



Outdoor PM_{2.5} air filtration: optimising indoor air quality and energy

EVANGELOS BELIAS

DUSAN LICINA

*Author affiliations can be found in the back matter of this article

ABSTRACT

Human inhalation exposure to fine particulate matter (PM_{2.5}), including the PM_{2.5} of outdoor origin, predominantly occurs indoors. To limit outdoor PM_{2.5} penetration into buildings, ventilation standards often require the filtration of outdoor air with a minimum efficiency. Nevertheless, the PM_{2.5} filter selection recommended by the standards is based on the annual average outdoor concentrations without considering seasonal or diurnal fluctuations. This could result in a waste of energy or elevated indoor PM_{2.5} exposures. Representative outdoor PM_{2.5} data from 37 cities worldwide in conjunction with a simulated office building are used to examine the impact of filtration strategies on indoor PM_{2.5} levels and the fan's energy consumption. Two energy-saving methods are tested: (1) the optimum filter selection that maintains the indoor PM_{2.5} below the World Health Organization's (WHO) air quality guidelines; and (2) the baseline filter recommended by standards in combination with a filter bypass. Relative to a standard recommended baseline case, the two applied methods could reduce energy demand by between 4% and 17%. This indicates that the outdoor air is over-filtered in the majority of the investigated cities. In cities with low-to-moderate outdoor PM_{2.5} levels, using a filter bypass can be an effective energy conservation method without compromising PM_{2.5} exposures indoors.

PRACTICE RELEVANCE

Protecting building occupants from outdoor originating PM_{2.5} without a high energy penalty is not a simple task. The majority of recommendations for ventilation system design typically do not consider temporal variation in outdoor PM_{2.5}. This study's data suggest that outdoor air filtration efficiencies required by building standards are not sufficient to protect the building occupants living in severely polluted areas. In these areas, outdoor air filtration should be supplemented with other measures to limit outdoor PM_{2.5} penetration. In areas with low or intermittent outdoor PM_{2.5} levels, bypassing the filter can significantly reduce the energy consumption from fans without compromising indoor air quality. The energy-saving potential increases with the increase of outdoor air quality. This study suggests that improved outdoor air filtration can be achieved by a stronger reliance on continuous outdoor air quality data recorded on site.

SPECIAL COLLECTION:
ALTERNATIVES TO
AIR CONDITIONING:
POLICIES, DESIGN,
TECHNOLOGIES,
BEHAVIOURS

RESEARCH

]u[ubiquity press

CORRESPONDING AUTHOR:

Evangelos Belias

Human-Oriented Built
Environment Lab, School
of Architecture, Civil and
Environmental Engineering,
École Polytechnique Fédérale de
Lausanne, Lausanne, CH
evangelos.belias@epfl.ch

KEYWORDS:

air filtration; building services;
dedicated outdoor air system;
energy-saving fans; human
exposure; indoor air quality;
outdoor air pollution; PM_{2.5}
removal

TO CITE THIS ARTICLE:

Belias, E., & Licina, D. (2022).
Outdoor PM_{2.5} air filtration:
optimising indoor air quality
and energy. *Buildings and Cities*,
3(1), pp. 186–203. DOI: <https://doi.org/10.5334/bc.153>

1. INTRODUCTION

Outdoor particulate matter (PM) is listed as one of the top 10 risk factors for human health (Gakidou *et al.* 2017). Within the full-size spectrum of suspended particles, $PM_{2.5}$ (a particle mass with a diameter $<2.5 \mu\text{m}$) provoke more severe health outcomes because they can penetrate deeper into the lungs and reach the bloodstream (Feng *et al.* 2016; Kappos *et al.* 2004). The relevant adverse health effects include allergic reactions (Mimura *et al.* 2014), childhood asthma (Hua *et al.* 2014), strokes (Liu *et al.* 2016), chronic bronchitis, cardiovascular and respiratory diseases (Sarigiannis *et al.* 2015), acute pulmonary infections, heart diseases and lung cancers (Song *et al.* 2017), and premature deaths (Feng *et al.* 2016; Song *et al.* 2017). These health outcomes have significant economic impacts on societies (Dutton *et al.* 2013; Sarigiannis *et al.* 2015; Zhao *et al.* 2015). Thereby, the majority of inhalation exposures to $PM_{2.5}$, including the $PM_{2.5}$ of outdoor origin, occur while being indoors (Nazaroff 2018). This highlights the importance of the proper design and management of building defence mechanisms against the outdoor $PM_{2.5}$, including the provision of adequate air filtration systems.

The building envelope serves as a passive barrier that limits the penetration of outdoor $PM_{2.5}$ indoors (Chen & Zhao 2011; Martins & Carrilho da Graça 2018). Among active techniques used to limit the penetration of outdoor $PM_{2.5}$, outdoor air (OA) filters are the most commonly used. Buildings equipped with adequate OA filters were found to have a significantly lower indoor-to-outdoor $PM_{2.5}$ ratio (Oh *et al.* 2014; Ren *et al.* 2017). However, arrestance efficiency and resistance to airflow vary across different filter grades (Liu *et al.* 2017; Martins & Carrilho da Graça 2018). Filters with higher particle-capture efficiencies create higher pressure drops in the ventilation system, which leads to higher energy use in fans (Liu *et al.* 2017; Montgomery *et al.* 2012; Zaatari *et al.* 2014).

The majority of building standards recognise the importance of outdoor $PM_{2.5}$ filtration. They propose minimum filtration efficiencies according to building type and outdoor air pollution levels (ASHRAE 2019; CIBSE 2020; EN 16798-3 2017). With the most comprehensive and rigorous methodology, EN 16798-3 (2017) classifies outdoor air quality into three outdoor air categories (ODA) based on the annual average or maximum diurnal $PM_{2.5}$ concentrations. Following the outdoor air evaluation based on the data provided by the governmental authorities, EN 16798-3 gives recommendations for the particle filter selection according to the desired supply air class and outdoor air pollution category. In regions where outdoor air pollution is episodic, the standard proposes bypassing filtration during the periods when the outdoor air is clean in order to economise energy and extend the filters' lifetime (EN 16798-3 2017).

Several research studies investigated the optimal OA particle filter selection according to the outdoor $PM_{2.5}$ levels. Stephens *et al.* (2016) proposed customisable filters selection based on annual average outdoor $PM_{2.5}$ levels to reduce occupant exposure and, at times, to economise energy. Zimmer (2019) presented a simple tool named Comfort IAQ, which aids designers in selecting the appropriate air filter to optimise indoor air quality (IAQ) by considering the annual mean outdoor $PM_{2.5}$ concentrations and solving a steady-state mass-balance equation. Yu *et al.* (2020) introduced a method that, besides the annual mean, includes the minimum–maximum and the probability distributions of the outdoor $PM_{2.5}$ concentrations. Ben-David & Waring (2018) probed the effect of various filter efficiencies and OA ventilation rates on indoor $PM_{2.5}$ levels and buildings' energy consumptions in several US cities. Beyond this work conducted in the context of several countries or regions, relatively little is known about optimising OA filter selection that mitigates indoor $PM_{2.5}$ exposures whilst optimising energy use. Additionally, the available knowledge is limited when it comes to the potential use of filter bypasses in the ventilation system. The optimal selection of air filtration merits close attention due to the role filters have on particle penetration indoors (and the associated health implications) and their energy use.

To address the knowledge gap, this study evaluated the performance of outdoor $PM_{2.5}$ air filtration methods in relation to indoor $PM_{2.5}$ exposures and energy use. First, a large-scale outdoor $PM_{2.5}$ data collection and analysis was performed to identify the representative year-long hourly concentrations for 37 selected cities across the globe. Two methods to reduce the

fan's energy consumption were then investigated in relation to standard recommended baseline filtration: (1) the optimum filter selection that maintains the indoor $PM_{2.5}$ below the World Health Organization's (WHO) (2006) air quality guidelines; and (2) the baseline filter recommended by standards in combination with a filter bypass. A mass-balance model was applied to a theoretical office building. This quantified the indoor $PM_{2.5}$ concentrations and the potential energy savings for the examined filtration methods.

The paper is structured as follows. The next section presents the methods used, including the outdoor $PM_{2.5}$ data sourcing, the selection of representative data, the simulation model and the methods for energy saving. The results and discussion present the findings regarding the outdoor $PM_{2.5}$ penetration indoors and energy use as a result of different filtration methods. The limitations are then considered. The final section briefly restates the key findings and highlights the importance of this work.

2. METHODS

2.1 SELECTION OF CITIES AND DATA SOURCING

For the study sample, 37 cities were selected from six continents based on their populations, coverage of different geographical locations and climatic conditions (Figure 1). Where available, the data were collected from multiple measuring stations in a selected city. Hourly $PM_{2.5}$ data were accessed and retrieved from the website of official, governmental air quality measurement stations, as listed in the Table S1 in the supplemental data online. In total, data were collected from 86 different outdoor $PM_{2.5}$ measurement stations. The locations and names of the investigated stations are presented in Table S2 online.

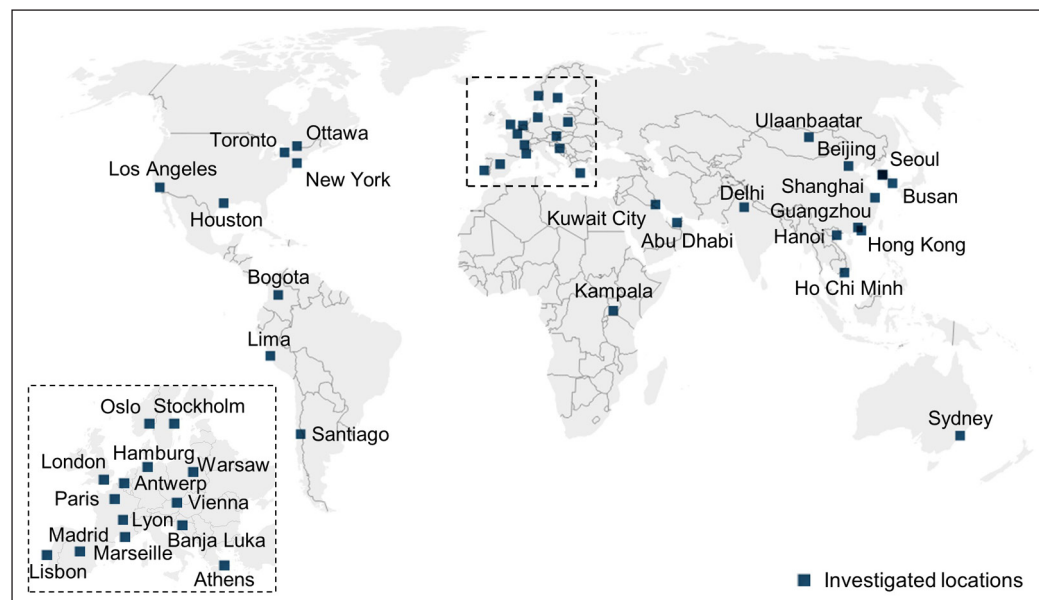


Figure 1: World map presenting the investigated cities.

2.2 REPRESENTATIVE HOURLY $PM_{2.5}$ DATA SELECTION

The hourly data were collected over a five-year period (2015–19) to create a sufficient sample of representative concentrations. Data from 2020 were excluded on purpose because they cannot be characterised as representative owing to the Covid-19 pandemic (Dutheil *et al.* 2020).

Currently, the most comprehensive methodology that selects year-long hourly representative data is presented by Chen *et al.* (2019). Their method selects representative data with the goal to create a complete hourly time series of a typical year. The present study adopts this methodology as a baseline and creates an expanded database with representative $PM_{2.5}$ concentrations on a global scale.

To address the issue of missing data and provide complete time series, a linear interpolation was used, because its performance in filling short gaps of missing air quality data is satisfactory. Monthly time series with more than 10% of missing data or more than 12 consecutive missing records were excluded from further analyses, because linear interpolation cannot efficiently impute data gaps of this size (Junninen *et al.* 2004).

The next step was to select the representative hourly concentrations. The Sandia method (Hall *et al.* 1978) used to create typical meteorological years (TMY) was applied to select the representative PM_{2.5} data. This method selects specific full-month datasets from different years based on the comparison of their cumulative distribution function (CDF) with the CDF of the long-term data for each targeted month. According to this method, the year-long hourly data are clustered by month. For each month, hourly data are used to create the CDFs for the long-term concentrations, which are further used to select the representative data according to the long-term concentrations and validate the representativeness of the selected data.

While the selection process for the TMYs takes into consideration various meteorological variables (e.g. air temperature, humidity, wind and solar radiation), the study used only the outdoor PM_{2.5} concentration data. The statistical indicator to compare the CDFs used in the Sandia method is Finkelstein-Schafer (FS) statistics (Finkelstein & Schafer 1971), which measures the difference between the two CDFs:

$$FS = \left(\frac{1}{n} \right) \sum_{i=1}^n \delta_i \quad (1)$$

where δ_i is the absolute difference between the CDF of the targeted month and the long-term data CDF at each point $X(i)$ ($i = 1, 2, \dots, n$); and n is the number of hourly recordings in the specific month.

The FS statistics calculate the difference between the CDF of each month's long-term data and the CDF of each targeted full month. The smaller is the FS index, the closer are the two compared CDFs. Hence, the FS index can evaluate how close/far is the selected dataset from the long-term (five-year) data trend, and if the selected data are sufficiently representative. A 5% limit for the FS statistic, which is an indicator of good data representativeness, is adopted (Chen *et al.* 2019, 2020). Finally, the selected months were merged in order to create a year-long dataset with the representative PM_{2.5} values.

2.3 BUILDING SIMULATION MODEL

A theoretical reference open-space office building model was created for the present study. The floor-to-ceiling height of the model was selected to be 2.8 m to represent the typical floor-to-ceiling heights of European and North American office buildings (EN 15265 2007; DOE 2021). The total floor area was 849 m². For this floor area, according to EN 16798-1 (2019) and for ventilation Category II and low-polluting buildings, the OA ventilation rate during occupied hours was 944 l/s (3398.4 m³/h). This is aligned with the nominal airflow for the energy efficiency evaluation of the air filters (Eurovent 4/11 2014; Eurovent 4/21 2018). During the unoccupied hours, as required by EN 16798-1 (2019), the OA ventilation rate was 127.4 l/s (458.5 m³/h) to dilute the emissions from building materials. The OA ventilation system of the building was a dedicated outdoor air system (DOAS). The speed of the DOAS's supply fan was variable in order to supply the defined OA rates according to the schedule. The study focused only on the OA ventilation system; therefore, the heating/cooling systems were not considered.

The EN 16798-1 (2019) building standard was also used to define the occupancy density and schedule. The adopted occupancy density was 17 m²/person, and the building was occupied from 07.00 to 18.00 hours during the workdays. The infiltration air change rate of the theoretical building was assumed to be constant and equal to 0.1/h in order to represent the infiltration rates of energy-efficient office buildings (Ben-David & Waring 2016). Additional simulations with different infiltration rates were conducted to reveal how this parameter influenced the results.

The study examined two common DOAS fan energy-saving methods in order to explore their impact on energy savings and indoor $PM_{2.5}$ levels. Together with the baseline scenario based on the EN-16798-3 (2017) standard procedure, the total energy consumption of the fan and the indoor $PM_{2.5}$ levels were compared for the following three scenarios (**Figure 2**):

- **Baseline scenario:** the DOAS filters were selected for each city according to the EN 16798-3 (2017) procedure. Specifically, an F7 filter was used when the annual mean outdoor $PM_{2.5}$ concentration was $<10 \mu\text{g}/\text{m}^3$ (in compliance with WHO 2006 guidelines; ODA 1), a combination of M5 + F7 filters when the annual mean outdoor $PM_{2.5}$ concentration was between 10 and $15 \mu\text{g}/\text{m}^3$ (exceedance of the reference values by a factor up to 1.5; ODA 2), and a combination of F7 + F7 filters when the annual mean outdoor $PM_{2.5}$ concentration was $>15 \mu\text{g}/\text{m}^3$ (exceedance of the reference values by a factor >1.5 ; ODA 3). This scenario was used to define the *baseline* for the fan's energy consumption and the indoor $PM_{2.5}$ levels for each selected city.
- **Optimum scenario:** the simulation model was programmed to test seven different filter grades (**Table 1**) and to select the filter with the minimum arrestance efficiency and pressure drop, which can maintain the indoor $PM_{2.5}$ levels in compliance with WHO (2006) air quality guidelines (annual mean = $10 \mu\text{g}/\text{m}^3$; 24-h mean = $25 \mu\text{g}/\text{m}^3$).
- **Bypass scenario:** it used the baseline filters (required by EN 16798-3 2017 as described in the baseline scenario) in combination with the filter bypass. During the hours when the outdoor $PM_{2.5}$ concentration was $<10 \mu\text{g}/\text{m}^3$, the filter's bypass was used. When the bypass was in use, no filtration was applied, meaning that both the $PM_{2.5}$ arrestance efficiency and filter's pressure drop were zero.

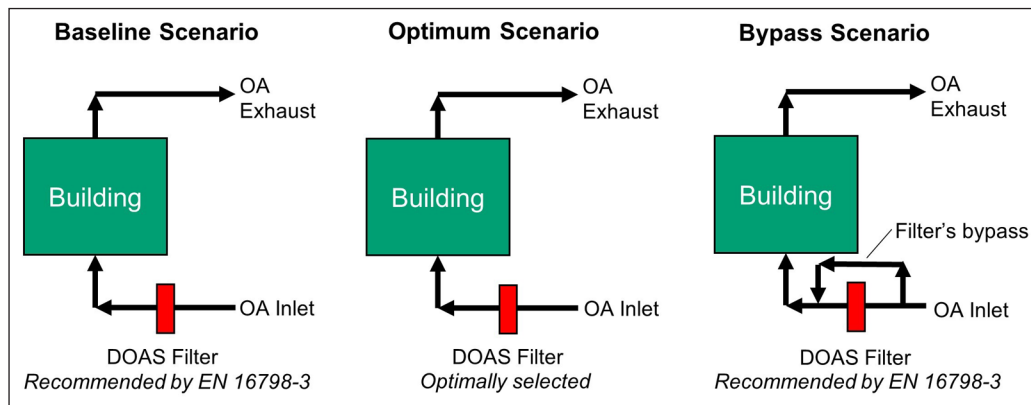


Figure 2: Dedicated outdoor air system (DOAS) configurations for the three operation scenarios: baseline scenario (DOAS with a baseline filtration), optimum scenario (DOAS with an optimal filter grade) and bypass scenario (DOAS with a baseline filter plus a filter bypass).

2.5 FAN OPERATION: ENERGY CALCULATION

The energy for the DOAS's fan operation was calculated based on the evaluation procedure applied by Eurovent for the air filter's energy efficiency (Eurovent 4/21 2018). The fan's energy consumption in a DOAS is a function of airflow rate, operation time, total pressure difference and the fan's total efficiency:

$$E = \frac{Q_v \bar{\Delta}_p t}{\eta} \quad (2)$$

where E (kWh) is the total energy consumption of the fan to overcome the system's pressure drop; Q_v (m^3/h) is the ventilation airflow rate; t (h) is the operation time; $\bar{\Delta}_p$ (Pa) is the average pressure drop of the system; and η (-) is the total energy efficiency of the fan (efficiency of the fan and efficiency of the fan motor). The η was considered equal to 0.5 (-) for all calculations, because this number well represents the efficiency of the fans used in the heating, ventilation and air-conditioning (HVAC) systems (Eurovent 4/21 2018). For the fan's energy consumption calculation,

the pressure drop provoked by the filter and the other elements of the ventilation system was considered. The pressure drops induced by the other elements of the ventilation system (air ducts, heat recovery unit, humidifier, cooling/heating coils, terminal device, air inlet and outlet) were assumed based on the recommendations of CEN/TR 16798-4 (CEN/TR 2017) to be 640 (Pa) for an airflow of 0.944 m³/s (during occupied hours).

In this study, the pressure drop of the filters was considered to be static. For the OA ventilation airflow during occupied hours, the average pressure drops of each filter grade were assumed based on Eurovent's energy efficiency classification table (Eurovent 4/11 2014), as summarised in **Table 1**. It was considered that the used filters belong to energy class C, because this class is the most common among commercially available air filters (Vadoudi & Kelijian 2019).

FILTER-GRADE EN 779 (CEN 2012)	FILTER-GRADE MERV	PM _{2.5} ARRESTANCE EFFICIENCY (%)	$\overline{\Delta}_p$ (Pa)
G4	MERV 7	20%	70
M5	MERV 8	25%	80
M6	MERV 10	30%	97
F7	MERV 12	70%	150
F8	MERV 14	80%	203
F9	MERV 15	90%	264
HEPA	HEPA	99.7%	450

Table 1: Filter grades, PM_{2.5} arrestance efficiencies and pressure drops for a ventilation airflow of 0.944 m³/s (during occupied hours).

Note: HEPA = high-efficiency particulate arrestance (filter); MERV = minimum efficiency reporting values.

As the OA ventilation rates were lower during unoccupied hours, the pressure drops were also reduced. The reduced pressure drop was calculated using equation (3), as the static pressure drop can be considered proportional to the square of the airflow and to a proportionality constant *C* (Stephens *et al.* 2010):

$$\overline{\Delta}_p = CQ_v^2 \quad (3)$$

where $\overline{\Delta}_p$ (Pa) is the average pressure drop of the system; *C* (-) is the proportionality constant; and *Q_v* (m³/h) is the ventilation airflow rate.

2.6 IAQ MODEL

In order to calculate the indoor PM_{2.5} concentration at each hourly time step, a mass-balance model was applied. The indoor PM_{2.5} concentrations were calculated using:

$$\frac{dC_{in}(t)}{dt} = P\lambda C_{out}(t) + (1 - \eta_v) \frac{Q_v(t)}{V} C_{out}(t) + \frac{S_r(t)}{V} - \lambda C_{in}(t) - \frac{Q_v(t)}{V} C_{in}(t) - kC_{in}(t) \quad (4)$$

where *dC_{in}*(*t*) (µg/m³) is the time-dependent indoor PM_{2.5} concentration, *C_{out}*(*t*) (µg/m³) is the outdoor hourly representative PM_{2.5} concentration; *λ* (/h) is the infiltration/exfiltration rate; *P* (-) is the outdoor PM_{2.5} penetration coefficient; *η_v* (-) is the PM_{2.5} arrestance efficiency of the filter; *Q_v*(*t*) (m³/h) is the OA ventilation airflow rate; *S_r*(*t*) (µg/h) is the PM_{2.5} emission rate from resuspension; *k* (/h) is the PM_{2.5} deposition rate; and *t* (h) is the time.

For the simulated theoretical office building, the only indoor PM_{2.5} source considered was the resuspension due to the occupants' walking, because it was assumed that there were no other significant PM_{2.5} sources. The particle emission rate from resuspension can differ significantly according to the floor coverings and occupants' activities (Qian *et al.* 2014; Thatcher 1995; Tian *et al.* 2014). Based on occupancy activity detection studies, each office occupant walks on average

4 min/h (Anderson *et al.* 2019; Brakenridge *et al.* 2016; Jancey *et al.* 2014). With the assumption that the floor was covered by a hard material, the emission rate from resuspension (S_r) was 0.01 mg/min/walking person (Qian *et al.* 2014; Thatcher 1995).

The $PM_{2.5}$ penetration coefficient (P) can differ significantly from building to building because it depends on the envelope's characteristics and nature of its cracks. For the purpose of this study, P was assumed to be 0.8 (-) based on previous studies (Chen *et al.* 2012; Chen & Zhao 2011; Li *et al.* 2017). The $PM_{2.5}$ deposition rate (k) was assumed to be 0.5/h based on previous studies (Ruan & Rim 2019; Zhao & Stephens 2017).

Unlike the EN ISO 16890-1 (2016) standard, the ASHRAE 52.2 (ASHRAE 2017) and BS EN 779 (CEN 2012) standards for filter grade classifications do not explicitly report the $PM_{2.5}$ arrestance efficiencies. Thus, the $PM_{2.5}$ arrestance efficiencies were assigned by the authors and were based on Eurovent's recommendations (Eurovent 4/23 2018) for BS EN 779 and on Azimi *et al.* (2014) for ASHRAE 52.2 (ASHRAE 2017) filter grades accordingly. The $PM_{2.5}$ arrestance efficiencies of the investigated filter grades are presented in **Table 1**. As the EN 16798-3 (2017) standard requires a combination of air filters for the ODA 2 and ODA 3 outdoor air quality categories, the total $PM_{2.5}$ arrestance efficiencies for these combinations were calculated using:

$$\eta_{vt} = 100 * \left\{ \left[\left(1 - \frac{\eta_{v1}}{100} \right) * \left(1 - \frac{\eta_{v2}}{100} \right) \right] \right\} \quad (5)$$

where η_{vt} is the total $PM_{2.5}$ arrestance efficiency; and η_{v1} and η_{v2} are the arrestance efficiencies of the first and second filters, respectively. The $PM_{2.5}$ arrestance efficiencies of the M5 + F7 and F7 + F7 filter combinations used in this study are presented in **Table 2**.

FILTER-GRADE EN 779 (CEN 2012)	FILTER-GRADE MERV	$PM_{2.5}$ ARRESTANCE EFFICIENCY (%)	$\overline{\Delta_p}$ (Pa)
M5 + F7	MERV 8 + 12	77.5%	230
F7 + F7	MERV 12 + 12	91.0%	300

Table 2: Total $PM_{2.5}$ arrestance efficiencies and pressure drops for an outdoor air (OA) ventilation airflow of 0.944 m³/s (during occupied hours).

Note: MERV = minimum efficiency reporting values.

All the simulations of the IAQ and fan's energy consumption model were conducted using scripts in MATLAB programming language. The inputs and outputs of the IAQ and fan's energy modeling are summarised in **Figure 3**.

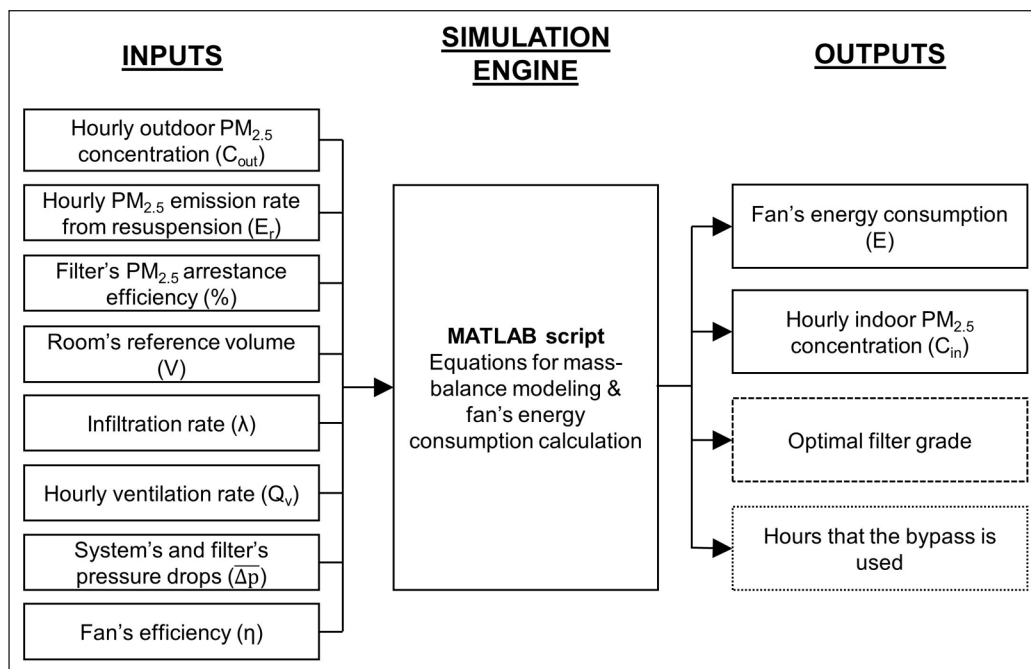


Figure 3: Summary of the inputs to and outputs from the simulation engine's inputs and outputs.

3. RESULTS AND DISCUSSION

3.1 OUTDOOR AND INDOOR PM_{2.5} CONCENTRATIONS

As shown in *Figure 4*, the outdoor PM_{2.5} levels differed across the cities, so the selected filters also varied according to the procedure described in EN 16798-3 (2017). *Figure 5* presents the average outdoor and indoor PM_{2.5} levels categorised based on the outdoor air classification categories and corresponding filters used in baseline scenario.

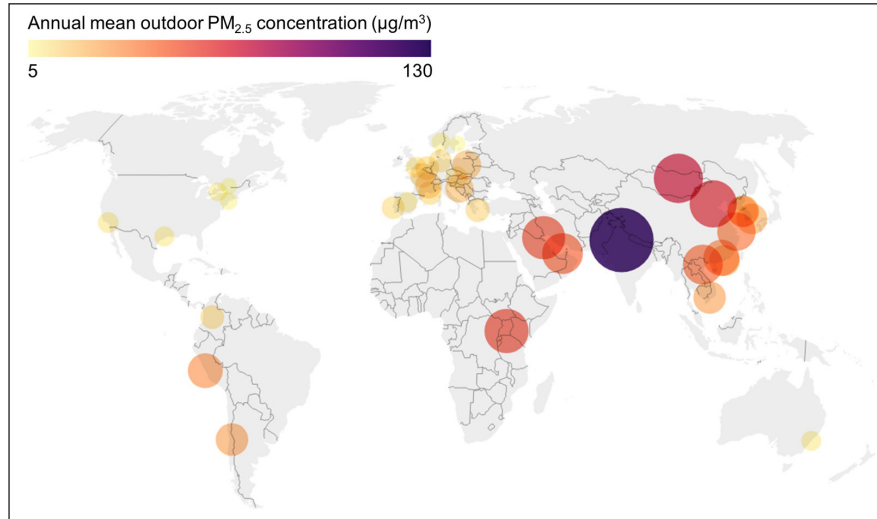


Figure 4: Representative annual mean outdoor PM_{2.5} concentrations in the investigated cities.

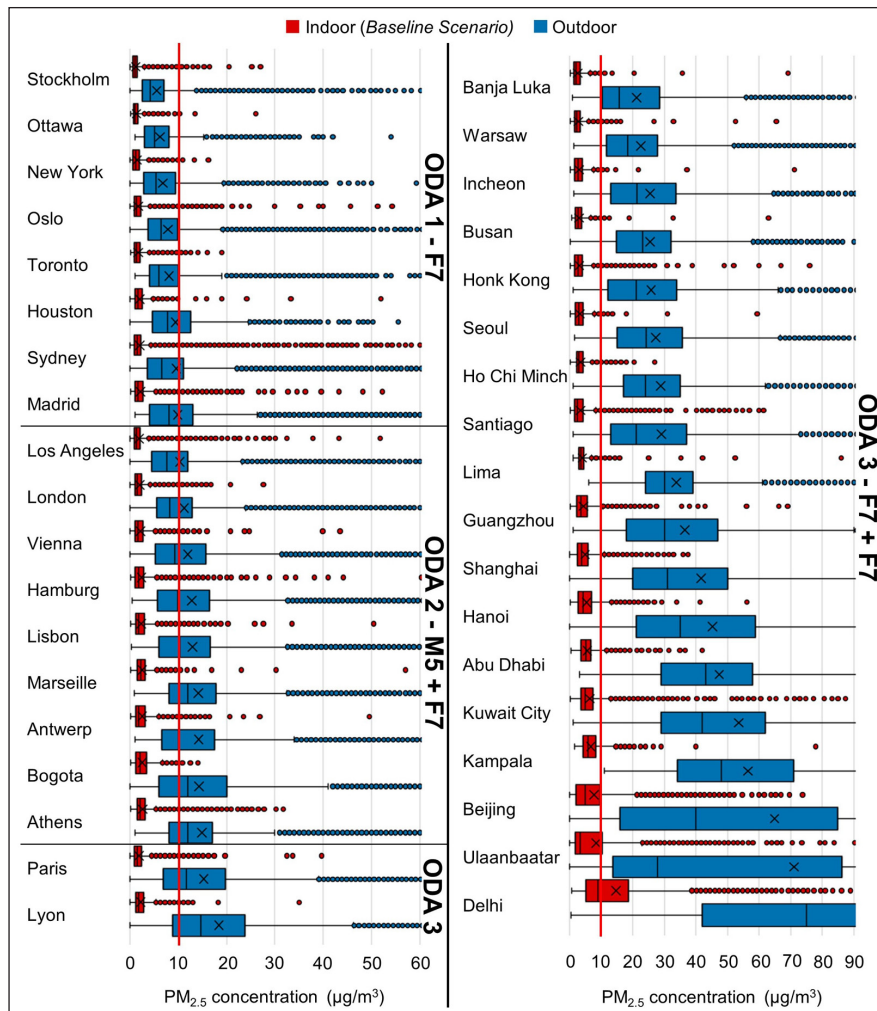


Figure 5: Outdoor and indoor PM_{2.5} concentrations in relation to outdoor air classifications (ODA) (EN 16798-3 2017) and corresponding filter grades for baseline scenario (air filtration according to EN 16798-3).

Note: Box plots indicate the minimum, 1st quartile, mean (black cross), median and 3rd quartile, maximum and outlier values. The cross-cutting red line indicates the threshold for the annual mean concentration (10 µg/m³) imposed by WHO (2006) guidelines.

For the baseline scenario, it was observed that filters recommended by EN 16798-3 (2017) were able to maintain the indoor $PM_{2.5}$ levels in compliance with the WHO's (2006) air quality guidelines for the majority of the investigated cities. As shown in **Figure 5**, the average indoor $PM_{2.5}$ concentrations were $1.7 \mu\text{g}/\text{m}^3$ for ODA 1, $2.2 \mu\text{g}/\text{m}^3$ for ODA 2, and $4.8 \mu\text{g}/\text{m}^3$ for ODA 3 areas. These results were expected, given that the EN 16798-3 (2017) is the most stringent available standard for filter selection. The compliance with the indoor $PM_{2.5}$ levels was not achieved only in Delhi (India), Ulaanbaatar (Mongolia) and Beijing (China). For Ulaanbaatar and Beijing, the maximum 24-h limit of $25 \mu\text{g}/\text{m}^3$ was exceeded more than three times. In the case where only annual average outdoor $PM_{2.5}$ data were used, it would be impossible to detect this non-compliance. In Delhi, both the annual mean and the 24-h $PM_{2.5}$ limits were not compliant with the WHO (2006) guidelines. These results reveal that the process for the OA filters selection proposed by EN 16798-3 (2017) is able to select filters that can sufficiently protect the occupants of non-residential buildings from high exposures to outdoor originating $PM_{2.5}$ for all European cities and in the majority of non-European cities. However, this does not fully apply to cities with severe continuous or temporary air pollution episodes.

Figure 6 summarises the annual indoor $PM_{2.5}$ concentrations in the selected cities resulting from the three different outdoor air filtration scenarios. The optimum scenario, which aims to balance indoor $PM_{2.5}$ exposures and energy use, increased the indoor $PM_{2.5}$ concentrations relative to the baseline scenario in almost every city. Exceptions were Kuwait City, Beijing, Ulaanbaatar and Delhi, where higher grade filters were selected to maintain compliance with the WHO's air

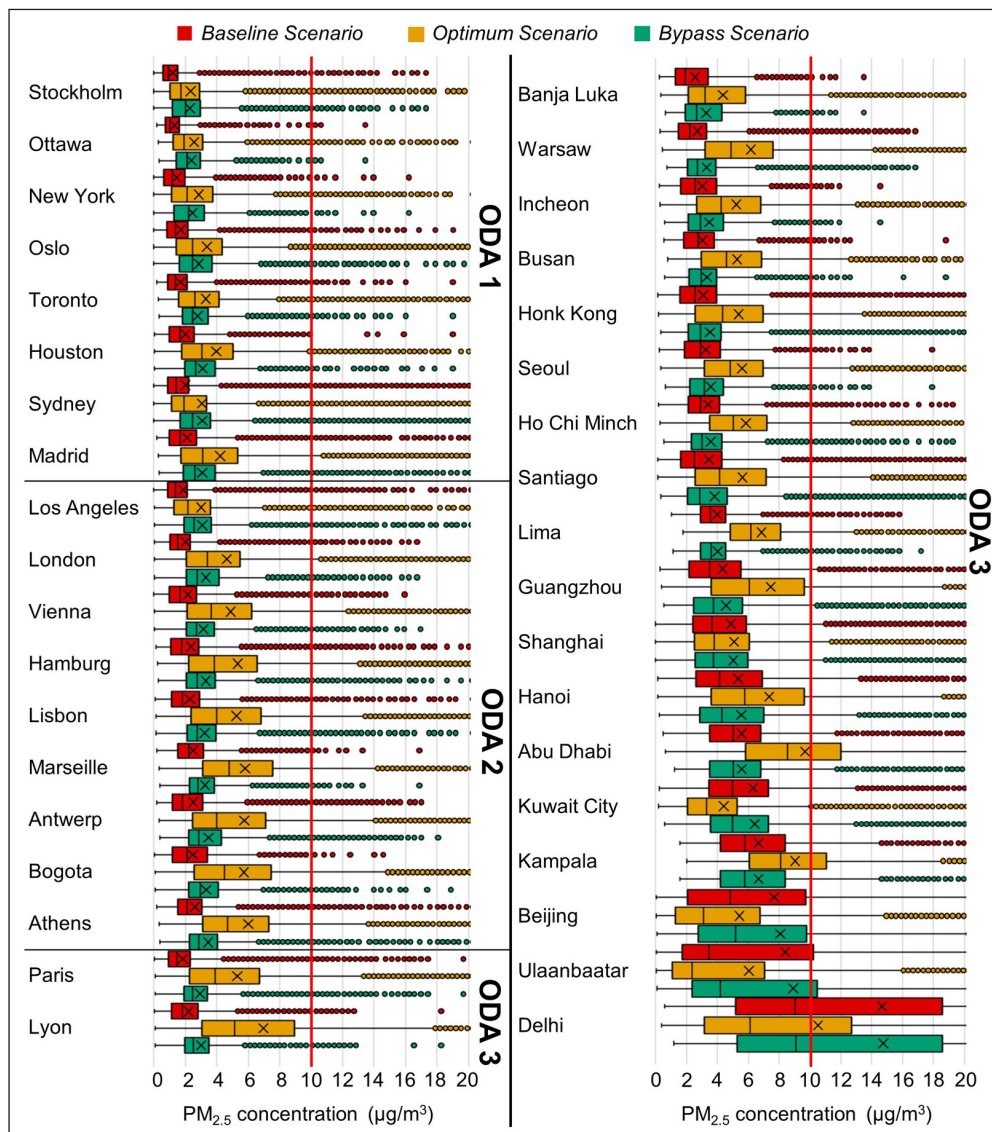


Figure 6: Indoor $PM_{2.5}$ concentration in relation to outdoor air classifications (ODA) (EN 16798-3 2017) and as the result of the three air filtration scenarios.

Note: Box plots indicate the minimum, 1st quartile, mean (black cross), median and 3rd quartile, maximum and outlier values. The cross-cutting red line indicates the threshold for the annual mean concentration ($10 \mu\text{g}/\text{m}^3$) imposed by WHO (2006) guidelines.

quality guideline. The annual average indoor $PM_{2.5}$ concentrations in the optimum scenario were $3.2 \mu\text{g}/\text{m}^3$ for ODA 1, $5.2 \mu\text{g}/\text{m}^3$ for ODA 2, and $6.4 \mu\text{g}/\text{m}^3$ for ODA 3 areas. Despite the optimum scenario increasing the indoor $PM_{2.5}$ levels relative to the baseline scenario, the indoor air usually remained compliant with the WHO (2006) guidelines. Exceptions again were Beijing, Ulaanbaatar and Delhi, where even the high-efficiency particulate arrestance (HEPA) filter (99.7% $PM_{2.5}$ arrestance efficiency) failed to prevent the excess penetration of outdoor $PM_{2.5}$. In these cases, airflow infiltration through cracks in the building envelope played a critical role. This highlights that in severely polluted cities, the selection of an OA filter alone cannot eliminate the problem of outdoor $PM_{2.5}$ penetration, and that filtration should be combined with other measures, such as the appropriate airtightness of the building.

As shown in **Figure 6**, the bypass scenario expectedly increased the indoor $PM_{2.5}$ concentration relative to the baseline scenario. The $PM_{2.5}$ levels in the bypass scenario were on average $2.7 \mu\text{g}/\text{m}^3$ for ODA 1, $3.2 \mu\text{g}/\text{m}^3$ for ODA 2, and $5.2 \mu\text{g}/\text{m}^3$ for ODA 3 areas.

The compliance with the WHO's (2006) air quality guidelines remained equivalent across the baseline, optimum and bypass scenarios. Relative to the baseline scenario, on average, the optimum scenario led to greater increases in the indoor $PM_{2.5}$ levels compared with the bypass scenario. Notably, indoor $PM_{2.5}$ concentrations remained substantially below the WHO limits also for the optimum and bypass scenarios. This clearly indicates that when the filtration recommended by EN 16798-3 (2017) is applied, the air is unnecessarily over-filtered for the majority of the time and in the majority of cities.

The created typical outdoor air pollution profiles were validated regarding their ability to select representative data and maintain the variations of outdoor $PM_{2.5}$. **Figure S1** in the supplemental data online presents the values of the FS statistics, which were used for this validation. **Figure S2** online presents the $PM_{2.5}$ concentrations of a selected location as a time-series plot, where seasonal/diurnal/hourly $PM_{2.5}$ variations can be observed.

The presented results were calculated assuming that the infiltration rate was 0.1/h. Section 3 in the supplemental data online summarises the information regarding the contribution of the infiltration in the indoor $PM_{2.5}$ levels. In particular, **Figure S3** online presents the annual average $PM_{2.5}$ indoor levels for the baseline scenario by highlighting the contribution of infiltration. It was observed the infiltration becomes more critical as the outdoor pollution levels and the filter's efficiency increase. Furthermore, **Tables S3, S4** and **S6** online present the indoor mean annual $PM_{2.5}$ concentrations for the baseline, optimum and bypass scenarios, respectively, when different infiltration air change rates were applied. For the baseline and bypass scenarios, the higher infiltration rates led to higher indoor concentrations, while in the optimum scenario, the indoor concentrations were increased in the cases where the selected optimum filter remained the same. **Table S5** online summarises the selected optimum filter grade for the optimum scenario per examined location under different infiltration air change rates.

3.2 FAN'S ENERGY CONSUMPTION

Figure 7 shows the calculated energy consumption required by the fan to overcome the pressure drops of the ventilation system in the three analysed scenarios. For the baseline scenario, the annual energy consumptions were 5.74 , 6.3 and $6.79 \text{ kWh}/\text{m}^2 \text{ year}$ when F7, M5 + F7, and F7 + F7 filters were used, respectively.

With the exception of the severely polluted cities of Delhi, Ulaanbaatar, Beijing and Kuwait City, where HEPA filters were selected, the optimum scenario had a substantially lower energy consumption by fans relative to the baseline scenario in all the investigated cities. In addition, the bypass scenario also reduced energy consumption relative to the baseline scenario in all cases worldwide, except for Kampala (Uganda), where the outdoor $PM_{2.5}$ concentration never dropped below $10 \mu\text{g}/\text{m}^3$.

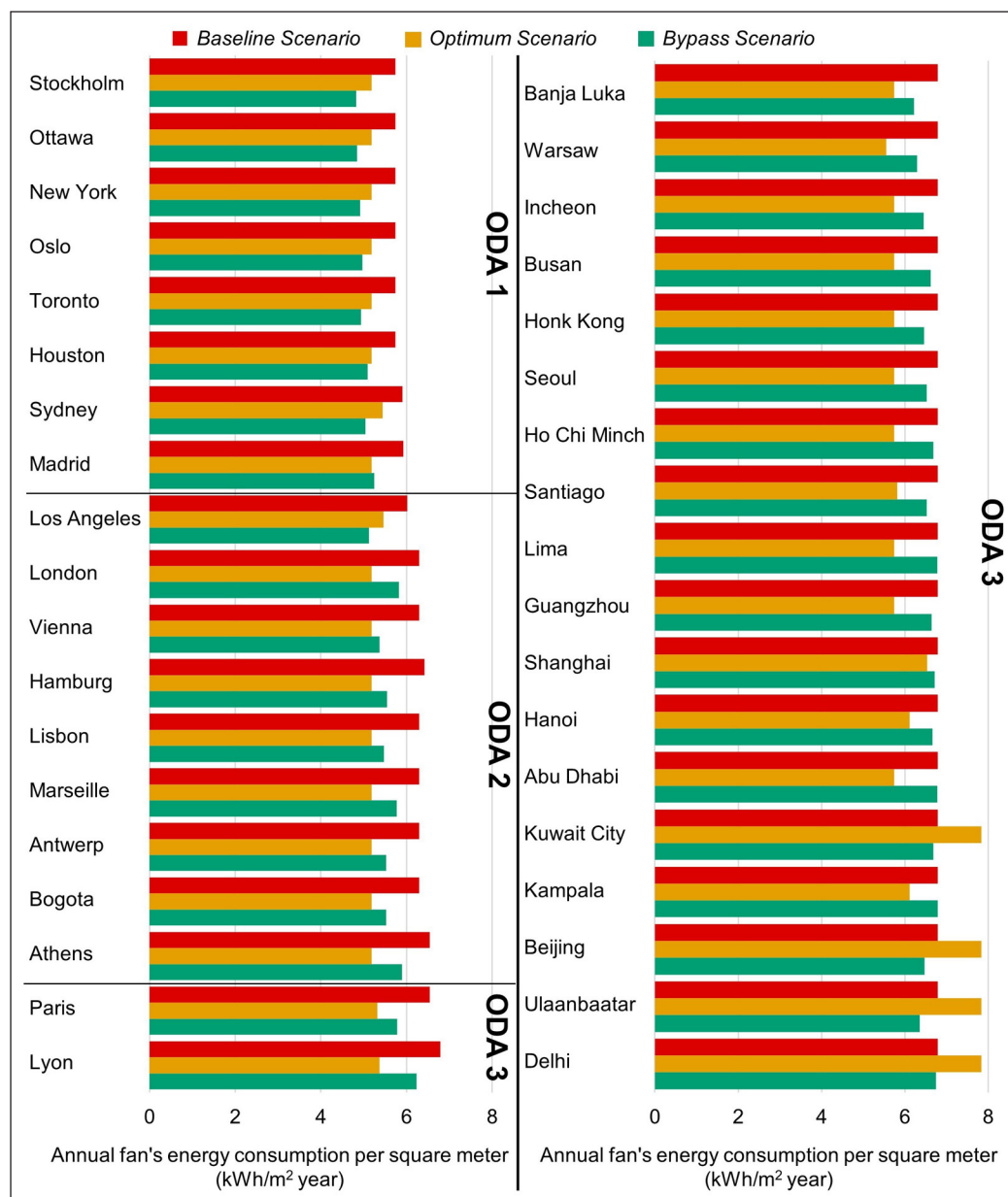


Figure 7: Annual energy consumption of the fans to overcome the total pressure drops of the ventilation system as a result of the three different filtration scenarios.

As presented in **Figure 8**, the relative reduction in the annual energy consumption by fans for the optimum scenario was on average 12% for ODA 3, 17% for ODA 2, and 9% for areas with ODA 1. The bypass scenario achieved an average relative reduction in the energy consumption of 4% for ODA 3, 14% for ODA 2, and 14% for ODA 1 areas. This reveals that the bypass scenario was more efficient for energy savings in areas with low $PM_{2.5}$ pollution levels (ODA 1), while the optimum scenario was more efficient for the areas with moderate or high $PM_{2.5}$ pollution levels. In the cities with low $PM_{2.5}$ concentrations, the duration of time when the filter bypass can be used was significantly higher compared with the cities with higher $PM_{2.5}$ levels (**Figure 9**), which led to higher energy savings in these cases. Without access to continuous outdoor $PM_{2.5}$ data, it would be impossible to reveal this potential for energy savings.

The demonstrated energy-saving potential could be significant in nearly zero-energy buildings with a primary energy demand of 80–100 kWh/m² year (Economidou *et al.* 2020). In these buildings, the reduction in the total primary energy demand can reach up to 3.7% when the electricity is not produced on-site by renewables, and if the proposed primary energy factor for Europe, which is 2.1 (-), is considered (European Commission 2021). Moreover, the use of bypasses can also extend

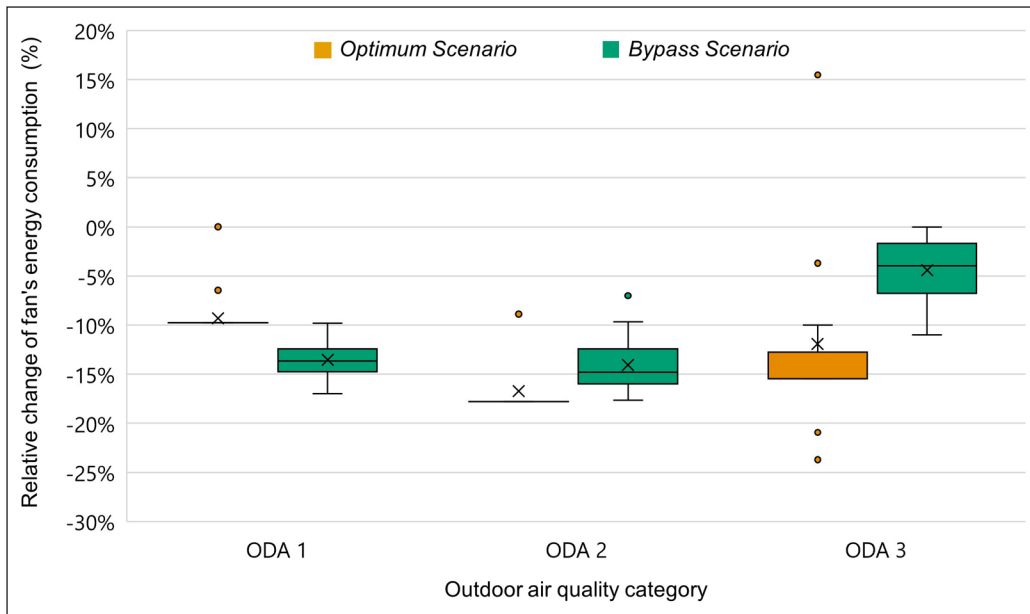


Figure 8: Change of the annual total fan's energy consumption for the optimum and bypass scenarios relative to the baseline scenario.

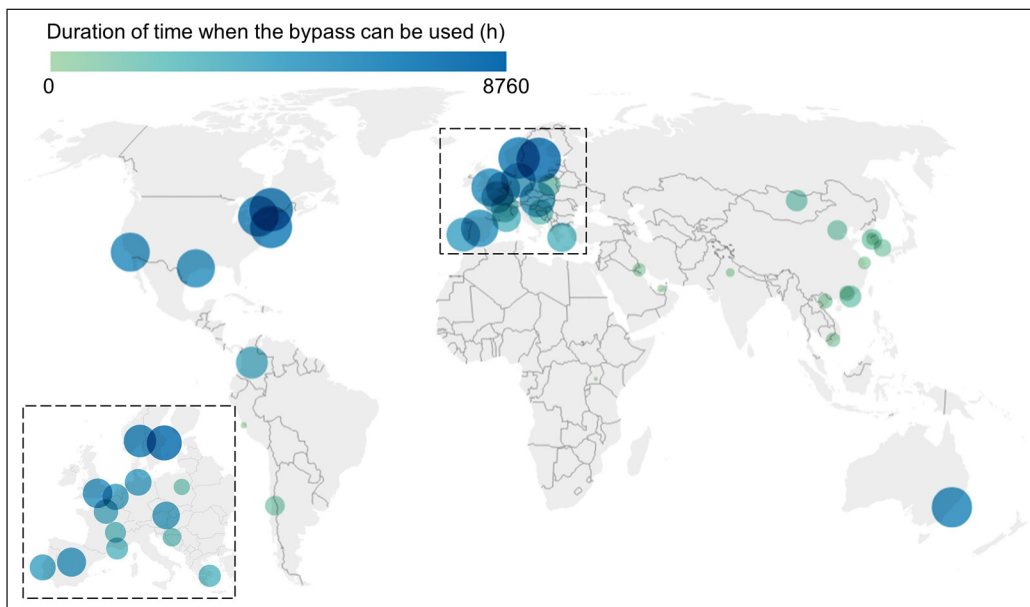


Figure 9: Map presenting the duration of time in a year when the filter bypass can be used at each investigated city.

the filter's lifetime and reduce maintenance costs (EN 16798-3 2017). Hence, the designers should give greater attention to the selection of OA filters in order to design more energy-efficient and healthy buildings.

3.3 TRADE-OFFS BETWEEN ENERGY SAVINGS AND INDOOR $PM_{2.5}$ CONCENTRATIONS

As the energy savings resulting from less efficient particle filtration are associated with the greater penetration of outdoor $PM_{2.5}$, the optimum and bypass scenarios were examined to ascertain their ability to save energy with the minimum increase in indoor $PM_{2.5}$ while remaining compliant with the WHO (2006) air quality guidelines. The ratio of the annual fan's energy consumption reduction (ΔE) to the indoor $PM_{2.5}$ increase ($\Delta PM_{2.5}$) was calculated. The results (**Figure 10**) reveal that the bypass scenario was more efficient in reducing the fan's energy consumption without significantly increasing the indoor $PM_{2.5}$ levels, as the values of this ratio were significantly higher in all the cities except one.

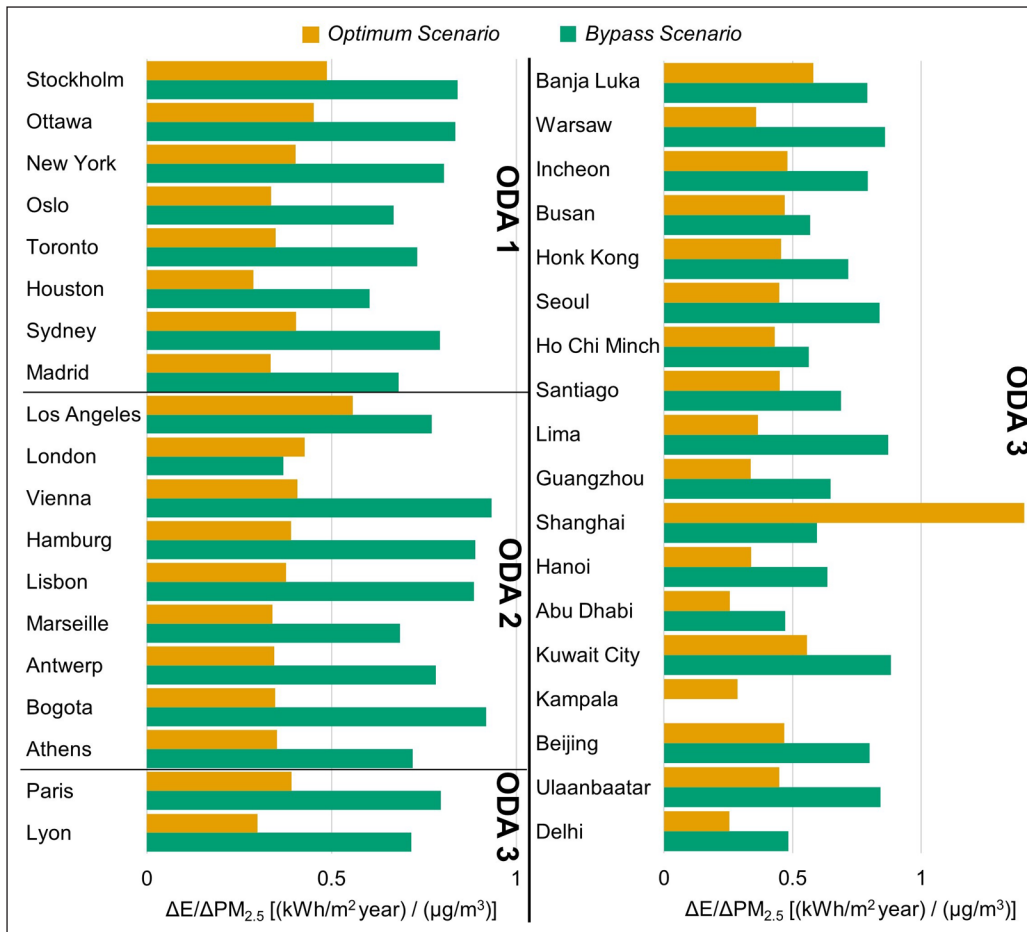


Figure 10: Ratio between average energy savings of the fan and the increase in indoor average PM_{2.5} levels [(kWh/m² year)/(µg/m³)] for the optimum and bypass scenarios in each investigated city.

Note: Data in the city of Kampala were partially presented as the $\Delta E/\Delta PM_{2.5}$ ratio and cannot be defined for the bypass scenario. The outdoor PM_{2.5} concentration was never <10 µg/m³, and the bypass was never activated. Hence, both ΔE and $\Delta PM_{2.5}$ were equal to zero.

4 SCOPE AND LIMITATIONS

In interpreting the results of the present study, several limitations should be acknowledged. This exploratory simulation study demonstrated that there is a potential for energy savings in the ventilation fans when the outdoor air pollution is considered more comprehensively. The results from the simulations were cross-validated, as the results for the indoor PM_{2.5} concentrations in North American cities are comparable with the previously reported results in the US when the F7 (minimum efficiency reporting values (MERV) 12) filter was applied (Ben-David & Waring 2018). In addition, the total energy consumption of the fan was in the range of the energy consumption of ventilation systems reported in previous studies (Bonato *et al.* 2020; Flourentzou & Pantet 2015). However, only one building type, infiltration rate and occupancy profile with a specific OA ventilation system were simulated using the two different energy-saving methods. Therefore, the results could differ for different building types, ventilation systems, indoor sources and airflow rates. Future studies should explore other energy-saving methods in OA filtration. It is recommended that designers carefully investigate and provide an ad hoc solution for OA filtration of each building case.

Additionally, the methodology used in this study for the representative data selection (Chen *et al.* 2019, 2020) excluded months with extreme concentrations (either too low or too high), as they are not considered typical. The goal of the study was to reveal the opportunities for energy savings under typical conditions. Thus, extreme PM_{2.5} pollution events such as wildfires (Brambilla *et al.* 2021) were not specifically targeted by the analyses.

In addition, the present study focused on only one air pollutant: PM_{2.5}. Particles with different aerodynamic diameters, such as coarse particles (PM₁₀), are known to have adverse health effects, but are less significant compared with PM_{2.5} (Kappos *et al.* 2004). Furthermore, ultrafine particles are also known to provoke deleterious health outcomes (Chen *et al.* 2016), but since the available

data are sparse, this particle size range was not analysed. Other gaseous pollutants with well-known effects on human health (Logue *et al.* 2012) should also be considered in future studies. Furthermore, the present study considered that if the indoor PM_{2.5} levels comply with the WHO (2006) guidelines, there are no significant adverse health effects. In fact, some studies suggest that there is no clear lower limit for PM_{2.5} exposures that can be considered completely safe (WHO 2013). In addition, the last update of the WHO (2021) air quality guidelines recommends a lower limit of 5 µg/m³ for the annual mean PM_{2.5} concentration.

5 CONCLUSIONS

The present study investigated the impact of three air filtration scenarios on energy consumption and indoor particulate matter PM_{2.5} levels. The application of the outdoor air (OA) filter selection methodology recommended by the EN 16798-3 (2017) building standard (the baseline scenario) was found to provide acceptable indoor PM_{2.5} concentrations for all the investigated areas, except for the cities of Beijing, Ulaanbaatar and Delhi.

It was found that energy savings, on average from 4% to 14%, for the fan can be achieved if a bypass process is used that combines the baseline filter with a filter bypass. This maintains the indoor PM_{2.5} below the WHO's limits.

The energy-saving potential of the bypass scenario was greater in areas with low annual average PM_{2.5} concentrations (<10 µg/m³), where it achieved average energy reductions of up to 14%, whereas the optimum scenario could save on average 9% of the total fan's energy. This indicates that in areas with clean or periodically polluted outdoor air, the filter bypass offers significant potential for energy savings without compromising inhalation exposures indoors. In cities with high PM_{2.5} levels, the average energy savings were 12% for the optimum scenario and 4% for the bypass scenario. The achieved energy savings indicate that the filters proposed by even the most advanced existing building standards result in unnecessary over-filtration of the OA and lead to a waste of energy by the fans in the majority of the investigated cities around the world. Overall, in 34 out of 37 investigated cities, the bypass scenario offered the best trade-offs between energy conservation and limiting indoor PM_{2.5} exposures.

The present study highlights the need for building designers to consider a dynamic variation of local outdoor PM_{2.5} when selecting the OA filtration in order to reduce energy demand from the mechanical ventilation fans without compromising indoor air quality. Future investigations should encompass a broader range of building typologies, ventilation systems and indoor sources in order to develop the improved selection matrix between indoor PM_{2.5} exposures and energy-efficient filtration techniques. Such efforts promise to aid designers and engineers to implement efficient ventilation systems that can protect occupants from unwanted outdoor PM_{2.5} exposures while, in parallel, cutting energy consumption.

AUTHOR AFFILIATIONS

Evangelos Belias  orcid.org/0000-0003-3308-950X

Human-Oriented Built Environment Lab, School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, CH

Dusan Licina  orcid.org/0000-0001-5945-0872

Human-Oriented Built Environment Lab, School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, CH

AUTHOR CONTRIBUTIONS

Conceptualisation: E.B. and D.L.; methodology: E.B. and D.L.; data collection: E.B.; modeling, data analysis and visualisations: E.B.; original draft preparation: E.B.; review and editing: D.L.; and funding acquisition: E.B. and D.L. Both authors have read and agreed to the published version of the manuscript.

The authors have no competing interests to declare.

DATA AVAILABILITY

Data are available from the authors upon request.

FUNDING INFORMATION

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement number 754354.

SUPPLEMENTAL DATA

Supplemental data for this article can be accessed at: <https://doi.org/10.5334/bc.153.s1>.

REFERENCES

- Anderson, J., Granat, M. H., Williams, A. E., & Nester, C.** (2019). Exploring occupational standing activities using accelerometer-based activity monitoring. *Ergonomics*, 62(8), 1055–1065. DOI: <https://doi.org/10.1080/00140139.2019.1615640>
- ASHRAE.** (2017). *ANSI/ASHRAE Standard 52.2-2017—Method of testing general ventilation air-cleaning devices for removal efficiency by particle size*. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). https://www.ashrae.org/File%20Library/Technical%20Resources/COVID-19/52_2_2017_COVID-19_20200401.pdf
- ASHRAE.** (2019). *ANSI/ASHRAE Standard 62.1-2019—Ventilation for acceptable indoor air quality*. CRC Press. DOI: <https://doi.org/10.1201/9780849338960.ch6>
- Azimi, P., Zhao, D., & Stephens, B.** (2014). Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin. *Atmospheric Environment*, 98, 337–346. DOI: <https://doi.org/10.1016/j.atmosenv.2014.09.007>
- Ben-David, T., & Waring, M. S.** (2016). Impact of natural versus mechanical ventilation on simulated indoor air quality and energy consumption in offices in fourteen U.S. cities. *Building and Environment*, 104, 320–336. DOI: <https://doi.org/10.1016/j.buildenv.2016.05.007>
- Ben-David, T., & Waring, M. S.** (2018). Interplay of ventilation and filtration: Differential analysis of cost function combining energy use and indoor exposure to PM 2.5 and ozone. *Building and Environment*, 128, 320–335. DOI: <https://doi.org/10.1016/j.buildenv.2017.10.025>
- Bonato, P., D'Antoni, M., & Fedrizzi, R.** (2020). Modelling and simulation-based analysis of a façade-integrated decentralized ventilation unit. *Journal of Building Engineering*, 29, 101183. DOI: <https://doi.org/10.1016/j.jobbe.2020.101183>
- Brakenridge, C. L., Fjeldsoe, B. S., Young, D. C., Winkler, E. A. H., Dunstan, D. W., Straker, L. M., & Healy, G. N.** (2016). Evaluating the effectiveness of organisational-level strategies with or without an activity tracker to reduce office workers' sitting time: A cluster-randomised trial. *International Journal of Behavioral Nutrition and Physical Activity*, 13(1), 115. DOI: <https://doi.org/10.1186/s12966-016-0441-3>
- Brambilla, A., Candido, C., Sangiorgio, M. F., Gocer, O., & Gocer, K.** (2021). Can commercial buildings cope with Australian bushfires? An IAQ analysis. *Buildings & Cities*, 2(1), 583–598. DOI: <https://doi.org/10.5334/bc.87>
- CEN.** (2012). *BS EN 779: Particulate air filters for general ventilation—Determination of the filtration performance*. European Committee for Standardization (CEN). <https://shop.bsigroup.com/products/particulate-air-filters-for-general-ventilation-determination-of-the-filtration-performance-1/standard>
- CEN/TR.** (2017). *EN 16798-4: Energy performance of buildings—Ventilation for buildings—Part 4: Interpretation of the requirements in EN 16798-3—For non-residential buildings—Performance requirements for ventilation and room-conditioning systems (Modules M5-1, M5-4)*. European Committee for Standardization (CEN). <https://www.en-standard.eu/pd-cen-tr-16798-4-2017-energy-performance-of-buildings-ventilation-for-buildings-interpretation-of-the-requirements-in-en-16798-3-for-non-residential-buildings-performance-requirements-for-ventilation-and-room-conditioning-systems-modules-m5-1-m5-4/>

- Chen, C., & Zhao, B.** (2011). Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. *Atmospheric Environment*, 45(2), 275–288. DOI: <https://doi.org/10.1016/j.atmosenv.2010.09.048>
- Chen, C., Zhao, B., Zhou, W., Jiang, X., & Tan, Z.** (2012). A methodology for predicting particle penetration factor through cracks of windows and doors for actual engineering application. *Building and Environment*, 47, 339–348. DOI: <https://doi.org/10.1016/j.buildenv.2011.07.004>
- Chen, J., Augenbroe, G., Zeng, Z., & Song, X.** (2020). Regional difference and related cooling electricity savings of air pollutant affected natural ventilation in commercial buildings across the US. *Building and Environment*, 172, 106700. DOI: <https://doi.org/10.1016/j.buildenv.2020.106700>
- Chen, J., Brager, G. S., Augenbroe, G., & Song, X.** (2019). Impact of outdoor air quality on the natural ventilation usage of commercial buildings in the US. *Applied Energy*, 235, 673–684. DOI: <https://doi.org/10.1016/j.apenergy.2018.11.020>
- Chen, R., Hu, B., Liu, Y., Xu, J., Yang, G., Xu, D., & Chen, C.** (2016). Beyond PM_{2.5}: The role of ultrafine particles on adverse health effects of air pollution. *Biochimica et Biophysica Acta—General Subjects*, 1860(12), 2844–2855. DOI: <https://doi.org/10.1016/j.bbagen.2016.03.019>
- CIBSE.** (2020). *CIBSE TM40: Health and wellbeing in building services*. Chartered Institution of Building Services Engineers (CIBSE). <https://www.cibse.org/Knowledge/CIBSE-TM/TM40-2019-Health-Issues-and-Wellbeing-in-Building-Services>
- DOE.** (2021). *Prototype building models*. US Department of Energy (DOE). <https://www.energycodes.gov/prototype-building-models>
- Dutheil, F., Baker, J. S., & Navel, V.** (2020). COVID-19 as a factor influencing air pollution? *Environmental Pollution*, 263, 114466. DOI: <https://doi.org/10.1016/j.envpol.2020.114466>
- Dutton, S. M., Banks, D., Brunswick, S. L., & Fisk, W. J.** (2013). Health and economic implications of natural ventilation in California offices. *Building and Environment*, 67, 34–45. DOI: <https://doi.org/10.1016/j.buildenv.2013.05.002>
- Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., & Castellazzi, L.** (2020). Review of 50 years of EU energy efficiency policies for buildings. *Energy and Buildings*, 225, 110322. DOI: <https://doi.org/10.1016/j.enbuild.2020.110322>
- EN 15265.** (2007). *EN 15265: Thermal performance of buildings—Calculation of energy needs for space heating and cooling using dynamic methods—General criteria and validation procedures*. European Committee for Standardization (CEN). <https://standards.iteh.ai/catalog/standards/cen/3b7d56e1-21c8-4f7f-8fe0-eb9a39c80893/en-15265-2007>
- EN 16798-1.** (2019). *EN 16798-1: Energy performance of buildings—Ventilation for buildings—Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics—Module M1-6*. European Committee for Standardization (CEN). <https://standards.iteh.ai/catalog/standards/cen/b4f68755-2204-4796-854a-56643dfcfe89/en-16798-1-2019>
- EN 16798-3.** (2017). *EN 16798-3: Energy performance of buildings—Ventilation for buildings—Part 3: For non-residential buildings—Performance requirements for ventilation and room-conditioning systems (Modules M5-1, M5-4)*. European Committee for Standardization (CEN). <https://standards.iteh.ai/catalog/standards/cen/9e321a29-86c6-4226-8331-0c62c69f1924/en-16798-3-2017>
- EN ISO 16890-1.** (2016). *EN ISO 16890-1: Air filters for general ventilation—Part 1: Technical specifications, requirements and classification system based upon particulate matter efficiency (ePM) (ISO 16890-1:2016)*. European Committee for Standardization (CEN). <https://www.iso.org/standard/57864.html>
- European Commission.** (2021). *Directive of the European Parliament and of the Council on energy efficiency*. European Commission. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en
- Eurovent 4/11.** (2014). *Eurovent 4/11: Energy efficiency classification of air filters for general ventilation purposes (second)*. Eurovent. <https://eurovent.eu/?q=content/eurovent-411-2014-energy-efficiency-classification-air-filters-general-ventilation-purposes>
- Eurovent 4/21.** (2018). *Eurovent 4/21: Energy efficiency evaluation of air filters for general ventilation purposes (third)*. Eurovent. <https://eurovent.eu/?q=content/eurovent-421-2018-energy-efficiency-evaluation-air-filters-general-ventilation-purposes>
- Eurovent 4/23.** (2018). *Eurovent 4/23: Selection of EN ISO 16890 rated air filter classes for general ventilation applications (second)*. Eurovent. <https://eurovent.eu/sites/default/files/field/file/Eurovent%20REC%204-23%20-%20Selection%20of%20EN%20ISO%2016890%20rated%20air%20filter%20classes%20-%202017.pdf>

- Feng, S., Gao, D., Liao, F., Zhou, F., & Wang, X. (2016). The health effects of ambient PM_{2.5} and potential mechanisms. *Ecotoxicology and Environmental Safety*, 128, 67–74. DOI: <https://doi.org/10.1016/j.ecoenv.2016.01.030>
- Finkelstein, J. M., & Schafer, R. E. (1971). Improved goodness-of-fit tests. *Biometrika*, 58(3), 641–645. DOI: <https://doi.org/10.2307/2334400>
- Flourentzou, F., & Pantet, S. (2015). Theoretical and real ventilation heat losses and energy performance in low energy buildings. In *36th AIVC—5th TightVent—3rd Venticool Conference Proceedings*, 10.
- Gakidou, E., Afshin, A., Abajobir, A. A., Abate, K. H., Abbafati, C., Abbas, K. M., Abd-Allah, F., Abdulle, A. M., Abera, S. F., Aboyans, V., Abu-Raddad, L. J., Abu-Rmeileh, N. M. E., Abyu, G. Y., Adedeji, I. A., Adetokunboh, O., Afarideh, M., Agrawal, A., Agrawal, S., Ahmadieh, H., ... Murray, C. J. L. (2017). Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2016: A systematic analysis for the Global Burden of Disease Study 2016. *Lancet*, 390(10100), 1345–1422. DOI: [https://doi.org/10.1016/S0140-6736\(17\)32366-8](https://doi.org/10.1016/S0140-6736(17)32366-8)
- Hall, I. J., Prairie, R., Anderson, H., & Boes, E. (1978). *Generation of typical meteorological years for 26 SOLMET stations*. Sandia Laboratories. <https://books.google.ch/books?id=LfHJnQEACAAJ>
- Hua, J., Yin, Y., Peng, L., Du, L., Geng, F., & Zhu, L. (2014). Acute effects of black carbon and PM_{2.5} on children asthma admissions: A time-series study in a Chinese city. *Science of The Total Environment*, 481, 433–438. DOI: <https://doi.org/10.1016/j.scitotenv.2014.02.070>
- Jancey, J., Tye, M., McGann, S., Blackford, K., & Lee, A. H. (2014). Application of the Occupational Sitting and Physical Activity Questionnaire (OSPAQ) to office based workers. *BMC Public Health*, 14(1), 762. DOI: <https://doi.org/10.1186/1471-2458-14-762>
- Junninen, H., Niska, H., Tuppurainen, K., Ruuskanen, J., & Kolehmainen, M. (2004). Methods for imputation of missing values in air quality data sets. *Atmospheric Environment*, 38(18), 2895–2907. DOI: <https://doi.org/10.1016/j.atmosenv.2004.02.026>
- Kappos, A. D., Bruckmann, P., Eikmann, T., Englert, N., Heinrich, U., Höpfe, P., Koch, E., Krause, G. H. M., Kreyling, W. G., Raufuss, K., Rombout, P., Schulz-Klemp, V., Thiel, W. R., & Wichmann, H.-E. (2004). Health effects of particles in ambient air. *International Journal of Hygiene and Environmental Health*, 207(4), 399–407. DOI: <https://doi.org/10.1078/1438-4639-00306>
- Li, A., Ren, T., Yang, C., Lv, W., & Zhang, F. (2017). Study on particle penetration through straight, L, Z and wedge-shaped cracks in buildings. *Building and Environment*, 114, 333–343. DOI: <https://doi.org/10.1016/j.buildenv.2016.12.024>
- Liu, G., Xiao, M., Zhang, X., Gal, C., Chen, X., Liu, L., Pan, S., Wu, J., Tang, L., & Clements-Croome, D. (2017). A review of air filtration technologies for sustainable and healthy building ventilation. *Sustainable Cities and Society*, 32, 375–396. DOI: <https://doi.org/10.1016/j.scs.2017.04.011>
- Liu, J., Han, Y., Tang, X., Zhu, J., & Zhu, T. (2016). Estimating adult mortality attributable to PM_{2.5} exposure in China with assimilated PM_{2.5} concentrations based on a ground monitoring network. *Science of The Total Environment*, 568, 1253–1262. DOI: <https://doi.org/10.1016/j.scitotenv.2016.05.165>
- Logue, J. M., Price, P. N., Sherman, M. H., & Singer, B. C. (2012). A method to estimate the chronic health impact of air pollutants in U.S. residences. *Environmental Health Perspectives*, 120(2), 216–222. DOI: <https://doi.org/10.1289/ehp.1104035>
- Martins, N. R., & Carrilho da Graça, G. (2018). Impact of PM_{2.5} in indoor urban environments: A review. *Sustainable Cities and Society*, 42, 259–275. DOI: <https://doi.org/10.1016/j.scs.2018.07.011>
- Mimura, T., Ichinose, T., Yamagami, S., Fujishima, H., Kamei, Y., Goto, M., Takada, S., & Matsubara, M. (2014). Airborne particulate matter (PM_{2.5}) and the prevalence of allergic conjunctivitis in Japan. *Science of The Total Environment*, 487, 493–499. DOI: <https://doi.org/10.1016/j.scitotenv.2014.04.057>
- Montgomery, J. F., Green, S. I., Rogak, S. N., & Bartlett, K. (2012). Predicting the energy use and operation cost of HVAC air filters. *Energy and Buildings*, 47, 643–650. DOI: <https://doi.org/10.1016/j.enbuild.2012.01.001>
- Nazaroff, W. W. (2018). The particles around us. *Indoor Air*, 28(2), 215–217. DOI: <https://doi.org/10.1111/ina.12444>
- Oh, H.-J., Nam, I.-S., Yun, H., Kim, J., Yang, J., & Sohn, J.-R. (2014). Characterization of indoor air quality and efficiency of air purifier in childcare centers, Korea. *Building and Environment*, 82, 203–214. DOI: <https://doi.org/10.1016/j.buildenv.2014.08.019>
- Qian, J., Peccia, J., & Ferro, A. R. (2014). Walking-induced particle resuspension in indoor environments. *Atmospheric Environment*, 89, 464–481. DOI: <https://doi.org/10.1016/j.atmosenv.2014.02.035>
- Ren, J., Liu, J., Cao, X., & Hou, Y. (2017). Influencing factors and energy-saving control strategies for indoor fine particles in commercial office buildings in six Chinese cities. *Energy and Buildings*, 149, 171–179. DOI: <https://doi.org/10.1016/j.enbuild.2017.05.061>

- Ruan, T., & Rim, D. (2019). Indoor air pollution in office buildings in mega-cities: Effects of filtration efficiency and outdoor air ventilation rates. *Sustainable Cities and Society*, 49, 101609. DOI: <https://doi.org/10.1016/j.scs.2019.101609>
- Sarianni, D. A., Karakitsios, S. P., & Kermenidou, M. V. (2015). Health impact and monetary cost of exposure to particulate matter emitted from biomass burning in large cities. *Science of The Total Environment*, 524–525, 319–330. DOI: <https://doi.org/10.1016/j.scitotenv.2015.02.108>
- Song, C., He, J., Wu, L., Jin, T., Chen, X., Li, R., Ren, P., Zhang, L., & Mao, H. (2017). Health burden attributable to ambient PM_{2.5} in China. *Environmental Pollution*, 223, 575–586. DOI: <https://doi.org/10.1016/j.envpol.2017.01.060>
- Stephens, B., Brennan, Terry, & Harriman, Lew. (2016). Selecting ventilation air filters to reduce PM_{2.5} of outdoor origin. *ASHRAE Journal*, 9, 12–20.
- Stephens, B., Novoselac, A., & Siegel, J. (2010). The effects of filtration on pressure drop and energy consumption in residential HVAC systems (RP-1299). *HVAC&R Research*, 16(3), 273–294. DOI: <https://doi.org/10.1080/10789669.2010.10390905>
- Thatcher, T. (1995). Deposition, resuspension, and penetration of particles within a residence. *Atmospheric Environment*, 29(13), 1487–1497. DOI: [https://doi.org/10.1016/1352-2310\(95\)00016-R](https://doi.org/10.1016/1352-2310(95)00016-R)
- Tian, Y., Sul, K., Qian, J., Mondal, S., & Ferro, A. R. (2014). A comparative study of walking-induced dust resuspension using a consistent test mechanism. *Indoor Air*, 24(6), 592–603. DOI: <https://doi.org/10.1111/ina.12107>
- Vadoudi, K., & Kelijian, G. (2019). Status of Air filter energy performance and product characteristics. In *40th AIVC—8th TightVent—6th Venticool Conference Proceedings*, 7.
- WHO. (2006). *Air quality guidelines: Global update 2005: Particulate matter, ozone, nitrogen dioxide, and sulfur dioxide*. World Health Organization (WHO). http://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?jsessionid=4283873D40CB19EC7B21F91F3ADF27EE?sequence=1
- WHO. (2013). *Review of evidence on health aspects of air pollution—REVIHAAP project: Final technical report*. World Health Organization (WHO). <https://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report>
- WHO. (2021). *WHO global air quality guidelines: Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. World Health Organization (WHO). <https://apps.who.int/iris/handle/10665/345329>
- Yu, W., Wang, L., Wang, Q., Wang, X., Li, G., Wang, J., & Awbi, H. (2020). Design selection and evaluation method of PM_{2.5} filters for fresh air systems. *Journal of Building Engineering*, 27, 100977. DOI: <https://doi.org/10.1016/j.jobbe.2019.100977>
- Zaatari, M., Novoselac, A., & Siegel, J. (2014). The relationship between filter pressure drop, indoor air quality, and energy consumption in rooftop HVAC units. *Building and Environment*, 73, 151–161. DOI: <https://doi.org/10.1016/j.buildenv.2013.12.010>
- Zhao, D., Azimi, P., & Stephens, B. (2015). Evaluating the long-term health and economic impacts of central residential air filtration for reducing premature mortality associated with indoor fine particulate matter (PM_{2.5}) of outdoor origin. *International Journal of Environmental Research and Public Health*, 12(7), 8448–8479. DOI: <https://doi.org/10.3390/ijerph120708448>
- Zhao, H., & Stephens, B. (2017). Using portable particle sizing instrumentation to rapidly measure the penetration of fine and ultrafine particles in unoccupied residences. *Indoor Air*, 27(1), 218–229. DOI: <https://doi.org/10.1111/ina.12295>
- Zimmer, T. (2019). Comfort IAQ—A new tool to simulate the indoor particulate matter pollution in relation to the chosen supply air filter quality. *E3S Web of Conferences*, 111, 02024. DOI: <https://doi.org/10.1051/e3sconf/201911102024>

TO CITE THIS ARTICLE:

Belias, E., & Licina, D. (2022). Outdoor PM_{2.5} air filtration: optimising indoor air quality and energy. *Buildings and Cities*, 3(1), pp. 186–203. DOI: <https://doi.org/10.5334/bc.153>

Submitted: 10 September 2021

Accepted: 11 March 2022

Published: 06 April 2022

COPYRIGHT:

© 2022 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See <http://creativecommons.org/licenses/by/4.0/>.

Buildings and Cities is a peer-reviewed open access journal published by Ubiquity Press.

