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INDOOR/OUTDOOR CORRELATIONS REGARDING INDOOR AIR POLLUTION WITH PARTICULATE MATTER

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Abstract

This paper presents the results of a case study conducted between 2.04 and 24.04.2013 in order to establish the most relevant indicators that characterize the influence of outdoor air pollution, with particulate matter having a nominal diameter less than 2.5µm (PM2.5), on the quality of indoor air from a new building. The tests consisted in simultaneous determination of the daily average PM2.5 concentrations at four indoor sites and at one outside, nearby the building.
The average PM2.5 concentration was 38.41±7.4µg/m^3, but only 70% of the outdoor performed tests were above the daily limit of 35µg/m^3, set by the U.S. Environmental Protection Agency. The indoor air pollution with PM2.5 was lower than outdoor with an average concentration of 21.78±6.22 µg/m^3.
Both Pearson's statistical correlation analysis and linear regression analysis showed a good direct correlation between indoor and outdoor PM2.5 concentrations, the proper insulation of the building and the absence of major indoor sources of PM2.5 particles.
The results of this study demonstrated that for a new building the indoor/outdoor (I/O) ratio and infiltration factor (F_{in}) could give a correct estimation of the outdoor air pollution influence on the indoor air quality.
Further information could be provided by statistical correlation and linear regression analysis; the value of the intercept could be a good indicator of the presence of indoor sources.

*Keywords:*I/O ratio, indoor air, infiltration factor, penetration factor, PM2.5

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1. Introduction

Indoor Air Quality (IAQ) represents a broad interest area in the scientific field due to their effects on the quality of life and to the general health of population. The evolution of modern society induced major changes not only in Economics but also in different social areas of our lives, since we spend over 85% of the time indoors (Ioan and Ursu, 2012; Massey et al., 2012).

The recent studies showed the presence of a broader range as well as a higher concentration of chemical compounds found indoors compared to those detected outdoors (Uhde and Salthammer, 2007; Wolkoff et al., 1997).

Sources of indoor pollution include cooking, smoking, office activities (Adgate et al., 2007; Ren et al., 2006), use of cleaning products, general maintenance and decorating (Diodiu et al., 2016; Massey et al., 2013; Mentese et al., 2012; Ott and Siegmann, 2006; Uhde and Salthammer, 2007; Wolkoff et al., 1997), but the most important source of indoor pollutants is the outdoor air pollution, especially in urban areas (Kearney et al., 2011; Massey et al., 2012; Wolkoff et al., 1997). Among the pollutants identified in indoor air, a special attention is given to breathable particulate matter with a nominal diameter smaller than 2.5 µm (PM2.5). Due to their small size, these particulates can penetrate the pulmonary alveoli and may accumulate in the

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respiratory system generating serious cardiovascular, cerebrovascular and respiratory problems to the people working, studying or living in these conditions (Anderson et al., 2012; Oprea et al., 2017; Postolache et al., 2013; Zhang and Smith, 2003; Wolf et al., 2018).

The studies performed in schools and residential buildings revealed other aspects relating to indoor air quality such as the presence of metals (Dongarra et al., 2010; Kulshrestha et al., 2009; Mahima et al., 2013), polycyclic aromatic hydrocarbons (PAHs) and various organic compounds (Jedrychowski et al., 2007; Lewis et al., 1999; Ren et al., 2006; Ward et al., 2009) and microorganisms from human or animal hosts (Portnoy and Flappan, 2001) which could amplify the effects of indoor air pollution on human health.

To assess the impact of outdoor air pollution on indoor air quality, Chen and Zhao (2011) recommend taking into consideration the following indicators: I/O ratio, infiltration factor (F_{in}) and penetration factor (P), depending on the particular situation examined.

I/O ratio is the most used indicator for characterizing indoor air quality and the contribution of outdoor pollutants inside the building (Kliucininkas et al., 2014; Zorpas and Skouroupatis, 2016). To calculate the I/O ratio, is used Eq. (1):

$$I / O = Cin / Cout \quad (1)$$

where: C_{in} and C_{out} are the indoor and outdoor concentration of particles.

The infiltration factor ***(F_{in})*** is the equilibrium fraction of outdoor particles that penetrates indoors and remains suspended in the air; for particles, only air suspended particulate matter is taken into account, neglecting the deposits and the re-suspension phenomenon, compared with gas pollutants, which refer to the whole mass of pollutants that enter the building. This factor highlighted the contribution of the infiltration compared to the contribution of emissions from indoor sources.

The general formula of the infiltration factor is expressed by the Eq.(2):

$$Cin = FinCout + Cs \quad (2)$$

where: Cs is the concentration of pollutants from indoor sources.

Based on linear regression analysis, Hoek et al. (2008) estimated the infiltration factor value (F_{in}); therefore, the slope was interpreted as being the infiltration factor and the intercept, as the source of indoor particles.

It can be observed that, if no additional indoor emission sources exist, or if they are negligible compared to outdoor sources, the infiltration factor has the same value as the I/O ratio.

Penetration factor ***(P)*** is defined as the fraction of particulate matter infiltrated into the cracks and pores of a building. Tung et al. (1999) measured PM10 and determined its penetration factor in an office building using the Eq. (3):

$$Cin(t) = \left[Ci - \frac{S + aPVCout}{(a+K)V} \right] e^{-(a+K)t} + \frac{S + aPVCout}{(a+K)V} = \\ = \left[Ci - Cf \right] e^{-(a+K)t} + Cf \quad (3)$$

If $C_i = C_{in}$ *(t=0)* and $C_f = C_{in}$ *(t=∞)* when no additional indoor sources exist, the penetration factor is calculated using the Eq.(4):

$$P = \frac{(a+K)Cf}{aCout} \quad (4)$$

where: V is the room's volume, t represents the time, a is the exchange rate of the indoor air due to infiltration, P is the penetration factor, K is the rate of deposition and S is the rate of indoor emission sources. All parameters with the exception of V and a, are functions characterized by two variables: time and particle size.

Currently statistical analysis data by Pearson's correlation and linear regression could provide additional information about the impact of outdoor air pollution on indoor air quality.

The article presents a case study developed in a new building in order to establish the most useful indicators involved in detection of pollution sources and determination of their contribution to indoor air quality, referring to PM2.5 indoor pollution.

2. Case study

The case study performed between 2.04 and 24.04.2013 took place in a new building with five floors from Bucharest's outskirts, the largest industrial and commercial urban center of Romania. Although in recent years industrial activities constantly declined, Bucharest ranks among the most polluted capitals of Europe (Pascal et al., 2013).

The road traffic is an important air pollution source with particulate matter, NO_2, SO_2, CO, heavy metals, PAH as well as other organic compounds (Cheng et al., 2010; Querol et al., 2007; Singh et al., 2018). The old auto park (58% from total cars are older than 10 years), which is mostly using fossil fuels such as gas and diesel (more than 94% of cars), as well as the increased road traffic generate together a significant amount of pollutants which could seriously affect the health of Bucharest's approximately 1,800,000 inhabitants (Polichetti et al., 2009; Trasande and Thurston, 2005).

The recent studies conducted in major cities with a heavy road traffic have revealed that an important part of the particulate matter from the air was comprised by PM2.5 particles, generated mainly by combustion processes and by the road traffic in particular (Cheng et al., 2010; Khan et al., 2010). The concentration of PM2.5 particulate matter is considered an indicator of the air pollution level in urban areas, due to its effects on human health (Adgate et al., 2007; Jedrychowski et al., 2007).

The present study was conducted inside and outside a new building located on a residential area (away from industrialized sites), called Giulesti Sarbi, belonging to North-West of Bucharest's outskirts. The road traffic in this area is reduced toward North-West Bucharest's exit direction compared other Bucharest's exits.

The building did not have a central air recirculation system, so the indoor air quality is provided by natural ventilation. For this reason, the tests were conducted at a time of the year when the windows were opened for less than 10% of the time, due to low outdoor temperature.

2.1. Tests conducted in the case study

During the 23 days of the test, PM2.5 samples were collected from both inside and outside of the building which was located in an area characterized by low traffic and with no major sources of industrial pollution.

Four rooms were selected to determine the PM2.5 concentration inside the buildingby taking into consideration various parameters such us room size, height from the ground level (the floor) and the number of people present or transiting the room as well as their activities inside the rooms (Table 1.).

The entrance represented a transit area during entering or exiting the building. In addition, the entrance had a buffer area to prevent the loss of heat. Most of the time the entrance area was populated by a single person, with the exception of 15-30 min during the beginning and the closing working time when this particular area was transited by all the people working in the building. The natural ventilation was achieved by opening the doors during the exiting or entering the building.

E3-13 and E1-23 were two rooms functioning as offices. In E3-13 office there were six people working (occupancy of 6.5 occupants/100m^3) and their main activity was writing and printing documents on two printing machines. The ventilation was realized by opening the windows. On the opposite, there was a single person from E1-23 office without any related equipment and the ventilation was realized indirectly thru the adjacent office room.

E3-22 is the weighing room equipped with 4 balances. The presence in this room was very scarce and it was estimated to be about 2 hours /day for one person. The ventilation was realized by opening the window. Due to the activities held in this room the dust was removed 2-3 times per day by washing the floor. In all other rooms the cleaning was performed only once per day at the end of the working day.

Inside the building, the sample collection point was placed in the middle of the room at 1.5m from the sol. Outside sampling point was placed on a area with small vegetation, at 20m from the building and from the street (Fig. 1). The obtained data of a PM2.5 concentration indoor and outdoor were used to calculate I/O ratio, infiltration factor (F_{in}) as well as other indicators used to identify the sources of air pollution and to evaluate the indoor air quality. Moreover, the penetration factor (P) detected was negligible due to the fact that this study was conducted in a new building.

2.2. Analytical methods and statistical tests

The PM2.5 concentration was determined by gravimetric method according to EN 14907:2006. The particles were retained on cellulose esters filters Ø47mm (Millipore, type: 0.8µm, white AAWP) using LECKEL SVEN Ingenieurbüro GmbH samplers. Daily samples were taken at a flow rate of 2.3m^3/h.

Before and after sample collections, the filters were conditioned for 48 hours in a climatic chamber (Memmert, HPP 108) in stable temperature (20±0.5°C) and relative humidity (50±5%), then weighed with an analytical balance AG 135 (Mettler-Toledo GmbH, Greifensee, Switzerland) with 0.01mg resolution. The weight gain of the filters represented the mass of PM2.5 from the volume of air sample; the concentration of PM2.5, expressed in µg/m^3, was determined by dividing the mass of particles, in µg, to the volume of air sample, in m^3.

For the quality assurance of the test results, only calibrated equipments were used; daily, the analytical balance was calibrated by using standards weights and the flow rate of the samplers were calibrated weekly by using Defender 510-M flow calibrator. AnalyseIt software for statistical interpretation of data was used to Pearson's correlation coefficient, **r**, calculation and for linear regression analysis.

Table 1. The constructive and functionality proprieties of the rooms tested inside the building

Room	***Activities, equipments***	***Floor***	***V, (m^3)***	***Number of persons***	***Occupancy, occupants/100m^3***
Entrance	Reception, transit, double door, reduced ventilation;	P	58	1	1.7
Office E3-13	Office activities/ 6 computers, 2 copy machines	3	92	6	6.5
Office E1-23	Office activities, natural indirect ventilation / no equipment	1	40	1	2.5
Weighing room, E3-22	Weighing /4 balances	3	27	0.25*	0.9

***** *it has been estimated for one person in the room, 2 hours/day*

Fig. 1. The sampling site

3. Results and discussion

In order to assess indoor air quality, it may be taken into consideration: (i) age of the building, (ii) blueprint of the building, (iii) ventilation system, (iv) outdoor air pollution with particulate matter, (v) type of activities performed indoor, (vi) occupancy degree as well as other specific factors (Adgate et al., 2007; Kearney et al., 2011; Massey et al., 2012; Ward et al., 2009). Characterization of indoor air quality was based on the pollutant concentration as well as on the identification of the pollution sources and on the control of the pollutant emission. Generally, it has been acknowledged two major sources of indoor air pollution: (i) the outdoor pollution which penetrate indoor and (ii) the indoor sources due mainly to the type of activities and the presence of the building personnel.

In order to characterize the influence of outdoor pollution on indoor air quality, Chen and Zhao (2011) recommended taking into consideration the I/O ratio, infiltration factor (F_{in}) and penetration factor *(P)* and, for the identification of the indoor sources, the intercept value, obtained by the linear regression analysis of the outdoor and indoor concentration of particulate matter. As it was mention before, the penetration phenomenon as well as the penetration factor was negligible.

3.1. Indoor and outdoor particulate matter PM2.5 concentrations

In the Table 2 are presented the data collected from indoor and outdoor air monitoring as well as the values of standard deviation, maximum and minimum values of particulate matter concentrations and I/O ratio. The PM2.5 concentration outdoor, determined during 2.04-24.04.2013, was of 38.41±7.4μg/m^3 which is above the daily limit value of 35μg/m^3, set by the U.S. Environmental Protection Agency (CRS, 2013). During the interval of time between 2.04 and 24.04.2013, in ambient air, 70% of the daily concentrations were above the limit value which indicates a significant pollution with PM2.5 (Fig. 2.). In spite of the fact that there were no significant industrial sites nearby the analyzed area and also the road traffic was reduced, there was a significant pollution degree in this area. We speculate that the air suspended particles were brought from the downtown by wind blowing towards NW direction.

The concentration of PM2.5 reached a maximum of 59.39μg/m^3 on the 17th of April 2013, day being characterized by strong winds and lack of rainfall. Recent studies (Gradon, 2009; Harrison et al., 2012; Nicholson, 1988) showed that the raised concentration of air suspended particles detected during this meteorological condition was linked to resuspension phenomenon of the particles. During the testing time PM2.5 concentration of the four rooms remained the same regardless of its outdoor concentrations (Fig. 2). Moreover, the I/O ratio was low in the rooms with a reduced number of personnel (E3-22 and E1-23), due to reduced ventilation by opening the windows, therefore a high degree of isolation from outdoor pollution. On the other hand, a higher concentration of pollution was detected in the rooms with high transit (entrance) and with more personnel (6 occupants in E3-13 room).

Interestingly, there were no reliable correlations between indoor and outdoor concentrations of PM2.5. These observations correlated with a high I/O ratio could be explained by the existence of some indoor sources of pollution which added to the outdoor sources. In order to determine the input of each indoor or outdoor source, we took into consideration the I/O ratio, infiltration factor (F_{in}) and the intercept value obtained by the linear regression analysis.

3.2. I/O ratio

I/O ratio, the most used indicator to assess the influence of outdoor air pollution to the indoor air quality (Chen and Zhao, 2011; Hoek et al., 2008; Jedrychowski et al., 2007) was calculated using the relation (1). In general, a value of I/O ratio smaller than 1 indicates no indoor sources of pollution and a value greater than 1 indicates the presence of indoor sources of pollution which will add to the outdoor sources. This rule applies to the building with natural ventilation or with mechanical ventilation without air refreshing or particles retention.

All our values obtained from the four rooms had a I/O ratio smaller than 1, which indicate, in this stage of evaluation, that there were no indoor sources and the major pollution sources were from outside the building (Table 2). The range of these values was between 0.28 (E1-23) to 0.82 (E3-13), so a more detailed analysis of the indoor factors involved in this variation of the concentration should be performed.

Table 2. Indoor and outdoor PM2.5 concentration

Sampling point/Period	*PM 2.5 mean, µg/m³*		*I/O ratio*
	outdoor	*indoor*	
Entrance/ 02-08.04.2013	38.64	23.36	0.62
Office E3-13/ 09-14.04.2013	34.39	28.04	0.82
Office E1-23/15-18.04.2013	48.81	12.21	0.28
Weighing room, E3-22/19-24.04.2013	36.92	18.75	0.54
mean, µg/m³	**38.41**	**21.78**	**0.59**
sd, µg/m³	7.4	6.22	
min, µg/m³	27.54	11.09	
max, µg/m³	59.39	35.31	

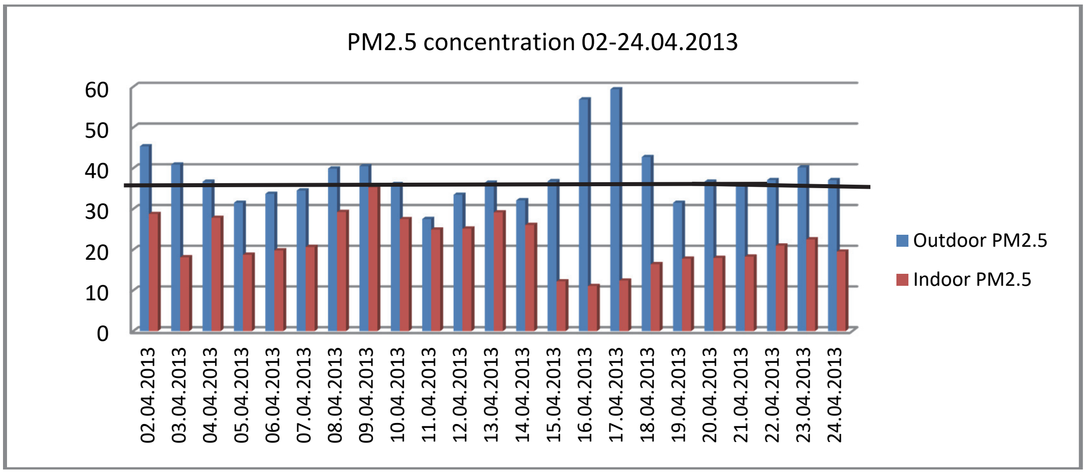


Fig. 2. Temporal variation of indoor and outdoor air PM2.5 concentrations compared with EPA daily limit value (35µg/m³)

3.3. The infiltration factor (F_{in})

The infiltration factor (F_{in}) is the equilibrium fraction of outdoor particles that penetrates indoors and remains suspended and it was determined by linear regression. According to Hoek et al. (2008), the slope was interpreted as being the infiltration factor and the intercept, as the source of indoor particles.

The results obtained by linear regression and Pearson's correlation: the values for Pearson's correlation coefficient, **r**, linear regression coefficient, $\mathbf{r^2}$, slope and intercept are presented in Table 3 and Fig. 3. In the same Table 3 there are also presented the difference between I/O ratio and F_{in} and were taken from Table 2, I/O ration, F_{in} and the occupancy,useful information for a proper interpretation of the data.

The I/O ratio and F_{in} values were very close in three out of four rooms (E3-22, E3-13 and Entrance). In the weighing room (E3-22), the difference between I/O ratio and F_{in} was of 0.005, which suggested the main pollution source was from outdoor and the indoor source was negligible.

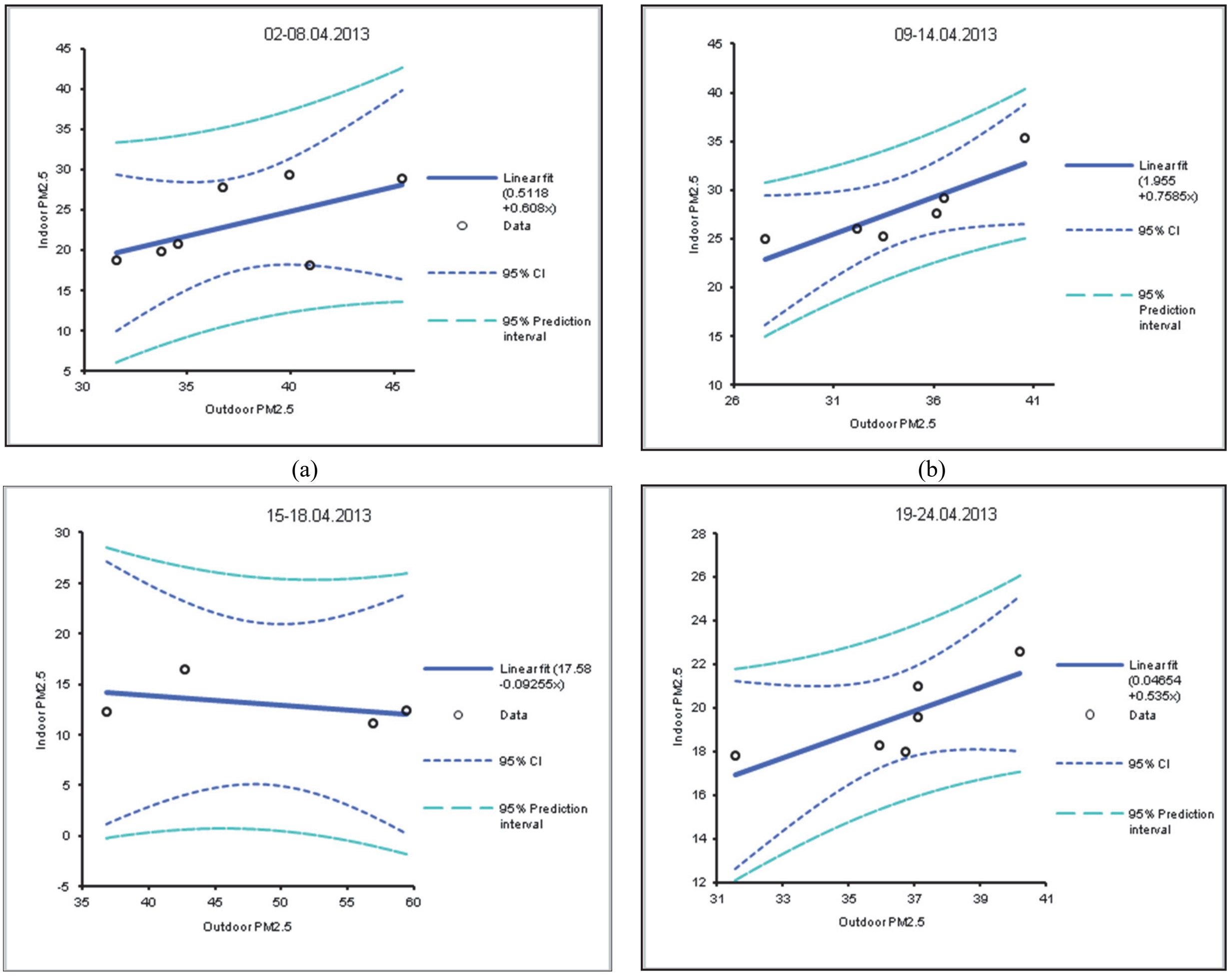
On the other hand, major differences between I/O ratio and F_{in} of 0.061 and 0.012 were detected in the room E3-13 and Entrance, respectively. This difference implied some indoor sources of pollution.

In the case of the office room E1-23, the small value for I/O ratio (0.28) as well as the negative value of F_{in} indicated an unusual data pattern, probably due to the particular type of construction (ventilation of the room was performed via the adjacent room). This particularity maintained constantly the air particle concentrations and regards less of the outside variations (Fig. 2, from 15.04 to 18.04.2013).

Values associated to I/O ratio and F_{in} are useful to characterized the effect of outdoor air pollution on indoor air quality as well as bringing new information about the possible indoor pollution sources.

Table 3. Pearson correlation and linear regression analysis results

Sampling room/Period	*Pearson correlation coefficient, r*	*Linear regression analysis*			*Occupancy, occupants/ 100m³*	*I/O*	*Differen ce between I/O and F_{in}*
		r^2	*Slope, F_{in}*	*Intercep t*			
Entrance/ 02-08.04.2013	0.58	0.34	0.608	0.512	1.7	0.62	0.012
Office E3-13/ 09-14.04.2013	0.86	0.74	0.759	1.955	6.5	0.82	0.061
Office E1-23/15-18.04.2013	-0.43	0.19	-0.093	17.58	2.5	0.28	-
Weighing room, E3-22/19-24.04.2013	0.79	0.62	0.535	0.047	0.9	0.54	0.005



(a) (b)

(c) (d)

Fig. 3. PM 2.5 indoor/outdoor Linear Regression Analysis curves for entrance (a), E3-13 (b), E1-23 (c) and E3-22 (d)

3.4. The value of intercept

The most information regarding indoor pollution sources were obtained by the value of the intercept from the linear regression analysis (Table 3). The highest values of the intercept were found in the room E3-13 (1.955) and Entrance (0.512), the same rooms where the values of difference between I/O ratio and F_{in} indicated the presence of some indoor pollution sources. The lowest value of intercept (0.047) was detected in the weighing room, were the value of the difference between I/O ratio and F_{in} was the lowest, too. In these conditions our hypothesis according to which the value of difference between the I/O Ratio and F_{in} can provide evidence for the existence of sources of indoor pollution is confirmed.

Regarding the identification of indoor sources, the transfer of particles from the personnel clothes and shoes to the rooms can be a potential source of particulate matter. Pearson's correlation coefficient value (r = 0.99) indicates a very good direct correlation between the intercept value and the occupancy (for Entrance, E3-13 and E3-22 rooms). More personnel inside the room generated more input from the indoor sources (Table 3), so the E3-13 office (6.5 occupants /100m^3) had the highest value of the intercept. Based on these results, we showed that the occupancy could be a good indicator of the possible internal pollution sources, too. Other possible internal sources could be the type of activities performed in the room, for instance, printing and copying of the documents.

Particles re-suspension in the air from the furniture and floor, induced by personnel circulation in the room, could be another important factor related to the indoor pollution (Gradon, 2009; Thatcher and Layton, 1995). A frequent dusting of the room minimizes the air particle concentration. On the opposite side, a deficient cleaning and maintenance of the air re-circulatory system is a source of pollution in the rooms. These possible issues could be avoided by a well-defined maintenance schedule of the air recycling. The values obtained in E1-23 for the intercept are due to inadequate ventilation and constructive peculiarities of the room.

*3.5. Pearson's corellation coeficient, **r***

The Pearson product-moment correlation coefficient is a measure of the strength of the linear relationship between two variables. It is referred to as Pearson's correlation or simply as the correlation coefficient (***r***). Pearson's ***r*** can range from -1 to 1. An ***r*** of -1 indicates a perfect negative linear relationship between variables, an ***r*** of 0 indicates no linear relationship between variables, and an ***r*** of 1 indicates a perfect positive linear relationship between variables. The degree of correlation between variables could be: (i) very weak if ***r*** ϵ [0;0.2], (ii)weak if ***r*** ϵ [0.2;0.4], (iii)moderate if ***r*** ϵ [0.4;0.6], (iv)good if ***r*** ϵ [0.6;0.8] and (v)very good if ***r*** ϵ [0.8;1].

Pearson correlation analysis of indoor and outdoor PM2.5 concentrations gives information about on the contribution of outdoor pollution on indoor air quality. Based on Pearson's corellation coeficient, ***r***, for all four rooms (Table 3.) we observed o very good correlation (r = 0.86) between outdoor and indoor of room E3-13, a good correlation (r = 0.79) for room E3-22 and an moderate correlation (r = 0.58) for the Entrance. One more time, the existence of other factors for E1-21 was determined based on Pearson's corellation.

A good correlation between outdoor and indoor is mainly based on the natural ventilation and on the low contribution of indoor sources; introducing a ventilation system for air refreshing and purification will enhance the indoor air quality and reduce the outside input inside the building. Since the outdoor PM2.5 concentration is often above the legal limit, the implementation of the above-mentioned improvements will be more than welcome.

Moreover, through the regression coefficient, $\mathbf{r^2}$, it can be determining the indoor percentage of particulate matter from the total concentration which is due to the intake from outdoor. On one side, for E3-13 around 74% of the particles amount originated in the outside sources, but on the other side, for the Entrance only 34% from the total air particles originated from outside.

4. Conclusions

The results of this study have shown the possibility of evaluating the indoor air pollution with particles based on indoor and outdoor monitoring.

By statistical analysis of data, it is possible to identify useful indicators involved in detection of pollution sources and determination of their contribution to indoor air quality, such as: (i) infiltration factor, F_{in}; (ii) Pearson's correlation coefficient; (iii) I/O ratio and (iv) value of the regression curve intercept.

The building design, type of ventilation and office activities as well as the occupancy, too, bring more information in evaluating the air quality of the building.

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