Supply air filtration and fine particle levels in indoor air of occupied dwellings

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ABSTRACT

Indoor Air quality (IAQ) of dwellings is the result of several sources and processes, and the impact of ventilation system is the one amongst many others. Definition and metrics of IAQ are several and we choose in this study to focus on airborne particle levels. Our question was: How the filtration of supply air impacts particle levels in indoor air?

On-site measurement campaigns were carried out in occupied dwellings between 2016 and 2019. Three houses and one flat located in the city and in the countryside were instrumented during three weeks. Two of the dwellings were equipped with balanced mechanical ventilation systems, one with mechanical exhaust air system and the last one with mechanical supply air system. Optical particle counters, measuring in number particle concentrations between 0.3 and 3 µm, were used to monitor particle levels of outdoor air, supply air and extract air, every 30 seconds. Supply air filtration was changed every week in order to follow the impact of the level of filtration on indoor air particle concentrations: fine filter, coarse filter or no filter on supply air. To be able to understand fluctuations over time, occupants were asked to fulfil questionnaires informing about activities (cooking, cleaning, airing, etc.) and room occupancies.

The first finding is that on-site measurement in occupied dwellings can imply strong variations on external parameters, but also on occupant-related sources. It makes it difficult the comparison between measurement periods. Therefore, both time curves and statistical indicators, based on box plot or weekly curves between indoor and outdoor concentrations for each size of particles, have been used to analyze the results. Moreover measurements during occupancy and during night time have been analyzed separately.

Regarding the filter efficiency, on-site measurements of filter penetration index (ratio between supply air and outdoor air concentrations) are consistent with efficiencies measured in the laboratory, for each particle size category. In particular, medium filters have a low impact on particles smaller than 1 µm.

The main conclusion of this study is that indoor air quality does not only depend on the quality of the air entering the dwelling. The behaviors of the occupants, the opening of doors and windows, the cooking activities with, for example, the use of recirculating kitchen hoods are important elements. However, the contribution of the supply air filtration on indoor air particles concentrations is real and positive, linked with the efficiency for each size of particles. We haven't seen much impact, using medium filters, while the impact was positive with fine filters. To keep this impact positive, attention should be drawn to the need for good maintenance of these filters to avoid a decrease in airflow due to clogging, and to air renewal.

KEYWORDS

IAQ, Filtration, On-site measurement, Occupants behavior, Particles

1 INTRODUCTION

Indoor air is a complex mixture of hundreds of species, varying over time and space. Many measurement campaigns show that indoor pollution comes from the occupants (humidity, carbon dioxide, bioeffluents) and theirs activities but also from the building itself (construction materials, decoration), furniture, maintenance activities (cleaning) and from outdoor pollution.

While the survey of atmospheric pollution has long been the subject of particular attention, Indoor Air Quality (IAQ) has long been wrongly considered as a marginal component of environmental and health issues. The definition of good indoor air quality (IAQ) is still under discussion. For ASHRAE 62.1, acceptable IAQ is air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction. This definition assumes a good knowledge of indoor air pollutants, their sources and their spreads.

Among the pollutants of interest, WHO (2021) and Kotzias D. et al. (INDEX project, 2005) agree on particulate matters (PM) which have harmful effects on health (asthma, breathing difficulties). These particles may include, for example, dust, smoke or liquid drops. Particulate matters in indoor air can come from several sources. They can be emitted directly from a source (e.g. fireplace, construction material) or result from complex chemical reactions. Kalaiarasan, G. (2017) showed that particulate matters can also come from outside (industries or automotive) and penetrate inside (infiltration, air renewal).

The link between outdoor and indoor particles is complex and still misunderstood. Massey et al. (2009) studied this relationship between indoor and outdoor in 14 naturally ventilated houses. They showed that the fine particulate concentration's levels rises due to indoor activities. They showed also positive correlation with outdoor concentrations. Wang et al. (2016) studied indoor and outdoor air $PM_{2.5}$ concentrations in four residential dwellings characterized with different building envelope air tightness levels and HVAC-filter configurations but no occupants activities (windows closed, no cooking or smoking). Although they highlighted relation between indoor and outdoor $PM_{2.5}$, the absence of indoor activities does not fully reflect the actual conditions of housing occupancy.

The purpose of this study was to assess the impact of supply air filtration on the level of fine particles in the indoor air of occupied dwellings. For this purpose, CETIAT performed on-site measurement campaigns in 4 occupied dwellings between 2016 and 2019 in order to monitor the levels of indoor and outdoor particles for different type of filtration on supply air.

First, measurement campaign is presented, with details of accommodation, experimental setup and procedure. Then, an analysis of the results is provided. This analysis concerns the measurement observations but also the relevance of the analysis tools and the limits of on-site measurements. Finally, recommendations are also proposed to improve IAQ.

2 MEASUREMENT CAMPAIGN

2.1 Accommodations

The study was carried out in three houses and one flat located in countryside or urban area, all in Lyon area. All dwellings were inhabited. Table 1 resumes main housing characteristics.

Table 1 – Main housing characteristics

Dwelling	Type	Location	Elevation	Construction date	Renovation	Area	Number of floors
1	House	Countryside	293 m	2016	No	160 m²	Single floor
2	House	Countryside	279 m	2010	No	123 m²	2 floors
3	House	Countryside	381 m	1981	Windows Attic insulation	90 m²	Single floor
4	Apartment	Urban area	190 m	1960	Windows N&S facades insulation	100 m²	Top floor

Dwelling	No. main rooms	No. utility rooms	Occupants	Ventilation system	Kitchen hood	Chimney	Measurement dates
1	5	6	2 adults 1 children 1 dog	Mechanical extract and supply MHRV*	Recycling hood	No	July - August 2017
2	5	6	2 adults 2 children 1 cat	Mechanical extract DCV humidity control	Exhaust hood	Closed fireplace	March 2018
3	4	3	2 adults 1 children (Wednesday) 1 dog	Mechanical supply	No	Open fireplace	October 2018
4	4	4	2 adults 1 children	Mechanical extract and supply MHRV*	Recycling hood	No	September 2019

* Mechanical Heat Recovery Ventilation

Most of the occupants were carrying out a professional or educational activity and their presence at home was therefore intermittent during the daily hours, except occupants of the dwelling 3 who were retired. Thus, in order to understand fluctuations of particles level over the time, occupants were asked to fulfil questionnaires informing about their presence and activities (cooking, cleaning, windows opening, etc.).

For every accommodation, indoor and outdoor particles numbers were continuously monitored during three weeks in a row. Each week, filtration level on supply air was changed: one week without filter, one week with coarse filter (G4 according to EN 779:2012) and one week with fine filter (F7 according to EN 779:2012).

2.2 Assessment of dwellings and ventilation systems

All accommodations were equipped with a mechanical ventilation system. Measurements of ventilation flow rates, ductworks leakage class according to EN 12237:2003 and building air leakage rate at 4 Pa $Q_{4Pa\text{-}Surf}$ according to EN ISO 9972:2015 and its application guide FD P50-784:2016 were carried out during an initial visit of the dwellings. Results of these measurements are presented in Table 2.

Table 2 - Details of ventilation system and building permeability

Dwelling	$Q_{4Pa\text{-}Surf}$	Ventilation airflow	ACH	Ductworks leakage class according
1	0.44 m³/h/m²	Supply: 143 m^3/h Extract: 152 m^3/h	0.4	Supply: A Extract: A
2	0.79 m³/h/m²	Extract: 124 m^3/h (DCV)	0.4 – 0.5	Extract: A
3	Unknown	Supply: 110 m^3/h	0.5	Unknown
4	1.28 m³/h/m²	Supply: 133 m^3/h Extract: 140 m^3/h	0.56	Supply: A Extract: A

The filters used in every ventilation system were those specified by the manufacturer. Initial efficiency according to ISO 16890:2016 of every filter has been measured in CETIAT laboratory before their installation on site. Figure 1 resumes the results of initial particulate matter efficiency ePM of the filters used.

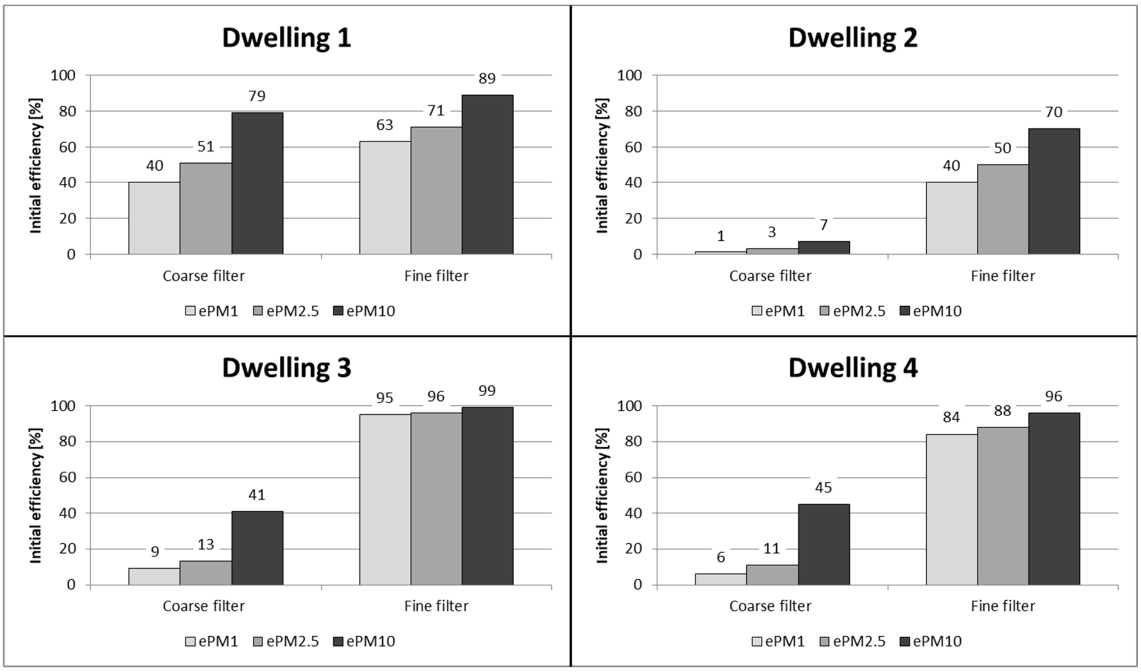

Figure 1 - Initial particulate matter efficiency ePM of the filters according to ISO 16890:2016

2.3 Measurements of particles

Measurements of particle levels have been done with Optical Particle Sizer TSI 3330 (dwellings 1, 2 and 3) and AeroTrak Handheld Particle Counter (dwelling 4). Those devices were able to count dynamically particles from size 0.3 to 10 or 25 µm in six channels of simultaneous data. For this study, only three channels from sizes 0.3 to 3 µm (0.3-0.5, 0.7-1.0 and 2.0-3.0 µm for finer analysis) were considered for analysis. For larger sizes, the number of particles counted was two small to be exploited.

In order to carry out measurements in different locations of the dwelling, an automatic sequencing system made up of solenoid valves and Teflon pipes was used. Samplings were taken at ventilation ductwork connection points or directly into the dwelling. Table 3 indicates the locations of the sampling points in each dwelling.

Table 3 – Locations of the sampling points

Dwelling	Ventilation system	Outdoor air sampling point	Supply air sampling point	Indoor air sampling point
1	MHRV	Outdoor air spigot of the ventilation unit	Supply air spigot of the ventilation unit	Extract air spigot of the ventilation unit
2	Extract mechanical ventilation	Air inlet upstream	Air inlet downstream	Living room
3	Supply mechanical ventilation	Outdoor air spigot of the ventilation unit	Supply air spigot of the ventilation unit	Corridor
4	MHRV	Outdoor air spigot of the ventilation unit	Supply air spigot of the ventilation unit	Extract air spigot of the ventilation unit

This instrumentation was easy to install and space saving, therefore well suited for inhabited sites where the devices should not disturb the occupants. Moreover, all the samples had the same measurement uncertainty, which simplifies the analysis of the data.

However, there are some disadvantages. The number of sampling points was limited by their distance from the optical particle counter. In addition, samplings on ventilation ductwork did not allow discerning space-time phenomena like resuspension of particles or formation of aerosols. Finally, the results were in number of particles by size and not in global mass concentration, which made difficult the comparison with the threshold values of the guidelines and regulations.

In addition to the samples, atmospheric $PM_{2.5}$ levels were collected using open access data from ATMO stations, in order to compare with the evolution of outdoor air particles counts.

3 RESULTS AND ANALYSIS

3.1 On-site measurements in real conditions

A first observation was that the presence of the occupants strongly modifies the measurement conditions. Although instructions were given, they were not followed all the time. For example, some occupants have changed the ventilation rate of their installation during the measuring period, despite the instructions. In addition, the window openings differed a lot from one dwelling to the other. Figure 2 presents number of window openings per dwelling.

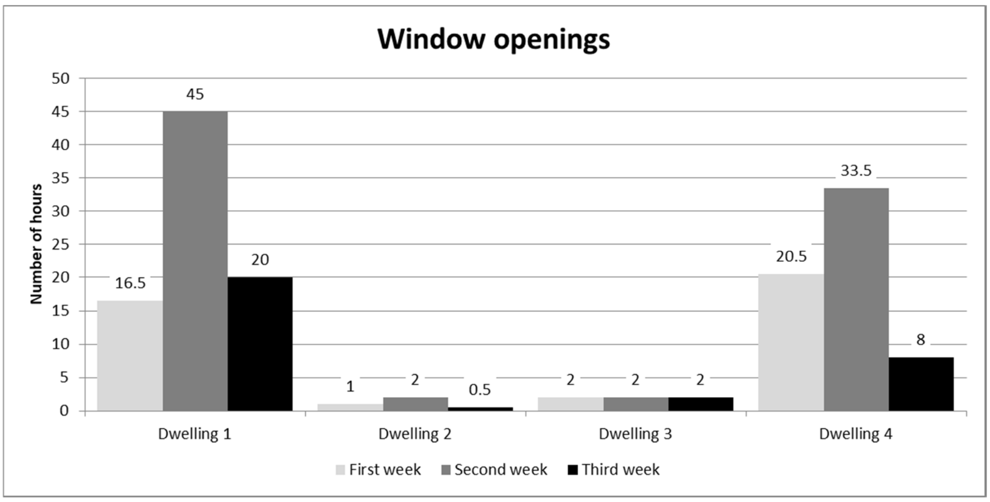

Figure 2 - Window openings per dwelling

This difference was mainly due to the test season. For dwellings 1 and 4, the measurements were carried out during the summer period, where sunny weather was conductive to windows opening, while for dwellings 2 and 3, the measurements were performed during spring or autumn, where the cold and rainy weather did not encourage windows opening.

Consequently, window openings, as well as the airtightness of the building or the variable airflow control of the ventilation system (DCV in dwelling 2), make impossible to achieve and maintain fixed global air renewal in real conditions.

A second observation was that the disparity of the weather (rain, wind), as well as the outdoor concentrations of $PM_{2.5}$ made measurement conditions between dwellings unrepeatable. Figure 3 presents $PM_{2.5}$ outdoor concentration in the environment of the accommodations.

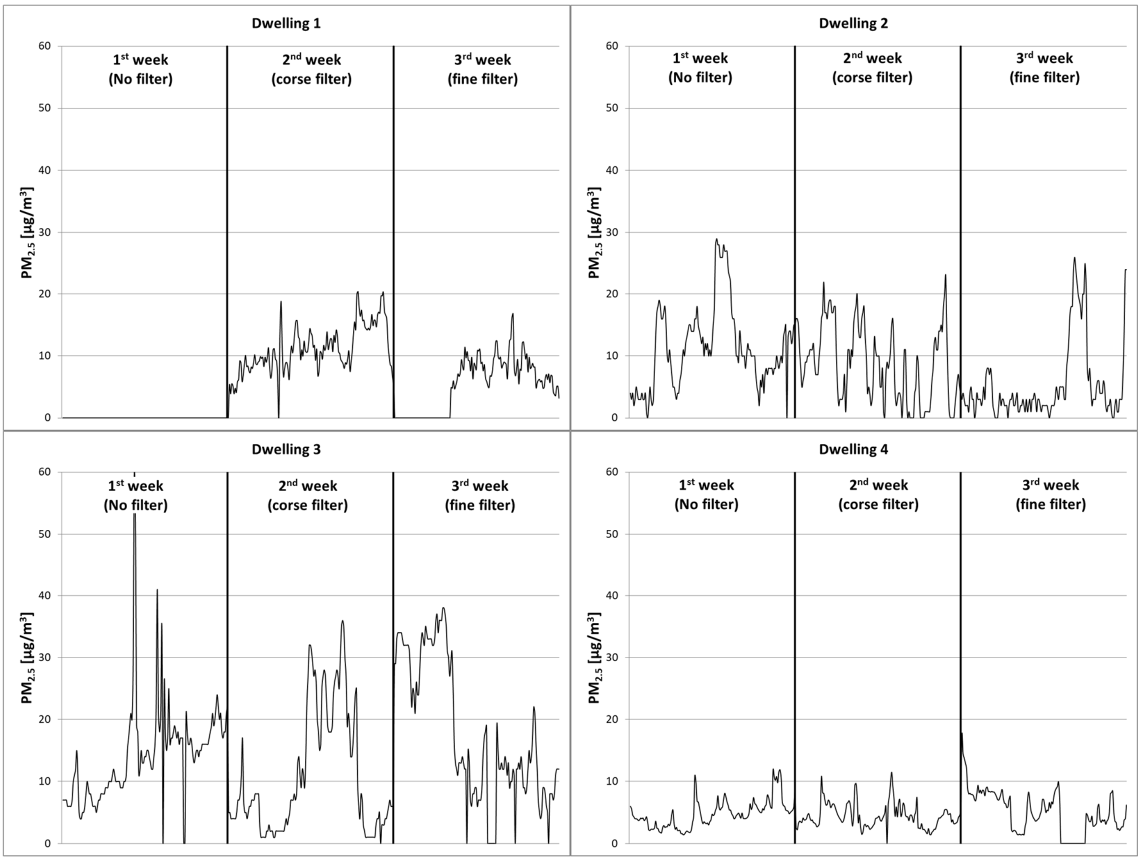

Figure 3 - $PM_{2.5}$ outdoor concentration (ATMO open access data)

The variations in concentration were significant from one site to another. For example, on the site of accommodation 3, there was a peak of 60 µg/m^3 during the first week, while for dwelling 1 and 4, the concentrations were always below 20 µg/m^3 over three weeks. Moreover, the variations in concentration over the 3 weeks on a same site can be significant. For example, on the site of accommodation 2, there were strong variations on first two weeks but the concentrations were more stable during third week, except a peak in the second part of the week. Extending the measurement duration is not enough to overcome the influence of this parameter. External phenomena and their impacts need to be better understood.

3.2 Filter penetration

To evaluate the on-site filters efficiency, the filter penetration, equal to the ratio between supply air and outdoor air particles, was used. The instantaneous value was calculated continuously. The results are represented with box plot statistics tool, which allows visualizing the median value but also summarizes the distribution of values.

Figure 4, Figure 5 and Figure 6 present the filter penetration per week of all four dwellings.

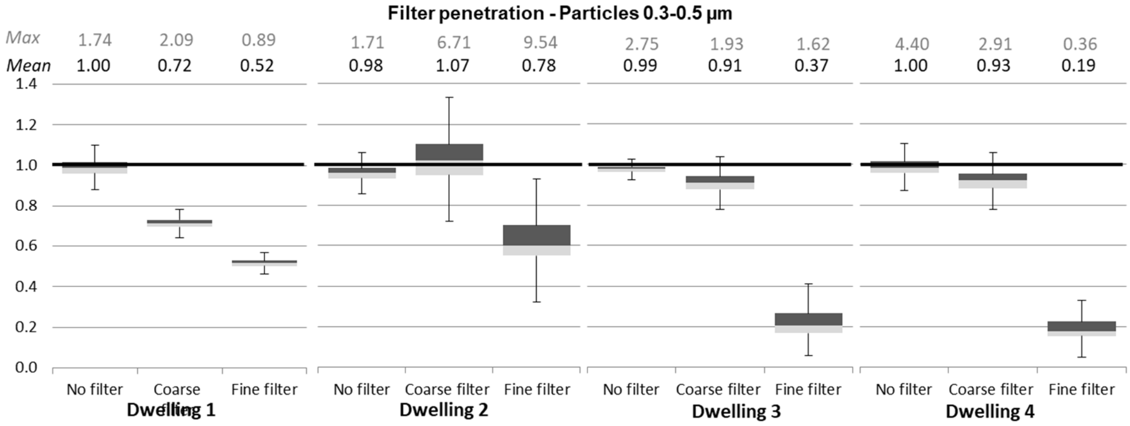

Figure 4 - Filter penetration measured on sites – Particles 0.3-0.5 µm

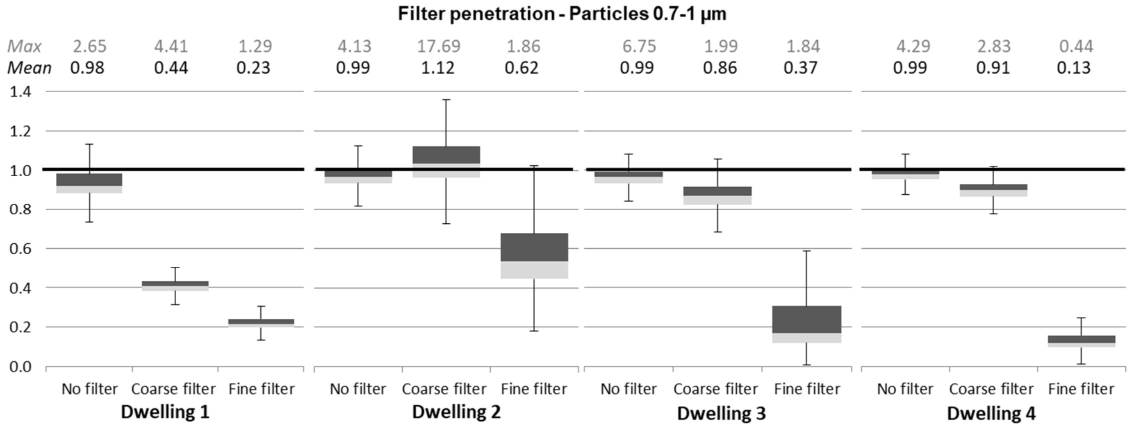

Figure 5 - Filter penetration measured on sites – Particles 0.7-1 µm

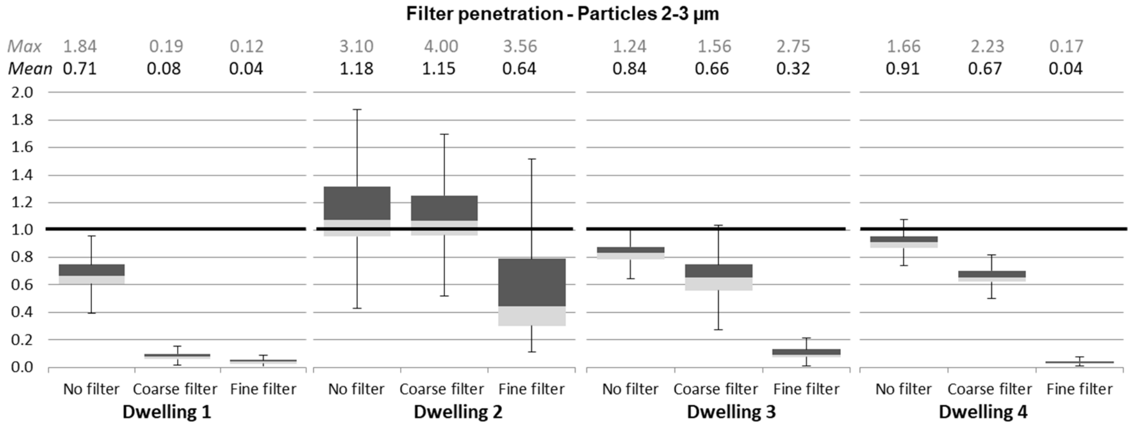

Figure 6 - Filter penetration measured on sites – Particles 2-3 µm

It was observed that the number of particles in the supply air was lower than the number of particles in the outdoor air in the presence of a filter. This reduction was greater with fine filter than with coarse filter. The efficiency of the coarse filters was mainly visible on particles bigger than 1 µm. These on-site measurements were therefore consistent with filter efficiencies measured in laboratory. This highlights that filtration has a real impact on the level of particles entering the accommodation. Particle reductions are obviously linked to filter e-PM efficiencies.

3.3 Time curves analysis

Among the analysis tools, the time curve plot was the most evident. It allowed viewing the evolution of the particles number as function of time. The presence of the occupants and their activities (cooking, cleaning) were also plotted. Logarithmic scale was used for a better visualization of the peaks without flattening the other variations.

Time curves of the indoor air particles and occupant activities for all four dwellings are presented on Figure 7, Figure 8, Figure 9 and Figure 10.

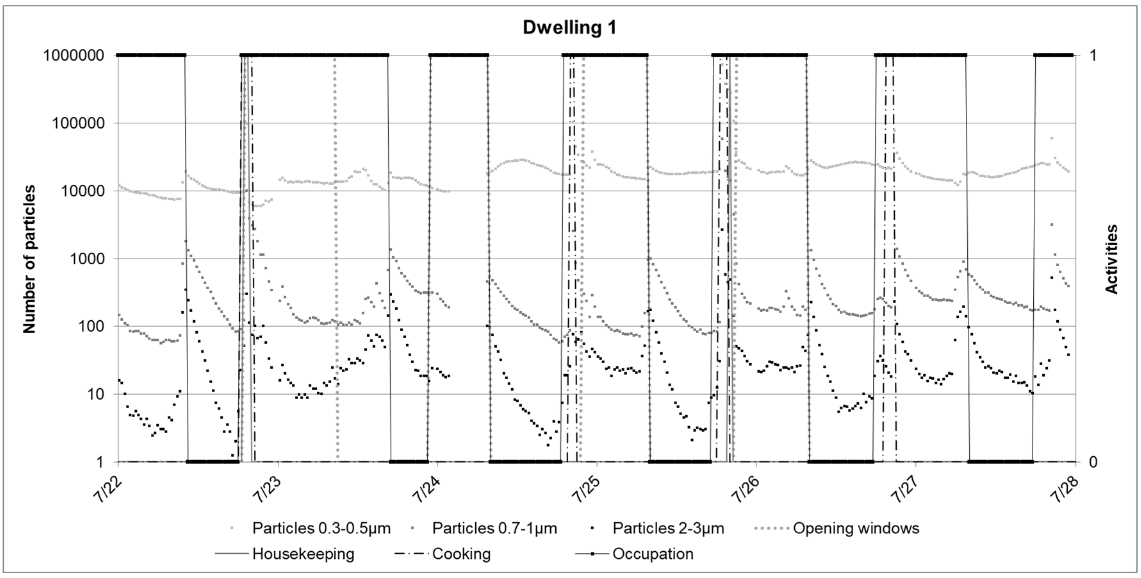

Figure 7 - Time curves of the indoor air particles and activities - Dwelling 1

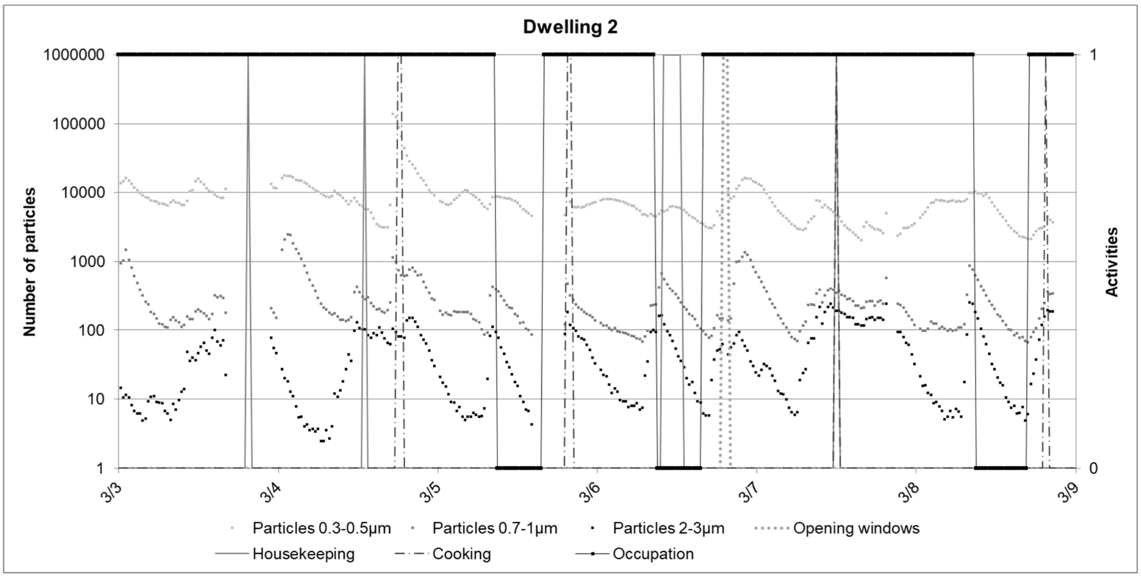

Figure 8 - Time curves of the indoor air particles and activities - Dwelling 2

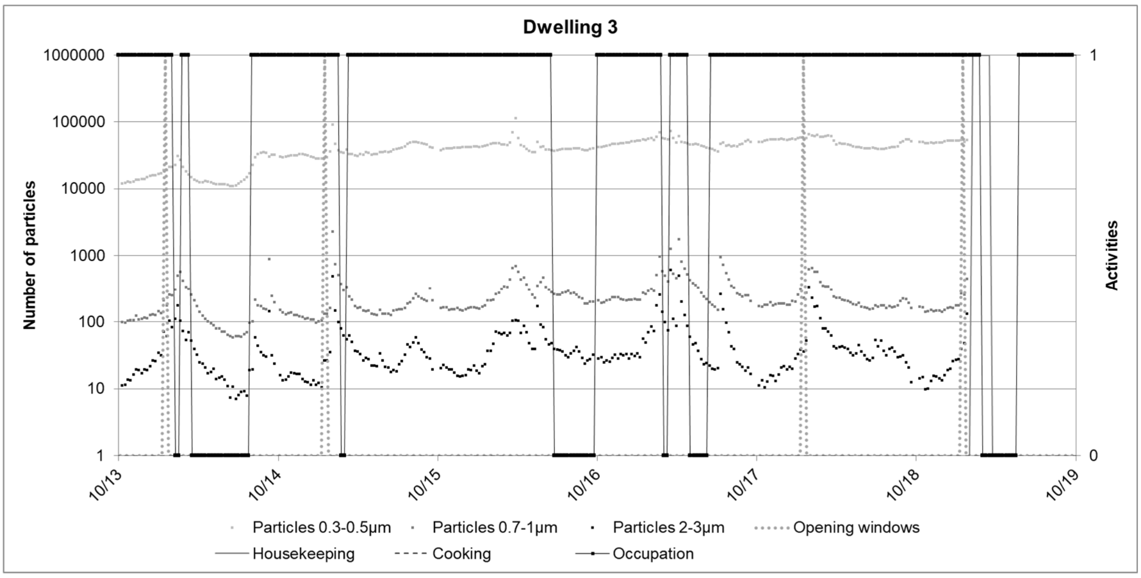

Figure 9 - Time curves of the indoor air particles and activities - Dwelling 3

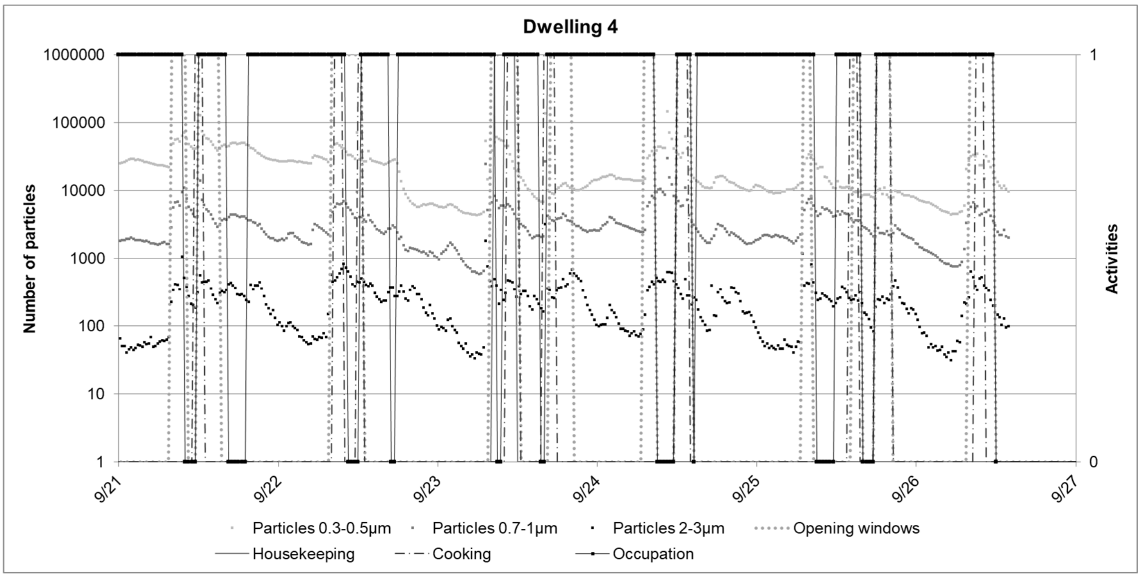

Figure 10 - Time curves of the indoor air particles and activities – Dwelling 4

A first observation was that a particle peak always occurred after an activity. These peaks were generated directly by the activity, especially cooking, or indirectly by resuspension of particles, like vacuuming or dusting. A correlation between the activities of the occupants and the level of particles inside the dwelling can therefore clearly be established.

In addition, in dwelling 1, low cost PM sensors were placed in rooms. They showed high increase of particles concentration in the living room during cooking activities despite the use of the kitchen hood. It questioned a potential air recirculation inside the dwelling due to recycling hood.

It was noted also that particles levels decreased slowly after a peak generated by an activity. If some assumptions such as insufficient air renewal or slow sedimentation rate could be made, none of them fully explains this finding.

3.4 Statistical analysis

In order to assess the impact of filtration on the level of particles in indoor air, one analysis tool was the I/O ratio, equal to the ratio between indoor and outdoor air particles and commonly used to describe the indoor and outdoor air pollutants relationship. This ratio was computed in different ways: a first method was to calculate I/O ratio of instantaneous indoor and outdoor PM values. A second method was to average daily values of indoor and outdoor PM and calculate I/O ratio of those average values. In order to evaluate impact of the occupant activities, daytime and nighttime I/O ratios were computed separately.

Box plots of I/O ratio calculated in these different ways are presented on Figure 11, Figure 12 and Figure 13.

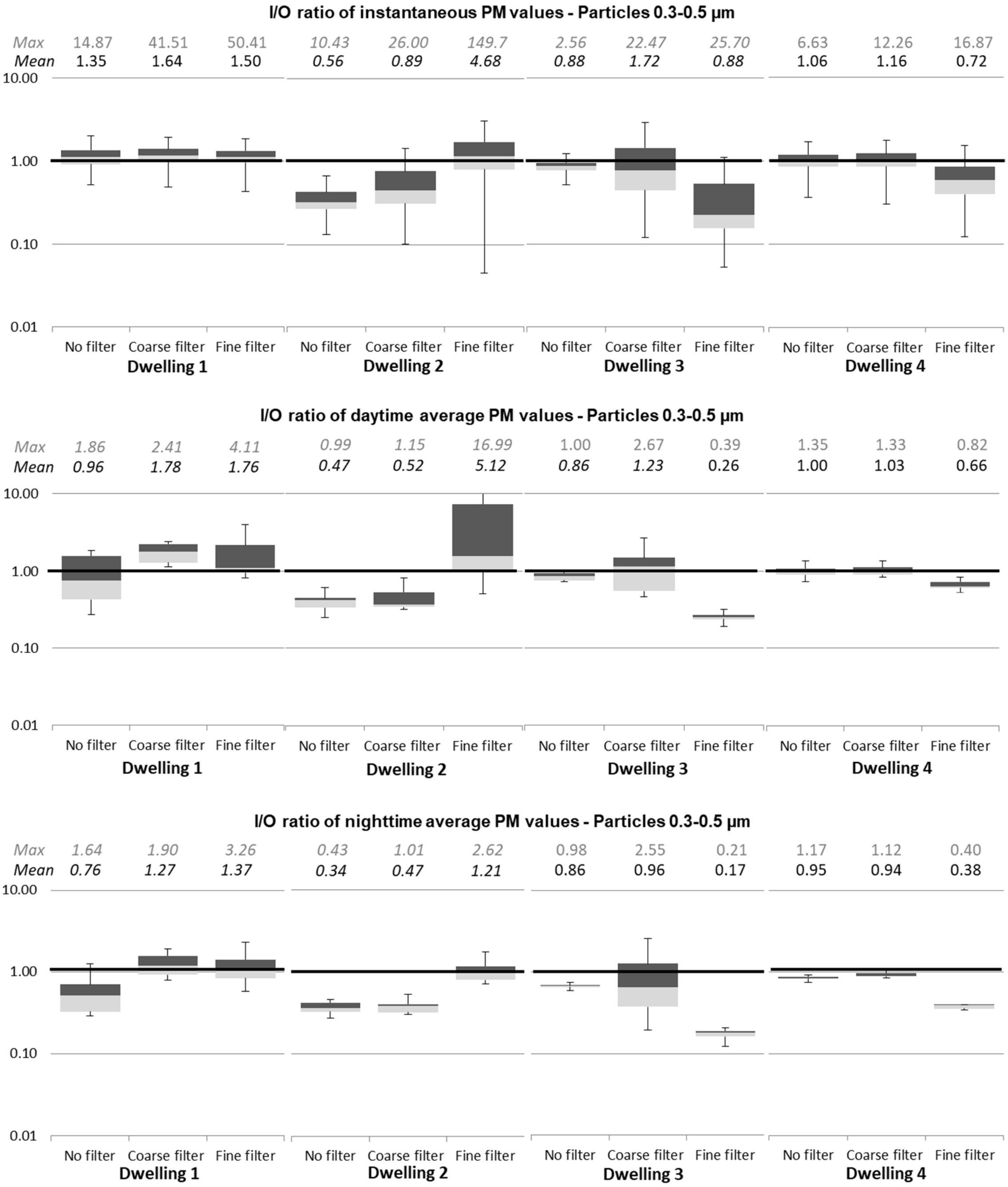

Figure 11 – Statistical data of I/O ratio - Particles 0.3-0.5 µm

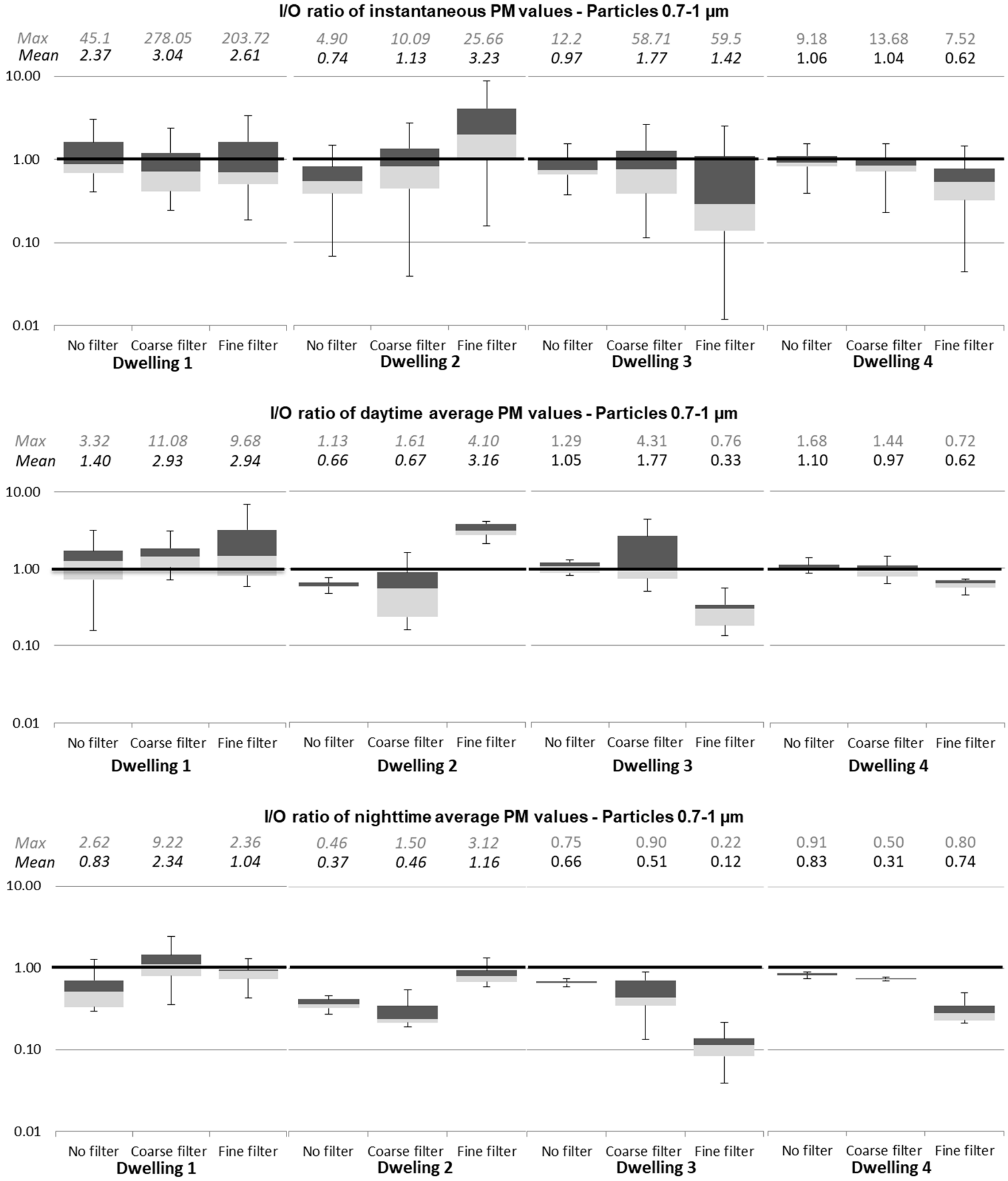

Figure 12 - Statistical data of I/O ratio - Particles 0.7-1 µm

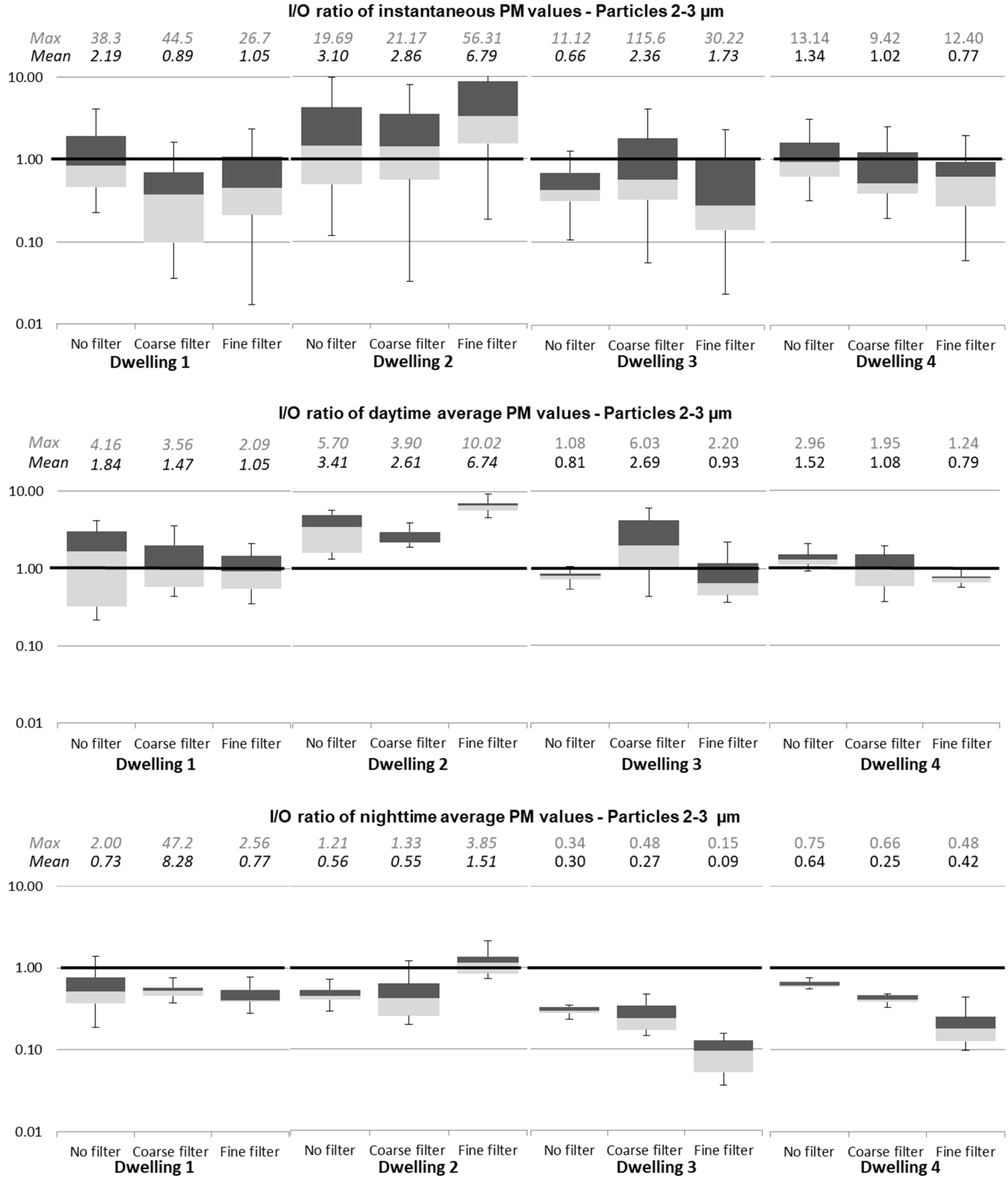

Figure 13 - I/O ratio - Particles 2-3 µm

A first observation concerning the calculation methods was that the I/O ratios of daytime and nighttime particulates averages were lower than the instantaneous I/O ratios. Indeed, the instantaneous I/O ratio was sensitive to the peaks of indoor particles. It could vary by a factor of 1 to 100 over 24 hours. One advantage of the I/O ratio of the daily diurnal and nocturnal particulate averages is to avoid impact of peaks and offset.

Moreover, it was noted that the instantaneous I/O ratio was often greater than 1, whatever the level of filtration. Thus, if the filtration of supply air reduces the level of particles in supply air of the dwelling, it is not sufficient by itself to predict and reduce entirely the level of indoors particles.

Finally, it was noted I/O ratios higher during the day than during the night. This confirms a strong impact of occupant activities on indoor levels of particles.

It can be concluded that the I/O ratio is therefore not sufficient to clear up the penetration of outdoor particles into indoor air.

3.5 Linear–regression curves between indoor and outdoor

The last analysis tool used for this study was the linear–regression curves between indoor and outdoor. Indoor particles were plotted as function of outdoor particles. Linear regression curves were calculated to identify the relationship between indoor and outdoor particles. Coefficients of determination R^2 were also computed to evaluate the degree to which level of fine particles measured indoors could be attributed to infiltration of outdoors particles. In order to evaluate the impact of the occupant activities, daytime and nighttime were distinguished.

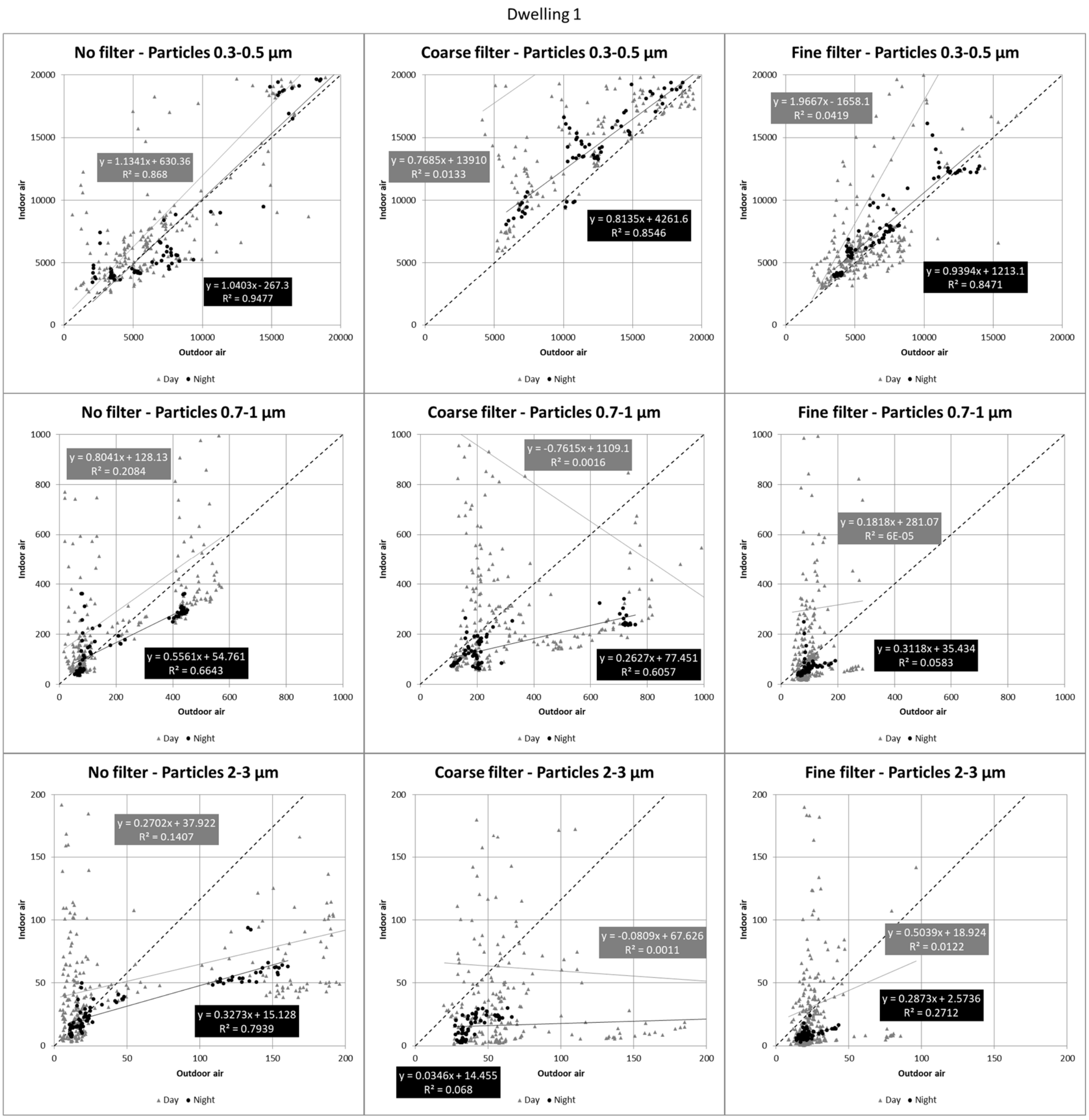

Figure 14 - Linear–regression curves between indoor and outdoor in dwelling 1

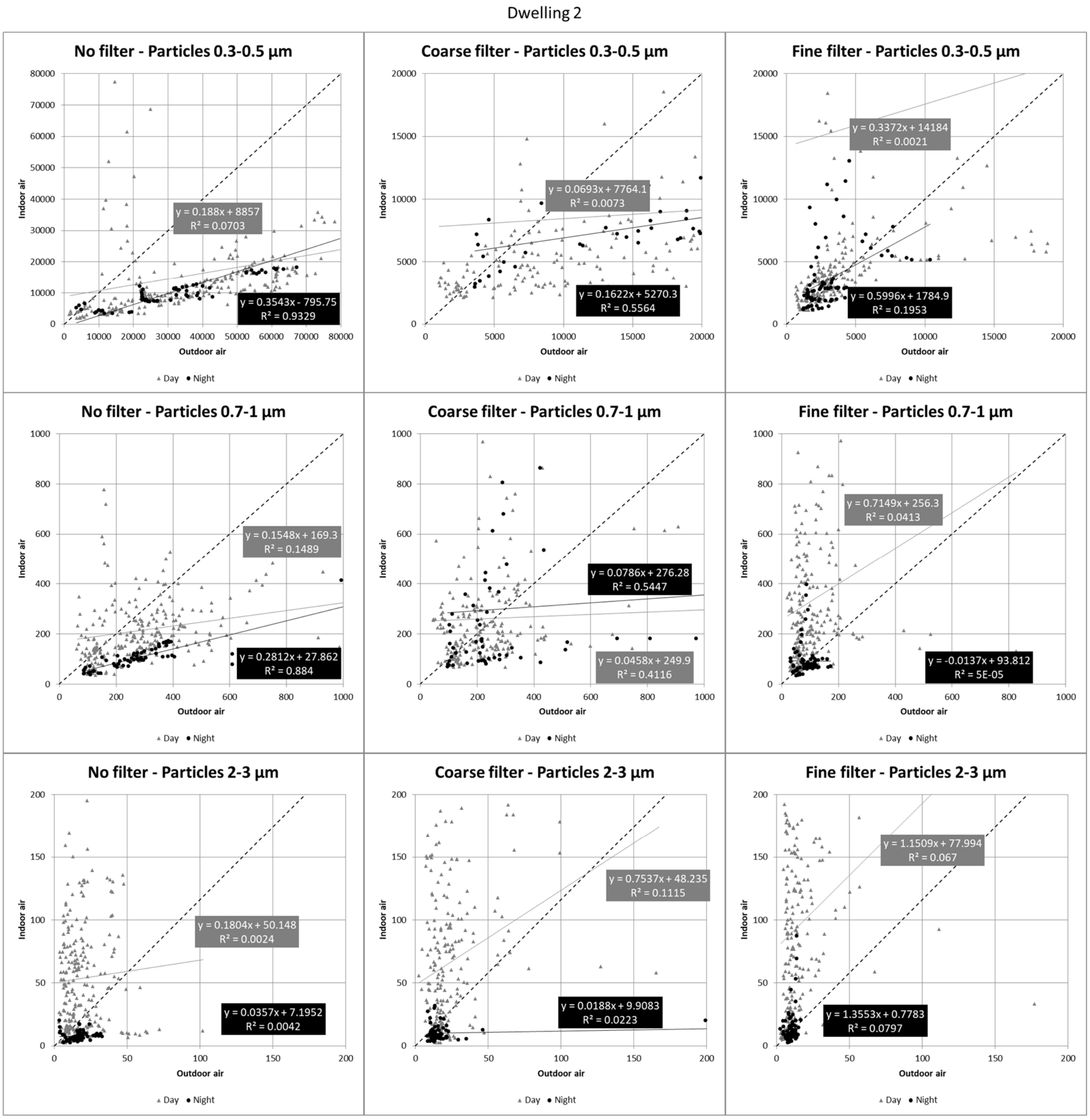

Figure 15 - Linear–regression curves between indoor and outdoor in dwelling 2

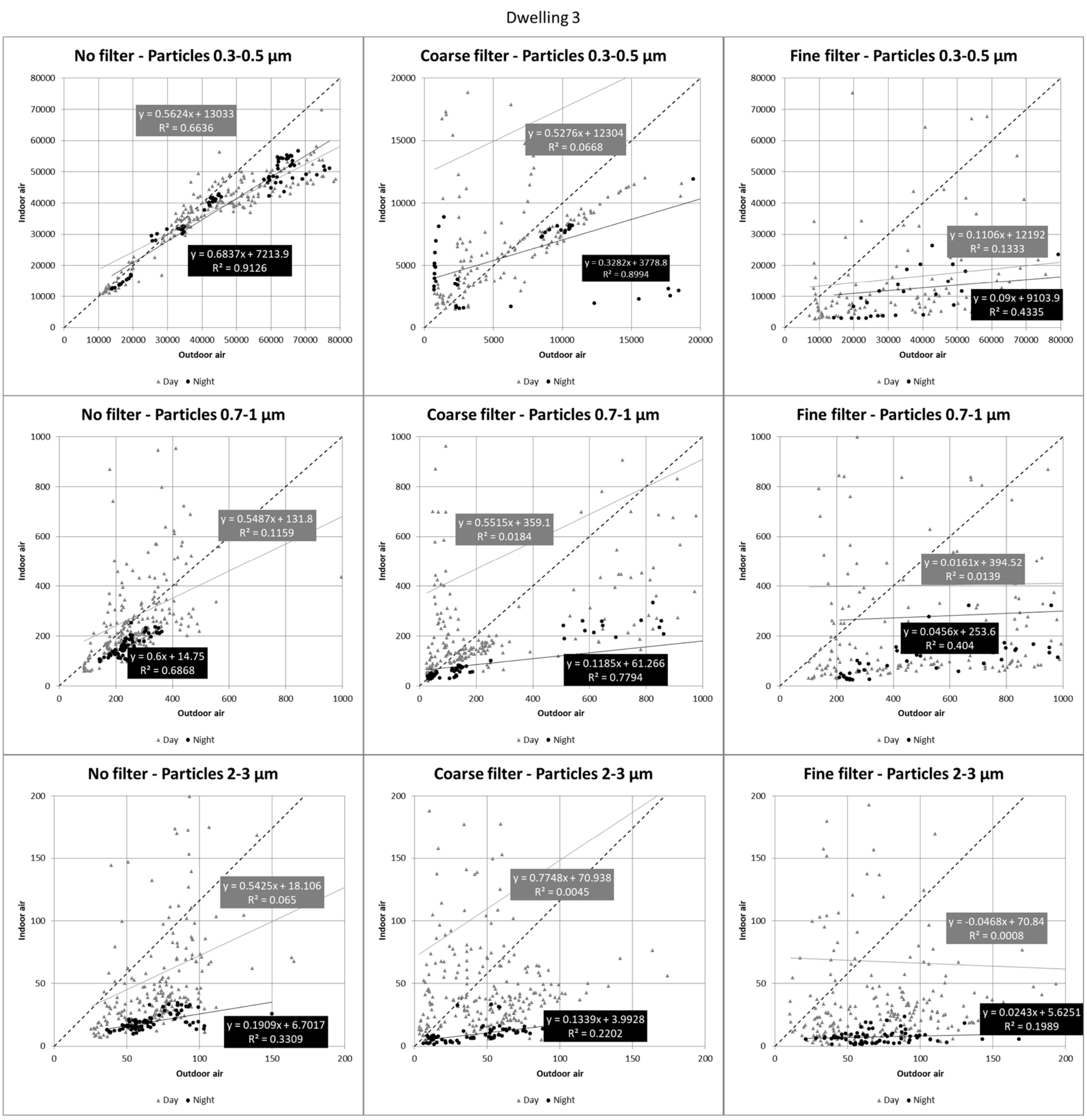

Figure 16 - Linear–regression curves between indoor and outdoor in dwelling 3

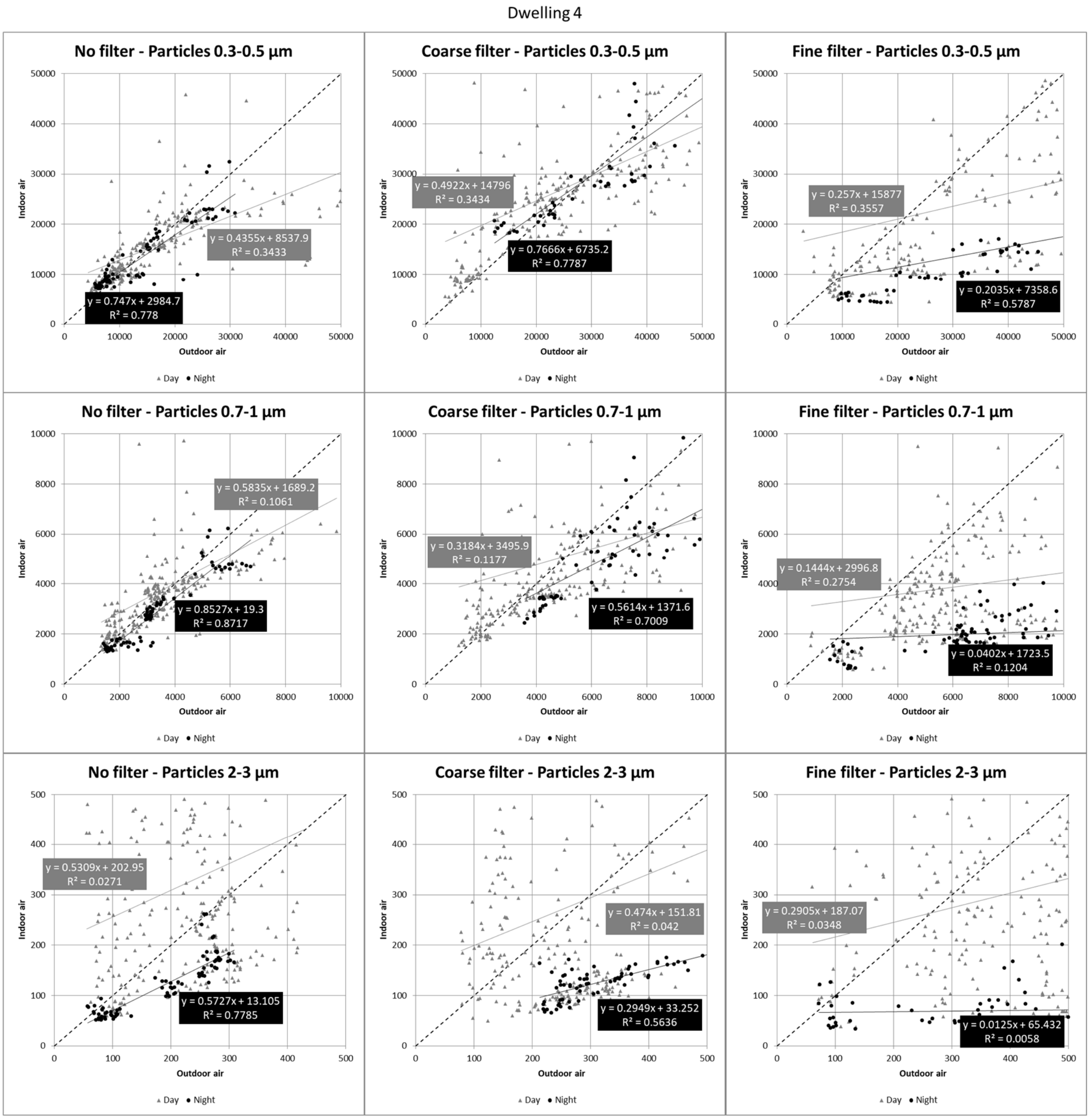

Figure 17 - Linear–regression curves between indoor and outdoor in dwelling 4

A first observation was that coefficients of determination R^2 were higher during the night than during the day. The link between indoor and outdoor particles is thus lower during the day. It confirms that occupant activities have a strong impact on indoor particle levels.

Moreover, coefficient of determination decreased with level of filtration. The higher the level of filtration is, the more the link between indoor and outdoor particles decreases. It suggests that the filtration of the supply air decorrelates the link between outdoor and indoor particles but does not on its own reduce the level of particles in the indoor air.

However, coefficients of determination were too low to be significant, and therefore those interpretations should be taken as suggestive rather than definitive.

4 CONCLUSIONS AND DISCUSSIONS

The assessment of the impact of supply air filtration on the level of fine particles in the indoor air of 4 occupied dwellings was investigated. The number of particles was monitored using Optical Particle Sizer or AeroTrak Handheld Particle Counter. Indoor and outdoor particles levels were monitored continuously during three weeks in a row. Every week, filtration level on supply air was changed: one week with no filter, one week with coarse filter (G4 according to EN 779:2012) and one week with fine filter (F7 according to EN 779:2012).

It emerges from this study that the presence of occupant is essential for assessment of residential IAQ. Consequently, the results of on-site measurements are specific to each dwelling, not repeatable and unfortunately cannot be generalized to all dwellings or all ventilation systems. Location, weather or behavior of the occupants have an impact on the results. Anyway, we can conclude on general trends.

Air supply filtration has a real impact on the levels of particles entering the dwelling, especially if this dwelling is exposed to targeted outdoor pollution such as car pollution for example. Its impact depends on its filtration efficiency according to particle size. A particular attention should be paid to the clogging of the filter so that it does not reduce the ventilation rate and the air renewal in the dwelling. The ventilation system must provide enough pressure to balance filter clogging and associated pressure drop. In addition, a regular filter change must be carried out.

However, filtering supply air is not sufficient by itself to predict and reduce entirely the level of indoors particles. Indeed, IAQ is also function of multiple indoor sources such as cleaning or cooking activities or behavior of the occupants as well.

In order to improve the IAQ, efficient ventilation is necessary. It is also recommended to reduce the sources of pollution and extract them as close as possible with an extraction kitchen hood for example.

5 ACKNOWLEDGEMENTS

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