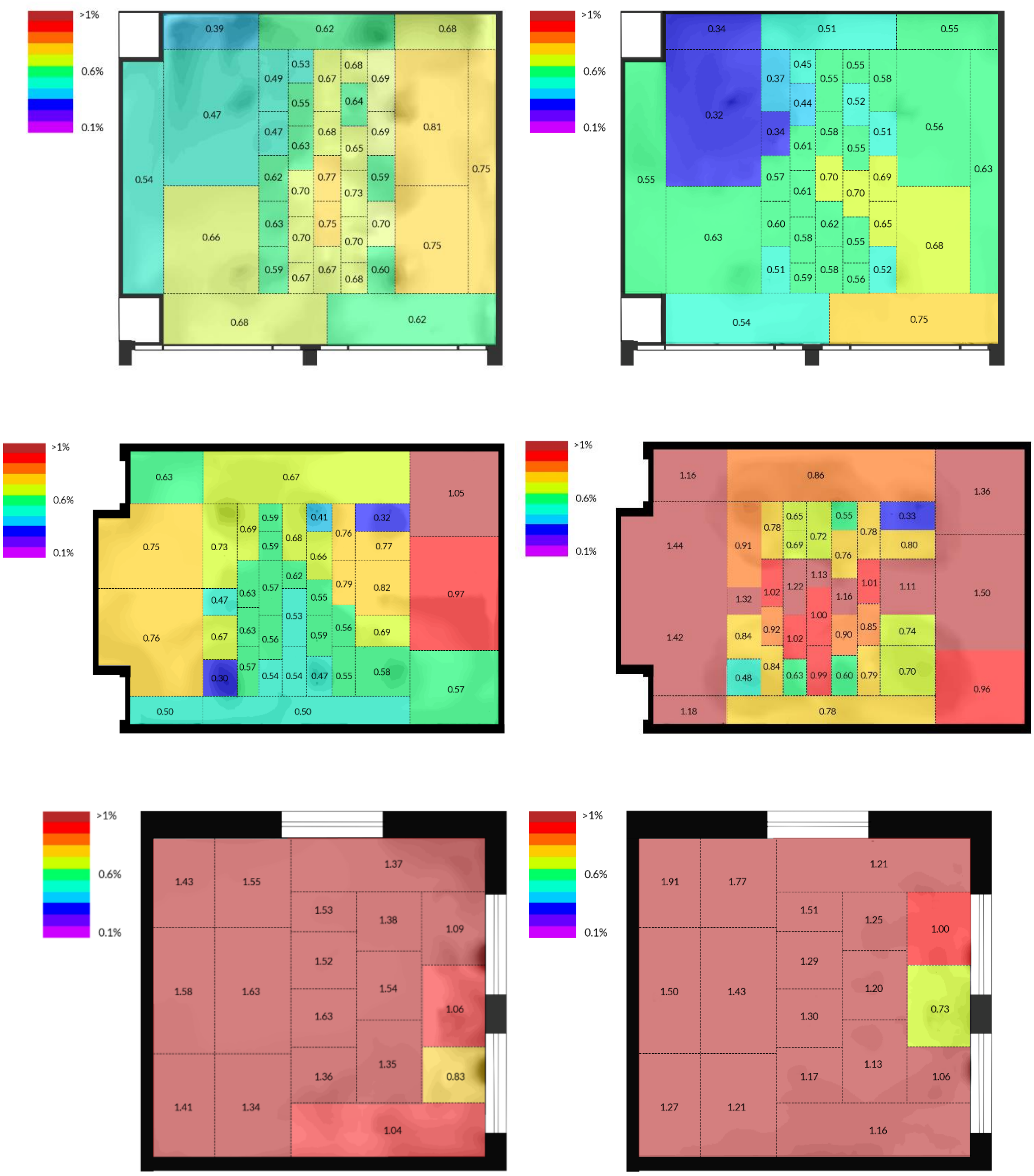

Fig. 4 – Infection probability calculated for the different zones in Class A (above), B (central) and C (below) during summer (left) and winter (right) conditions. The gray area below the graph identifies the flux of fresh air provided by the ventilation system or the window

are found for lower exposures. This division enables more efficient management of classrooms favoring student health. For example, it is possible to recommend certain positions in the classroom depending on the probability of infection, especially if room capacity is not at the maximum.

The extreme cases are Class A, which remains totally below the critical probability of 1 %, and Class C, with a probability above 1 % in practically every position. In the latter case, it is necessary to find solutions that do not involve the positioning of students, since there are no areas of lower risk.

The case of Class B is interesting, since it presents a great variety of situations within it. The best area is in the middle, near the ventilation system, and at the back where there are windows (albeit closed). The side at the back of the classroom furthest from the windows is more critical, although this is not a problem, since this area is a corridor that is not usually occupied by students.

In conclusion, this methodology allows for the efficient management of university spaces, favoring the health of the occupants.

5. Conclusion

The importance of guaranteeing safe and healthy conditions in classrooms has become increasingly relevant, especially after the Covid-19 pandemic. However, the impact of adequate ventilation on students' health and productivity has always been a crucial point for researchers and building designers. Indeed, there is a necessity to provide sufficient air changes to enhance indoor air quality.

In this scenario, to assess the conditions of health indoors, infection probability has been often associated with ventilation rate, using predictive models that assume that air distribution in the room is uniform. However, it can be noticed that, in several cases, classrooms do not present uniform conditions due to the positioning of the ventilation systems or the window or door openings. It is necessary to verify that these non-uniformities do not lead to an underestimation of the infection risk, compromising students' health. With a CFD model, it was possible to simulate different scenarios using university classrooms that presented diverse building characteristics and operation modes as a case study. Results indicate that the less critical situation can be found in mechanically ventilated classrooms, which provide adequate ventilation for the duration of exposure. Furthermore, results show that these models can be applied, despite the different conditions that can be encountered in classrooms, as the assumption of uniform distribution of the air tends to be pro-safety with no risk of underestimating infection probability.

Furthermore, division into equal-risk zones allows for intelligent management of the classroom, which permits students' positioning according to the most favorable conditions indoors, improving their health. Moreover, the new methodology has an important practical application, since it is possible to optimize the HVAC system position in the design phase.

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