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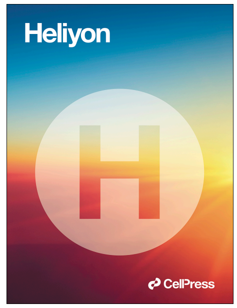

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PII: S2405-8440(24)03908-2

DOI: https://doi.org/10.1016/j.heliyon.2024.e27877

Reference: HLY 27877

To appear in: *HELIYON*

Received Date: 3 September 2023

Revised Date: 1 March 2024

Accepted Date: 7 March 2024

Please cite this article as: , Investigating the effectiveness of a new indoor ventilation model in reducing the spread of disease: A case of sports centres amid the COVID-19 pandemic, *HELIYON* (2024), doi: https://doi.org/10.1016/j.heliyon.2024.e27877.

INVESTIGATING THE EFFECTIVENESS OF A NEW INDOOR VENTILATION MODEL IN REDUCING THE SPREAD OF DISEASE: A CASE OF SPORTS CENTRES AMID THE COVID-19 PANDEMIC

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ABSTRACT

The ventilation of buildings is crucial to ensure indoor health, especially when demanding physical activities are carried out indoors, and the pandemic has highlighted the need to develop new management methods to ensure adequate ventilation. In Spain, there are no specific ventilation regulations to prevent the spread of pathogens such as the coronavirus. Therefore, it is necessary to have a theoretical tool for calculating occupancy to maintain sports facilities in optimal safety conditions. The proposed theoretical method is based on the analysis of mathematical expressions from European standardisation documents and uses the concentration of CO_2 as a bioeffluent. It is also based on the concept of background and critical concentration, which allows its application to be extrapolated to future crises caused by pathogens. This study presents a unique and novel dataset for sports centres. For this purpose, the calculation methods were applied to the data set provided by Mostoles City Council, Spain, during the pandemic years with the highest incidence of COVID-19, when the government introduced the assimilation of COVID-19 sick leave to occupational accidents. The data on this type of sick leave provided by the City Council correspond to the period between March 2020 and February 2022. Similarly, the data on the average use of sports facilities by activity, provided by the Sports Department, correspond to the years 2020 and 2021. In this way, it was possible to verify the effectiveness in preventing the spread of any type of coronavirus. In conclusion, the implementation of a theoretical occupancy calculation method based on the concentration of carbon dioxide as a bioeffluent can be an effective tool for the management of future crises caused by pathogens or hazardous chemicals in the air, and demonstrated its effectiveness in sports centres such as gyms, sports fields, and indoor swimming pools during the COVID-19 pandemic.

Keywords: *COVID-19, sports centres, indoor ventilation, air change rate, air quality*

1. Introduction

The recirculation of fresh air indoors within buildings is an aspect of particular importance in the design and conceptualization of residential buildings, given that the concentration of pathogenic substances can affect both the health and the quality of life of their inhabitants [1-4]. Concern over the indoor air quality of classrooms for teaching activities where the concentration of individuals from different environments can contribute to the propagation of diseases obliges us to guarantee special public health conditions [5-11]. It is also especially important to consider this circumstance in hospitals and clinics since the presence of airborne pathogenic substances affects not only the health personnel who work within them but may also affect the lives of people in convalescence [12-17].

Concern over the effects of stale and contaminated air on public health has given rise to regulatory initiatives, through specific normative provisions in different countries. For example, in the European Union, the Environmental Health Action Plan 2004-2010 [18, 19] had previously referred to the need to improve air quality within buildings. Moreover, the Spanish Strategy on Air Quality, promoted by the Environment Ministry, created a working group for the study of the incidence of air quality on public health [20]. The outcome was the publication, in 2013, of the National Plan on Air Quality and Protection of the Atmosphere 2013-2016 [21], and in 2017 the National Plan on Air Quality 2017-2019 [22]. Likewise, the World Health Organisation has recently updated environmental pollution limits to which the public can be exposed without risk to their health, considerably raising the reference values [23].

In Spain, Technical Instruction 1.1.4.2, in the government code of regulations on Thermic Installations in Buildings (RITE) [24] sets down the requirements for indoor air quality as a function of their typology and use [25]. In the area of biological contamination, in

2020, the Ministerio para la Transición Ecológica y Reto Demográfico in coordination with the Health Ministry, published a set of recommendations and references on the prevention of contagions produced by SARS-CoV-2, to guide the activities of ventilation equipment installation and maintenance firms [26].

Besides this type of consideration, given the public health situation generated by the COVID-19 pandemic, it is necessary to consider the reference parameters for guaranteeing air quality within buildings and their updating, to minimise any risk of contamination [27-29]. For this purpose, higher air recirculation rates are required, to avoid the concentration of health-threatening pathogens, among which the coronaviruses such as SARS-CoV-2 [30-35].

The Spanish National Research Council (CSIC) has recently published a Guide for the Ventilation of Classrooms, intending to reduce the risk of COVID-19 contagion [36] at teaching centres, taking as a reference the Steady State CO_2 methodology published by the University of Harvard [37]. Likewise, the Working Group on Ventilation of Centres of Education, of the Association of Manufacturers of Air Conditioning Equipment (AFEC) published a set of recommendations for the recirculation of air in secondary school and university classrooms, intending to reduce the risk of disease transmission, ensuring healthier spaces and thereby improving the performance of students [38].

This paper proposes a calculation procedure to ensure proper ventilation of indoor spaces for buildings of different types and uses, such as sports centres, libraries, senior centres, social service centres, and swimming pools, all belonging to the Mostoles City Council in Madrid. For this purpose, the CO_2 concentration is taken as an indicator because this compound is considered a bioeffluent similar to COVID-19 [39, 40]. The CO_2 in the indoor environment of buildings comes, for the most part, from human metabolism, although, increasingly, pollution of the outdoor environment also contributes to increasing its concentration in enclosed spaces [41, 42].

The CO_2 concentration inside buildings can be considered an indicator of air quality, which varies according to the number of people in a room at the same time and the degree of ventilation of the room [43-45]. Thus, CO_2 expired by people is diluted by turbulent mixing in the air or by diffusion, due to concentration gradients [46, 47]. Adequate ventilation guarantees a reduction in the persistence time of the gaseous atmosphere of an enclosure and, therefore, the concentration of possible pathogens present in it [48, 49]. Therefore, the determination of this parameter is a good indicator to determine the degree of occupancy inside buildings [50, 51].

Considering this possibility of airborne transmission as the most probable, as was already the case with SARS-CoV-2 during the COVID-19 pandemic [52, 53], a working methodology based on the direct analysis of an indicator bio effluent, carbon dioxide, is proposed, which is studied and analyzed to understand its behavior in confined spaces and its ability to spread in confined spaces, with the ultimate goal of establishing preventive measures against contagion caused by coronaviruses or pathogens similar to SARS-CoV-2 inside buildings [54].

The research shown in this paper has been carried out in sports buildings of the Mostoles City Council (Community of Madrid, Spain). Specifically, the paper develops a study showing the effectiveness of carbon dioxide as a bioeffluent indicator for the management of crises produced by coronaviruses and dangerous toxic gases, as demonstrated in the sports centres of the Mostoles City Council (Community of Madrid, Spain) during the COVID-19 pandemic.

2. Background

The occupancy calculation method for the prevention of SARS-CoV-2 has been put into practice in the sports centres belonging to Mostoles City Council (which include sports facilities such as a gymnasium, swimming pool, or sports facilities), during the peak of the pandemic period, from 2020 to early 2022. The information referred to the surface of the enclosures, ventilation flow rates, and number of positive cases of COVID-19 among public employees, have been provided by the public administration itself, which guarantees the impartiality of the data obtained.

The average occupancy of each sports facility was estimated in different ways. On the one hand, the number of users was obtained using the statistics on attendance at sports activities prepared by the Mostoles City Council (maximum capacities have been established for the use of municipal facilities following the limitations established by the COVID-19 pandemic), compiled monthly by the Sports Department. On the other hand, the number of workers was established due to the internal limitations imposed by the institution itself, in which municipal employees combine teleworking with on-site work, to guarantee adequate ventilation in each area.

For the development of the study, reference values are proposed based on the application of the European EN Standards, obtained by comparison with the volumetric flow rates of ventilation air available. In this way, it is possible to establish the estimated occupancy inside an enclosure, depending on the activity carried out.

For this reason, the analysis of the method was carried out by comparing the actual occupation of the sports facilities with the limits proposed in this study, evaluating its effectiveness by analyzing the infections of municipal workers, which occurred only in the work environment.

The proposed reference values have been previously validated using the Steady State CO_2 method [37, 39], establishing, as the basis of the study, the Air Changes per Hour (ACH) parameter as a way of measuring air renewal in a given volume per unit of time. For this purpose, the methodology presented in this research establishes, as a target, five air changes per hour (which is an excellent level according to the Steady State CO_2 method).

2.1 Recommended benchmarks

The Regulation of Thermal Installations in Buildings (RITE for its acronym in Spanish) [24], applicable in Spain, establishes that the air quality in office premises must be Category IDA2, which corresponds to good quality air. This implies that the indoor CO_2 concentration, above the outdoor air concentration level, cannot exceed 500 ppm, which implies the need for an airflow rate of 10 l/s per person.

If the indirect method of outdoor airflow per person, proposed by RITE, is applied, 45 m^3/h per person (12.5 l/s) is obtained, a value slightly lower than that proposed in the Steady State CO_2 method [37, 39], but which can serve as a reference as a threshold value for adequate ventilation of indoor spaces.

For this purpose, the classic levels of action in Industrial Hygiene for this limit (75%, 50%, and 25%), i.e. 15.62 l/s, 18.75 l/s, and 21.87 l/s, are considered for the calculations (Table 1). Consequently, the reference values of ΔCO_2 are, respectively, 230 ppm, 270 ppm, and 320 ppm, assuming an outdoor concentration between 400 ppm and 500 ppm, so that the values referenced indoors will be 730 ppm, 770 ppm, and 820 ppm. Indicates that, outdoors, the concentration established in the Steady State CO_2 method [37, 39] is 420 ppm. Similarly, the ΔCO_2 considered is 378 ppm and the value referenced indoors is 878 ppm.

Table 1. Reference values.

Performance levels	ΔCO_2 (p.p.m.)	CO_2 (p.p.m.)
75 %	230	730
50 %	270	770
25 %	320	820
Steady State CO_2	378	878

The available ventilation flow rate is compared with the required air flow rate.

2.2 Pathogen propagation Prevention through indoor occupancy calculation

By comparing the proposed reference values with the volumetric air flow rates, the estimated occupancy inside an enclosure is obtained as a function of the activity carried out. Based on the EN ISO 8996:21 [55] method for calculating metabolic consumption (Table 2), the carbon dioxide emission rates per activity are obtained.

Table 2. Metabolic rate by activity performed.

Activity	Metabolism (W)	Metabolism (W/m^2)
Rest	100 - 125	55.55 – 69.44
Low activity	125 -235	69.44 – 130.55
Moderate Activity	235 -360	130.55 – 200.00
High activity	360 - 465	200.00 – 258.33
Very high activity	> 465	258.3

The available ventilation flow rate is compared with the required air flow rate, depending on the limiting value selected from those proposed. For this purpose, the carbon dioxide generation rate and the required external air flow rate are calculated, depending on the activity carried out. To have the same level of safety, the dilutions of emissions produced by humans during respiration must be increased in the same proportion as the growth of the transmission of a coronavirus or pathogen of a similar nature.

Thus, a $Q_{required}$ value is obtained, for each of the four proposed reference values: 75%, 50%, and 25%, i.e., a ΔCO_2 of 230 ppm, 270 ppm, and 320 ppm, as well as the ventilation value considered adequate by the Steady State CO_2 method [37, 39], ΔCO_2 of 378 ppm.

For each reference value of 75%, 50%, 25% and Steady State CO_2, the required ventilation flow rate in the enclosure under consideration in the following equations 1 to 4:

$$Q_{required\ 75\%} = \frac{q_{CO_2}}{230} \cdot 10^6 \quad \text{(Equation 1)}$$

Among them, $Q_{required\ 75\ \%}$ is the necessary ventilation flow in l/s per person, for the reference value at 75% (1).

$$Q_{required\ 50\%} = \frac{q_{CO_2}}{270} \cdot 10^6 \quad \text{(Equation 2)}$$

Among them, $Q_{required\ 50\ \%}$ is the necessary ventilation flow in l/s per person, for the reference value at 50% (2).

$$Q_{required\ 25\%} = \frac{q_{CO_2}}{320} \cdot 10^6 \quad \text{(Equation 3)}$$

Among them, $Q_{required\ 25\ \%}$ is the necessary ventilation flow in l/s per person, for the reference value at 25% (3).

$$Q_{required\ (Steady\ State\ CO2)} = \frac{q_{CO_2}}{378} \cdot 10^6 \quad \text{(Equation 4)}$$

Among them, $Q_{required\ (Steady\ State\ CO2)}$ is the necessary ventilation flow in l/s per person, for the reference value at Steady State CO_2 (4).

In this way, a ventilation flow rate is available for each person inside an enclosure, depending on the activity, without the need for all occupants to perform the same activity. In addition, it is even possible to have a value adjusted according to the physical characteristics of the occupants (height and weight).

For the calculation process, the most restrictive case is taken as a reference, considering as a safety level a concentration at 75% of the limit value established during the execution of a sedentary activity, for an enclosure whose occupants coincide with the dimensions of a person of average or standard corpulence (Table 3). Under these conditions, the carbon dioxide generation rate per person is 0.0045 l/s.

The required ventilation flow per person is established at 19.35 l/s (1).

$$Q_{required\ 75\%} = \frac{q_{CO_2}}{230} \cdot 10^6 \quad \text{(Equation 1)}$$

$$\Rightarrow Q_{required\ 75\%} = \frac{4.4505 \cdot 10^{-3}}{230} \cdot 10^{6} \Rightarrow Q_{required\ 75\%} = 19{,}35\ {}^{l}/_{s} \cdot person$$

Thus, the reference values at the different action levels are obtained for all the activities considered.

Table 3. Required ventilation flow by activity.

Type of Activity	Metabolism (W/m^2)	qCO_2 (l/s·person)	$Q_{required\ 75\%}$ (l/s·person)	$Q_{required\ 50\%}$ (l/s·person)	$Q_{required\ 25\%}$ (l/s·person)	$Q_{required}$ (l/s·person) Steady State CO_2
Sedentary work	70	0.0045	19.35	16.49	13.91	11.78
Light standing work	100	0.0064	27.65	23.56	19.88	16.83
Walking (1.6 Km/h)	100	0.0064	27.65	23.56	19.88	16.83
Light work	130	0.0083	35.95	30.62	25.84	21.87
Dancing	165	0.0105	45.63	38.87	32.79	27.76
Moderate work	165	0.0105	45.63	38.87	32.79	27.76
Walking (5 Km/h)	200	0.0127	55.30	47.11	39.75	33.65
Heavy work	230	0.0146	63.60	54.18	45.71	38.70
Gym/swimming recreation	260	0.0165	71.90	61.24	51.68	43.75
Gym /Team sport	300	0.0191	82.96	70.67	59.63	50.48
Swimming	300	0.0191	82.96	70.67	59.63	50.48

The theoretical occupancy of the enclosure is obtained through the equation as follows (5):

$$Theoretical\ occupation = \frac{Q_w}{Q_{required}} \cdot 10^{3} \quad \text{(Equation 5)}$$

Occupancy, therefore, is obtained by comparison with the reference value $Q_{required}$, which is specific to each activity performed (Figure 1).

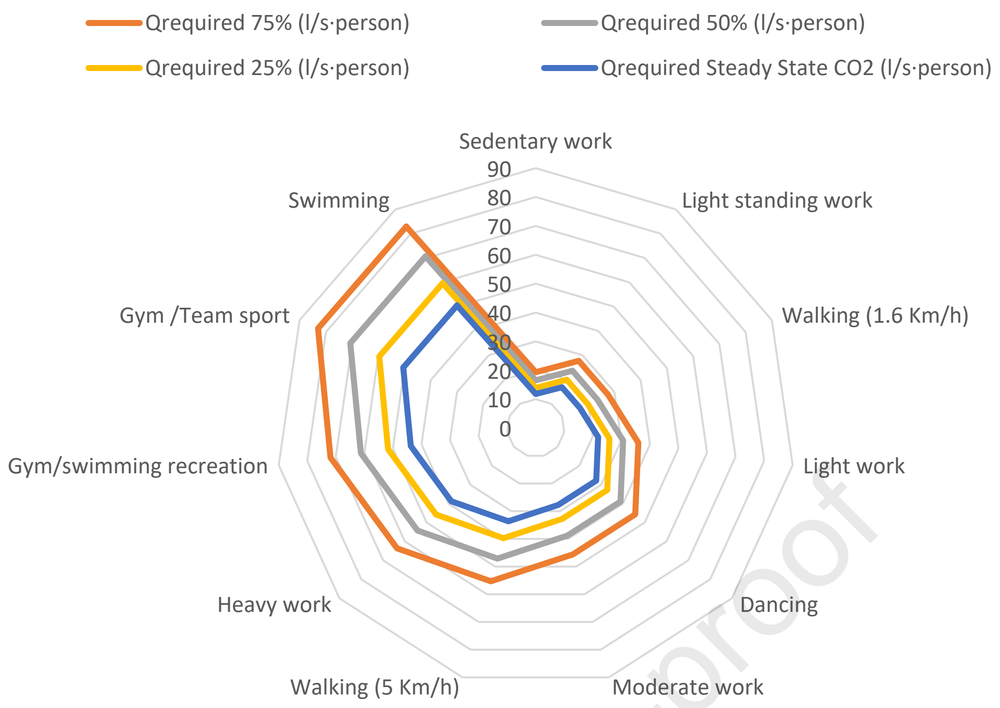

Figure 1. Required ventilation flow by activity.

3. Method

The occupancy calculation method for the prevention of SARS-CoV-2 has been put into practice in the sports centres and facilities of the Mostoles City Council during the pandemic period.

The data on surface area, ventilation flow, as well as the number of positive cases suffered by municipal workers, have been provided by the public administration itself. The average occupancy of each facility has been estimated in different ways: on the one hand, the Sports Department prepares attendance statistics for all the sports activities offered by the Mostoles City Council. On the other hand, the public access centres have maximum capacities adapted to the new reality, the pandemic produced by COVID-19, and municipal workers combine teleworking with face-to-face work, so that the capacities are appropriate to the available ventilation, in each enclosure.

3.1. Method application: the Villafontana Sports Centre

The buildings under study correspond to the sports centres managed directly by the Mostoles City Council. The calculation process shown corresponds to the Villafontana Sports Centre, located in the city of Mostoles.

To obtain the theoretical occupancy under the conditions previously established, it is necessary to know the characteristics of the enclosure under study, as well as its ventilation and the one in which the activity is being carried out.

As an example of the calculation process carried out in the administration area of the aforementioned building. The data supplied by the Mostoles City Council during the study period are as follows: the average occupancy was four people out of the seven who perform their tasks on the premises, as a result of the municipal policy of simultaneous teleworking and on-site work, the premises have a surface area of 69.05 m^2 corresponding to a volume of 172.63 m^3 and the available ventilation is 1.2 $l/s \cdot m^2$.

To determine the theoretical occupancy of the enclosure considered, the available forced ventilation is established (6) as follows.

$$Q_w = \frac{Area\ of\ the\ enclosure\ under\ consideration \cdot available\ ventilation}{1000}$$

$$Q_w = \frac{69{,}05 \cdot 1{,}2}{1000} \Rightarrow Q_w = 0{,}083\ {}^{m^3}/_{s} \quad \text{(Equation 6)}$$

Among them, Q_w is the volumetric air flow in m^3/s (6).

With these data, the number of air renewals can be obtained by applying (7):

$$C = \frac{Q_w}{volume} \cdot 3600 \quad \text{(Equation 7)}$$

$$\Rightarrow C = \frac{0{,}083}{172{,}63} \cdot 3600 \Rightarrow C = 1{,}73\ h^{-1}$$

Among them, C is the number of air renewals in h^{-1} and Q_w is the volumetric air flow in m^3/s (7).

The theoretical occupancy concerning the ventilation flow rate required to reach 75% of the limit value is as follows (5):

$$Theoretical\ occupation_{Q_{required\ 75\,\%}} = \frac{Q_w}{Q_{required\ 75\%}} \cdot 1000$$

$$\Rightarrow\ Theoretical\ occupation_{Q_{required\ 75\,\%}} = \frac{0{,}083}{19{,}35} \cdot 1000 = 4{,}28\ persons \quad \text{(Equation 5)}$$

Considering that the average occupancy of the site was four people, compliance with the parameter considered was 0.93 (8):

$$Compliance_{Q_{required\ 75\%}} = \frac{Actual\ occupation}{Theoretical\ occupation_{Q_{required\ 75\%}}} \quad \text{(Equation 8)}$$

$$\Rightarrow = \frac{4}{4{,}28} = 0{,}93$$

Consequently, the management of the Villafontana Sports Centre complied, during the study period, with the most restrictive safety parameter of those proposed.

This process is carried out for all the activities considered, for example, the winter pool of the Villafontana Sports Centre. In this case, the activity considered is sports training in the swimming activity.

The theoretical occupancy, obtained from the Self-Protection Plan of the enclosure, was 402 people, while the actual occupancy was calculated from the data provided by the Department of Sports of Mostoles City Council, based on the number of users who accessed the facilities by time slots, stood at 12.75 swimmers.

The enclosure has a surface area of 804 m^2, a volume of 3,216 m^3, and a forced ventilation of 2.01 m^3/s.

With these data, the number of air renewals in the winter pool basin is (9):

$$C = \frac{Q_w}{volume} \cdot 3600 \quad \text{(Equation 9)}$$

$$\Rightarrow C = \frac{2{,}01}{3216} \cdot 3600 \Rightarrow$$

$$C = 2{,}25\ h^{-1}$$

The rate of carbon dioxide generation per person, considering that all individuals respond to the dimensions in weight and height considered as standard, for the swim training activity, physical activity associated with a metabolic consumption of 300 W/m^2, CO_2 generation during exhalation is 0.019 l/s.

For each reference value, the required ventilation flow rate is obtained for the activity considered, in the winter pool basin (equations 1 to 4).

The ventilation required to bring the concentration to 75% of the proposed limit value is 82.60 l/s·person, at 50% it is 70.37 l/s·person, at 25% and 57.37 l/s·person and using the criteria established in the Steady State CO_2 method 50.26 l/s·person.

The theoretical occupancy concerning the required ventilation flow rate, to place us in the different levels of action, is (equation 5) at 75% of the proposed limit value is 24.33 persons, at 50% it is 28.56 persons, at 25% it is 33.85 persons and using the criterion established by the Steady State CO_2 method it is 39.99 persons.

Finally, compliance with occupancy is determined concerning the values considered (equation 8), obtaining 0.52, 0.45, 0.38, and 0.32, respectively, for each of the levels considered (75%, 50%, 25%, and Steady State CO_2).

This theoretical occupancy can be obtained by considering groups of people performing different activities. Considering that in the previous case, there was a public, it would be possible to determine the maximum number of people wandering around the sports facilities.

The physical activity of walking, considering as such, a movement at 1.6 km/h, is considered associated with a metabolic consumption of 100 W/m^2, the associated carbon dioxide generation rate is 6.36 ·10^{-3} l/s.

The required ventilation flow rate for swim training is already calculated above, so it is only necessary to obtain these values for the "walking" activity (1).

$$Q_{required\ walk\ 75\%} = \frac{q_{CO_2}}{230} \cdot 10^6 \text{ (Equation 1)}$$

$$\Rightarrow Q_{required\ walk\ 75\%} = \frac{6{,}36 \cdot 10^{-3}}{230} \cdot 10^6$$

$$= 27{,}65\ {}^{l}/_{s} \cdot person$$

The theoretical occupancy is obtained, considering both activities simultaneously, by implementing the parameter η, which represents the ratio between the number of occupants performing each of the activities contemplated. It is defined as follows (10) to calculate the ratio of people walking concerning the occupancy of the site:

$$\eta_{walk} = \frac{number\ of\ walking\ occupants}{number\ of\ occupants\ in\ the\ enclosure} \quad \text{(Equation 10)}$$

To calculate the ratio of people swimming concerning the occupancy of the pool, the following equation is applied (11):

$$\eta_{swim\ training} = \frac{number\ of\ occupants\ swimming\ training}{number\ of\ occupants\ in\ the\ enclosure} \quad \text{(Equation 11)}$$

The relationship between the two parameters, if only two activities are considered simultaneously: walking and swimming, is as follows (12):

$$\eta_{walk} = 1 - \eta_{swim\ training} \quad \text{(Equation 12)}$$

To calculate the theoretical occupancy concerning the value referenced to 75%, for two simultaneous activities: walking and swimming, it will be necessary to apply the following (13):

$$Theoretical\ occupation_{Q_{required\ 75\ \%}} = \frac{Q_w}{\eta_{swim\ training} \cdot Q_{required\ swim\ 75\%} + (1 - \eta_{swim\ training}) \cdot Q_{required\ walk\ 75\%}} \cdot 1000 \quad \text{(Equation 13)}$$

$$= \frac{2{,}01}{\eta_{swim\ training} \cdot 82{,}60 + (1 - \eta_{swim\ training}) \cdot 27{,}65} \cdot 1000$$

For the imposed condition to be fulfilled, it is required to calculate the maximum theoretical occupancy with respect to the value referenced to 75% by means of (14):

$$Compliance_{Q_{required\ 75\%}} = \frac{Actual\ occupation}{Theoretical\ occupation_{Q_{required\ 75\ \%}}} = 1 \quad \text{(Equation 14)}$$

$$Actual\ occupation = Theoretical\ occupation_{Q_{required\ 75\ \%}}$$

The average number of swimmers in the facility during the period studied was 12.75 people, applying the equations mentioned above, the number of people that can be allowed to stay in the facility is obtained (15).

$$\eta_{swim\ training} = \frac{12{,}75}{12{,}75 + \ number\ of\ walking\ occupants} \qquad \text{(Equation 15)}$$

$$Theoretical\ occupation_{Q_{required\ 75\,\%}} = \ number\ of\ walking\ occupants\ (nwo) + number\ of\ occupants\ swimming\ training$$

$$number\ of\ walking\ occupants + 12{,}75 = \frac{2{,}01}{\left(\frac{12{,}75}{12{,}75 + nwo}\right) \cdot 82{,}60 + \left(\frac{nwo}{12{,}75 + nwo}\right) \cdot 27{,}65} = 38{,}09$$

With these results, it was determined that, in the facilities analyzed, with an average of 12.75 swimmers training, 38 people could have been allowed to stay in the facility, applying the most restrictive criterion of those proposed in this study.

The same calculation method can be used for all other reference values (equations 2 to 4), resulting in 23.55 l/s·person at 50% of the proposed limit value, 19.87 l/s-person at 25% of the proposed value and 16.82 l/s·person using the criterion established by the Steady State CO_2 [37, 39].

Using numerical interaction, it is possible to obtain theoretical occupancies, for all the activities, which are considered necessary to be carried out simultaneously in an enclosure.

3.2. Application of the method to other pathogens or hazardous substances

The background concentration is the average concentration in the air within a closed volume, after a period during which a steady state has been established between the emission and the airflow induced by ventilation, consequently, it allows for evaluation of the effectiveness of ventilation in the dispersion of the pathogen or pollutant [46].

The background concentration is directly related to the hazardous concentration, through the concept of critical concentration, therefore, any pathogen or substance whose hazardous concentration is known, is susceptible to be controlled indoors, through the application of this study.

The critical concentration corresponds to one-fourth of the volume considered dangerous for the pathogen or substance under consideration

In the present case, the concentration of the pathogen in the air exhaled by people is small, and this air will tend to move along with the general air mass and show a neutral behavior concerning it.

Based on the volume of oxygen consumed during the performance of a sedentary task, by applying the UNE EN 8996:21 Standard [55], the volume of air inhaled by the individual is obtained. As mentioned above, the metabolic consumption of the individual, performing light exercise, is 70 W/m2.

The aforementioned standard considers the concentration of oxygen in the air to be 20.09%, while the fraction of oxygen in exhaled air is 16.20%.

$$M = EE \cdot V_{O_2} \cdot \frac{1}{A_{D_U}}$$

$$70 = 5{,}68 \cdot V_{O_2} \cdot \frac{1}{1{,}8} \Rightarrow V_{O_2} = 22{,}18\ l/h$$

$$V_{O_2} = V_{out}\left(0{,}209 - F_{O_2}\right)$$

$$22{,}18 = V_{out} \cdot (0{,}209 - 0{,}162)\ \Rightarrow V_{out} = 471{,}91\ l/h$$

$$V_{O_2} = V_{out}(0{,}209 - 0{,}162)$$

The background concentration (vol/vol), can be evaluated as (16):

$$X_b = \frac{Q_g}{Q_g + Q_1} \qquad \text{(Equation 16)}$$

Among them, X_b is the background concentration (vol/vol), Q_g is the exhaled air volumetric flow rate (l/s), and Q_1 is the ventilation volumetric flow rate (l/s) (16).

The critical concentration is related to the dangerous concentration of SARS-CoV-2, using the following expression (17):

$$X_{crit} = 0{,}25 \cdot C_{dangerous} \qquad \text{(Equation 17)}$$

Among them, x_{crit} is the critical concentration (vol/vol) and $c_{dangerous}$ is the dangerous concentration of SARS-CoV-2 (vol/vol) (17).

The criterion of equality between the background concentration and the critical concentration is implemented, taking into account that the required flow parameter at 75% has the concept of the critical concentration incorporated (18).

$$X_b > X_{crit}$$

$$X_b = X_{crit} \Rightarrow \frac{V_{ext}}{Q_{limit\ value}} = 0{,}25 \cdot C_{dangerous} \qquad \text{(Equation 18)}$$

For the calculation of the limit value for SARS-CoV-2, with respect to the value referred to 75%, the following equation is applied (19).

$$X_b = X_{crit} \Rightarrow \frac{V_{out}}{Q_{required\ 75\%}} = C_{dangerous} \qquad \text{(Equation 19)}$$

$$X_b = X_{crit} \Rightarrow \frac{471{,}91/3600}{19{,}56} = C_{dangerous}$$

$$C_{dangerous} = 6{,}70 \cdot 10^{-3}\ vol./vol.$$

The direct comparison between the hazardous air concentration of SARS-CoV-2 (vol/vol), and the pathogen or hazardous substance to be controlled, allows the application of the presented method for its control.

Comparing the value obtained with those considered harmful to the health of other environmental pollutants, the bad quality level according to the Air Quality Index (ICA, for its acronym in Spanish) [60], is 37 times higher than that of O_3, 33 times higher than that of NO_2 and 19 times higher than that of SO_2.

4. Results and discussion

The results obtained from the application of the methodology described in the previous section of the paper, Section 3.1., for the specific case of the Villafontana Sports Centre facilities, are shown in the Appendix A section.

The parameters used for the calculations are shown (Table 4), the required ventilation flow rates (Table 5), the theoretical occupancy of the building (Table 6), based on its Self-

Protection Plan, as well as the actual occupancy during the study period, data provided by the Sports Department of the Mostoles City Council, the theoretical occupancy calculated in each enclosure, based on the performance parameters (75%, 50%, 25% and Steady State CO_2) (Table 7) and finally, the compliance with the proposed values during the study period is obtained (Table 8).

The number of available air renewals is 2.57 h^{-1} in all the facilities of the Villafontana Sports Centre, except Management and the Sports Track whose values are 1.73 and 0.96 h^{-1} respectively. The low ventilation of the Sports Track is particularly significant since the activity carried out in this area corresponds to the highest metabolic activity together with the Fitness Centre and Winter Pool areas.

The proposed ventilation values are higher than those obtained through the application of the Steady State CO_2 method. In the most restrictive situation, when the required ventilation is at 75% of the proposed limit, 82.96 l/s·person is required for the areas where the highest intensity physical activity is performed, Fitness Centre, Winter Pool, and Sports Track, while in the area with the lowest intensity, Management, it drops to 19.36 l/s·person.

The average occupancy during the study period was lower in all areas of the Villafontana Sports Centre except for the Judo Gym and Reception, concerning the different limit values proposed.

The tool presented applies to any airborne pathogen or contaminant, introducing the concept of background concentration.

4.1 Results obtained in the sports centres managed by the Mostoles City Council

The results obtained for compliance with the proposed values are shown in the Appendix B section for the rest of the sports centres analyzed: Las Cumbres Swimming Baths, Joan Miró Sports Centre, and La Loma Sports Centre (Tables 9 to 11). For this purpose, the methodology described in Section 3.2. of this paper is applied.

The activity areas whose average occupancy during the study period was higher than that proposed, considering an occupancy at 75% of the established limit, was 60% at Las Cumbres Swimming Baths, 25% at Joan Miró Sports Centre and 20% at Las Lomas Sports Centre, while considering the proposed ventilation values in the Steady State CO_2

method, the situation was the same at Joan Miró Sports Centre, the percentage was reduced to 40% at Las Cumbres Swimming Baths and was not exceeded in any of the facilities at Las Lomas Sports Centre.

It should be taken into consideration that an occupancy at 75% of the established limit value implies a concentration of the virus in air four times lower than that considered safe, so transmission is very unlikely and in this situation has been found, as a general rule during the study period 38.5% of all sports areas of Mostoles City Council.

4.2. Analysis by comparing the incidence of SARS-CoV-2 in the centres analyzed and the incidence among the population

The incidence of SARS-CoV-2 among the thousand six hundred and fifty-seven municipal workers of the Mostoles City Council was studied to determine its behavior.

For this purpose, the fourteen-day incidence rate per hundred thousand workers was analyzed (Figure 2), based on the sick leave caused by SARS-CoV-2, and compared with data from the Community of Madrid (Figure 3) [56].

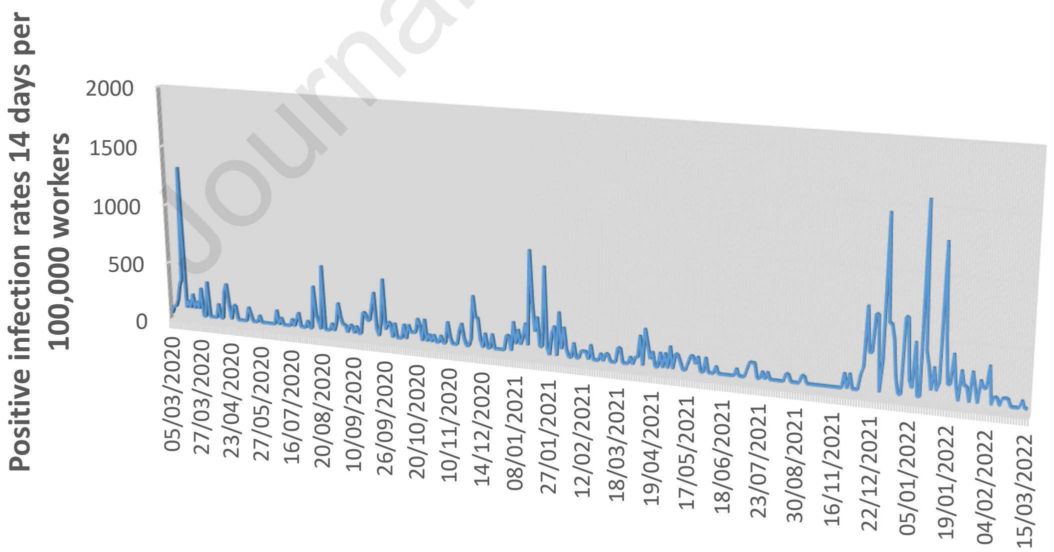

Figure 2. 14-day incidence rate per 100,000 workers based on infection data provided by the Mostoles City Council.

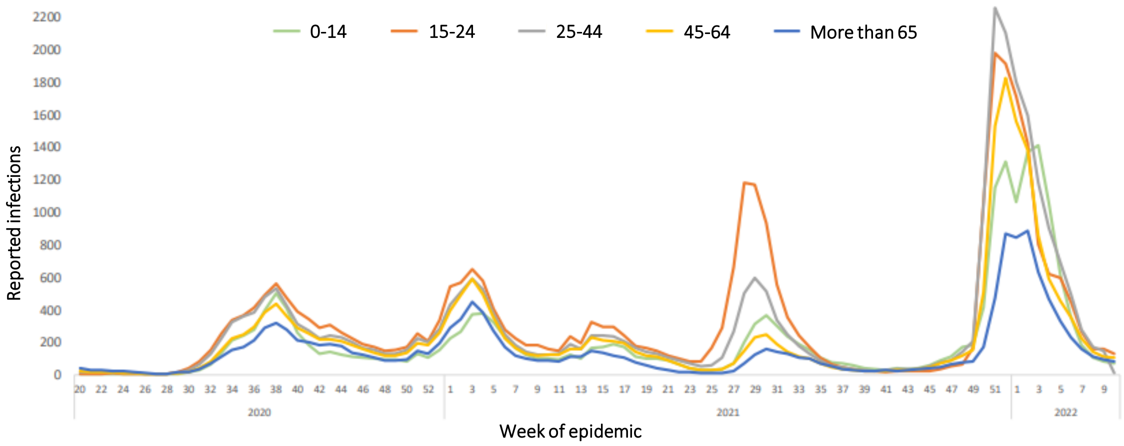

Figure 3. The incidence rate of 14 days per 100,000 inhabitants is based on data from the Community of Madrid.

It can be seen that the trend coincides with the different waves experienced in the Community of Madrid, for people aged between 25 and 64 years (Figures 2 and 3). The municipality of Mostoles is compared with the Community of Madrid because the municipal workers of the Mostoles City Council do not necessarily live in that municipality. In week 20 of the year 2020, the incidence in the Community of Madrid was 600, a value coinciding with the incidence of the workers of the Mostoles City Council; the same occurred between January and March 2020, with an incidence of 800; in April 2021 with an incidence of 400; and between December 2021 and March 2022, an incidence between 1,600 and 1,800.

However, although the fourteen-day incidence rate per 100,000 inhabitants of SARS-CoV-2 among municipal workers, during the period from March 2020 to February 2022, shows values similar to the data provided by the Community of Madrid, analyzing the data on infections by workplace, if fourteen days are considered as the period of transmission, only 32.97% of the cases are likely to have occurred in the workplace, while considering a time difference of between ten and seven days, 28.57% and 24.48%, respectively, could be considered infections caused by the ventilation conditions of the work centres, while the centres under study in this study have had compliance concerning the four proposed reference values of 51.11%, 60.00%, 64.44% and 77.78%, respectively.

To be able to discriminate infections produced in the workplace from those produced in the private sphere and, therefore, as a direct consequence of ventilation conditions, the time limit applied coincides with the different quarantines established to prevent the transmission of the disease in passengers from other countries upon their arrival in Spain: fourteen days according to Order SND/403/2020 [57] and ten days according to Order SND/413/2021 [58], or that of seven days according to Decree 867/2021 Extension [59], established by the Argentine Government.

Percentage results of infections that can be considered as a consequence of ventilation conditions, in the buildings under study.

Table 12. The percentage of infections by COVID-19, suffered by municipal workers, is ascribed to the sports centres managed by the Mostoles City Council.

	% Infection (≤14 days)	% Infection (≤ 10 days)	% Infection (≤ 7 days)
Villafontana Sports Centre	46.67	40.00	26.67
Las Cumbres Sports Centre	40.00	40.00	40.00

Fifteen infections were recorded in each of the two sports centres listed in Table 12, between March 2020 and February 2022. It should be noted that, for the results shown in Table 12, the Joan Miró and La Loma Sports Centres do not have municipal workers assigned to these centres of the Mostoles City Council, so no data is available for both.

Table 13 shows the results obtained among the sports workers of the Mostoles City Council.

Table 13. Percentage of COVID-19 infections suffered by sports workers accessing different facilities in the course of their work.

	% Infection (≤14 days)	% Infection (≤ 10 days)	% Infection (≤ 7 days)
Sports workers	35.71	14.29	14.28

Table 14 below shows the results obtained for all the buildings corresponding to the Sports Department of the Mostoles City Council.

Service operators rotate through all sports centres and fourteen COVID-19 infections were recorded between March 2020 and February 2022.

Table 14. The percentage of COVID-19 infections, suffered by municipal workers, is ascribed to the Sports Department of the Mostoles City Council.

	% Infection (≤14 days)	% Infection (≤ 10 days)	% Infection (≤ 7 days)
Sports Department	50.00	37.50	37.50

As can be seen, these are workers performing administrative tasks, among whom eight COVID-19 infections were recorded between March 2020 and February 2022.

There is hardly any variation between the percentage of infections occurring with a 10-day and a 7-day deficiency, but there is a difference when we take 14 days as a reference.

Most of the sick leaves caused by SARS-CoV-2 occurred with a temporary absence longer than the quarantines implemented to prevent transmission of the virus, which implies that the infection did not occur in the workplace.

In all municipal buildings, for a difference of more than 14 days between infections, 67.03% of the centres are considered not to have been infected in the workplace, while 71.43% and 75.52%, considering a time difference of ten and seven days, respectively, would not be considered infections caused by the ventilation conditions of the workplaces.

Table 15. Percentage of infections, in the totality of municipal centres, with the temporary shortages.

COVID-19 sick leave (les tan 14 days)			COVID-19 sick leave (les tan 10days)			COVID-19 sick leave (les tan 7 days)		
No of centres < 75 %	No of centres < 50 %	No of centres < 25 %	*No of centres < 75 %*	No of centres < 50 %	No of centres < 25 %	*No of centres < 75 %*	No of centres < 50 %	No of centres < 25 %
1.10	0.00	0.00	11.00	4.39	3.30	27.47	19.78	17.58

The total number of COVID-19 infections among the municipal workforce between March 2020 and February 2022 was nine hundred and fifty-four cases.

For this research, Municipal Police and Social Services workers are not taken into account, since their activity is mainly carried out outside municipal buildings, their tasks being to attend to citizens.

5. Conclusions

During the SARS-CoV-2 pandemic period, an occupancy calculated based on available ventilation has been established in the work centres of the Mostoles City Council, using the present exposed method, whose effectiveness has been evaluated by analyzing the infections of municipal workers, registered as sick leave.

The study is notable for its comprehensive analysis of ventilation conditions in sports facilities, which is particularly relevant during the COVID-19 pandemic. It is based on a distinctive dataset that covers several sports centres managed by the Mostoles City Council, providing detailed information on ventilation rates, occupancy levels, and compliance with ventilation standards. The research introduces the innovative concept of background concentration, extending its relevance beyond COVID-19 to address various airborne pathogens. Additionally, the study highlights the potential impact of ventilation on workplace infections by comparing SARS-CoV-2 incidence among municipal workers and the general population. The study's comprehensive approach reinforces its findings, highlighting its significance in developing efficient ventilation plans for indoor sports facilities and comparable settings.

The exposed working method has its limitations, firstly, the results have been validated by comparison between the incidence of the virus suffered among the general population and the data of infections suffered by workers during their stay in municipal centres. Discrimination between infections occurring in the workplace and those occurring in the private sphere was made by applying a time limit coinciding with the quarantines established to prevent transmission of the disease: if two municipal workers performing their duties in the same work centre were infected with the virus with a time difference greater than that established by the quarantine, this implies that the infection occurred in the private sphere. Thus, all infections occurring in the workplace have been considered as such, but possibly also some occurring in the private sphere. This implies that the error made has always been in the sense of safety, estimating the ventilation values offered as less safe than they are.

On the other hand, we have only been able to obtain data on infections among municipal workers, in no case of users, to whom corresponds the highest percentage of the occupancy density of sports centres, in addition to the activities with the highest percentage of viral load emission, in case any of the users were infected.

The average occupancy was obtained from data provided by the Sports Department and is based on the registration of users both in and out of the municipal sports centres, crossed with the activities in which users were enrolled, so there may be peaks of high concentration in areas not contemplated such as hallways, turnstiles, and dryers area.

Finally, it should be noted that, during the three years of the pandemic, no official agency has published the minimum airborne virus concentration necessary to generate an infection, nor has it made available methods of biological analysis in the air, for any of the variants that we have suffered.

These uncertainties, together with the impossibility of continuous CO_2 measurements and direct control over occupancy density, constitute the real limitations of the study. Nevertheless, the results obtained allow us to conclude that the application of the method has allowed us to obtain satisfactory results in the centres analyzed.

The 14-day incidence rate per 100,000 inhabitants of SARS-CoV-2 among municipal workers during the period from March 2020 to February 2022, shows values similar to the data provided by the Community of Madrid, however, analyzing the data of infections by workplace, if we consider the period of transmission to fourteen days, only 32.97% of the cases are likely to have occurred in the workplace, while considering a time difference of ten and seven days, 28.57% and 24.48%, respectively, could be considered infections caused by ventilation conditions in the workplace.

It should be noted that the UNE-EN 8996:21 standard [55], makes it possible in the future to have exact occupancy values adapted to the activity carried out in the work centre, by applying the study individually, taking into account the height and weight of each individual who accesses the facility, and even the occupancy ratios could be established by monitoring the heart rates of users who are performing sports activities.

The work method presented is a useful tool in future crises, through the implementation of the concept of background concentration, which allows an adaptation by comparison between the calculated SARS-CoV-2 hazardous air concentration and that of the new pathology or hazardous substance to be addressed.

Acknowledgements

We would like to express our gratitude to the Mostoles City Council (Community of Madrid, Spain) for having provided us with the data used in the research under the agreed terms, without which this study could not have been carried out.

Data availability statement

No additional information is available for this paper. The data used are confidential since they were provided by the Mostoles City Council through its Sports, Maintenance, and Human Resources Departments. On the one hand, they contain personal medical information of its workers and, on the other hand, they contain data that the entity considers sensitive for the security of its facilities.

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Appendix A

Below are the corresponding parameters at the Villafontana Sports Centre of Mostoles.

Table 4. Parameters obtained at the Villafontana Sports Centre of Mostoles.

Building area	Judo Gym	Fitness Centre	Locker rooms	Reception	Management	Winter pool	Sports track
Theoretical occupation	18.00	12.00	16.00	2.00	7.00	402.00	127.00
Enclosure surface (m^2)	183.61	128.82	50.00	5.67	69.05	804.00	1,274.15
Forced enclosure ventilation (m^3/s)	0.46	0.32	0.13	0.01	0.08	2.01	2.04
Enclosure volume (m^3)	642.64	450.87	175.00	19.85	172.63	3,216.00	7,644.90
No. of renewals “C” (h^{-1})	2.57	2.57	2.57	2.57	1.73	2.25	0.96
Metabolic rate (M)	260.00	300.00	100.00	100.00	70.00	300.00	300.00
Carbon dioxide generation rate qCO_2 (l/s)	0.02	0.02	0.01	0.01	0.00	0.02	0.02

Table 5. Ventilation flow rates at the Villafontana Sports Centre in Mostoles.

Building area	Judo Gym	Fitness Centre	Locker rooms	Reception	Management	Winter pool	Sports track

Ventilation flow required at 75% (l/s·person)	71.90	82.96	27.65	27.65	19.36	82.96	82.96
Ventilation flow required at 50% (l/s·person)	61.24	70.67	23.56	23.56	16.49	70.67	70.67
Ventilation flow required at 25% (l/s·person)	51.68	59.63	19.88	19.88	13.91	59.63	59.63
Ventilation flow required at Steady State CO_2 (l/s·person)	43.75	50.48	16.83	16.83	11.78	50.48	50.48

Table 6. Theoretical and actual occupancy at the Villafontana Sports Centre in Mostoles.

Building area	Judo Gym	Fitness Centre	Locker rooms	Reception	Management	Winter pool	Sports track
Theoretical occupation	18.00	12.00	16.00	2.00	7.00	402.00	127.00
Actual occupation	24.70	0.00	4.00	1.00	4.00	12.73	22.18

Table 7. Theoretical occupation obtained at the Villafontana Sports Centre in Mostoles.

Building area	Judo Gym	Fitness Centre	Locker rooms	Reception	Management	Winter pool	Sports track
Occupation at 75%	6.38	3,88	4,52	0,51	4,28	24,23	24,57
Occupation at 50%	7,49	4,56	5,31	0,60	5,03	28,44	28,85
Occupation at 25%	8,88	5,40	6,29	0,71	5,96	33,71	34,19
Occupation at Steady State CO_2	10,49	6,38	7,43	0,84	7,04	39,82	40,39

Table 8. Compliance with the proposed values at the Villafontana Sports Centre in Mostoles.

Building area	Judo Gym	Fitness Centre	Locker rooms	Reception	Management	Winter pool	Sports track
Compliance required at 75%	3.87	0.00	0.88	1.95	0.93	0.53	0.90
Compliance required at 50%	3.30	0.00	0.75	1.66	0.80	0.45	0.77
Compliance required at 25%	2.78	0.00	0.64	1.40	0.67	0.38	0.65
Compliance required at Steady State CO_2	2.35	0.00	0.54	1.19	0.57	0.32	0.55

Appendix B

Results were obtained in the sports centres managed by Mostoles City Council.

Table 9. Occupancy concerning the proposed limits, based on the data provided by the Mostoles City Council for the "Las Cumbres" Swimming Baths.

Las Cumbres Swimming Baths	Occupancy concerning $Q_{required\ 75\%}$	Occupancy concerning $Q_{required\ 50\%}$	Occupancy concerning $Q_{required\ 25\%}$	Occupancy concerning $Q_{required\ Steady\ State\ CO_2}$
Male changing room	1.71	1.46	1.23	1.04
Female changing room	1.82	1.55	1.31	1.11
Family changing room	0.00	0.00	0.00	0.00
Main pool	2.20	1.87	1.58	1.34
Paddling pool	2.54	2.16	1.83	1.55
Pool area	1.11	0.94	0.80	0.67
Seating around pool	0.00	0.00	0.00	0.00
Meeting room	0.00	0.00	0.00	0.00
Office	1.03	0.88	0.74	0.63
Administration	0.66	0.57	0.48	0.40

Table 10. Occupancy concerning the proposed limits, based on the data provided by the Mostoles City Council for the "Joan Miró" Sports Centre.

Joan Miró Sports Centre	Occupancy concerning $Q_{required\ 75\%}$	Occupancy concerning $Q_{required\ 50\%}$	Occupancy concerning $Q_{required\ 25\%}$	Occupancy concerning $Q_{required\ Steady\ State\ CO_2}$
Seating	0.00	0.00	0.00	0.00
Athletics track	0.83	0.71	0.60	0.51
Office (2)	2.30	1.96	1.66	1.40
Games room	0.00	0.00	0.00	0.00

Table 11. Occupancy concerning the proposed limits, based on the data provided by the Mostoles City Council for the "La Loma" Sports Centre.

La Loma Sports Centre	Occupancy concerning $Q_{required\ 75\%}$	Occupancy concerning $Q_{required\ 50\%}$	Occupancy concerning $Q_{required\ 25\%}$	Occupancy concerning $Q_{required\ Steady\ State\ CO_2}$
Offices	0.98	0.83	0.70	0.59
Balcony	0.00	0.00	0.00	0.00
Changing rooms	0.98	0.83	0.70	0.60
Multi-sports track	1.47	1.25	1,05	0.89

Seating	0.00	0.00	0,00	0.00