Article

CO_2 concentration and occupancy detection of educational buildings for energy efficiency purposes: an experimental analysis

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Abstract: The problem of real-time estimation of occupancy of buildings (number of people in various zones at every time instant) is relevant to a number of emerging applications that achieve high energy efficiency through feedback control. The measurement of CO_2 concentration can be considered an important indicator that allows to define the occupation of closed and crowded spaces. Interesting cases can be school buildings and other buildings used in civil and residential (shopping centres, hospitals, etc.).
This paper, starting from an experimental analysis in different classrooms of a University campus in real operating conditions, in different period of the year, proposes a possible correlation between CO2 concentration and the occupancy profile of the spaces. The acquired data are used to present some graphical correlations and to understand the most important variables or combination of them. Starting from an accurate analysis of the data, attempts are made to define a preliminary estimation method through the development of a mathematical models of occupancy dynamics in a building, which show interesting results.

Keywords: carbon dioxide; energy efficiency; occupancy detection; indoor air quality; measurement; data analysis.

1. Introduction

During the last decades, the issue of energy saving is increasingly attracting given the goal of decreasing carbon emissions and energy consumption set by the EU through the European 2020 standard. In European countries, the buildings sector is often the largest energy consuming sector, accounting for over than one-third of final energy consumption globally and an equally important source of carbon dioxide (CO_2) emissions. High energy consumption in buildings can be caused by several factors including a reduced thermal insulation of the envelope, a bad management of the thermal and electrical system, a non-accurate use of energy equipment and energy waste of any kind. Moreover, given the final use of the building, it may be difficult to identify a clear path of utilization and for that reason more energy consumption can occur [1]. The accurate determination of occupancy detection in buildings has been recently estimated to save energy in the order of 30-40% [2]. Some experimental measurements reported that energy savings can be increased up to 80% [3] when occupancy data was used as an input for HVAC control algorithms.

The study of the building energy demand has become a topic of great importance, because of the increasing interest in energy sustainability. University campuses is in general a group of different buildings, with significant energy consumption. They consist of many different buildings, representing small-scale town for itself, with different end-use, different thermal envelopes and different occupancy profiles. Therefore, they provide an interesting testbed to characterize and understand energy consumption of groups of “mixed-use“ buildings. An energy characterization of such kind of buildings may reveal a key factor to identify possible actions or refurbishments with the purpose of reducing consumptions. Several papers in the literature have considered the problem, using a general perspective (e.g. [4-5]), or specific cases (e.g. [6-9]). Schools and University buildings present a much higher occupancy than any other buildings: the number of occupants per unit of area can be four times higher than in office buildings [10]. In University buildings with several end-use, different problem emerges: within the same envelope there could be laboratories, offices, lectures room, classes, open spaces, halls, gyms which have different energy needs. Moreover, a university building has different usage profile during the year. During lectures periods, classes will be relatively full and many internal gains will occur so in order not to waste thermal energy the heating system should consider all those factors; furthermore, while high occupancy is registered a high plug-in load might occur, so high consumptions during those periods should not be considered waste all the same. During examination period, lower occupancy might be registered in classes but, somewhere else like cafeteria, library, or laboratories there might be a higher occupancy, without considering the high occupancy during written or oral tests. Anyway, a relevant element of analysis is the occupation of the buildings. Occupant presence release latent and sensible heat that changes thermal conditions warranting increased in air-conditioning. They also release pollutants such as CO_2 which is also an important quantitative indicator for ventilation adequacy. Monitoring of presence in crowding spaces is important both for the purpose of maintaining controlled thermo-hygrometric comfort conditions and also for the purpose of forecasting and optimizing energy consumption. In particular, forecasting the occupation of the buildings is very important to have a better control of the operation of the thermal control systems.

At present, the energy certification of buildings is done on a basis exclusively linked to the facility and the structure of the building, without taking into account in any way the real use of the structures and the presence. In fact, one of the elements that defines the difference between design conditions (ideals) and operating conditions (real) in all the structures using thermal control plants, is the number of people inside the building. This determines significant deviations from the design conditions (for example, in a crowded place the internal temperature will be higher than the one that would be in the same place with less overcrowding) both concerning the use of thermal energy as well as of electricity. Furthermore, the current legislation does not consider for example what are the electrical uses related to the overcrowding of places. In spaces such as universities, this is manifested by the presence of numerous devices (i.e. notebooks, smartphone chargers, various educational equipment) that significantly increase, and sometimes not easily predictable, the consumption of electricity. Moving from some recent trends in the research, in which the measurement of CO_2 concentration has been recently proposed in the literature, for estimate the number of occupants [11-13], the paper try to analyse the perspectives of CO_2 based prediction and evaluation of occupancy of building as an effective mean to obtain operational efficiency increase and of the quality of the environment. The step presented concern an attempt of obtaining a correlation between the CO_2 concentration and some quantitative indicator starting from an experimental analysis carried out in university buildings. The prediction of the number of occupants in a space is essential for the effective management of the main operational functions of the building, as well as for improving environmental quality and energy efficiency. One of the methods to estimate the number of occupants is based on the analysis of CO_2 concentration and its variation over time. This study, using some university classrooms as case studies, aims to analyse the possible correlation between the measured CO_2 values and the actual number of occupants. From the results it is possible to conclude that the CO_2 concentration follows the occupation scheme: the higher the occupation, the higher the CO_2 level. However, many other factors (such as the opening of windows and doors, the delay time between the occupation pattern and the CO_2 concentration) have a strong influence on the CO2 concentration and their effects are difficult to predict.

2. Energy efficiency, environmental quality and use of the buildings: the importance of occupancy estimation

In the literature there are several studies that highlight the most important aspects to be considered for carry out an analysis of the energy demand and energy efficiency of a public building. Demand side management, together with thermal energy storage and renewable energy technologies, have mainly been studied at a building scale. Method of analysis and models able to generate thermal energy demand profile, with detailed time resolution, at an urban district scale are of relevant importance in order to promote energy efficiency measures and relevant introduction of renewables. [14]. An energy characterization of the buildings may reveal a key factor to identify possible actions or refurbishments with the purpose of reducing energy consumptions. An overview of the various energy performance assessment models for common buildings in the literature is provided in [15]. The first datum that characterizes a building from an energy point of view is its primary energy consumption (gas and/or electricity). In general, there are three strategies with which the energy consumptions of a building can be estimated, namely: the analysis of bills, the direct measurements and the modelling using commercial computational codes.

The first method, based on the analysis of the energy bills, is the simplest one, it is economic but it can be considered the less accurate since it is not possible to obtain consumption with a frequency other than the monthly one not even isolate the energy consumption of a certain area if there is only one counter. Disaggregating energy bills into end-use provides a better understanding on energy use and results in a better assessment for systems and equipment.

The second method, based on direct measurements, provides an energy characterization of the buildings much more accurate and allows to get much more information This method is implemented through the use of specific meters, carefully positioned inside the building that can provide data with variable sampling frequency (hourly, daily, monthly consumption etc.) and related to particular areas.

The third method, largely diffused in the recent literature, provides a mathematical model of the building and performs a dynamic simulation of the behaviour considering the internal use and the various users. The construction of the dynamic model of a building requires inputs that should be firstly collected and then be fed into a so-called simulation engine to describe detailed mathematic models. Typical inputs for a dynamic simulation tool of this kind may include three groups of parameters: the weather conditions, the building description and the components for the end-use.

There are many influencing factors in energy efficiency benchmarking, such as end-use characterization, building typology (i.e. old, refurbished or new structures), occupancy is also one of these. Energy consumption and indoor environment quality (IEQ) of buildings is certainly strongly connected with the number of occupants. Predicting the number of occupants in an internal space will be essential for the effective management of various building operation functions as well as to improve the energy efficiency. Ever since occupancy detection has been of primarily importance in energy efficiency of public buildings, many techniques have been proposed, each one with its advantages and disadvantages.

Considering the correlation between the use of the building and the CO_2 concentration in indoor environments, it seems very interesting to elaborate models that, starting from an evaluation based on indirect experimental measurement of the occupancy, can also define a correlation with the energy consumption. This could be really interesting in order to determine a prediction of energy consumption referred to the occupants and to produce a feedback on the operation of the thermal control system in order to obtain beneficial effects both in term of air quality and environmental comfort and energy saving. Recently, it was proposed to estimate the number of occupants, in an office room, from environmental parameters, in particular such as temperature, humidity, and CO_2 concentration [16-17]. Amongst these parameters, CO_2 concentration is the one that most correlates with the number of occupants [18]. Hence the analysis of the dynamics of CO_2 concentration variations may be employed in determining the number of occupants inside closed volumes. The measurement of CO_2 is useful not only for the occupancy detection but, since CO_2 is a gas that, after long-time exposure, can cause undesired effects on the occupants, for comfort purposes too. For

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example, using data from CO_2 sensors, in conjunction with building models to solve a CO_2 mass balance equation, has been applied to detect occupancy in [19-21].

Considering school and universities, a recent study has demonstrated that air quality and temperatures in classrooms are important factors in the learning process and improving them should be given as much priority as improving teaching materials and methods, [22]. Implementing the use of CO_2 sensors into the air handling unit could bring to a double benefit: accurate estimation of occupancy and control of comfort assessment. Considering the fact that CO_2 sensors are little and do not represent a disturbance of any kind to the unfolding of activities within the rooms in which they are installed, the developing of techniques of occupancy definition using CO_2 concentration represent a valid and effective way.

3. CO_2 concentration values for outdoor and confined spaces

In order to understand the qualitative value of CO_2 concentration that can be measured, it is important to have a quantitative definition. CO_2 typical exposure limits for outdoors and for different public spaces have been established by a number of governmental health and industrial safety groups. Each of these standards of air concentrations is expressed in parts per million (ppm). Air levels for CO_2 that indicate that indoor air quality may be a problem have been established by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) but also by European Standards too.

CO_2 concentration in the range between 250-600 ppm is the typical level for ambient air in outdoor spaces: the upper levels indicate a very crowded town, while the lower levels can be measured in countryside. Typical values can be 350-400 ppm. The reference outdoor value is 400 ppm atmosphere, considering 300-320 ppm a level typical of pure air and up to 700 ppm the polluted atmosphere [23].

The human body exhales even about 2-4% this is why in enclosed areas the concentration of CO_2 can be higher. The acceptable level of CO_2 is related to building category and is defined in European Standard 13779 [24]. The standard establishes that the typical CO_2 concentration ranges above the outdoor level are: for buildings of Category I less than 400 ppm, for Category II in the range 400-600, for Category III in the range 600-1000 and finally for Category IV greater than 1000. For confined spaces, several sources indicate that indoor air problems are significantly reduced at 600 ppm or less of CO_2. In general, a guideline of 600-1000 ppm or less is preferred in offices and schools due to the fact that the majority of occupants are young and considered to be a more sensitive population in the evaluation of environmental health status [25]. The level of 5000 ppm is considered a Permissible Exposure Limit/Threshold Limit Value meaning an upper limit for which no acute (short term) or chronic (long-term) health effects. But a level above 2000 ppm is certainly deleterious to the operational efficiency of people. Considering a confined space, a concentration over the value of 1000 ppm can be connected with a relevant occupation of the spaces and/or an indicator of ventilation adequacy for the confined spaces so that all the standards for the air quality control recommends adjustment of the building's ventilation system. In recent years it is indicated that the level of 800 ppm is the one for which further investigation is necessary. The case of Universities and University campuses is a particular one due to the fact that different activities with different levels of occupation are possible in the same day, making very difficult to control the air quality without a direct feedback on the control system.

4. Experimental analysis

From the previous section, it clearly emerges the fact that CO_2 concentration monitoring is a not well explored field, mainly concerning some particular structures as University buildings however, the outcome of the previous researches suggests that it may be a very promising one. People produce and exhale CO_2 as a consequence of metabolic processes, thus, the CO_2 concentration in occupied buildings is higher than the outdoors CO_2 concentration. The magnitude of the indoor-outdoor concentration difference decreases as the ventilation rate increases. If the building has a nearly constant occupancy for several hours and the ventilation rate is nearly constant, the ventilation rate per person can be estimated from the maximum steady state difference between indoor and outdoor CO_2 concentration. In many real buildings, occupancy and ventilation rates are not stable for sufficient time to enable an accurate determination of ventilation rate from CO_2 data, however CO_2 concentrations remain an approximate, easily measured and widely used for defining ventilation rate per occupant [26].

4.1. CO_2 concentration measurement activities

It has been set up an analysis procedure that comprehend different kind of sites and environmental conditions. All the monitoring activities have been performed within the School of Engineering at the University of Pisa. The School of Engineering (a satellite view of the area in which the buildings are is reported in Fig. 1) is a mixed stock of new and old buildings, characterized by different building materials and inner room size. The School of Engineering is composed by four main buildings. In order to evaluate the features that influence the comfort, and consequently energy savings that could arise, within highly crowded classrooms in University buildings, several campaigns have been performed. Said campaigns consists in the utilization of sensors in properly crowded classroom during exams and lessons.

4.2. Sensors used for the measurement

The sensors utilized are of commercial type, model Chauvin Arnoux C.A 1510. The C.A 1510 is an instrument for measuring physical quantities that combines measurements of: CO_2 concentration, ambient temperature, relative humidity. The particular instrument works out air quality criteria based either on the level of CO_2 or on a combination of the three physical quantities measured. The characteristics of the sensors used for the experimental investigation are the following.

For the measurement of CO_2 concentration, the instrument is provided with a Dual-beam infrared cell, using the Non-Dispersive Infrared technology. The measurement range goes from 0 to 5000 ppm, with an intrinsic uncertainty of ±3% ±50 ppm at 25 °C and atmospheric pressure. The resolution of the instrument is 1ppm. The temperature error is 1 ppm/°C in the range from −10 to 45 °C. The influence of pressure can be obtained with the equation CO_2-Real=CO_2-Measured (1 + 0.0014(1013−P)), with P pressure expressed in mbar.

For the measurement of temperature, the instrument is provided with a CMOS sensor that can furnish a relatively accurate measure in the range between −10 and 60 °C. The uncertainty is of ±0.5 °C at 50% of relative humidity.

For the measurement of relative humidity (RH), the instrument is provided with a capacitive sensor that range from 5 to 95 % RH, the intrinsic uncertainty is outside the range stated before. Moreover, the instrument presents a resolution of 0.1 % RH and a hysteresis of 1 % RH.

4.3. Buildings used for the experimental analysis

The monitoring activity has been carried out in eleven classrooms in four different buildings, with different structural and geometrical peculiarities. A summary description of the four buildings is given in this section.

Building A- This is identified by the green circle in the Fig. 1. It is the historical location of School of Engineering at the University of Pisa, its structure is composed by heavy masonry walls and the classroom have high ceilings. Moreover, there are various kind of classroom such as, drawing room, restrooms, computer labs, corridors, scientific labs, offices, lecture room and open spaces. The measurements have been done in a classroom, identified with label 1 in Tab. 1.

Building B- This is identified by the yellow circle in the Fig. 1. It was built at the end of the 60s of the last century as a temporary building it is now made permanent. Its walls are preassembled light weight walls and the rooms have lower ceilings. There are study rooms, restrooms, corridors, classrooms, computer labs and a cafeteria. The structure presents a geometric articulation articulated by three fronts, one with respect to the other, with a rigid partition due to the repetition of the modules of the opaque covering and the fixtures. The inner walls are fine and characterized by poor

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materials and the insulation is provided by glass wool and wood fibres. Within its envelope there are two big-size classrooms up to 1426 m^3 and 370 seats, 8 from low to medium size classrooms, 7 computer labs, a restroom, a study room and a cafeteria. The classrooms are, except for the two big classrooms previously mentioned, characterized by low ceilings and thus by a small volume/surface ratio. In this building two classrooms have been selected for the monitoring activity: a computer lab, identified with label CL1 and a classroom, identified with label 2 in Tab.1.

Building C- This is identified by the blue circle in Fig. 1. It was built in the early nineties (1993-1994) and is a building with only classrooms. The building outer design is simple and plain, being made of bricks in a very geometrical fashion. The building is articulated on 4 store and a central stairwell that constitutes a big inner open space. The purpose of the building is merely educational being provided with only classrooms of various sizes, spacing from a minimum of 18 seats to a maximum of 150. The classrooms are characterized by low ceiling as was the trend during the period in which the building was built. In this building only one classroom has been monitored. The room is located in the 4th floor and has a small volume. Its design makes it a perfect example to evaluate the air dynamics in the Building C building. This is identified with the label 3 in Tab. 1.

Building F- This is identified by the red circle in Fig. 1. It was previously a barn and it have been refurbished with educational purposes, and was operating in 2006. The classrooms inside are characterized by high ceilings (most of the rooms have “sheds”) and the walls thickness is halfway between Building A and Building B. Those triangular structures, that can be observed in Fig. 1, is characterized rooms with a good light penetration but also with a great volume and thus a great volume to surface ratio. In this building, seven different classrooms have been selected for monitoring activity, identified: they are identified with the labels 4, 5, 6, 7, 8, 9 and 10 in Tab. 1.

Figure 1. A complete view of the buildings of the School of Engineering (University of Pisa).

Considering the different classrooms where the experimental sensors have been placed, it is possible to observe that the highest volume to surface ratio, as expected, is reached in some classrooms of Buildings identified with labels A and F; this is mainly due to the fact that these buildings design is characterized by high ceilings. The computer lab CL1 and the classroom identified with label 3, meanwhile, reach the lowest value whether classroom 2 (although its big volume) and 10 are characterized by lower height so that the total volume is substantially reduced. The highest air volume per student ratio in maximum occupancy conditions is generally reached by the building F classrooms, and in the Computer Lab (CL1). In this case it is determined by the low number of seats available. Considering a quantitative point of view, the main features that distinguish the classrooms are: volume, surface, maximum occupancy, type of air conditioning system, end-use (normal classroom or computer lab), structure of the walls, form and number of windows and ventilation rate.

Table 1. Characteristics of the monitored classrooms.

Room	Building	Floor	Maximum occupancy (n)	Floor Surface, S (m^2)	Volume, V (m^3)	Ratio V/S (m^3/m^2)	Minimum volume for student (m^3)
1	A	1st	108	88	481	5.47	4.45
CL1	B	1st	116	216	583	2.70	5.02
2	B	1st, 2nd	370	336	1426	4.24	3.85
3	C	4th	74	73	212	2.90	2.86
4	F	1st	305	286	1587	5.55	5.20
5	F	1st	212	216	1220	5.65	5.75
6	F	1st	109	130	721	5.54	6.61
7	F	1st	198	197	1093	5.54	5.52
8	F	1st	104	129	716	5.55	6.88
9	F	1st	109	128	710	5.55	6.50
10	F	1st	140	131	438	3.34	3.12

In Tab. 1 an accurate description of the monitored classrooms is given taking into account the quantitative value of some variables. As already mentioned, the monitoring activity has been performed in the eleven different classrooms in different periods of the year 2018, in the period from January to April. The monitoring campaigns have been performed during both the examination period (January and February 2018) and the lecture period (March and April 2018), in various different climatic conditions. The classrooms are different for typology (typical didactic use only or informatics rooms) volume, walls composition, maximum occupation, daytime of the analysis (from early morning to late afternoon) and external conditions. All the classrooms are provided with thermal controls systems in one case and with an air conditioning system that works both during heating and cooling periods in the other three cases. But due to the nature of the buildings and the use, characterized by continuous movement of students, the air conditioning system provides little or no air exchange given the fact that the fixtures of the entire building, like many other historic building, allows the outer air to penetrate the envelope and flow into the building. Moreover, being the air exchange of great importance, relevant care was given to design an optimal air penetration through fixtures. For each classroom a minimum of two measurement points and a maximum of four measurement points have been considered as it will be exposed in detail in the next section.

The data have been subsequently analysed with two different objectives, as follow. To identify the features of the room that most influence CO_2 concentration. Factors like volume, air exchange rate, surface are undoubtedly bound to the air pollution and acknowledging their influence can help in reducing the risk of high CO_2 concentration without spending too much energy through the air handling unit. To define a possible correlation between CO_2 concentration, the occupancy of a room and the time. The recognition of the CO_2 concentration during certain occupancy levels could bring to the possibility to set the cooling system in order to provide the needed comfort reducing the energy consumption. Moreover, such expression might be useful to the identification of certain occupancy patterns that could be used in appropriate computer software that forecast energy consumption and thus, the ability of the energy manager to minimize it. The authors have clear in mind that the measurement of CO_2 concentration is largely influenced by the position of the sensors in the

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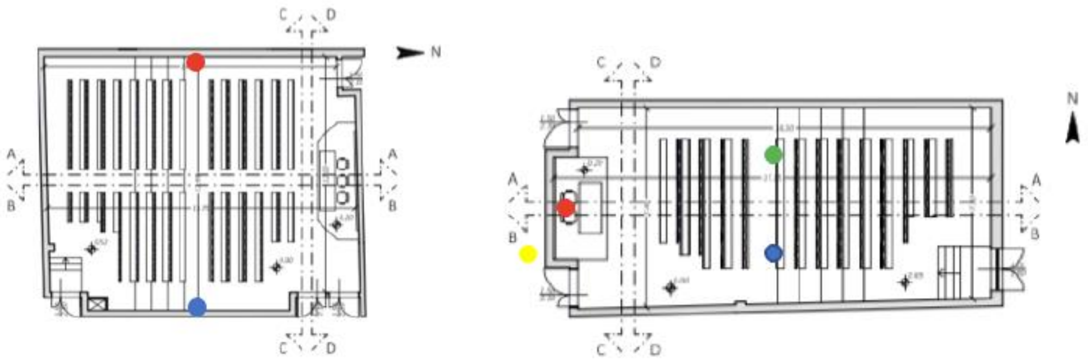
classrooms and by the mixing value of the CO_2. It is neglected the measure of the air exchange rates. It is quite difficult to analyse the occupancy pattern when the air-conditioning system is operating and the CO_2 concentration is decreasing so the analysis is based on the assumption of quite constant values of CO_2 generation rate per student. But it is surely interesting to analyse first of all the trend of CO_2 concentration in usual operating conditions.

5. CO_2 air concentration campaigns: results and discussions

The experimental analysis consisted in the utilization of sensors in properly crowded classroom during normal activities like examinations and lessons. As mentioned before, the period of analysis has been three months (between January and April). In this period due to the typical winter climate conditions the thermal control system was in heating mode. The sampling period have been chosen to be four data per minute. The whole results of the experimental activity are contained in [27]. During the campaign the activities within the room under analysis are performed without particular caution compared to how they would have been in normal circumstances. The instruments for the measurement are placed in proper positions (generally at the two opposite side of the rooms) and records the occupancy schedule, noting whether any particular event occurred (for example the opening of a door). Fig. 2 provides the typical position of the sensors in the case of two (a) or four sensors (b). Even if is not possible to be sure that the CO_2 is completely mixed in the classrooms, the configuration with four different sensors (one is outside to have a check for the commons parts too) used in the case of high volumes permits to obtain an average value of the concentration, representative of the situation.



(a) (b)

Figure 2. Positions of the sensors in the classrooms: (a) with two sensors, (b) with four sensors.

Fig. 3 shows some typical results obtained during the measurements in a specific room during a lesson of three hours considering the four point of measurement as exposed in Fig. 2b. In particular Fig. 3a shows the results obtained with the sensors in the position identified with the red circle, Fig. 3b in the position identified with the green circle, Fig. 3c in the position identified with the blue circle (two doors are present on the side). Finally, Fig. 3d shows the results obtained with the sensor located in the outdoors. In all the graphs of Fig. 3 in the y-axis the CO_2 concentrations are expressed in part per million (ppm). Considering the results of Fig. 3, that is a typical one among the various measurements during a typical lesson activity, it is evident how the quite fast increase of the CO_2 concentration during the first part of the lesson when the doors are closed. A sensible decrease, quantified in the order of magnitude of 1000 ppm is obtained when the lesson is suspended for some minutes. After that the lesson starts again and a new increase of the CO_2 concentration can be evidenced.

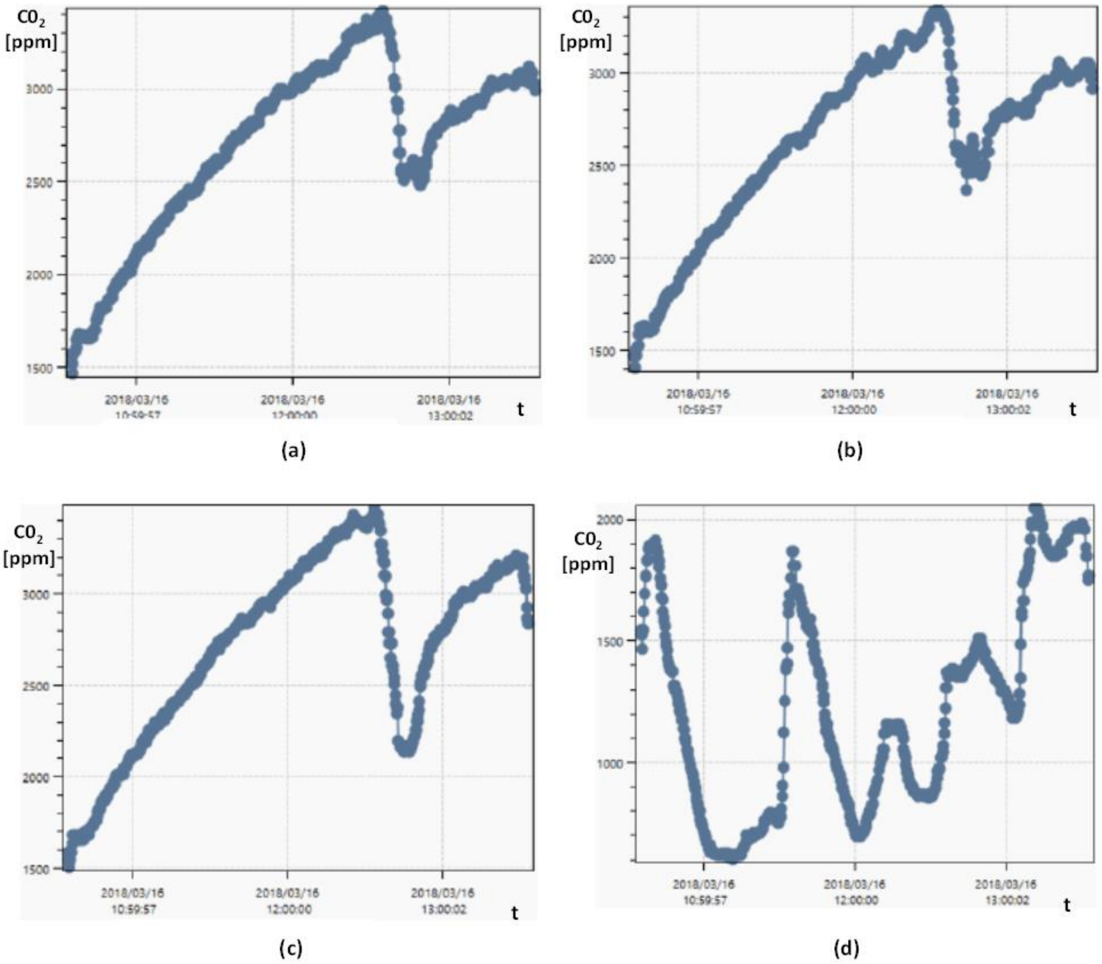


Figure 3. CO_2 concentration and time evolution during a lesson of three hours, in three different zones of the classroom 9 (see Figs.3a, 3b, 3c) and in the outside space in front of the classroom (see Fig. 3d).

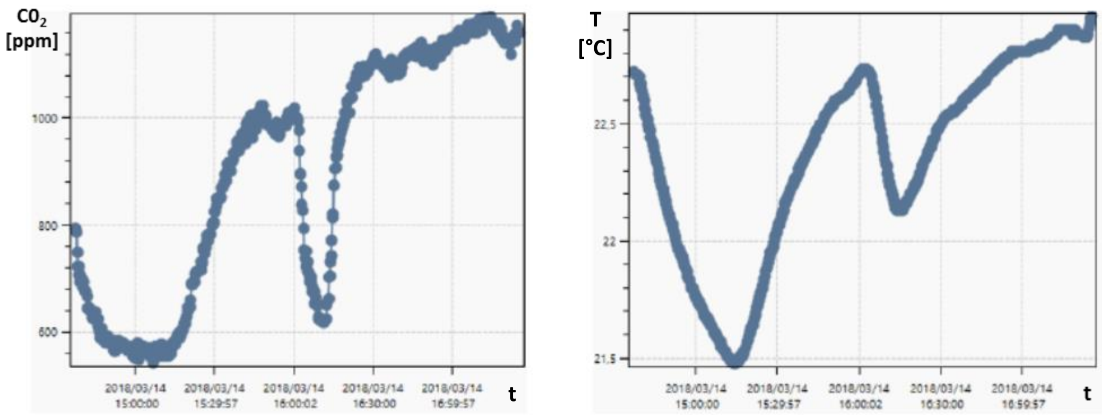


Figure 4. CO_2 concentration and temperature variation in the computer lab (CL1) during an examination of 3 hours, due to the operation of the thermal control system.

Another interesting result, that can be evidenced from the analysis of Fig. 4 is the connection between air exchange ratio and CO_2 concentration. This represent the typical CO_2 and temperature increase trends during a lesson. In this case it is evident the beneficial effect of the air conditioning system and of the air change, that permits to reduce both the temperature in the room and the CO_2

concentration. The connection between the air exchange rates (AER) and the use of measured CO_2 has been already evidenced in [13]. A summary of the results obtained in the various monitoring activities, in the different rooms, is provided in Tab. 2. In the left column it is possible to read the classroom and the sequential number of the activity.

Table 2. Results of monitoring activities.

Room (#experience)	Volume (m^3)	Occupation (n)	VAPS (m^3/n)	dCO_2/dt (ppm/s)	CO_2 (t=0) (ppm)	CO_2 (t=t*) (ppm)	t* (min)
7 #2	1093	181	6.03	0.46	2581	3885	47
1 #2.2	481	75	6.41	0.75	1056	3719	59
1 #2.1	481	75	6.41	0.67	900	3102	55
5 #1	1220	167	7.31	0.52	1138	4914	120
7 #1	1093	146	7.48	0.40	791	3296	105
10 #1.2	438	56	7.71	0.35	2077	3640	74
10 #1.1	438	56	7.71	0.32	1733	3579	95
10 #2.2	438	50	8.64	0.44	697	2409	65
10 #2.1	438	50	8.64	0.40	695	2763	87
5 #3	1220	106	11.51	0.25	1100	3408	152
9 #2.1	710	59	12.03	0.26	1647	3389	51
9 #2.2	710	59	12.03	0.28	2386	3115	42
9 #1.2	710	54	13.15	0.44	1495	2810	50
9 #1.1	710	54	13.15	0.43	1511	2333	32
9 #1.3	710	54	13.15	0.36	1861	3246	64
8 #1	716	54	13.26	0.37	1205	2382	53
4 #3	1587	93	17.06	0.17	596	2684	206
8 #2	716	39	18.35	0.28	1358	2124	45
4 #2	1587	86	18.45	0.21	792	1409	48
5 #2.1	1220	62	19.68	0.13	2165	2994	110
4 #1	1587	58	27.36	0.11	678	1740	155

The double number as #2.1 and #2.2 identifies two activities obtained in the same classroom and in the same day but in different time. As it can be seen in a lot of the exposed cases, all characterized by extremely severe conditions in terms of occupation of the classrooms, the level of CO_2 is considerably higher than 1000 ppm. Considering the results of the various monitoring activities, it is evident that the concentration of CO_2 with time is a function of different variables (i.e. the volume of the room, the number of occupants and the time t), so that:

$$[CO_2](t) = f(V, n, t, [CO_2](t = 0), VAPS, AER) \quad (1)$$

where: $[CO_2](t)$ is the concentration of CO_2 expressed in ppm at the time t; V is the volume of the room; n is the number of occupants; VAPS is the air volume per each student at full occupancy; T is the total duration of the activity; $[CO_2](t=0)$ is the CO_2 concentration expressed in ppm at the starting time t=0 (i.e. the initial concentration); AER is the air exchange ratio that can be obtained with a thermal control system.

In Fig. 5 it is shown the attempt made to establish a correlation between the increase of CO_2 concentration in the various rooms and the time t, represented by the derivative of CO_2 concentration and the volume available in each room. This last value is representative of the occupancy level of the volume. In this case, though if an interesting correlation among the two variables can be evidenced, some discrepancies with the linear behaviour can be observed.

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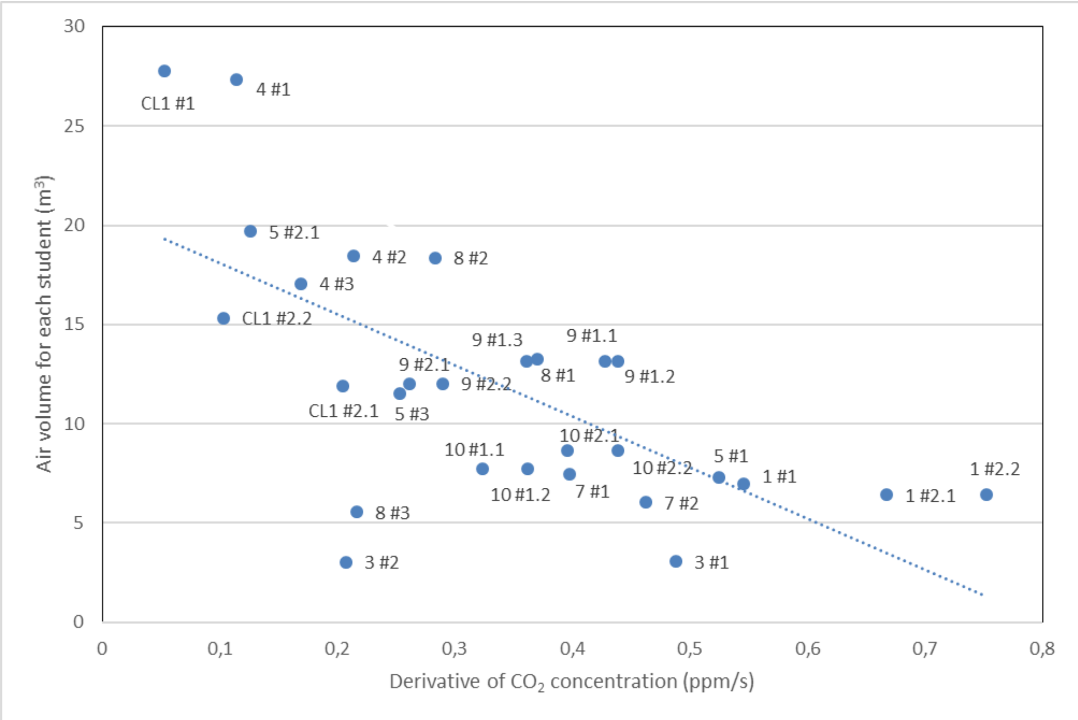

Figure 5. CO_2 concentration correlation with the available volume.

Considering the results of Fig. 5, in some specific cases it is possible to put in evidence the important role of some of the variables, like for example the specific volume available for each person inside the room and the time. This conclusion can be drawn analysing the evolution of the derivative of the CO_2 concentration with time, expressed in ppm per seconds, that appears to be close to the linearity, so that it is possible to state that the first derivative of the CO_2 concentration for a quite "closed" volume is mainly dependent on the volume available for each student, even if an approximation as the one exposed in the Eq. (2) can be accepted only in some specific cases:

$$\frac{d[CO_2]}{dt} = \frac{[CO_2](t)-[CO_2](0)}{t} \sim f\left(\frac{V}{n}\right) \quad (2)$$

Considering the results of the various monitoring activities, some qualitative and quantitative elements can be highlighted concerning the link between the CO_2 concentration and the occupation profile of a specific classroom. Summarizing, the following elements can be evidenced:

- the volume per student is an influencing factor because the higher this ratio the less the air concentration will rise
- the initial CO2 concentration, in a crowded building, can influence the CO_2 level within the room even if it has been closed;
- the presence of certain factors (such as the opening of windows and doors) can influence the CO_2 concentration, but their effect is difficult to predict; in general, classrooms with large doors or windows have a higher air exchange rate and a lower increase in CO_2 levels;
- the CO_2 concentration follows the occupancy pattern: the higher the occupation, the higher the CO_2 levels;
- the presence of a time delay between occupancy pattern and CO_2 concentration, is due to the fact that it takes some time for the CO_2 to spread all over the room, the bigger the room, the higher the delay.

The authors calculated dCO_2/dt based upon Eq.(2) and the first derivative of the CO_2 concentration can be considered mainly dependent on the volume available for each student. Really this value can be also related to the air exchange rates and the CO_2 generation rate per student, but this can be considered a quite constant value. Anyway, even if the measurements are performed in real utilization conditions in the great part of the rooms the air exchange is not mechanically controlled. Another important element of influence could be the air exchange rates. In this case, the influence of the air exchange rates is not considered because the air conditioning system, during the periods of experimental analysis provides little or no air exchange and the major contribution to the air conditioning rate is given by natural exchange by doors and windows. Basing upon the mass balance equation of indoor CO_2 concentration, 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 the time. Obviously in general cases, a linear correlation between the air volume for each student and the derivative of the CO_2 concentration might be unsuitable due to the various source of air exchange from the classroom to the external spaces and due to the variation of the number of occupants during the typical period of observation (lesson or examinations in this case).

6. Conclusions

Energy consumption and indoor environment quality (IEQ) of buildings are clearly linked to the occupation. Predicting the number of occupants in a space is essential for the effective management of various building operation functions as well as for improving environmental quality and energy efficiency. One of the emerging methods to estimate the number of indoor occupants can be the analysis of the CO_2 concentration and in particular the analysis of the dynamics of CO_2 concentration variation. Considering that the measurement of CO_2 can be useful not only for the occupancy detection but, since CO_2 is a gas which, after long-time exposure, can cause undesired effects on the occupants for comfort purposes too. This study has the objective of analysing the possible correlation between CO_2 measured values and actual occupant numbers. Analysis is performed in various classroom, characterized by different characteristics and volumes, during a period of 4 months, in order to test the correlation between CO_2 concentration and occupancy in various condition and to provide some elements for a possible quantification. Some data can be remarked: the CO_2 concentration increase with time is a very dispersed value in the range from 0.1 to 0.8 ppm for seconds; this means that for each minute an average increase of 20-25 ppm for each minute can be observed. The higher values of the concentration increase are directly correlated with the reduction of the volume available for each student. Values over 0.40 ppm/s can be observed if the volume for student is less than 10 m^3.

An attempt has been made in order to establish a correlation between the increase of CO_2 concentration with time, represented by the derivative of CO_2 concentration and the volume available in each room shows that the first variable is surely important and this means that CO_2 can be really an important qualitative indicator to establish the occupancy level of a space. Even if it is possible to conclude that the CO_2 concentration follows surely the occupancy pattern: the higher the occupation, the higher the CO_2 levels, a lot of secondary factors like the opening of windows and doors, and the delay time between occupancy pattern and CO_2 concentration, due to the fact that it takes some time for the CO_2 to spread all over the room in dependence on the total volume of the classroom may have a strong influence on the CO_2 concentration and their effect is hardly forecastable. For this motivation, the use of this indicator for quantitative analysis is not so simple excluding the case of "fully closed" volumes. Although the findings considered in the paper could be interesting, a more detailed and quantitative analysis could be useful taking into account also the consideration of air exchanger rates control in the rooms.

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