Journal of Building Engineering 32 (2020) 101714

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: http://www.elsevier.com/locate/jobe

Measurement of CO_2 concentration for occupancy estimation in educational buildings with energy efficiency purposes

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ARTICLE INFO

Keywords:
Measurement
Carbon dioxide
Energy efficiency
Occupancy estimation
Indoor air quality
Air ventilation rate

ABSTRACT

The measurement of CO_2 concentration is a relevant indicator for defining the occupation of indoor spaces. The real-time knowledge of occupation of such spaces is relevant both for maintaining indoor air quality standards and for energy efficiency purposes connected with the operation of heating, ventilation, and air-conditioning (HVAC) systems. The exact knowledge of occupation allows for rapid feedback from and the regulation of an HVAC system and the ventilation rate. Interesting applications include educational buildings and other buildings of the civil sector (e.g., shopping centres and hospitals).

This paper provides the results of an experimental analysis in different classrooms of a university campus under real operating conditions, in different periods of the year, and with different kinds of activities. The correlation between the CO_2 concentration and occupancy profiles of the spaces is then analysed. Some graphical trends of the CO_2 concentrations in these indoor spaces are provided to determine the most important variables affecting such concentrations. The basic elements of the mathematical models for estimating the occupation of classrooms in relation to increases in CO_2 concentration are also discussed and analysed.

1. Introduction

In industrialized countries, civil–residential is often the largest energy consuming sector. Over 40% of the final energy consumption can be connected to this sector. As a consequence, buildings are a relevant source of CO_2 emissions. The high energy use of civil buildings is often connected to a non-optimal management strategy [1]. The accurate determination of building occupancy is a relevant factor for energy savings: A reduction in energy consumption of 30–40% up to 80%, in some special cases, can be expected [2].

Studying the energy demands of civil buildings was relevant importance to the topic of energy sustainability. In this specific field, educational buildings have common peculiarities. University campuses are, in general, a group of different buildings and commonly have a significant energy consumption level. They represent small-scale towns in and of themselves, with different end-uses, structural elements, and occupational profiles. Thus, campuses provide interesting test cases for the development of methods for forecasting the energy use profiles of groups of buildings with different characteristics and different end-user profiles.

The operation of the heating, ventilation, and air-conditioning (HVAC) systems responsible for indoor comfort and occupant wellness determines the largest amount of energy consumed in buildings together with the number of electrical and electronic devices used inside. The interest in such topics has recently been exacerbated by the well-known COVID-19 pandemic; in this case, strict indoor air quality (IAQ) control with high air ventilation rates is important because such measures can prevent airborne virus transmission in crowded spaces but contradict the objective of energy efficiency.

An energy analysis of these particular buildings will help define the possible actions for planning an optimal HVAC control strategy with the purpose of maintaining high standards of indoor environmental quality (IEQ) and increasing energy efficiency. Various papers have highlighted this problem, both in general (e.g. Ref. [3–5]) and considering some specific case studies (e.g. Ref. [6–9]). Educational buildings like schools and universities often present higher occupation levels than other public buildings, and the length of the time spent in the classroom is also higher. For example, the number of occupants per unit area is estimated to be four times higher in classrooms than in office buildings, as discussed in Ref. [10].

Moreover, in university buildings, due to the different activities that occur, different energy amounts are required, making it challenging to

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https://doi.org/10.1016/j.jobe.2020.101714
Received 23 August 2019; Received in revised form 29 July 2020; Accepted 30 July 2020
Available online 7 August 2020

establish benchmark data. In addition, in university buildings, different load profiles can be identified during the year, considering both thermal and electrical uses; thus, it is a relevant problem to define the correct load profiles of plants for climatization and indoor air quality (IAQ) control. During lecture periods, classes are relatively full, and many internal gains in energy input occur due to both the metabolic activity of the people inside and the operations of various instruments and devices (e.g., laptops and smartphones). Thus, for universities, an optimal operational strategy for the heating and cooling system and ventilation rate should carefully consider all these factors. During examinations, lower occupancy levels are observed in the classrooms. A simple analysis of the monthly reports of energy consumption shows that it is possible to establish a well-defined correlation between occupation and energy consumption.

This problem is quite complex because if the electricity consumption connected to the operation of the various devices is directly proportional to the number of students, the energy consumption of the thermal control systems (cooling or heating) is highly influenced by the number of occupants. The presence of people inside the indoor spaces determines the changes in thermal conditions due to sensible and latent heat release. People also release carbon dioxide (CO_2), which can be also controlled to maintain adequate air quality conditions. For this reason, accurately monitoring the occupation of crowded spaces is important. Ultimately, the different occupation levels of internal spaces determine the relevant discrepancies between the energy consumption of heating or cooling systems in both design conditions and real operating conditions. The same is true for electricity use. One method for estimating the occupancy of indoor spaces is a time dependent analysis of CO_2 concentration [11–13].

Considering the recent trends in the research on sustainability issues, this paper considers the measurement of CO_2 concentrations and their variation to define the real-time occupation of indoor spaces inside public buildings as a method to define the optimal operation of an HVAC. In particular, using demand-controlled ventilation was proposed in various studies [14–17]. Exact knowledge of the occupational profiles of indoor spaces is fundamental to achieve an operational efficiency increase of the HVAC system and control the environment while maintaining high standards of quality with reduced energy consumption. The central idea involves balancing health, user comfort, and energy efficiency, for which accurately controlling occupation appears to be of fundamental importance.

The paper is organized as follows. After a short overview of estimating the occupation of buildings via direct and indirect methods, the results of an accurate experimental analysis of a university campus are presented. The final part of this paper provides a possible correlation between CO_2 concentration trends and the occupational levels of indoor spaces with the objective of controlling the operation of the HVAC system and defining accurate demand-controlled ventilation (DCV) strategies based on the direct measurement of CO_2 concentrations.

2. Methods for predicting the energy loads of public buildings

The thermal and electrical energy demand profile at a defined time resolution is the first element for promoting energy efficiency measures and introducing renewable resources. Both are relevant measures for the sustainability of buildings and for pursuing net-Zero Energy Buildings (n-ZEB), a combination of efficiency measures and the use of renewables [18]. An energy analysis of the buildings is important to identify the relevant actions related to energy consumption [19]. Three different strategies are available for defining the energy consumption profile of a building: the analysis of bills, direct measurements, and modelling using commercial computational code.

The first strategy is the simplest one and has low accuracy because it permits one to obtain consumption with monthly frequency, and it is not possible to separate the energy consumption of various buildings or areas of buildings. In some special cases, it is possible to disaggregate the energy bills for a single building, which allows for a more accurate analysis. Moreover, no information on this dynamic behaviour is available.

The second strategy is based on the direct measurements of specific quantities (natural gas, water, electricity, temperatures, and air flow rate). In this way, it is possible to obtain a characterization of buildings from an energy perspective that is accurate and time dependant; the reference period of observation can range from 15 min to 1 h. However, the application of this method requires the use of a certain number of sensors to provide data with the required sampling frequency.

The third strategy, which is frequently employed today, provides a mathematical (dynamic) model of the building, which is usually obtained via multi-purpose commercial software and allows one to obtain a dynamic simulation of the energy loads considering the typical climatic conditions, occupation levels, and energy uses of the various occupants. Defining the dynamic model requires a series of inputs on the users and structural characteristics that must first be collected. Typical inputs include at least three groups of parameters related to the weather, the structure of the building, and the components used inside the building.

Many elements have an influence on energy efficiency benchmarking in the civil–residential sector. For example, it is possible to define the characteristics of the building under analysis (old, refurbished, or new) alongside the characteristics of the users and the activities within. However, for a well-defined field of activity, knowing the occupation of the space is important. Energy consumption and the parameters defining the quality of the indoor environment are directly connected to the occupancy profile. Estimating the number of occupants in a room from an analysis of environmental data, such as temperature, humidity, and CO_2 concentration, is commonly found in the literature [20,21].

Predicting the number of persons inside, starting from an evaluation based on indirect experimental measurements, is essential to estimate the energy consumption of each kind of civil or residential building and to control the operation of the HVAC system for maintaining air quality and environmental comfort standards under reduced energy consumption. Considering the various data that can be acquired for indoor spaces, CO_2 concentration has a direct correlation with the number of occupants. The correlation between the occupancy profile and environmental parameters has been investigated for a long period of time [22]. Monitoring CO_2 concentrations could be important not only for occupancy estimations but also because medium-to long-term exposure to CO_2 causes undesired health and comfort effects.

For example, data on CO_2 concentrations obtained with specific sensors in conjunction with mathematical models based on the CO_2 mass balance have been used to detect occupancy in some past studies [23–25]. Thus, the continuous measurement of CO_2 concentrations using CO_2 sensors can accomplish two objectives: furnishing a datum for the estimation of occupancy and assessing air quality to maintain satisfactory levels of comfort.

In this work, we analyse the methodology with reference to a particular test case to provide specific results and basic elements that will be useful for increasing knowledge in this interesting field of analysis.

2.1. CO_2 concentration values for indoor and outdoor spaces

For the measurement of CO_2 concentrations in indoor spaces, it is important to define some quantitative details. The CO_2 concentration limits for indoor and outdoor public buildings are defined by different government health protocols and industrial safety documents. For example, the air levels of CO_2 that indicate a "quality level" of indoor air were established directly by the European Standards [26] and indirectly by Persily [27,28], who specified the minimum ventilation rates and other measures for new and existing buildings (referring to ASHRAE Standard 62). These measures are intended to provide indoor air quality that is acceptable to human occupants and minimizes adverse health effects.

In all the documents, the standards of CO_2 concentrations in the air are expressed in ppm (parts per million). A value of CO_2 concentration in the range 250–600 ppm is the reference value for outdoor spaces (environment): A higher level indicates a value measured in a crowded town, while a lower level is typical of the countryside. A concentration of 400 ppm is the reference outdoor value.

In indoor spaces, humans exhale CO_2 that remains in the air. Thus, the concentrations of CO_2 are generally higher in indoor spaces than the reference outdoor level of 400 ppm. In a simplified case, the IAQ, represented by temperature, and the CO_2 concentration and energy consumption maintain the required CO_2 concentrations and are strictly correlated via the air ventilation rate. A value of 1000 ppm has become the de facto standard in many applications [27], whereas a concentration of 1500 ppm represents the upper acceptable value of IAQ according to European Standards [26]. For the European Standard 13,779 [26], buildings are grouped into four different categories from I to IV. In buildings of Category I, a CO_2 concentration of less than 400 ppm is used as the reference value; for Category II, the CO_2 concentration is in the range of 400–600 ppm; those of Category III have a value in the range of 600–1000; and buildings of Category IV have values of CO_2 concentration greater than 1000.

A level of 600–1000 ppm is considered optimal in offices and educational building like schools and universities. This low level is justified because the occupants are young people who are more sensitive to health problems [29,30]. A concentration over 1000 ppm is considered poor. Higher values can be caused by overcrowding or suboptimal operation of the HVAC systems. However, it is well established that a CO_2 concentration over 1500 ppm should be avoided to maintain healthy indoor conditions. For educational buildings, the importance of maintaining a controlled value of CO_2 concentration is not only connected to health and safety problems. The air quality and temperature in classrooms are important factors for teaching materials and methods, as well as for improving the learning process [31]. Moreover, it is generally recognized that a level above 2000 ppm is dangerous and reduces human operational efficiency. Exposure is possible only for a short period of time, after which acute or chronic health effects can be observed.

To establish a quantitative correlation between the number of persons inside a room and the evolution of the CO_2 concentration over time, an accurate value of the CO_2 generation rate per occupant is required.

A CO_2 generation rate ranging from 0.20 l/min to a maximum value of 0.45 l/min per person is provided in the literature [32,33][. In general, for technical engineering standards, under sedentary activity levels, a level of about 18 l/h, which equals 0.3 l/min per adult person, has been proposed based on medical standards [32] and monitoring campaigns [33].

In general, a direct correlation between CO_2 concentration variations and various parameters can be observed. For example, the CO_2 variation in a room can also be written as

$$C_{\{CO_2\}}(t) = \mathrm{C}_{\{\mathrm{CO_2}\}}(t=0)\exp\left(-\frac{\dot{m}}{V}\,t\right) + \left(C_{ext} + r\frac{\mathrm{n}}{\dot{m}}\right)\left(1 - \exp\left(-\frac{\dot{m}}{V}t\right)\right) \tag{1}$$

where $C_{(CO2)}$ represents the indoor concentration, V is the volume of the room, n is the number of occupants, r is the CO_2 generation rate per person, m is the air flow rate due to the ventilation rate (mechanical in natural due to infiltration), and C_{ext} is the outdoor CO_2 concentration.

In the absence of mechanical ventilation, and considering the generation rate, r, as the predominant factor of CO_2 concentration, the variation inside the room can be estimated by

$$\frac{dC_{\{CO_2\}}(t)}{dt} = r\frac{n}{V} \tag{2}$$

If the number of occupants is known, the ventilation rate and the consequent outdoor air change rate for maintaining the required standards of CO_2 concentration can be defined, but if the number of occupants is not directly available, the ventilation rate can be established by indirectly monitoring the increase of CO_2 concentration in the room.

3. Measurement of CO_2 concentration: the experimental analysis

Monitoring CO_2 concentrations is a well explored field, mainly for specific structures, such as university buildings. The outcomes of previous studies suggest that the data obtained can be correlated with several elements, this correlation is most relevant with the occupancy profile. Further, due to their metabolic processes, people inside a building emit CO_2 levels that are proportional to the intensity of the activity. Thus, the CO_2 concentrations in confined spaces are higher than those outdoors. Indoor concentrations are strongly correlated with the ventilation rate [34,35].

The experimental analysis proposed in this paper was developed in the classrooms of educational building at the engineering campus of the University of Pisa. The engineering campus (a view of the area is provided in Fig. 1) has a structure that is typical of the historical university campus, with buildings of different origins and characteristics. The objective of this analysis is to measure the air temperature, relative humidity, and CO_2 concentrations in some classrooms during normal teaching activities to establish the correlation between CO_2 concentration and temperature increases with some quantitative indicators of occupation while referring to surface and volume.

3.1. The measurement apparatus and the sensors used

Chauvin Arnoux CA 1510 sensors were used for the experimental analysis. Using this particular sensor, direct measurements of physical quantities were possible, such as the CO_2 concentration, air temperature, and relative humidity.The CO_2 concentration was measured with a dual-beam cell operating with infrared technology. The range of measurement was 0–5000 ppm, and the available resolution was 1 ppm. The uncertainty was ±50 ppm at 25 °C and 1.013 bar. The accuracy of the measurement was 1 ppm/°C from −10 to 45 °C. The correction of the measured value with pressure can be obtained using a specific equation that includes the absolute pressure and the reference pressure. The temperature value was measured via a CMOS sensor. The accuracy was ±0.5 °C in the range −10 and 60 °C at 50% relative humidity. The relative humidity (RH) was measured using a capacitive sensor. Values between 5 and 95% RH can be measured with an accuracy of 0.1%.

3.2. Detailed description of buildings and the selection of classrooms for the experimental analysis

The experimental analysis was performed in eleven classrooms located in four different buildings with different structural and geometrical peculiarities. All selected classrooms were medium to large in size. A small classroom has a minimum size of 74 available seats, while a large one has 366 seats. Small-sized classrooms were not considered for the monitoring activity. From a quantitative point of view, the main data that characterize the classrooms are the following: the total volume, floor surface, maximum number of seats, type of air conditioning system and typical end-use (normal classroom or computer lab), structure of the walls, form and number of windows, and the HVAC system. A short description of the four buildings is given below.

Building A—This building is located inside the green circle shown in Fig. 1. This building was constructed in 1930–1936 and has a typical heavy capacitive structure. The classrooms have high ceilings; consequently, their volumes are very high. Various kinds of classrooms are present, but the building features many different spaces, including science labs, offices, and lecture halls. The structure is characterized by the presence of open spaces and long corridors. Heating is obtained via

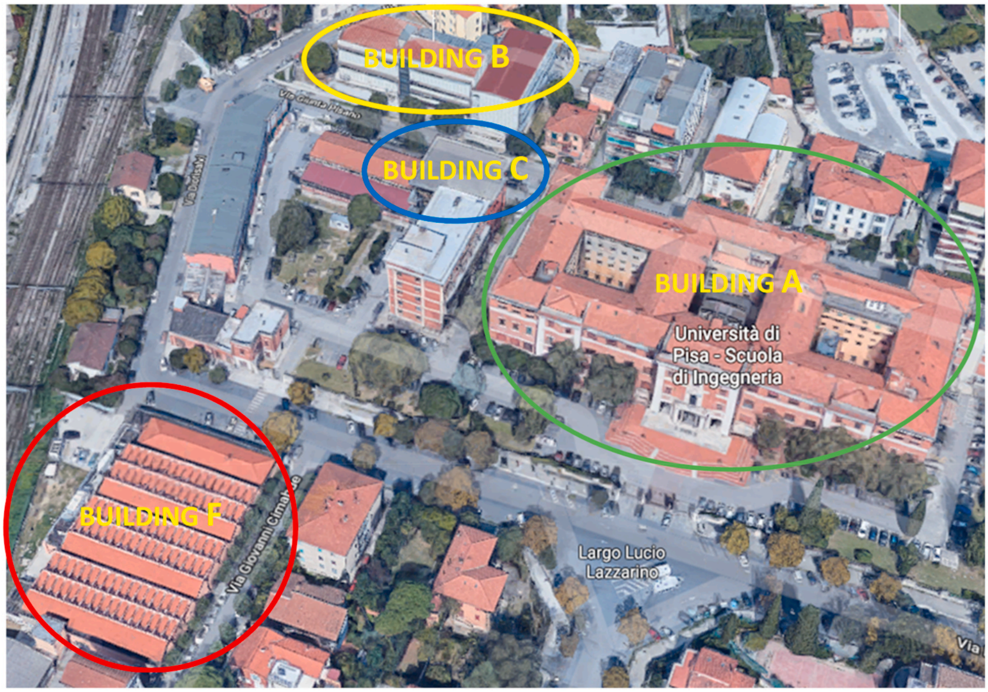


Fig. 1. Overview of the "Engineering campus" (the four buildings are shown).

radiators, and no mechanical ventilation rate is provided. Since the various classrooms in the building are similar and characterized by large volumes, only a single classroom was selected for the experiments and is identified with label 1 in Table 1.

Building B—This building, located in the yellow circle in Fig. 1, was constructed in 1968–1969. It is a general-purpose building featuring classrooms and computer labs alongside study rooms, restrooms, and a bar. The structure is a light type with inner walls, low capacity materials, and wall insulation. Two large-sized classrooms are located in the building, with a total volume of over 1400 m^3 and 366 seats. There are also eight small-to medium-sized classrooms (from 33 seats to 216 seats) and 6 computer labs. The classrooms in this building, except for the three large-sized classrooms, are characterized by low ceiling levels (less than 3 m). An HVAC with mechanical ventilation is used to control the indoor air parameters. Two classrooms in the building were selected for the experiments: a large computer lab (CL1) and one of the largest classrooms, which is identified with label 2 in Table 1.

Building C—This building is located inside the blue circle in Fig. 1. It was built in 1993–1994 and features 4 levels. In this building, only classrooms (a total number of 10) of various sizes are present. The smaller classrooms have a minimum number of seats equal to 18, while the biggest one has 180 seats. All the classrooms are characterized by low ceiling levels (less than 3 m) and reduced volume. An HVAC with mechanical ventilation is used to control the indoor air parameters. Only one classroom in this building was selected for the experimental analysis. This room is present on the 4th floor and is identified with label 3 in Table 1.

Building F—The final building is marked with the red circle in Fig. 1. This building was an old factory modified for educational purposes in 2006. The 9 classrooms inside have high ceilings and "sheds" for lighting purposes. The classrooms have relatively high volumes and volume to surface ratios. An HVAC with mechanical ventilation is used to control the indoor air parameters. Seven different classrooms identified with the labels 4, 5, 6, 7, 8, 9, and 10 in Table 1 were selected for the experimental tests. One of them is the room with the largest total volume (close to 1600 m^3), albeit with 309 seats available. Considering the differences of the four buildings, the eleven classrooms for the detailed experimental analysis were selected to cover a relevant range of geometrical parameters, such as the minimum volume available to each student (from 3 to 6.5 m^3 considering 100% occupation), calculated as the ratio between the total volume of the classroom and the maximum number of seats inside. Table 1 summarizes the main data of the classrooms. All selected classrooms are provided a thermal control system. This is a conventional heating system that operates only in the winter for building A, while the other three buildings feature HVAC systems that work during both heating and cooling periods to maintain typical temperature values in winter and summer.

Table 1
The main data of the 11 monitored classrooms.

Classroom	Building	Level	Maximum occupation, N ( )	Floor Surface, A (m^2)	Volume, V (m^3)	Ratio V/A (m^3/m^2)	Minimum volume per student, V/N (m^3)
1	A	1st	108	88	482	5.48	4.46
CL1	B	1st	116	216	583	2.70	5.03
2	B	1st, 2nd	366	336	1426	4.24	3.90
3	C	4th	72	73	212	2.90	2.94
4	F	1st	309	286	1587	5.55	5.14
5	F	1st	208	216	1220	5.65	5.87
6	F	1st	109	130	721	5.55	6.61
7	F	1st	196	197	1094	5.55	5.58
8	F	1st	104	129	717	5.56	6.89
9	F	1st	109	128	711	5.55	6.52
10	F	1st	140	131	439	3.35	3.14

3.3. Description of the experimental analysis

The experimental test was performed during the year 2018 from January to April during periods of examinations (January and February) and lectures (March and April) under different climatic conditions in winter and spring. Due to the nature of the buildings and their use, characterized by the occupation and continuous movement of students, as well as the typical climatic conditions of Pisa, the HVAC system operates only for short periods because the control variable is the temperature. The number of students inside the classrooms determines a temperature increase, and reduced ventilation is used, which determines the relevant increases of CO_2 concentration in the classrooms. During the winter period, during many of the days observed, the HVAC systems were turned off. In this case, the ventilation rate is guaranteed in natural mode through doors and windows or through infiltrations from the window frames. This value can be estimated from an analysis of the CO_2 monitoring data as long as the doors/windows remain closed, assuming relatively constant values of the CO_2 generation rate per student.

The experimental analysis was performed during the conventional didactic activities of the semester; for this reason, the occupation of the classrooms was not uniform during the various tests, varying from a minimum of 19% (classroom #4) to a maximum of 100% occupancy (classroom #3). In each classroom, two or four sensors were placed based on the volume. This was done because, as presented in the literature, the measurement of the CO_2 concentration can be influenced by the position of the sensors and the mixing value of CO_2.

Using the above setup, we first analysed all the trends of CO_2 concentrations in the various classrooms under several operating conditions. Two condition reflect the specific objectives of this analysis: identifying the characteristics (parameters) of the room that influence CO_2 concentration and defining a correlation between this value and the number of students present inside the classroom over time to establish possible feedback on the HVAC system, based not only on controlling the temperature but also on the CO_2 concentration.

4. CO_2 air concentration data: analysis of the results and discussions

The measurements were done during regular didactic activities and were made without considering whether the conditions were typical or not. The instruments for the measurements were placed on the two sides of the classrooms, as described in Fig. 2a (for two sensors) and Fig. 2b (for the simultaneous use of four sensors). Although it was not possible to ensure that the CO_2 was completely mixed in the classrooms, the configuration with four different sensors (one outside of the classroom to also assess the common elements) used in for high volumes enabled us to obtain an average value of the concentration that was representative of each situation. Fig. 3 shows some typical results obtained in a specific room during a lesson lasting 3 h, considering the four points of measurement presented in Fig. 2b.

Fig. 3a–b shows the results of the measurements obtained with the two different sensors inside the classroom 10 when the ventilation was not active. The CO2 concentration increased monotonically for a period of about 1.5 h. Subsequently, the doors were opened, and, in a few minutes, the starting level was obtained. Fig. 3a provides the results obtained from the sensors in the position of the red circle, while Fig. 3b shows the concentration obtained as the average value of the sensors in the zones of the green circle and the blue circle. The differences between the results obtained using the three sensors are not particularly relevant for the increase phase, meaning that a completely mixed zone is adequate.

The importance of the mechanical ventilation rate is strongly demonstrated by the results in Fig. 4, which provides the results obtained during a 3-h examination in the computer lab (classroom CL1 in Table 1). In the first part of the examination (1 h), the ventilation was active. For this reason, no meaningful increase in CO_2 concentration was observed. The cooling system was sometimes activated periodically when the temperature was over 24 °C (and in other cases). During the examination, the cooling system was activated only one time; this moment is evidenced by a 1.5 °C reduction in temperature. A CO_2 concentration level of 1000 ppm was never reached during the 3 h.

The results obtained from the various experiences in the computer lab provide some outliers with a reduced increase in the derivatives of CO_2 concentration with respect to time.

A summary of the results obtained for some of the most relevant measurements in the 11 classrooms is reported in Table 2. In the first column, a sequential number that identifies each room is provided. The second number after the pound sign identifies different experimental analyses in the same classroom during different time of the same day (e.g., morning #1.1 and afternoon #1.2) or on different days (#1 and #2). In many cases, the results were characterized by extremely severe conditions in the occupied classrooms, where the levels of CO_2 rose well beyond the level of 1000 ppm. In some cases, the measured levels were over 3000 ppm.

By analysing the data, the link between the measured CO_2 concentration and occupancy can be studied for each classroom tested. It can be observed that CO_2 concentration follows the occupancy profile, where the volume available for each person is the most relevant variable.

The initial value of CO_2 concentration is also important. This value influences the increase in the CO_2 level and the CO_2 level within the room after some hours, primarily if the doors of the classroom are closed and no controlled ventilation is active. Different factors, such as the opening of windows and doors, can influence the results, even if their effects are difficult to quantify. In general, classrooms with large doors or windows have a higher ventilation rate and a lower increase in CO_2 levels. Another observable element is the difference in the initial

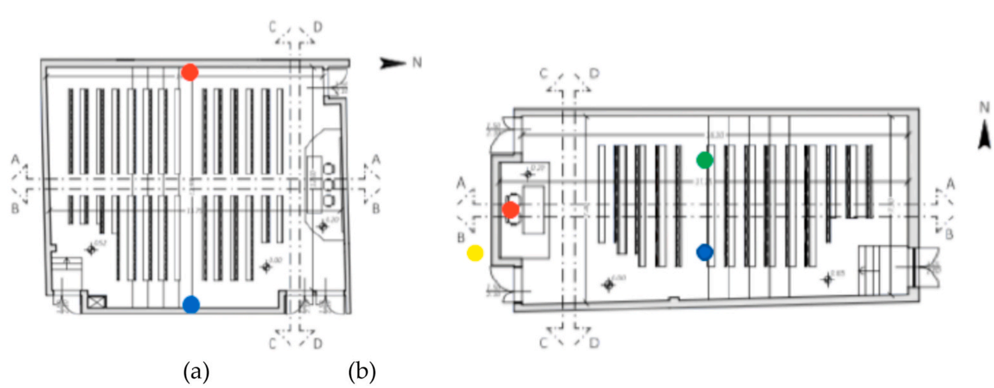
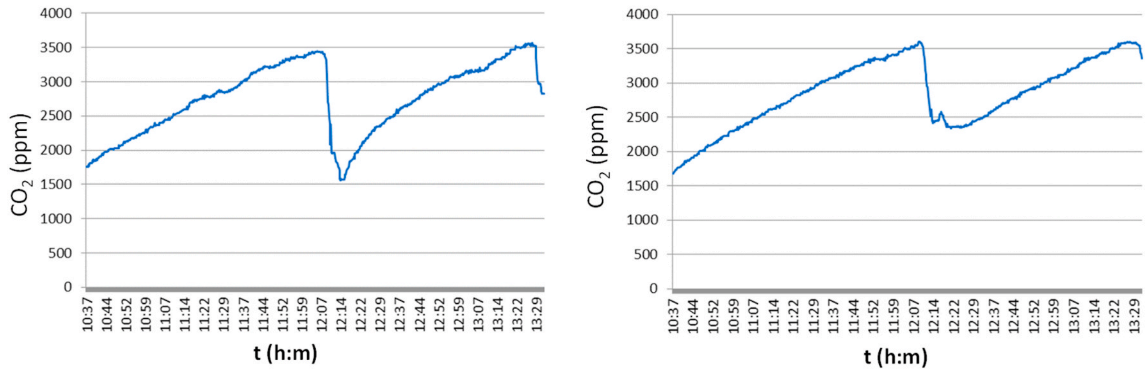
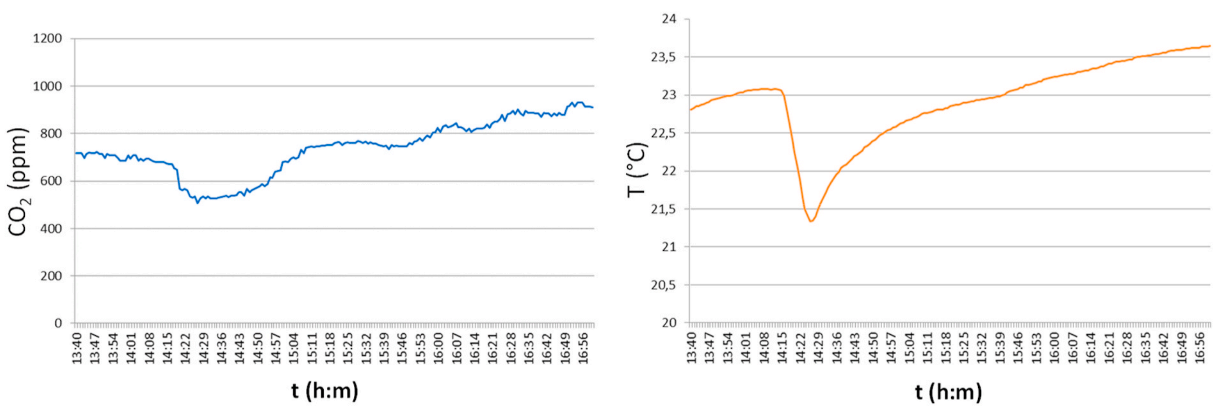


Fig. 2. Position of the sensors in the classrooms: two sensors (a) and four sensors (b).



(a) (b)

Fig. 3. CO_2 concentration (ppm) trend over time in classroom 10 during a 3 h lesson: (a) data from sensor 1 (red circle in Fig. 2a); (b) the average data from sensors 2 and 3 (the green and blue circles in Fig. 2b). . (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



(a) (b)

Fig. 4. CO_2 concentration and temperature variations in room CL1 during an examination lasting 3 h with the thermal control system active.

Table 2
Results of the monitoring activities in the various experimental tests.

Classroom (#experience)	Total volume, V (m^3)	Effective number of occupants, n ( )	V/n (m^3)	dCO_2/dt (ppm/s)	CO_2 conc. (t = 0) (ppm)	CO_2 conc. (t = t*) (ppm)	Length of analysis t* (min)
7 #2	1094	181	6.04	0.462	2582	3886	48
1 #2.2	482	75	6.41	0.753	1057	3720	60
1 #2.1	482	75	6.41	0.672	901	3103	56
5 #1	1220	167	7.31	0.522	1139	4915	121
7 #1	1094	146	7.49	0.401	792	3297	106
10 #1.2	439	56	7.82	0.349	2078	3641	75
10 #1.1	439	56	7.82	0.322	1734	3579	95
10 #2.2	439	50	8.76	0.441	698	2410	66
10 #2.1	439	50	8.76	0.397	696	2764	88
5 #3	1220	106	11.51	0.251	1100	3409	151
9 #2.1	711	59	12.03	0.262	1648	3389	52
9 #2.2	711	59	12.03	0.284	2387	3116	43
9 #1.2	711	54	13.15	0.443	1496	2811	51
9 #1.1	711	54	13.15	0.429	1511	2334	33
9 #1.3	711	54	13.15	0.362	1861	3247	65
8 #1	717	54	13.26	0.371	1206	2383	54
4 #3	1587	93	17.06	0.168	597	2685	207
8 #2	717	39	18.36	0.282	1358	2125	46
4 #2	1587	86	18.45	0.211	792	1410	49
5 #2.1	1220	62	19.68	0.129	2165	2995	111
4 #1	1587	58	27.36	0.112	678	1741	156

increase of CO_2 concentration. In rooms with a higher total volume, time is needed for the CO_2 to become mixed.

Considering the specific experimental analysis and some of the results available in the literature, the concentration of CO_2 over time depends on single specific variables (total volume, number of occupants, time, air exchange rate, etc.). Even if a model of completely mixed gas cannot be assumed with certainty, the configuration with four different sensors (one outside of the classroom) used for high volumes allows one to obtain the average value of the concentration. Fig. 3 shows the results of the four measurement points in a specific room during a 3-h lesson considering the four points of measurement shown in Fig. 2b. Thus, the expression given in Eq (1) can be rearranged as

$$[CO_2](t) = f(V,\ n,\ t\ [CO_2](t=0),\ VAPS, VR) \tag{3}$$

where VAPS represents the volume available for a single student at the maximum occupation level, and VR is the ventilation rate (in the primary part of the analysed cases due to infiltrations).

Even if all the mentioned variables appear to be meaningful, the experimental results show that a type of hierarchical distribution can be identified among the variables, the most relevant of which seems to be the volume available for each student. Fig. 5 summarizes the experimental results obtained and offers a possible way to correlate the increase in CO_2 concentration with the quantitative value of the volume available for each person inside.

The experimental analysis was carried out during different didactic activities. Thus, it is possible to observe the relevant variations in the volume available to each student, thereby obtaining V/n (where V is the total volume of the classroom divided by the effective number of occupants). In some cases, a level of 3 m^3 was observed (classroom 3 at full occupation), while in opposite cases, a level of 27–28 m^3 was obtained for the students.

Based on the results obtained, the CO_2 concentration varies over time depending on the value of V/n according to a linear trend, but another relevant effect is connected to the action of the ventilation rate available. The data range from 0.11 ppm/s in the best case to 0.75 ppm/s in the worst case. In the first case, considering a starting level of 500 ppm, the increase would be 6 ppm/min, which means that the ventilation can operate after 80–90 min (1000 ppm is considered an acceptable level). However, the relevant increase was 50 ppm/min, which means that after 10 min, the action of the ventilation is required. Increases around 0.40 ppm/s are measured when the volume available to student is lower than 10 m^3. This value is the maximum reference value used for designing buildings for educational purposes. Thus, it is possible to obtain an estimation of the CO_2 increase trend over time to express the derivative of the CO_2 concentration over time as a function of the volume per student according to the following law:

$$\frac{d[CO_2]}{dt} = \frac{[CO_2](t) - [CO_2](0)}{t} \sim f\left(\frac{V}{n}\right) \tag{4}$$

This means that the increase in CO_2 concentration over time is correlated with the CO_2 generation rate per student, which is a relatively constant value for the specific activities under investigation (examinations or lectures). In this way, we confirm the possibility of using the CO_2 monitoring results for estimating the space occupation. However, considering the correlation among the two variables described in Fig. 5, some discrepancies incompatible with linear behaviour can be observed.

An important element that influences the increases in CO_2 in indoor spaces (and consequently the values of the derivatives reported in the abscissa of Fig. 5) is the ventilation rate. Even if the measurements are obtained under real utilization conditions, in most parts of the rooms, the air exchange was not mechanically controlled: In some cases, the ventilation rate was only due to infiltration through window frames, but in other rooms, the doors and windows were opened during certain phases of the experimental analysis.

For this reason, when analysing the experimental data, the influence of the air exchange rates could not be quantitatively considered, excluding the case of the computer lab (CL1). However, in general, because the air conditioning system during the periods of the experimental analysis (from January to April) provided reduced (or no) air exchange, the primary contribution to air exchange was determined in a natural way via doors and windows. Based on the mass balance equation, the derivative of the CO_2 concentration should be proportional to the occupant density if the air exchange rate is zero, and the CO_2 generation rate per student is constant during that time. In many real cases, a linear correlation between the air volume available to each student inside the classrooms and the derivative of the CO_2 concentration might be unsuitable due to the various source of ventilation i the classroom to external spaces and due to the variation in the number of occupants

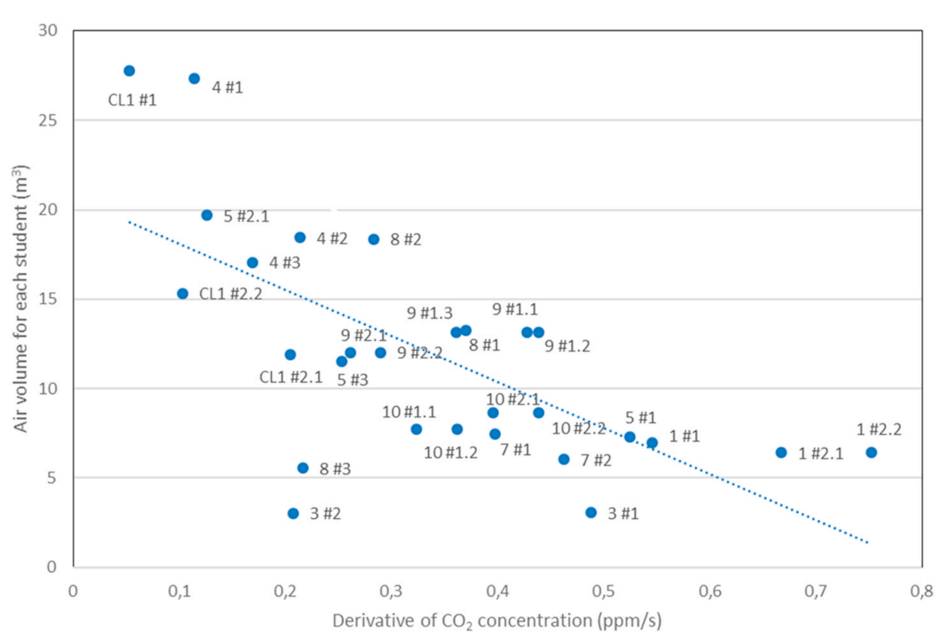


Fig. 5. CO_2 concentration increase as a function of the available volume.

during the typical period of observation (the number of the students at the beginning and end of the period of observation was observably different).

5. Conclusions

The energy consumption needed to maintain thermal comfort and high indoor air quality in educational buildings is strongly influenced by the occupation of the space, which is not always simple to evaluate in public buildings.

Predicting the number of occupants is an essential factor to achieve the optimal management of HVAC systems both to maintain the required levels of temperature, humidity, and pollutant concentrations and to ensure minimum energy consumption.

The main elements of this study are the results of an experimental analysis carried out in various classrooms of the Engineering University Campus at Pisa during typical teaching activities over a period of four months from January to April. The classrooms selected for the experimental analysis (a total of 11) are characterized by different geometric surface and volume parameters and internal occupation levels. To separate the different relevant effects, the experimental analysis was performed both with the mechanical ventilation operating and with the ventilation turned off.

The acquired experimental results demonstrate that, as expected, the CO_2 concentration is directly correlated with occupancy. Some interesting data emerged from the analysis. During the various experiments, the increase in CO_2 concentration over time changed mainly as a function of the volume available for a single student. The measured values ranged from a minimum of 0.1 ppm/s to a maximum of 0.8; an average value of 0.4–0.45 ppm/s was identified, and after 1 min, an increase of 25–28 ppm/min was observed, with 50 ppm/min as the peak value.

This study demonstrated the correlation between the measured values of CO_2 and the number of occupants through a synthetic variable defined as the volume available per person. The higher values of concentration were obtained when the classrooms were very crowded (occupation rates over 70%), presenting a reduced value of the volume for each student. In particular, the maximum values were observed only when the per-capita volume was lower than 8 m^3. Values over 0.4 ppm/s were obtained when the per-capita volume was below 10 m^3. In such cases, mechanical air exchange is clearly required. The linear correlation between the increase in CO_2 concentration and the volume available for each occupant can be used for a preliminary estimation of the increase in CO_2 concentration, mainly in the phases when the air exchanger is not operational.

The experimental analysis also shows that many different factors are relevant for defining the correlation between CO_2 concentration and occupation. We observed that some occurrences, such as the opening of doors and windows during a lesson or an examination, can create differences in the measurements. The delay time of the CO_2 concentration increase is correlated with the total volume: A perfect-mix model is acceptable for a classroom of a reduced volume/surface ratio, but the same is not appropriate for a classroom of a high volume. For this reason, it is challenging to define a model for correlating CO_2 concentration and occupation, excluding cases of “fully closed” volumes.

Monitoring CO_2 concentrations and their variation over time in indoor spaces appears to be a valid method for estimating the real number of occupants, thereby activating demand controlled ventilation (DCV) to maintain indoor environmental quality (IEQ) with reduced energy consumption and balancing health, user comfort, and energy efficiency.

Interest in the present topic has recently been further exacerbated by the spread of the COVID-19 pandemic. Several countries have started planning their post-lock-down activities, and, in general, all relevant documents agree with the idea of maintaining strict indoor air quality controls to prevent airborne virus transmission in crowded spaces. From this perspective, an indirect estimation of indoor space occupation using increases in CO_2 concentration appears to be relevant.

CRediT authorship contribution statement

Alessandro Franco: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Software, Supervision, Funding acquisition, Writing - original draft, Writing - review & editing. **Francesco Leccese:** Conceptualization, Writing - review & editing.

Declaration of competing interest

The authors declare no financial interest and personal relationships which may be considered as potential competing interests: The author declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgments

The authors would like to express appreciation to the University of Pisa for the research grant “Fondi di Ateneo”. University of Pisa and School of Engineering are also acknowledged for providing the classrooms in which the experimental analysis was carried on. Dr. Lorenzo Marchi, a former student of the Master Degree in Energy Engineering is acknowledged for the support during the experimental analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2020.101714.

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