Occupancy modelling of buildings based on CO₂ concentration measurements: 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 CO₂ 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 centers, hospitals, etc.). This paper starting from an experimental analysis conducted of a University campus in different operating conditions, with different model for occupancy simulation in multi-zone multi-occupant buildings and its preliminary validation from experimental data acquired in different cases. The acquired data are used to present some graphical models and perform occupancy estimates. 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 promising results.

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. The buildings sector is the largest energy consuming sector, accounting for over than one-third of final energy consumption globally and an equally important source of carbon dioxide (CO₂) emissions. High energy consumption in buildings can be caused by several factors including a reduced insulation determined by the thermal envelope, a bad management of the thermal and electrical system, improper 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]. Among the various buildings for public activities, University Campuses and Schools in general are interesting structures made up of different types of buildings, with different end-use (sometimes with different end-use within the same envelope), different thermal envelopes and different occupancy profiles. 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 these aspects, analyzing the problem with a general perspective, for example [2] and [3], or with reference to specific cases, for example some interesting papers, such as [4-6], or Master Thesis, [7]. Assessing university building with several end-use, different problems emerge. Within the same envelope there could be laboratories, offices, lectures room, classes, open spaces, halls, gyms which have different energy needs. For that reason, a building cannot be characterized by its consumptions only, but in relation with its end use. Moreover, university has different usage profile during the year: during lectures period, 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, during lecture periods 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. Moreover, 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. Also, both in lecture and exams periods during
weekends, pre-holidays and holidays very reduced occupancy is expected. In order to maintain the comfort within certain parameters anyway, specific profiles should be considered for the thermal control system. Anyway, a relevant element of analysis is the occupancy of the various structures. Occupant presence release latent and sensible heat that changes thermal conditions warranting increased in air-conditioning. They also release pollutants such as carbon dioxide (CO$_2$) which is also an indicator for ventilation adequacy. Monitoring of presence and crowding 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 of 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. 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 (notebooks, smartphone chargers, various educational equipment) that significantly increase, and sometimes not easily predictable, the consumption of electricity.

High consumption in buildings could have been caused by several factors including a bad behavior of the thermal envelope, a bad management of the thermal and electrical system, improper 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.

University Campuses are made up of different types of buildings, with different end-use (sometimes with different end-use within the same envelope), different thermal envelopes and different occupancy profiles. 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. The study of the building energy demand has become a topic of great importance, because of the significant increase of interest in energy sustainability. University Campuses represent specific groups of diverse buildings, with significant energy consumption. They consist of many different buildings, representing small-scale town for itself. Therefore, they provide an interesting testbed to characterize and understand energy consumption of groups of “mixed-use” buildings.

Moving from some recent trend in the research, the paper tries to analyze 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 method has been recently proposed in the literature, as clearly evident analyzing, among the other, recent papers such as [8-10]. 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 a University building.

2. Energy efficiency, environmental quality and the effective use of building: the importance of occupancy estimation and the connection with CO$_2$ concentration

In the literature there are several studies that highlight the most important aspects to be considered for carry out an analysis of the energy efficiency of a public building. An energy characterization of the buildings may reveal a key factor to identify possible actions or refurbishments with the purpose of reducing consumptions. An overview of the various energy performance assessment models for common buildings in literature has been made in [11].

The first datum that characterizes a building from an energy point of view is its primary energy consumption (gas and/or electric energy). In general, there are three strategies with which the energy consumption of a building can be estimated, namely: the analysis of bills and total energy consumption, direct consumption measurement and modelling.

Energy bill is a type of high quality measurement data. The method based on the analysis of the energy bills is, among the three, the simplest method, economic but 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. Direct measurement, on the other hand, is a method of energetic characterization of the building much more accurate and that allows you to get much more information. This strategy is implemented through the use of
specific meters, carefully positioned inside the building can provide data with variable sampling frequency (hourly, daily, monthly consumption etc.) and related to particular areas. The third strategy, largely diffused in the recent literature is to provide a mathematical model of the building and to perform a dynamic simulation of the behaviour. 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 four groups of parameters, as weather conditions, building description and component description. There are many influencing factors in energy efficiency benchmarking, such as end-use characterization, building typology (old, refurbished or new structures) and occupancy is one of those. Energy consumption and indoor environment quality (IEQ) of buildings appears to be strongly linked to human occupants. Predicting the number of occupants in a space is essential for the effective management of various building operation functions as well as improve 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.

Currently, the occupancy sensor market is dominated by infrared and ultrasonic detectors. These relatively simple devices provide fine-grained information on peoples’ presence and location. Their output is of binary type, it detects the state “occupied” vs. “not occupied”. In addition, these sensors are often unreliable in capturing immobile occupants. Hence, infrared and ultrasonic sensors can be only detectors of presence and do not provide information on count. This fact determines their applicability, which is limited to lighting control systems. The simplest way to obtain information regarding the level of room occupancy is to employ more advanced, especially dedicated equipment, such as vision sensors for example video cameras and RFID (Radio Frequency Identification) tags. Video cameras are a reliable and accurate way to determine not only if a space is occupied, but also the number of occupants. However, counting people directly may be challenging due to partial/complete object occlusion. Video images are either observed by human operators or analysed by computer tools. Main drawbacks of this technology are: the need of large data storage capacity, the fact that commercially available software-based image analysis for application to building system control is still under development and, above all, this solution interferes with privacy concerns. That is why several works using low-resolution cameras or even developing “reduced” sensor from camera, with a very different appearance from conventional video camera, have been proposed to obtain enough information to detect person’s position and movement status, while reducing the psychological resistance against having a picture taken. Electromagnetic signal detection systems, radio frequency identification have the capacity to provide occupancy information on location, number of occupants, their identities and track. RFID is an effective technology for indoor localization that can provide adequate accuracy and fine-grained occupancy information. It is cost-efficient, does not require line of sight conditions. In addition, it has onboard data storage capacity that can be used for another purpose such as building asset management. The disadvantages of this technology result from the privacy (psychological resistance of the tag users), technical problems and some inconvenience. Occupants must possess the RFID tag. Therefore, users feel they are constantly being monitored. Frequently, occupants use more than one device generating EM (electromagnetic) signals, which can be detected by the radio frequency identification system. It results in false registration of presence and count as well as incorrect location. The terminal device held by the user is usually battery powered and not sustainable for long-term data acquisition. A complex and advanced signal processing station is often required. The RFID tag must be attached to the occupant. It causes some inconveniences for the user performing everyday activities.

The drawbacks of the direct determination of occupant number make this approach unsuitable in certain situations. Therefore, indirect inference of occupancy levels in rooms or buildings is considered. This alternative approach exploits signals originating from different buildings systems and indoor environment. Considering the correlation between the use of structures and the CO2 concentration in indoor environments, it seems very interesting to elaborate models that, starting from an evaluation on indirect experimental bases of the occupation, can also define a correlation of this 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 indoor occupants from environmental parameters, in particular such as temperature, humidity, and CO2 concentration, see for example [12]. Amongst these parameters, CO2 concentration is the one that most correlates with the number of occupants. As mentioned above, humans naturally exhale this gas depending on their metabolic rate. Hence the analysis of the dynamics of CO2 concentration may be employed in determining the number of occupants inside room.
Moreover, the measurement of CO₂ is useful not only for the occupancy detection but, since CO₂ is a gas which can cause undesired effects on the occupants after long time exposure, also for comfort purposes. In order to understand the qualitative value of CO₂ concentration that can be measured a preliminary quantitative definition is important.

Carbon dioxide 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). Carbon dioxide concentration in the range between 250-600 ppm is the typical level for ambient air in outside 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 [13]. The acceptable level of carbon dioxide is related to building category and is defined in European Standard 13779 [14]. The standard states that the typical ranges of CO₂ concentration above the outdoor level are for building category I lower than 400 ppm, category II, 400-600 ppm, category III, 600-1000 ppm and category IV over than 1000 ppm. For confined spaces, several sources indicate that indoor air problems are significantly reduced at 600 ppm or less of carbon dioxide. 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, [15]. 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 for long time exposure. Considering confined spaces, 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. But the case of Universities and University campus 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. Implementing CO₂ sensors into the air handling unit could bring to a double benefit, that is occupancy definition and comfort assessment. Considering the fact that CO₂ 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 CO₂ concentration represent a valid and effective way.

3. CO₂ concentration measurement activity: selection of appropriate instrumentation and rooms

From the analysis exposed in the previous section, it clearly emerges the fact that CO₂ concentration monitoring within university building is a not well explored field even if it may be a very promising one. For these reasons 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 area (a satellite view is reported in figure 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 4 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 of the utilization of sensors in properly crowded classrooms during exams and lessons.

3.1 Sensors used for the measurement

The sensors utilized are of commercial type, model Chauvin Arnoux CA1510. These sensors are very small and do not emit any kind of sound or substance that can pollute the surrounding are. For that reason, they can be easily placed in crowded situation without being even noticed. The CA1510 is an instrument for measuring physical quantities that combines the following functions:

- Measurement of Carbon Dioxide concentration in the air (CO₂);
- Measurement of the ambient temperature;
- Measurement of the relative humidity (RH).

The particular instrument works out air quality criteria based either on the level of CO₂ 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 CO₂ concentration, the instrument is provided with a Dual-beam infrared cell, using the Non-Dispersive Infrared technology. The measurement is from 0 to 5000 ppm with an intrinsic uncertainty of ±3% at 25°C and atmospheric pressure. The resolution of the instrument is 1 ppm. The temperature error is 1 ppm/°C in the range from −10 to 45°C. The influence of pressure can be obtained with the following equation: \( \text{CO₂ real} = \text{CO₂ measured} \times (1+(1013-P) \times 0,0014) \) (P is the pressure expressed in mbar);
- for the measurement of temperature, the instrument is provided with a CMOS sensor that can furnish a measure in the range between -10 and 60°C with uncertainty of ±0.5°C at 50% RH;
- 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 ±2% at RH from 10 to 90%. But this measurement is not considered for the purposes of the present paper.

3.2 Locations for the measurement

The monitoring activity has been carried out in various classrooms in four different buildings where the measurements have been performed have different characteristics.

- **Building A**: This is identified by the green circle in figure 1 and is the historical location of Engineering in 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, cellular office, lecture room and open spaces. The measurements have been done in a classroom, that is well representative of the various, that has been identified with number 1.

- **Building B**: This is identified with the yellow circle in figure 1. It was built at the end of the 60s of the last century. 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 materials and the insulation is provided by glass wool and wood fibers. Within its envelope there are two big-sized classrooms up to 1426 m³ and 370 seats available, some little and medium sized classrooms, computer labs, restrooms, 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: a computer lab, identified with the name CL1 and a classroom, identified with the number 2.

- **Building C**: This is identified with the blue circle in figure 1. The structure has been constructed in the early nineties with classrooms only. 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 the building was built. In this building, that has been identified with number 3, only one classroom has been monitored, the room is located at the 4th floor and has a small volume.

- **Building F**: This is identified with the red circle in figure 1. It was previously a barn and it have been refurbished with educational purposes, and was operating in 2006. The classroom 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, visible in figure 1, provided the rooms with a good light penetration but also with a great volume and thus a great volume to surface ratio. In this structure seven classrooms have been selected for monitoring activity, identified with the numbers 4, 5, 6, 7, 8, 9 and 10.

It is possible to observe that the highest volume to surface ratio is, as expected, reached in some classrooms of Buildings F and A, given the fact that these buildings design is characterized by high ceilings. CL1 and classroom 3, meanwhile, reach the lowest value whether classroom 2 (although its big volume) and 10 are halfway. 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. Not being previously aware of the classrooms’ features that most influence air composition, and CO₂ concentration in particular, it has been necessary to monitor a wide range of classrooms. Fortunately, the study site is a heterogeneous mix of
various classroom types and it has been possible to program an effective monitoring activity. The main characteristics that distinguish the different classrooms tested are:

- volume;
- surface;
- maximum occupancy;
- tightness;
- air conditioning system;
- end-use;
- structure of the walls.

In Table 1 an accurate description of the buildings and the classrooms is given. As already mentioned, the monitoring activity thus has been performed in 11 classrooms in different periods of the year 2018. 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 classrooms situated in the different buildings of the School. The classrooms are different in typology (typical didactic use only or informatics rooms) volume, walls composition, air exchange rate, occupancy, daytime and external conditions.

For each classroom a minimum of three measurement points and a maximum of four measurement points have been considered. The data have been subsequently analyzed with a double objective:

- To identify the features of the room that most influence CO₂ concentration. Factors like volume, air change ration, surface are undoubtedly bound to the air pollution and acknowledging their influence can help future building in reducing the risk of high CO₂ concentration without spending too much energy through the air handling unit.

- To define a possible correlation between CO₂ concentration, the occupancy of a room and the time. The recognition of certain path in the CO₂ 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.

Figure 1. A complete view of the buildings of the School of Engineering (University of Pisa)
Table 1. Characteristics of the rooms object of monitoring

| Room | Building | Floor | Maximum occupancy (n) | Floor Surface (m²) | Volume (m³) | Ratio Vol/surface (m³/m²) | Minimum vol. for student (m³) |
|------|----------|-------|-----------------------|-------------------|-------------|--------------------------|-------------------------------|
| 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                          |

4. CO₂ air concentration campaigns report and analysis of the results

The experimental analysis consists in the utilization of sensors in properly crowded classroom during exams and lessons. The sampling period is 4 data per minute. During the experiments the activities within the room under analysis are performed without particular caution. The operator places the instruments in proper positions (generally at the two opposite side of the rooms) and records the occupancy schedule, observing whether any particular event occurred (for example the opening of a door, the sudden change in the students’ activity etc.). Figure 2 shows the results obtained in the measurements in a specific room during a lesson.

![Figure 2](image_url)

**Figure 2.** CO₂ concentration (ppm) as a function of time (t) in three different zones of the classroom 9 (a), (b) and (c) and in the outside corridor (d) during a lesson of three hours.
In the y-axis the CO$_2$ concentration, expressed in part per million (ppm) is represented while in x-axis time $t$ is reported. Considering the results of figure 2, that represent a typical report of the various measurements, 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, that can be quantified in the order of magnitude of 1000 ppm can be obtained when the lesson is suspended for some minutes. After that the lesson starts again and consequently a new increase of the CO$_2$ concentration can be evidenced.

Another interesting result, that can be evidenced from the analysis of figure 3 is the connection between air change 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 change ratio (ACR) and the measured CO$_2$ level has been already evidenced in [6]. A summary of the results obtained in the various experiments in the different rooms is provided in Table 2. In the left column it is possible to read the classroom and the sequential number of the experiment. The double number as #2.1 and #2.2 identifies two experiences obtained in the same classroom and in the same day but in different time (for example morning and afternoon).

![Figure 3. CO$_2$ concentration and temperature variation in the computer lab (CL1)](image)

| Room/Experience | Volume (m$^3$) | Occupation (n) | VAPS (m$^3$/n) | $d$CO$_2$/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              | 3113              | 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    |

Table 2. Results of monitoring activity
Considering the various experiments, the CO₂ concentration (expressed in ppm) with time (t), \([CO_2](t)\) is a function of different variables, like the volume of the room, \(V\), the number of occupants, \(n\), and others:

\[
[CO_2](t) = f(V, n, t, [CO_2](t = 0), VAPS, ACR)
\]  

where VAPS is the air volume per each student in the full occupancy conditions, \(T\) is the total duration of the experiments; \([CO_2](t=0)\) is the CO₂ concentration at the starting time \(t=0\) (i.e. the initial concentration) and ACR, the air change ratio that in general can be obtained only with a mechanical system. In figure 4 an attempt is made to establish a correlation between the increase of CO₂ concentration with time, represented by the derivative of CO₂ concentration and the volume available in each room for the single occupant: this last value is representative of the occupancy level. Though if an interesting correlation among the two variables can be evidenced, some discrepancies with the linear trend can be observed.

Considering the data of figure 4, it is possible to put in evidence the predominant role of some variables, like the specific volume available for each person (VAPS). This appears to be close to the linearity, so that it is possible to state that the first derivative of the CO₂ concentration can be considered mainly dependent on the volume available for each student:

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

Considering the results of the various experimental analyses, some qualitative and quantitative elements can be highlighted concerning the link between the CO₂ concentration and the occupation of the room:

- the volume per student is an influencing factor: the higher this ratio the less the CO₂ concentration rise;
- the initial CO₂ concentration level is important;
- the CO₂ concentration follows the occupancy pattern: the higher the occupation, the higher the CO₂ levels;
- a time delay between occupancy pattern and CO₂ concentration increase can be observed, due to the fact that it takes some time for the CO₂ to spread all over the room, the bigger the room, the higher the delay.

![Figure 4. CO₂ concentration correlation with the available volume: a possible correlation](image-url)
5. 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 to improve energy efficiency and environmental quality. One of the methods to estimate the number of indoor occupants is the analysis of CO\textsubscript{2} concentration and of CO\textsubscript{2} concentration variation. CO\textsubscript{2} measurement is useful not only for occupancy detection but for comfort purposes too.

This study analyzes the correlation between CO\textsubscript{2} measured values and actual occupant numbers. Analysis is performed in different classrooms of the School of Engineering at the University of Pisa, characterized by different characteristics and volumes, during a period of 4 months. The objective has been to test the correlation between CO\textsubscript{2} concentration and occupancy in various condition giving quantitative elements. Some data can be remarked: the CO\textsubscript{2} concentration increase with time is a very dispersed value ranging 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\textsuperscript{3}. The attempt to establish a correlation between the increase of CO\textsubscript{2} concentration with time, represented by the derivative of CO\textsubscript{2} concentration and the volume available in each room shows that CO\textsubscript{2} can be really an important qualitative indicator to establish the occupancy level of a space.

At the end of the analysis it is surely possible to conclude that the CO\textsubscript{2} concentration follows surely the occupancy pattern. But a lot of secondary factors like the opening of windows and doors, and the delay time between occupancy pattern and CO\textsubscript{2} concentration, due to the fact that it takes some time for the CO\textsubscript{2} to spread all over the room in dependence on the total volume of the classroom may have a strong influence on the CO\textsubscript{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.

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