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# Indoor environmental quality classification of school environments by monitoring PM and $CO_2$ concentration levels

Luigi Schibuola, Chiara Tambani*

*University IUAV of Venice, Dorsoduro 2206, 30123, Venice, Italy*

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ABSTRACT

Nowadays the control of indoor healthiness and comfort has become a key issue in school environments. Indoor environment quality (IEQ) as regards indoor air quality (IAQ), ventilation requirement as well as health effects assessed by Hazard Index and Cancer Risk were investigated in a naturally ventilated school by monitoring indoor/outdoor $CO_2$ concentrations and particulate matter (PM) levels. This way, a $CO_2$ fluxes balance permitted to calculate actual ventilation rates used to classify the classrooms on the basis of the proposal contained in fpEN 16,798 standard. The relationship between ventilation, $CO_2$ levels and PM was also studied. In absence of appreciable internal pollution sources, the indoor concentrations of chemical pollutants were correlated to the corresponding outdoor concentrations by the comparison of indoor/outdoor PM whose differences in this case depend only by indoor deposit and resuspension. Heavy metals (As, Cd, Ni, Pb) and PAHs were considered as required by CEN recommendations. A simple procedure was carried on to assess the potential health hazards of pollutants on students. Hazard Index and the total Cancer Risk of the inhalation exposure were evaluated as proposed by United States Environmental Protection Agency. The calculated values resulted normally acceptable if related to daily school period, but not completely satisfactory because they highlighted that the indoor contaminant concentrations were not acceptable for 24 h exposure. Therefore these chemical pollutants reduce the no health hazard exposure capacity of the children in the remaining part of the day.

## 1. Introduction

Indoor environmental quality (IEQ) concerns the environment existing inside a building and it depends by various factor like thermal and hygrometric comfort, lighting, acoustic and indoor air quality (IAQ). IAQ is the final effect of the presence of air pollutants and of the existing ventilation which is able to dilute them.

An incontestable evidence links poor IAQ and harmful health effects inducing respiratory and cardiopulmonary pathologies (Yang et al., 2009). In such a context, school environments are therefore object of great concern about IEQ among the scientific arena. In fact students spend a significant part of their school time inside classrooms characterized by higher occupancy density than the most part of other buildings and often by inadequate ventilation rate. The exposure to contaminants is by far more critical for children as they inhale more air per unit of body weight and present higher resting metabolic rates if compared to adults (Annesi-Maesano et al., 2003). These larger specific doses involve their less able to deal with toxic chemicals (Bates, 1995). Indirect indicators, such as school absenteeism, give testimony of the effect of air pollutants on children's health (Pekey et al., 2013). In addition, many studies have clearly showed that an increased ventilation rate improves the interpersonal relationships in schools (Finell et al., 2018) and the academic performance of students (Wyon, 2004).

As normally in school environments pollution is caused essentially by the occupancy. The measure of carbon dioxide ($CO_2$) concentration level can be used as an indicator of the quality of the ventilation and IAQ, also because the effects of the other bio-effluents (body odors) can be correlated to $CO_2$ concentrations (Stabile et al., 2016). Therefore several regulations and standards establish values of $CO_2$ concentration levels to decide the acceptability of ventilation rates and IAQ conditions. However other pollutants with dangerous concentrations can be present inside and not immediately correlated with $CO_2$ levels (Mi et al., 2006). Their presence can deeply affect IAQ. Among air pollutants, particulate matter (PM) have a significant effect on IAQ. In fact the exposure via inhalation is an important source of PM hazard for human health. Concentrations, duration of exposure, size and composition of the particles determine the level of health risk (Buonanno et al., 2017; Pacitto et al., 2018). The coarse fraction (diameters >

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* Corresponding author.
*E-mail address:* chiara.tambani@iuav.it (C. Tambani).

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $ADI_i$ | Average Daily Intake for i-th pollutant [mg $kg^{-1}$ $d^{-1}$] |
| $AR$ | Absorption Rate [%] |
| ARPAV | Regional environmental agency |
| $AT$ | Averaging time [d] |
| $BW$ | Body Weight [kg] |
| $C_i$ | Concentration for i-th pollutant [mg $m^{-3}$] |
| $CR_t$ | Total Cancer Risk for inhalation pathway[-] |
| $CR_i$ | Cancer Risk for i-th pollutant [(-] |
| $Cref_i$ | Concentration for i-th pollutant measured as content in the $PM10_{ref}$ [mg $m^{-3}$] |
| $CSF_i$ | Cancer Slope Factor for i-th pollutant [(kg d $mg^{-1}$] |
| $ET$ | Exposure Time [$m^3$ $d^{-1}$] |
| $EF$ | Exposure Frequency [d $year^{-1}$] |
| $ED$ | Exposure Duration [years] |
| $E$ | Specific Exposure rate [$m^3$ $kg^{-1}$ $d^{-1}$] |
| $HI$ | Hazard Index [-] |
| $HQ_i$ | Hazard Quotient for i-th pollutant [-] |
| $IAQ$ | Indoor Air Quality |
| $IEQ$ | Indoor Environmental Quality |
| $IUR_i$ | Inhalation Unit Risk for i-th pollutant [(μg $m^{-3}$)$^{-1}$] |
| $IR$ | Inhalation Rate [$m^3$ $d^{-1}$] |
| $LDI_i$ | Lifetime Daily Intake for i-th pollutant [mg $kg^{-1}$ $d^{-1}$] |
| PAH | Polycyclic aromatic hydrocarbons |
| $PM$ | Particulate matter [μg $m^{-3}$] |
| $PM_{10ref}$ | Outdoor mean $PM_{10}$ measured in the winter period [μg $m^{-3}$] |
| $PM_{10day}$ | Daily mean $PM_{10}$ measured [μg $m^{-3}$] |
| $RfD_i$ | Reference Dose for i-th pollutant [mg $kg^{-1}$ $d^{-1}$] |
| $Rfc_i$ | Reference concentration for i-th pollutant [mg $m^{-3}$] |

2.5 μm) has predominantly natural sources (geological material, such as resuspended dust) and biological material. In the fine fractions (diameters < 2.5 μm) are predominant combustion derived particles, consisting mainly of organic and inorganic elements adsorbed onto the surface of a carbonaceous core (Brüggemann et al., 2009). The carbonaceous fraction consists of aggregates of carbon on which are adsorbed metals like Pb, Cd, V, Ni, Cu, Zn, Mn, Fe, organic compounds and biological constituents (U.S. EPA, 2004). This way, fine particles become an effective means to transport different kinds of pollutants deeply into the lung (Reich et al., 2009; Sager and Castranova, 2009). As toxic and carcinogenic effects of these pollutants are well known, a precise assessment of the concentration is required of the airborne particulate as well as its chemical composition. Recently these investigations were extended also to indoor environments and in particular in classrooms where they showed that increasing levels of $PM_{10}$ and $PM_{2.5}$ may provoke an increased prevalence of acute and chronic health effects, like asthma, among pupils (Daisey et al., 2003; Mendell and Heath, 2005).

Several investigations related to schools have indicated that the outdoor environment plays a fundamental role on the indoor pollutant levels (Chaloulakou et al., 2003; Diapouli et al., 2008; Goyal and Khare, 2009; Guo et al., 2010). The pollutants in the air within a classroom are predominantly the same of the outdoor air coming in through airing and infiltration. In the absence of indoor sources, indoor concentrations of chemical pollutants, show similar trends to outdoor environments, particularly in naturally ventilated buildings, and therefore can be estimated from the outdoor concentrations (Jones et al., 2000; Kumar and Morawska, 2013). But other pollutants (VOCs, Formaldehyde, etc) can be originated from inside, such as those from furniture and paint (Sakhi et al., 2019). An increasing ventilation eases the introduction of outdoor pollutants and therefore the removing and diluting effect of pollutants from indoor sources is counterbalanced by an increasing amount of pollutants coming from outdoors (Stabile et al., 2017; Vervoort et al., 2019).

In schools, indoor PM is largely of outdoor origin (Raysoni et al., 2011). Typical indoor PM sources such as smoking, heating and cooking (in absence of cafeteria) are normally not present in schools. The use of chalk inside classrooms can be an important source (Dorizas et al., 2015). Inorganic materials like silicates, silica and limestone, most of crustal origin (Almeida et al., 2011; Oliveira et al., 2016) are also present among the airborne particles from outside and eventually incremented by internal sources. Floor surface type and level of cleaning of indoor surfaces are important factors in maintaining low dust levels as they affect the resuspension of the deposit.

Furthermore, $PM_{10}$ concentrations were reported as strongly influenced by occupants and their activities, being the resuspension of particles responsible for the high levels observed (Ferro et al., 2004). About this issue, high indoor/outdoor (I/O) ratio of $PM_{10}$ were found (Chithra and Shiva Nagendra, 2012) in schools and its trend indicated the influence of classroom occupancy. In fact higher $PM_{10}$ concentrations were detected during the periods when the classroom was occupied and a significant contribution of resuspension of particles from room surfaces was related to physical activity of the pupils (Blondeau et al., 2005; Poupard et al., 2005). On the contrary, lower I/O ratios for $PM_1$ indicated that no indoor sources of finer particles were in classrooms thus confirming their origin due to vehicular emissions and from the generation of secondary organic aerosols essentially outside in rooms characterized by the absence of ozone sources (Fan et al., 2003; Huang et al., 2011).

In this paper an investigation about IAQ is presented based on a long term monitoring in a school environment. Simultaneous I/O measurements of $CO_2$ levels and PM concentrations were executed in order to elaborate a simple procedure to evaluate the indoor quality considering both ventilation requirement and indoor pollutant levels.

In fact despite the great number of studies about ventilation in schools, the impact of airing on indoor pollutants and the correlation between ventilation requirement and pollutant control exigency are still not completely understood. Additional experiences concerning this topic can provide greater certainty. In synthesis the analysis here presented is aimed to verify: i) the possibilities but also the limits in the use of a mathematical model able to calculate the actual ventilation rate based on the measurements of $CO_2$ level trends, ii) the evaluation of the IEQ category of the monitored environments as required by recent standards by using $CO_2$ measurements, iii) the correlation between ventilation rate and indoor PM trends in school environments, iv) the calculation procedure of health risk indexes for the classrooms.

## 2. Background

Natural ventilation is widespread in mild climates, however, many studies (Rosbach et al., 2013; Santamouris et al., 2008; Schibuola et al., 2016) show that internal $CO_2$ levels are worse in countries where schools are mainly equipped with natural ventilation systems, while mechanical ventilation systems have been recognized as useful to positively influence the pollutants levels in internal environments (Canha et al., 2016; Schibuola et al., 2018a, 2018b; Yuan et al., 2018). Recent studies (Jacobson et al., 2019; Zhang et al., 2016, 2017) show a variability of acceptability limits of indoor $CO_2$ concentrations and different prescriptions have been adopted in various states. In 2008 the Committee for Indoor Guidelines Value of German Federal Environment Agency defined $CO_2$ concentrations: below 1000 ppm as “hygienically acceptable”, between 1000 ppm and 2000 ppm as “hygienically noticeable" and concentrations higher than 2000 ppm as "hygienically" unacceptable " (Ad hoc, 2008). In 2006, United Kingdom ventilation standards established that $CO_2$ concentrations in classrooms should not exceed 5000 ppm within the school day and the average concentration should not exceed 1500 ppm (Bb101, 2006). The Hong Kong Indoor Air Quality Management Group (IAQMG) evaluates school classes with a $CO_2$ concentration average during 8 h of 800 ppm as "excellent class" and 1000 ppm as "good class" (IAQMG, 2003). Recommended indoor $CO_2$ concentration in American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 62.1 (ASHRAE, 2010) is 1000 ppm.

Currently, the World Health Organization (WHO) does not classify $CO_2$ as a pollutant, but as a good indicator of IAQ (Apte et al., 2000; Chatzidiakou et al., 2015). Ventilation is one of the strategies used to control IAQ, it provides outdoor air useful to remove and dilute indoor air pollutants. The ASHRAE 62.1 standard (ASHRAE, 2010) provides two possible procedures for the assessment of ventilation requirements, both based on the traditional approach of diluting pollutants by external air, but they differ in the method used to determine air flow rates. First procedure (ventilation rate procedure), based on occupancy level, specifies the amount of outside air (expressed in l/s per person or sometimes in l/s per $m^2$) sufficient to dilute indoor pollutant concentrations until a level that is no longer dangerous or cause of discomfort for occupants. Different ventilation amounts are proposed based on the destination of use for the building. Second procedure (indoor air quality procedure) is based on specific pollutant control, for which relevant emission rates are assumed to be in the building. Its target is to find the external air quantity sufficient to dilute the internal one up to reach concentration levels, for predetermined pollutants, lower than the limits imposed. EN 15251 (2007) and EN 13779 (2007) standards mainly follow the same approaches included in ASHRAE 62.1. EN 13779 contains guide values of air quality acceptability applicable exclusively to non-residential environments, while EN 15251 is applicable both to residential and non-residential environments. These standards contain required ventilation expressed in terms of alternative descriptors: difference to be obtained between indoor/outdoor $CO_2$ concentrations, specific air flow rate per occupant or per unit area. On the basis of these requirements, EN 15251 provides an IAQ classification. EN 15251 and EN 13779 are currently under revision by prEN 16798-1 (prEN 16798–1, 2017) and prEN 16798-3 (prEN 16798–3, 2017) which contain similar approaches to classify indoor environmental quality (IEQ) based on ventilation rate requirement or I/O $CO_2$ levels difference. An important addition, as a result of HealthVent research project (HealthVent, 2013), is that the revision of the standards specifies the ventilation rate of 4 l/s per person as base rate during the occupation in any case guaranteed for physiological exigency. Four IEQ categories are introduced: $IEQ_I$ (High), $IEQ_{II}$ (Medium), $IEQ_{III}$ (Moderate), $IEQ_{IV}$ (Low), which are related to the level of expectation of the occupants may have. Category Medium would be normally pursued. Higher level may be chosen for persons with special needs (children, elderly persons, etc). Lower levels do not necessarily cause health risks but decrease comfort perception. In these new standard proposals, about IEQ categorization of IAQ, three different methods are considered: method based on perceived air quality, method using criteria for pollutant concentration and method based on pre-defined ventilation air flow rate (only for mechanical ventilation). In the first method, used in this paper, the total ventilation rate $q_{tot}$ to define the required minimum ventilation rate of each category is calculated as the sum of a quota depending from occupancy and a quota related to dilution exigency of indoor pollutants in building by the following formula:

$$q_{tot} = n \cdot q_p + A_R \cdot q_B \tag{1}$$

where $n$ is the number of persons in the room, $q_p$ is the ventilation rate per person, $A_R$ is the floor area and $q_B$ the ventilation rate to dilute the pollutant emissions from building. The coefficients $q_p$ and $q_B$ for each IEQ category are provided by prEN 16798-1 (prEN 16798–1, 2017) in Table I1 and I2 of annex I. The IEQ classification can be obtained by considering the average I/O difference of $CO_2$ concentration levels as proposed in Table I4 of annex I of prEN 16789-1.

None of the cited standards shows a consistent and clear strategy about ventilation flow rate design that refers directly and meets medical requirements. As a result, guidelines are needed to define the health-based ventilation rates in a systematic way. To extend the current air quality guidelines (WHO, 2005), in 2010 the World Health Organization (WHO, 2010) issued specific guidelines for indoor air quality covering nine pollutants: carbon monoxide, nitrogen dioxide, benzene, trichlorethylene, tetrachlorethylene, formaldehyde, naphthalene, polycyclic aromatic hydrocarbons (PAHs) and radon (WHO, 2009). Substances included in these guidelines are common indoor pollutants, but they are only some of hundreds chemical substances that can be identified in indoor space. The list is therefore not exhaustive. The Directive 2008/50/EC (European Parliament; European Council, 2008) of the European Parliament establishes annual target values for the concentration of As, Cd, Ni and Pb determined in $PM_{10}$ monitored in ambient air so as to avoid, prevent or reduce harmful effects of these substances.

## 3. Method

### 3.1. Monitoring mode

An experimental campaign was carried on in a primary school located near Treviso in North Italy, during winter period from 29th January to 24th March 2018 (eight weeks). Natural ventilation by manual airing and only heating by radiators characterize the HVAC system of this school. The indoor measurements were performed in four classrooms named 1A, 3A, 3E, 4B respectively. The tests lasted two weeks for each classroom and were in succession from 29th January to 23rd March. Simultaneous outdoor samplings were collected by the installation of instruments on the flat roof of the building. All the classrooms have similar features as concerning shape, dimensions, design occupancy, type and dimension of the windows. The school is open from Monday to Friday. Only in two days, different for each classroom, there are lessons in the afternoon. Dimensions and occupancy characteristics of these four classrooms are reported in Table 1.

The presence of electronic boards in the classrooms has strongly reduced chalk and markers usage.

The monitoring was performed by using various instruments. Two Testo model 435-2 devices, equipped with IAQ probes able to measure simultaneously temperature, relative humidity and $CO_2$ concentration, were installed for I/O measurements. As regards $CO_2$ measurement accuracy of the IAQ probes, non dispersive infrared (NDIR) sensors were used for the $CO_2$ concentration with an accuracy ± 50 ppm ± 2% of the measure value until 5000 ppm.

Same way, the I/O PM was measured by two airborne particle counters GrayWolf PC-3016A which also calculated directly mass concentrations in μg/$m^3$ for various PM sizes including $PM_{0.5}$, $PM_1$ and $PM_{2.5}$, $PM_5$, $PM_{10}$. As concerns accuracy, counting efficiency is 50% for particles with diameter > 0.3 μm and becomes 100% for particles > 0.45 μm (per ISO 21501-4). At the beginning of

**Table 1**
Characteristics of the classrooms.

| Classroom | 1A | 3A | 3E | 4B |
|---|---|---|---|---|
| Surface ($m^2$) | 45.6 | 44.2 | 45.5 | 45.5 |
| Height (m) | 3 | 3.2 | 3 | 3 |
| Volume ($m^3$) | 136.8 | 141.4 | 136.5 | 136.5 |
| Pupils (female/male) | 7/9 | 12/8 | 11/14 | 15/10 |
| Volume per person ($m^3$/pers) | 8.05 | 6.73 | 5.25 | 5.25 |
| Nominal occupancy (pers/$m^2$) | 0.37 | 0.48 | 0.57 | 0.57 |

experimental campaign, the instruments were calibrated making a comparison with the gravimetric method which is the reference method for particle mass concentration measurements. Some gravimetric samples provided 24-h average $PM_{10}$ levels which confirmed this calculation with a correlation value $R^2$ of 0.848.

At the same time, a IAQ monitor mod. Yes Air-A+ with four gas sensors was used to verify the possible presence of internal sources of pollutants as Carbon Monoxide (CO), Formaldehyde ($CH_2O$), Ozone ($O_3$) and Total Volatile Organic Compound (TVOC). Indoor sensors were always installed on a desk, at a height of 80 cm from the floor, distant from windows or doors and in a central position in the classroom. All the data were recorded every 10 min.

### 3.2. Air change per hour (ACH) calculation

Ventilation flow rate and consequently ACH were assessed by a simple balance on carbon dioxide concentration in the volume *V* of the classroom taking into account inside generation rate due to attendance and the $CO_2$ flow rate exchanged with the outdoor. If *ACH* is known, Eq. (2) calculates the indoor $CO_2$ concentration *C(t)* after a time step *t* by using the measures of initial indoor $CO_2$ concentration $C_0$, outdoor $CO_2$ concentration $C_{ext}$. Internal $CO_2$ production *G* is estimated 0.0025 l/s for male pupils, 0.0023 for female pupils and 0.0024 l/s for female teachers considering a sedentary activity (met 1) (Persily and de Jonge, 2017):

$$C(t) = C_{ext} + \frac{G\cdot 10^6}{(ACH\cdot V)/3600} - \left(C_{ext} - C_0 + \frac{G\cdot 10^6}{(ACH\cdot V)/3600}\right)\cdot e^{-ACH.\ t/3600} \tag{2}$$

On the other hand, Eq. (2) can be used in an iterative procedure to calculate *ACH* by fixing tentative values of *ACH* until convergence on a measured value of *C(t)*.

### 3.3. Risk assessment

The risk level caused by the contaminants present in the $PM_{10}$ was evaluated for the pupils attending the monitored school rooms. The analysis considered the chemicals monitored outdoor in the same period near the school by the regional environmental agency ARPAV as required on the basis of the recommendations of CEN (European Parliament; European Council, 2008) and in detail some heavy metals (As, Cd, Ni, Pb) and PAHs. Carcinogenic and non-carcinogenic effects of these contaminants were considered separately by using different indexes and in detail the Hazard Index (*HI*) for non carcinogenic and the total Cancer Risk ($CR_t$) for carcinogenic effects. Only inhalation of pollutants presented in particulate matter ($PM_{10}$) was considered in this analysis.

#### 3.3.1. Hazard Index (HI) evaluation

In accordance with standard U.S.EPA (NATA U.S. EPA, 2014) the cumulative *HI* is the sum of the $HQ_i$ of all considered chemicals with non-carcinogenic effects. The *HI* and $HQ_i$ of the i-th contaminant are calculated as in the following equation:

$$\mathrm{HI} = \sum_i HQ_i = \sum_i \frac{ADI_i}{RfD_i} \tag{3}$$

where for the i-th contaminant, $ADI_i$, average daily intake, is the estimated daily dose the receptor is exposed to, in this case for inhalation route, and $RfD_i$ is the reference dose i.e. the dose that is believed to be without effect. As shown in eq. (4), $ADI_i$ is the product of the specific exposure rate *E* and the concentration $C_i$ of the i-th contaminant of the air breathed.

$$ADI_i = E\cdot C_i \tag{4}$$

*E* is calculated by eq. (5) where *IR* is the inhalation rate of the individual (0.7 $m^3$/h), *ED* is the exposure duration (6 years), *AT* is the averaging time (365 day/year x *ED* for non-carcinogens). This values are derived from (U.S.EPA, 1989; 2009, 2011). *ET* is the current exposure time per day provided by monitoring. *EF* is the exposure frequency i.e. in this case the official school days which in Italy are 200. *BW* is the body weight for 6–10 aged pupils obtained from Zoppi et al. (1996) as function of the students' gender.

$$E = \frac{IR\cdot ET\cdot EF\cdot ED}{BW\cdot AT} \tag{5}$$

The daily mean concentration $C_i$ in the air breathed in the classroom is calculated by assuming for the $PM_{10}$ measured inside school rooms the same chemical composition of the outdoor $PM_{10}$ monitored by ARPAV in the same period near the school building. It means that the production of the contaminants considered in this analysis is only outdoor (traffic, industry, etc) and negligible inside the classrooms. This fact was confirmed by the Yes Air instrument measurements relative to the indoor source contaminants more probable inside schools. This way, the trend in the concentration of a contaminant in the air breathed depends only by the indoor $PM_{10}$ variation with respect to the outdoor value. Therefore the daily mean concentration $C_i$ can be calculated as in the following equation:

$$C_i = \frac{C_{ref_i}}{PM_{10ref}}\cdot PM_{10day} \tag{6}$$

where $C_{ref_i}$ is the concentration of i-th contaminant in the outdoor mean $PM_{10ref}$ measured by ARPAV and $PM_{10day}$ is the daily mean $PM_{10}$ inside the classroom. $Rfd_i$ derived from the reference concentration $Rfc_i$ by eq. (7) where *AR* is the absorption rate (100%):

$$Rfd_i = \frac{Rfc_i\cdot IR\cdot AR}{BW\cdot 100} \tag{7}$$

The values assumed for the various parameters used in the equations derived from U.S.EPA (U.S.EPA, 2018) and are reported in Table 2. Values of *HI* above unity indicate greater levels of concern for potential non-cancer effects (NATA U.S. EPA, 2014).

#### 3.3.2. Cancer risk (CR) evaluation

For carcinogenic chemicals, a Cancer Risk (*CR*) was used which quantifies the probability of cancer occurring in the exposed population over 70-year lifetime (U.S.EPA, 2009). In this paper this index was applied to assess the harmfulness of each monitored day by projecting the cancer effect over a time horizon of 70 years. Of course, this is not an estimation of the actual *CR* of the pupils over their whole life. But this procedure is frequently used to compare the toxicity of different indoor air conditions even if monitored for limited exposure periods (Lee et al., 2006; Liao and Chiang, 2006; Lu et al., 2014).

**Table 2**
$RFC_i$ and *IUR* values from USEPA data base, concentration $Cref_i$ measured by ARPAV and threshold values $C_{lim}$ from directive 2008/50/EC for the pollutants considered in this assessment.

| I-th pollutant | $RFC_i$ ($mg/m^3$) | $IUR_i$ $(\mu g/m^3)^{-1}$ | $C_{refi}$ ($ng/m^3$) | $C_{lim}$ ($ng/m^3$) |
|---|---|---|---|---|
| Arsenicum (As) | $1.5\ 10^{-5}$ | $4.3\ 10^{-3}$ | 0.7 | 6.0 |
| Cadmium (Cd) | $1\ 10^{-5}$ | $1.8\ 10^{-3}$ | 0.5 | 5.0 |
| Nichel (Ni) | $9\ 10^{-5}$ | $2.4\ 10^{-4}$ | 10.1 | 20.0 |
| Lead (Pb) | $1.5\ 10^{-4}$ | – | 8.7 | 500.0 |
| Benzo[a]pyrene (BaP) | $2\ 10^{-6}$ | $6\ 10^{-4}$ | 1.9 | 1.0 |
| Benzo[b]fluoranthene (BpFA) | – | $6\ 10^{-5}$ | 1.9 | – |
| Benzo[k]fluoranthene (BkFA) | – | $6\ 10^{-5}$ | 0.9 | – |
| Benzo[a]Anthracene (BaA) | – | $6\ 10^{-5}$ | 0.8 | – |
| Dibenzo[ah]Anthracene (DBahA) | – | $6\ 10^{-4}$ | 0.1 | – |
| Chrysene (CHR) | – | $6\ 10^{-7}$ | 1.5 | – |
| Indeno [1,2,3-c,d]pyrene (IP) | – | $6\ 10^{-5}$ | 1.5 | – |

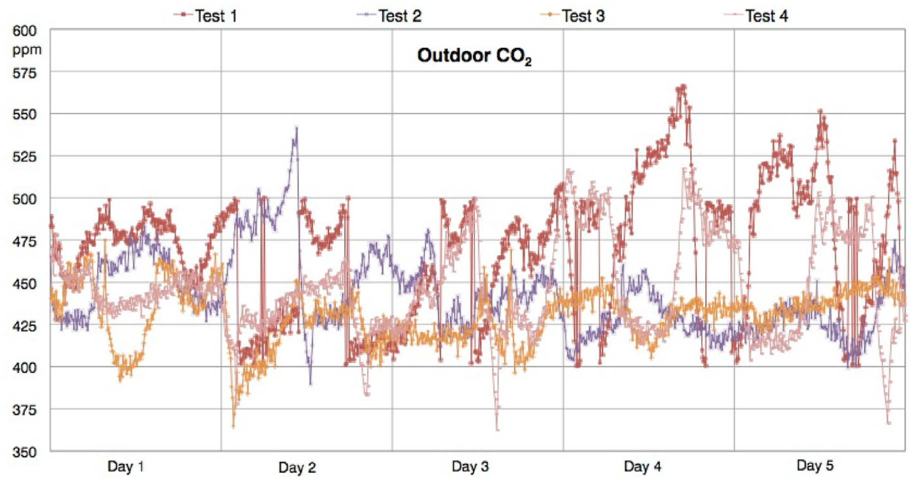


**Fig. 1.** Outdoor $CO_2$ trends measured during one work week for each test.

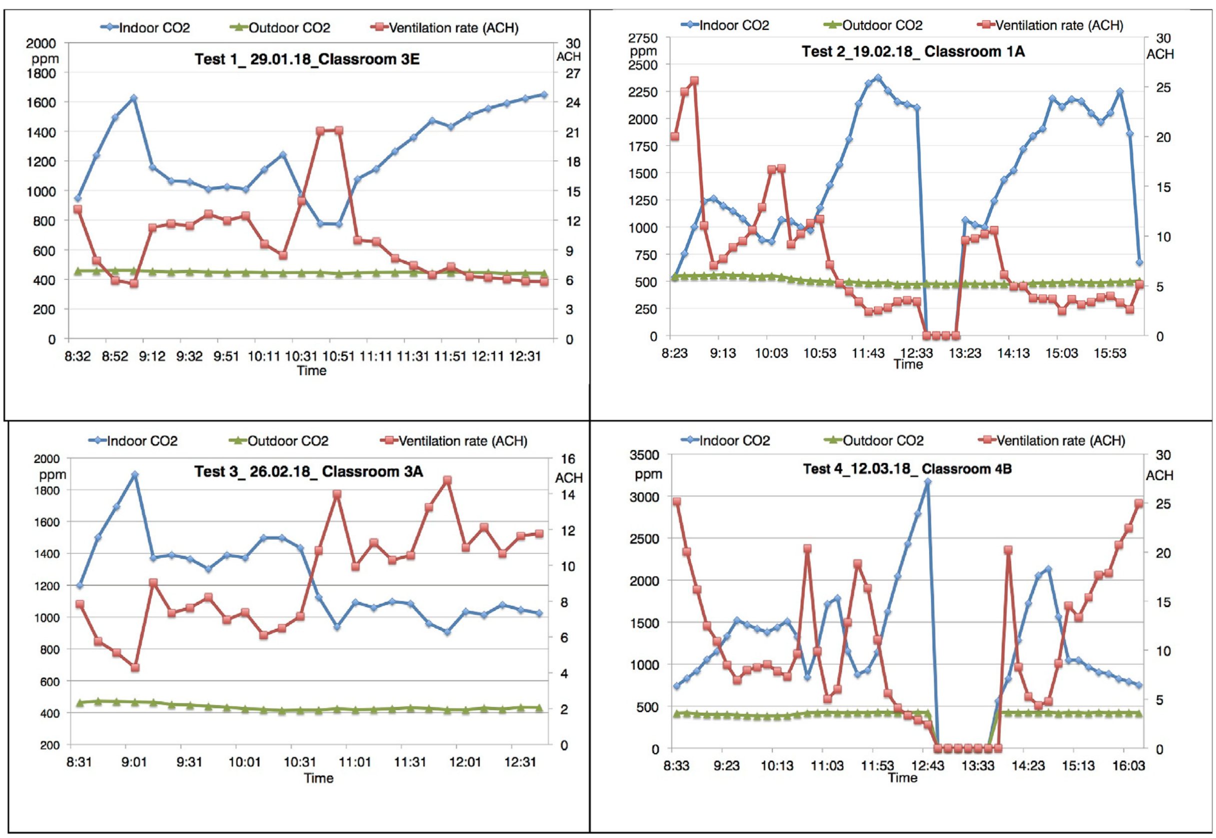


**Fig. 2.** I/O $CO_2$ concentrations and corresponding ACH trends calculated by eq. (2) in the hours of. occupation in one day for each test.

**Table 3**
ACH, ventilation per person and I/O $CO_2$ average values during the hours of occupancy for the four tests. Consequent Indoor Environmental Quality category classification calculated by prEN 16789 is also reported.

| | Test 1 classroom 3E 29.01.-10.02 | Test 2 classroom 1A 12.02–24.02 | Test 3 classroom 3A 26.02–10.03 | Test 4 classroom 4B 12.03–24.03 |
|---|---|---|---|---|
| Average ACH | 12.3 | 16.6 | 8.3 | 9.8 |
| Average ventilation (l/s) | 155.4 | 203.4 | 104.9 | 123.7 |
| Average ventilation per person (l/s/p) | 9.1 | 9.7 | 4.1 | 4.8 |
| Average indoor $CO_2$ (ppm) | 1326 | 987 | 1695 | 1617 |
| Average outdoor $CO_2$ (ppm) | 523 | 433 | 421 | 418 |
| Average $CO_2$ I/O difference (ppm) | 803 | 564 | 1274 | 1199 |
| Indoor Environmental Quality (IEQ) category | II(Medium) | II (Medium) | IV (Low) | III (Moderate) |

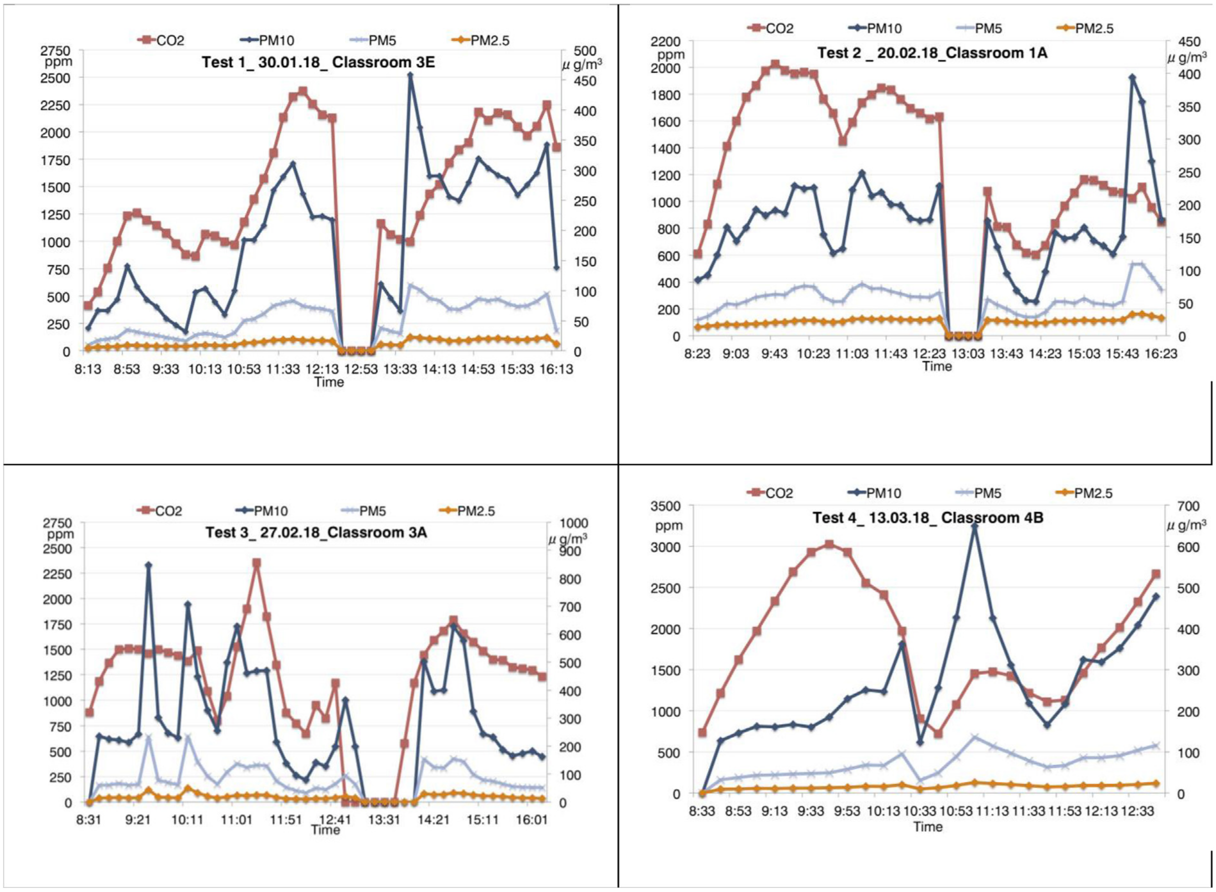


**Fig. 3.** Trends of $CO_2$ concentrations and $PM_{2.5}$, $PM_5$, $PM_{10}$ levels during the occupancy hours in one day for each test.

**Table 4**
Indoor and outdoor $PM_{2.5}$, $PM_5$ and $PM_{10}$ averages (µg/m$^3$) measured during the hours of occupancy for the four tests. The corresponding average I/O ratios are also reported.

| | Test 1 classroom 3E 29.01.-10.02 | Test 2 classroom 1A 12.02–24.02 | Test 3 classroom 3A 26.02–10.03 | Test 4 classroom 4B 12.03–24.03 |
|---|---|---|---|---|
| Indoor $PM_{10}$ | 168 | 184 | 388 | 234 |
| Indoor $PM_5$ | 52 | 51 | 117 | 63 |
| Indoor $PM2._5$ | 16.9 | 29.7 | 24.8 | |
| Outdoor $PM_{10}$ | 19 | 37 | 35 | 11 |
| Outdoor $PM_5$ | 16 | 32 | 16 | 9 |
| Outdoor $PM2._5$ | 14,8 | 33.5 | 13.5 | 7.2 |
| I/O $PM_{10}$ | 11.8 | 5.0 | 11.1 | 20.9 |
| I/O $PM_5$ | 4.9 | 1.6 | 7.1 | 7.3 |
| I/O $PM2._5$ | 1.15 | 0.9 | 1.8 | 2.2 |

For the inhalation route of exposure, the total Cancer Risk ($CR_t$) is the sum of the $CR_i$ calculated for each i-th pollutant presented in the air breathed as in the following equation:

$$CR_t = \sum_i CR_i = \sum_i (LDI_i \cdot CSF_i) \tag{8}$$

where the Lifetime Daily Intake $LDI_i$ is the dose of i-th contaminant the individual is exposed to over a lifetime of 70 years. It is evaluated as:

$$LDI_i = E \cdot C_1 \tag{9}$$

where $E$ and $C_i$ are calculated again as in eqs. (5) and (6) where for carcinogens here $AT$ is 365 day/year x 70 years (U.S.EPA, 1989). The Cancer Slope Factor $CSF_i$ is an estimate of the carcinogenic potential of the i-th chemical for causing cancer. It is calculated by eq. (10) on the basis of the Inhalation Unit Risk $IUR_i$:

$$CSF_i = \frac{IUR_i \cdot BW \cdot 1000}{IR} \tag{10}$$

Also for $CR$ calculation, the values of the various parameters assumed in the equations are reported in Table 2 (U.S.EPA, 2018). $CR$ measures the excess of cancer risk due to the exposure to the contaminants considered with respect to the background risk i.e. the cancer risk normally estimated for a variety of causes. Environmental agencies normally use acceptable $CR$ levels in the range from $10^{-6}$ to $10^{-4}$. A $CR$ equal to $10^{-4}$ means that there is a risk of one additional occurrence of cancer in ten thousand people at a given exposure assumption if compared to an unexposed population.

Normally the limit of $10^{-6}$ is used for individual chemicals while for cumulative cancer risk $CR_t$ of all potential carcinogenic contaminants the maximum acceptable value is $10^{-4}$. However, in this analysis we have considered only the contaminants in $PM_{10}$ controlled as required by directive 2008/50/EC. Therefore, we have prudently assumed $10^{-6}$ as maximum acceptability limit.

## 4. Discussion of the results

As regards indoor monitoring of Carbon Monoxide, Formaldehyde, Ozone and TVOC, only weak traces of these gases were found in the four classrooms, with concentrations strongly inferior to the limits considered by current standards. Therefore their presence was not analyzed in this study being considered negligible.

In Fig. 1 the trends of the outside $CO_2$ concentration measured for 1 week day are reported for each of the four tests carried on. During the whole monitoring campaign the maximum $CO_2$ value recorded (during test 1) was 566 ppm while the minimum one (during test 4) was

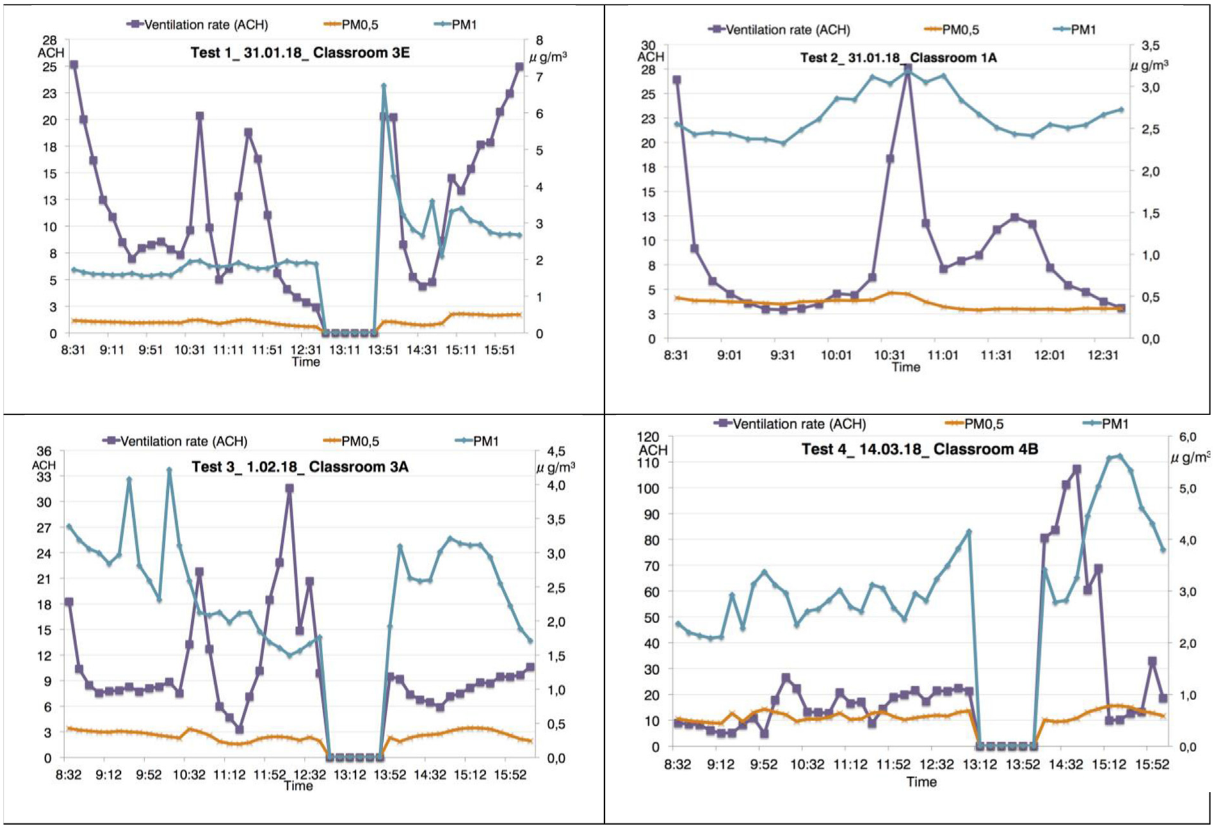


**Fig. 4.** Trends of ventilation rates (ACH) and $PM_{0.5}$, $PM_1$ levels during the occupancy hours in one day for each test.

**Table 5**
Indoor and outdoor $PM_{0.5}$ and $PM_1$ averages (μg/m$^3$) measured during the hours of occupancy for the four tests. The I/O ratios are also reported.

| | Test 1 classroom 3E 29.01.-10.02 | Test 2 classroom 1A 12.02–24.02 | Test 3 classroom 3A 26.02–10.03 | Test 4 classroom 4B 12.03–24.03 |
|---|---|---|---|---|
| Indoor $PM_1$ | 5.0 | 4.4 | 2.4 | 2.9 |
| Indoor $PM_{0.5}$ | 0.8 | 0.6 | 0.2 | 0.5 |
| Outdoor $PM_1$ | 8.1 | 16.1 | 2.8 | 3.6 |
| Outdoor $PM_{0.5}$ | 1.1 | 1.1 | 0.4 | 0.6 |
| I/O $PM_1$ | 0.8 | 0.3 | 0.8 | 0.8 |
| I/O $PM_{0.5}$ | 0.8 | 0.6 | 0.5 | 0.8 |

363 ppm.

The high variability of the values confirms the necessity to use actual value of the outside $CO_2$ concentration in the calculation of ACH by eq. (2) instead of daily or monthly averages.

By way of example, Fig. 2 shows the trends of indoor and outdoor $CO_2$ measured and the corresponding ACH calculated by eq. (2) in the school hours of four days, one day for each test period. In Fig. 2 the time intervals when the students were out of the classroom are identified by the reset of the values reported.

In Fig. 2, as concerns outdoor $CO_2$, the minimum value is 383 ppm (test 4), the maximum value is 560 ppm (test 2) and therefore also considering only the school hour range, $CO_2$ variability indicates the necessity to use measured values instead of reference averages. The calculated ACH is subject to strong oscillations which however result realistic and coherent with the trend of the indoor $CO_2$ measured. The analysis highlights the effect on ACH and inside $CO_2$ level of probable unexpected opening of windows or doors and variation of occupancy density. Therefore, the use of eq. (2) as predictive model for $CO_2$ trend calculation on the basis of an estimated average of ACH appears an unreliable procedure in such a context.

In Table 3 the average values of ACH obtained from the ACH trends calculated by eq. (2) and consequent ventilation rates during the hours of occupancy are showed for the four tests. Corresponding I/O $CO_2$ levels measured are also reported. The classification in terms of IEQ category is obtained as proposed by prEN 16,789 on the basis of ventilation rate compared with the four minimum required ventilation rates of the IEQ categories calculated for each classroom by eq. (1). However the same classification outcomes are obtained referring to the average I/O differences of $CO_2$ concentration.

Fig. 3 shows the trends of $CO_2$ concentrations and $PM_{2.5}$, $PM_5$ and $PM_{10}$ levels measured during the school hours in one day for each test. Indoor coarse particulate concentration is clearly influenced by the resuspension caused by the activity of the pupils.

In fact high values of indoor $PM_5$ and $PM_{10}$ are normally contemporaneous to the increment of $CO_2$ levels caused by a full occupancy. In addition the particulate concentration peaks are in correspondance with interval periods, lesson change (normally every one or 2 h) and exit from the classroom. Lunch breaks are clearly detectable by the reset of reported values when all students are out of the classroom.

Normal activity in a classroom is frontal lesson with pupils sitting at the desks therefore it is a sedentary activity only interrupted by intervals and lesson changes which caused resuspension. These effects result strongly reduced for $PM_{2.5}$. As just highlighted above, this is in accordance with the results from other authors (Blondeau et al., 2005; Poupard et al., 2005). Which emphasize the importance of occupant's movement and of a reduced ventilation in the indoor particulate level. Even a reduced activity can have a remarkable impact on airborne particles with diameters greater than 5 μm. During the monitoring campaign the mass of coarse fraction was sometimes incremented by almost 100%. On the contrary, particles smaller than 2.5 μm resulted more slowly resuspended. $PM_{2.5}$ trend showed rarely a modest

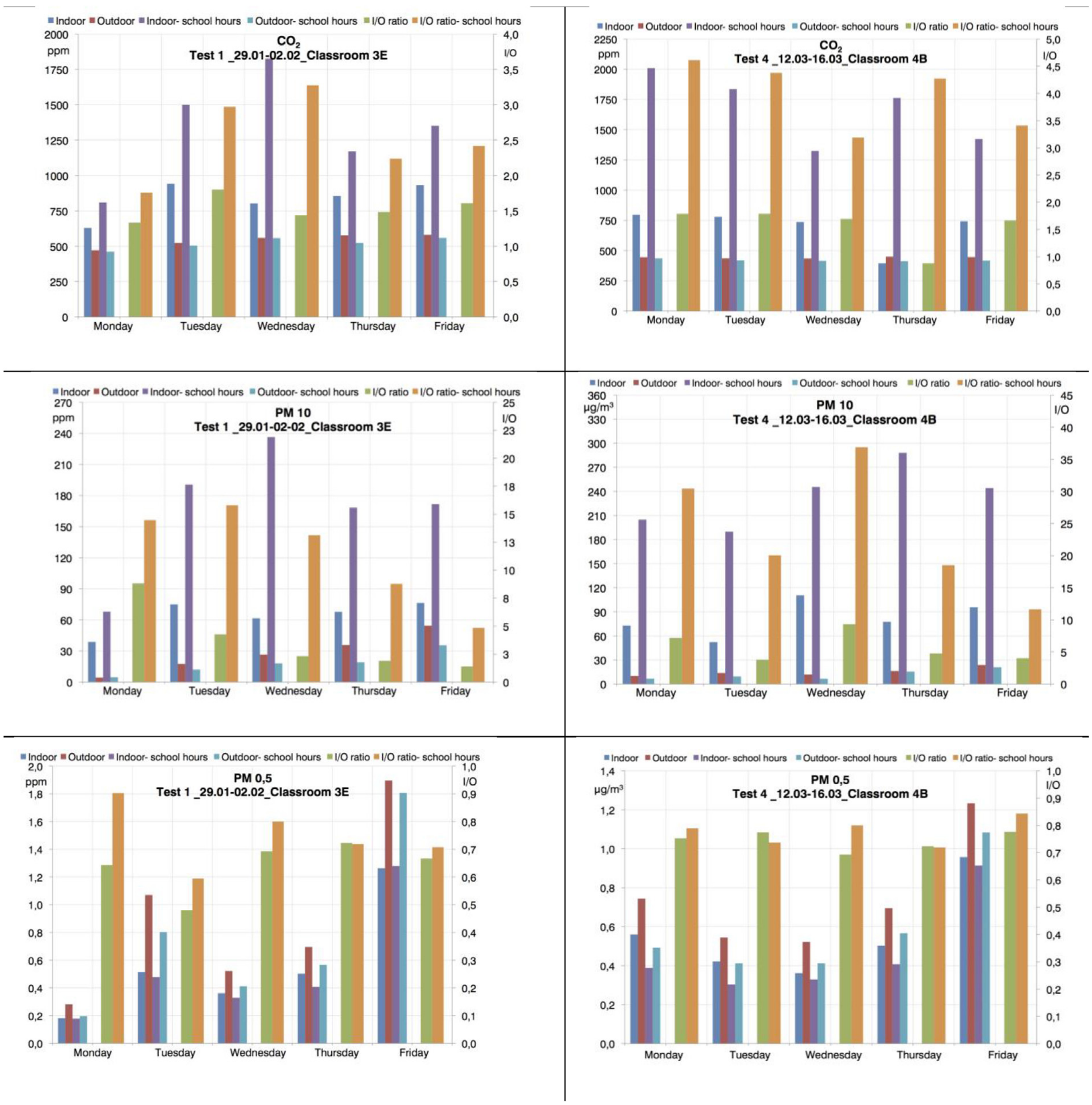


**Fig. 5.** Daily averages of $CO_2$ levels, $PM_{0.5}$ and $PM_{10}$ during a week for tests 1 and 4 in the whole day or in the occupancy hours only. Corresponding I/O ratios are also reported.

correspondance with the peaks of the coarse particulate.

Due to resuspension, indoor $PM_5$ and $PM_{10}$ values are strongly incremented with respect to outdoor value. This effect can be observed in Table 4 where are reported the mean values of indoor and outdoor $PM_{2.5}$, $PM_5$ and $PM_{10}$ and the corresponding average I/O ratios referred to the occupancy hours for the whole period of each tests. The modest influence on $PM_{2.5}$ is again evident.

Fig. 4 shows the trends of $PM_{0.5}$ and $PM_1$ levels for the occupancy hours of one day for each test. The corresponding ventilation rates calculated by eq. (2) are also reported. As expected, no significant variability caused by resuspension as in the case of $PM_5$ and $PM_{10}$ is now observed. Indoor submicron particulate concentration can be rather correlated to the variability of the ventilation rate. In fact outdoor submicron particle concentration is normally greater than the corresponding indoor concentration as its production depends only by outdoor factors (industry, traffic) and it is not influenced by activities inside the school environment. An increasing of ACH can involve an increment of indoor submicron particulate concentration especially in the moments when the external pollution reaches the top (Stabile et al., 2017). These considerations can be certainly applied to our case study as demonstrated by the average submicron particle concentrations reported in Table 5. In Table 5 the mean values of indoor and outdoor $PM_{0.5}$ and $PM_1$ and the corresponding average I/O ratios are reported referred to the occupancy hours for the whole period of each tests.

In Fig. 5 Indoor and outdoor daily averages of $CO_2$ concentrations, $PM_{10}$ and $PM_{0.5}$ during one week for tests 1 and 4 are reported together with the corresponding I/O ratios. The averages are referred to the whole day or only to the occupancy hours. The average $CO_2$ values are significantly variable also in the same classroom and week especially those referred to the occupancy period. In some days these values are below 1500 ppm and thus sometimes acceptable for the aforementioned standards while in the remaining days are above. This strong variability is therefore caused by human behaviour and demonstrates the difficulty to predict and manage natural airing. A possible solution is the installation in each classroom of a simple and cheap $CO_2$ meter to inform teacher about ventilation exigency. As concerns particulate, I/O ratios

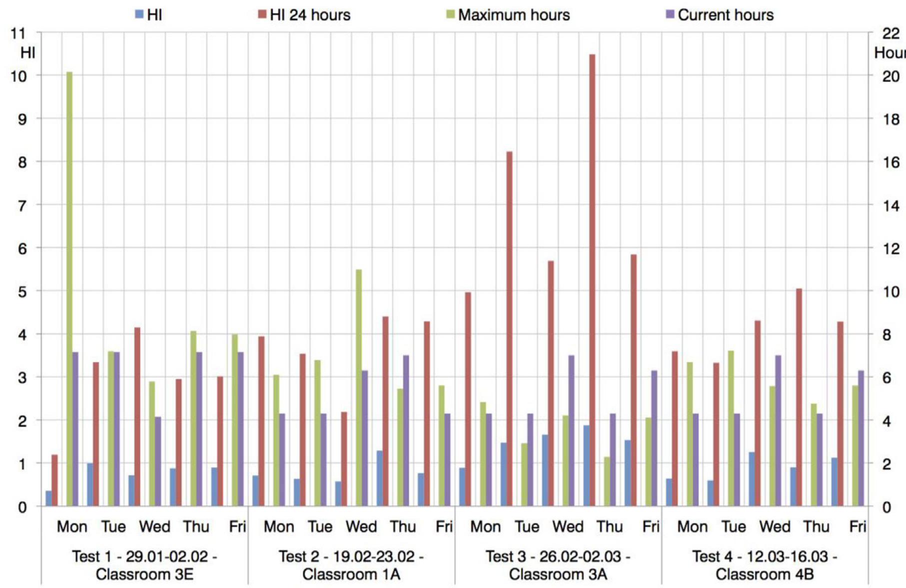


**Fig. 6.** *HI* and *HI*-24 h calculated for each school day of four weeks for the four tests. The acceptable maximum hours of exposure to the contaminants and the current school hours are also reported.

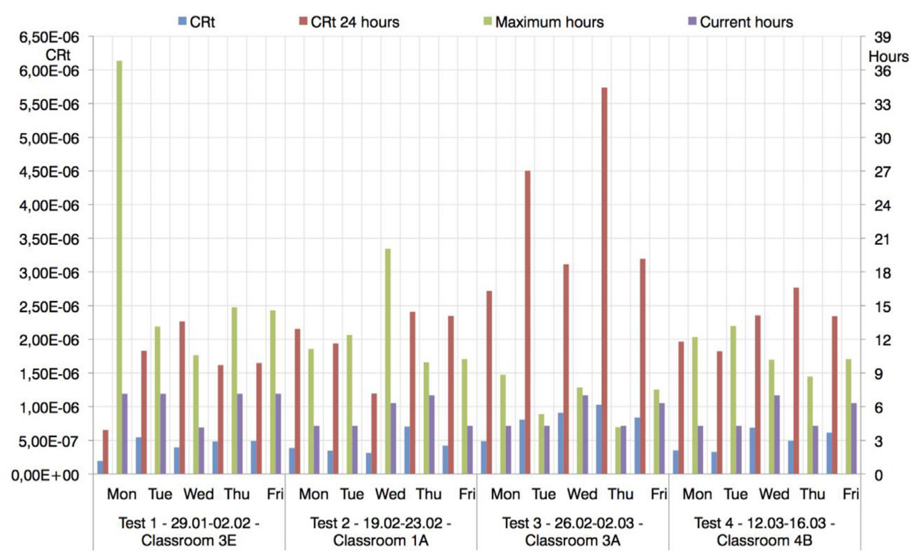


**Fig. 7.** $CR_t$ and $CR_t$-24 h calculated for each school day of four weeks for the four tests. The acceptable maximum hours of exposure to the contaminants and the current school hours are also reported.

result significantly variable day by day for $PM_{10}$, because, like $CO_2$ levels, indoor values are strongly influenced by human activity (re-suspension) and insufficient ventilation. Instead for $PM_{0.5}$ the I/O ratios are more stable because, in absence of internal sources of submicron particulate matter, they are influenced only by scarce airing. In this condition the building works as a barrier for outdoor submicron particles and I/O ratio can be considered as a penetration efficiency of the building (Stabile et al., 2017). Therefore a growing ventilation can reduce indoor $CO_2$ levels but at the same it increases the immission of outdoor generated submicron particulate.

Fig. 6 shows *HI* and *HI*-24 h calculated for each school day of four weeks for the four tests. *HI*-24 h is the *HI* calculated with the same pollution concentrations, but with an exposed period extended to the whole day. This value informs about the acceptability of this pollution level as daily level for children. The acceptable maximum hours of exposure to the contaminants and the current school hours are also reported in Fig. 6. Maximum hours inform about the maximum exposure period acceptable ($HI = 1$) with this pollution concentration. They must be compared with the current hours the children are in the classroom in that day. As concerns non acceptability ($HI > 1$) limited to the occupancy hours, tests 1 and 2 show results under the limit except one day in test 2, test 3 is unacceptable except one day and tests 4 presents discordant values.

Therefore by the comparison of these acceptability results with the categories expressed in Table 3 we can conclude that there is a clear correlation about a reduction of chemical contaminant exposure and a good IAQ expressed in term of reduced $CO_2$ levels achieved by an adequate ventilation as foreseen in prEN 16,798. However also in tests 1 and 2 we found *HI*-24 h greater than 1. It means that the acceptability depends by less pollution levels for the children during the remaining part of the day. Therefore, the ventilation demonstrates to be not completely satisfactory also in these cases. This acceptability is expressed more effectively by the comparison between the maximum hours of exposure without effect for the health and the current hours of exposure.

Fig. 7 shows the results of *CR* analysis presented in the same way of

Fig. 6. Only one day in test 3 presents a $CR_t$ value slightly higher than the acceptable limit of $10^{-6}$. In this event the maximum hours of exposure are 4.2 h rather than the current hours which were 4.3 h. However $CR_t$-24 h are normally higher than the limit and therefore the investigation indicates that this contaminant concentration is not acceptable for 24 h exposure and therefore the children must be exposed to less contaminant levels in the remaining part of the day practically in every day analyzed.

## 5. Conclusion

The continuous monitoring of the I/O $CO_2$ concentrations and indoor actual occupancy permitted to calculate the trends of ventilation rates in each classroom by a model based on $CO_2$ indoor balance. The outcomes highlighted the high variability of these ventilation rates caused by a human behaviour difficult to predict. Furthermore, the variability of outdoor $CO_2$ levels recommends to avoid the use of typical values suggested by technical literature. Consequently, a $CO_2$ based model results not suitable for predictive purpose. On the contrary, in existing naturally ventilated buildings this model can be used to classify the IEQ of the indoor environment by the ventilation rates calculated on the basis of the monitored $CO_2$ levels. As an example, in this study a IEQ classification of the classrooms was elaborated by using the recent proposal of fpEN 16,798. The simultaneous monitoring of PM and its consequent relationship with the calculated ventilation showed the necessity to introduce in IEQ evaluation also the presence of other possible indoor pollutions eventually present in addition to $CO_2$. In particular the relevant increment of I/O ratio of $PM_{10}$ raised the question of the health hazardous of the growth of the indoor concentration of pollutants brought by $PM_{10}$ with respect to the outside. This fundamental issue was dealt by proposing a simplified method to quantify the corresponding health risk. The method permits to estimate the risk even in absence of indoor measurements of these contaminants by using only particle counters. Here its application concerned heavy metals and PAHs because strongly considered by EU directives. In absence of internal sources of these contaminants, their indoor concentration increment can be related to the monitored variation of I/O ratio of $PM_{10}$. Therefore the Hazard Index and total Cancer Risk relative to the presence in $PM_{10}$ of these pollutants measured in proximity of the school by the environmental agency were calculated in the school environments on the basis of daily exposure of the children. The same procedure can be extended to other outdoor contaminants if monitored. In the studied school rooms the strong growing of indoor $PM_{10}$ with respect to the outdoor one did not cause an exceeding of the acceptable limit values for health risk due to these pollutants even if the daily school time exposure was often not acceptable if extended to 24 h.

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