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Review

The Influence of Outdoor Particulate Matter $PM_{2.5}$ on Indoor Air Quality: The Implementation of a New Assessment Method

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Abstract: Epidemiological research has shown that there is a positive correlation between the incidence of disease and mortality in humans and the mass concentration of particulate matter. An average 1 g of suspended dust emitted in a room results in the same exposure as 1 kg emitted to the outside air. In this study, the authors described the state of knowledge on dust pollution inside and outside buildings (I/O ratios), and methods of testing the PM infiltration process parameters. According to the law of indoor–outdoor particle mass balance and the physical basis of aerosol penetration theory, a relatively simple but new method for estimating the penetration factor P was tested. On the basis of the curve of dynamic changes of internal dust concentration in the process of particle concentration decay and next of the followed curve of dynamic rebound of particle concentration, authors measured penetration factor of ambient $PM_{2.5}$ through building envelope. Authors modification of the method is to be used for determining the value of the particle deposition rate k not from the course of the characteristics in the transient state (the so-called particle concentration decay curves) but from the concentration rebound course, stimulated by natural particle infiltration process. Recognition measurements of the mass concentration of suspended $PM_{2.5}$ and PM_{10} particles inside the rooms were carried out. In this study, the choice of the prediction particle penetration factor P calculation method was supported by the exemplary calculation of the p value for a room polluted by $PM_{2.5}$. The preliminary results of the penetration factors determined by this method $P = 0.61$ are consistent with the P factor values from the literature obtained so far for this dimensional group of dusts.

Keywords: particulate matter; dust pollution; IAQ; indoor–outdoor concentration ratio; penetration factor; air quality control

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1. Introduction

The aim of the article is to present the authors' proposal for a new method of assessment of the influence of outdoor particulate matter $PM_{2.5}$ on indoor air quality indirectly by determining the value of the parameter that determines the intensity of dust penetration into the interior of the building. This parameter is the penetration factor, i.e., the ratio of the amount of dust entering from the outside, ending the infiltration processes, to the amount of dust retained outside.

In this study, the authors described the state of knowledge concerning dust pollution inside and outside buildings (I/O ratios), and methods of testing the PM infiltration process parameters. Methods known in the literature are based on the observation of the process of dynamic air pumping from a dusty external environment into a room with the use of an exhaust blower or an air cleaner. However, the process is not only dependent on the difference in PM concentration levels but more on the O/I air pressure difference produced. The authors' proposal includes the observation of the PM concentration rebound curve of the dust indoor concentration level increasing caused by the natural process of dust infiltration from the outside, to achieve dust balance in the exterior and interior of the building protected by a dust-permeable envelope.

The authors' field study aimed to estimate indoor air quality, especially particulate matter concentration in relation to the infiltration process through the buildings' envelope. Several analyses based on air quality measurements and calculation procedures were undertaken. On the basis of the curves of dynamic changes of internal dust concentration in the processes of particle concentration decay and next followed curves of dynamic change particle concentration rebound the authors proposed the method of estimating the value of the penetration factor of ambient $PM_{2.5}$ through a building envelope. Information on the value of the P factor can be a reliable parameter that classifies buildings in terms of resistance to dust infiltration into their interior, which partly characterizes the condition of the envelope structure and its resistance to dust penetration into the building. According to research in residential buildings, a large proportion of both groups of particles and their mass concentration are attributed to human activities such as cooking, smoking, vacuuming, gas stoves, the burning of solid fuels and candles, electrical appliances, cleaning, washing and walking. Both sources influence the characteristics of indoor particulate matter, and their concentrations are increased by the resuspension of particles deposited on internal surfaces in the air.

The term PM_{10} is used for particles with an aerodynamic diameter <10 µm. The term $PM_{2.5}$ defines aerodynamic particles with a diameter <2.5 µm. The coarse fraction contains particles with an aerodynamic diameter between 2.5 µm and 10 µm. The "ultrafine particles" fraction has an aerodynamic diameter <0.1 µm. A commonly used indicator describing particulate pollution is the mass concentration of PM_{10}.

Thatcher and Layton's [1] experiments concluded that PM > 5 µm may be resuspended, particles < 5 µm are not easily resuspended and particles < 1 µm show almost no tendency to re-suspend at high human activity.

In the project INDEX PM [2], it was demonstrated that indoor air PM dust pollution mainly consists of salt (ammonium sulphate, ammonium nitrate, sodium and potassium chloride), soot (elemental carbon, EC), minerals (silicon oxides, aluminium, calcium, iron, manganese, titanium, zinc, etc.), organic substances (shredded organic matter, also called organic carbon, OC) and materials of biological origin (bacteria and fungi, dandruff, pollen, fragments of plants and insects). All of these components have different particle size distributions and mechanisms, which are strongly dependent on particle size and are involved in removing particles from the indoor air. Sedimentation is the most important mechanism for the removal of coarse particles (>10 µm), diffusion and the agglomeration/coagulation of ultrafine particles (<0.1 µm).

Particles (0.1–1.0 µm) are most stable in air. A typical input fraction (fraction of the total PM mass emitted from the source that will be inhaled by the whole population) for an indoor PM source is 10^{-2} to 10^{-3}, compared to 10^{-5} to 10^{-6} for outdoor PM sources: An average 1g of suspended dust emitted in a room results in the same exposure as 1kg emitted to the outside air. Consequently, while internal sources are less efficient and their total emission loads are smaller than the PM of external sources, each of these sources, if present, may dominate both the sum of individual exposures and the inhalation risks of PM.

Between 1999 and 2016, the Canadian Census Health and Environment Cohort (CanCHEC) conducted panel studies involving approximately 2.5 million Canadians [3]. The relationship between non-accidental mortality and the concentration of fine particulate matter ($\leq$2.5 µm; $PM_{2.5}$), ozone (O_3) and nitrogen dioxide (NO_2) in the environment was investigated. Models with combinations of these contaminants have also been tested and $PM_{2.5}$ was found to be associated with an increased risk of non-accidental mortality, i.e., lung cancer, diabetes and ischemic heart disease. The results obtained provide evidence that long-term exposure to these three key components of ambient air pollution is associated with an increased risk of non-accidental mortality. Cumulative risk models suggest that exposure to $PM_{2.5}$ alone does not fully characterise the toxicity of a mixed atmosphere and cannot fully explain the mortality risks associated with exposure to environmental contamination. The strongest cumulative risk estimate is for mortality from diabetes (HR = 1.180; 95% CI: 1.125, 1.236). Assuming the additive exposure of individual pollutants, HR (Health Risk) in 95% CI (Confidence Interval), as estimated using three pollutant models showed that a change in exposure by an average of 5% for all three pollutants together resulted in impact synergies of 1.075. The effect of $PM_{2.5}$ and O_3 was weaker than the effect of NO_2 alone, but HR increased with the combination of all three pollutants, i.e., adding NO_2.

It has also been proved that the strongest correlation between $PM_{2.5}$ concentration and mortality increased by 1.5% when $PM_{2.5}$ concentration increased by 10 $\mu g/m^3$ per day [3], because particulate matter $<PM_{2.5}$ enters into the bloodstream.

The health effects of $PM_{2.5}$ were also studied by Hvelplund [4]. The Brownian motion of particles in the respiratory system is only visible for particles below 0.05 μm. The same tendency was found by Wang et al. [5], who investigated the deposition efficiency of particles with aerodynamic diameters between 0.001 and 300 μm moving through the nasal cavity with an air mass flow of 0.6 m^3/h. Studies in this area have shown that the lowest deposition efficiency is in the range of 0.015 to 10.0 μm due to the low influence of diffusion and the effects of impact and gravity settling.

The number of exhaled particles is debatable, e.g., most particles below 1.0 μm were predicted to escape through the bronchiolar orifices. It is not the case, however, that all particles escape because some of them are absorbed directly into the bloodstream through the bronchioles, which in human airways make up most of the levels of the tracheobronchial tree. Particles larger than 5–10 μm are usually removed from the upper respiratory tract, indicating that the mucosa and nasal hair contribute greatly to the filtration of particles.

According to [4], inhalation exposure to particulate pollutants is one of the main threats to public health. Most existing airway morphometry models are theoretical or semi-empirical in nature; they were designed to predict the deposition fraction for an averaged subgroup of the general population. It is difficult to tailor a quick and accurate prediction to suit individual needs.

Hvelplund et al. [4] aimed to analyse the local particle deposition along an anatomically reconstructed model of the airways, which was developed from computed tomography images of healthy subjects. Computational simulations of airway fluid dynamics show that most particles are deposited in the bronchi. The accumulation of particles (0.1–2.0 μm) is the smallest fraction, about 11%, of sediment in the lower respiratory tract. Increasing the aerodynamic diameter >2.0 μm of the particles increased the fraction of deposited particles. This study determined the size related to the site of particle deposition in the airways. It turned out that most of the particles in the studied bands are deposited in a narrow region of the airway model, such as the BC (bronchi) and larynx.

Already in the 1980s, many epidemiological studies had shown that $PM_{2.5}$ has obvious side effects on human health Lin et al. [6]. Research in China on the relationship between $PM_{2.5}$ and human health has fully demonstrated that $PM_{2.5}$ can increase the incidence of heart and lung disease, respiratory disease, cardiovascular disease, cancer and other diseases, and even the risk of death. Long-term exposure to environmental $PM_{2.5}$ may be an important risk factor for hypertension and is responsible for the significant burden of hypertension in adults in China, as it leads to a reduction in lung function. $PM_{2.5}$ is a risk factor for childhood asthma, attributed to decreased immunoregulation and deterioration in ventilation function. Exposure to $PM_{2.5}$ can also affect reproductive health.

The I/O indicator describing the temporary steady state of dust pollution in a building is related to the process of infiltration of suspended dust from the outside into the building's interior and can be described with the assumption that there are no internal sources generating dust particles:

$$\frac{\mathrm{I}}{\mathrm{O}} ratio = \frac{C_{in}}{C_{out}} \tag{1}$$

Lee et al. [7] found that room temperature and floor level (expressed by the story where the room is located in the building) are powerful I/O predictors and gave the I/O equation for $PM_{2.5}$, which is:

$$\frac{\mathrm{I}}{\mathrm{O}} = 0.629 + 0.0102 \cdot T - 0.00654 \cdot FL \tag{2}$$

where T and FL are temperature and floor level, respectively.

The indoor/outdoor (I/O) index is a measure for assessing the difference between the levels of indoor solid concentrations and the current outdoor concentrations, but it may be also recognised as an indicator of the persistence of particulate matter sources inside buildings.PM concentrations are affected by dust infiltration from the outside into buildings and internal sources. I/O ratios can vary considerably due to the building's design, location and the different activities of the occupants. The I/O ratio is also calculated to compare the dynamics of flows between indoor and outdoor PM in different apartments and buildings. As far as health protection is concerned, it is clearly the best when the I/O ratio for each dimensional fraction of dust is less than 1, asthisshows that the structural properties of a residential building reduce the penetration of PM from outside and, accordingly, reduce the residents' exposure to PM.

In epidemiological studies of external contamination, the concentration of external contaminants was previously used as an indicator of the stressor. Thus, the appropriateness of using suspended dust concentrations from the building surroundings as a proxy in personal exposure studies was questioned, and both outdoor and indoor concentrations began to be measured to investigate their correlation with external conditions, as well as the correlations among other pollutants. Positive correlations were found for PM, O_3 and NO_2.

While exposure to indoor air pollution changes under the influence of many factors, such as the type of microenvironment and the source of internal pollution, building characteristics and its location, ventilation parameters and assumed comfort conditions (Branco et al. [8]), as well as individual building occupant activity, studies have shown that only some of these factors are important. Therefore, several parameters of I/O interaction (Kalimeri et al. [9])were selected in order to minimise the error resulting from the use of concentrations in the external environment as a surrogate for estimating the exposure of the PM environment to humans indoors. These parameters are the infiltration coefficient (F_{inf}) (i.e., the equilibrium fraction of particles from the environment that have penetrated into the interior and remain suspended), the P coefficient of penetration efficiency of particles through the leaks of the building envelope (i.e., the fraction of particles that entered the interior from the infiltration path through the external walls of the building, $P < F_{inf}$) and the I/O ratio (the ratio of internal to external concentration of similar PM particles). Lv et al. [10] argued that regression analyses of the ratio of inside and outside particle concentration values confirm that the degree of correlation of changes in these concentrations expresses the infiltration coefficient.

Nadali et al. [11] found that coarse particles, e.g., PM_{10}, have higher falling velocities than fine PM, which leads to lower levels in rooms, because coarse particles (PM) settle under the influence of gravity or settle on doors, window frames and furniture as a result of the effects of electric charges and turbulent diffusion.

In their research, the concentration of solid particles, expressed by the average I/O ratio, also differed significantly in apartments, and did not solely depend on the location of the buildings. This was because, although the air with PM outside can have a significant impact on the concentrations inside, the composition of the air in the room is mostly influenced by the sources (activities and materials) in the rooms, which can be identified as contributing significantly to the internal mass concentration of PM.

Bai et al. [12] addressed the question why the I/O ratio is so important in practice. Everyday health is characterised by the equation of health detriment for each individual, based on an environmental risk assessment from the "receptor" perspective of

$$HHD_{i,j}^{inhalation} = C_{i,j} \cdot \left(\frac{IR \times t_j}{m} \right) \cdot EF \tag{3}$$

where C is the concentration of particulate matter (μg/m^3) with the indices: i = spring or summer or autumn or winter (1:1:1:1 annually), j = inside or outside (ratio 80:20), HHD is damage to human health t is the daily exposure time h, m is an I/O mixing ratio of 1, EF is an influence factor of 78 DALY/kg (or disease cases/kg of chemical intake), IR is the daily inhalation rate of air for each person, which is 13/24 (m^3/h).

In questionnaire studies [12], the daily ratio of the students' exposure time to air polluted with dust inside and outside was calculated, and the mixing coefficient m was determined (the same as the I/O ratio). Due to different daily $PM_{2.5}$ concentrations, health effects at different concentrations were calculated from Equation (3). The daily damage to the health of each person multiplied by the period of a year is the annual damage to the health of one person.

2. The State of Knowledge on Dust Pollution Inside and Outside Buildings

2.1. Characteristics of Actual Air Pollutants in the Internal Environment

According to the European programme INDEX-PM [2], the indoor air sources of PM are classified as:

1. PM from external sources transferred to the premises via ventilated or infiltrated air;
2. PM from external sources, transferred to the premises as settled dust and then re-suspended in the air in the room;
3. suspended dust from indoor combustion sources, such as tobacco smoke, cooking, candles or forest fires;
4. particles of biological origin; and finally;
5. particulate matter produced by indoor air chemistry, e.g., oxidation of cleaning ingredients (e.g., terpenes) by ozone.

Zhang and Duan [13] showed that burning a mosquito on a heating coil can release 626 μg/m^3 $PM_{2.5}$, which is 8.3 times the permissible concentration for a residential environment. Bai et al. [12] examined the concentration of $PM_{2.5}$ in households using coal for cooking and found that it was significantly higher than in households using gas or electricity, and if coal was switched to gas or electricity, the concentration of $PM_{2.5}$ in the kitchen would decrease by 40–70%. Zhang et al. [14] investigated different culinary habits, cooking methods, ingredients and even spices and found that they strongly influenced the composition of particulates. Culinary habits were also the subject of research by another group of researchers, Xue, Zhou et al. [15], who warn against the residential combustion of coal with a high sulphur content, as it can cause the total concentration of air pollutants to contain as much as 11.6% PM_{10} and even 27.5% SO_2 in the winter heating season.Zhou, Liu. [16] indicated that human activities such as walking, dressing and cleaning may increase the concentration of $PM_{2.5}$ indoors by 33%. Chinese researchers conducted experiments on the influence of wet sweeping and dry sweeping in the air in an office. The average levels of $PM_{2.5}$ concentrations in the rooms before cleaning were 47.3 μg/m^3, 40.6 μg/m^3 and 39.4 μg/m^3, respectively. The average levels of $PM_{2.5}$ concentrations inside the premises after cleaning were 109.7 μg/m^3, 97.5 μg/m^3 and 43.3 μg/m^3, respectively. The mean concentrations of $PM_{2.5}$ increased 2.3 times, 2.3 times and 1.1 times, respectively. Therefore, it is recommended to wet sweep as often as possible under ventilation conditions. Printing also plays a role in increasing indoor dust concentration, and the release of $PM_{2.5}$ from printers with different performance varied.

Some systematisation of the main sources of indoor air pollutants in our living environment is a necessary step to facing and reducing the associated health risks. Three different environments are described: Home, school and office, and the pollutants for the home, including particulate matter, are listed in Table 1. These were data published at the Healthy Building conference by Simeone et al. [17] supplemented by data from the literature.

Table 1. Indoor air pollution list based on [16–24].

Sources	**Contaminants**	
	Bedroom	**Office**
Furniture	Formaldehyde, VOC, allergens, mites, mould, particulate matter (sink effect)	Formaldehyde, VOC, allergens, mites, mould particulate matter (sink effect)
Walls, floorsand ceilings	Asbestos, formaldehyde, VOC, bacteria, mould, radon, particulate matter (sink effect)	Asbestos, formaldehyde, VOC, bacteria, mould, radon, particulate matter (sink effect)
Environmental tobacco smoke	CO, NO, benzene, formaldehyde, PAH, VOC, particulate matter etc.	CO, NO, benzene, formaldehyde, PAH, VOC, particulate matter etc.
Tapestry	Mites, mould, bacteria, formaldehyde, VOC, particulate matter	Mites, mould, bacteria, formaldehyde, VOC, particulate matter
Clothes (laundry)	Formaldehyde, VOC, PAH, mites, particulate matter	Formaldehyde, VOC, PAH, mites, particulate matter
Air conditioning	Mites, mould, allergens, particulate matter	Mites, mould, allergens, particulate matter
Candles, incenses and deodorants	CO, NO_2, SO_2, particulate matter, benzene, formaldehyde, PAH, VOC	
Personal care products (hairspray)	Aliphatic hydrocarbons, formaldehyde, VOC, acetone, benzene, particulate matter	
Cleaning products	Acetone, terpenes, aldehydes, 1-butanol, hexanal, ultrafine particulate matter	Acetone, terpenes, aldehydes, 1-butanol, hexanal, particulate matter
Cooking, boiling, frying, ovens, toasters *	Aldehydes, terpenes, xylenes, benzene, toluene, nonane, limonene	
Building products	Octanal, formaldehyde, acetaldehyde, benzaldehyde, particulate matter	Octanal, formaldehyde, acetaldehyde, benzaldehyde, particulate matter
Laserprint	O_3, formaldehyde, VOC, breathable particulate matter	O_3, formaldehyde, VOC, breathable particulate matter
Photocopiers		O_3, formaldehyde, VOC, carbon black, benzene, particulate matter
Pets	Allergens, mites, bacteria, fungi	
Outdoor environment	CO, NO_2, SO_2, particulate matter, O_3, pesti-cides, benzene, PAH, pollen, asbestos, noise, electromagnetic fields, radon	CO, NO_2, SO_2, particulate matter, O_3, pesti-cides, benzene, PAH, pollen, asbestos, noise, electromagnetic fields, radon

* Isaxon et al. [19] report the peak number concentration of ultrafine particles for these activities: cooking 1.80×10^5 p cm^{-3}, boiling 5.6×10^4 p cm^{-3}, frying 1.4×10^4 p cm^{-3}, oven 2.3×10^5 p cm^{-3}, toaster 1.6×10^5 p cm^{-3}.

According to Wallace and Ott [20], cooking on gas or electric stoves and electric toaster ovens was a major source of UFP, with peak personal exposures often exceeding 100,000 particles/cm^3 and estimated emission rates in the neighbourhood of 10^{12} particles/min.

He, Morawska and Gilbert [25] investigated submicrometric particle number concentration measured during the cooking test and found that it was in the size range from 0.015 to 0.685 µm.

Jantunen [18], in a study with multiple regression models using data collected from the EXPOLIS from six European cities, determined the internal concentrations of $PM_{2.5}$, starting from the concentration generated by smoking (16%), a gas cooker (1.4%), construction dust and a gas cooker (all < 4%).Smoking and cooking also generated NO_2 emissions. The research focused on the short-term effects of internal sources of PM, which are, e.g., different cooking methods generating concentrations of various solid particles in rooms, with peak concentrations of 30–60 μg/m^3 for $PM_{0.02–0.5}$ and 10–300 μg/m^3 for $PM_{0.7–10}$. Cleaning activities (8 μg/m^3 for $PM_{0.02–0.5}$ and 30 μg/m^3 for $PM_{0.7–10}$) and those related to the mobility of residents (4 μg/m^{3}for $PM_{0.02–0.5}$ and 20 μg/m^3 for $PM_{0.7–10}$) contributed much less. Oven roasting was the most intense source of $PM_{0.5}$ indoors, as well as frying (PM_{10}).

Morawska et al. [26] report that some types of activity of inhabitants result in particularly high concentrations of $PM_{2.5}$ in rooms. These include frying (median peak value: 745 μg/m^3), grilling (718 μg/m^3), candle evaporating eucalyptus oil (132 μg/m^3) and smoking (79 μg/m^3). The high maximum concentrations caused by these activities may result in the US EPA $PM_{2.5}$ standard being exceeded for 24 h at 65 μg/m^3 in homes where such activities are carried out, provided that the activity is carried out for more than 24 h.

The reported emission rate of 0.99 mg/min^{-1} from smoking is comparable with the results reported in the literature. For example, Klepeis et al. [27] measured the emissions factor of the respirable particle ($PM_{3.5}$) emitted in an apartment where smoking took place. It turned out that the average $PM_{3.5}$ emission index ranged from 0.98 mg/min^{-1} (cigar) to1.9 mg/min^{-1} (Marlboro cigarette). Brauer et al. [28] measured cigarette smoking using a nephelometer positioned in an environmental chamber and found that the emission rate of $PM_{2.5}$ particles was 1.67 mg/min^{-1}.

In a US indoor/outdoor air study, it was determined that smoking and cooking were the predominant activities associated with an elevated concentration of “fine particles”. Smoking can add 20 μg/m^{-3} (24 h average) of particles per household smoker [29] with short-term peaks of 300 μg/m^{-3} that may persist for up to 30 min after the cigarette is extinguished. Home cooking generated particles (0.1 μm) accounted for 30% of the particle volume [30]. The cooking method, and particularly frying, variably increased particle concentration, and the consensus states that the I/O ratios were somewhat higher in houses with gas cookers than in houses without such cookers and heating sources. Large particles (>2.5 μm in diameter) are generated in homes with activities such as home cleaning (vacuuming and sweeping) [30,31], which can lead to the re-suspension of particles embedded in horizontal surfaces such as floors, carpets and furniture. The ratio between indoor and outdoor particle concentrations gives an indication of whether particles found indoors are the result of indoor generation.

2.2. Limit Values for Indoor PM Concentrations

The data taken from the Health-Based Ventilation Guidelines: Principles and Framework, which were published in [32,33], can be considered as setting the latest limit values for the exposure of humans to indoor pollutants, see Table 2 The guidelines adopted the data from the WHO Air Quality Guidelines, Global Update 2005 published in 2006 by the Regional Office for Europe (Copenhagen) [34] concerning the most life-threatening pollutants NO_2, PM_{10}, $PM_{2.5}$ and O_3, but also SO_2, considered by some researchers to be an equally hazardous pollutant.

Table 2. Current air quality guidelines (figures in brackets indicate the average time for which the guideline values apply) [32,33].

Air Pollution [μg/m^3] / **Time of Exposure**	**NO_2**	**SO_2**	**PM_{10}**	**$PM_{2.5}$**	**O_3**
Short-term	200 (1 h)	500 (10min)	50 (24 h)	25 (24 h)	100 (8 h)
Long-term	40 (1 year)	20 (24h)	20 (1 year)	10 (1 year)	-

2.3. Characteristics of Actual Air Pollutants in the Outdoor Environment in Statistical Terms

Primary particles from the industry and agriculture are usually larger than 10 μm, and their share in primary PM emissions is usually lower than that of PM_{10} and $PM_{2.5}$. The same applies to non-road exhaust emissions from traffic sources (road, tyre and brake wear), which are a secondary source of particles smaller than 2.5 μm. Soot (BC–black coal) emissions mainly come from combustion processes in the transport sector (diesel vehicles) and from small domestic boilers The projected share in primary PM_{10} and $PM_{2.5}$ emissions in the EU (Poland and 14 other countries) was included in the basic scenario of the European CAFE programme (European Commission's Clean Air for Europe) implemented in the CAFE programme for 2020, as illustrated in Figure 1.

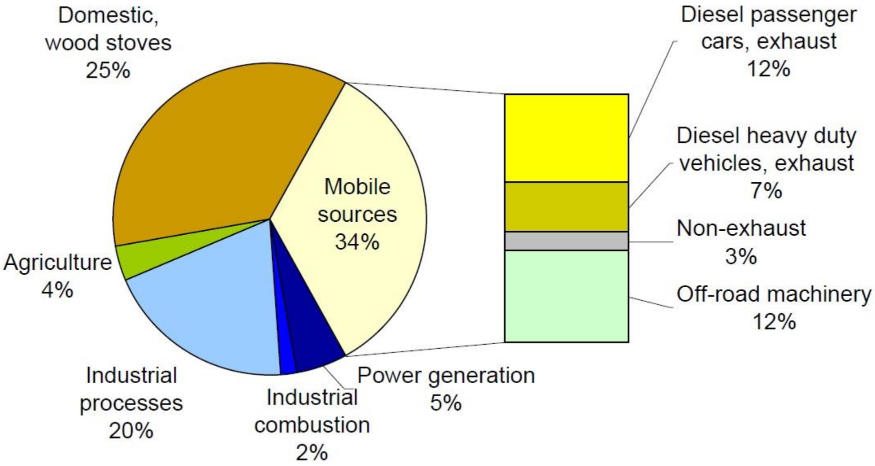


Figure 1. Sectoral emissions of $PM_{2.5}$ projected in the years 2000 to 2020 in the CAFE programme [35].

Overall, the CAFE baseline estimated that PM_{10} emissions were expected to decrease by around 40% in new Member States between 2000 and 2010. For 2020, it is planned that the sources of $PM_{2.5}$ emissions from diesel exhaust gases will drop from 12% to 6% and that the largest source of primary $PM_{2.5}$ emissions will reduce their emissions by 40%. On 21 November 2011, the European Commission took Poland to the European Court of Justice, accusing the country of lack of progress in the implementation of Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (CAFE).

According to the WHO recommendation, the standards of the average daily concentration of PM_{10} may not be exceeded more than 35 times a year. Unfortunately, in Poland, it happens that during the winter months, days when the concentration of suspended dust is within the norm can be counted on the fingers of one hand Samek [36]. In China, from the statistics of $PM_{2.5}$ and PM_{10} on the pollution levels of2015–2017, it was observed that the annual average of $PM_{2.5}$ mass concentration was decreased Wang [37]. In Shenyang, $PM_{2.5}$ decreased from 72 to 51 $\mu g/m^3$ and PM_{10} mass concentration decreased from 115 to 88 $\mu g/m^3$ Yu [38].

This has disastrous consequences for the health of the inhabitants of large cities (Figures 2 and 3).

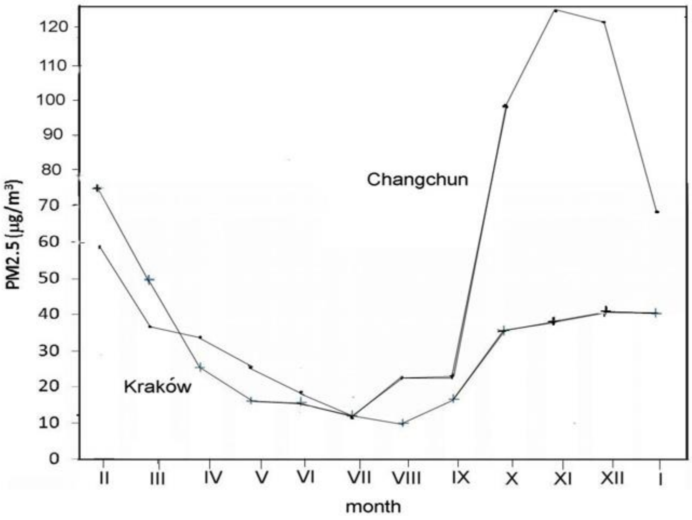


Figure 2. Measured by Samek et al. [36] average concentrations of $PM_{2.5}$ in µg/m^3 in Krakow (2014) and average concentrations of $PM_{2.5}$ in µg/m^3 measured in Changchun [12].

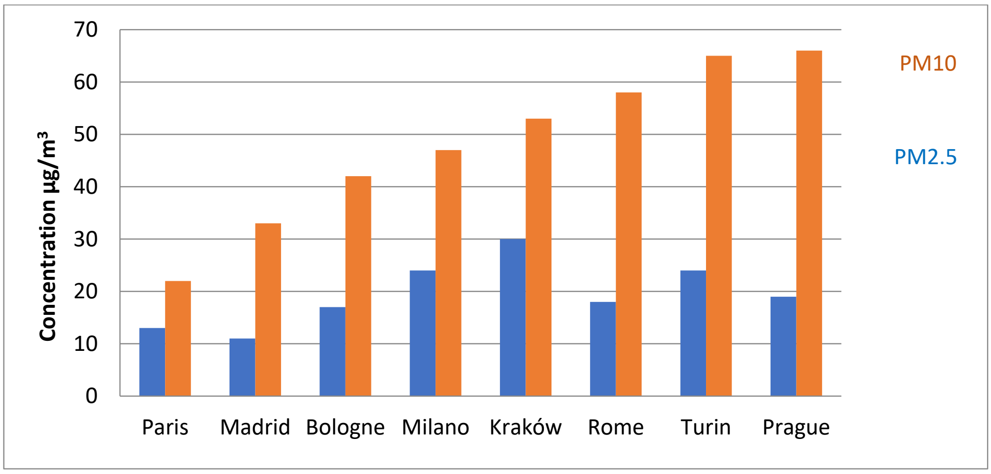


Figure 3. Average concentrations of suspended dust PM_{10} (red) in µg/m^3 measured in European cities in 2004 [39] and $PM_{2.5}$ (blue) in µg/m^3 observed in the same cities in 2016 [40].

The World Health Organization (WHO) has established specific standards for particulate matter concentrations in the outside air. Currently these are:

- the standard of the average daily concentration of PM_{10} dust: 50 µg/m^3;
- the standard of the average annual concentration of PM_{10} dust: 20 µg/m^3;
- the standard of the average daily concentration of $PM_{2.5}$ dust: 25 µg/m^3;
- the standard of the average annual concentration of $PM_{2.5}$ dust: 10 µg/m^3.

2.4. Research on Actual Dust Pollution of the External Environment in Polish Cities

The study was conducted in Warsaw as part of a project conducted by Juda-Rezler et al. [40] from the Warsaw University of Technology. The average concentration of $PM_{2.5}$ in Warsaw in 2016 was 18.8 µg/m^3 (measured with standard deviation ±11.9 µg/m^3), when the EU annual limit value for $PM_{2.5}$ was 25 µg/m^3; WHO's annual air quality (10 µg/m^3) was not met. PM pollutants in the atmospheric air differ in size and composition and according to an author [40], it is a mixture of primary sources (emitted from anthropogenic and natural sources) and secondary sources (formed in the atmosphere compounds as a result of the reaction of primary pollutants). The combustion of fossil fuels in the energy and smelting industry and the housing and road transport sector produces the most significant anthropogenic source of both solid and gaseous precursors of secondary particles, including sulphur dioxide (SO_2), nitrogen oxides (NOx) and volatile organic compounds (VOCs). Most of the particulate mixture in the atmospheric air are mineral dust organic matter, secondary inorganic aerosols (including nitrates, sulphates, and ammonia) and water. Many other components, however, are associated with PM, including micronutrients such as, for example, silicon (Si), magnesium (Mg), aluminium (Al), calcium (Ca), potassium (K), titanium (Ti) and trace metals including detrimental heavy metals, such as copper (Cu), arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb) and zinc (Zn). The chemical composition of particulate matter, as well as other PM characteristics, may vary widely in different areas.

According to researchers Samek et al. [36] from the AGH University of Science and Technology in Kraków, in industrial areas of Poland such as Silesia or urban areas such as Kraków and some other cities, the levels of pollution cleanings often exceed air quality standards. The dust masses (PM) are the most important component of atmosphere pollution. The research was carried out in 2014 with an extension to the 2015 heating season. During this period, approximately 200 samples were collected, showing a daily variability of $PM_{2.5}$ concentration in the air. The AGH University of Science and Technology team determined the lowest monthly concentration value for August 2014, amounting to about 10 $\mu g/m^3$, the highest for February 2014 (70 $\mu g/m^3$), while the annual mean value was approximately 31 $\mu g/m^3$. Additionally, the samples were analysed for content and particle size distribution. Research by the AGH team also included the determination of the black carbon content (BCN).

The team of Ścibor et al. [41] from the Jagiellonian University in Kraków conducted a study in 2014–2015 of the percentage of $PM_{2.5}$ dust in relation to the mass of PM_{10} dust indoors, with open and closed windows, and found that this share reached about 70% for both types of weather conditions: Good—at high wind speed; and bad—at low wind speed. The total share of PM_{10} and $PM_{2.5}$ dust masses penetrating into the interior of the rooms from the outside was higher by about 10% in good weather (high winds) than in bad weather. Opening the window had no significant effect here. Due to the lower degree of dilution and chemical transformations, and also with a larger number of occupants indoors, the impact of exposure per unit mass of $PM_{2.5}$ emitted in a room is two to three orders of magnitude greater than that of exposure from the same emissions in the outdoor environment.

The results obtained in Kraków by the Samek and Ścibor teams can be compared, for example, with the work of Morawska et al. [26] who studied the relationship between indoor/outdoor airborne particles in 16 localised residential homes in a suburb of Brisbane, Australia. By measuring the mass concentration of particles smaller than 2.5 μm, the Australian team showed that, while the periodic values of the I/O index varied widely from $PM_{0.2}$ to $PM_{2.5}$ with both less and more effective ventilation, their average I/O ranged from 1.01 to 1.08, so that the I/O ratios were much higher than in Kraków. Ścibor et al. [41] showed that the mean I/O values for PM_{10} and $PM_{2.5}$ were higher in the rooms when the windows were closed under bad weather conditions. In good weather conditions, the relationship was the same for PM_{10}, while for $PM_{2.5}$, opening the window increased the value of the I/O ratio.

The results for Kraków show that I/O values were significantly below 1, but the fact that indoor concentrations are much lower than outdoors should be juxtaposed with the concentration level situation in this city where there are much higher outdoor and indoor dust concentrations than in many other cities. Therefore, it can be assumed that in Kraków there are much larger amounts of PM dust migrating inside buildings.

In the case of Kraków, I/O values in good weather conditions were much higher (0.92 for cases with open windows and 0.79 for closed windows) than values in bad weather conditions (0.46 and 0.47, respectively), which was consistent with the results of the regression analysis. Indoor PM concentrations were then significantly lower than outdoors. High I/O values for $PM_{2.5}$ occurred in good weather, when the concentrations of

$PM_{2.5}$ indoors were two to four times higher than outdoors. The t-test showed that weather conditions and window opening are factors with a statistically significant impact on I/O.

2.5. Influence of Meteorological and Building Parameters on the Level of Indoor Dust Pollution

Weather conditions are considered to be the main factor influencing the quality of atmospheric air because of their role in dispersing, transforming and removing pollutants from the atmosphere. In urban environments, episodes of severe pollution are mainly caused by unfavourable weather conditions. Precipitation has a large impact on the concentration of particulate matter and washes away mainly coarse particles, but has little effect on changes in the concentration of fine particles. Therefore, atmospheric conditions are important for the level of indoor air pollution.

In a study on Hong Kong, Chan [42] has researched how changes in temperature, humidity, pressure, atmospheric stability, building insulation, wind, etc., influence constantly changing outdoor conditions and can modify the infiltration of outdoor air into a building in a built environment, regardless of which airflow systems one refers.

Chan [42] investigated the I/O ratios for respirable suspended particles (PM) and nitrogen oxides (NO_x) in various meteorological conditions. At higher outside temperatures, pollutants in the air are pushed inside through the doors and gaps in the windows, while the reverse is true for lower outside temperatures. This also explains the small slope of the relationship with the windows closed. Conversely, it has also been found that this effect is slightly more significant for the gaseous NO_x pollutant compared to the effect size for the particulate matter. This is because when the room is relatively well sealed, most of the air comes from the air conditioning vent, which effectively filters a large proportion of particulate matter but likely does not filter NO_x. Chan also noticed that in most cases the I/O for particulate matter was slightly lower than for NO_x, especially at higher temperatures. Overall, it can be seen that the I/O ratio for PM increases with increasing temperature (although at a slightly slower rate than for NO_2).

Chan [42] also investigated the dependence of the I/O index on relative air humidity. In general, the I/O ratio increased with increasing outdoor humidity, which explains the fact that both the PM and NO_x pollutants are readily absorbed or washed away by the water vapour in the atmosphere. Presumably, for the particulate form, this was of greater importance. The I/O ratios for PM increased slightly more for PM than for NO_x, which may confirm that the leaching effect to the outside of the building was more significant for PM than for NO_x.

The results of Chan's research were partially confirmed by Klaic et al. [43],who studied winter correlations between the spread of $PM_{1.0}$ dust indoors and outside weather conditions in Zagreb. Xu et al. [44] showed a decrease in PM_1 with a simultaneous increase in outdoor temperature, rainfall and horizontal wind speed, as well as an increase in indoor $PM_{1.0}$ concentration with increasing relative humidity outside the building.

The question of the correlation of the PM concentration level in interiors with humidity and rainfall outside of buildings posed the most doubts, as shown by further research. Zheng et al. [45], in Beijing, addressed this concern by demonstrating the obvious impact of precipitation on the removal of solid particles from atmospheric air. Researchers observed that the mean concentration of $PM_{2.5}$ decreased by 56.3% as a result of precipitation, and the mass concentration of $PM_{2.5}$ fell below 60 g/m^3 in 72 h after precipitation. Within one hour following rain, the $PM_{2.5}$ concentration level remained almost unchanged, but during the next 12 h it decreased. The large thickness of the mixed layer and the unstable structure of the atmospheric layers help to reduce the mass concentration of $PM_{2.5}$.

A different look at the existing correlations between the PM concentration in interiors and meteorological parameters is presented by a team of Iranian researchers in the article by Nadali et al. [11]. They built, like Klaic et al. [43], a symmetric linear correlation matrix in which they analysed the possibilities of correlation of C_{in} concentration with air temperature and relative humidity, as well as wind speed. Since these newer results were based on a large number of buildings and because they partially contradict earlier results, it is worth mentioning that the correlation coefficients (r) between the PM concentration in the interior and the parameters were as follows: With temperature the correlation is negative; with relative air humidity, however, the correlation is r = 0.07, which means that no significant relationship was observed between the concentrations of solid particles and air humidity. This problem merits further investigation.

The positive correlation between the concentration of solids and temperature may be caused by the impulse to the phenomenon of thermal diffusion. At higher temperatures, external PMs are forced into buildings through windows and gaps in doors, while the opposite is true at lower ambient temperatures. The results of Nadali et al. [11] confirmed the positive correlations between I/O ratios and wind speed.

The existing correlations between the indoor concentrations of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ in the parameters of a building were presented by Nadali et al. [11]. A symmetrical linear correlation matrix was built, which examined the possibilities of correlating the concentration of particles with a given particle diameter size (PM_{10}, $PM_{2.5}$ and $PM_{1.0}$), i.e., indoor concentration C_{in} with building parameters: Age of building, building type, number of windows, ventilation, indoor smoking and particles of other dimensions. A less significant correlation was found between the age of construction and the number of windows, ventilation and cigarette smoke in rooms, and more significant correlations ($p > 0.05$) between the concentrations of PM particles of different sizes.

2.6. Sources of Air Pollution by Particulate Matter (PMF Numerical Methods of Outdoor Sources Apportionment)

The first databases on separate sources of air pollution (outside) of buildings with PM_1 and $PM_{2.5}$ dusts were created in2014 by the World Health Organization. These data were organised and collected by Karagulian et al. [46].

In order to reduce the health impacts of air pollution, it is important to understand the sources of pollutants contributing to environmental exposure. This study systematically reviewed and analysed the distribution of available sources for particulate matter surveys (10 and 2.5 microns in diameter, PM_{10} and $PM_{2.5}$) performed in cities in order to estimate typical source contributions by country and region.

The percentage of separate sources of $PM_{2.5}$ and PM_{10} dust in the urban environment for the Central and Eastern Europe region per source category according to the World Bank's list of economies (2012) for Central and Eastern Europe, provided by [46], is shown in Figure 4.

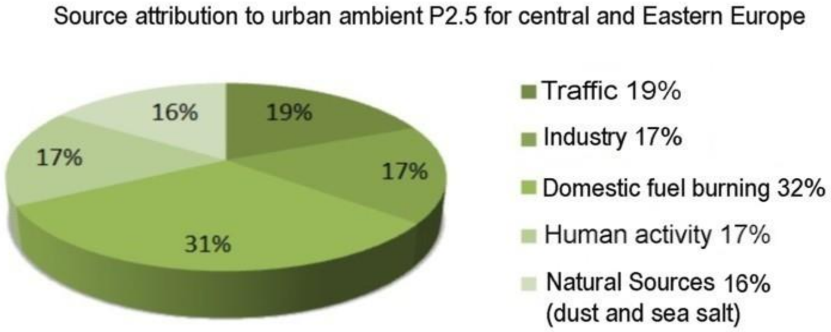


Figure 4. First source attribution to urban ambient particulate matter pollution by source category for Central and Eastern Europe according to [42].

The available records regarding the distribution of sources, however, show significant heterogeneity in the assessed source categories and incompleteness in some countries/regions.

In the years 2014–2017, receptor models tested using the PMF (Positive Factorised Matrices) method were increasingly used to isolate the sources of pollution in the outside air. The basis for the application of such a model by Samek et al. [36] in urban areas such as Kraków, where the levels of pollution often violate air quality standards, was the collection of measurement data on air pollution, especially $PM_{2.5}$, considered to be the most hazardous to health. In 2014, approximately 200 samples were collected.

The lowest monthly concentration values were found for August 2014—around 10 $\mu g/m^{-3}$.The highest was for February 2014—70 $\mu g/m^{-3}$—while the annual average value was around 31 $\mu g/m^{-3}$. Using the X-ray fluorescence method to test PM concentration, 15 elements were determined for each sample and eight inorganic ions were analysed by ion chromatography. Additionally, the samples were analysed for soot (PNE). The average concentration of $PM_{2.5}$ in Kraków (31 $\mu g/m^{-3}$) was twice as high as in 2009–2013 in Genoa, Barcelona and Florence, and similar to Milan.

A receptor model adapted to the research with the EPA PMF 5.0 program was developed, which was used to identify sources of air pollution with suspended dusts and chemical components (elements and ions) generated by separate sources. As a result of the modelling, six sources were identified. The sources of dust and their quantitative share in the total mass of $PM_{2.5}$ was determined. The following sources have been identified: (1) Combustion, (2) secondary nitrates and sulphates, (3) biomass burning, (4) industry, (5) the soil and (6) road traffic. Monthly deviations of the efficiency of the source of pollution with $PM_{2.5}$ dust are presented.

In the Warsaw area, the Juda-Rezler et al. [40] team also applied the positive matrix factorisation (PMF) method, supported by the analysis of enrichment factors, in order to identify the six main sources of $PM_{2.5}$ dust: Residential combustion (fresh and old aerosols) (46% by weight of $PM_{2.5}$), road fumes (21%) and unused exhausts (10%), mineral dust/construction works (12%), high temperature processes (8%) and steel processing (3%). In this analysis, primary organic carbon (POC) and secondary organic carbon (SOC) were classified as two separate components that helped distinguish between primary and secondary aerosol sources. Identification of the sources was also supported by the study of their annual and weekly profiles, as well as the analysis of the correlation of particulate components with meteorological conditions. Comparison of the attributed sources of air pollution with dust in Warsaw and Kraków is shown in Table 3.

The most expressive elements of PM sources in Warsaw are SOC, Cl^{-} and As for combustion in apartments, $NH_4{}^{+}$, Sb and POC for road transport, Ca and Mg for construction works, and $SO_4{}^{2-}$ for PM transport over long distances.

The analysis of the collected data, including carbon species, eight main water-soluble ions, 21 small trace elements and local meteorological conditions were used to assess the nature and seasonal variability of PM aerosols in Warsaw, as well as to identify the contribution of natural and anthropomorphic sources to the aerosol levels.

The method of studying the active sources of dust pollution from which the pollutants originate in school buildings located near Athens, Greece, was investigated by [47]. The tests using the PMF method were carried out in 2017 and they referred to the mass concentrations (the highest was 72.02 $\mu g/m^{-3}$) and the chemical analysis of PM_{10}. Seasonal fluctuations were also examined.

Lv et al. [10] studied the concentration of solid particles in Daqing China, from the outside C_{out}, and their percentages expressed in mass concentrations in buildings of various applications, as well as the correlations of internal pollution with the locations of buildings exposed to external sources of dust of various origins (office: C_{out} = 22 $\mu g/m^3$ and ρ = 79.4% (ρ–contribution rate I/O of indoor and outdoor particle sources to the concentration of indoor particulate matter); classroom: 20 $\mu g/m^3$ and 87.6%; city residence: 30 $\mu g/m^3$ and 75.0%; rural house: 34 $\mu g/m^3$ and 90.2%). The researchers found that the share of external sources in the concentration of PM indoors exceeds 70%, and in classrooms and in the countryside it exceeds 90%.

Table 3. Comparison of the attributed sources of air pollution with dust in Warsaw and Kraków.

Warsaw (Juda–Rezler et al. [40])			**Kraków (Samek et al. [36])**		
Sources	**Percentage %**	**Concentration μg/m^3**	**Sources**	**Percentage%**	**Concentration μg/m^3**
Residential combustion (fresh andaged aerosols)	45.6	6.7	Combustion	22.9	27.3
			Secondary nitrate	17.1	11.4
			Secondary sulphate	19.3	10.5
Exhaust traffic emissions from gasoline and diesel engines	21.1	3.1	Traffic	8.3	1.6–4.0
Non-exhaust traffic emissions from abrasion of road, brake pads and tyres	10.2	1.5			
Mineral dust/construction works	12.2	1.8	Biomass burning	15.6	10.0
High temperature industrial processes–ferrous and non-ferrous metal processing	8.2	1.2	Industry and/or soil	2.5	0.5–1.2
Steel processing	2.7	0.4			
			Unidentified	14.3	

3. Materials and Methods

3.1. Preliminary Measurements of Mass Concentrations of Dust Pollutants Inside Rooms

There are two types of PM measurement instruments: Those that provide average concentrations over the sampling period and those that provide real-time instantaneous concentration monitoring. Instruments based on the gravimetric method are considered as reference methods and must meet the requirements of PN-EN 12341:2014 [48]. The principle of the reference method is to collect the particulates on a circular filter. This must be a glass fibre filter (GFF), a quartz fibre filter (QFF), polytetrafluoroethylene (PTFE) or PTFE-coated glass fibre, and must be thoroughly conditioned before and after collection. The filter itself should be weighed before and after collection.

Optical instruments based on light scattering, absorption or occultation of light by particles are used to measure dust concentration in real time. They must have certificates confirming their equivalence with the reference method.

A detailed description of the measurement strategy for airborne particles and legal measuring equipment can be found in ISO 16000-34:2018 [49] and ISO 16000-37:2019 [50]. Measurement of $PM_{2.5}$ mass concentrations describes the strategies and procedures for measuring the mass concentration of $PM_{2.5}$ indoors.

Tests of dust air pollutants in selected rooms were carried out from 27 January 2020 to 10 March 2020 in a low office building (two-story high), located in the centre of Warsaw in an urban development. Three office rooms with a different area and a different proportion of external and internal walls were selected for the study of air pollution. The rooms were empty, the leaks had been identified and taped over, leaving only airflow through the window vents and the undercutting of the front door. Localisation of the measurement devices in rooms is shown in Figure 5. The cubic volumes and number of windows of the analysed rooms were as follows:

Room 1–23.48 m^3, 1 window
Room 2–48.75 m^3, 2 windows
Room 3–93.14 m^3, 3 windows

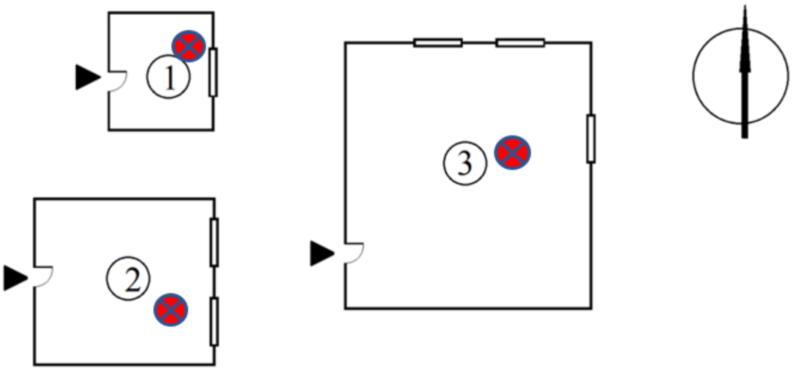


Figure 5. Rooms 1,2,3 where measurements were performed with indicated point of measurement devices.

The rooms were situated on the ground floor of the building (approximately 2 m above ground level and 104 m above sea level). At the time of the test, the exhaust ventilation was turned off, and the ventilation was turned off one hour before the start of the measurements. In the immediate vicinity of the building in question, there are other office buildings and multi-occupancy residential buildings connected to the municipal central heating. In terms of height, the adjacent buildings can be characterised as low (height above ground level up to 12 m), medium (height above ground level up to 25 m) and tall (height above ground level up to 55 m). There are local access roads with low traffic around the office building in question. At a distance of approximately 120 m from the building in question, there is a main road with heavy traffic.

3.2. Measurement Methods (Measuring Instruments and Procedures of Particle Concentration Measurements Inside and Outside the Building)

Measurements of the mass concentration of dust inside were carried out by the AEROCET 831 Handheld Particle Counter (Met One Instruments Inc, Grants Pass, OR, USA) operating on the optical principle with a laser diode, and by the TSI QUEST EVM-7 optical-gravimetric environment monitor, indicating the mass concentration of particles, but also their size fractions $PM_{2.5}$, PM_4, PM_{10} (in terms of measuring the particle size distribution, the optical device is classified as a laser light scattering aerosol spectrometer—LSAS—for measuring particle sizing). The TSI QUEST EVM-7 environment monitor (TSI INCORPORATED, Shoreview, MN, USA) also measures the CO_2 concentration inside the rooms. Used equipment is shown in Figure 6. Used devices are under the supervision of the environmental laboratory and are regularly checked and periodically calibrated. Each device was checked and calibrated before the experiments. Meters from Table 4, the dust and environmental condition measuring devices AEROCET and the TSI were set to zero prior to the measurement using the “filter 0” in order to “reset” the measurement path.

Figure 6. Set of measuring devices for indoor environment testing.

Table 4. Equipment for measuring the thermal parameters of the internal environment and the mass concentration of PM_{10} and $PM_{2.5}$ particles in selected rooms and outside the building.

Type of Measuring Device		Measured Quantities	Units	Resolution	Measurement Range	Accuracy
TSI QUEST EVM-7		Mass concentration of particles	$\mu g/m^3$	1	0–20,000	±15%
		Particle sizing	µm	N/A	0.1–10	±2.5%
		CO_2 concentration	ppm	1	0–5000	±100 ppm
AEROCET 831		Selective mass concentration of particles	$\mu g/m^3$	0.1	0–1000	±10%
ALMEMO 2690-8AKSU (for microclimate parameters)	FHAD46C sensor	Temperature	°C	0.1 K	−20–+80 °C	±2K
		Relative Humidity (RH)	% RH	1	5–98	±2% RH at 23 °C
		Atm. Pressure	hPa	0.1	300–1100	±2.5 hPa at 23 °C
	FV A605-TA1 Thermo-anemometer	Air flow	m/s	0.001	0.001–1	± 3 %

The operating principle of a LSAS relies on particles being guided individually through an intensely illuminated volume. Commercially available equipment enables the particle mass concentrations to be estimated and displayed by the monitor, using evaluation software. Normally, these programs assume the ideal spherical form of particles and convert them to mass concentration. Calibration of the TSI QUEST EVM-7m is required and usually performed with PM latex particles of a defined diameter as the test aerosol. A comparison with other gauges should, however, always be made carefully because ultimately what is determined by LSAS is the particle equivalent optical diameter determined by calibration with monodisperse spherical latex particles.

The lower detection limit depends very much on particle size: The larger the particles, the lower the limit of quantification. The characteristics of the devices used for measuring the internal environment, including PM_{10} and $PM_{2.5}$ dust, are shown in Table 4 below.

Outdoor concentrations of PM_{10} and $PM_{2.5}$ on both measurement days will be based on CIEP-Chief Inspectorate of Environmental Protection, pol. GIOŚ archival data and the results of measurements made with the AEROCET 831 m.

At CIEP, dust concentrations were measured using an automatic method, by a CIEP environmental monitoring station located closest to the building selected for the study. CIEP provides access to hourly monitoring data on air quality in Poland, produced as part of the State Environmental Monitoring and collected in the JPOAT2.0 database.

The CIEP pollution measurement stations taken into account during the tests differ from each other in terms of their location, as well as their location in relation to communication routes affecting the measured pollution levels.

At the same time, measurements of the mass concentration of PM_{10} and $PM_{2.5}$ were performed using the AEROCET 831 m described in Table 4, placed outside, right next to the window opening of the monitored room, i.e., outside the building. Due to the use of different devices at the Building Research Institute and CIEP, the not fully established measurement procedure of "outside the window" (a critical increase in the AEROCET 831m indications was noticed when the cleaner was turned on), different distances and positioning of the monitored rooms in relation to the sides of the world from the official air quality control points, the results of the present study's measurements are not fully comparable with the results presented by CIEP. Self-readings of outdoor concentrations should be more reliable for comparison because they were carried out at the same time points as the indoor pollutant concentration. The outdoor environmental parameters were observed and recorded during experimental campaign. In these preliminary tests, the air velocity in the immediate external environment was not measured.

During the measurements of the mass concentration of dusts, the concentration of CO_2 was also measured with the TSI QUEST EVM-7 m in each test room.

The measurements of the time curves of decay (measuring particle decay curve) and the particle concentration rebound curve in the interiors were carried out in time cycles of 150 min. The concentration of suspended dusts was rebuilt as a result of natural dust penetration through the external wall of the building and the gaps near windows and doors in the time period of from −50 to 0 min, as the cleaner was turned on in the time interval from 0 to 150. At point 0 (on the x-axis), when the cleaner was switched off, the indoor dust concentration was measured and had a minimum value. The second part of the transient curve is the concentration rebound curve.

3.3. Procedures for Measurements of $PM_{2.5}$ Mass Concentration in the Indoor Mode Performed at ITB

During the tests, which were carried inside each room on three days, when the air pollution by $PM_{2.5}$ outside was different, the following weather conditions were recorded, as shown in Table 5.

Table 5. Weather conditions during air quality and dust concentration measurements (source: www.weather.com and www.meteomodel.pl, accessed on 27 January 2020, 28 January 2020, 10 March 2020).

	Temp (°C)	**Atm (hPa)**	**Wind (km/h)**	**RH (%)**	**Precipitation (mm)**
Day 1 (27 January 2020)	3.0	1013.75	12.5	87.1	0.0
Day 2 (28 January 2020)	1.0	1002.50	15.0	93.1	0.0
Day 3 (10 March 2020)	9.0	1008.75	16.0	75.0	0.0

Indoor air pollution tests in three selected rooms were carried out according to the following scheme:

1. An initial measurement of the concentration of PM_{10}, $PM_{2.5}$ and CO_2 was performed.
2. The Samsung AX90R7080WD/EU air cleaner was turned on and PM mass concentration measurements were performed until the minimum dust concentration was achieved.
3. After turning off the air cleaner, measurements of the concentration of PM_{10} and $PM_{2.5}$ dust were taken until reaching “saturation”—the state where indoor PM concentration no longer decreases.
4. After achieving the point of a steady state of PM concentration the measurements of the concentration of PM_{10} and $PM_{2.5}$ dust were going on until reaching equilibrium of I/O concentration.

Thus, this study measured the transient concentration decay curves of the decrease in dust concentration in the room after the air cleaner was turned on until it was turned off at point $C_{in,0}$, and the transient PM concentration rebound curves of the recovery of dust concentration in specific time intervals determined on a real-time basis. The particle concentration rebound curves not the particle concentration decay curves were used in our research to measure the penetration factor. This modification of the method is to be used for determining the value of the particle deposition rate k not from the course of the characteristics in the transient state, the so-called particle decay curve, but from the course of the further time stimulated by infiltration, the so-called particle concentration rebound curve. This method was used to determine the value of k and then P was recognized as correct by He [25] andDiapuoli [51] but it has not been used so far.

One person stayed in the room during the measurements, hence the constant increase in the concentration of carbon dioxide, which was also measured with the TSI QUEST EVM-7 m.

The CO_2 concentrations marked as c_0 and c_t were measured on each measurement day at the beginning and at the end of the measurements of $PM_{2.5}$ mass concentrations.

The results of CO_2 concentration measurements in room 1 (with one window) and in room 3 (with three windows) in ppm are given in Table 6 (assumed CO_2 concentration outside equal to 500 ppm); according to the statement of the Minnesota Department of Health: 'The outdoor concentration of carbon dioxide is about 400 parts per million (ppm) or higher in areas with high traffic or industrial activity. The present authors' assumption is determined by localisation of the measurements points and their own experience in this area.

Table 6. The results of indoor CO_2 concentration measurements (ppm).

Room 1; One Window		**Room 3; Three Windows**	
Initial measurement	Final measurement	Initial measurement	Final measurement
1600 ppm	3400 ppm	1000 ppm	1400 ppm

Dust concentration tests in individual rooms were carried out sequentially (not simultaneously); therefore, the external environment for rooms 1–3 may differ slightly.

4. Results and Discussion

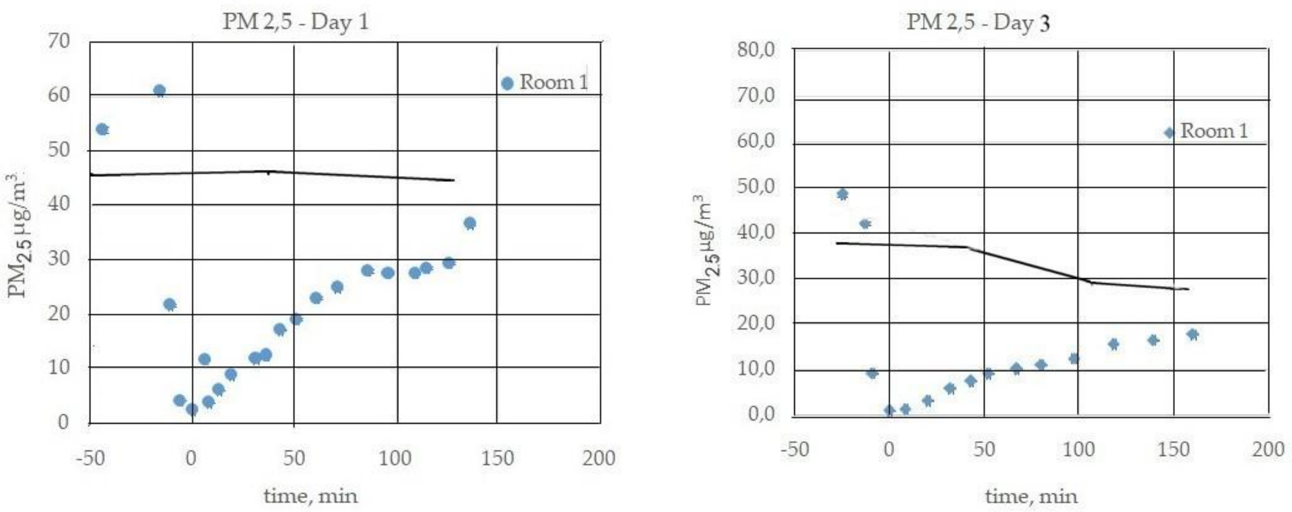
4.1. Results and Discussion of Preliminary Measurements of Indoor $PM_{2.5}$ and PM_{10} Concentrations

The concentrations of PM_{10} and $PM_{2.5}$ outside were taken from published data on the basis of measurements made by the CIEP Environmental Protection Station closest to the studied rooms (Warsaw, Wokalna 7and Al. Niepodległości 227/233). Measurements of air quality stations are reported with an hourly interval and shown in Table 7.

Table 7. Outdoor air quality conditions during air quality and dust concentration measurements (source: GIOŚ).

	Station	**Hour Interval**	**PM_{10} ($\mu g/m^3$)**	**$PM_{2.5}$ ($\mu g/m^3$)**	**NO_2 ($\mu g/m^3$)**	**CO ($\mu g/m^3$)**	**Benzene ($\mu g/m^3$)**
Day 1 (27 January 2020)	Wokalna	9:00–10:00	60.8	46.2	33.0	-	-
		10:00–11:00	61.0	45.9	-	-	-
		11:00–12:00	58.8	44.0	-	-	-
		12:00–13:00	55.1	40.4	30.7	-	-
		13:00–14:00	48.6	33.8	34.8	-	-
	Niepodległości	9:00–10:00	65.6	62.5	66.9	1.5	3.0
		10:00–11:00	65.1	60.9	-	-	-
		11:00–12:00	68.8	61.2	-	-	-
		12:00–13:00	82.0	62.6	47.0	1.1	2.4
		13:00–14:00	87.6	54.8	58.2	1.1	2.1
Day 2 (28 January 2020)	Wokalna	8:00–9:00	58.9	43.5	35.6	-	-
		9:00–10:00	58.7	42.8	37.9	-	-
		10:00–11:00	51.3	36.6	34.3	-	-
		11:00–12:00	40.5	29.2	28.3	-	-
	Niepodległości	8:00–9:00	64.3	58.1	55.7	1.3	2.9
		9:00–10:00	64.2	59.6	51.7	1.1	2.7
		10:00–11:00	60.6	54.5	59.6	1.2	2.7
		11:00–12:00	52.3	44.0	60.5	1.1	2.5
Day 3 (10 March 2020)	Wokalna	6:00–7:00	41.5	37.1	36.7	-	-
		7:00–8:00	51,3	36.6	34.3	-	-
		8:00–9:00	31.7	28.9	39.1	-	-
		9:00–10:00	30.4	28.1	38.7	-	-
	Niepodległości	6:00–7:00	51.8	44.0	47.2	0.3	2.0
		7:00–8:00	60.6	54.5	59.7	1.2	2.7
		8:00–9:00	43.6	41.0	67.4	0.6	1.6
		9:00–10:00	40.7	39.9	84.5	0.8	1.9

Based on the data on dust concentrations obtained from the hourly monitoring of the Chief Inspectorate of Environmental Protection for PM_{10} and $PM_{2.5}$ dusts on Day 1 (27/01/2020), Day 2 (28/01/2020) and Day 3 (10/03/2020), the curves of dust concentration changes outside the building were determined. The curves of dust concentration inside the building in the indicated rooms were drawn on the basis of measurement data made with the AEROCET 831 m. Figure 7a–c show changes in the mass concentration of PM_{10} and $PM_{2.5}$ on the first, second and third days of measurements in rooms 1 and 3.


(**a**) 27 January 2020($PM_{2.5}$) Day 1–Room 1

(**b**) 10 March 2020($PM_{2.5}$) Day 3–Room 1

(**c**) 28 January 2020(PM_{10}) Day 2–Room 3

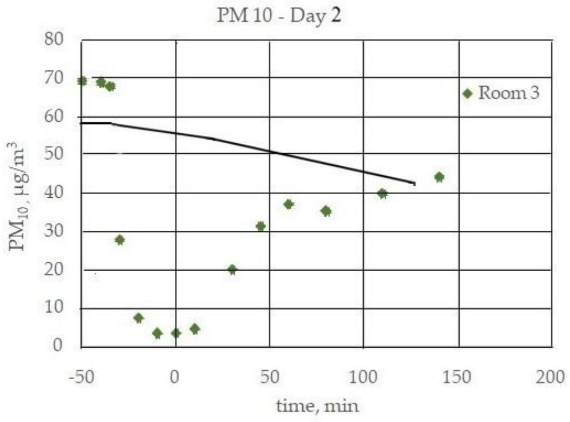


Figure 7. Forced changes in the concentration of PM_{10} and $PM_{2.5}$ dust inside the tested rooms (points) and outside the building (solid line) on three working days of dust concentration rebound curve measurements.

Comparing the measurements of $PM_{2.5}$ dust on day 1 (Figure 7a) and day 3 (Figure 7b) in room 1, it can be concluded that the rate of dust concentration level increase was higher on day 1, and the indoor pollution equilibrium state was reached by approximately100 min. The rate of dust concentration level was much lower on day 3, and the indoor pollution equilibrium state was reached by approximately150 min. This may be due to the smaller and continually decreased PM concentration gradient (C_{out}–C_{in}) (although at the same time during the measuring cycle, the temperature and wind speed were slightly higher). On day 3, the ambient concentration of dusts C_{out} measured by CIEP decreased in measuring time from 38 to 28 µg/m^3.

By analysing the course of the measurement of PM_{10} on day 2 (Figure 7c) in room 3, it is possible to notice also a uniform decrease in pollution outdoors caused by high relative air humidity; therefore, the concentration gradient (C_{out}–C_{in}) also decreased. According to theoretical assumptions, however, the equilibrium level of PM_{10} concentration inside the room is set at a level about 40% higher than the level of $PM_{2.5}$ concentration (Figure 7a). The measurement of the PM_{10} concentration rebound curve (Figure 7c) was completed when rainfall occurred. Authors found that the compliance between the CIEP (Chief Inspectorate of Environmental Protection) results with our $PM_{2.5}$ measurements outside the building is of the order of uncertainty in the measurement of PM concentrations inside regarding the used field instruments in accordance with Table 4.

Obtained results of preliminary experiments have shown that a system for measuring the concentration of $PM_{2.5}$ directly outside the window should be designed, which would be protected against disturbances caused by the operation of the air cleaner in the interior and changes by the meteorological parameters.

4.2. Theoretical Basis and Possibilities of Predicting Dust Penetration through the Building Envelope. A Dynamic Model of the Mass Balance Equation of Indoor Particle Concentration Levels

The process of penetration of dust from the outside into the interior of the building and the generation of PM by internal sources is a dynamic process [46]; therefore, all findings emphasise the importance but also the difficulty of determining separately the time courses of changes in the concentration of suspended dust in the interior, and the share in their mass of suspended particles from outdoors and the proportion of particles generated indoors. Such data are necessary for the interpretation of the results of epidemiological studies. In this framework, recent scientific research has focused on the study of factors influencing the penetration of particles through the building envelope and the quantification of the relative indoor proportion of particles coming from outside and remaining as dust suspended inside the room. The basic form of the dynamic mass balance equation is given in [25,51–56]; it describes the profiles of changes in the temporal concentration of PM during the particle decay curve or during the reconstruction of this concentration (particle rebound curve) in the room with Equation (4)

$$\frac{dC_{in(t)}}{dt} = a \cdot P \cdot C_{out}(t) - (a + k) \cdot C_{in}(t) + \frac{Q_{is}}{V} \tag{4}$$

where $C_{in}(t)$ and $C_{out}(t)$ are the concentrations of particles inside and outside at time t, respectively (mg/m^3); a is the multiplicity of air changes (h^{-1}); P is the dimensionless coefficient of particle penetration efficiency; k is the particle deposition rate (h^{-1}); V is the volume of the interior (m^3); and Q_{is} is the rate of generation of particles by the indoor sources(mg/h). Equation (4) assumes perfect mixing of indoor air. It also ignores particle mass losses or gains due to differences in the gas-phase concentrations of condensable substances and changes in temperature/relative humidity conditions between indoor and outdoor spaces. The penetration efficiency factor (P) and particle deposition loss rate (k) are also related to building characteristics and indoor/outdoor conditions, but these parameters also depend on particle size, composition and their electric charge.

The particle penetration factor (P) is defined as the mass fraction of the particles in the infiltrated air passing through the building envelope, which depends on particle diameter (d_p). This simple definition is

$$P = N_{escape} / N_{total} \tag{5}$$

where N_{escape} are the particles escaping through the leak outlet and N_{total} are the particles collected at the entrance of the leak in the building. The penetration factor is the most appropriate parameter for describing the mechanism of particle penetration through cracks and leaks in the building envelope, and at the same time the parameter describing the functionality of the building and, thus, its balance.

The main difficulty in the solution to this equation lies in the separate calculation of the penetration efficiency factor (P) and deposition rate (k). The values for these two parameters that are reported in the literature vary significantly. Deposition rate k presents the widest range of values in terms of size fractions in the literature. The penetration efficiency factor P seems to be more accurately calculated through the application of dynamic models.

Bennett and Koutrakis [57] developed a method for calculating the unknowns (P) and (k) using time-dependent indoor and outdoor particle concentrations and air exchange rate (a). Assuming there are no indoor particle sources, when using discreet time steps Δt, expressed as Equation (4), Equation (6) can be rewritten as follows

$$C_{in,t} = \frac{a_i P_i C_{out,t-\Delta t}}{(k + a_i)} \times \left(1 - e^{-(k_i + a_i)\Delta t}\right) + C_{in,t-\Delta t} \times e^{-(k_i + a_i)\Delta t} \tag{6}$$

Assuming steady-state conditions inside the building, no internal sources of suspended dust generation and no mechanical ventilation with a filter, Equation (6) can be transformed into a Equation defining the dust infiltration coefficient F_{inf}. The infiltration of air with particles suspended indoors is also described by the infiltration coefficient (F_{inf}), which determines the fraction of external particles that enters the internal microenvironment and remains suspended. The particulate matter infiltration process is defined by the following equation

$$F_{inf} = \frac{C_{in}}{C_{out}} = \frac{P \cdot a}{a + k} \tag{7}$$

where F_{inf} is the PM infiltration factor (-).

"When indoor particle emissions cannot be avoided, the method developed by Long et al. [58] which is based on the linear regression approach can be used for F_{inf} determination".

The analytical solution of Equation (6), based on field measurements of mass concentrations of $PM_{2.5}$ inside and outside the building was used by Chao Chen et al. [59] in their study of particle penetration through window gaps. They used Equation (6), where the Δt is time step Δt = 1 h; and a_i, P_i, k_i are hourly air exchange rate, penetration factor and deposition rate, respectively. Therefore, Equation (6) can be resolved when $C_{in,t}$ and $C_{out,}$ (i = 1, 2 . . . n) are known for a period Δt of time, where hourly indoor and outdoor $PM_{2.5}$ mass concentrations could be determined by field measured data, so the unknowns are air exchange rate (a_i), penetration factor (P_i) and deposition rate (k_i). As such, the number of equations is ($n - 1$) and the unknowns are 3(n−1) in the new Equation (4) ($n - 1$, a_i, P_i and k_i).

The experimental solution of the dynamic mass balance equation of indoor PM concentration is recommended by [25,52,53]. They argued that a dynamic variation of the PM concentration level in the sample room should be performed while simultaneously measuring the PM particle decay curve in real buildings.

When the test time is longer than the time constant, it is implied that the indoor $PM_{2.5}$ concentration has reached a steady-state condition, then

$$\frac{dC_i(t)}{dt} = 0 \tag{8}$$

Therefore Equation (4) can be summarized by Equation (9)

$$C_{in,t} = C_{in(0)} = \frac{P \cdot a \cdot C_{out}}{a + k} \tag{9}$$

where $C_{in,t}$ is the steady-state indoor $PM_{2.5}$ concentration.

Upon determining the "decay term" (a + k) and the air exchange rate a, the penetration efficiency factor P is described by the following equation, which assumes the absence of internal sources PM.

$$P = \frac{(a + k)}{a} \cdot \frac{C_{in,0}}{C_{out}} \tag{10}$$

where $C_{in,0}$ is the concentration C_{in} of the PM particles already at a steady state with time.

By estimating the coefficient of particle infiltration from outside into the room, F_{inf}, from the dynamic mass balance equation, it is difficult to determine independently the values of P and k. Over the last two decades, many methods have been used to estimate P

and k and calculate the relative contributions of particles from indoor and outdoor sources in the measured mass concentrations of given indoor particles. Diapouoli et al. [51] describe a broad overview of the methods for determining the values of these parameters, presenting different approaches, which they grouped into four categories according to the principles of their determination: (1) Steady-state assumption using the steady state of the mass balance equation; (2) dynamic solution of the mass balance equation using complex statistical techniques; (3) experimental studies using conditions that simplify model calculations (e.g., decreasing the number of unknowns); and (4) infiltration surrogates using a particulate matter (PM) constituent with no indoor sources to act as surrogate of indoor PM of outdoor origin. As they claim, however, the analysis of various methodologies and results shows that the estimation of particle infiltration parameters is still difficult.

The penetration factor P measurement principle, according to the authors' proposal, covers the realisation of the dynamic mass balance equation of indoor PM concentration, which is presented in Figure 8. Air exchange rate a is measured at first using the properly documented principle and therefore it is not described in Figure 8.

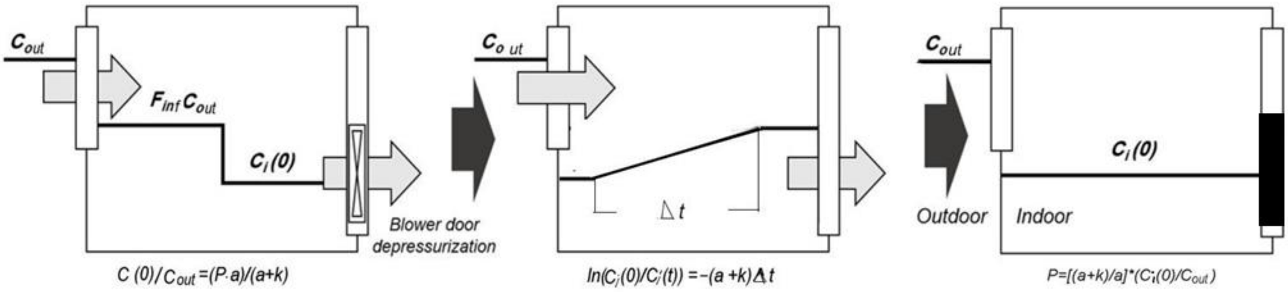


Figure 8. Schematic diagram of the P factor test procedure (with reference to Dong et al. [24]).

4.3. Method of Determination of the Penetration Efficiency Factor P

Air exchange rate in the internal microenvironment (a)

The rate of air exchange in the room (a) due to infiltration of air from the outside is a measurable parameter, and is mainly influenced by the construction and technical condition of the external wall of the building and the ventilation system, the activity of residents and meteorological conditions.

The size of (a) in the room where people are present can be estimated on the basis of the time curve of the decay of CO_2 concentration in the room at night. The air exchange rate can be estimated from the exponential curve of decay of CO_2 concentration over time, using Equation

$$a = \frac{1}{t - t_0} \ln\left(\frac{c - c_{out}}{c_0 - c_{out}}\right) \tag{11}$$

where a is the air change rate (h^{-1}), and the values of time t and t_0 are read at the end and the beginning of the concentration decay curve (h^{-1}), respectively. The values of c and c_0 are CO_2 concentrations (ppm) measured at times t and t_0, respectively, and c_{out} (ppm) is the concentration of PM outside at time t. The air change rate estimated for different measurement cycles shows seasonal fluctuations in the multiplicity of air changes. In naturally ventilated buildings, air flow is caused by differences in temperature or pressure inside and outside the building.

Equation (11) was used by the Czech–Norwegian team of Chatoutsidou et al. [54] in a study of the infiltration process in The Baroque Library Hall building in Prague with a natural ventilation system by infiltration in order to calculate the number of air changes. In this study, a dynamic mass balance model was used, taking into account the penetration of particles from external and internal losses (deposition, ventilation). The model was used to determine the particle deposition rate k and the penetration efficiency P. As a result of the three-year research, the values of a for spring were $a = 0.13$, for summer $a = 0.11$ and for winter $a = 0.15$. Equation (11) was also used in a simplified form by [25,60].

$$a = \frac{1}{t} \ln \frac{c_t}{c_0} \tag{12}$$

Deposition rate of airborne particles (k).

One of the simpler methods of determining the particle deposition coefficient is recommended by [25,51], who specified the factor of Equation (6) as the "decay term"—($a + k$) in the time interval Δt, using the regression analysis of the experimentally determined particle concentration decay curve. The temporary disappearance of the dust concentration in the interior, i.e., the C_{in0} concentration, to the C_{int} highest concentration (e.g., C_{in} level caused, for example, by the operation of the air cleaner) in accordance with equation

$$\ln\left(\frac{C_{in,0}}{C_{int}}\right) = -(a+k)\Delta t \tag{13}$$

is used to then derive the value of k from the value ($a + k$). An increasing trend was found for increasing particle sizes. At the maximum particle size, particle deposition rates are of the same order or even higher than their removal rates due to blown air exchange. According to the results of [1], higher deposition rates were found for larger particles, so the deposition coefficient k of PM_{10} particles is greater than k for $PM_{2.5}$ particles. They also found large differences in deposition rates among the six residences studied as a result of a discrepancy in surface material texture and roughness as confirmed by Abadie et al. [61]. They also demonstrated that the deposition effect is temperature dependent.

Particle penetration efficiency through the external walls of the building (P).

There are several different models in the literature for predicting the penetration efficiency P of particles through the gaps in the building envelope. The equation resulting from the Lagrangian model (Chen, Zhao [52]) is particularly interesting. It calculates the trajectory of each particle by integrating the equilibrium forces acting on individual particles.

The practical significance of the research conducted by Chao et al. [62] from the Hong Kong Technical University concerned the determination of the P and k coefficients in residences with natural ventilation. Both parameters were dependent on particle size but showed a different upward and downward inversion profile with respect to particle size. The main causes of loss by deposition and penetration effects are diffusion, inertial impact/interception and deposition (showing a different up-and-down inversion profile against particle size).

The efficiency of P is related to particle size, as demonstrated by many researchers who compared the penetration of particles of different sizes [1,25].

Chao et al. [62] studied six buildings and argued that 'the penetration coefficient showed a hill-shape with respect to particle sizes and there was a peak (0.79) at the size range of 0.853–1.382 μm'.

It follows that the deposition coefficient k of PM_{10} particles is greater than k of $PM_{2.5}$ particles while the penetration coefficient P of PM_{10} particles is less than P of $PM_{2.5}$ particles. The P particle penetration factor is, therefore, another important factor determining the value of the I/O ratio. If the building is ventilated by infiltration, however, the expansion of the particle penetration coefficient is a strong function of the air exchange coefficient a, particle size and fracture geometry in the building envelope.

Chao et al. [62] also described a simplified way to analyse the model of indoor particle behaviour.

This simplified method has been developed for users of particle counters, who need to express concentrations in the form of a particle number concentration, i.e., $(\times 10^3)$ p cm^{-3}, so that there is a need to convert the units in which the particle concentrations are recorded, i.e., convert the particle mass concentration units μg/m^{-3} per unit of particle number concentration $(\times 10^3)$ p cm^{-3}, assuming a spherical shape and uniform particle density and packing. Such conversions are performed for each particle size range.

Returning to the dynamic mass balance Equation (6), it can be said that all parameters in this equation are known values, except for the penetration efficiency coefficient P and the deposition rate k. Chao et al. [62] transformed Equation (6) into a transient form. For each particle size range, the concentration of particles in the interior during the forced change in dust indoor concentration is equal to Equation (14)

$$C_{in} = \frac{PaC_{out}}{(a+k)} + \left(C_{int} - \frac{PaC_{out}}{a+k}\right)e^{-(a+k)t} \tag{14}$$

where C_{int} the is the initial dust pollution on the transient concentration decay curve.

Equation (14) consists of two parts: $P{\cdot}a{\cdot}C_{out}/(a + k)$ and $(a + k)$, which are the steady-state particle concentration and the time constant of the transient term, respectively.

Chao et al. [62] performed an experiment of the process of particle concentration decay of C_{in} at time (t–t_o) caused by intensive cleaning of the room from particles using an air cleaner. A typical profile curve of such a process is given by [62] and is also cited by [63]. The experiment consisted in artificially increasing the PM concentration to the C_{int} highest concentration value in the room in order to obtain a "drive" for the increase in the deposition rate, and then quickly reducing the concentration of solid particles to the steady state C_{in0} by inducing ventilation present in the building. Substituting all measured particle concentrations and the air exchange rate a obtained in the tracer gas CO_2 decay test, the deposition rate from the particle decay curve can be expressed as follows:

$$k = \left(\frac{1}{t}\right)\ln\left(\frac{C_{in} - C_{in0}}{C_{int} - C_{in0}}\right) - a \tag{15}$$

The difficulty in applying this equation, however, lies in the correct choice of the time point in particle concentration decay curve at which the k value is to be calculated, since the chosen value of t will determine the value of $C_{in(t)}$ from the decay curve or from the particle rebound curve. The penetration rate P can be found from the steady-state particle concentration upon determining the deposition rate k, which is shown as follows:

$$P = \left(1 + \frac{k}{a}\right)\frac{C_{in0}}{C_{out}} \tag{16}$$

The penetration factor consists of the ratio of the concentration found inside to the level of particle concentration outside (I/O ratio) and from the expression to the ratio of the particle deposition rate to the air exchange rate. In the case where the deposition rate k is much slower than the air exchange rate a, the penetration coefficient is equivalent to the I/O ratio.

The particle decay method can be replaced by the particle concentration rebound method as mentioned by [25,51,52]. Then, it will be a reversed process, the transition curve of which will reflect more closely the ease of particle penetration. This is because the experiment takes place under conditions of natural pressure difference I/O, and reflects better the efficiency of penetration of particles through the building envelope.

4.4. Exemplary Determination of the Penetration Efficiency Factor Based on the Results of Tests of the Profile of Forced Changes in the Concentration of PM Particles in a Selected Room

As an example of a measurement cycle, the results of which were used to calculate the value of the penetration efficiency factor P of $PM_{2.5}$ particles through the external walls of the building, we chose the mass concentration C_{in} and C_{out} measurement cycle of 27 January 2020, made in room 1 (with one window), and presented in Figure 7a.

Assuming that for further calculations of the penetration coefficient, an experiment must be conducted that will force the concentration decay process, and then the process of restoring the concentration level of $PM_{2.5}$ in the selected room (as in experiments in [26,62]), the authors present the transient curve of this dynamic process with the penetration of $PM_{2.5}$ particles through the building envelope in Figure 7.

The first step was to determine the value of the air changes rate a in the selected room and under the thermal conditions of the measurement cycle. The CO_2 concentrations marked as c_0 and c_t were measured on each measurement day at the beginning and at the end of the measurements of $PM_{2.5}$ mass concentrations. The values of CO_2 concentration outside the building, c_{out} = 500 ppm, were assumed in accordance with ISO 16000-26:2012 [64]. The a value calculated from Equation (9) was for the selected room and measurement date $a = 0.28$.

The value a (ACH air changing rate h^{-1}) is calculated from equation

$$a = \frac{1}{(t - t_0)} \cdot \ln\left(\frac{c_t - c_{out}}{(c_0 - c_{out})}\right)$$

In order to use Equations (14)–(16), the authors had to convert the results of particle concentration measurements in the selected measurement cycle (Figure 9) from the mass concentration units $\mu g/m^{-3}$ to the numerical concentration units ($\times 10^3$) p/cm^{-3} (number of particles to cubic cm). The method of conversion was taken from the article by Morawska et al. [26], assuming (for the size range of $PM_{2.5}$ particles) the conversion factor of 21.3/18 of the values of mass concentration units to units of numerical concentration.

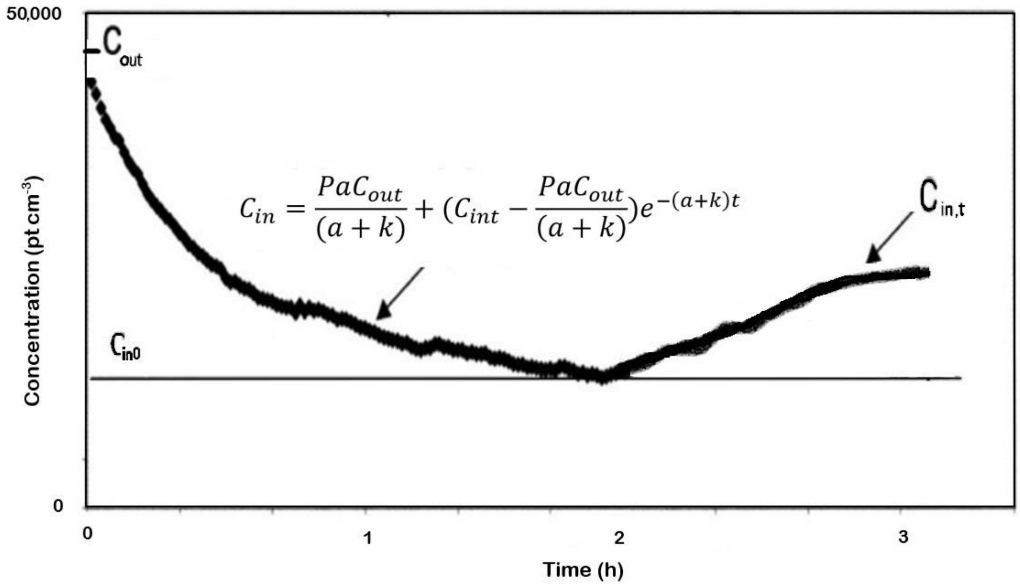


Figure 9. Coupled dynamic processes: Particle concentration decay curve combined with particle concentration rebound curve. Decay curve starts at the concentration point C_{int}.

The second step is to determine the value of particle deposition rate k (from the concentration decay curve C_{in} of $PM_{2.5}$ particles or from the particle concentration rebound curve (see Figure 7) in the selected time interval Δt (then, it is a reverse cycle) in the room under the conditions of the determined air change rate a (see Table 8). The k factor will be calculated for the measurement cycle shown in Figure 7, using Equation (7) simplified to the form (13) with the data from Table 9.

Table 8. Data for calculating the a value (air changing rate h^{-1}).

c_{out} = 500 ppm	Room 1 (one window)
c_0 = 1600 ppm	c_t = 3400 ppm
c_0–c_{out} = 1100 ppm	c_t–c_{out} = 2900 ppm
ln 2.64 = 0.97	$a = 0.28\ h^{-1}$

Table 9. Data for calculating the k value (deposition rate h^{-1}).

C_{in0} = 3.8 μg/m^{-3} = 4.5 × 10^3 p/cm^{-3} in time t = 0 h	$C_{in,t}$ = 26 μg/m^{-3} = 30.7 × 10^3 p cm^{-3} in time t = 1 h
ln(4.5/30.7) = ln(0.15) = (−1.90)	(−1.90) = −(a + k) × 1
1.90 = (a + k)	
a = 0.28	k = 1.62 h^{-1}

From the PM$_{2.5}$ particle concentration decay curve measured in Room 1 on 27 January 2020 (Figure 8) curve segment $\Delta t = t\text{-}t_0$ of the particle concentration rebound curve was selected. C_{in0} = 4.5 × 10^3 p cm^{-3} was calculated for time t_0 and C_{in} = 30.7 × 10^3 p cm^{-3} was calculated after 60 min for break point t of the particle level restoration curve. Based on Equation (13), the value (a + k) = 1.90 was determined, which gives, after subtraction, a = 0.28 and k = 1.62

Calculation of the value of k (deposition rate h^{-1}) from Equation (13)

$$\ln\left(\frac{C_{in0}}{C_{in,t}}\right) = -(a+k)\Delta t$$

In the literature, however, there is a large discrepancy in the values of the deposition rate factors for the size range of PM$_{2.5}$ particles, which are reported with the values of the air exchange rate.

In the range of a from 0.45 to 0.61 h^{-1}, i.e., in conditions similar to our air changing rate a = 0.28 h^{-1}, the value of k = 2.01 ± 1.11 h^{-1}was given in He, Morawska and Gilbert [25].The authors decided to compare the obtained value with others, e.g., Chao et al. [62] (k = 0.53 h^{-1} to k = 1 h^{-1}). We chose our value of k = 1.62 h^{-1} for further calculations because it is close to that given by [25] and because previously a similar value of k = 1.3 h^{-1} for PM$_{2.5}$ was obtained by the team Thatcher et al. [65] from the Lawrence Berkeley National Laboratory.

The third step is to calculate penetration P from Equation (16) with the data from Table 10.

$$P = \left(1 + \frac{k}{a}\right)\frac{C_{in0}}{C_{out}}$$

Table 10. Data for calculating penetration factor P.

C_{in0} = 3.8 μg/m^{-3} = 4.5 × 10^3 p/cm^{-3}	C_{out} = 44 μg/m^{-3} = 52 × 10^3 p/cm^{-3}
[(a + k)/a] [4.5/52] = (1.90/0.28) (4.5/52) = 0.61	
P = 0.61	

Thus, after converting the values of C_{in0} = 4.5 × 10^3 p/cm^{-3} and C_{out} = 52.0 ×10^3 p/cm^{-3}, and substituting all parameter values into Equation (16), the value P = 0.61 is obtained. From the course of the measurement cycle (Figure 7a), it can be seen that the value of P will be higher because the concentration level of C_{out} during the particle concentration rebound curve measurement was constantly decreasing.

The value is verified by the data collected by Chao et al. [62] who, based on their research, compiled the values of P factors for particles in wide particle size ranges.

For PM$_{2.5}$, it is possible to determine the P value of PM$_{2.5}$ particles by interpolating the P factor value from the chart prepared by Chao et al. [62]. The calculated value P = (2.458 + 2.642)/2 = 0.63 is roughly consistent with our value P = 0.61.

According to a recent study by Yu et al. [38], in diverse pressure differences, the 0.25–2.5 μm particles within the scope of penetration factor P is close to 1, which increased along with the pressure difference between the two sides of the gap. Four penetration factor models compared Chen and Zhao [52] and present much lower P values for PM$_{2.5}$.

5. Conclusions

Predicted infiltration factors F_{inf} in urban residences were collected, tested and classified by Baxter et al. [66] from the Harvard School of Public Health in Boston. They studied various factors related to occupant behaviours and home characteristics, which might influence ventilation patterns or infiltration factors. These include age of construction, housing type (multi- vs. single-occupancy homes), floor levels, opening windows, seasonal differences in F_{inf} and air conditioning or HVAC system use.

The transport of outdoor particles across the building envelope (i.e., penetration) is an important physical factor that contributes to particle concentration and size distribution inside buildings. The penetration factor can be equalised when doors and windows are open, but under different conditions the p values ought to be measured.

Outdoor pollution sources, rather than indoor pollution sources, are the principal contributors causing indoor particulate pollution in modern office buildings. When there are no substantial indoor particle pollution sources, 60–70% of the indoor $PM_{2.5}$ mass density comes from outdoor particulate pollution, according to the study.

This paper presents a modified method of determining the parameters of the process of penetration of $PM_{2.5}$ particles through leaks in the external walls of the building with the use of the processes of natural recovery of the levels of particle concentration. So far, dynamic tests of PM infiltration have been performed using the blower-door depressurization procedure by introducing the n-th power disturbance in the air flow caused by increasing the pressure gradient in the I/O system. The modified method promotes the measurement of C_{in} concentration during the process of equalizing the level of $PM_{2.5}$ concentrations inside and outside the building.

The preliminary results of the penetration factors determined by this method are consistent with the P factor values from the literature obtained so far for this dimensional group of dusts. Information on the P factor value can be a reliable parameter that classifies buildings in terms of resistance to dust infiltration into their interior, which may have a significant impact on indoor air quality. Obtained results of preliminary experiments have led to the conclusion that a system for measuring the concentration of $PM_{2.5}$ directly outside the window should be designed, which would be protected against disturbances caused by the operation of the air cleaner in the interior and changes by the meteorological parameters.

The authors have tried to describe the current state of knowledge in the field of research on interior pollution by dust and establish a roadmap for launching and improving measurement and test methods so that in the future a dynamic indoor particle model could describe indoor air quality, when exposure to $PM_{2.5}$ takes place. This model will be further tested using the Monte Carlo method before being included in the Combined IAQ model (Piasecki, Kostyrko [67,68]).

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