HVAC systems operation control based on indirect occupant-centric method for ensuring safety conditions and reducing energy use in public buildings after Covid-19

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Abstract

A stronger interest in energy independence from unreliable suppliers, together with an increasing awareness towards climate changes and possible consequences, are affecting and accelerating the so-called clean energy transition. Such a transition envisages several actions, and one of them is the need to improve the energy efficiency of buildings – which are one of the most energy-intensive sectors – leveraging on advanced energy monitoring systems. It is however well-established that strategies for energy efficiency should not jeopardize occupants' health and quality of life. Therefore, energy management systems should be ideally designed both to guarantee the required health conditions and acceptable comfort level, and at the same time to minimize energy wastes. A classic example is represented by ventilation systems, which especially in the post-pandemic period, are often left in full operation also when buildings are empty or with low occupancy.

Considering the topic and the available literature, this paper provides a multi-objective optimization approach to control HVAC systems to ensure Indoor Air Quality (IAQ) and healthy conditions by controlling energy use. The IAQ is guaranteed through the definition of an absolute threshold value of CO_2 concentration, while the minimization of the infection risk is ensured through the development of a relationship between this and the increase of CO_2 concentration over time. In this way, HVAC systems, and in particular ventilation rate, can be tailored around the actual occupancy of the building. The method is extensively tested in a real case study in educational buildings, and expected improvements in energy consumption are evaluated.

Keywords: Public shared buildings; Carbon dioxide monitoring; Demand-Controlled Ventilation; Energy-saving measures; Infection risk in public buildings; Occupant-centric HVAC optimal control.

Nomenclature

A	Floor area of the classroom [m^2]
ACR	Air Change Rate [l/s]
ACRH	Hourly Air Change Rate [Vol/h]
c_p	specific heat capacity at constant pressure [J/(kgK)]
C	Concentration in the environment [ppm]
$C_{\{CO_2\},set}$	Setted values for CO_2 concentration for optimal control
$C_{\{CO_2\},out}$	Reference value of external CO_2 concentration [ppm]
$C_{\{CO_2\},start}$	Initial value of CO_2 concentration [ppm]
$C_{\{CO_2\},max}$	Maximum permissible value of CO_2 concentration
En	Energy used for ventilation [J]
h_{dist}	Specific enthalpy at distribution condition [kJ/kg]
h_{ext}	Specific enthalpy of the external air [kJ/kg]
I	number of source patients (infectors) [-]
n_{occ}	number of occupants of indoor space [-]
p	Metabolic production of CO_2 [kg/s for person]
P	Infection probability [%]
q	quanta concentration of virus [1/hour]
Q	Volumetric air change rate [m^3/s]
$\dot{r}$	CO_2 production rate produced by each person [l/min]
RH_{ext}	Relative humidity (external value)
$RH_{set-point}$	Relative humidity (set point value)
T_{dist}	Temperature of air distribution [°C]
T_{int}	Internal set point air temperature [°C]
T_{ext}	External air temperature [°C]
V	Volume of the room or of the structure [m^3]
V_{min}	Minimum volume available for each occupant [m^3]
t	Time interval [s]
Δp	Pressure drop in the fan distribution circuit [Pa]
λ	Infection rate
η	Fan efficiency
ρ	Density [kg/m^3]

Abbreviations

ACR	Air Change rate
AHU	Air Handling Unit
BEMS	Building Energy Management Systems
EI	Energy Intensity
DCV	Demand Controlled Ventilation
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
MV	Mechanical Ventilation
NV	Natural Ventilation

1. Introduction

The maintenance of appropriate conditions of environmental health combined with the control of energy consumption is a problem of large interest in the management of shared public buildings, and it is receiving an increasing attention as it can contribute to the reduction of energy costs. At the same time, it is well known that it can reduce the impact of the spread of viral and bacterial diseases, such as flu syndromes and Covid-19, as well as reduce the impact of energy consumption in buildings. After the Covid-19 pandemic, a large amount of energy is now used for heating, cooling, and air ventilation [1]. Air quality is gathering an increasing interest because new regulations have been introduced to improve the safety of indoor environments and the operation of Heating, Ventilation and Air Conditioning (HVAC) systems.

1.1 Motivation of the work

This work addresses the consequences of many recent regulations that after the Covid-19 pandemic have redesigned the operation of HVAC devices, most notably the request that recirculation of air taken from inside the environment should be avoided in mechanical ventilation systems. This last measure is particularly restrictive since air recirculation had been extensively used in the previous years to obtain significant energy savings for HVAC systems operation [2-5]. Conversely, strict compliance with the Covid-19 regulations, together with the significant increase of mechanical ventilation (where this opportunity is available), or the use of natural ventilation (by opening doors and/or windows) where mechanical ventilation is not available, are triggering significant increases in energy consumption. In turn, this is determining significant economic costs and progressive deviations from sustainability objectives [6].

This is a relevant problem, among others, in educational buildings like university classrooms and schools. Obviously, the importance of ensuring healthy environments has become particularly evident after the Covid-19 outbreak. The airborne transmission of the virus has led the scientific community to focus on possible methods to mitigate the risk, and to recognize the pivotal role of ventilation systems. Indeed, in addition to the many non-surgical rules, such for instance reducing the number of allowed people in indoor environments, reducing duration of stay, wearing surgical masks, specific guidelines have been proposed to increase the ventilation rate to the maximum level, regardless of the actual indoor conditions [9]. This has triggered a relevant increase of energy use for maintaining the desired indoor temperature while maintaining full ventilation rate.

Many recent papers and project have proposed innovative monitoring/control solutions in energy management systems. All of them typically aim at minimizing energy consumption, mainly focusing on energy efficiency and environmental impact, while preserving the comfort perceived by the building occupants [7]. Some solutions are model-based, i.e., they have been designed under the assumption that the building characteristics and all the dynamics influencing energy consumption and occupants' comfort are accurately known or, at least, they can be modelled with a sufficient accuracy. Conversely, they pay little attention to the actual occupancy of the buildings, or the real-time data regarding energy consumption [8]. Other solutions, which can be usually found in case study projects, gather environmental and context information via many distributed physical sensors. Although using many power meters and/or sensor nodes helps in devising more advanced and context-aware control mechanisms, it also results in a more intrusive and expensive apparatus that may ask for substantial changes on the existing Building Energy Management Systems (BEMS').

In this work, we address the problem of exploiting measured data to develop occupant-centric HVAC control solutions, aiming at obtaining the desired level of air quality comfort, both in terms of a low level of CO_2 low probability of infection, while at the same time avoiding the energy wastes due to continuous utilization of mechanical ventilation systems, even with low levels of occupancy of the building. For this purpose, following the work of [10], we use the room size and CO_2 concentration as a proxy to assess indoor environmental conditions and occupancy.

1.2 State of the art, paper contribution and novelty of the approach

The recent Covid-19 outbreak has led to an increased awareness of the importance of the indoor environment on people's health [2]. In addition to the conventional rules for internal comfort, the role of ventilation in the reduction of the infection probability has been definitively proven [3], as through ventilation the outdoor air is introduced inside the environment. HVAC systems can play a fundamental role in the maintenance of health conditions and different ventilation strategies can be adopted to reduce the infection risk for different pandemic [4]. Guidelines have been implemented by National and International authorities, which address the importance of ventilation both for maintain adequate air quality and for reducing infection risks, in connection with the real occupancy profile of the building [5]. Furthermore, guidelines suggest that air recirculation should be avoided, bringing ventilation to 100%, and decreasing the setpoint of CO_2 concentration at quite low level, defined in connection with the different use [11]. This has led to a considerable increase in energy consumption for ventilation and climatization, which although may still be acceptable during the pandemic period, appears to be unsustainable in the long term. Threshold values of CO_2 concentration in the air have been often used both as an indication for the occupancy and as a feedback variable for infection risk control [12].

If a maximum value of CO_2 concentration may be used to guarantee a desired level of indoor air quality; the same value does not necessarily guarantee a predetermined level of infection probability, but the two elements can be correlated in some ways. But if the infection probability does not just depend on the absolute value of CO_2 concentration [13-14], (an empty room with high CO_2 concentration is of course safer than a crowded room with a low value of CO_2 concentration) in crowded spaces a correlation can be clearly identified. This last observation is not considered in many guidelines for air ventilation, such as EN 16798-1 for European countries [15] or ASHRAE 55/62.1 for USA [16], which are air-quality based norms that do not consider the airborne transmission of diseases. Conversely, other ventilation strategies have been proposed in the literature that are effective to reduce the infection probability considering the actual indoor conditions. These strategies are generally based on well-established models of indoor disease spreading, such as the Wells-Riley model [17] or similar [18], which relate the infection probability to the ventilation rate [19]. Optimal ventilation rate is a classic problem that has been already studied as in [20-22], where authors proposed demand-controlled ventilation (DCV) based on CO_2 concentration monitoring to limit airborne transmission. Different authors, like Kurnitski et al. [23] suggested a design method for ventilation based on the Wells-Riley model.

In general, the operation of HVAC system, often of the total air type, for ventilation and air conditioning at maximum load, aimed at overcoming the Covid-19 rules, determines a significant increase in energy use, which becomes particularly relevant in summer and winter cases, when the air exchange imposes a significant increase in energy uses and on the consequent costs, and this problem has been not properly considered and for this reason, it is important to define a clear connection between the ventilation of buildings and the actual occupancy level.

Moving from the above exposed considerations and from those already proposed in [21] and [24], intent of the authors is to propose and discuss the impact of the pandemic experience on energy efficiency targets in public shared buildings and to analyse the possibility of introducing an "occupant-centric" optimal control strategy for HVAC systems, to balance the energy efficiency, but considering as constraint the maintenance of healthy IAQ conditions, while discussing the comfort and safety level required by the recent legislation [25-29]. The analysis is developed considering real case studies, referred to university classrooms. Finally, we propose a control strategy based on the analysis of CO_2 concentration and its derivative in time to jointly control the air quality (through the CO_2 concentration) and the infection risk (through both the CO_2 concentration and its derivative). The methodology may be replicated in different environments, leveraging on the increasingly available data of occupancies in the post-Covid era.

The paper is organized as follows: next section briefly overviews data regarding energy consumption in the building sector, to highlight the importance of this problem, and the possible impact of mitigation strategies for energy consumption. Section 3 provides basic equations for the computation of energy consumption for HVAC systems, most notably, cooling and heating. Section 4 further evaluates, and validates, similar equations for mechanic ventilation strategies, showing the importance of the number of occupants of a room, and supporting the need of deriving occupant-centric models for optimized HVAC operation. Section 5 shows the impact of ventilation strategies in the contact rate of Covid-19 or other flu-like diseases. The prediction of infection probability is taken into explicit account in section 6, when a specific case study is presented. Section 7 is then dedicated to predicting the energy savings which could be obtained with the proposed strategy, while section 8 outlines a possible implementation when both CO_2 concentration and its derivative are measured. Finally, section 9 concludes the paper and summarizes the main findings.

2. Energy consumption in the public sector: recent trends before and after Covid-19

Analyses of energy consumption in European countries testify that the public sector is relevant and accounts for 15-20% of the total energy consumption. Interestingly, even before Covid-19, energy consumption was already decreasing in many countries, included Italy as shown in Fig. 1, with respect to the level of the beginning of the current century [25]. Fig. 1, extrapolated from [30], provides the trend of energy in the pre-pandemic period from 2000 to 2019. In 2019, the total energy consumption amounted to about 112 Mtoe (Mega tonnes of oil equivalent), corresponding to a primary energy consumption of about 151.5 Mtoe. In particular, the industrial compartment reduced energy consumption by more than 30% starting from 2005, at an average rate of about 3 Million of tons equivalent (Mtoe) per year. The same occurred in the transport sector, in which energy consumption decreased by 10% in the period 2000-2019. Conversely, energy consumption in the civil sector (sum of residential and services) has remained practically constant, and it corresponded to about 42% of the total energy consumption in 2019, as in Fig. 2. However, the proportion has further increased after the pandemic, due to the increased energy use of HVAC devices.

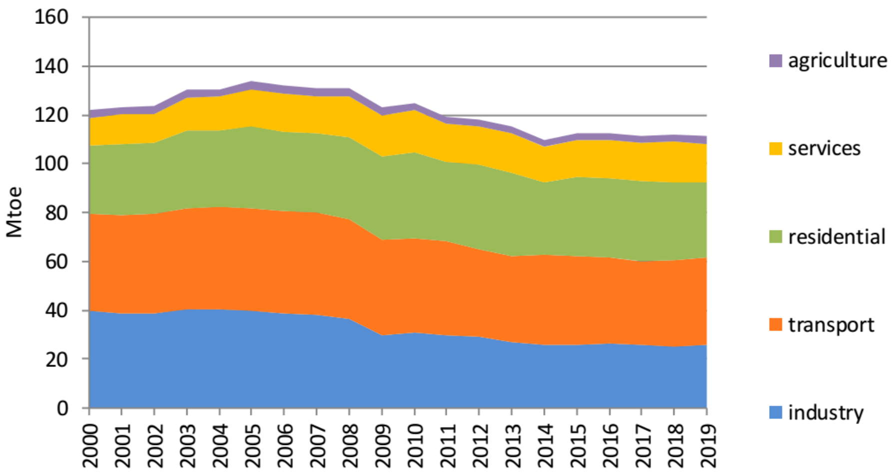

Figure 1. Final energy consumption in Italy by sector

There are several types of HVAC systems that can be used for public buildings, depending on factors such as the size of the building, the number of occupants, the local climate, and the energy efficiency goals of the building owners. A significant share of the energy used in buildings may be referred to the operation of the HVAC systems, as they provide heating (with humidification), cooling (with dehumidification) and ventilation functionalities, using different energy inputs (mainly electricity and natural gas).

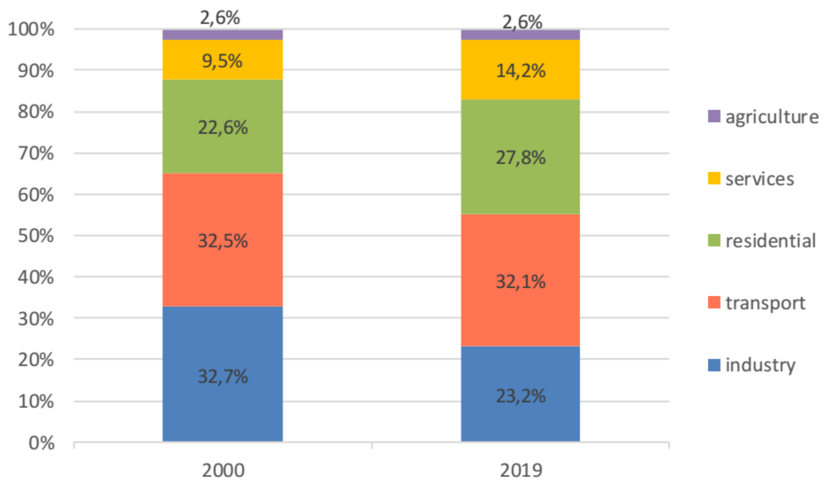

Figure 2. Share of energy consumption in Italy by sector

3. HVAC operation for ensuring safety conditions and comfort and related energy consumption

The experience of the Covid-19 pandemic has highlighted the importance of ventilation in public spaces. Today it is hardly possible to keep open public buildings that are not equipped with a mechanical ventilation (MV) system. The mechanical ventilation system is also part of the HVAC air conditioning systems, which are often air systems whose operation is well exemplified by the schematic diagram provided in Figure 3. Air change rate (ACR) has increased dramatically after Covid-19 pandemic to mitigate the risk of virus spreading, thus increasing the interest in ventilation, which is energy furthermore energy consuming. Many installed heat exchangers and thermal generators had been originally planned to match the demand of building heating with a guaranteed acceptable level of IAQ, under the assumption of air recirculation.

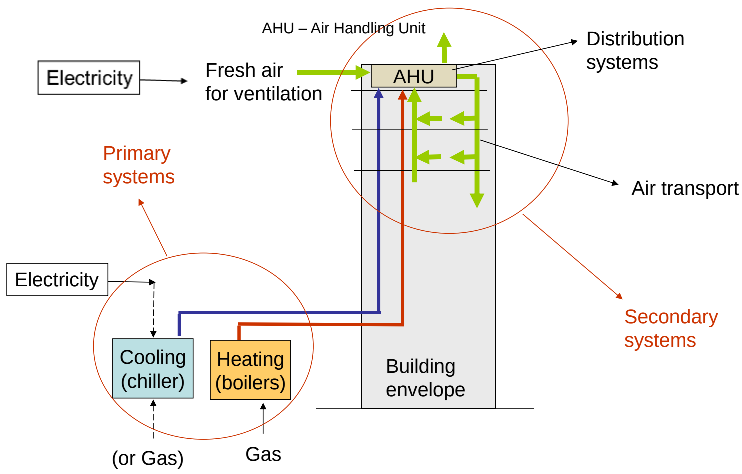

Figure 3. HVAC schematic operation and focus on air ventilation.

Air recirculation has been banned by many national recent legislations due to Covid-19, and thus an acceptable level of IAQ may not be achieved, unless at the expense of greatly increasing the use of mechanical ventilation, which increases energy consumption and energy costs. For such reasons, new approaches for designing HVAC systems, or for controlling HVAC operation, are necessary and urgent to make indoor spaces safe without compromising all the efforts and policies towards energy efficiency. Installation of instruments for IAQ monitoring is fundamental, together with implementation of intelligent building management and control systems. The attention to energy use should not compromise the requirement for a correct IAQ. A given amount of renewed fresh air is required to determine comfortable indoor environment, maintaining recommended values of relative humidity and pollutants concentrations. Several indicators can be linked to IAQ control: one of the most used ones is CO_2 concentration. CO_2 concentration can be considered as a simple proxy for occupancy of rooms, and consequently for assessing optimal ventilation rates. As ventilation is fundamental for maintaining adequate IAQ, the possibility of reducing energy needs associated with ventilation and ACR is a topic of particular interest too. The energy required for ventilation can be estimated starting from fan power

$$P_{fan} = \frac{Q\Delta p}{\rho}\frac{1}{\eta}, \quad (1)$$

where Q is the air exchange rate, required for maintaining the maximum amount of CO_2 concentration, expressed in m^3/s. The used energy depends on the mass flow rate and on indoor and external temperature. The energy required for the single heating component can be estimated through the following equation (referred to an operating time t):

$$E_{heating} = \rho Q c_p (T_{dist} - T_{ext}) t, \quad (2)$$

where c_p is a value of the specific heat of air that opportunely considers the relative humidity and the two temperatures of the internal environment and external air. The value of c_p may be considered constant for a typical observation period t, during which the difference between the distribution temperature T_{dist}, assuming a value sufficiently higher than the internal setup temperature, and the external temperature Text can be assumed constant as well (for example 1 hour). During the cooling period the energy required can be evaluated by directly using the enthalpy values

$$E_{cooling} = \rho Q (h_{dist} - h_{ext}) t \quad (3)$$

where Specific Enthalpy h is calculated considering the moisture content at inlet and the moisture content required at distribution (for example 60%), so that the total energy change can be obtained as the sum of the sensible and latent change. Then, integrating on the total operating hours of the building during a week, typical values of the energy required for maintaining the desired value can be estimated. The amount of removed water can be calculated by considering the specific moisture content of fresh air and the specific moisture content required at distribution.

4. Occupant-centric model for defining DCV based on the analysis of CO_2 concentration evolution.

It is more complicated to accurately estimate the energy consumption for ventilation. In principle, one could easily consider the mass balance equation of CO_2 in an indoor environment, assuming a well-mixed model with uniform and constant concentration of CO_2 in the room, and a well-defined value of the generation rate of the occupants.

Under the previous hypotheses, in a closed volume the rise of CO_2 concentration ($C_{\{CO_2\}}$) depends on the number of occupants. Using an estimate of the production rate $\dot{r}$, expressed in l/min (e.g., using the production rate *p* defined in Table 1 as a function of the activity of the individual), knowing the volume V of the room, and measuring the CO_2 concentration variation with time ($\frac{dC_{\{CO_2\}}(t)}{dt}$), then Eq. (4) may be used to estimate the number of occupants, n_{occ}:

$$V\frac{dC_{\{CO_2\}}(t)}{dt} = \dot{r}\, n_{occ}. \tag{4}$$

Eq. (4) can be also reformulated in terms of the volume available for each person (V/n_{occ}), which can be considered an accurate variable as long as the height of the room does not exceed the other two dimensions

$$\frac{V}{n_{occ}} = \dot{r}\frac{1}{\frac{dC_{\{CO_2\}}(t)}{dt}}. \tag{5}$$

From Eq. (5), it is easy to understand how the variation of CO_2 concentration can be related to the number of occupants if the rate of generation, strongly correlated with age, activity, and occupant's behavior, is known. If air ventilation is also considered, then the air ventilation rate Q can be imposed with a mechanical device (or may correspond to the one available under natural conditions, for instance if windows or doors are open), and the new equation becomes

$$V\frac{dC_{\{CO_2\}}(t)}{dt} = \dot{r}\, n_{occ} - Q\left(C_{\{CO_2\}}(t) - C_{ext}\right) \tag{6}$$

where Q is the air flow rate due to ventilation (mechanical of natural), in m^3/s, and C_{ext} is the outdoor CO_2 concentration. CO_2 concentration variation in the room can be written in explicit form, and thus its value at time t, can be estimated as:

$$C_{\{CO_2\}}(t) = C_{start}(t=0)\exp\left(-\frac{Q}{V}t\right) + \left(C_{ext} + \frac{\dot{r}\, n_{occ}}{Q}\right)\left(1 - \exp\left(-\frac{Q}{V}t\right)\right). \tag{7}$$

In all the equations, a fundamental role is played by the CO_2 production rate $\dot{r}$, which depends on different elements (age, weight, and type of activity); typical values of exhalation per person for some typical indoor activities are reported in Table 1, obtained according to the values given in [20], where major details about the synthetic description summarized in Eqs. (4)-(7) can be obtained. The idea is to define the appropriate value of the ACR, Q, to maintain a maximum value of CO_2 concentration in the room. In this way, after a first phase of increase of CO_2 concentration, an equilibrium condition is reached. If students are not in the room, the concentration decreases according to:

$$C_{\{CO_2\}}(t) = C_{out} + (C_{start} - C_{out}) \cdot e^{-\frac{Q}{V}t}. \tag{8}$$

Table 1. Typical value of CO_2 production rate depending on the occupant age and on the activity.

Type of indoor activity	Typical CO_2 production rate for person, p (kg/s / person)	CO_2 production rate for person, $\dot{r}$ (l/s / person)
adult people reading seated	0,0000079	0,0044
people sitting or involved in light intensity activities, seated	0,0000094	0,0052
people standing and operating a medium physical activity	0,0000114	0,0063
high intensity physical activities	0,0000315	0,0174

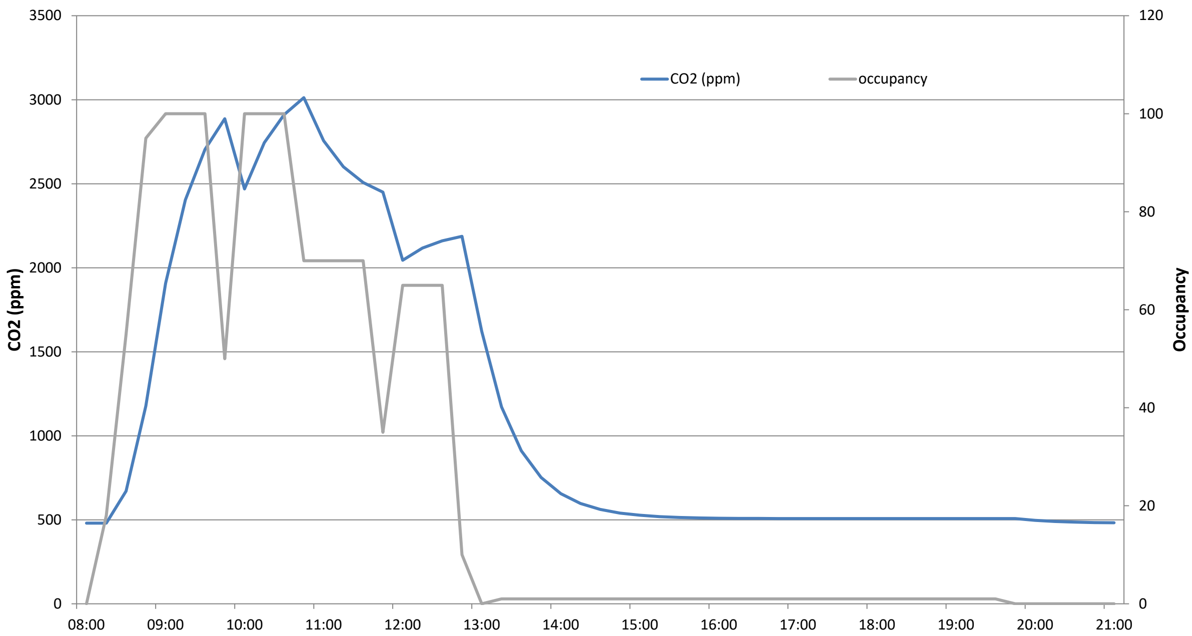

Figure 4. Evolution of CO_2 concentration in a crowded room without action of mechanical ventilation.

Figure 4 shows the evolution of CO_2 concentration in a classroom with an estimated volume of about 430 m^3 where about one hundred students follow a 2-hour lesson with a single break after one hour. After this, 80 students follow the subsequent class for another 2 hours with another similar break in the middle. In this case, MV is not active and the ACR is only determined by air infiltrations. It can be estimated that the CO_2 concentration after one hour assumes values well above the maximum allowed values (1500 ppm). In closed environments, the models for forecasting the evolution of CO_2 concentration are simple and can be based on basic principles of mass balance and energy conservation. However, in real-world environments, it can be difficult to control air infiltrations and other sources of variability, which can complicate the modeling process, so that the direct data-based monitoring appears more convenient.

In a recent paper, [10], the correlation between the variation of CO_2 concentration and the occupancy profile of the room was analyzed with experimental methodology by one of the authors of the paper. The data of the monitoring campaign are relative to cases characterized by different occupations. The monitored parameters were CO_2 concentration, air temperature (T_a), and relative humidity (RH). For the measurements, Chauvin Arnoux CA 1510 sensors were used. The sensors present the following characteristics: range of measurements 0-5000 ppm, resolution of 1 ppm and uncertainty ±50 ppm at 25 °C and 1.013 bar for the CO_2 measurement, accuracy equal to 0.5 °C (in the range −10 and 60 °C at 50% of RH) for the air temperature and accuracy 0.1% for the relative humidity. A detailed description of the instrument and of the experimental analyses is provided in [10]. The tests conducted in [10] have demonstrated the absolute reliability of CO_2 monitoring to make an indirect estimate of the occupation of the spaces and the experimental analysis was useful to evaluate the adaptivity of the model defined by Eqs. (2)-(6); in particular, referring to the data contained in Table 1, the typical carbon dioxide productivity (exhalation rate) has been defined, and this can be estimated in the value of 0,0000094 kg/s per person. The problem is quite complex because the CO_2 concentration increase depends on several variables such as the exhalation rate, the geometrical data of the room (volume V and area A), the number of occupants, the operational conditions (regular occupancy, occupancy with breaks), the ventilation rate (mechanical or natural) and on the opening of windows and doors. By simulating a typical operating condition and comparing the data with the various experimental data acquired, then, one can use Eqs. (4)-(6) to estimate the mechanical ventilation, or air flow rate, which should be activated to maintain optimal operating conditions, in terms of temperature and level of CO_2. Currently, guidelines for the operation of HVAC systems for public buildings require increasing the ventilation at the maximum capacity, without considering the indoor conditions, which include room occupancy, characteristics, possible natural ventilation, etc. Fig. 5 illustrates in a qualitative way how the air flow rate obtained with MV that can be used to control the CO_2 concentration. In all the cases, we assume that the initial value of CO_2 concentration is over 1000 ppm in a case in which a quite high occupancy of a classroom and MV starts operating if a concentration reaches 1500 ppm.

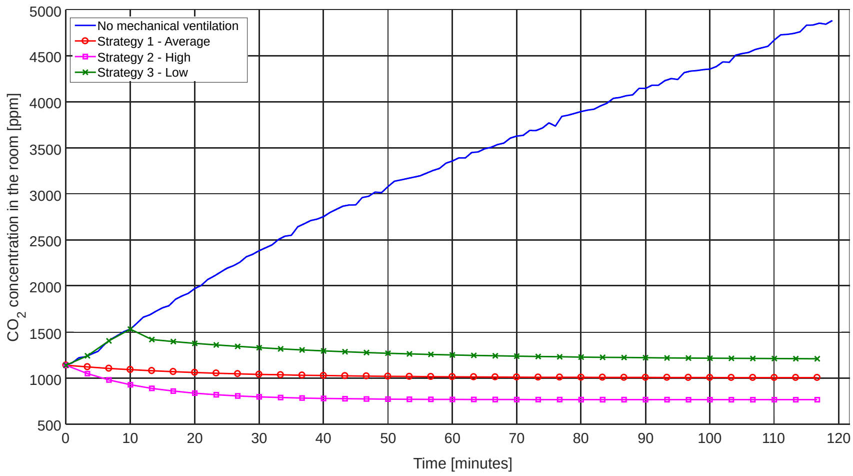

Figure 5. Simulation of different conditions in connection with different mechanical ventilation strategies for a crowded classroom, while the green area shows the trend when the ventilation is switched off.

5. The ventilation rate and the connection with Covid-19 infection and other pathogen diffusion probability

Mechanical ventilation represents the link between energy management and environmental control for Covid-19 risk prevention (Fig. 6) and is now mandatory in shared public buildings. Since the concentration of CO_2 has been widely used in the literature as a good indicator of both air quality and healthiness, in the following we shall also use it as the relevant variable for air quality control, as we shall discuss in the current section. The epidemiological risk of a disease is evaluated as the number of people that an infectious person may infect when he/she is introduced in a community. The greater this number is, the more contagious the pathogen is considered. One of the relevant elements to mitigate the infection risk is the ventilation of the indoor environment. There are several models that relate the infection probability to the ventilation rate, showing that the increase in ventilation can reduce the risk of airborne diseases [17], [18].

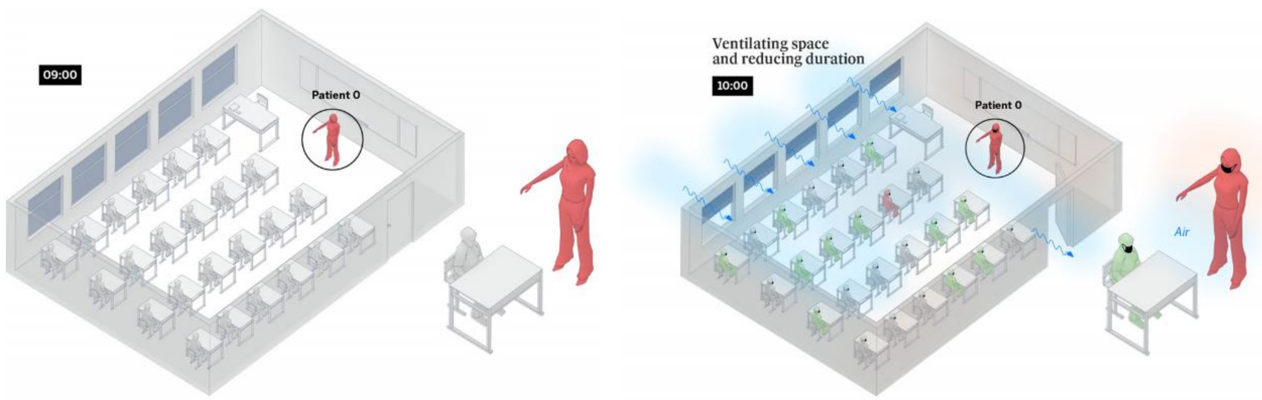

Figure 6. The measures for preventing Covid-19 infection: air ventilation

5.1 IAQ and health issues management

CO_2 concentration has been often used as an indicator for IAQ management, as it is a pollutant easy to monitor that is directly produced by people. CO_2 is not a dangerous pollutant by itself, but it can influence people's well-being, [24]. During the pandemic, several international organizations such as ASHRAE or REHVA remarked on the importance of maintaining IAQ in buildings, especially in schools. ASHRAE recommended maintaining 500-700 ppm, with action limits up to 1200 ppm [16], while REHVA proposed an "alarm system" that considers warning levels at 800 ppm and alarms above 1000 ppm [12]. However, these are the common threshold values given during normal operation of buildings to ensure indoor IAQ and are not related to the possible transmission of infectious diseases. Considering the aspects related to health, several guidelines address the importance of ventilation to manage the risk in indoor spaces, as it can dilute infectious pathogens. Guidelines often refer to previous norms regarding indoor air quality only and there is a need for assessing the possible risk that is not directly related to an absolute CO_2 limit. However, the CO_2 concentration can be used as an indicator of ventilation, which can be directly linked to the infection probability. Monitoring CO_2 concentration can provide indications not only on IAQ but also on the risk of infection probability connected to Covid-19.

5.2. Models for defining airborne infection risk in transient spaces with variable occupancy and activity levels

Riley et al. [17] introduced models, commonly referred to as the Wells-Riley model, for quantifying the risk of airborne infection of respiratory diseases. These models have been widely used in several applications and have been refined and extended as in [18] and [19]. During the Covid-19 outbreak, the same model has been also used to predict airborne infection risks, after appropriate tuning. In particular, the model can predict the infection rate λ caused by a specific virus or pathogen element, according to:

$$\lambda = \frac{Ipq}{Q}, \tag{9}$$

where *I* is the number of initially infected individuals, *p* is the CO_2 production rate produced by each person, value analyzed in Table 1, *q* in the unit of infection (quanta concentration) and *Q* is the ventilation rate, expressed in volume/time. The unit "quanta" used in the risk models is a hypothetical infectious dose unit calculated in epidemiological studies. One quantum is defined as a collection of pathogen particles that can infect susceptible people. The models described in the literature, even if they provide interesting qualitative indications, turns out to be rather uncertain, especially for the definition of parameters *p* and *q*. The infection probability *P* is correlated with the infection rate λ and with the exposition time *t* as:

$$P_I = 1 - e^{-\lambda t} \quad . \tag{10}$$

6. Prediction of infection probability based on CO_2 concentration: applications to a case study

The idea developed in the paper is to directly connect the ventilation rate required for the internal space and the probability of infection risks. Considering a closed volume, the probability of infection can be calculated using the method described in [18]; the application of the model can be done knowing the volume of the room, exposure time, and the type of activity and the occupancy. The results obtained in different situations shows that it is possible to find a correlation between CO_2 concentration level, and between the first derivative of the CO_2 concentration increase (d$C_{\{CO_2\}}$ =/dt) with the infection probability *P*. The methods have been tested in two buildings of different shape and characteristics. Those can be considered representative structures in Italian university buildings as they are dedicated only to student activities such as lessons, exams, and studies. Both buildings are in Pisa (1694 Heating Degree Days).

The first one, Building A, has five diverse levels, a floor surface of about 1560 m^2 and a gross volume of approximately 6200 m^3, of which about 4540 m^3 are occupied by classrooms (12 classrooms). At a full occupancy, the number of students inside the building is 878. The second structure, Building B, is an old factory, modified for educational purposes. The building has a floor area of about 2100 m^2 and a total volume of 11500 m^3. The external building area is approximately 5500 m^2, corresponding to an aspect ratio area/volume of about 0.53 m^{-1}. A total of 9 classrooms are present: four with 100-110 available seats, two with 140 and 150 places, one with 196, one with 208, and the biggest one with 310 seats. Full occupancy is considered in 1440 units. Table 2 summarizes the main geometrical elements of the two buildings object of the study (provided in Fig. 7), while Table 4 provides the details relative to the various classrooms.

Table 2. Main characteristics of the buildings used as test cases.

Building	Volume [m^3]	Levels	Total floor area [m^2]	External area [m^2]	Number of classrooms	Maximum occupancy	Maximum occupancy after Covid-19 pandemic	Ratio A/V (m^2/m^3)	Minimum volume per student, V/N (m^3)
A	6198	5	1560	2000	12	878	435	0.33	14.24
B	11500	1	2100	5500	9	1440	740	0.53	14.18

Figure 7. A view and a typical rendering of the two buildings, object of the analysis.

Table 3. Characteristics of the classrooms in the two buildings.

Classroom	Building	Floor	Maximum capacity	Area (m^2)	Maximum height (m)	Average height (m)	V (m^3)	Vmin-available (m^3/pers)	Ventilation mode
A1	A	2nd	162	175	2.9	2.9	508.4	3.1	NV
A2	A	4th	74	73	2.9	2.9	212	2.9	NV
A3	A	4th	38	44	2.9	2.9	127	3.3	NV
A4	A	4th	40	43	2.9	2.9	124	3.1	NV
B1	B	0	109	125	7.0	5.56	717	6.6	NV/MV
B2	B	0	140	131	3.6	3,35	438	3.1	NV/MV
B3	B	0	109	128	7.0	5,56	710	6.5	NV/MV
B4	B	0	148	145	7.0	5.55	805	5.4	NV/MV
B5	B	0	104	129	7.0	5,56	716	6.9	NV/MV
B6	B	0	198	197	7.0	5,56	1093	5.5	NV/MV
B7	B	0	212	216	7.0	5,64	1220	5.8	NV/MV
B8	B	0	305	286	7.0	5,55	1587	5.2	NV/MV

6.1 Analysis of typical operating conditions

Table 4 shows the conditions encountered in 3 meaningful cases, which include the activity performed in the class, the period of measurement, the number of occupants (n_{occ}), the volume of the room (V), the ratio between volume and occupancy (V/N), the initial (C_0), maximum (C_{max}), mean (C_{mean}) CO_2 concentration, and the increase in CO_2 concentration over time ($dC_{\{CO_2\}}$/dt). The data consider all the typical situations: natural or mechanical ventilation; the number of occupants in the classrooms is variable, ranging between 8 and 165 students. Three different situations can be detected:

(i) naturally ventilated classrooms with reduced volumes for high occupancy (ID1),

(ii) naturally ventilated classrooms with an average occupation (ID2),

(iii) and the mechanical ventilated on (ID3).

Regarding the CO_2 concentration, the most critical situation can be noticed in a situation like ID1, where the CO_2 increases up to 3000 ppm after 60 minutes. In this case, natural ventilation is not sufficient to ensure a good IAQ, which is impaired after about 20 minutes. The second case, provided by ID2 shows that the CO_2 increases less rapidly than in ID1, but it reaches very high values also because the room is not ventilated prior to the lecture (CO_2 is around 1000 ppm). Situations like the one identified with ID3 shows the condition of the mechanically ventilated classroom, with a rather low occupancy (26 people in a room with a capacity of 109 people). This leads to an increase of energy consumption which could be avoided by adjusting the flow rate according to the present conditions. The CO_2 concentration trend can be predicted using Eq. (4), considering situations in which mechanical ventilation is active or not. In all the previous cases, an exposure time of 1 hour was considered. Table 5, provides the infection probability, calculated after one hour of exposure for three different infection, Covid-19, Covid-19 variant, and the most common flu virus. In particular, the infection probability can be estimated using some refinements given by Gammaitoni-Nucci model, which was frequently used for the assessment of the infection probability during the Covid-19 pandemics, see for instance [17], even if the use of a different model does not change the perspective. For the analysis, the number of infected people (I) was considered as the 2% of the total number of occupants in the classroom (n_{occ}), consistently with the Covid-19 statistics [28], and the breathing ventilation rate (*p*) was set as defined in Table 1. Typical values suggested by the recent literature have been considered for the quanta exhalation rate (*q*). According to [13], a reference value equal to 1 was assumed for SARS-CoV-2 variant, 50% of this value has been assumed for SARS-CoV-2 and a value of 1/3 has been assumed for flu, [27]. Fig. 8 provides a quantitative trend of infection probability for one hour of exposure in three cases of Table 5 (ID1, ID2, and ID3). The most critical condition from the point of view of the infection probability is obviously the case labelled with ID1, which has the greatest increase in CO_2 over time, high occupation, and no mechanical ventilation. The analysis of case (c) demonstrates that when mechanical ventilation is fully active, the epidemiological risk is quite low, and ventilation could be reduced. Considering the law exposed before, the infection probability is connected to the various parameters and, it is decreasing with the increase of the ventilation rate Q. The estimation of the ventilation rate from a gas tracer such as CO_2 concentration can be based on the mass balance model, described in Section 4.

Table 4. Increase of CO_2 concentration over time ($dC_{\{CO_2\}}$/dt), and infection probability due to Covid-19, Covid-19 variant, and flu after one hour of exposure for all the cases considered.

ID	Class	$\dot{r}\ n_{occ}$	nocc	V/nocc	C_0 (ppm)	C_{max} (ppm)	C_{mean} (ppm)	$dC_{\{CO_2\}}$/dt (ppm/min)	P Sars-CoV-2	Sars-CoV-2 (Variant)	Flu
1	B7	51.5	165	7.4	1107	3289	2272	37.7	0.73	1.46	0.49
2	B2	17.5	56	7,8	2250	3370	2842	18.9	0.49	0.98	0.33
3	B1	8.1	26	16,8	666	884	841	2.8	0.13	0.26	0.09

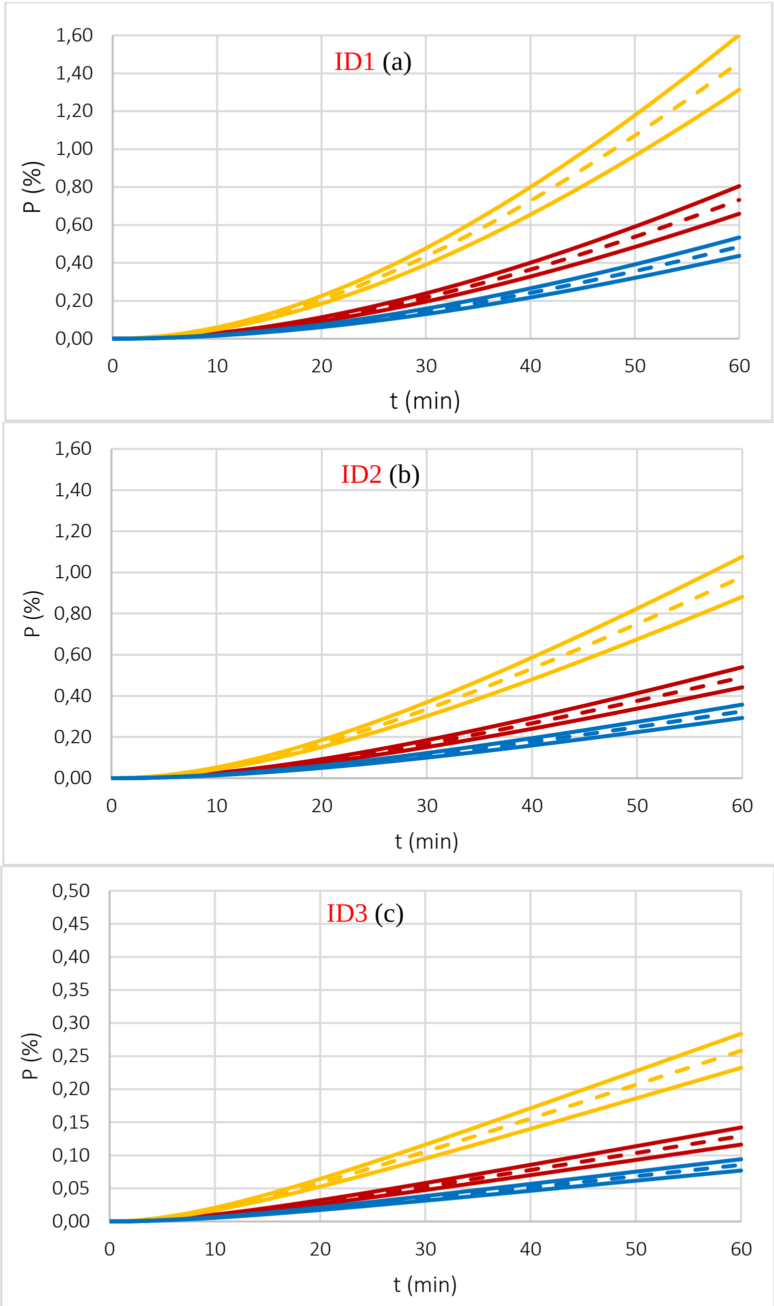

Figure 8. Infection probability in classrooms ID1 (a), ID2 (b), and ID3 (c) for Covid-19 (in red), Covid-19 variant (in yellow) and flu (in blue), considering a 10% error in the definition of the quanta exhalation rate.

A reasonable level of risk of infection can be estimated if the level of replacement guarantees a CO_2 concentration below 1000 ppm. The infection probability calculated after one hour of exposure (P1h) and the increase of CO_2 concentration with time ($dC_{\{CO_2\}}/dt$) for the various measurements permits to establish a kind of linear correlation between the infection risk and ($dC_{\{CO_2\}}/dt$) (Fig. 9). Optimal control of HVAC can be based not only on a threshold value of CO_2 concentration, but also on its increase over time ($dC_{\{CO_2\}}/dt$). Considering the maximum occupation, the requirements for the two academic structures previously tested could be identified in Table 5 in which the actual values is considered too. Considering building B, the nominal ventilation rate (about 35000 m^3/h), corresponding to approximately 3 Vol/h has been defined using the criterion established by the typical directive of ensuring an ACR of 7 l/s per each person inside a room or a building, according to the data contained in the most diffuse guidelines for non-residential buildings, as [16] and [29]. The ACRH value of approximately 3 Vol/h can guarantee in general the maintenance of the indoor conditions and of CO_2 concentrations at values below 1000 ppm considering a full occupation of the building. An ACR of 3 Vol/h permits to maintain a CO_2 concentration below 1500 ppm. This increase in ventilation rate brings a consistent increase of energy consumption, as HVAC systems are in continuous operation, even when not required.

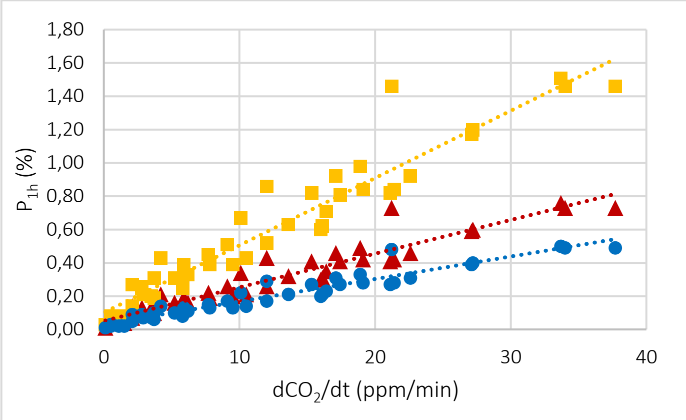

Figure 9. Correlation between d$C_{\{CO_2\}}$/dt and P_{1h} for Covid-19 (triangles), Covid-19 variant (squares), and flu (circles).

Table 5. Typical values of the air change flow rate of the two tested buildings with full occupation and ACR setted.

Building	Volume [m^3]	Levels	Total floor area [m^2]	Maximum occupancy	Required ACRH at maximum occupancy (Vol/h) 1000 ppm	Required ACRH at maximum occupancy (Vol/h) 1500 ppm	ACRH rate setted
A	6198	5	1560	878	7,64	3,61	NA
B	11500	1	2100	1440	6,57	3,03	3

The adaptation of ventilation rates to actual IAQ requirements represents the inclusion of the energy perspective when dealing with occupants' safety and comfort, and therefore consists in an action aimed at valorising those conflicting objectives. In this perspective, DCV strategies can be implemented. Using the model of the building, realized by one of the authors in a previous paper and described in [27], considering a structure like Building A of Fig. 4, considering a typical occupation profile with 50% of maximum occupation, the air change rate per person per hour (expressed in m^3) required for maintaining the value of the CO_2 concentration below the threshold is dependent on the value. In this case, the energy consumption can be estimated on the base of the number of occupants of the building and of an assumed value of the external temperature. The data in Table 6 are obviously indicative. The same objective of partialisation of the ventilation can be achieved either by working directly on the ventilation system and by regulating fan frequency (possible up to 30-40% of nominal flow rate) or by appropriately reducing the operating times, using on-off procedure, keeping the fan on only for a short time (for example some minutes for three/four hours in cases like the one of 10% of occupancy level).

Table 6. ACR required for maintaining CO_2 concentration below 1000 ppm at different occupancy profile.

Occupation	1440 (100%)	720 (50%)	432 (30%)	288 (20%)	144 (10%)
Air Change Rate (Vol/h)	6 (19200 l/s)	3 (9600 l/s)	1,61 (5150 l/s)	0,89 (2850 l/s)	0,1 (320 l/s)
Estimated hourly energy consumption during winter season if T_{out} = 5°C [kWh]	386	193	103	57	6,5

7. Application of the methodology in University classrooms and definition of DCV strategies

Educational buildings can be particularly energy-consuming since HVAC systems are switched on for a long period of time and can also be critical about IAQ and health conditions, as students remain still inside the classrooms for a prolonged amount of time. For this reason, they were chosen as a case study, to optimize the use of HVAC systems with a multi-objective purpose. Recently, one of the authors of the present work has conducted many experimental analyses on CO_2 detection within academic structures. Table 7 shows some typical situations related to the two structures described in Table 3. In each of the cases it is reported what, based on the model described in section 4, should be the level of air exchange required to maintain the appropriate health conditions. As can be seen, the operating conditions are very different, due to the different level of occupancy. For this reason, it would be very useful to be able to link the operation of HVAC systems directly to presence monitoring, using direct methods (such as visualization) or indirect methods, such as monitoring the concentration of CO_2. As can be seen from the analysis of the Table 8, the conditions that arise in the classrooms of university buildings are very variable. The ventilation system is often sized for averagely high occupations of the same and the rules imposed after the COVID-19 pandemic require their operation at maximum flow for the entire duration of the opening phases. This, if on the one hand guarantees compliance with the healthy air conditions and a reduced probability of virus transmission risks, on the other it leads to high energy use, especially in the winter and summer seasons, when the air exchange it determines not only consumption for ventilation, but also and above all for heating or cooling. The air that is drawn at the external temperature must in fact be distributed at a suitably higher temperature (in the winter season) or suitably lower (in the summer season). If additional humidification is not necessary in the winter period, then the load is mainly due to the sensible heat.

Table 7. Conditions encountered during the measurement campaign and required change rate for maintaining a CO_2 concentration below 1000 ppm considering a period of three hours.

ID	Classroom	Occupants, n (pers)	Volume, V (m^3)	V/N (m^3/pers)	Required ACR (Vol/h)
1	B7	165	1220	7.4	7,20
2	B7	62	1220	19.7	2,39
3	B8	58	1587	27.4	1,63
4	B8	86	1587	18.5	2,56
5	B5	52	716	13.8	5,04
6	B8	92	1587	17.3	2,79
7	B7	106	1220	11.5	4,42
8	B4	34	805	23.7	1,86
9	B6	147	1093	7.4	7,08
10	A2	69	212	3.1	18
11	B2	56	438	7.8	6,72
12	A2	71	212	3.0	18,5
13	B3	54	710	13.1	3,80
14	B5	69	716	10.4	4,94
15	B3	59	710	12.0	4,20
16	B2	31	438	14.1	3,51
17	A4	15	125	8.3	6,33
18	A4	11	125	11.4	4,49
19	A1	12	508.4	42.4	0,80
20	A3	23	126.5	5.5	9,75
21	B4	14	805	57.5	0,42
22	B8	50	1587	31.7	1,27
23	B7	37	1220	33.0	1,21
24	B5	22	716	32,5	1,20
25	B6	19	1093	57,5	0,42

Conversely, in summer the air must also be suitably dehumidified and therefore “sensible heat” must also be added to the “latent heat”. It is notorious how, in the climatic conditions typical of many Italian places, the latent heat is usually of the same order of magnitude or even higher than the sensible heat. Some analyses built on the model described in section 4 are reported below for two different scenarios: one of very high occupancy of the spaces (Fig. 10), in which the maintenance of high ventilation (3 Vol/h) is assumed during the period from 8 a.m to 21 p.m. and one with reduced occupancy profile (Fig. 11). The figures provide the trend of occupancy (in the right axis) and the CO_2 concentration (on the left axis) and, as additional information, the average CO_2 concentration during the whole day too. If in the first case, it is necessary to maintain maximum ventilation conditions throughout the day and indeed this is, in some cases, not sufficient to always keep the CO_2 level below the threshold value of 1000 ppm. In case of reduced occupancy, ventilation at 100% is redundant (Fig. 11). In this case it may be sufficient to maintain a ventilation level at 70% of the maximum (Fig. 12) or even at 50% of the maximum, while still guaranteeing excellent environmental conditions (Fig. 13).

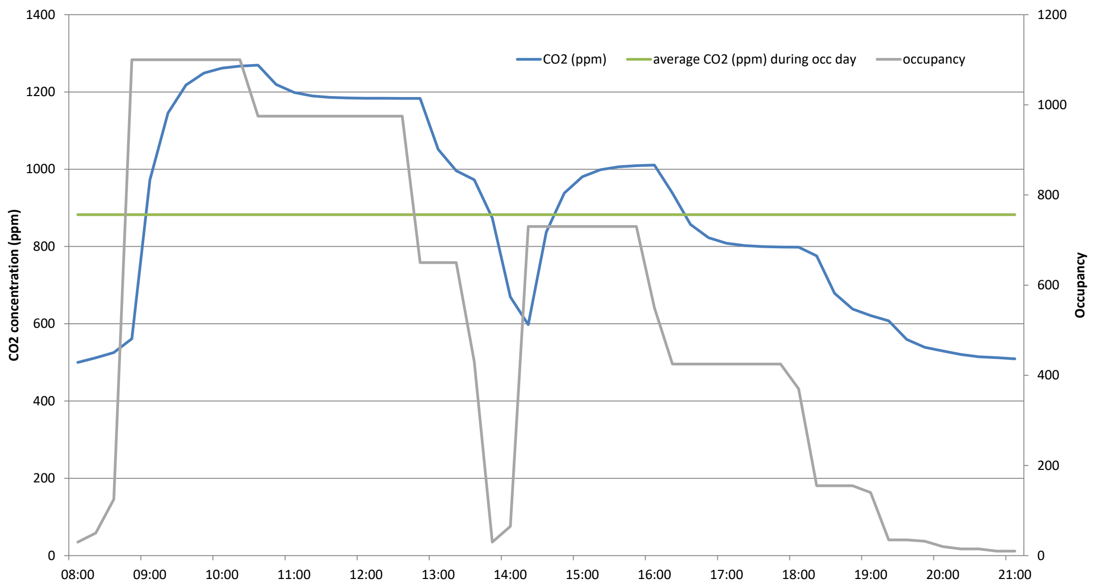

Figure 10. CO_2 concentration for daily operation of Building B with high occupancy profile and ACR at 3 Vol/h (9600 l/s)

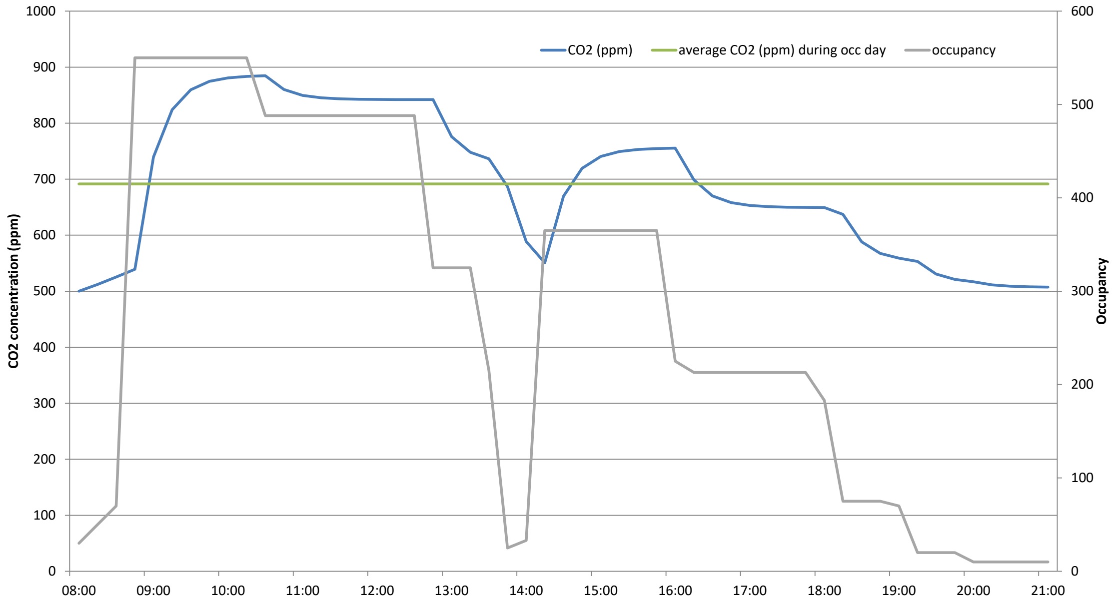

Figure 11. CO_2 concentration for daily operation of Building B at average occupancy (maximum of 560 persons) and ACR fixed at 3 Vol/h (9600 l/s)

In many hours of the year, the operation of the ventilation system at a fixed value of ACR of 3 Vol/h is oversized compared to the real needs. This involves an excessive reduction of CO_2 concentration level and of significant energy waste. A relevant energy saving could be avoided by directly linking the operation of the HVAC system with the number of occupants in the structure, today possible by connecting the operation of the HVAC system with opportune monitoring system. A correlation between the maximum permissible value of the CO_2 concentration and ACR can be estimated. Table 8 provides some indicative values of ACR for occupant: the required volume that must be changed for each our and for each occupant is estimated. Obviously, if very low value of CO_2 is required (e.g. 700 ppm), as suggested by some recent medical guidelines consequent to COVID-19 pandemic, a relevant amount of air flow rate could be required, and this could be unsustainable.

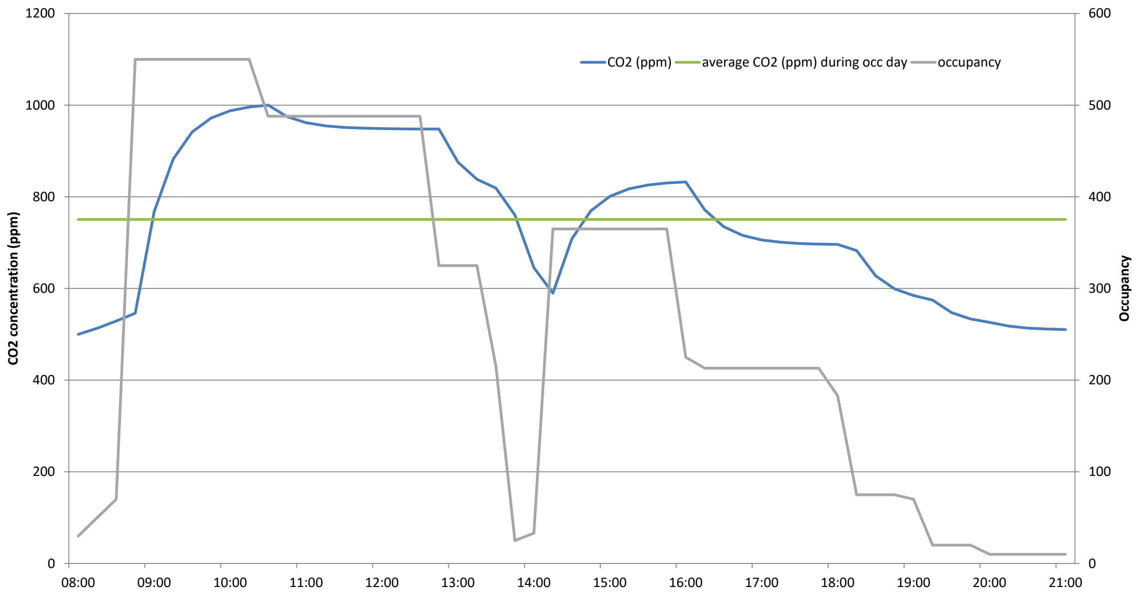

Figure 12. CO_2 concentration for daily operation of Building B at average occupancy ACR at 70% (2,1 Vol/h or 6950 l/s)

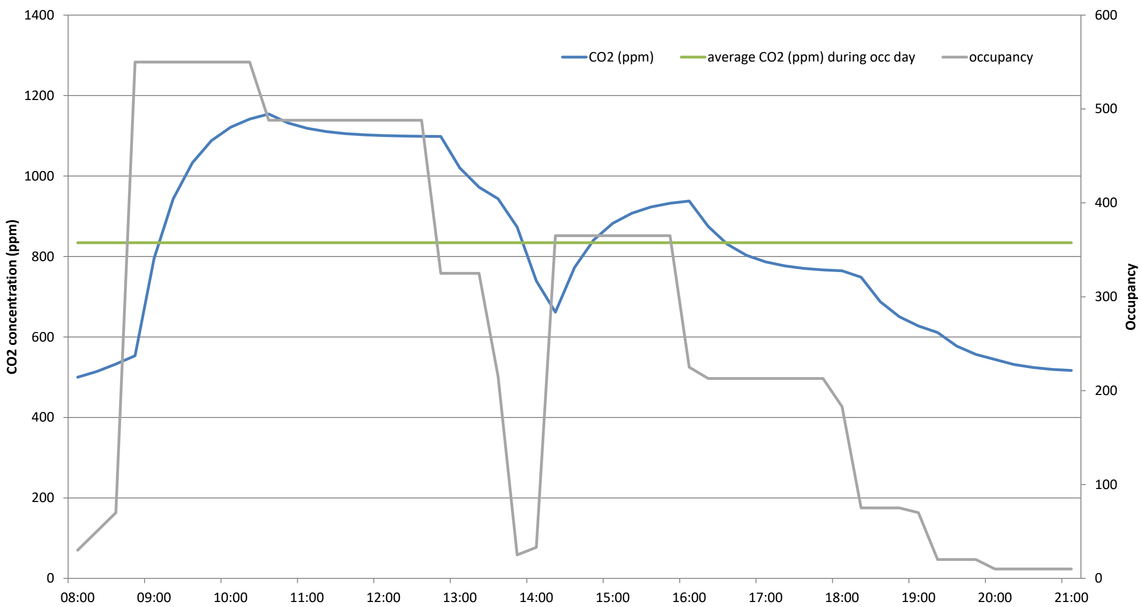

Figure 13. CO_2 concentration for daily operation of Building B at average occupancy, ACR at 50% (1,5 Vol/h or 4800 l/s)

Table 8. Estimated value of Air change rate for various CO_2 thresholds (data referred to the tested buildings)

CO_2 threshold [ppm]	600	700	800	900	1000	1100	1200
ACR per occupant [m^3/h]	280,0	137,5	90,5	66,75	52,75	43,25	36,4
ACRH required for Building B at full occupancy	35	17,2	11,3	8,35	6,57	5,30	4,55

So it can be concluded that the use of the maximum ventilation rate determines a significant energy consumption, especially in quite intensive climatic conditions (either during winter in northern climate, or during summer in southern climates). The limitation of the threshold to 900-1000 ppm, value for which the infection risk remain low, permits a reduction of energy consumption of 45% in winter period and of 25-30% in a typical summer week. There is then the need for balancing the three aspects of IAQ, health issues, and energy conservation in buildings. This purpose can be achieved through the definition of a demand-controlled ventilation rate. Equation (8) can be used to derive the energy required for the winter ventilation for one hour of exposure (E_{v1h}) considering different occupancy levels. Considering a single case like the one of class B7, in a particular situation during winter, with indoor temperature set at 20°C, and outdoor temperature at 9°C, weighted average of the mean monthly temperatures in Pisa during the heating period. The energy consumption related to CO_2 concentration energy used for ventilation has been roughly derived for different occupancies and the results reported in Fig. 14. Maintaining CO_2 concentrations slightly above the outdoor concentration (e.g. 600-700 ppm), which are currently required, leads to a considerable increase in energy consumption, especially when high occupancy occur (more than 70% of the total), while considering the idea of maintaining an acceptable level at a value of 1000 ppm, permits a reduction of energy use up to three or four times, especially in cold weeks during winter or in hot weeks during summer time, when occupancy of the rooms is sometimes at a reduced level.

The structure operates about 315 days a year being open for 16 hours, from 8 to 24. It is closed in a period of about 4 weeks during the summer, two weeks at Christmas and some spot days. In total, 315 operations (about 5060 hours) can be estimated. The main educational activities take place in the period between 8:30 and 19, while from 19 to 24 the structure operates as a study space for students. Only for a small number of hours is the occupation of the structure characterized by an occupation higher than 70% compared to the maximum (about 900) and only 1500 are characterized by an occupation higher than 50%. This means that over 3500 hours are characterized by occupations less than 50% of the maximum capacity and this makes the savings that can be obtained by checking the operation of the HVAC system directly correlated with the real occupation rather significant, as discussed in [31].

Table 10 provides an estimate of the energy consumption related to the operation of the system in typical summer or winter conditions in relation to different climatic conditions providing an estimate of the energy consumption related to the operation of the HVAC system in some typical operating conditions of the building B, considering a typical full load operation of the MV (ACR of 3 Vol/h) is typical environmental conditions. The analysis of the data in table 10 makes it clear that energy consumption associated with ventilation is necessary to maintain indoor air quality and ensure occupant health and comfort. However, when ventilation is combined with air conditioning, the energy consumption can increase significantly. HVAC systems that operate without considering the real needs and occupancy patterns can lead to wasted energy and increased costs. Therefore, it is important to implement HVAC systems that are designed to match the specific needs and occupancy patterns of the building, as well as regularly monitor and adjust the systems to optimize energy efficiency while maintaining occupant comfort and health.

Table 9. Clustering of occupancy share for building B during one year of activity

Occupancy	70-100%	50-70%	30-50%	10-30%	Less than 10%
Number of hours	894	577	788	986	1815
Share of total (5060)	17,66	11,40	15,58	19,49	35,87

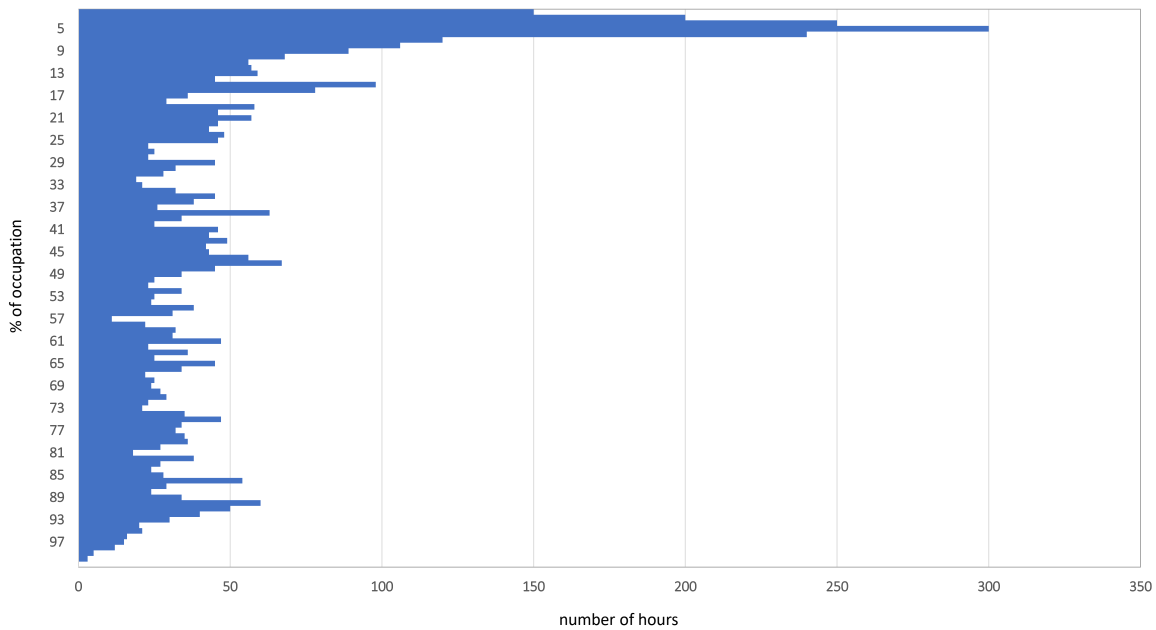

Figure 14. Typical occupation profile of building B during one year of operation

Table 10. Estimated energy use for building B during for one hour of operation in specific conditions

Condition	T_{ext}	RH_{ext}	T_{dist}	$RH_{set\text{-}point}$	Energy required for 1 hour for ventilation	Energy required for 1 hour for climatization (sensible heat and latent heat)	Energy required for 1 hour of operation
Winter day	5	80	22	Not controlled	13,0 kWh	194,0 kWh	207 kWh
Winter day	10	50	22	Not controlled	12,8 kWh	137,5 kWh	150,3 kWh
Mid-season day	18	60	Not operating		12,5 kWh		12,5 kWh
Summer day	30	60	24	60	11,9 kWh	133,0 kWh	144,9 kWh
Summer day	35	80	24	60	11,7 kWh	568,5 kWh	580,2 kWh

8. Definition of occupant-centric control approaches for an optimized DCV strategy

The increased monitoring capability offered by ubiquitous sensors interconnected in IoT networks [32, 33], as well as the availability of massive amounts of historical data, represent the key enabler for the development of occupant-centric HVAC control and operation in the short term. Such strategies, which often go under the name of Occupant Centric Control (OCC) systems, have the purpose to ensure the fulfillment of health or comfort requirements, tailoring energy consumption on the specific needs of occupants' behaviors. One of the most straightforward applications of such OCC techniques, is the design of ventilation strategies based on actual occupancy, which as largely argued in the present manuscript, allows one to match the desired IAQ with minimum energy consumption, avoiding useless overventilation of the rooms, and energy wastes in general. Hereafter, we consider a possible control strategy for the ventilation system that is based on the monitoring of two control variables, namely, CO_2 concentration and its derivative over time, under the assumption that the ventilation system can be only operated in on/off mode (i.e., it is either switched on or switched off, while intermediate ventilation rates are not allowed). This last assumption is typical of many Italian public buildings. Fig. 15 shows a possible framework of the proposed strategy, that combines NV and MV based on the real occupancy. This represents a “relay-based” control system, which is a type of feedback control system that operates based on predefined thresholds. In this case, the CO_2 concentration and its derivative are the input signals that determine whether the ventilation system should be switched on or off. The maximum and minimum values of the thresholds are set based on the desired IAQ and energy consumption objectives. For example, the maximum threshold may be set to a value that ensures IAQ is maintained within a safe range, while the minimum threshold may be set to a value that reduces energy consumption during periods of low occupancy. Overall, this type of control system allows for more efficient operation of the ventilation system by only activating it when necessary and turning it off when the IAQ has improved. This can result in significant energy savings while maintaining a healthy indoor environment. In particular, the minimum and the maximum of the variables ($C_{\{CO_2\},min}$ and $C_{\{CO_2\},max}$, $(dC_{\{CO_2\}}/dt)_{min}$ and $(dC_{\{CO_2\}}/dt)_{max}$) should be set taking into account the expected number of occupants, the room volume, the type of activity in the room, and the expected exposure time. The ventilation rate (Q) may be also set as a function of the number of occupants, when possible, also in relation to the energy issues previously defined. Then, the controller is initialized when the mechanical ventilation is still off, and a CO_2 sensor measures the CO_2 concentration value and its increase over time. It is recommended to set a monitoring frequency of 1-5 minutes to assess rapid variations in CO_2 concentration and to evaluate the increase over time every 5 minutes, to prevent possible outliers from impairing the control system. As previously stated, an HVAC system based on an on-off control was considered as it is very popular, and it was the one available for the case study, but similar strategies may be also used on a DCV system which controls the flow rate as a function of the number of people and CO_2 trend.

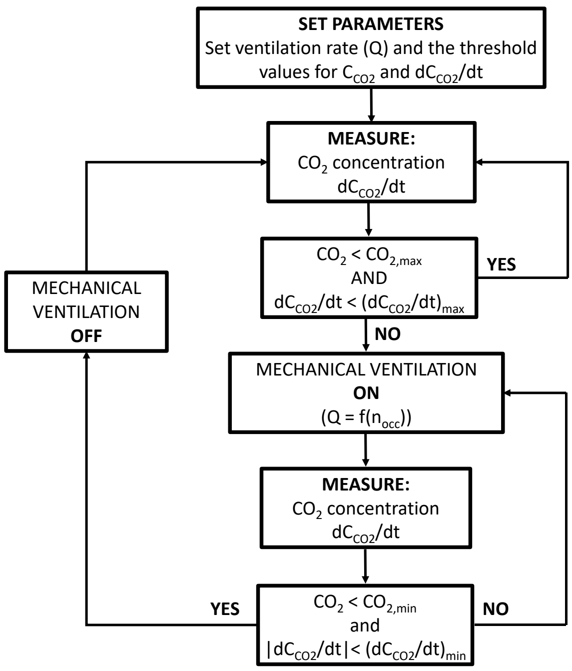

Figure 15. Framework of the proposed multi-objective ventilation strategy.

Furthermore, this method allows for controlling indoor air quality and health management decreasing energy waste due to overuse of mechanical ventilation. Under certain conditions, natural ventilation could also be used to reduce consumption by supplementing mechanical one. In any case, it seems essential to define strategies for optimal control of the operation of HVAC systems, which can be directly correlated with real occupancy data, so as not to determine unhealthy environmental conditions, while avoiding energy waste as much as possible.

9. Conclusions

The paper deals on an analysis of the operation of the HVAC systems for public shared buildings, considering in relation to the recent rules for the mitigation of the risk of transmission of viruses and other pathogenic agents. The problem is solved quite effectively by running the ventilation systems at maximum. This leads to rather significant energy consumption, especially when heating or cooling of the air is also required. A very effective method could be to control the operation of the HVAC system using CO_2 detection sensors, making the connection between the operation of the HVAC system and the actual presence of people inside the rooms, defining a kind of “occupant centric” based model.
From the analysis of the present paper, it is possible to conclude that:

- the level of hourly exchanges established by the common regulations, which impose values between 5 and 7 l/s per person, or in any case exchange values in the range between 3 Vol/h and 6 Vol/h in conditions of high occupancy of buildings, seem to be appropriate for maintaining environmental health and comfort;
- the design ventilation flow rates are instead absolutely oversized when the occupation is less than 50% of the maximum and this can lead to significant energy waste, especially in extreme climatic conditions;
- the energy waste determined by the request of maintaining a fixed ACR can be relevant especially in some specific days of winter and summer and that “occupant centric” HVAC control strategies, based on direct or indirect detection methods are paramount.

The paper finally proposes a system control based on the measurement of CO_2 concentration to address the issues of IAQ, health, and energy consumption. By considering the level of occupancy in the spaces, the proposed system control could result in significant energy savings, especially in cases of reduced occupancy, up to 50% in cases of intermediate occupancy levels. The paper also presents real-world examples from two teaching structures at the University of Pisa.
In particular, the air quality is guaranteed through a fixed absolute value of CO_2 concentration, while health is ensured thanks to the relationship found between the increase of CO_2 concentration over time (d$C_{\{CO_2\}}$/dt).
By ensuring air quality through a fixed absolute value of CO_2 concentration and health through the relationship between the increase of CO_2 concentration over time, HVAC systems can be used more efficiently, resulting in reduced energy wastes. The test conducted in a typical University building showed that limiting the threshold at values of 800-900 ppm can result in a significant reduction of energy consumption of 45-50% in winter and 25-30% in a typical summer week.

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