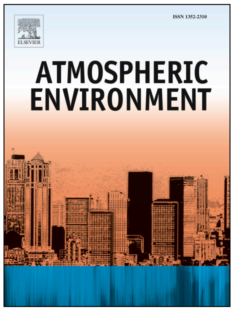

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DM and SS contributed to the conceptualization of the paper. SS conducted the formal analysis and original draft. All authors contributed to the methodology, data collection, review and editing of the paper.

A critical evaluation of the dynamic nature of indoor-outdoor air quality ratios

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Abstract

Long term, continuous indoor and outdoor pollutant monitoring was evaluated from a case study hospital, school, office and 18 apartments in the UK. Data was examined in order to explore the dynamic behaviour of indoor-outdoor ratios (I/O) for both particulate matter and nitrogen dioxide. Traditionally I/O ratios have been determined as single aggregate values or static parameters, from passive sampling or short periods of continuous monitoring. Whilst widely reported, I/O ratios are seen as too variable to be of wider use. However, this work reveals the dynamic nature of I/O ratios, with strong diurnal and seasonal variation observed for both particulate matter and nitrogen dioxide. Higher I/O ratios tended to be seen during core or occupied hours, associated with increased human activity and higher ventilation rates. This means that static I/O ratios determined by passive sampling techniques, rather than continuous measurements filtered to core hours, may underestimate I/O ratios associated with occupant exposure. Further, the I/O ratio is shown to be strongly influenced by occupant activity and window opening behaviour. As such, it may represent a personal variable as much as one associated with a building. It is argued that traditionally reported static I/O ratios simplify these dynamic behaviour and modes of operation into a single aggregate value, losing key information in the process. Further, without contextual information on the operation and use of a building during measurements a reported I/O ratio may be hard to interpret or compare to wider studies. Finally, it is argued that the I/O ratio, whilst a limited metric, when evaluated dynamically provides a useful building operation parameter, describing the relationship the building has with the outdoor environment. This can help better define ventilation strategies, schedules, the influence of occupant behaviour and significance of indoor sources.

1. Introduction

Although the most important environmental predictor driving health effects is considered to be individual-level exposure, most epidemiological studies concerning air pollution utilise outdoor concentrations at the nearest central monitoring station or modelled ambient concentrations often at postcode level (Hoek et al., 2013). Models for chronic health impacts and mortality tend to use outdoor annual mean concentrations (Lelieveld et al., 2015; Pedersen et al., 2013), without accounting for any diurnal /seasonal variations or modifying effects of building envelopes on indoor exposure. However, people spend most of their time indoors and within indoor microenvironments.

The use of outdoor concentrations as proxies of exposure therefore implicitly assumes the attenuation of ambient concentrations by buildings is the same for all participants (Cohen et al., 2009), with exposure estimates that do not take into account time activity patterns, indoor generated pollutants or factors influencing infiltration of pollutants indoors. Evidence from the built environment indicates that building characteristics, ventilation, penetration efficiency and indoor activities have a significant impact on indoor concentrations (Blondeau et al., 2005; Kim et al., 2019; Majd et al., 2019; Stranger et al., 2008; Wichmann et al., 2010).The influence of building characteristics has even been picked up within population health studies, for example, PM_{10} associated hospital admissions were lower in US cities with higher proportions of air conditioning (Janssen et al., 2002).

The modifying impact building envelopes have on outdoor concentrations penetrating in the indoor environment has not been adequately addressed in many health studies and therefore remains a potential source of exposure error and a cause of the large bandwidth seen in mortality estimates (Ji and Zhao, 2015; Sarnat et al., 2007).

In light of these concerns, some epidemiological studies and large scale building stock models have instead attempted to incorporate metrics to quantify the modifying effect of a building upon outdoor concentrations (Chen et al., 2012; Ji and Zhao, 2015; Taylor et al., 2019). To this purpose, an infiltration factor (F_{inf}), the fraction of outdoor pollutants remaining airborne after penetrating indoors, may be used. Under assumptions of ideal and instantaneous mixing, uniform air exchange rates and approximated steady state (i.e. analysed over a minimum of 24hours), indoor concentrations can be described by a first-order differential equation with the analytical solution: (Wallace and Williams, 2005):

$$C_{in} = F_{inf} C_{out} + \frac{S}{V \cdot (a+k)} \quad 1$$

Where the infiltration factor can further be defined as:

$$F_{inf} = \left(\frac{P \cdot a}{(a+k)}\right) \quad 2$$

Here, C_{in} and C_{out} are the indoor and outdoor mass concentration (µg/m^3), *P* is the penetration factor across the building envelope, *a* is the air exchange rate (h^{-1}), *k* is the total decay rate of particles (h^{-1}) that depends on the aerodynamic diameter, *S* is the source strength (µg/h^{-1}) and *V* is the volume of the building (m^3).

Estimates of F_{inf} can be generated through a variety of methods. Modelling studies may base estimates of *P, a* and *k* upon previous literature (e.g. Chen et al., 2012; Fabian et al., 2012; Fazli et al., 2021; Li and Friedrich, 2019), sometimes supported by building surveys and questionnaires, in order to determine the likely relationship between indoor and outdoor concentrations (Cohen et al., 2009). Alternatively, F_{inf} may be based upon direct measurements of pollutants with no internal sources (e.g. particulate sulfate (Wilson et al., 2000)), via linear regression or a range of dynamic solutions to the mass balance equation (Diapouli et al., 2013a; Wang et al., 2016). However, in reviewing these techniques Diapouli et al (2013) note the determination of *P* and *k* remains challenging, with reported values within the literature varying significantly. Similarly, approaches must consider how to accurately filter out or account for internally generated contributions across analytical periods. Finally, the air exchange rate, *a*, is considered a critical exposure factor that may potentially modify health effect estimates reported in epidemiological studies (Long and Sarnat, 2004). However, studies show significant variation in air exchange rates, both in time and between buildings, countries and occupants (Dimitroulopoulou, 2012; Dimitroulopoulou and Bartzis, 2014; Øie et al., 1998). Further, measurements of representative air exchange rates are subject to significant uncertainties, particularly regarding occupancy, multizonal airflows, sensor accuracies, temporal variations and analytical methods (Batterman, 2017; Johnston and Stafford, 2016; Kabirikopaei and Lau, 2020). As a result of these challenges, the determination of more accurate and relevant methods of determining the relationship between indoor and outdoor air is thought to be a key future task in air pollution exposure assessment (Sarnat et al., 2007).

An alternative, simpler metric is to define the ratio of indoor pollutant concentrations in relation to outdoor concentrations. This indoor-outdoor (I/O) ratio allows a more direct field measurement and avoids uncertainties in determining individual parameters in equation 2. The I/O ratio has been measured for particulate matter and nitrogen dioxide since the 1980s (Monn et al., 1997) and can be defined by:

$$I/O = \frac{C_{in}}{C_{out}} \qquad 3$$

Or, importantly when utilising continuous, real-time measurements:

$$I/O_{i.j} = \frac{\sum_i^j C_{in}}{\sum_i^j C_{out}} = \frac{\sum_i^j C_{in}/_n}{\sum_i^j C_{out}/_n} \qquad 4$$

Where i and j are the beginning and end of an analytical period and n is the number of measurements over that period. More fully, combining equation 4 and equation 1:

$$I/O = \frac{C_{in}}{C_{out}} = \left(\frac{P \cdot a}{(a+k)}\right) + \frac{S}{V \cdot (a+k) C_{out}} \qquad 5$$

As can be seen in equation 5, the I/O ratio is a function of a building's penetration factor (of each specific pollutant), air change rate, loss rate due to chemical sinks or deposition and the presence of any indoor sources. It can also be considered that in the absence of indoor sources ($S = 0$) the indoor-outdoor ratio can be considered equivalent to the infiltration factor ($I/O = F_{inf}$).

The I/O metric therefore not only describes the building as a pollutant modifier but also incorporates the operation of and activity within a building, including indoor sources. Estimates of I/O ratios have been established for a range of pollutants, buildings and countries, with significant review articles covering studies on nitrogen dioxide (Hu and Zhao, 2020; Kalimeri et al., 2019; Salonen et al., 2019), particulate matter (Chen and Zhao, 2011; Kalimeri et al., 2019) and ozone (Kalimeri et al., 2019; Weschler, 2000). Importantly, significant ranges in I/O estimates exist both across study samples, between studies and within buildings across time (Wallace and Williams, 2005). This latter point is important, with further studies indicating seasonal and shorter-term temporal variations in I/O ratios measured within a single building or zone (Allen Ryan W. et al., 2012; Cyrys et al., 2004).

The focus and scope of this paper is restricted to understanding I/O ratios within the context of human health and buildings designed and operated for occupied spaces. As such, some conclusions will not apply to other areas where I/O ratios have also been adopted, such as in cultural heritage where they are used to detail relationships between outdoor and various indoor environments, such as showcases and closed depositories (e.g. Grau-Bové and Strlič, 2013; Lazaridis et al., 2015).

1.1 Measuring the I/O ratio

Importantly, the definition of any measured I/O ratio is then further formed by the nature of the measurement itself. Many of the largest studies of indoor air quality have at least partly used some form of diffusive sampling over 5 to 14 day periods (e.g. Allen Ryan W. et al., 2012; Mandin et al., 2017; Schneider et al., 2001; Shaw et al., 2020; SINPHONIE, 2014). Some of these data sets have then been used to determine distributions of I/O ratios for different building types (Kalimeri et al., 2019). However, fundamentally this means the measured I/O incorporates significant unoccupied periods during which activities and building operation and indoor sources (S) are likely to significantly differ. For example, a 5-day passive measurement would typically represent just a third of core occupied school hours (e.g. 8am – 4pm) and two-thirds unoccupied periods. Similarly, out-of-hours sampling of internal VOCs has been found to either over or under-estimate concentrations, depending on the pollutant species (WHO Europe, 2020).

This bias in sampling period is further compounded by the non-static nature of buildings. Air exchange rates in both mechanically and naturally ventilated buildings are likely to increase during occupied hours, meaning these periods may experience a higher ingress of outdoor air pollution to the indoor environment than during unoccupied periods. More specifically, this can be considered an increase in the F_{inf} component, as a result of the higher air exchange rate across occupied periods. Even in a 24hour operation, sealed envelope hospital, demand-controlled ventilation has been found to result in higher I/O ratios for nitrogen dioxide across the core daytime hours (Stamp et al., 2020). The result is that any aggregated passive measurement is likely to underestimate the I/O experienced across this period. The potential bias in sampling period may be given further significance by the fact that the daytime periods with the highest I/O ratio may also coincide with the highest, traffic-related, outdoor concentrations.

Shorter-term aggregate sampling, taking place over a few hours or days and eliciting a single measured concentration for this time period, can avoid this out-of-hours sampling period bias (e.g. (Viana et al., 2014). However, even with measurements across multiple seasons (e.g. Li and Lin, 2003), these may only represent small snap-shots of a complex and highly variable parameter.

The alternative is to use continuous or real-time measurements (e.g. laser scattering, optical particle counters, electrochemical sensors). This approach allows careful filtering and selection of appropriate analysis periods. Until recently, with large, expensive and impractical equipment, continuous measurements have often been limited to periods of a few days to weeks (e.g. (Branco et al., 2014; Huang et al., 2015; Jones et al., 2000). However, improvements in sensing technologies can enable more affordable measurements at improved accuracies, in multiple locations, allowing I/O ratios to be assessed and examined at high resolutions across significantly longer periods (Chatzidiakou et al., 2019).

1.2 Aims

In summary, I/O ratios have been measured across numerous studies since the 1980s and continue to be widely reported for a range of pollutants in many IAQ studies. Whilst the I/O ratio has been directly used in a few health studies (Borrego et al., 2006; Setton et al., 2008), more commonly building modifiers are omitted or else infiltration factors preferred (Fazli et al., 2021). Therefore, whilst I/O ratios remain widely measured and reported, the large variation in measured values and range of influencing factors mean that they are unlikely to be useful to epidemiologists (Poupard et al., 2005).

This paper aims to use several long-term, continuous data sets from a range of UK building types to evaluate the variation seen in I/O ratios under greater detail. This includes variation due to diurnal and seasonal effects, measurement methods, building operation modes, occupant behaviour and measurement uncertainties. The aim of these investigations is to understand the dynamic nature of I/O ratios and the influential factors behind this variation. From this, a critique of the validity and relevance of I/O ratios can be made, particularly when they are evaluated as a static metric.

A further hypothesis is that the information held within a dynamically assessed I/O ratio might prove more insightful as a building operation parameter. Whilst individual, static I/O ratios may prove useful within a larger population of results, a dynamic I/O may indicate, on an individual building basis, how the influence of outdoor air, ventilation practices and indoor sources of pollutants impact indoor air quality – particularly when longer data sets can be acquired. Subsequently this may lead to improved evidence on how building design and operation might mitigate these effects.

2. Research Methods

Data from long-term, simultaneous outdoor and indoor air quality measurements has been re-analysed focusing on determining I/O ratios from continuous monitoring. This includes measurements from a hospital, a school, an office and in 18 low-energy apartments over a 6 - 12 month period. Further details of the case study buildings and monitoring campaigns can be found in previous publications (Cooper et al., 2021; Stamp et al., 2020). A summary of the case studies can be found in Table 1.

Table 1: Details of monitoring campaigns used in analysis.

Case Study	Monitored Locations	Monitored Duration	Ventilation strategy	Year of Completion	Air Permeability	Location
Hospital	1 (3 sampled indoor zones)	8 Months (Jan – Aug)	Mechanical Ventilation, fully sealed (F9 filters)	2015	< 5 $m^3 \cdot h^{-1}/m^2$ at 50 Pa	City Centre, UK
School	1 (3 sampled indoor zones)	6 Months (Jan-June)	Mechanical ventilation, openable windows (F7 filters)	2014	< 5 $m^3 \cdot h^{-1}/m^2$ at 50 Pa	South London, UK
Office	1 (3 sampled indoor zones)	8 Months (Jan – Aug)	Naturally ventilated	2014	4.7 m^3/h per m^2 at 50 Pa	Town-Centre, UK
Apartments (Site A)	11 (1 zone – living room)	Between 6 – 12 Months (June – May)	Background MVHR (G3 filters), openable windows	2015	2–3 $m^3/(h.m^2)$ at 50Pa	East London, UK
Apartments (Site B)	7 (1 zone – living room)	Between 6 – 12 Months (June – May)	natural ventilation and trickle-ventilators	2007	< 5 $m^3 \cdot h^{-1}/m^2$ at 50 Pa	East London, UK

The analysis of I/O ratio focuses on measurements of particulate matter ($PM_{2.5}$ and PM_{10}) and nitrogen dioxide (NO_2). Complimentary measurements of carbon dioxide (CO_2, as a proxy for ventilation rates) and TVOCs (as a proxy for internally generated pollutants) have been made simultaneously in all locations, alongside temperature, humidity and locally installed weather stations. Within the case study apartments, window-opening and occupant presence have additionally been monitored directly, allowing more explicit evaluation of occupant behaviours on I/O ratios. Details of the monitoring equipment is given in Table 2. Sensors have been co-located and evaluated against reference instruments, with appropriate linear corrections applied to improve accuracy or precision between the deployed sensors. Specific details can be found in the supplementary material of Stamp et al., (Stamp et al., 2020), with Chatzidiakou et al., (2019) providing a broader look this process and a more detailed evaluation of sensor performance. Particulate matter data has additionally been filtered to avoid bias at high humidity (>88%), because exposure of the particles to relative humidity (RH) results in hygroscopic growth of particles and leads to mass overestimation (Crilley et al., 2018). The optical particle counters limited ability to capture particles at the lower end of particle sizes (range 0.38 = 17 µm) may also impact the results of the study. For example, parts of the urban aerosol fine mode fraction (0.2 – 0.3 µm) may not be sufficiently observed. This may further limit the equivalence of I/O ratios (see section 4.6 for further discussion).

Measurements were aggregated to hourly intervals to estimate I/O ratios to reduce noise and reduce the effect of lags between indoor and outdoor concentrations. All analysis was performed in R software (R Core Team, 2021).

Table 2: Details of monitoring equipment used in case study buildings.

Parameter	Sensor	Range	Resolution	Accuracy
Temperature	Thermistor	-30.0 to 65.0°C	0.1°C	±0.2°C at 20°C ±0.4°C for -5 to 40°C ±1.0°C for -20 to 65°C
Relative Humidity	Capacitive	0.0 to 100.0%	0.10%	±2% RH (0 to 90% RH) ±4% RH (0 to 100% RH)
CO_2	Non-dispersive infra red (E+E Electronik)	0-5000ppm	1ppm	<±50ppm, +3%
Particulate Matter ($PM_{2.5}$ & PM_{10})	Optical Particle Counter (Alphasense OPC-N2) Size segregated particles in the range (0.38 to 17 μm)	0 to 500 μg/m^3	0.01 μg/m3	-
Airflow	-	0.00 to 500 ml/s	0.01 ml/s	-
Nitrogen Dioxide (NO_2)	Electrochemical (Alphasense NO2-A43F)	0.00 to 3.00 ppm	0.1 ppb	-
Total Volatile Organic Compounds (TVOCs)	Photoionization detector (Alphasense PID-AH2)	0.00 to 50.00 ppm	10ppb	-
Occupancy	Passive Infrared Sensors (PIR) (HOBO UX90-05)	0-1 (Unoccupied – Occupied)	-	-
Window Status	Reed Contact Switches (Eltek GS34)	0-1 (Open – Closed)	-	-

3. Results

Results from re-analysed I/O ratios are explored within this section. This includes diurnal variations (section 3.1), seasonal variations (3.2), differences associated with passive and continuous measurement methods (3.3), variations between apartments (3.4) and variations with occupant behaviour (3.5).

3.1 Diurnal Variations in I/O ratios

The diurnal behaviour of I/O ratios can be seen for the monitored hospital, school, office and 18 apartments in Figure 1.

In the mechanically ventilated hospital and hybrid school, the I/O ratio for nitrogen dioxide is seen to increase by a factor of two during core operation hours. Both buildings adopted CO_2 based demand-controlled ventilation strategies, that would increase ventilation rates during core hours to maintain low indoor CO_2 concentrations. However, by increasing the air change rate to maintain low indoor CO_2 concentrations, there was an unintended ingress of NO_2 from the outside air.

For particulate matter, within the fully mechanical hospital (F9 filters) and hybrid school (F7 filters), the impact of filtration is clear, with low I/O ratios for both $PM_{2.5}$ and PM_{10}. However, within all non-domestic buildings, the I/O ratio of particulate matter is again seen to increase across core hours. Again, this may be associated with increased ingress from outdoors, but, given particle filtration in mechanically ventilated buildings, the more significant contribution to this is likely to by indoor generated and re-suspended particles during the occupied periods, particularly for PM_{10}.

With more varied occupancy schedules, apartments show altogether different diurnal patterns. The I/O ratio for NO_2 again peaks during the middle of the day, but peaks in particulate matter occur during the evening, associated with increased occupant activity. A strong peak is seen around 19:00-20:00, with I/O ratios reaching above 1.5 for $PM_{2.5}$ and above 2 for PM_{10}. These indicate the strong influence of internal sources, e.g. cooking, across these periods.

Such diurnal variations are seen in other studies, with indoor concentrations and I/O ratios varying significantly across the day (Challoner and Gill, 2014; Jones et al., 2000), and between weekdays and weekends (Branco et al., 2014) or peaking during core hours in schools (Branco et al., 2019) and hospitals (Cyrys et al., 2004).

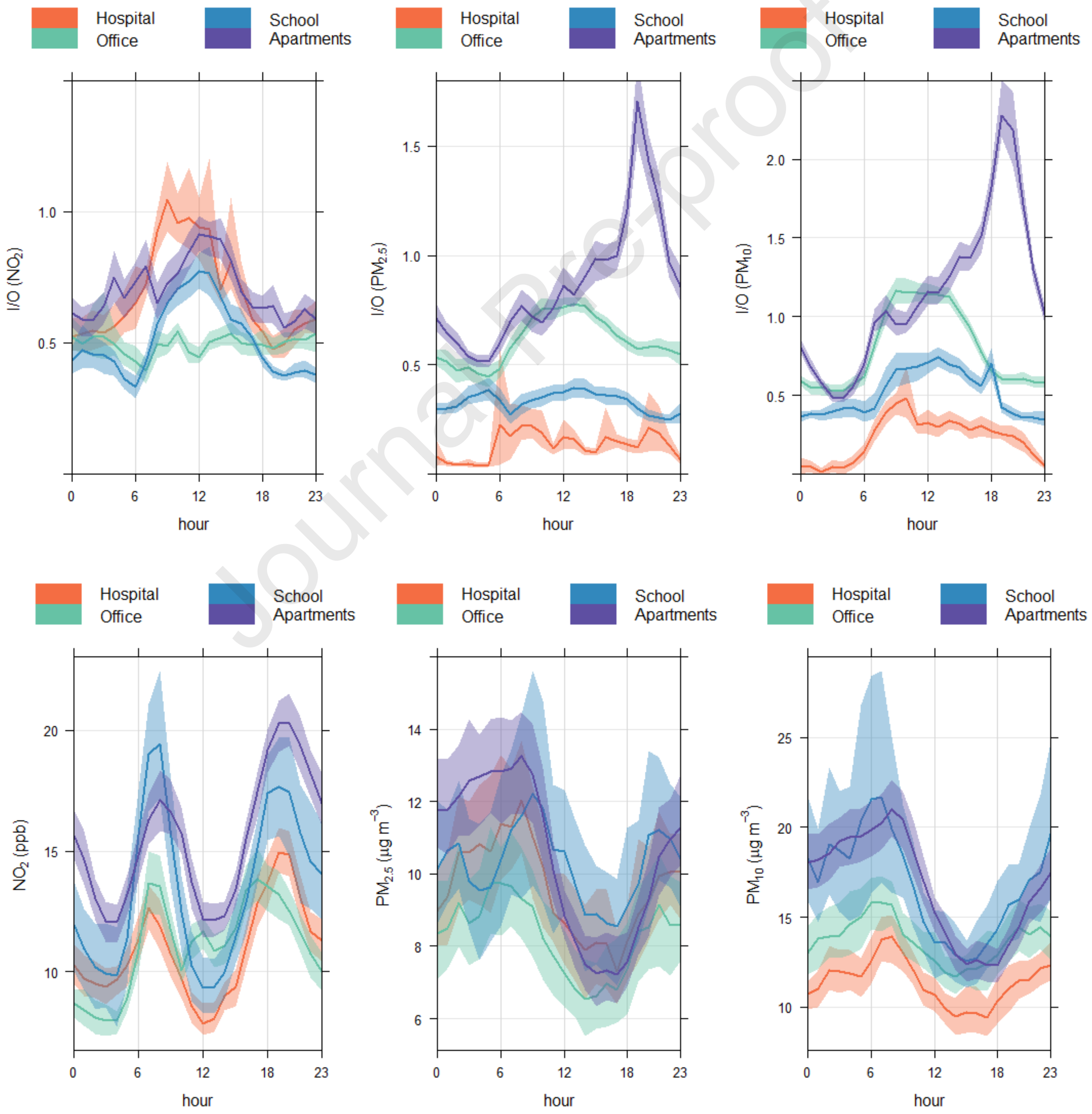


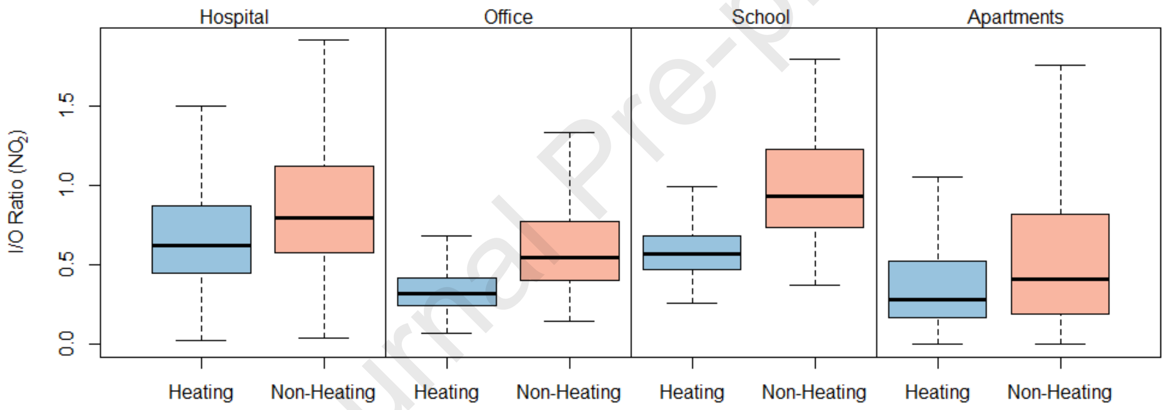
Figure 1: Top row - Aggregated or 'typical' I/O ratios for NO_2, $PM_{2.5}$ and PM_{10}. Evaluated over 6-9 month periods in a school, hospital, office (3 internal zones in each -Mon-Fri only) and 18 apartments (living rooms). Bottom row – corresponding outdoor concentrations for each site and pollutant.

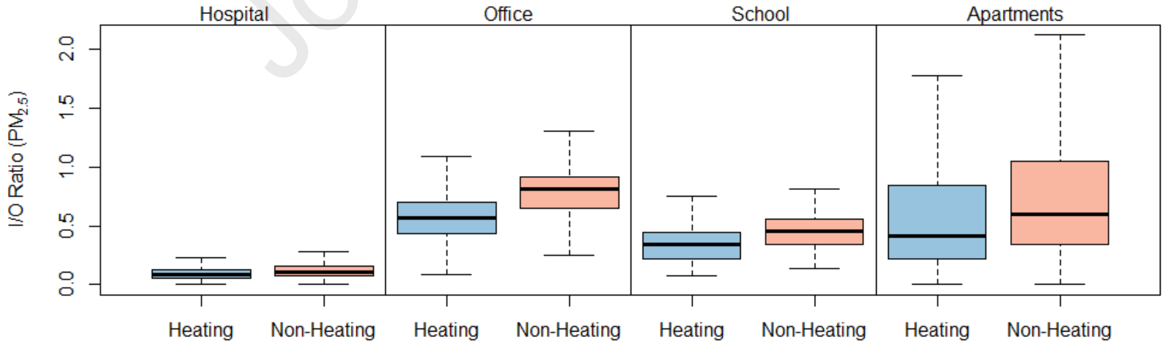
3.2 Seasonal variations in I/O ratios

Figure 2 shows the I/O ratios for NO_2, $PM_{2.5}$ and PM_{10} in the heating (Oct-Mar) and non-heating seasons (Apr-Sep). Increases in the I/O across the non-heating season can be observed in all cases for NO_2 and $PM_{2.5}$. Such differences are not seen for PM_{10}, where potentially higher indoor contributions and the impact of re-suspension may negate any seasonal effect.

Similar seasonal variations have been picked up in a number of previous studies. Trends may be dependent on the significance of internal sources, but typically higher I/O ratios have been observed during the summer under higher ventilation rates (Cyrys et al., 2004; Hu and Zhao, 2020; Martuzevicius et al., 2008; Stamp et al., 2021). This trend corresponds to findings of a stronger association between both ambient NO_2 and $PM_{2.5}$ concentrations and mortality during warm seasons, when along with spending more time outside, increased ventilation rates resulted in higher ingress of ambient NO_2 to the indoors (Rojas-Bracho et al., 2002; Samoli Evangelia et al., 2013).

The seasonality seen here has two main implications. Firstly, it re-enforces the need to capture seasonal variation within I/O measurements. Secondly, it indicates the influence of changing building operation and occupant behaviours between the two seasons.





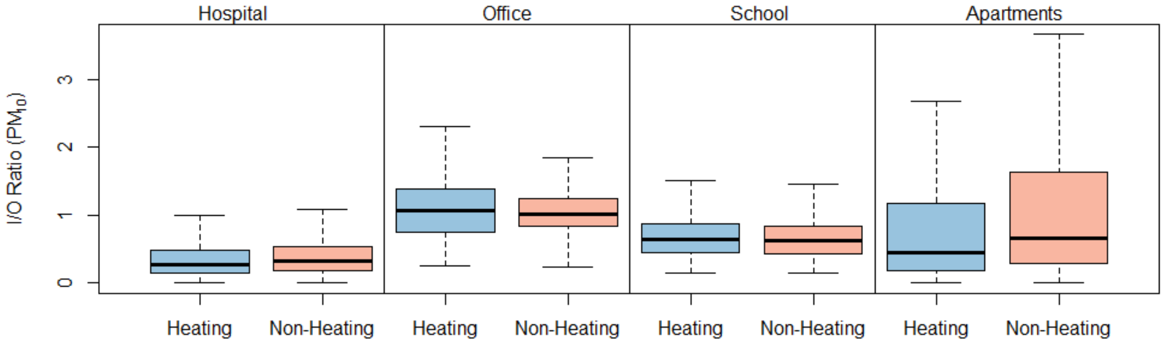


Figure 2: Seasonal variations in I/O ratios for the case study hospital, school and office (all working hours only), as well as the 18 apartments.

3.3 Comparing I/O ratios defined by diffusive and continuous sampling

For a metric to be comparable and provide useful insights, it must be consistent across potential measurement methods. However, there is a risk that I/O ratios measured by either passive or continuous sampling yield different results. The diurnal variations already seen in section 3.1 suggest that out-of-hours sampling period bias may significantly impact passive sampling methods, where a static I/O ratio is measured across full 24-hour periods.

In Figure 3, continuously measured I/O ratios for the non-domestic case studies have been re-analysed into a series of hypothetical 5-day passive measurements and compared to hourly continuous estimates utilising occupied hours only (i.e. the full data set has been analysed with either a range of average 5-day indoor and outdoor concentrations across this period, representing passive measurements of the I/O ratio, or as continuous measured and calculated hourly I/O ratios, across core hours only).

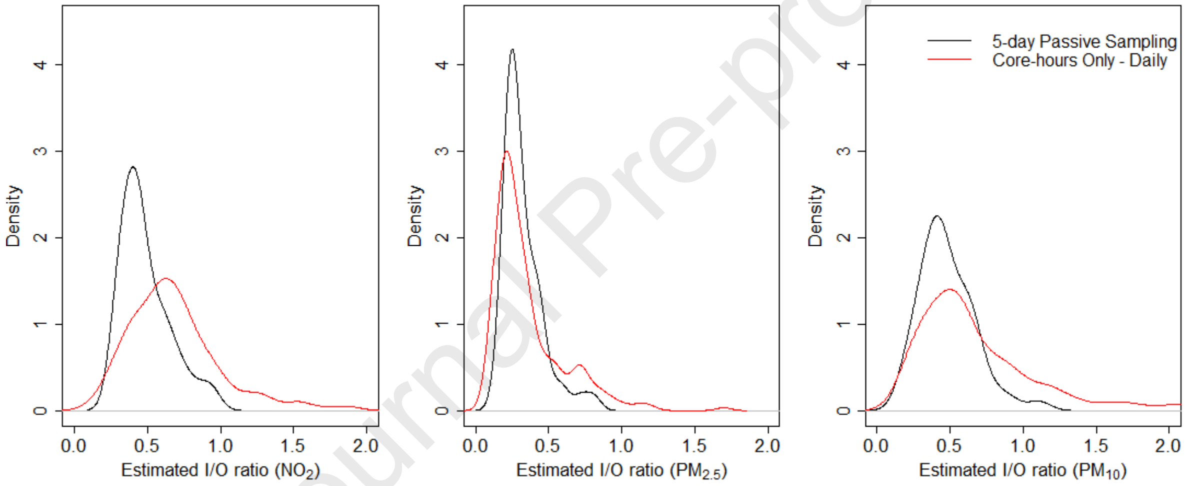
In some cases, for example NO_2 within the naturally ventilated office, there is little observable difference between the passive and continuous approaches, as I/O ratios are not seen to drastically vary across the day (Figure 1). However, when building operation is significantly different during core hours (e.g. hospital – NO_2) or when human activity increases across core hours (e.g. office – particulate matter) significant differences are seen. The overall difference between I/O ratios defined in core hours, outside core hours and across all weekday hours can be seen in Table 3.

When bias occurs, it can have a significant impact, particularly as core building hours may coincide with peaks in external traffic-related pollutants. For example, annual mean ambient NO_2 concentrations, across all hours at the school site were 19 ppb. Applying the median I/O ratio of 0.43, calculated across all hours (i.e. as if from passive measurements) would give a mean internal concentration of 8.2ppb. However, applying the typical daily profile of the I/O ratio (as seen in Figure 1), across outdoor concentrations during core hours (23.8ppb), would give a concentration during core occupied hours of 12.2ppb (49% higher). Similarly, for $PM_{2.5}$ the two approaches lead to mean internal concentrations of 3.2 and 6.3 µg/m^3 respectively (97% higher).

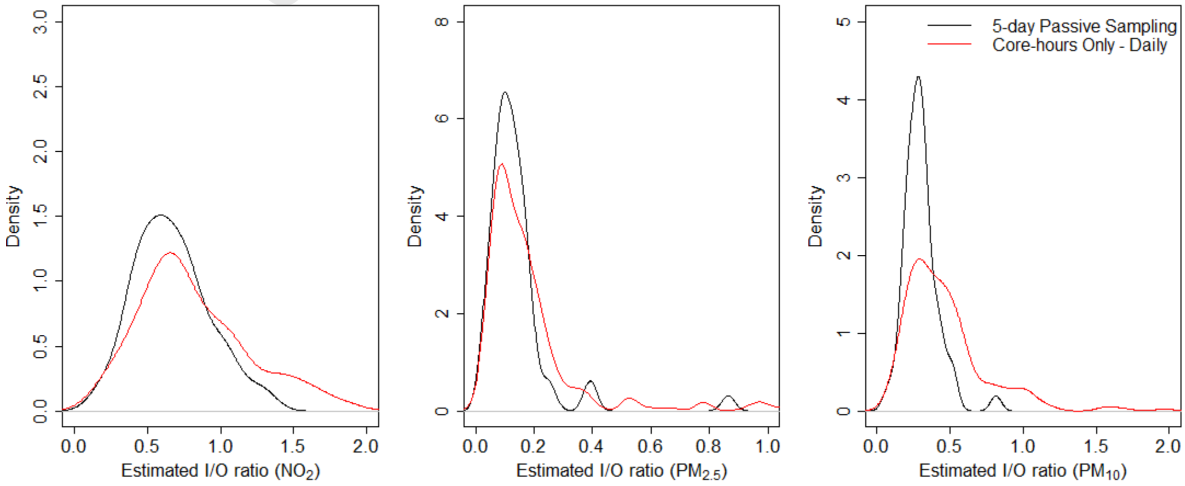
Table 3: I/O ratios during core and outside of core hours. Note: ALL is still only working days, not including weekends.

	Pollutant	**Core Hours - median**	**Outside Hours - median**	**All Hours - median**
Office	NO_2	0.40	0.41	0.40
	$PM_{2.5}$	0.71	0.50	0.58
	PM_{10}	1.01	0.57	0.69
Hospital	NO_2	0.71	0.48	0.57
	$PM_{2.5}$	0.09	0.05	0.07
	PM_{10}	0.25	0.09	0.16
School	NO_2	0.61	0.39	0.43
	$PM_{2.5}$	0.37	0.29	0.31
	PM_{10}	0.63	0.39	0.45

School



Hospital



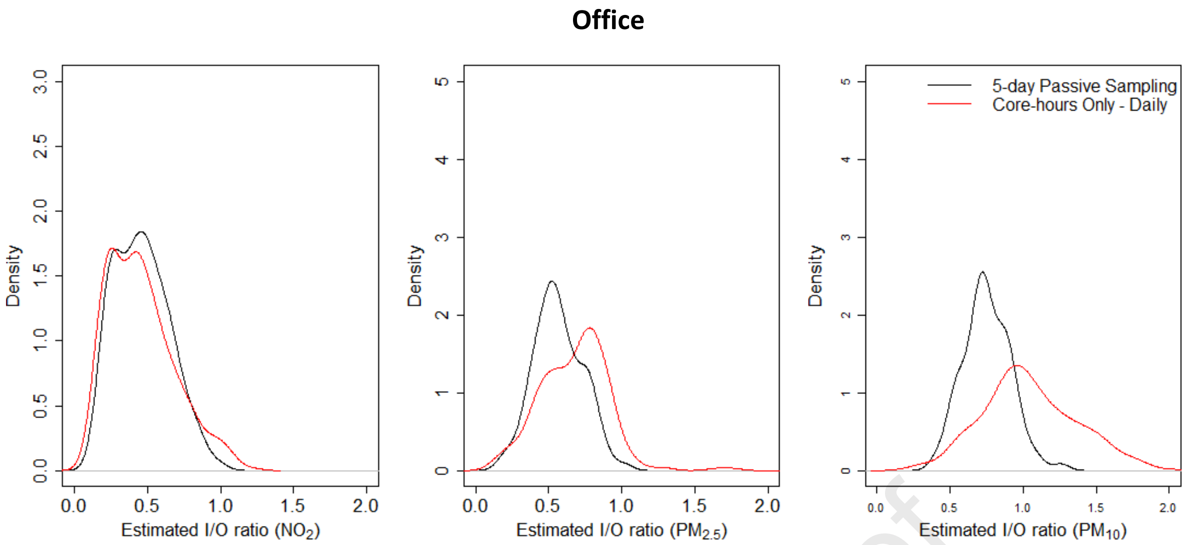


Figure 3: Comparison of I/O ratio measured by hypothetical 5-day passive sampling (black) and continuous sampling based upon core hours only (red), across full 6-8month monitoring campaigns.

3.4 Variations in between and within apartments

The variable and dynamic nature of I/O ratios can be further explored by looking at data across 6-12 months in cumulative distribution plots from 18 individual apartments (Figure 4). Initially, it should be noted that there is both a significant range in the I/O ratio defined within each individual apartment over the measurement period, but also between apartments and between the two different developments as a whole. Differences may be observed in the distribution of I/O ratios at values less than 1, generally more reflective of the relationship between indoor and outdoor air, and in the proportion of time spent with an I/O ratio greater than 1, a reflection of the magnitude, frequency and decay rate of indoor sources.

Two cases are highlighted in the left image of Figure 4. Case A reveals significant periods in which the I/O ratio is greater than 1, with 24% of total recorded time spent above this threshold. In contrast, case B exceeds an I/O ratio above 1 for just 2.7% of the total monitored period. This is a clear response to the strength, duration and frequency of indoor sources experienced in each apartment.

Cumulative frequency plots can be seen for I/O ratios for NO_2 in Figure 5. Here, apartment C is highlighted as having a significantly lower I/O ratio when the I/O ratio is less than 1. Apartment C had a window open in the living room just 19% of the time, compared to an average of 46% of time across all apartments, indicating a lower rate of ingress from the external environment.

Previous studies have typically defined buildings with I/O ratios below 0.8 as having few internal sources and above 1.2 as likely having significant indoor sources (Deng et al., 2017). Here it can be seen that using static I/O ratios in such definitions may be a simplification of a range of modes in each apartment. This may include various use of mechanical ventilation, configurations of openable windows and internal partitions and activities within the apartments. The measurement of I/O ratios over extended periods of time therefore can be useful in understanding the variation of I/O ratio under different modes of operation and the significance of internal sources.

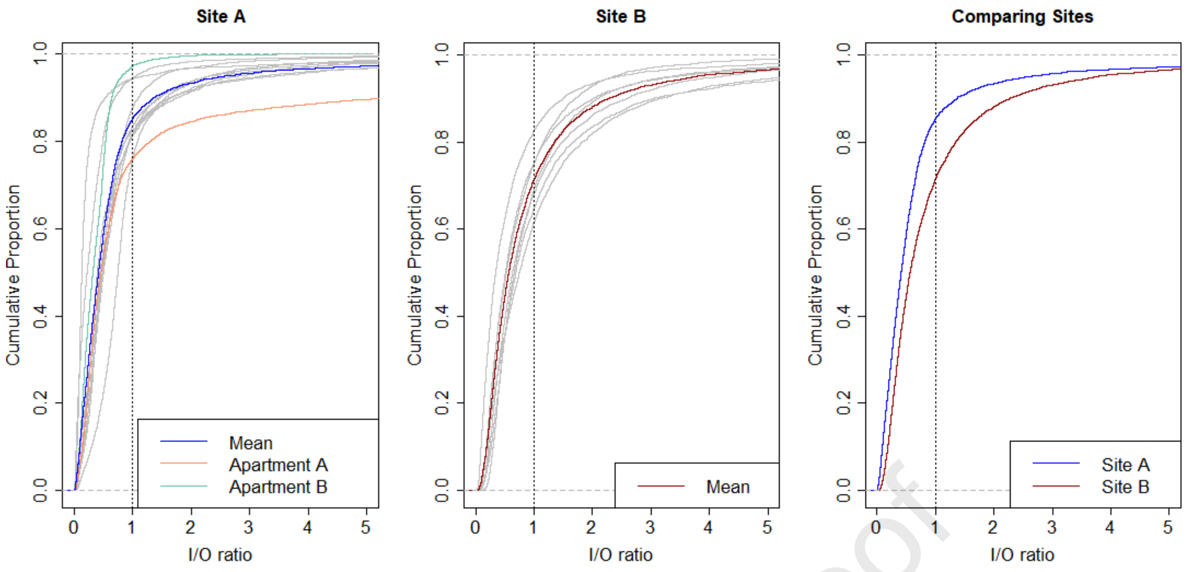


Figure 4: Cumulative frequency plots for I/O ($PM_{2.5}$) for individual flats within two developments. Individual apartments are represented with grey lines, mean of all apartments in blue/red.

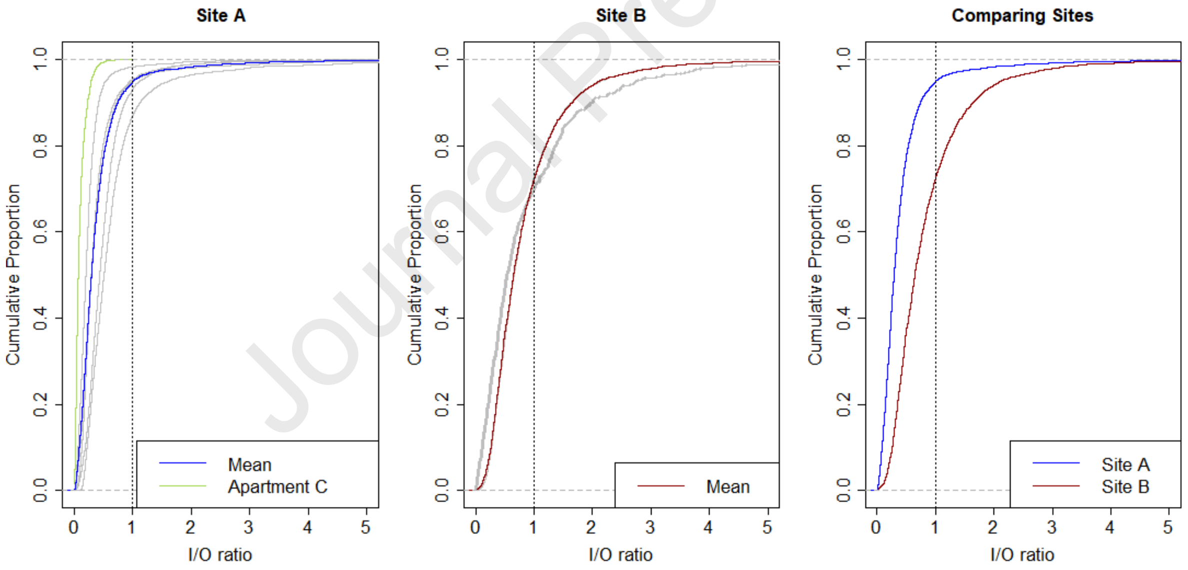


Figure 5: Cumulative frequency plots for I/O (NO_2) for individual flats within two developments. Individual apartments are represented with grey lines, mean of all apartments in blue/red. Fewer flats recorded NO_2 across the full period than particulate matter (N=7).

3.5 Variations in I/O ratios due to occupant behaviour – window use

The role of occupant behaviour as a driving force of varying I/O ratios can be more directly investigated through window monitoring. Measurements in the 18 apartments were accompanied by recordings of both window use (open/shut) and occupancy. This allows a more direct examination of occupant actions upon the I/O ratio and on indoor air quality more generally.

Table 4 shows the median I/O ratio under a range of conditions between the apartments. Firstly, I/O ratios show significant increases between periods in which windows are closed or open, increasing from 0.38 to 0.63 for $PM_{2.5}$, 0.37 to 0.74 for PM_{10} and 0.42 to 0.69 for NO_2. This indicates the strong influence of ventilation practices and occupant behaviours within apartments.

Additionally, passive infrared (PIR) and CO_2 sensors can be used to help determine occupancy. The most significant difference between occupied and unoccupied periods can again be see for PM_{10} (0.35-0.60). Given the I/O ratio only increases at this higher particle size, it is thought this largely relates to particle resuspension during occupied periods. Further, infiltration factors may be obtained by selecting periods in which both windows are closed and the apartment has been unoccupied for at least the proceeding 4 hours (to remove lingering indoor sources). These values are again significantly lower than within other periods and may prove useful in understanding the proportion of pollutant ingress that occurs via uncontrolled infiltration through the fabric.

Table 4: I/O in apartments under different conditions.

	Median I/O		
	$PM_{2.5}$	**PM_{10}**	**NO_2**
All Data	0.47	0.49	0.51
Windows Open	0.63	0.74	0.69
Windows Closed	0.38	0.37	0.42
Occupied	0.49	0.60	0.52
Unoccupied	0.47	0.35	0.43
Windows Closed – Unoccupied for 4 hr	0.19	0.11	0.13

The impact of window actions can be seen across short timescales in Figure 6 and Figure 7. Here, the average indoor concentration or I/O ratio is shown for CO_2, $PM_{2.5}$, NO_2 and TVOCs as a function of the duration a window has been open (Figure 6) or shut (Figure 7). Whilst opening a window leads to reductions in both CO_2 and TVOCs, the I/O for both $PM_{2.5}$ and NO_2 is seen to increase in response, indicating a higher proportion of outdoor pollutants enter the indoor environment.

When a window is closed, the opposite effect can be observed. Increasing CO_2 and TVOC concentrations are accompanied by reducing I/O ratios in both NO_2 and $PM_{2.5}$. Across shorter measurements in both open and closed states, both Cyrys et al., (2004) and Yin et al., (2019) noted similar increases in I/O ratios for particulate matter when widows were open. This is further evidence not only in the dynamic nature of I/O ratios but also on the direct influence of occupant behaviour, leading to seasonal effects seen elsewhere.

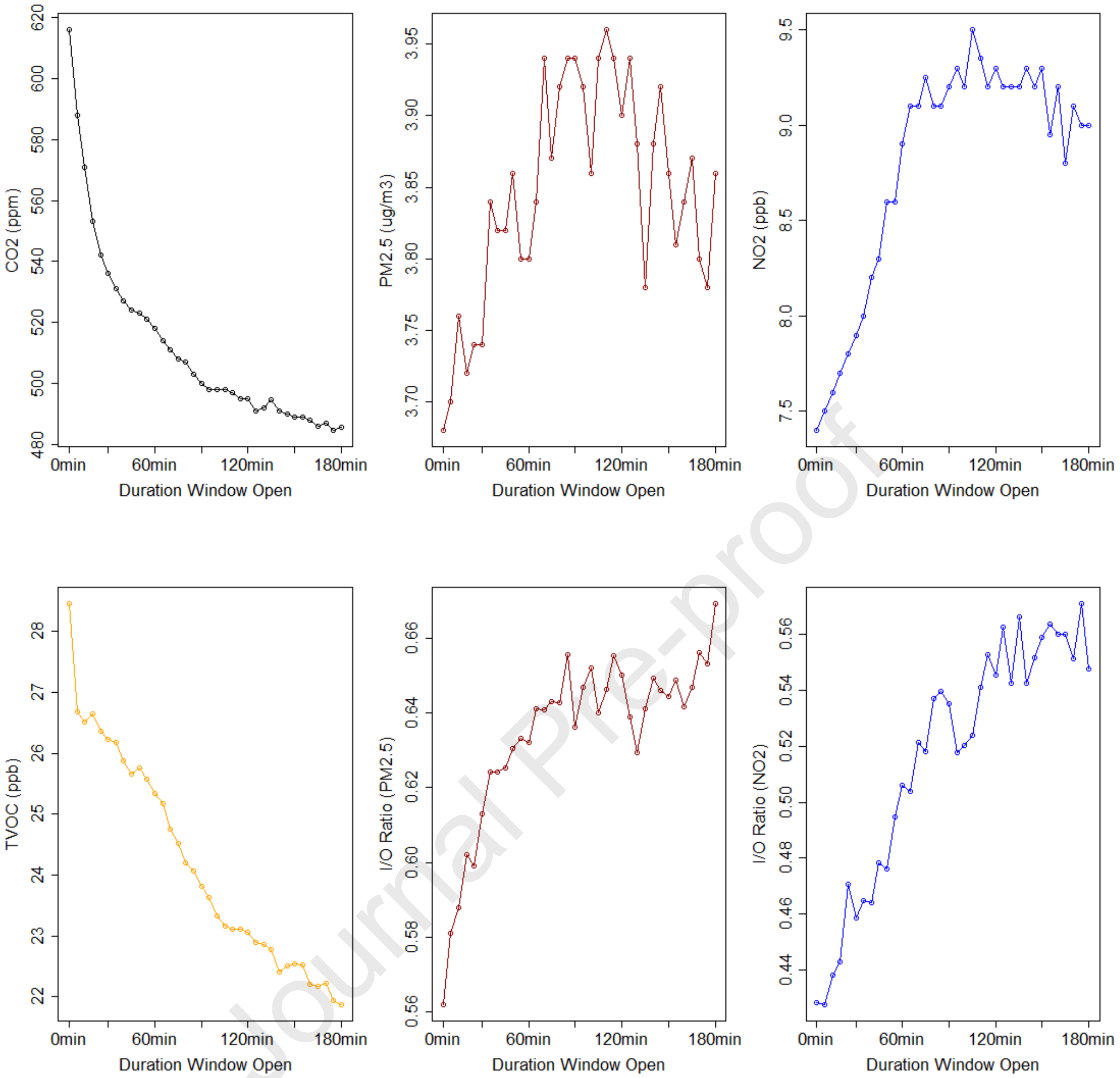


Figure 6: Impact of opening a window upon CO_2, $PM_{2.5}$, NO_2, TVOC, I/O ratio ($PM_{2.5}$) and I/O ratio (NO_2). Aggregated response from whole monitoring periods within the 18 apartments from moment of window opening/closing and the subsequent 3 hours. Data from full monitored periods (June-May).

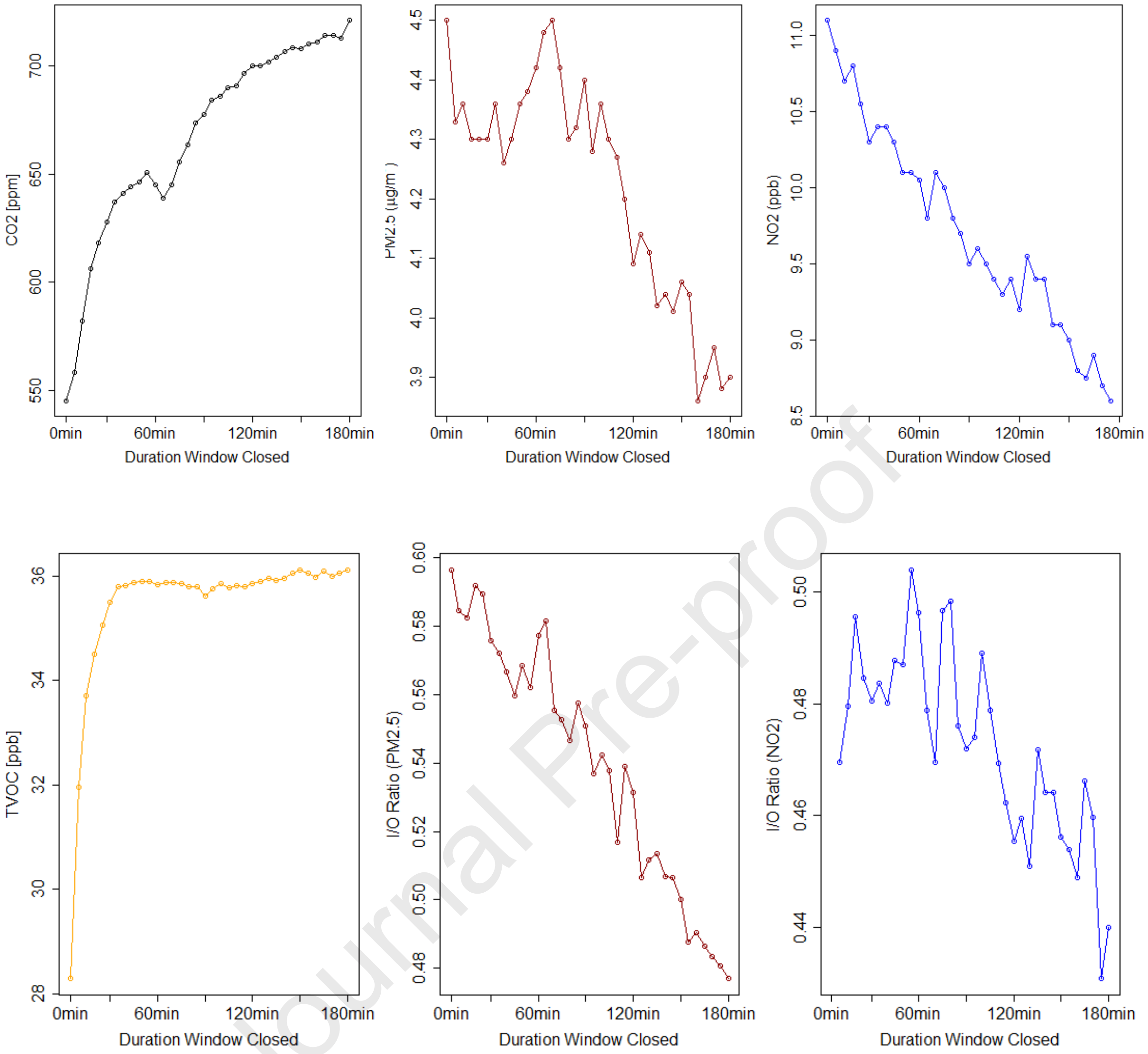


Figure 7: Impact of shutting a window upon CO2, PM2.5, NO2, TVOC, I/O ratio (PM2.5) and I/O ratio (NO2). Aggregated response from whole monitoring periods within the 18 apartments from moment of window opening/closing and the subsequent 3 hours. Data from full monitored periods (June-May).

4. Discussion

4.1 Static I/O ratios

Previous studies have helped to establish the relationship between I/O ratios and ventilation types (Ho et al., 2004; Hu and Zhao, 2020), building locations (Nunes et al., 2016), airtightness (Chatzidiakou et al., 2015; Poupard et al., 2005) and therefore identifying the potential for higher exposure in such settings. In particular, cheaper, non-intrusive passive sampling has allowed larger samples of buildings to be assessed, helping to determine values or distributions of I/O ratios to be used within modelling or epidemiological studies.

However, as analysis here has shown, passive sampling over several full 24-hour periods is likely to lead to a sampling period bias in many buildings. In most cases, this will have the effect of underestimating the I/O ratio which is associated with core operation hours and most strongly associated with exposure. Significantly, static measurements of I/O ratios using passive sampling may also dampen the difference between buildings with significant operational differences. For example, if we considered two identical schools, one with a 5 L/s.p ventilation rate the other adopting 10 L/s.p. Across occupied hours we would expect a significant increase in penetration of pollution from outdoors into the building with higher ventilation rate (assuming that the ventilation air is 100% outdoor air and not filtered). However, through static measurements this difference is largely diminished through the inclusion of 16 unoccupied hours alongside the 8 occupied hours. This means that such passively measured values should not be used in further modelling or epidemiological studies and may not accurately reflect a building's operation or exposure of occupants. Equally, in the absence of contextual details (e.g. ventilation rate, hours of operation, window status, weather conditions) the use of such values is prone to mis-interpretation.

4.2 Dynamic I/O ratios

Assessing I/O ratios on a dynamic basis will allow data to be filtered and sampling period bias to be avoided, with the estimated I/O values more closely linked to exposure during occupation. These may therefore provide more suitable values for modelling and epidemiological studies. Sensor costs, performance and intrusiveness have limited the length and scale of such measurements to date, although technological improvements in air quality sensors may overcome these challenges and capture longer term behaviours.

Beyond the determination of the I/O for use in wider studies, it may also be argued that a dynamically assessed I/O ratio may be useful as a building performance metric. This may provide useful information on an individual building basis. For example, dynamic I/O ratios demonstrated here have shown the impact on indoor air quality of opening windows, CO_2 demand-controlled ventilation (with and without filtration), ingress from infiltration, cases with significant indoor sources and the influence of particulate resuspension during occupancy. This might lead to suitable interventions, for example scheduling ventilation rates around external pollution, control based on external pollutants, optimising window opening or improving extraction to reduce internal peaks.

4.3 Limitations in I/O as a metric

The broader limitations of a I/O, whether analysed statically or dynamically, can also be considered. In their review, Chen and Zhao, (2011) concluded that the considerable variation of I/O ratios meant that they were 'hardly helpful for understanding the indoor-outdoor relationship', with the penetration factor a more relevant metric. However, given the influence of ventilation and window opening on exposure during occupied hours, it would seem understanding ventilation and occupant behaviours remains crucial.

4.4 I/O ratio as a physical or personal variable

The I/O ratio has been described as a building modifier, representing the impact the building fabric and services might have on outdoor pollutants reaching the indoor environment. However, results here indicate that two key influential factors are related to the occupant(s) rather than the building itself. Both indoor generation and window opening, are shown to be influential variables for the I/O ratio. However, both vary significantly between buildings or apartments and may be linked to a much wider range of social-physical factors. Within dwellings, particularly where the occupant has significant control over ventilation, the I/O ratio may therefore provide a much stronger description of the occupants than the building itself.

4.5 Uncertainty in I/O

Uncertainty in estimated I/O ratios is a result of the uncertainty in both indoor and outdoor measurements. Error propagation rules would define the uncertainty in an I/O ratio as:

$$\frac{\delta(I/O)}{I/O} = \left[\left(\frac{\delta C_{in}}{C_{in}}\right)^2 + \left(\frac{\delta C_{out}}{C_{out}}\right)^2\right]^{1/2}$$

Where, $\delta(I/O)$, δC_{in} and δC_{out} are the uncertainties in the I/O ratio, measured indoor and measured outdoor pollutant concentrations.

The EU Directive 2008/50/EC defines acceptable levels of uncertainty for indicative ambient air quality measurements of particulate matter (50%) and sulphur dioxide, nitrogen dioxide and carbon monoxide (25%) and Ozone (30%). If both indoor and outdoor measurements incorporated uncertainties at these limits, this would translate to overall significant uncertainties in I/O estimates for particulate matter (70%), sulphur dioxide, nitrogen dioxide and carbon monoxide (35%) and Ozone (42%). Clearly, even with good quality instrumentation and stable conditions, any estimated I/O ratio will contain significant measurement uncertainty, particularly at low concentrations. This supports the argument that the dynamic I/O ratio works better as an informative metric, rather than an absolute value.

4.6 Lack of equivalency between measurements.

Measurement uncertainties are further compounded by the lack of equivalency between measurement systems, particularly with lower cost portable systems (Karagulian et al., 2019). Such inequivalent indoor and outdoor measurements will only serve to increase the uncertainty in I/O estimates. Even if identical measurement systems are used in both indoor and outdoor measurements, their performance may alter with the varying composition of pollutants and their respective environments, with humidity and temperature bias impacting measurements of many pollutants (Crilley et al., 2018). An example within this study is the limitations of low-cost sensors to capture fine-mode aerosols in the urban environment. Where compositions of outdoor and indoor air differ, these limitations in measurements may lead to further bias.

Estimates of I/O ratios have also been determined with C_{out} based upon local central monitoring stations (e.g. Braniš et al., 2009; Tang et al., 2018). Whilst this may improve the accuracy of outdoor measurements, issues around equivalency remain and such approaches may introduce further spatial uncertainty between the central monitoring station and at the site of a case study building.

Finally, there may be significant definitional uncertainty in estimated I/O ratios. Definitional uncertainty is defined by JCGM 100 as ‘Component of measurement uncertainty resulting from the finite amount of detail in the definition of a measurand’. In this case, it applies to the uncertainty in the definition of the I/O ratio and in particular the location of an external measurement. For example, an I/O ratio of an apartment defined by an external measurement at ground level will not be equivalent to an I/O ratio defined by an external measurement at the height of the apartment. Whilst urban background and roadside measurements are generally well defined, what external measurement point is most appropriate or indeed informative is less clear, particularly with mixed mode ventilation strategies, and may be a function of ventilation intake locations, natural ventilation openings, local spatial effects and practical constraints.

4.7 Comparisons to F_{inf}

Infiltration factors have been cited as less variable and therefore more useful in health studies than I/O ratios (Poupard et al., 2005). There is however an important note of terminology.

Within the built environment, infiltration is typically defined as uncontrolled air movement between indoor and outdoor environments (e.g. via cracks and gaps in the building fabric). On the other hand, ventilation describes the controlled provision of outdoor air either via mechanical systems or via openable windows etc. The infiltration factor is perhaps therefore a misnomer. The air exchange rate of a building is tied to both infiltration and ventilation rates. Particularly in modern, low-energy, airtight buildings, it is the ventilation component that is likely to dominate, particularly during occupied hours. The infiltration factor is therefore closely linked to ventilation practices and as such, to the operation of a building and actions of its occupants. Given the strong associated with ventilation practices, F_{inf} is again expected to be a function of both a building and its occupants, varying in similar ways to the I/O ratio investigated here.

5. Conclusions

The study has analysed long term indoor and outdoor pollutant monitoring in a hospital, school, office and 18 apartments. The results indicated strong diurnal and seasonal variation in I/O ratios for particulate matter and nitrogen dioxide. Diurnal variation was shown to reveal the potential for significant bias if static I/O ratios are measured through passive sampling. As a result, static I/O measurements may not reasonably account for, and are likely to underestimate, the expected exposure levels in associated indoor environments. This is likely to result in many of the I/O ratios and infiltration factors previously estimated to underestimate actual indoor concentrations during occupied periods.

The results presented indicate how I/O ratios are strongly influenced by ventilation rates, window opening actions and by the occupancy patterns and activities within a building. Therefore I/O ratios should not be thought of as a physical building parameter, but rather a metric that describes both the building and the behaviour of the occupants that occupy and manage it. Whilst academic literature has focused on measuring and reporting I/O ratios over the past four decades, the dynamic nature and behavioural component of I/O ratios means that drawing together and making use of reported I/O ratios is not straightforward and it is perhaps unsurprising that reported values demonstrate too much variation to often be useful. Static I/O ratios hide this dynamic behaviour and as a result, such comparisons or compiled data sets may mean little without contextual information, both on the measurement made and the state of the building during the measurement (e.g. ventilation rate, window opening, activities, occupancy).

However, it is argued that the I/O ratio, when evaluated dynamically from continuous measurements, provides a useful building operation parameter. Dynamic I/O ratios may help describe the relationship the building has with the outdoor environment and importantly the role of building operation and occupant behaviour. This can help better understand ventilation strategies, schedules, the influence of occupant behaviour and the significance of indoor sources. The use of a dynamic I/O ratio may therefore provide effective information for designing and operating buildings to improve indoor air quality.

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References

Allen Ryan W., Adar Sara D., Avol Ed, Cohen Martin, Curl Cynthia L., Larson Timothy, Liu L.-J. Sally, Sheppard Lianne, Kaufman Joel D., 2012. Modeling the Residential Infiltration of Outdoor PM2.5 in the Multi-Ethnic Study of Atherosclerosis and Air Pollution (MESA Air). Environ. Health Perspect. 120, 824–830. https://doi.org/10.1289/ehp.1104447

Batterman, S., 2017. Review and Extension of CO2-Based Methods to Determine Ventilation Rates with Application to School Classrooms. Int. J. Environ. Res. Public. Health 14, 145. https://doi.org/10.3390/ijerph14020145

Blondeau, P., Iordache, V., Poupard, O., Genin, D., Allard, F., 2005. Relationship between outdoor and indoor air quality in eight French schools. Indoor Air 15, 2–12.

Borrego, C., Tchepel, O., Costa, A.M., Martins, H., Ferreira, J., Miranda, A.I., 2006. Traffic-related particulate air pollution exposure in urban areas. Atmos. Environ. 40, 7205–7214. https://doi.org/10.1016/j.atmosenv.2006.06.020

Branco, P.T.B.S., Alvim-Ferraz, M.C.M., Martins, F.G., Sousa, S.I.V., 2019. Quantifying indoor air quality determinants in urban and rural nursery and primary schools. Environ. Res. 176, 108534. https://doi.org/10.1016/j.envres.2019.108534

Branco, P.T.B.S., Alvim-Ferraz, M.C.M., Martins, F.G., Sousa, S.I.V., 2014. Indoor air quality in urban nurseries at Porto city: Particulate matter assessment. Atmos. Environ. 84, 133–143. https://doi.org/10.1016/j.atmosenv.2013.11.035

Braniš, M., Šafránek, J., Hytychová, A., 2009. Exposure of children to airborne particulate matter of different size fractions during indoor physical education at school. Build. Environ. 44, 1246–1252. https://doi.org/10.1016/j.buildenv.2008.09.010

Challoner, A., Gill, L., 2014. Indoor/outdoor air pollution relationships in ten commercial buildings: PM2.5 and NO2. Build. Environ. 80, 159–173. https://doi.org/10.1016/j.buildenv.2014.05.032

Chao, C.Y.H., Tung, T.C., 2001. An empirical model for outdoor contaminant transmission into residential buildings and experimental verification. Atmos. Environ. 35, 1585–1596. https://doi.org/10.1016/S1352-2310(00)00458-1

Chatzidiakou, L., Krause, A., Han, Y., Chen, W., Yan, L., Popoola, O.A.M., Kellaway, M., Wu, Y., Liu, J., Hu, M., Barratt, B., Kelly, F.J., Zhu, T., Jones, R.L., 2020. Using low-cost sensor technologies and advanced computational methods to improve dose estimations in health panel studies: results of the AIRLESS project. J. Expo. Sci. Environ. Epidemiol. 30, 981–989. https://doi.org/10.1038/s41370-020-0259-6

Chatzidiakou, L., Krause, A., Popoola, O.A.M., Antonio, A.D., Kellaway, M., Han, Y., Squires, F.A., Wang, T., Zhang, H., Wang, Q., Fan, Y., Chen, S., Hu, M., Quint, J.K., Barratt, B., Kelly, F.J., Zhu, T., Jones, R.L., 2019. Characterising low-cost sensors in highly portable platforms to quantify personal exposure in diverse environments. Atmospheric Meas. Tech. 12, 4643–4657. https://doi.org/10.5194/amt-12-4643-2019

Chatzidiakou, L., Mumovic, D., Summerfield, A.J., Tàubel, M., Hyvärinen, A., 2015. Indoor air quality in London schools. Part 2: long-term integrated assessment. Intell. Build. Int. 7, 130–146. https://doi.org/10.1080/17508975.2014.918871

Chen, C., Zhao, B., 2011. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. Atmos. Environ. 45, 275–288. https://doi.org/10.1016/j.atmosenv.2010.09.048

Chen, C., Zhao, B., Weschler, C.J., 2012. Indoor Exposure to "Outdoor PM10": Assessing Its Influence on the Relationship Between PM10 and Short-term Mortality in U.S. Cities. Epidemiology 23, 870–878. https://doi.org/10.1097/EDE.0b013e31826b800e

Cohen, M.A., Adar, S.D., Allen, R.W., Avol, E., Curl, C.L., Gould, T., Hardie, D., Ho, A., Kinney, P., Larson, T.V., Sampson, P., Sheppard, L., Stukovsky, K.D., Swan, S.S., Liu, L.-J.S., Kaufman, J.D., 2009. Approach to Estimating Participant Pollutant Exposures in the Multi-Ethnic Study of Atherosclerosis and Air Pollution (MESA Air). Environ. Sci. Technol. 43, 4687–4693. https://doi.org/10.1021/es8030837

Cooper, E., Wang, Y., Stamp, S., Burman, E., Mumovic, D., 2021. Use of portable air purifiers in homes: Operating behaviour, effect on indoor PM2.5 and perceived indoor air quality. Build. Environ. 191, 107621. https://doi.org/10.1016/j.buildenv.2021.107621

Crilley, L.R., Shaw, M., Pound, R., Kramer, L.J., Price, R., Young, S., Lewis, A.C., Pope, F.D., 2018. Evaluation of a low-cost optical particle counter (Alphasense OPC-N2) for ambient air monitoring. Atmospheric Meas. Tech. 11, 709–720. https://doi.org/10.5194/amt-11-709-2018

Cyrys, J., Pitz, M., Bischof, W., Wichmann, H.-E., Heinrich, J., 2004. Relationship between indoor and outdoor levels of fine particle mass, particle number concentrations and black smoke under different ventilation conditions. J. Expo. Sci. Environ. Epidemiol. 14, 275–283. https://doi.org/10.1038/sj.jea.7500317

Deng, G., Li, Z., Wang, Zhichao, Gao, J., Xu, Z., Li, J., Wang, Zhiyong, 2017. Indoor/outdoor relationship of PM2.5 concentration in typical buildings with and without air cleaning in Beijing. Indoor Built Environ. 26, 60–68. https://doi.org/10.1177/1420326X15604349

Diapouli, E., Chaloulakou, A., Koutrakis, P., 2013a. Estimating the concentration of indoor particles of outdoor origin: A review. J. Air Waste Manag. Assoc. 63, 1113–1129. https://doi.org/10.1080/10962247.2013.791649

Diapouli, E., Chaloulakou, A., Koutrakis, P., 2013b. Estimating the concentration of indoor particles of outdoor origin: A review. J. Air Waste Manag. Assoc. 63, 1113–1129. https://doi.org/10.1080/10962247.2013.791649

Dimitroulopoulou, C., 2012. Ventilation in European dwellings: A review. Build. Environ., International Workshop on Ventilation, Comfort, and Health in Transport Vehicles 47, 109–125. https://doi.org/10.1016/j.buildenv.2011.07.016

Dimitroulopoulou, C., Bartzis, J., 2014. Ventilation rates in European office buildings: A review , Ventilation rates in European office buildings: A review. Indoor Built Environ. 23, 5–25. https://doi.org/10.1177/1420326X13481786

Fabian, P., Adamkiewicz, G., Levy, J.I., 2012. Simulating indoor concentrations of NO2 and PM2.5 in multifamily housing for use in health-based intervention modeling. Indoor Air 22, 12–23. https://doi.org/10.1111/j.1600-0668.2011.00742.x

Fazli, T., Dong, X., Fu, J.S., Stephens, B., 2021. Predicting U.S. Residential Building Energy Use and Indoor Pollutant Exposures in the Mid-21st Century. Environ. Sci. Technol. 55, 3219–3228. https://doi.org/10.1021/acs.est.0c06308

Grau-Bové, J., Strlič, M., 2013. Fine particulate matter in indoor cultural heritage: a literature review. Herit. Sci. 1, 8. https://doi.org/10.1186/2050-7445-1-8

Ho, K.F., Cao, J.J., Harrison, R.M., Lee, S.C., Bau, K.K., 2004. Indoor/outdoor relationships of organic carbon (OC) and elemental carbon (EC) in PM2.5 in roadside environment of Hong Kong. Atmos. Environ. 38, 6327–6335. https://doi.org/10.1016/j.atmosenv.2004.08.007

Hoek, G., Krishnan, R.M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., Kaufman, J.D., 2013. Long-term air pollution exposure and cardio- respiratory mortality: a review. Environ. Health 12, 43. https://doi.org/10.1186/1476-069X-12-43

Hu, Y., Zhao, B., 2020. Relationship between indoor and outdoor NO2: A review. Build. Environ. 106909. https://doi.org/10.1016/j.buildenv.2020.106909

Huang, L., Pu, Z., Li, M., Sundell, J., 2015. Characterizing the Indoor-Outdoor Relationship of Fine Particulate Matter in Non-Heating Season for Urban Residences in Beijing. PloS One 10, e0138559. https://doi.org/10.1371/journal.pone.0138559

Janssen, N.A.H., Schwartz, J., Zanobetti, A., Suh, H.H., 2002. Air conditioning and source-specific particles as modifiers of the effect of PM(10) on hospital admissions for heart and lung disease. Environ. Health Perspect. 110, 43–49.

Jeremy A. Sarnat, *, Christopher M. Long, ‡, Petros Koutrakis, †, Brent A. Coull, §, Joel Schwartz, † and, Suh†, H.H., 2002. Using Sulfur as a Tracer of Outdoor Fine Particulate Matter [WWW Document]. https://doi.org/10.1021/es025796b

Ji, W., Zhao, B., 2015. Estimating Mortality Derived from Indoor Exposure to Particles of Outdoor Origin. PLOS ONE 10, e0124238. https://doi.org/10.1371/journal.pone.0124238

Johnston, D., Stafford, A., 2016. Estimating the background ventilation rates in new-build UK dwellings – Is n50/20 appropriate?: Indoor Built Environ. https://doi.org/10.1177/1420326X15626234

Jones, N.C., Thornton, C.A., Mark, D., Harrison, R.M., 2000. Indoor/outdoor relationships of particulate matter in domestic homes with roadside, urban and rural locations. Atmos. Environ. 34, 2603–2612. https://doi.org/10.1016/S1352-2310(99)00489-6

Kabirikopaei, A., Lau, J., 2020. Uncertainty analysis of various CO2-Based tracer-gas methods for estimating seasonal ventilation rates in classrooms with different mechanical systems. Build. Environ. 179, 107003. https://doi.org/10.1016/j.buildenv.2020.107003

Kalimeri, K.K., Bartzis, J.G., Sakellaris, I.A., de Oliveira Fernandes, E., 2019. Investigation of the PM2.5, NO2 and O3 I/O ratios for office and school microenvironments. Environ. Res. 179, 108791. https://doi.org/10.1016/j.envres.2019.108791

Karagulian, F., Gerboles, M., Barbiere, M., Kotsev, A., Lagler, F., Borowiak, A., European Commission, Joint Research Centre, 2019. Review of sensors for air quality monitoring.

Kim, J., Hong, T., Lee, M., Jeong, K., 2019. Analyzing the real-time indoor environmental quality factors considering the influence of the building occupants' behaviors and the ventilation. Build. Environ. 156, 99–109. https://doi.org/10.1016/j.buildenv.2019.04.003

Lazaridis, M., Katsivela, E., Kopanakis, I., Raisi, L., Panagiaris, G., 2015. Indoor/outdoor particulate matter concentrations and microbial load in cultural heritage collections. Herit. Sci. 3, 34. https://doi.org/10.1186/s40494-015-0063-0

Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525, 367–371. https://doi.org/10.1038/nature15371

Levy, J.I., 1998. Impact of Residential Nitrogen Dioxide Exposure on Personal Exposure: An International Study. J. Air Waste Manag. Assoc. 48, 553–560. https://doi.org/10.1080/10473289.1998.10463704

Li, C.-S., Lin, C.-H., 2003. Carbon profile of residential indoor PM1 and PM2.5 in the subtropical region. Atmos. Environ. 37, 881–888. https://doi.org/10.1016/S1352-2310(02)00998-6

Li, N., Friedrich, R., 2019. Methodology for Estimating the Lifelong Exposure to PM2.5 and NO2—The Application to European Population Subgroups. Atmosphere 10, 507. https://doi.org/10.3390/atmos10090507

Long, C.M., Sarnat, J.A., 2004. Indoor-Outdoor Relationships and Infiltration Behavior of Elemental Components of Outdoor PM2.5 for Boston-Area Homes. Aerosol Sci. Technol. 38, 91–104. https://doi.org/10.1080/027868290502281

Majd, E., McCormack, M., Davis, M., Curriero, F., Berman, J., Connolly, F., Leaf, P., Rule, A., Green, T., Clemons-Erby, D., Gummerson, C., Koehler, K., 2019. Indoor air quality in inner-city schools and its associations with building characteristics and environmental factors. Environ. Res. 170, 83–91. https://doi.org/10.1016/j.envres.2018.12.012

Mandin, C., Trantallidi, M., Cattaneo, A., Canha, N., Mihucz, V.G., Szigeti, T., Mabilia, R., Perreca, E., Spinazzè, A., Fossati, S., De Kluizenaar, Y., Cornelissen, E., Sakellaris, I., Saraga, D., Hänninen, O., De Oliveira Fernandes, E., Ventura, G., Wolkoff, P., Carrer, P., Bartzis, J., 2017. Assessment of indoor air quality in office buildings across Europe – The OFFICAIR study. Sci. Total Environ. 579, 169–178. https://doi.org/10.1016/j.scitotenv.2016.10.238

Martuzevicius, D., Grinshpun, S.A., Lee, T., Hu, S., Biswas, P., Reponen, T., LeMasters, G., 2008. Traffic-related PM2.5 aerosol in residential houses located near major highways: Indoor versus outdoor concentrations. Atmos. Environ. 42, 6575–6585. https://doi.org/10.1016/j.atmosenv.2008.05.009

Mohammed, M.O.A., Song, W.-W., Ma, W.-L., Li, W.-L., Ambuchi, J.J., Thabit, M., Li, Y.-F., 2015. Trends in indoor–outdoor PM2.5 research: A systematic review of studies conducted during the last decade (2003–2013). Atmospheric Pollut. Res. 6, 893–903. https://doi.org/10.5094/APR.2015.099

Monn, C., Fuchs, A., Hogger, D., Junker, M., Kogelschatz, D., Roth, N., Wanner, H.U., 1997. Particulate matter less than 10 mu m (PM10) and fine particles less than 2.5 mu m (PM2.5): relationships between indoor, outdoor and personal concentrations. Sci. Total Environ. 208, 15–21. https://doi.org/10.1016/S0048-9697(97)00271-4

Nunes, R.A.O., Branco, P.T.B.S., Alvim-Ferraz, M.C.M., Martins, F.G., Sousa, S.I.V., 2016. Gaseous pollutants on rural and urban nursery schools in Northern Portugal. Environ. Pollut., Special Issue: Urban Health and Wellbeing 208, 2–15. https://doi.org/10.1016/j.envpol.2015.07.018

Øie, L., Stymne, H., Boman, C.-A., Hellstrand, V., 1998. The Ventilation Rate of 344 Oslo Residences. Indoor Air 8, 190–196. https://doi.org/10.1111/j.1600-0668.1998.t01-1-00006.x

Pedersen, M., Giorgis-Allemand, L., Bernard, C., Aguilera, I., Andersen, A.-M.N., Ballester, F., Beelen, R.M.J., Chatzi, L., Cirach, M., Danileviciute, A., Dedele, A., van Eijsden, M., Estarlich, M., Fernandez-Somoano, A., Fernandez, M.F., Forastiere, F., Gehring, U., Grazuleviciene, R., Gruzieva, O., Heude, B., Hoek, G., de Hoogh, K., van den Hooven, E.H., Haberg, S.E., Jaddoe, V.W.V., Kluemper, C., Korek, M., Kraemer, U., Lerchundi, A., Lepeule, J., Nafstad, P., Nystad, W., Patelarou, E., Porta, D., Postma, D., Raaschou-Nielsen, O., Rudnai, P., Sunyer, J., Stephanou, E., Sorensen, M., Thiering, E., Tuffnell, D., Varro, M.J., Vrijkotte, T.G.M., Wijga, A., Wilhelm, M., Wright, J., Nieuwenhuijsen, M.J., Pershagen, G., Brunekreef, B., Kogevinas, M., Slama, R., 2013. Ambient air pollution and low birthweight: a European cohort study (ESCAPE). Lancet Respir. Med. 1, 695–704. https://doi.org/10.1016/S2213-2600(13)70192-9

Poupard, O., Blondeau, P., Iordache, V., Allard, F., 2005. Statistical analysis of parameters influencing the relationship between outdoor and indoor air quality in schools. Atmos. Environ. 39, 2071–2080. https://doi.org/10.1016/j.atmosenv.2004.12.016

R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rojas-Bracho, L., Suh, H.H., Oyola, P., Koutrakis, P., 2002. Measurements of children's exposures to particles and nitrogen dioxide in Santiago, Chile. Sci. Total Environ. 287, 249–264. https://doi.org/10.1016/S0048-9697(01)00987-1

Salonen, H., Salthammer, T., Morawska, L., 2019. Human exposure to NO2 in school and office indoor environments. Environ. Int. 130, 104887. https://doi.org/10.1016/j.envint.2019.05.081

Samoli Evangelia, Stafoggia Massimo, Rodopoulou Sophia, Ostro Bart, Declercq Christophe, Alessandrini Ester, Díaz Julio, Karanasiou Angeliki, Kelessis Apostolos G., Le Tertre Alain, Pandolfi Paolo, Randi Giorgia, Scarinzi Cecilia, Zauli-Sajani Stefano, Katsouyanni Klea, Forastiere Francesco, null null, 2013. Associations between Fine and Coarse Particles and Mortality in Mediterranean Cities: Results from the MED-PARTICLES Project. Environ. Health Perspect. 121, 932–938. https://doi.org/10.1289/ehp.1206124

Sarnat, J.A., Wilson, W.E., Strand, M., Brook, J., Wyzga, R., Lumley, T., 2007. Panel discussion review: session 1 — exposure assessment and related errors in air pollution epidemiologic studies. J. Expo. Sci. Environ. Epidemiol. 17, S75–S82. https://doi.org/10.1038/sj.jes.7500621

Schneider, P., Gebefugi, I., Richter, K., Wolke, G., Schnelle, J., Wichmann, H.E., Heinrich, J., 2001. Indoor and outdoor BTX levels in German cities. Sci. Total Environ. 267, 41–51. https://doi.org/10.1016/S0048-9697(00)00766-X

Setton, E.M., Keller, C.P., Cloutier-Fisher, D., Hystad, P.W., 2008. Spatial variations in estimated chronic exposure to traffic-related air pollution in working populations: A simulation. Int. J. Health Geogr. 7, 39. https://doi.org/10.1186/1476-072X-7-39

Shaw, C., Boulic, M., Longley, I., Mitchell, T., Pierse, N., Howden-Chapman, P., 2020. The association between indoor and outdoor NO2 levels: A case study in 50 residences in an urban neighbourhood in New Zealand. Sustain. Cities Soc. 56, 102093. https://doi.org/10.1016/j.scs.2020.102093

SINPHONIE, 2014. SINPHONIE – Schools Indoor Pollution and Health Observatory Network in Europe - Final Report [WWW Document]. EU Sci. Hub - Eur. Comm. URL https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/sinphonie-schools-indoor-pollution-and-health-observatory-network-europe-final-report (accessed 2.18.20).

Stamp, S., Burman, E., Shrubsole, C., Chatzidiakou, L., Mumovic, D., Davies, M., 2021. Seasonal variations and the influence of ventilation rates on IAQ: A case study of five low-energy London apartments. Indoor Built Environ. 1420326X211017175. https://doi.org/10.1177/1420326X211017175

Stamp, S., Burman, E., Shrubsole, C., Chatzidiakou, L., Mumovic, D., Davies, M., 2020. Long-term, continuous air quality monitoring in a cross-sectional study of three UK non-domestic buildings. Build. Environ. 107071. https://doi.org/10.1016/j.buildenv.2020.107071

Stranger, M., Potgieter-Vermaak, S.S., Van Grieken, R., 2008. Characterization of indoor air quality in primary schools in Antwerp, Belgium. Indoor Air 18, 454–463. https://doi.org/10.1111/j.1600-0668.2008.00545.x

Tang, C.H., Garshick, E., Grady, S., Coull, B., Schwartz, J., Koutrakis, P., 2018. Development of a modeling approach to estimate indoor-to-outdoor sulfur ratios and predict indoor PM 2.5 and black carbon concentrations for Eastern Massachusetts households. J. Expo. Sci. Environ. Epidemiol. 28, 125–130. https://doi.org/10.1038/jes.2017.11

Taylor, J., Shrubsole, C., Symonds, P., Mackenzie, I., Davies, M., 2019. Application of an indoor air pollution metamodel to a spatially-distributed housing stock. Sci. Total Environ. 667, 390–399. https://doi.org/10.1016/j.scitotenv.2019.02.341

Tung, T.C.W., Chao, C.Y.H., Burnett, J., 1999. A methodology to investigate the particulate penetration coefficient through building shell. Atmos. Environ. 33, 881–893. https://doi.org/10.1016/S1352-2310(98)00299-4

Viana, M., Rivas, I., Querol, X., Alastuey, A., Sunyer, J., Alvarez-Pedrerol, M., Bouso, L., Sioutas, C., 2014. Indoor/outdoor relationships and mass closure of quasi-ultrafine, accumulation and coarse particles in Barcelona schools. Atmospheric Chem. Phys. 14, 4459–4472. https://doi.org/10.5194/acp-14-4459-2014

Wallace, L., Williams, R., 2005. Use of personal-indoor-outdoor sulfur concentrations to estimate the infiltration factor and outdoor exposure factor for individual homes and persons. Environ. Sci. Technol. 39, 1707–1714. https://doi.org/10.1021/es049547u

Wang, F., Meng, D., Li, X., Tan, J., 2016. Indoor-outdoor relationships of PM2.5 in four residential dwellings in winter in the Yangtze River Delta, China. Environ. Pollut. 215, 280–289. https://doi.org/10.1016/j.envpol.2016.05.023

Weschler, C.J., 2000. Ozone in Indoor Environments: Concentration and Chemistry. Indoor Air 10, 269–288. https://doi.org/10.1034/j.1600-0668.2000.010004269.x

Wheeler, A.J., Wallace, L.A., Kearney, J., Van Ryswyk, K., You, H., Kulka, R., Brook, J.R., Xu, X., 2011. Personal, Indoor, and Outdoor Concentrations of Fine and Ultrafine Particles Using Continuous Monitors in Multiple Residences. Aerosol Sci. Technol. 45, 1078–1089. https://doi.org/10.1080/02786826.2011.580798

WHO Europe, 2020. Methods for sampling and analysis of chemical pollutants in indoor air. World Health Organisation.

Wichmann, J., Lind, T., Nilsson, M.A.-M., Bellander, T., 2010. PM2.5, soot and NO2 indoor–outdoor relationships at homes, pre-schools and schools in Stockholm, Sweden. Atmos. Environ. 44, 4536–4544. https://doi.org/10.1016/j.atmosenv.2010.08.023

Wilson, W.E., Mage, D.T., Grant, L.D., 2000. Estimating Separately Personal Exposure to Ambient and Nonambient Particulate Matter for Epidemiology and Risk Assessment: Why and How. J. Air Waste Manag. Assoc. 50, 1167–1183. https://doi.org/10.1080/10473289.2000.10464164

Yin, H., Liu, C., Zhang, L., Li, A., Ma, Z., 2019. Measurement and evaluation of indoor air quality in naturally ventilated residential buildings. Indoor Built Environ. 28, 1307–1323. https://doi.org/10.1177/1420326X19833118

Highlights: A critical evaluation of the dynamic nature of indoor-outdoor air quality ratios

- *I/O ratios are shown to have significant dynamic variation, varying diurnally, seasonally as well as with building operation and occupant behaviour.*
- *Whilst static I/O ratios are widely reported, they hide this dynamic behaviour, limiting their interpretation and comparability..*
- *I/O ratios measured passively across integer 24 hour periods will be meaningless in many buildings.*
- *I/O ratios are shown to be strongly related to occupant behaviours and therefore represent a personal variable as much as a physical building metric.*
- *Dynamically assessed I/O ratios may prove useful as building performance metrics, indicating the relationship between indoor-outdoor air and the role of building operation.*

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: