Influence of ventilation and filtration on indoor particle concentrations in urban office buildings

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Abstract

This study aimed to quantify the efficiency of deep bag and electrostatic filters, and assess the influence of ventilation systems using these filters on indoor fine (<2.5 µm) and ultrafine particle concentrations in commercial office buildings. Measurements and modelling were conducted for different indoor and outdoor particle source scenarios at three office buildings in Brisbane, Australia. Overall, the in-situ efficiency, measured for particles in size ranges 6 to 3000 nm, of the deep bag filters ranged from 26.3 to 46.9% for the three buildings, while the in-situ efficiency of the electrostatic filter in one building was 60.2%. The highest PN and PM\textsubscript{2.5} concentrations in one of the office buildings (up to 131% and 31% higher than the other two buildings, respectively) were due to the proximity of the building’s HVAC air intakes to a nearby bus-only roadway, as well as its higher outdoor ventilation rate. The lowest PN and PM\textsubscript{2.5} concentrations (up to 57% and 24% lower than the other two buildings, respectively) were measured in a building that utilised both outdoor and mixing air filters in its HVAC system. Indoor PN concentrations were strongly influenced by outdoor levels and were significantly higher during rush-hours (up to 41%) and nucleation events (up to 57%),

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compared to working-hours, for all three buildings. This is the first time that the influence of new particle formation on indoor particle concentrations has been identified and quantified. A dynamic model for indoor PN concentration, which performed adequately in this study also revealed that using mixing/outdoor air filters can significantly reduce indoor particle concentration in buildings where indoor air was strongly influenced by outdoor particle levels. This work provides a scientific basis for the selection and location of appropriate filters and outdoor air intakes, during the design of new, or upgrade of existing, building HVAC systems. The results also serve to provide a better understanding of indoor particle dynamics and behaviours under different ventilation and particle source scenarios, and highlight effective methods to reduce exposure to particles in commercial office buildings.

**Keywords:** Ultrafine particles, indoor, I/O ratio, deep bag filter, electrostatic filter, dynamic model.

### 1 Introduction

The association between fine (< 2.5 µm) particle concentrations and increases in respiratory and cardiovascular morbidity and mortality has been reported by many studies (Davidson et al., 2005; Pope, 2000; Schwartz and Neas, 2000; WHO, 2006). Other studies have indicated that the health effects of ultrafine (< 0.1 µm) particles could be even more harmful than those of PM$_{2.5}$ (Franck et al., 2011; Oberdorster, 2000). The concentrations of fine and ultrafine outdoor particles in urban environments are mainly influenced by vehicle exhaust emissions (Harrison et al., 1999; Perez et al., 2010; Pey et al., 2008; Shi et al., 1999) and new particle formation from photochemical reactions (Cheung et al., 2011; Cheung et al., 2012; Pey et al., 2009; Quang et al., 2012). These particles can reach the interior of buildings, especially those located close to busy traffic areas, via penetration through their envelopes (Thornburg et al., 2001), and through mechanical ventilation systems (Koponen et al., 2001; Morawska et al., 2009b; Weschler et al., 1996). Indoor activities, such as movement of building occupants, can also affect and increase indoor particle levels (Abt et al., 2000a; Long et al., 2000). Recent
research has indicated that laser printers, a widely-used piece of office equipment, can make a significant contribution to indoor particle levels (He et al., 2007; He et al., 2010; McGarry et al., 2011; Morawska et al., 2009a; Schripp et al., 2008).

The filtration systems of mechanically ventilated buildings can reduce indoor particle concentrations which originated both outdoors and indoors (Hanley et al., 1994; Hinds, 1999; Jamriska et al., 2003). Several studies have quantified the efficiency of dry-media and electrostatic filters used in mechanically ventilated office buildings, but they mainly focused on particles >300 nm (Fisk et al., 2000; Zuraimi and Tham, 2009). Other work has focused on ultrafne particle, but these investigations were performed under laboratory conditions, and not in operating buildings (Hanley et al., 1994; Jamriska et al., 1998). Indoor particle deposition can also be an important factor affecting indoor particle levels, with a number of studies published on this topic. However, these mainly focused on residential houses (Abt et al., 2000b; He et al., 2005; Long et al., 2001; Thatcher et al., 2002; Thatcher and Layton, 1995) or naturally ventilated office buildings (Smolík et al., 2005). Only one study calculated indoor particle deposition rate in an office building during working-hours (Jamriska et al., 2003). Two studies employed static models to simulate particle concentrations inside office buildings (Fisk et al., 2000; Zuraimi and Tham, 2009). Matson (2005) also built a dynamic model for this purpose, but did not consider the influence of filtration and indoor sources.

Another dynamic model was developed by Jamriska et al. (2003) to study particle dynamics in a hypothetical office building, however it was not applied to real buildings.

Currently, there is only limited information on in-situ filter efficiency in mechanically ventilated office buildings, where a substantial proportion of the population spend a large amount of time each day, and the scientific understanding of the factors which impact indoor particle concentrations and occupant exposures in these buildings is incomplete. To help address these gaps in knowledge, and provide information for the selection and location of appropriate filtration media in office building HVAC systems, we aimed to: (1) quantify
indoor and outdoor particle concentrations and air exchange rates in three office buildings; (2) test the in-situ efficiencies of different filter types under real-world conditions; (3) assess the factors that impact on I/O ratios under different ventilation and filtration schemes and particle source scenarios; (4) investigate indoor particle sources; and (5) modify, assess the performance of, and apply, a mathematical model to further evaluate the important factors which affect the concentration and dynamics of indoor particles.

2 Research methods

2.1 Sampling sites – building description

Three urban office buildings in the subtropical city of Brisbane, which is the capital city of Queensland, Australia, were selected for measurements. These buildings, referred to here as A, B and C, were chosen to represent different building heights, ages, ventilation systems and nearby traffic density. Building A is 4 storeys, was built in 2008, is ~17 m high and located on relatively flat ground and ~7 m from a busway (a bus-only roadway with a daily traffic volume of about 900 buses). Building B is 18 storeys, was built in 1980, is ~77m high, located in the centre of Brisbane City and is surrounded by other high rise buildings and busy city roads, with a daily traffic volume of about 11,000 vehicles. Building C is 6 storeys, was built in 1998, is ~25 m high, and located ~7 m from a freeway with a daily traffic volume of about 110,000 vehicles. All three office buildings had a steel frame and glass exterior walls. The floors of the working spaces were fully carpeted, and furnishings included desks, chairs, filing cabinets, desktop computers, laser printers and photocopiers. All of the buildings were non-smoking. Further information on the characteristics and location of these buildings is provided in Quang et al. (2012).

2.2 Ventilation systems

Four types of ventilation systems, including three central ventilation systems and one single split system, operated in the buildings studied. A central ventilation system is one in which air
is supplied from a central plant room, where fresh outdoor air and recirculation air from the
building are mixed, then cleaned and conditioned by deep bag (DB) filters and air handling
units (AHUs), respectively, before being introduced into each office space via ducts. The
pockets of a DB filter are formed and sewn by using multiple polyester fibers.

A split system consists of indoor and outdoor units that work together. The outdoor unit
consists of condenser coils, which transport the thermal energy from the hot air inside the
building to the outdoors. The indoor unit consists of evaporator coils, which collect and
remove heat and moisture from the indoor air. Both condenser coils and evaporator coils are
connected to the refrigerant lines, which are powered by a compressor.

At Building A, two central ventilation plants were located centrally at the front of each floor
to treat and provide supply air to the open plan offices. The flow rates of supplied air were
controlled by variable air volume (VAV) boxes located in the office ceilings and AHUs were
located in the plant rooms. Outdoor air was taken from air intakes located at the front of each
plant room, which were close to the nearby busway. DB filters were located in the air stream
of mixed outdoor and recirculation air. Individual office spaces (such as meeting rooms) were
conditioned by a separate split system, in which supply air was drawn in directly from
outdoors, near the central plant room, and then treated by indoor fan coil units (FCUs), which
contained a basic filter, before being distributed to the space.

At Building B, a central plant room was located on the rooftop level and provided conditioned
air for levels 3 to 18. Outdoor air was introduced via air intakes and then mixed with return air
from all levels. After the mixed air was filtered and conditioned by DB filters and AHUs,
respectively, the treated air was supplied to each floor space via a riser duct system.

In contrast, Building C had one central plant room which was located towards the centre-rear
section of each floor. Outdoor air was drawn from air intakes and filtered primarily by
electrostatic (ES) filters located in a rooftop plant room, before being supplied to individual
plant rooms on each level via raiser ducts. The ES filter is a two stage air cleaner comprising ionising wires and collecting plates that operated at voltages of about 13 and 6.5 kV DC, respectively. In each individual floor’s plant room, the pre-filtered outdoor air was mixed with recirculation air, and then re-filtered and conditioned by DB filters and AHUs, respectively, before being supplied to the offices via a duct system.

2.3 Instruments and measured parameters

Two TSI 3934 Scanning Mobility Particle Sizers (SMPSs) were used for measuring particle number size distribution (PNSD) in the range 8.5 – 370 nm in the downstream and upstream air flow of each filter device to quantify its efficiency. Each SMPS comprised a TSI 3071 Electrostatic Classifier (EC) that classified particles according to their electrical mobility, and a TSI 3010 Condensation Particle Counter (CPC). The duration of each scan was 180 s. Indoor and outdoor particle number (PN) concentrations in the range 6 – 3000 nm were measured by TSI Model 3025 and 3781 CPCs at an averaging interval of 5 s and 15 s, respectively. Two TSI 8520 DustTrak aerosol monitors, each with a 2.5 μm inlet, were used to measure indoor and outdoor PM$_{2.5}$ concentrations at an averaging interval of 10 s and 30 s, respectively. It should be noted that the DustTrak operates based on light scattering technique where the amount of scattered light is proportional to the volume concentration of the aerosol, and is not calibrated for measurement of combustion aerosols. In order to obtain representative PM$_{2.5}$ values, data collected by the DustTraks in this study were corrected against a Thermo Scientific (Franklin, MA) 1405-DF tapered element oscillating microbalance (TEOM), by using an equation obtained by Morawska et al. (2003): $PM_{2.5(TEOM)} = 0.394 PM_{2.5(DustTrak)} + 4.450$ (with $r^2 = 0.83$). A TSI model 8525 PTrak was used for mobile measurement of possible indoor PN sources. TSI Model 8552 and 7545 QTraks were used to measure temperature, relative humidity and CO$_2$ levels inside offices and outdoors, respectively. TSI Model 8705 and 9535 hot wire anemometers were used to simultaneously measure the velocities of outdoor air (OA), return air (RA) and mixing air (MA) in each plant
room to determine total flows. The anemometers operated continuously in the center of OA intake(s), RA outlet(s), and MA intake(s), while the VelociCalc was used to traverse these air intakes and outlets in order to capture the average total flow of OA, RA and MA. All instruments were tested and calibrated in the laboratory before being used for field measurements. Comparative quality assurance tests for all particle instruments were also conducted simultaneously with all instruments co-located and sampling outdoor air during the last day of each field campaign.

2.4 Measurement procedures

2.4.1 Air exchange rate

Outdoor air exchange rates (AERs) for each office space were calculated based on two methods: the outdoor air flow rate measurement and indoor CO$_2$ decay measurements. When the HVAC system was turned on, the outdoor air flow rate introduced to each plant room was calculated based on average air velocity, measured at the relative outdoor air intake(s). Then an AER for the relevant office space was estimated based on the following equation:

\[ AER = \frac{Q_{oa}}{V_{room}} \]  \hspace{1cm} (1)

in which $Q_{oa}$ is the outdoor air flow rate (m$^3$ h$^{-1}$) and $V_{room}$ is the effective volume of the relevant office space (m$^3$). This equation denotes that the outdoor air flow rate should include the portion penetrated via the building envelope. However, during operation of the ventilation system, the inside air pressure usually remained positive and therefore, in this case, the infiltration portion was considered negligible compared to ventilated outdoor air.

When the HVAC system was turned off outside of work hours, the indoor CO$_2$ decay method (He et al., 2005; Weichenthal et al., 2008) was applied to calculate outdoor AER (i.e. infiltration) based on real-time measurements of indoor CO$_2$, according to the following equation:
\[ AER = \frac{\ln C_o - \ln C_t}{\Delta T} \] (2)

in which \( C_o \) is the initial indoor CO\(_2\) concentration and \( C_t \) is the lower indoor CO\(_2\) concentration after the time needed (\( \Delta T \)) for a continuous decay of well-mixed CO\(_2\). To correct for the background contribution of outdoor CO\(_2\), ambient concentrations were subtracted from the initial and final measured CO\(_2\) concentrations. Typically, AERs were estimated between 18:00 to 19:00, when the HVAC system was turned off, occupants had left but CO\(_2\) remained mixed throughout the building, and cleaning activities had not yet commenced.

### 2.4.2 Indoor and outdoor air quality

Indoor and outdoor air quality parameters were measured continuously and simultaneously at different levels, and the measurements ran for two to three weeks at each building. However, air quality variables at the front of the air intakes on the rooftop level and inside the offices on level 3 of each building, which was the level closest to, or most strongly influenced by, particle emissions from the surrounding roads (see Quang et al. (2012)) were used for the purpose of this study. Indoor PN, PM\(_{2.5}\), and CO\(_2\) concentrations, along with temperature and relative humidity, were measured inside the offices by a set of instruments comprising a 3025 CPC, a DustTrak and an 8552 QTrak. The indoor air sampling sites were set up in the middle of the office, at a height of approximately 1.2 m, and their locations were carefully considered to avoid the direct influence of nearby occupants and air outlets.

A second set of instruments, consisting of an SMPS, a CPC 3781 and a DustTrak, was used to measure PNSD, PN and PM\(_{2.5}\) concentrations at a location adjacent to the outside air intake on the rooftop level of each building. The air sampled from outdoors (i.e. outside the plant room) was delivered to the instruments via a 1 m long conductive tube, with an inner diameter of 6 mm. The locations of all outdoor air sampling points were carefully selected to avoid the influence of nearby HVAC exhaust air. A flow splitter was to distribute air from the sample...
point to the instruments. Indoor and outdoor particle concentrations were measured simultaneously and measurements were performed continuously for at least 24 hours at each location.

At the same time, background PN and PM$_{10}$ concentrations corresponding to each measurement campaign were obtained from a Queensland Department of Environment and Heritage Protection air quality station, located at the Queensland University of Technology (QUT station), in Brisbane’s CBD (Central Business District). Background PM$_{2.5}$ concentrations for Brisbane CBD were calculated based on PM$_{10}$ concentrations measured at the QUT station, and ratios of PM$_{2.5}$ and PM$_{10}$ concentrations measured at the South Brisbane station, which is another station belonging to the Queensland Department of Environment and Heritage Protection located about 2 km SSE of the QUT station.

2.4.3 Filter testing

Tests to measure the particle removal efficiency of the total AHU system (AHS), which consisted of DB filters and the air handler itself, were conducted in the level 3 plant rooms of buildings A and C, as well as in the rooftop plant room of Building B. The ES filter used for outdoor air cleaning at the rooftop of Building C was also tested. Two sets of instruments, including the SMPSs, CPCs and DustTraks, were used to simultaneously measure PNSD, PN and PM$_{2.5}$ concentrations. One set measured upstream, while the other measured downstream of the ES and AHS filters, simultaneously. In addition, the filtration efficiency of a fan coil unit (FCU) in one meeting room of Building A was also tested based on measured PN and PM$_{2.5}$ concentrations at the outdoor air intake (upstream) and the supply air outlet (downstream) of the FCU. All filter tests were performed continuously for at least 1 hour. Based on the measured data, the efficiency of each filter was then quantified using the equation below:

$$FE = \left(1 - \frac{c_{down}}{c_{up}}\right) \times 100\% \quad (3)$$
in which $C_{\text{down}}$ is the PN or PM$_{2.5}$ concentration downstream of the filter (p cm$^{-3}$ or µg m$^{-3}$, respectively) and $C_{\text{up}}$ is the PN or PM$_{2.5}$ concentrations at the upstream of the filter (p cm$^{-3}$ or µg m$^{-3}$, respectively).

2.5 Investigation of indoor particle sources

Laser printers were recently identified as a sources of indoor particles in office environments (He et al., 2007; He et al., 2010; He et al., 2004; McGarry et al., 2011; Morawska et al., 2009a; Schripp et al., 2008). Similarly, vacuum cleaning has also been reported as an indoor particle emission source in domestic and office locations (Afshari et al., 2005; Corsi et al., 2008; Knibbs et al., 2011; Trakumas et al., 2001). Whilst vacuuming is usually done outside working hours, both laser printer and vacuum cleaner emissions were investigated in all three office buildings, in order to gather information suitable for modeling particle concentrations over 24-h periods.

All laser printers identified during a walk-through survey of the office areas in each building were tested. The TSI PTrak was placed 0.5 m above the printer to measure the background office PN concentration (when the printer was off), as well as PN concentration after the printer had printed one page. Ratios of peak PN concentrations after printing to the background PN concentrations were used to classify the printers into four groups, including: non-emitters (ratio ≤ 1); low emitters (1 < ratio ≤ 5); medium emitters (5 < ratio ≤ 10); and high emitters (ratio > 10) based on the approach of He et al. (2007). The frequency and duration of printing were recorded by the investigators for some of the printers in each office and these data, together with printer emission rates obtained from our previous work (He et al., 2007) were used to simulate particle generation by laser printers in these offices.

In-situ emission rates of vacuums were quantified based on the time-series records of PN concentrations inside office areas and records of evening cleaning activities, when the activity
mainly comprised of vacuuming, by using the following Equation 4.4 presented by He et al (2004):

\[
Q_s = \frac{V}{60n} \left[ \frac{C_{\text{int}} - C_{\text{ino}}}{\Delta T} + (a + \lambda)C_{\text{in}} - aP_{\text{out}} \right] \quad \text{(p min}^{-1}) 
\] (4)

where \(Q_s\) is the average emission rate (p min\(^{-1}\)), \(V\) is the effective volume of measured enclosure room (cm\(^3\)), \(n\) is the number of concurrently operated vacuum cleaners, \(C_{\text{int}}\) and \(C_{\text{ino}}\) are the peak and initial indoor PN concentrations, respectively (p cm\(^{-3}\)), \(C_{\text{in}}\) and \(C_{\text{out}}\) are the average concentrations of indoor and outdoor PN during the time \(\Delta T\), from initial to peak indoor PN concentration (p cm\(^{-3}\)), \(a\) is the air exchange rate (h\(^{-1}\)), \(\lambda\) is the deposition rate (h\(^{-1}\)), and \(P\) is the penetration factor. The equation was previously applied under natural ventilation conditions, however, it can also be used for quantifying vacuum emission rates in office buildings if the mechanical ventilation system is turned off during cleaning activities, as was the case in this study.

2.6 Particle concentration modelling

2.6.1 Model modification

A dynamic mathematical model derived by Jamriska et al. (2003) was modified by separating the right hand side of the equation into individual components that contribute to indoor particle concentration at time \(t_i\), including (i) the decay of previous indoor particle concentration at time \(t_{i-1}\), (ii) the contribution of indoor sources, and (iii) the contribution of outdoor sources, respectively. Parameters in each component were modified according to the real conditions in each building and assumed constant within one time step. The new model is presented in Equation 5. A schematic of the HVAC system and the model input parameters is shown in Figure S1.

\[
C_{\text{in}}^{t_i} = C_{\text{in}}^{t_{i-1}} e^{-\alpha_t \Delta t} + \int_{t_{i-1}}^{t_i} \frac{\sum G_i}{V} e^{-\alpha_t \Delta t} \, dt + C_{\text{out}}^{t_i} \beta_{t_i} \Delta t \quad \text{(p cm}^{-3}) 
\] (5)
In cases where the building was located close to busy traffic areas, and indoor PN concentration was mainly influenced by outdoor sources, the influence of indoor particle sources was omitted, and Equation 5 was reduced as follows:

\[
C_{in}^{t_i} = C_{in}^{t_{i-1}}e^{-\alpha t_i\Delta t} + C_{out}^{t_i}\beta t_i\Delta t \quad (p \text{ cm}^{-3}) \tag{6}
\]

where:

- \(C_{in}^{t_i}\): indoor PN concentration at time \(t_i\) (p cm\(^{-3}\))
- \(C_{in}^{t_{i-1}}\): indoor PN concentration at time \(t_{i-1}\) (p cm\(^{-3}\))
- \(\Delta t\): time step (h)
- \(\alpha t_i\): total removal rate of the indoor PN concentrations

\[
\alpha t_i = \frac{3.6\times10^3k}{V} \left( Q_{RA}^{t_i} F_{E_{AHS}} + Q_{exc}^{t_i} + Q_{Exf}^{t_i} + V \lambda t_i \right) \quad (h^{-1}) \tag{7}
\]

- \(k\): mixing factor (unitless) \((k = 1\) if perfect air mixing conditions are assumed\)
- \(V\): effective volume of the enclosure room (m\(^3\))
- \(Q_{RA}^{t_i}\): return air flow rate at time \(t_i\) (m\(^3\) s\(^{-1}\))
- \(F_{E_{AHS}}\): the overall efficiency of the air handing system filter (decimal)
- \(Q_{exc}^{t_i}\): general and local exhaust flow rates at time \(t_i\) (m\(^3\) s\(^{-1}\))
- \(Q_{Exf}^{t_i}\): exfiltration flow rate at time \(t_i\) (m\(^3\) s\(^{-1}\))
- \(\lambda t_i\): particle deposition rate at time \(t_i\) (s\(^{-1}\))
- \(\Delta t\): time period, in which indoor particles are generated (h\(^{-1}\))
- \(C_{i}^{t_i}\): indoor particle emission rate at time \(t_i\) (p s\(^{-1}\))
- \(C_{out}^{t_i}\): outdoor PN concentration at time \(t_i\) (p cm\(^{-3}\))
- \(\beta t_i\): total penetration rate of outdoor particle indoor

\[
\beta t_i = \frac{3.6\times10^3}{V} \left[ Q_{OA}^{t_i} (1 - F_{E_{OA}})(1 - F_{E_{AHS}}) + Q_{Inf}^{t_i} P_{Inf}^{t_i} \right] \quad (h^{-1}) \tag{8}
\]

- \(Q_{OA}^{t_i}\): outdoor air flow rate at time \(t_i\) (m\(^3\) s\(^{-1}\))
- \(F_{E_{OA}}\): the overall efficiency of the outdoor air filter (decimal)
- \(Q_{Inf}^{t_i}\): infiltration flow rate at time \(t_i\) (m\(^3\) s\(^{-1}\))
- \(P_{Inf}^{t_i}\): penetration factor via the building envelope at time \(t_i\) (unitless)
2.6.2 Model performance assessment

The real ventilation conditions, outdoor particle concentrations, and particles generated from printing and vacuum cleaning in each building were used to run the model based on assumptions that the changes in particle concentration due to chemical reactions are negligible and the pollutants are well mixed (Kulmala et al., 1999; Nazaroff and Cass, 1989). Predicted indoor particle concentrations were then compared to measured values in these buildings. Quantitative and qualitative tools for evaluation of indoor air quality (IAQ) models provided by ASTM Standard D5157 (ASTM-1997, 2008) were applied to assess the performance of the model. The statistical tools for evaluating the accuracy of the model predictions include (i) the correlation coefficient of predictions compared to measurements ($r$), for which the value should be 0.9 or greater; (ii) the line of regression between the predictions and measurements, which should have a slope ($b$) between 0.75 and 1.25, and an intercept ($a$) less than 25% of the average measured concentration; and (iii) the normalised mean square error (NMSE), for which the value should be less than 0.25. All were used to assess our model outputs. Additionally, the bias of the model was measured based on (i) normalised fractional bias of the mean concentration ($FB$), for which the value should be 0.25 or lower; and (ii) fractional bias based on the variance ($FS$), for which the value should be 0.5 or lower.

2.7 Estimation of indoor particle deposition rates

Equation 6 was applied to estimate indoor particle deposition rates in the office buildings when the ventilation was turned off and indoor particle sources were absent (overnight when no cleaning activities occurred). If the air exchange rate and the penetration factor are assumed to not vary, the equation becomes.

$$C_{in}^{t_i} = C_{in}^{t_{i-1}} e^{-3.6 \times 10^3 (a + \lambda) \Delta t} + 3.6 \times 10^3 C_{out}^{t_i} a P \Delta t \quad (\text{p cm}^{-3})$$

and the indoor particle deposition rates will be estimated as:
\[ \lambda = -\frac{1}{3.6 \times 10^3 \Delta t} (a + ln \frac{C_{out}^{t_i} - 3.6 \times 10^3 C_{in}^{t_{i-1}}}{C_{in}^{t_i}} a P \Delta t) \quad (s^{-1}) \]  

(10)

where \( C_{out}^{t_i} \) and \( C_{in}^{t_i} \) are the outdoor and indoor PN concentrations (p cm\(^{-3}\)) at time \( t_i \), respectively; \( C_{in}^{t_{i-1}} \) is the indoor PN concentration (p cm\(^{-3}\)) at time \( t_{i-1} \); \( \Delta t \) is the time step (h); \( a \) and \( P \) are the air exchange rate (h\(^{-1}\)) and penetration factor, respectively, when the ventilation system is turned off.

2.8 Data analysis

The results from the particle measurements were grouped according to their outdoor and indoor location, along with the time period of the measurements, and 24-h average concentrations were calculated for each building space. The indoor air concentrations were then classified as: (1) HVAC ON and no indoor occupants and activities (6:00 – 8:30 and 17:00 – 18:00); (2) HVAC ON during working hours (8:30 – 17:00); (3) HVAC OFF and no indoor occupants and activities (18:00 – 19:00, 23:00 – 6:00, and during the weekend); (4) HVAC OFF and cleaning activities (usually from 19:00 to 23:00 on weekdays); (5) during rush-hours (from 6:00 – 9:00 and 16:00 – 19:00 on weekdays); and (6) during nucleation events. The identification of nucleation events during each field measurement campaign was reported in our previous work (Quang et al., 2012). All statistical analyses (correlation, regression, t-test and One-Way ANOVA) were conducted using SPSS for Windows version 18 (SPSS Inc.). The 5% level was used to indicate statistical significance in all cases.

3 Results and discussion

3.1 Air exchange rates and CO\(_2\) concentrations

Average air exchange rates (AERs) for level 3 of each building are presented in Table 1. As expected, the AERs were markedly higher when the ventilation was turned on compared to when it was off, even with consideration of the different measurement methods used. It is important to note that the ventilation system in Building B was operated in energy saving...
mode during the summer, which resulted in a significantly lower AER for Building B when
the ventilation system was on compared to the other two buildings, where the measurement
were performed during the winter. This also led to a significantly higher CO₂ concentration
(ppm) in Building B (Mean ± SD, 826 ± 91) compared to Buildings A (674 ± 28) and C (675
± 61) (p < 0.01), however the CO₂ concentrations were not significantly different when the
ventilation systems were turned off in all three buildings over the weekend (475 ± 6, 467 ± 5
and 481 ± 23 for Buildings A, B and C, respectively) (p = 0.46). The overall average CO₂
concentrations in all three buildings were lower than the guideline concentration of 1000 ppm
for office buildings, as outlined in the ANSI/ASHRAE 62.1 Standard (ASHRAE, 2010).

Table 1. Average air exchange rates (Mean ± SD) (h⁻¹)

<table>
<thead>
<tr>
<th>Site</th>
<th>HVAC ON*</th>
<th>HVAC OFF**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>1.19± 0.26</td>
<td>0.08± 0.04</td>
</tr>
<tr>
<td>Building B</td>
<td>0.37± 0.04</td>
<td>0.11± 0.06</td>
</tr>
<tr>
<td>Building C</td>
<td>0.89± 0.08</td>
<td>0.12± 0.03</td>
</tr>
</tbody>
</table>

* Based on ventilated outdoor air flow rates; ** Based on the decay of CO₂ concentrations

3.2 Outdoor and indoor particle concentrations

A summary of the descriptive statistics for outdoor and indoor particle concentrations at each
building are presented in Figure 1 and Table S1. In general, overall 24-h average outdoor
particle concentrations were significantly higher than indoor concentrations for all three
buildings (p < 0.01). Apart from PN concentration for Building B, outdoor particle
concentrations were also significantly higher than background concentrations measured
simultaneously in Brisbane CBD; the results of these comparisons are presented in Table S2.
Both outdoor PN and PM₂.₅ concentrations for Building A were significantly higher than
those for Buildings B and C (p < 0.01), while their relevant background concentrations were
comparable. This was due to location of Building A’s air intakes, which were sited proximate
to the busway, compared to those of Building B and C, which were located on higher rooftop
levels (level 18 and level 6, respectively). Indoor PN concentrations in the three buildings
were comparable with the PN concentrations measured in an office building in Brisbane’s
CBD by Jamriska et al. (2000). However, indoor PN and PM$_{2.5}$ concentrations were
significantly higher in Building A compared to Buildings B and C ($p < 0.01$). The highest
indoor particle concentrations in Building A were the result of higher outdoor particle
concentrations and outdoor ventilation rates for this building.

![Box plots of indoor and outdoor particle concentrations at Buildings A, B, and C.](image)

Figure 1. Overall 24-h average indoor and outdoor particle concentrations at Buildings A, B
and C. Box plots represent the maximum, minimum, 75th percentile, 25th percentile, and
median. The presented data are excluded outliers.

### 3.3 Filter efficiency measurements

#### 3.3.1 Central filtration systems

Overall and fractional filter efficiencies for the air handling system (AHS - consisting of a DB
filter and an AHU) at Buildings A, B and C, and the ES filter for Building C, are presented in
Figures 2 and 3, respectively. The overall filter efficiency, for Building A ($46.9 \pm 11.6 \%$) was
significantly higher than those for Building B ($26.3 \pm 4.1 \%$) and Building C ($26.4 \pm 2.3 \%$) ($p$
The higher filter efficiency for Building A was likely to be due to higher dust-loading, because outdoor and indoor particle concentrations at this building were significantly higher than those at Buildings B and C (Hanley et al., 1994). The overall filtration efficiencies of the AHS for each building were comparable to the efficiency of an office building AHU system (34%) with deep-bag filters in Brisbane reported by Jamriska et al. (2000). This validates the results of both the present study and that performed by Jamriska et al. (2000) to some extent, and further analyses are presented in the following sections.

Fractional efficiencies of the filters decreased with increasing particle size, and reached a minimum for particles approximately 70-110 nm in size, prior to increasing again for larger particle sizes (Figure 3). The increase in filtration efficiency for smaller and larger particles is caused by diffusion and impaction processes, respectively (Hanley et al., 1994). The overall filter efficiency for Buildings B and C were not significantly different. However, the fractional filter efficiencies at Building B compared to Building C were respectively higher and lower for 9-60 nm and 60-340 nm particles. These differences are likely to be due to the use of ES filters in Building C, which can significantly reduce the concentration of smaller outdoor particles in the air, before they are transported to the DB filter.

The overall filtration efficiency of the ES filters in the rooftop plant room of Building C was 60.2 ± 9%. This result was lower than the results of previous laboratory studies (80 – 95%), which were reported by Jamriska et al. (1998). In addition, the fractional efficiency of the ES filter was at a maximum for particles around 10 nm in size, which then decreased as particle size increased, while laboratory tests for new ES filters showed a maximum efficiency for particles in the size range 40-50 nm, with a large drop in filtration efficiency below 30 nm and a gradual decrease for particles larger than 60 nm (Jamriska et al., 1998).
3.3.2 Fan coil unit

Particle concentrations downstream (in the supply air at an air outlet) and upstream (in the outdoor air at an air intake) of a fan coil unit (FCU) were measured for a meeting room in Building A (Figure 4). In general, it can be seen that variations in downstream particle concentration followed variations in upstream particle concentrations when the FCU was turned on (indicated by the sharp decrease in indoor temperature), however when the FCU was turned off, the downstream particle concentrations started to decline. The filtration efficiency of the FCU, including its upstream air duct, was (21 ± 14) %, which is significantly lower than for the filters in the central plant room of this building ($p < 0.01$). This implies that
directly drawing outdoor air via the FCU, in order to introduce more fresh air into the room, also introduced an increased proportion of outdoor particles than would be expected if the room was ventilated by the central AHU.

Figure 4. Time-series of particle concentrations in outdoor air and supply air before, during and after the operation of the FCU.

3.4 I/O ratios of particle concentrations

Indoor to outdoor (I/O) ratios of PN and PM$_{2.5}$ concentrations for different time periods and ventilation scenarios, including: Daily (24-h), Cleaning (during cleaning with the HVAC system off), Off/absence (vacant office with the HVAC system off), On/absence (vacant office with the HVAC system on) and Working (during working hours with the HVAC system on), are presented in Figure 5 and Table S3. The comparisons of the I/O ratios during different time periods and ventilation scenarios for each building are presented in Table 2, while the comparisons of indoor particle concentrations and their I/O ratios during nucleation
events and rush-hour periods with their working-hours periods, respectively are presented in Table 3.

In general, the I/O ratios for both PN and PM$_{2.5}$ concentrations were less than 1, and agree well with the results of other studies conducted in mechanically ventilated buildings (Koponen et al., 2001; Wang et al., 2010; Wu et al., 2012). However, the I/O ratios of PM$_{2.5}$ concentrations were significantly higher than those for PN concentrations for all three buildings ($p < 0.01$). This implies that indoor PN concentration was strongly influenced by high outdoor PN sources, while indoor PM$_{2.5}$ levels were more influenced by sources inside the buildings, which is similar to the previous studies (Abt et al., 2000a; Abt et al., 2000b; Long et al., 2000). Another contribution factor is the lower efficiency of the DB filters for particles at the lower end of the PM$_{2.5}$ range (~0.1 micron).

The I/O ratios for both PN and PM$_{2.5}$ during cleaning had the highest values compared to other time periods at all three buildings ($p < 0.01$). This is not surprising, given that vacuum cleaner motors can release large amounts of fine and ultrafine particles (Afshari et al., 2005; Géhin et al., 2008; He et al., 2004; Knibbs et al., 2011; Trakumas et al., 2001), and vacuuming can also re-suspend larger size particles (Corsi et al., 2008; Ferro et al., 2004; Vaughan et al., 1999) inside the building.

When the office was vacant, the I/O ratios for PN and PM$_{2.5}$ were significantly lower when the HVAC system was on compared to when it was off at all three buildings ($p < 0.05$). This shows that the filters not only contributed to preventing the penetration of outdoor particles indoors, but they also served to reduce existing indoor particle concentrations (Jamriska et al., 2003; Zuraimi and Tham, 2009).

The I/O ratios for PN and PM$_{2.5}$ in the presence of the office occupants were significantly higher than those measured in their absence ($p < 0.05$) at all buildings. The movement of occupants and the activities they undertake, together with the operation of office equipment,
particularly laser printers, have been shown to increase indoor particle concentrations during working hours (He et al., 2007; He et al., 2010; Long et al., 2000; McGarry et al., 2011; Morawska et al., 2009a; Schripp et al., 2008). Further discussion of these factors is provided in Section 3.6.3.

When the ventilation system was turned on, the I/O ratios of PN concentration during both the absence and presence of occupants for Building C were significantly lower than those for Buildings A and B ($p < 0.01$). As discussed earlier, the use of the ES filters in Building C markedly reduced the amount of smaller particles which penetrated from outdoors.

The I/O ratios during rush-hours and nucleation events were significantly lower than those during overall working hours on the measurement days, however, the opposite was true for indoor PN concentrations (refer to Table 3 for comparative results). In addition, the correlations of indoor and outdoor PN concentrations during these periods were relatively high for all three buildings. These results show that indoor PN was mainly influenced by outdoor concentrations, and therefore, building occupants were exposed to higher particle concentrations from outdoors during rush-hours and nucleation events.

Table 2. I/O ratios (Mean ± SD) for different time periods and ventilation scenarios for each building

<table>
<thead>
<tr>
<th>Building</th>
<th>Unoccupied</th>
<th>HVAC on</th>
<th>p</th>
<th>Unoccupied</th>
<th>Occupied</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HVAC off</td>
<td>HVAC on</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>PN</td>
<td>0.34 ± 0.1</td>
<td>0.20 ± 0.03</td>
<td>&lt; 0.01</td>
<td>0.20 ± 0.03</td>
<td>0.34 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$</td>
<td>0.51 ± 0.07</td>
<td>0.38 ± 0.02</td>
<td>&lt; 0.01</td>
<td>0.38 ± 0.02</td>
<td>0.53 ± 0.10</td>
</tr>
<tr>
<td>B</td>
<td>PN</td>
<td>0.25 ± 0.07</td>
<td>0.20 ± 0.09</td>
<td>&lt; 0.05</td>
<td>0.20 ± 0.09</td>
<td>0.29 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$</td>
<td>0.71 ± 0.08</td>
<td>0.65 ± 0.04</td>
<td>&lt; 0.05</td>
<td>0.65 ± 0.04</td>
<td>0.66 ± 0.10</td>
</tr>
<tr>
<td>C</td>
<td>PN</td>
<td>0.20 ± 0.03</td>
<td>0.13 ± 0.05</td>
<td>&lt; 0.05</td>
<td>0.13 ± 0.05</td>
<td>0.18 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$</td>
<td>0.76 ± 0.03</td>
<td>0.74 ± 0.1</td>
<td>0.37</td>
<td>0.74 ± 0.01</td>
<td>0.91 ± 0.03</td>
</tr>
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</table>
Table 3. Indoor particle concentrations and I/O ratios during rush-hours and nucleation events

<table>
<thead>
<tr>
<th></th>
<th>Concentrations (Mean ± SD)</th>
<th></th>
<th>I/O ratio (Mean ± SD)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Working hours</td>
<td>Nucleation</td>
<td></td>
<td>Working hours</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td></td>
<td></td>
<td>p</td>
</tr>
<tr>
<td>A</td>
<td>PN ($\times 10^3$ p cm$^{-3}$)</td>
<td>3.64 ± 0.52</td>
<td>4.02 ± 0.62</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ (µg m$^{-3}$)</td>
<td>8.62 ± 0.57</td>
<td>9.0 ± 0.22</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>B</td>
<td>PN ($\times 10^3$ p cm$^{-3}$)</td>
<td>4.56 ± 3.38</td>
<td>7.14 ± 2.92</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ (µg m$^{-3}$)</td>
<td>5.22 ± 0.22</td>
<td>5.14 ± 0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>C</td>
<td>PN ($\times 10^3$ p cm$^{-3}$)</td>
<td>3.4 ± 0.64</td>
<td>4.0 ± 0.52</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$ (µg m$^{-3}$)</td>
<td>5.16 ± 0.3</td>
<td>4.93 ± 0.13</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

Figure 5. I/O ratios of PN and PM2.5 concentrations for Buildings A, B and C. Note: P1 stands for PN; P2 - PM$_{2.5}$; 1 - Daily; 2 - Cleaning; 3 - Off/absence; 4 - On/absence; and 5 - Working. Box plots represent the maximum, minimum, 75th percentile, 25th percentile, and median. The presented data are excluded outliers.
3.5 Investigation of indoor particle sources

A summary of the printer investigations conducted in the offices on level 3 of each building is presented in Table S4. These data, together with the printer emission rates reported by He et al. (2007) were used as model input data to quantify the number of particles generated by printing (Table S5).

The total emission rates of vacuuming (i.e. the vacuum emission and resuspension) were quantified based on Equation 4, using the measured data from Buildings A and C. The calculated emission rates were $5.05 \times 10^{11}$ p min$^{-1}$ and $5.34 \times 10^{11}$ p min$^{-1}$ for Building A and C, respectively. These results are higher than the emission rates from vacuum cleaners reported by Knibbs et al. (2011), Szymczak et al. (2007), and He et al. (2004). However, they are lower than the emission rate obtained by Gehin et al. (2008). Then these emission rates were used for 24-h modeling of indoor particle levels to determine the contribution of cleaning.

3.6 Modelling of indoor PN concentrations

3.6.1 Model input parameters

The mathematical model, which was presented by Jamriska et al. (2003) for theoretical studies, was modified to account for the real conditions encountered in each building we assessed. Model input parameters were based on both measured data and those reported in the literature. The penetration factor was determined based on the experimental measurement by Liu and Nazaroff (2003). As mentioned previously, the exterior walls of all three buildings were made from glass, so the main penetration pathway for outdoor air was cracks in aluminium window frames. The height and the length of cracks was assumed 0.25 mm and 4.3 cm, respectively, which were the lower range in the experiment and were appropriate for tighter envelopes of air-conditioned office buildings. The penetration rate was found to be 0.8
and 0.6 when the ventilation was on (I-O pressure difference $\Delta P = 10$ Pa) and off ($\Delta P = 4$ Pa), respectively.

Particle deposition rates with the ventilation turned on were based on a previous calculation (Jamriska et al., 2003), while rates when ventilation was turned off were quantified based on Equation 10 and the measured data in Building B. The measured indoor and outdoor PN concentrations, as well as the ventilation flow rates, filter efficiencies and particle concentrations generated from laser printing and vacuum cleaning in each building were used to run the 24-h model simulations. The input data used in the model are summarised in Table S5.

### 3.6.2 Model performance assessment

The 24-h modelled and measured PN concentrations for the three buildings are presented in Figures 6, S2 and S3, respectively. Statistical indicators from ASTM D5157 were applied to evaluate the performance of the model, including correlation coefficients of predictions compared to measurements ($r$), the slope ($b$) and intercept ($a$) of the line of regression between the predictions and measurements, normalised mean square error ($NMSE$), normalised fractional bias of the mean concentration ($FB$), and fractional bias based on the variance ($FS$). These indicators were calculated for each building, with the ventilation system turned on and off, and are shown in Table S6. All simulations for Building A met the ASTM D5157 indicator criteria, as did those for Buildings B and C when the ventilation system was turned off. When the ventilation system was turned on, the correlation coefficient for Building B was lower than the criterion, as were the correlation coefficient, the slope of the regression line and the normalized mean square error values for Building C. These results indicate that the model performed better when evaluating the 24-h PN concentrations for Building A and the night-time PN concentrations (i.e. when the ventilation system was turned off) for Buildings B and C. This is unsurprising since there are less variables to influence
concentration (both in terms of number and intensity) when the ventilation is turned off. It was also found that the accuracy of the predicted concentrations was higher when the main source of indoor particles was from outdoor air, or when ventilation was turned off. Nevertheless, model performance remained serviceable even when the ASTM criteria were unmet, as Table S6 and Figures 6, S2 and S3 highlight. This indicates the appropriateness of this approach for predicting PN concentrations and the factors that influence them in office buildings. Emmerich and Nabinger (2001) also applied the ASTM D5157 standard to evaluate an experimental indoor PN concentration model. However, to the best of our knowledge there is no information available in the literature regarding the use of these criteria for assessment of theoretical dynamic model for indoor PN concentration.

3.6.3 Evaluation of the influence of ventilation/filtration on indoor PN concentration

Indoor PN concentrations were also predicted using the model, for situations where concentrations were only influenced by outdoor sources, named “only outdoor”, and when they were influenced by both outdoor sources and printer emissions, named “outdoor and
printing”. Ratios of predicted indoor PN concentrations, together with measured indoor PN concentrations during the working-hours for each building were calculated and are presented in Table 4. The average ratio of “only outdoor” sources for Building A was significantly higher than for the other two buildings, while the average ratio for Building C was significantly lower ($p < 0.01$). This indicates that indoor PN concentrations for Building A were more strongly influenced by outdoor particles, while Building C was less strongly influenced by outdoor particles, as a result of the use of ES filters for cleaning outdoor air. Comparing “only outdoor” ratios and “outdoor and printing” ratios for the three buildings, we found that the contribution of printing and other indoor sources was significantly higher for Building C, but significantly lower for Building A compared to the other buildings. In addition, these ratios can be used to estimate the contribution of different sources to indoor PN concentration levels. For instance, the percentage contribution of outdoor sources, printing, and other indoor sources to indoor particle concentration in Building A and C were approximately 85%, 2%, 13%, and 66%, 11%, 23%, respectively.

To further evaluate the influence of filtration on indoor particle concentrations, the existing filters at Building A were assumed to operate under three different scenarios: (1) filtration of mixing air only (which is currently used), (2) filtration of outdoor air only, and (3) filtration both mixing air and outdoor air. The indoor PN concentrations for these different filtration scenarios are illustrated in Figure 7. The predicted concentrations were close to the measured values when the filter was applied to the mixing air flow. However, they are predicted to increase by 77% and decrease by 43% if the filter is applied to the outdoor air flow only, or both outdoor air and mixing air flows, respectively. These results indicate that, not only the efficiency of a filter, but also the air streams which pass through it, has a significant influence on indoor particle levels, and using filters for both mixing and outdoor air flows can dramatically reduce indoor particle levels in mechanically ventilated buildings. Also, the effects of changes in filter type, efficiency and position in the air stream on indoor particle
concentrations can be predicted relatively simply using the approach outlined here, which is often a more practical option compared to the more time and cost-intensive alternative of measurements.

Table 4. Ratios (Mean ± SD) of predicted and measured indoor PN concentrations during working hours

<table>
<thead>
<tr>
<th>Site</th>
<th>Only outdoor</th>
<th>Outdoor and printing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>0.85 ± 0.13</td>
<td>0.87 ± 0.12</td>
</tr>
<tr>
<td>Building B</td>
<td>0.72 ± 0.17</td>
<td>0.80 ± 0.15</td>
</tr>
<tr>
<td>Building C</td>
<td>0.66 ± 0.24</td>
<td>0.77 ± 0.19</td>
</tr>
</tbody>
</table>

Figure 7. Indoor PN concentrations at Building A at different scenarios.

4 Conclusions

We investigated the influence of ventilation and filtration on indoor particle concentrations within office buildings located close to busy traffic areas based on both experimental measurements and modelling. The findings of this study and their implications are summarised below.
The average indoor PN and PM$_{2.5}$ concentrations were $(2.46 - 5.71) \times 10^3$ p cm$^{-3}$ and $5.2 - 6.81$ µg m$^{-3}$, respectively, and the average outdoor PN and PM$_{2.5}$ concentrations were $(8.94 - 17.4) \times 10^3$ p cm$^{-3}$ and $9.25 - 13.9$ µg m$^{-3}$, respectively, for the three buildings. The significantly higher indoor and outdoor particle concentrations for Building A compared to Buildings B and C were due to the proximity of this building’s air intakes to a strong outdoor particle source (i.e. busway). This suggests that the physical position of the HVAC system’s outdoor air intakes can significantly reduce the impact of outdoor particles on indoor air, and this should always be considered at the HVAC design phase.

The in-situ efficiency of deep bag filters ranged from 26.3 to 46.9% for the three buildings, while the efficiency of the electrostatic filter in Building C was 60.2% and the efficiency of the FCU filter in Building A was 21%. The results show that the efficiency of the DB filters was strongly affected by particle characteristics, in particular particle size and particle upstream concentration. The efficiency of the ES filter was lower than those tested in the laboratory, which could be due to the different operating conditions and upstream particle characteristics between the real-world and laboratory environments. However, this work only measured one ES filter in one office building and therefore, further investigations into in-situ ES filter efficiency under different conditions are required prior to any conclusive recommendations regarding their relative advantages and disadvantages compared to DB filters. Additionally, the overall filtration efficiency of the FCU filter was significantly lower than in the central plant rooms. This result strongly suggests that FCUs should be assessed for their capacity to clean outdoor air to the same extent as the central HVAC system, such that changes can be made accordingly.

The I/O particle concentration ratios showed that mixing air filters not only prevent outdoor particles penetrating indoors but they also reduce the impact of indoor particle sources on indoor particle concentrations. Also, the utilisation of both outdoor and mixing air filters can
significantly influence on and keep indoor particle concentration levels lower when compared
to mixing air filters alone.

Based on the comparison of I/O particle concentration ratios and their I/O correlation during
rush-hours, nucleation events and overall working-hours, the results indicate that indoor PN
concentration was strongly influenced by outdoor PN concentration during rush-hours and
nucleation events. Many studies have investigated outdoor particle formation and its effect on
regional environments or climate change, but they are yet to focus on their effects on indoor
environments, especially office buildings where many people spend an appreciable proportion
of their day. This work highlights the potentially under-acknowledged role of nucleation in
producing particles that can penetrate inside buildings and contribute to exposures incurred by
large numbers of people.

A previously developed dynamic model for indoor PN concentration was modified, evaluated
and applied to assess the influence of filtration and ventilation on indoor particle levels under
different indoor and outdoor particle source conditions. The results of 24-h modelling for all
buildings indicated that the model generally performed very well against evaluation criteria
under most scenarios, and offered serviceable performance even when for criteria were not
met.

These findings provide scientific grounds for the selection and location of appropriate filters
and air intakes in building HVAC systems, in order to minimise occupant exposure to high
outdoor particle concentrations from both combustion products and new particle formation in
urban areas. The modelling approach reported here can be used either prior to construction to
determine optimum filtration media and operating characteristics or post-occupancy to
determine the likely effects of changes to these. The results also provide information to
improve understanding of indoor particle dynamics and behaviours in office buildings under
different ventilation and particle source scenarios.
Acknowledgement

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Supplementary Materials

Table S1. Descriptive statistics for indoor and outdoor particle concentrations at Buildings A, B and C

<table>
<thead>
<tr>
<th>Site</th>
<th>Statistic description</th>
<th>PN ($\times 10^3$ p cm$^{-3}$)</th>
<th>I/O</th>
<th>PM$_{2.5}$ ($\mu$g m$^{-3}$)</th>
<th>I/O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Indoor</td>
<td>Outdoor</td>
<td>Indoor</td>
<td>Outdoor</td>
</tr>
<tr>
<td>Building A</td>
<td>Mean</td>
<td>5.71</td>
<td>17.4</td>
<td>0.40</td>
<td>6.81</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>1.82</td>
<td>10.9</td>
<td>0.17</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>Min</td>
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<td>5.47</td>
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<tr>
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<td>9.59</td>
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<tr>
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<td>14.1</td>
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<tr>
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<td>21.9</td>
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<tr>
<td></td>
<td>Max</td>
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<td>68.8</td>
<td>0.95</td>
<td>9.90</td>
</tr>
<tr>
<td></td>
<td>95% CI</td>
<td>0.22</td>
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<tr>
<td>Building B</td>
<td>Mean</td>
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<td>8.94</td>
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<tr>
<td></td>
<td>SD</td>
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<tr>
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<td>0.15</td>
<td>0.37</td>
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</tbody>
</table>
Table S2. Comparisons of overall 24-h average outdoor particle concentrations at each building with those measured simultaneously in Brisbane’s CBD at a background site

<table>
<thead>
<tr>
<th></th>
<th>PN ($\times 10^3$ p cm$^{-3}$) (Mean ± 95% CI)</th>
<th>PM$_{2.5}$ (µg m$^{-3}$) (Mean ± 95% CI)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>17.4 ± 1.33</td>
<td>13.9 ± 0.38</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Brisbane CBD</td>
<td>7.42 ± 0.34</td>
<td>8.16 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>Building B</td>
<td>8.94 ± 1.12</td>
<td>9.5 ± 0.28</td>
<td>0.25</td>
</tr>
<tr>
<td>Brisbane CBD</td>
<td>7.65 ± 1.89</td>
<td>6.33 ± 0.34</td>
<td></td>
</tr>
<tr>
<td>Building C</td>
<td>11.48 ± 0.58</td>
<td>9.25 ± 0.27</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Brisbane CBD</td>
<td>8.59 ± 0.4</td>
<td>5.7 ± 0.14</td>
<td></td>
</tr>
</tbody>
</table>

Table S3. I/O ratios of PN and PM$_{2.5}$ concentrations at Buildings A, B and C

<table>
<thead>
<tr>
<th>Site</th>
<th>SD</th>
<th>Daily</th>
<th>Cleaning</th>
<th>Off/absence</th>
<th>On/absence</th>
<th>Working</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>Mean</td>
<td>0.40 0.51 0.67 0.59</td>
<td>0.34 0.46 0.20 0.34 0.34 0.48</td>
<td>0.17 0.13 0.18 0.06</td>
<td>0.10 0.06 0.03 0.02 0.09 0.09</td>
<td>0.13 0.30 0.16 0.30</td>
</tr>
<tr>
<td>Building B</td>
<td>Mean</td>
<td>0.37 0.64 0.46 0.67</td>
<td>0.25 0.59 0.20 0.54 0.29 0.61</td>
<td>0.20 0.09 0.12 0.05</td>
<td>0.10 0.07 0.09 0.03 0.10 0.09</td>
<td>0.10 0.44 0.28 0.59</td>
</tr>
<tr>
<td>Building C</td>
<td>Mean</td>
<td>0.25 0.59 0.36 0.63</td>
<td>0.20 0.59 0.13 0.57 0.18 0.70</td>
<td>0.15 0.11 0.14 0.03</td>
<td>0.03 0.03 0.05 0.07 0.05 0.02</td>
<td>0.06 0.27 0.20 0.58</td>
</tr>
</tbody>
</table>

...
Table S4. Printer profiles on level 3 of Buildings A, B and C

<table>
<thead>
<tr>
<th>Building</th>
<th>Total printers</th>
<th>Printer emission classification*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Non</td>
</tr>
<tr>
<td>A</td>
<td>15</td>
<td>7</td>
</tr>
<tr>
<td>B</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>14</td>
<td>1</td>
</tr>
</tbody>
</table>

*The criteria to determine printer emission class was defined in the section 2.5

Table S5. Summary of model input parameters

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Sym.</th>
<th>Building A</th>
<th>Building B</th>
<th>Building C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow rate (m$^3$s$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation ON</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor $Q_{oa}$</td>
<td>2.5-3.25</td>
<td>0.45</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>Return $Q_{ra}$</td>
<td>12.5-13.3</td>
<td>7.25</td>
<td>4.85</td>
<td></td>
</tr>
<tr>
<td>Supply $Q_{sa}$</td>
<td>15.8</td>
<td>7.7</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>Exceed $Q_{exc}$</td>
<td>2.25-2.92</td>
<td>0.32</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>Infiltration $Q_{inf}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Exfiltration $Q_{exf}$</td>
<td>0.25-0.33</td>
<td>0.13</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Ventilation OFF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor $Q_{oa}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Return $Q_{ra}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Supply $Q_{sa}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Exceed $Q_{exc}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Infiltration $Q_{inf}$</td>
<td>0.18</td>
<td>0.13</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Exfiltration $Q_{exf}$</td>
<td>0.18</td>
<td>0.13</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Room effective volume (m$^3$)</td>
<td>$V_{room}$</td>
<td>$7.94 \times 10^3$</td>
<td>$4.38 \times 10^3$</td>
<td>$4.25 \times 10^3$</td>
</tr>
<tr>
<td>Mixing factor $k$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Filter efficiency (mixing air) $FE_{AHS}$</td>
<td>0.47</td>
<td>0.26</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Filter efficiency (outdoor air) $FE_{OA}$</td>
<td>-</td>
<td>-</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Penetration factor $P_{bld}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation ON</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Ventilation OFF</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Deposition rate (s$^{-1}$)</td>
<td>$\lambda$</td>
<td>$4.51 \times 10^5$</td>
<td>$4.51 \times 10^5$</td>
<td>$4.51 \times 10^5$</td>
</tr>
<tr>
<td>Ventilation ON</td>
<td>$2.71 \times 10^5$</td>
<td>$2.51 \times 10^5$</td>
<td>$2.59 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>Laser printer emission rate (p min$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low emission</td>
<td>$9 \times 10^9$</td>
<td>$9 \times 10^9$</td>
<td>$9 \times 10^9$</td>
<td></td>
</tr>
<tr>
<td>Medium emission</td>
<td>$90 \times 10^9$</td>
<td>$90 \times 10^9$</td>
<td>$90 \times 10^9$</td>
<td></td>
</tr>
<tr>
<td>High emission</td>
<td>$150 \times 10^9$</td>
<td>$150 \times 10^9$</td>
<td>$150 \times 10^9$</td>
<td></td>
</tr>
<tr>
<td>Vacuum cleaner emission rate (p min$^{-1}$)</td>
<td>$2.02 \times 10^{12}$</td>
<td>-</td>
<td>$2.14 \times 10^{12}$</td>
<td></td>
</tr>
</tbody>
</table>
Table S6. Summary of model evaluation indicators based on comparison of measured and modelled results

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>$r$</th>
<th>$a$</th>
<th>$b$</th>
<th>NMSE</th>
<th>FB</th>
<th>FS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building A</td>
<td>Ventilation on</td>
<td>0.92</td>
<td>-356</td>
<td>0.92</td>
<td>0.04</td>
<td>-0.14</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Ventilation off</td>
<td>0.94</td>
<td>59</td>
<td>0.99</td>
<td>0.01</td>
<td>0.00</td>
<td>0.09</td>
</tr>
<tr>
<td>Building B</td>
<td>Ventilation on</td>
<td>0.84</td>
<td>37</td>
<td>0.78</td>
<td>0.10</td>
<td>-0.23</td>
<td>-0.15</td>
</tr>
<tr>
<td></td>
<td>Ventilation off</td>
<td>0.93</td>
<td>-167</td>
<td>1.04</td>
<td>0.00</td>
<td>-0.02</td>
<td>0.23</td>
</tr>
<tr>
<td>Building C</td>
<td>Ventilation on</td>
<td>0.88</td>
<td>1124</td>
<td>0.50</td>
<td>0.36</td>
<td>-0.34</td>
<td>-1.04</td>
</tr>
<tr>
<td></td>
<td>Ventilation off</td>
<td>0.91</td>
<td>47</td>
<td>1.02</td>
<td>0.05</td>
<td>0.05</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Figure S1. Schematic diagram of HVAC system and model input parameters for an indoor office space.
Figure S2. PN concentrations for Building B (Modeled versus Measured).

Figure S3. PN concentrations for Building C (Modeled versus Measured).