Indoor Air Quality

in London's Schools

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Indoor Air Quality in London's Schools

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Non-Technical summary

The Mayor of London has commissioned a report on Indoor Air Quality in London's Schools to review existing evidence and investigate the level of indoor air pollution in London's schools. This study is based on the UK elements of the SINPHONIE (Schools Indoor Pollution and Health: Observatory Network in Europe) project funded by European Commission and two studies delivered under educational Building Design and Performance Research Programmes.

It is very important that the school environment protects children's health and does not increase exposure to air pollution. School-aged children spend a great deal of time inside school buildings. They are more vulnerable to airborne pollutants than adults not only because of their narrower airways, but also because they generally breathe more air per kilogram of body weight. The exposure of children's developing lungs to air pollution can result in reduced lung function that persists through to adulthood, increasing susceptibility to respiratory and cardiovascular diseases.

The GLA study on Indoor Air Quality in London's schools provides an extensive literature review on the subject and consists of six Case Studies: five of primary state schools and one of a nursery. The study found notable differences in the characteristics of indoor air pollution between seasons and classrooms depending on their microenvironment, building characteristics, operation and maintenance. School Indoor Air Quality is particularly important as it may affect the health, performance and comfort of school students and staff.

Key messages from case study schools (NO_2 and Particulate Matter)

- This study found notable differences in the characteristics of indoor air pollution between seasons and classrooms depending on their microenvironment, building characteristics, operation and maintenance.
- Outdoor NO_2 concentrations and the airtightness of the building envelope explained 84% of the NO_2 variation between classrooms, indicating the influence of strong outdoor pollution sources and the importance of the building envelope.
- Higher levels of all PM fractions were recorded during the heating season. The difference in indoor PM levels between urban and suburban schools was not statistically significant. Indoor PM_{10} concentrations during the occupied period were consistently higher than outdoors. Mean indoor PM_{10} and $PM_{2.5}$ levels recorded in all classrooms in both seasons were higher than 20 μg/m^3 and 10 μg/m^3 respectively, indicating that annual personal exposure to PM in the classroom may be higher than WHO 2010 guidelines. In most classrooms, PM concentrations were above daily guideline values.

Health, comfort and cognitive performance

The UK has the highest prevalence of childhood asthma among all European countries. The school represents a significant exposure environment that can trigger health symptoms among susceptible children.

A review of existing studies concluded that children living or attending schools near high traffic density roads were exposed to higher levels of motor vehicle exhaust gases, and had higher incidence and prevalence of childhood asthma and wheeze. A higher incidence of childhood asthma was positively associated with exposure to nitrogen dioxide (NO_2). Exposure to particulate matter (PM) was also associated with a higher incidence of wheeze in children.

Although there is limited evidence, some studies indicate significant improvement in cognitive performance of students when temperature in classrooms drops from 25 °C to 20 °C. The evidence also suggests that ventilation rates keeping carbon dioxide (CO_2) levels between 600 and 1,000 ppm may improve cognitive performance of students.

Understanding Indoor to Outdoor (I/O) ratios of pollutants

In urban areas, a significant proportion of indoor air pollution is due to outdoor air pollution that penetrates through the buildings. Peak penetration of pollutants into buildings occurs when high concentrations of pollutants coincide with high pressure weather fronts. Understanding these factors can become extremely complex in urban areas due to the close proximity and configuration of surrounding buildings. It is, thus, also true that internal concentrations in an urban building close to busy roads can vary greatly depending on the time of day, or location within the building.

The relationship between the indoor (I) and outdoor (O) air pollution levels for a building at a given time is usually expressed in terms of the I/O ratio. The I/O ratio gives an indication of the protective effect of a building for a given pollutant. However, I/O ratios are affected by many factors, such as ventilation rates and local meteorology. I/O ratios have been shown to vary greatly, even with the same building.

Acknowledgements

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Contents

List of Figures

List of Tables

Abbreviations

AD	**A**pproved **D**ocument
ASHRAE	**A**merican **S**ociety of **H**eating, **R**efrigeration, and **A**ir-Conditioning **E**ngineers
BB101	**B**uilding **B**ulletin 101
BMS	**B**uilding **M**anagement **S**ystem
BPE	**B**uilding **P**erformance **E**valuation
BSF	**B**uilding **S**chools for the **F**uture
CIBSE	**C**hartered **I**nstitution of **B**uilding **S**ervices **E**ngineers
DfE	**D**epartment **f**or **E**ducation
EPBD	**E**uropean **E**nergy **P**erformance of **B**uildings **D**irective
FS	**F**ixed monitoring **S**tation
IAQ	**I**ndoor **A**ir **Q**uality
IEQ	**I**ndoor **E**nvironmental **Q**uality
I/O	**I**ndoor to **O**utdoor Ratio
ISAAC	The **I**nternational **S**tudy of **A**sthma and **A**llergies in **C**hildhood
GLA	**G**reater **L**ondon **A**uthority
LOD	**L**imit **O**f **D**etection
L/s-p	litres per second per person
MM	**M**ixed-**M**ode Ventilation
MV	**M**echanical **V**entilation
N_s	Number of schools
ND	No Data
NV	**N**atural **V**entilation
PID	**P**hoto**I**onisation **D**etector
RH	**R**elative **H**umidity
SINPHONIE	**S**chools **I**ndoor **P**ollution and **H**ealth **O**bservatory **N**etwork in **E**urope
TEA	Triethanolamine
TVOCs	**T**otal **V**olatile **O**rganic **C**ompounds
VOC	**V**olatile **O**rganic **C**ompound
qPCR	quantitative Real-time polymerase chain reaction
WHO	**W**orld **H**ealth **O**rganisation

Nomenclature

σ	standard deviation
95%CI	95% **C**onfidence **I**nterval
BTX	Benzene Toluene Xylenes
CO_2	Carbon Dioxide
HCHO	formaldehyde
PM	**P**articulate **M**atter
NO_2	Nitrogen Dioxide
NO_x	Nitric Oxides (NO + NO_2)
NO	Nitric Oxide
O_3	Ozone
$PM_{2.5}$	Airborne particles with a diameter less than or equal to 2.5 μm
PM_{10}	Airborne particles with a diameter less than or equal to 10 μm
ppm	**P**arts **P**er **M**illion
T3CE	trichloroethylene
T4CE	tetrachloroethylene
Q1-Q3	25^{th} - 75^{th} interquartile range

Glossary

Definitions of terms used in this report. The terms are underlined in the main text.

Prevalence	A statistical concept referring to the number of cases of a disease that are present in a particular population **at a single point in time**
Incidence	The number of instances of illness commencing, or of people becoming ill **during a given period in a specified population**
Meta-analysis	A method for systematically combining pertinent qualitative and quantitative study data from several selected studies to develop a single conclusion that has greater statistical power
Heterogeneity in Meta-analysis	Inevitably, studies brought together in a systematic review will differ. Any kind of variability among studies in a systematic review may be termed heterogeneity. It can be helpful to distinguish between different types of statistical heterogeneity. Variability in the participants, interventions and outcomes studied may be described as **clinical heterogeneity**, and variability in study design and risk of bias may be described as **methodological heterogeneity**. Statistical heterogeneity manifests itself in the observed intervention effects being more different from each other than one would expect due to random error (chance) alone. The I-squared statistic describes the percentage of variation across studies that is due to heterogeneity rather than chance. I-squared is an intuitive and simple expression of the inconsistency of studies' results. Significant statistical heterogeneity arising from methodological diversity or differences in outcome assessments suggests that the studies are not all estimating the same quantity, but does not necessarily suggest that the true intervention effect varies. In particular, heterogeneity associated solely with methodological diversity would indicate the studies suffer from different degrees of bias (Higgins & Green 2011).

Forest plot is a graphical representation of a meta-analysis. It is usually accompanied by a table listing references (author and date) in the left-hand column.

The next column visually displays the study results. The boxes show the effect estimates from the single studies, while the diamond shows the pooled result.

The horizontal lines through the circles illustrate the length of the confidence interval. The longer the lines, the wider the confidential interval, the less reliable the study results. The width of the diamond serves the same purpose.

The vertical line is the line of no effect.

- If the outcome of interest is adverse (e.g. asthma attack), the result estimates are located to the right of the vertical line, it means that the outcome of interest occurred more frequently at higher exposure to the specific pollutant (risk factor).
- If the outcome of interest is desirable (e.g. no asthma attack), the result estimates are located to the left of the vertical line, it means that the outcome of interest (e.g. remission) occurred less frequently at higher exposure to the specific pollutant (protective effect).
- The last possibility: if the diamond touches the vertical line, the overall (combined) result is not statistically significant.

The next column contains exactly the same information as is contained in the diagram, just in numerical format as Odds Ratio with 95% Confidence Intervals (see below).

The last column shows the weight of each study (see below).

Weighting of studies The weight (in %) indicates the influence an individual study has had on the pooled result. In general, the bigger the sample size and the narrower the confidence interval (CI), the higher the percentage weight and more the influence the study has on the pooled result.

Odds Ratio (OR) and confidence interval	An odds ratio (OR) is a measure of association between an exposure and an outcome. The OR represents the odds that an outcome will occur given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure. The 95% confidence interval (CI) is used to estimate the precision of the OR. A large CI indicates a low level of precision of the OR, whereas a small CI indicates a higher precision of the OR.
control for variables	A confounder is a variable whose presence affects the variables being studied so that the results do not reflect the actual relationship. Control refers to various methodologies aimed to exclude confounding variables.

1 Building Regulations and guidelines in the UK schools

School buildings are complex spaces to design as they need to perform well in all aspects of indoor environmental quality (IEQ). The term IEQ encompasses Indoor Air Quality (IAQ), thermal conditions, as well as noise and light. Providing an adequate IEQ while accommodating periods with very high occupant densities can be particularly challenging. These high occupancy densities in school classrooms result in high internal heat gains, high carbon dioxide (CO_2) levels and emissions of body odours together with various indoor pollutants (physical, chemical and microbial).

Driven by the growing population, and many years of intensive use, the UK building stock is in need of rapid expanding, extensive refurbishment and maintenance.

1.1 Overview of regulations and policy drivers for refurbished and new school buildings

In July 2015, the UK Government declared that it was abandoning the zero carbon buildings policy first announced in 2007. As a result, the 2019 target for non-domestic zero carbon buildings including schools has been withdrawn, and there will be no technical changes to Building Regulations Part L (Conservation of Fuel and Power) (HM Government, 2016) until 2019. This 'zero carbon' target was set before the recast of the European Energy Performance of Buildings Directive (EPBD), and currently the UK is still committed to all new buildings being 'nearly zero energy' from January 2021 through the EPBD. Therefore, the 2019 revision of the UK Building Regulations Part L will be critical in setting the energy standards. As the EPBD addresses both **new** and **refurbished** buildings, in the UK there is now a single goal, i.e. 'nearly zero energy'.

IEQ in UK buildings is also addressed through Building Regulations. Whilst Part L, to some extent, addresses overheating by ensuring adequate passive measures are in place to control solar gain as well as energy, it is Building Regulations Part F (Means of Ventilation) that deals with issues of Indoor Air Quality (HM Government, 2013) . It is essential that Parts L and F are joined up sufficiently to ensure that alongside the energy goal, healthy, comfortable and productive indoor environments are achieved (Mumovic et al. 2009). To date, there has been limited research on the performance gap between design and operational IEQ in the UK, but some research in schools (Chatzidiakou et al. 2015a,b, 2014a), suggests the IAQ parameters may exceed design thresholds.

1.2 Indoor Air Quality guidelines in relation to building regulations

Regarding the external pollution the BB101 *Consultation Document* (2016) states: *"Where external air pollutants exceed the levels in National Air Quality Standards, consideration will need to be given to means of reducing pollutant levels in the indoor air. This is especially important in Air Quality Management Areas 15 (where, by definition, external pollution levels of at least one pollutant have exceeded the Air Quality Standards) and in Low Emission Zones."* EN 13779 gives the standards that apply to the design of ventilation systems to reduce the ingress of external air pollutants (BS EN 13779: 2007). It includes the classification of outdoor air quality and supply air classes and guidance on filtration classes.

The BB101 states: *"AD F gives recommended performance levels for indoor air quality in office-type accommodation and this guidance should be met in schools. These performance levels agree with the World Health Organisation (WHO) indoor air quality guidelines. The WHO indoor air quality guidelines have been used as the basis of the DfE standards in this document as they are more up to date and comprehensive than the levels quoted in AD F."*

The WHO guidelines provide a scientific basis for legally enforceable standards (WHO 2006, WHO 2010). The guidelines focus on air pollutants that are often found indoors in concentrations of health concern. WHO 2006 and 2010 guideline values of gaseous pollutants and particulate matter are presented in Table 1.

Table 1: IAQ guideline values (WHO 2006, WHO 2010)

Pollutant	Averaging time	guideline value ($\mu g/m^3$)
Ozone (O_3)	8h, daily maximum	100
Nitrogen Dioxide (NO_2)	1 year	40
	1h	200
Particulate Matter		
$PM_{2.5}$	1 year	10
	24h (99th percentile)	25
PM_{10}	1 year	20
	24h (99th percentile)	50
VOCs		
benzene	.	no safe level of exposure can be recommended
naphthalene	annual average	10
tetrachloroethylene (T4CE)	annual average	250
formaldehyde	30-minute average	100

Approved Document C sets out the requirements for site preparation and resistance to contaminants (including radon and moisture) (HM Government, 2013). The excess relative health risk, based on long-term (30-year) average radon exposure is about 16% per increase of 100 Bq/m^3. The WHO proposes a Reference Level of 100 Bq/m^3 to minimise health hazards due to indoor radon exposure.

However, if this level cannot be reached under the prevailing country-specific conditions, the chosen reference level should not exceed 300 Bq/m^3. Current action level in the UK is set at 200 Bq/m^3. If high radon values are found, established remediation techniques are available. Once the building has been remediated, the indoor radon level should be measured to confirm the operation of remediation system and the records retained. Public Health England maintains a useful website: `www.ukradon.org`.

Volatile Organic Compounds (VOCs) in schools originate from a combination of emissions from indoor building materials, human activities and outdoor sources. Potential emission sources in school classrooms include cleaning products, paints, teaching materials, interior finishing and furniture introduced in the classroom. Specific VOCs have been linked to carcinogenicity in humans (such as benzene) and WHO 2010 sets no safe limits of exposure in relation to health risk. The concentrations of airborne trichloroethylene (T3CE) associated with an excess lifetime cancer risk of 1/10,000 and 1/100,000 and 1/1,000,000 are 230, 23 and 2.3 μg/m^3 respectively. As it is possible to detect more than 50 different compounds indoors, each at a low concentration but higher than outdoors, the concept of total Volatile Organic Compounds (TVOCs) has been introduced in existing literature (Molhave 2009). In the UK, the recent version of AD F (HM Government, 2010) based on the European Collaborative Action (ECA, 1992) recommends concentrations below 300 μg/m^3 for domestic buildings.

A moderate relationship between mean indoor CO_2 levels and mean TVOCs concentrations was detected in a meta-analytic study (Chatzidiakou et al. 2012) of school classrooms (Figure 1). Concentrations may vary significantly between different settings depending on the strength of emission sources. However, mean indoor TVOCs concentrations of 200 μg/m^3 (which is the lowest threshold value of discomfort in the UK) occurred when indoor CO_2 levels were around 1,300 ppm (95% CI: 1,200 - 1,400 ppm).

1.3 Regulations on indoor CO_2 levels and ventilation rates in school classrooms

Ventilation is the process of exchanging indoor polluted air with potentially fresher and cleaner outdoor air. Indoor CO_2 levels, produced by metabolic breathing of the occupants, are a reliable indicator of ventilation rates, as increased outdoor airflow dilutes indoor concentrations (Figure 2). CO_2 levels and corresponding ventilation rates are therefore a good indicator of pollutants with indoor sources (such as bio-effluents); however they are poor indicators of traffic related pollutants. The relationship between CO_2 levels and ventilation rates is described by an exponential curve (Figure 2). The

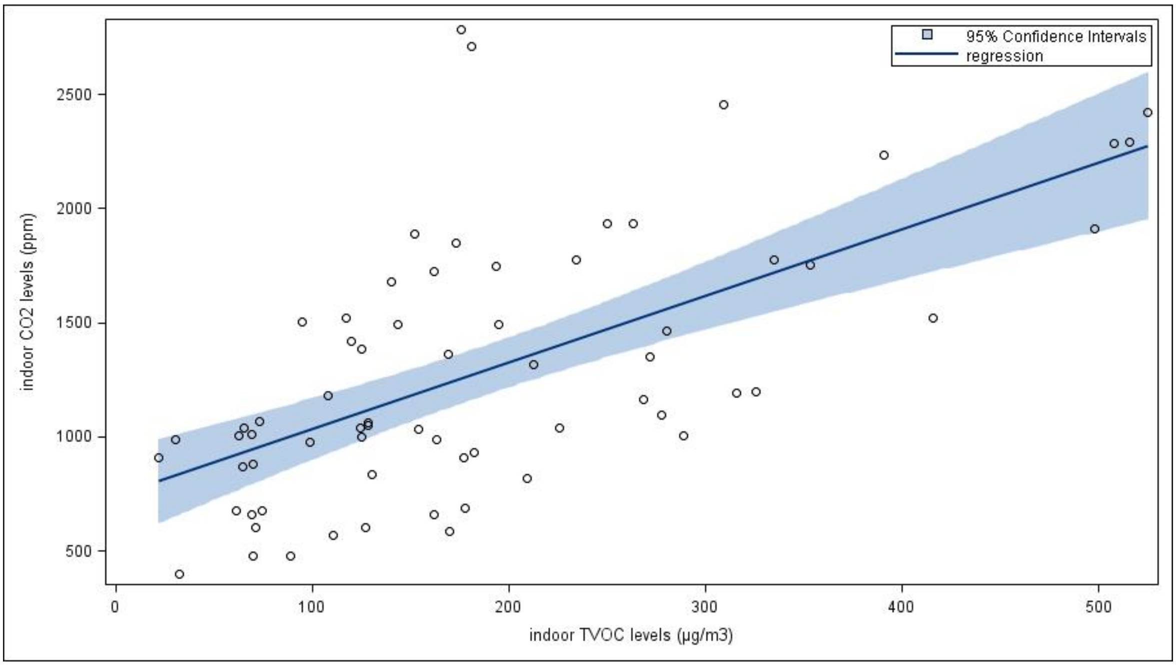

Figure 1: Moderate relationship between CO_2 concentrations and TVOCs in 132 classrooms in published literature (Chatzidiakou et al. 2012)

large number of studies clustered in Figure 2 towards the lower end of the range of ventilation rates suggests that low ventilation rates, and high CO_2 levels in schools are common.

In North America and some other countries, minimum ventilation rates are regulated by ASHRAE 62.1-2016 and are dependent on strength of indoor pollution sources and occupancy. In the UK, BB101 2016 *"Consultation Document"* provides guidelines on maximum CO_2 levels and minimum ventilation rates to ensure adequate IAQ in classrooms. In addition to the general ventilation requirements of Section 4 of Approved Document F (AD F) 2010, the following Department for Education (DfE) performance standards for teaching and learning spaces apply (same as BB101, 2016):

1. In general teaching and learning spaces where mechanical ventilation is used or when hybrid systems are operating in mechanical mode, sufficient outdoor air should be provided to achieve a daily average concentration of CO_2 during the occupied period of less than 1,000 ppm so that the maximum concentration does not exceed 1,500 ppm for more than 20 consecutive minutes each day, when the number of room occupants is equal to, or less than the design occupancy.

2. In general teaching and learning spaces where natural ventilation is used or when hybrid systems are operating in natural mode, sufficient outdoor air should be provided to achieve a daily average concentration of CO_2 during the occupied period of less than 1,500 ppm so that the maximum concentration does not exceed 2,000 ppm for more than 20 consecutive minutes each day, when the number of room occupants is equal to, or less than the design occupancy.

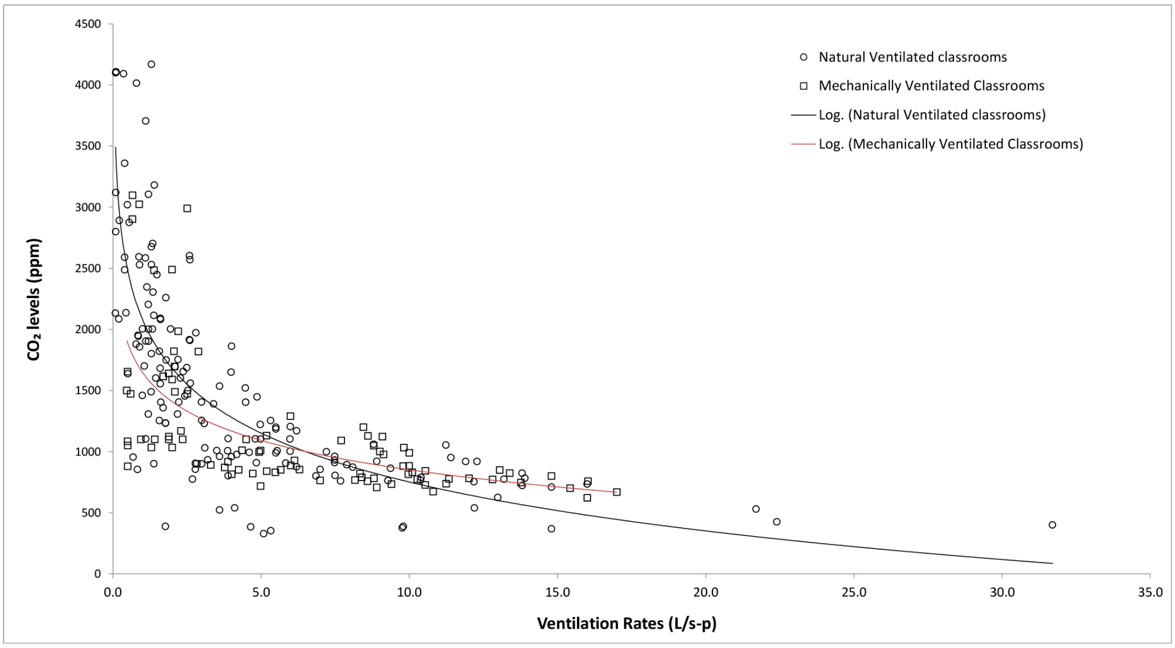

Figure 2: Correlation between indoor CO_2 levels and ventilation rates in naturally and mechanically ventilated classrooms synthesised in a meta-analytic study (Chatzidiakou et al. 2012)

3. As well as designing to meet the maximum CO_2 criteria given in paragraphs 1 and 2 above; the system should be designed to achieve a CO_2 level of less than 800 ppm above the outside CO_2 level for the majority of the occupied time during the year.

1.4 Regulations on thermal comfort

There has been extensive research on thermal comfort over several decades, which has led to two main approaches, the thermo-physiological and the adaptive comfort approach. Both approaches form the basis for existing thermal comfort standards, which include ISO 7730 (BS EN ISO 7730: 2005), the "American Society of Heating Refrigerating and Air-Conditioning Engineers" Standard 55 (ASHRAE, 2013) and at the European level EN 15251 (BS EN 15251: 2007).

The adaptive approach (now included in the latest versions of the above standards) evaluates thermal comfort of a non-fully conditioned indoor environment allowing for a wider band of temperatures and corresponding energy savings. The required operative temperature is estimated as a function of a weighted running mean of the exterior temperature. Based on those standards, the UK Building Bulletin 101 (BB101) (DfE, 2016) recommendation focuses on preventing overheating in the non-heating season. A summary of the assessment criteria for overheating is presented in Table 2. Regarding the heating season, regulatory framework focuses on minimum indoor temperatures in the workplace of 16 °C (Health and Safety Executive, 2013).

Table 2: Overheating assessment criteria applicable to schools. At least two criteria must be met for every occupied zone

Assessment Criteria	Building Bulletin 101 (Building Bulletin 101, Ventilation of school buildings, 2006) (Department for Education (DfE) 2016)	CIBSE TM52/ BS EN 15251	
		Free running buildings	Mechanically conditioned buildings
Criterion 1: Exceedance	Air temperature should not be greater than 28 °C for more than 120 hours during occupied period of 9:00-15:30, Monday to Friday between May to September.	Operative temperature should not be greater than adaptive maximum temperature for more than 3% of occupied hours.	Similar to free running buildings except that operative temperature is compared against fixed maximum temperatures: 26 °C in summer and 24 °C in winter for classrooms.
Criterion 2: Severity	Average difference between internal and external air temperature during this period should not be greater than 5 °C.	Daily degree-hours above adaptive maximum temperature should not exceed 6 degree-hours.	Daily degree-hours above fixed maximum temperature must not exceed 6 degree-hours.
Criterion 3: Max ΔT	Air temperature during this period should not exceed 32 °C.	Operative temperature should not exceed adaptive maximum temperature by more than 4 °C.	Operative temperature must not exceed fixed maximum temperature by more than 4 °C.

2 Understanding Indoor to Outdoor ratios in the urban context

The aim of this chapter is to address the fundamental principles related to the urban indoor/outdoor air quality modelling and monitoring. Specific details presented in this section are for information only. The UK National Air Quality Archive is recommended as an excellent source of outdoor air quality information. In general, the following types of air quality sampling locations are characteristic of urban microenvironments:

1. **Urban kerbside:** sites with sample inlets within 1 m of the edge of a busy road and sampling heights between 2 and 3 m;
2. **Urban centre:** non-kerbside sites located in an area representative of typical population exposure in town or city centre areas, e.g. pedestrian precincts and shopping areas; with sampling heights typically between 2 and 3 m;
3. **Urban background:** urban locations distanced from sources and broadly representative of city-wide background concentrations, e.g. elevated locations, parks and urban residential areas.

Taking into account the capital and operating costs of permanent air quality monitoring stations, it is of paramount importance to determine their best location. The different siting considerations for the permanent air quality monitoring stations in Central London was investigated by UCL researchers (Croxford & Penn 1998) and provided an insight into both temporal and spatial variations of carbon monoxide (CO) distribution in the Bloomsbury area of central London. The area was largely homogeneous in terms of building height, with most streets having a canyon type profile with an aspect ratio (height to width) ranging from 0.7 to 1.7. All the measurement points were at the same height (2 m) and as far from any street junction as possible. Radical variations were observed between monitors located at sites within a few metres of one another, prompting a simple protocol on positioning of air quality monitoring equipment within urban areas.

The second similar study (Vardoulakis et al. 2005) detected the strong spatial and temporal variability of traffic-related air pollution in the vicinity of a permanent monitoring station in central Paris. Diffusive benzene, toluene and xylene (BTX) samplers were exposed to ambient air for 28 consecutive 7-day periods, placed at 2.6-metre intervals at the 10 roadside locations (horizontally and vertically). Comparing with additional data from the permanent air quality monitoring station, it was concluded that the measurements from this site do not give a representative picture of air quality in the surrounding area and are, therefore, inappropriate for population exposure studies.

Using both monitoring and modelling it has been shown (Mumovic et al. 2006) that the dispersion of air pollutants within street canyons is controlled primarily by the micro-meteorological effects of urban geometry. However, by analysing the flow field patterns in urban street canyons, qualitatively, we can observe the following:

- lower concentrations at the windward-facing side of street canyons which are almost perpendicular to the wind direction;
- higher concentrations at the leeward-facing side of street canyons which are almost perpendicular to the wind direction;
- wash-out and accumulation effects along those canyons whose axes are parallel to the wind direction.

In addition, comparison of the distribution of mostly gaseous pollutants for the same wind direction, but different low to high wind speeds showed that considerable differences can be observed in concentration values:

- during low wind periods the convective transport of the pollutant is greatly reduced, causing higher concentration at the very lower levels of street canyons;
- during periods of very high wind speed, the wash-out effect increasing significantly, generally lowering the concentration levels within the city centre.

The summary of the local concentration gradients is given in Table 3 assuming that the observed cross sections are located away from crossroads, and that the height of buildings on both sides of the analysed canyons is the same.

Table 3: Assessment of local concentration gradients

WIND INCIDENT	LOCAL CONCENTRATION GRADIENTS	
	SMALL	LARGE/MEDIUM
PERPENDICULAR	upper leeward side vortex centre lower windward side	lower leeward side (large) bottom of the canyon (large)
OBLIQUE	upper leeward side vortex centre lower windward side	lower leeward side (medium) bottom of the canyon (medium)

In urban areas, a significant proportion of indoor air pollution are due to penetration through the building facade of pollutants generated outdoors. Pollutant levels within a building, resulting from outdoor sources, depend on:

- complex dispersion processes around the building;
- the ventilation strategy of the building (i.e. natural or mechanical);
- the locations of air intakes (for mechanically-ventilated buildings);
- the airtightness of the building (affecting the rate of infiltration);
- the specific pollutant and its physical and chemical properties.

Other environmental parameters, such as the local meteorology, also play important roles in influencing indoor pollution concentrations in indirect ways. Once indoors, the concentration may be decreased by indoor chemical reactions, by deposition onto indoor surfaces and through ventilation back to the outdoors (Figure 3).

A key distinction is between long-range and short-range sources of air pollution. For far-off releases (typically, more than 500 m away), the concentration in the envelope surrounding the building may be assumed to be relatively constant due to vertical and lateral spreading of the plume. However, for closer releases (less than 500 m) the outdoor concentration close to the building may not be assumed to be constant. For such sources, concentrations are usually high at short ranges and vary considerably over the surface of the building, fluctuating over time periods as short as seconds.

Peak penetration of pollutants into buildings occurs at points of both high pressure and high contaminant concentration, the patterns of both of which can become extremely complex in urban areas due to the close proximity and configuration of surrounding buildings. It is, thus, also true that internal concentrations in an urban building close to busy roads can be highly spatially and temporally variable.

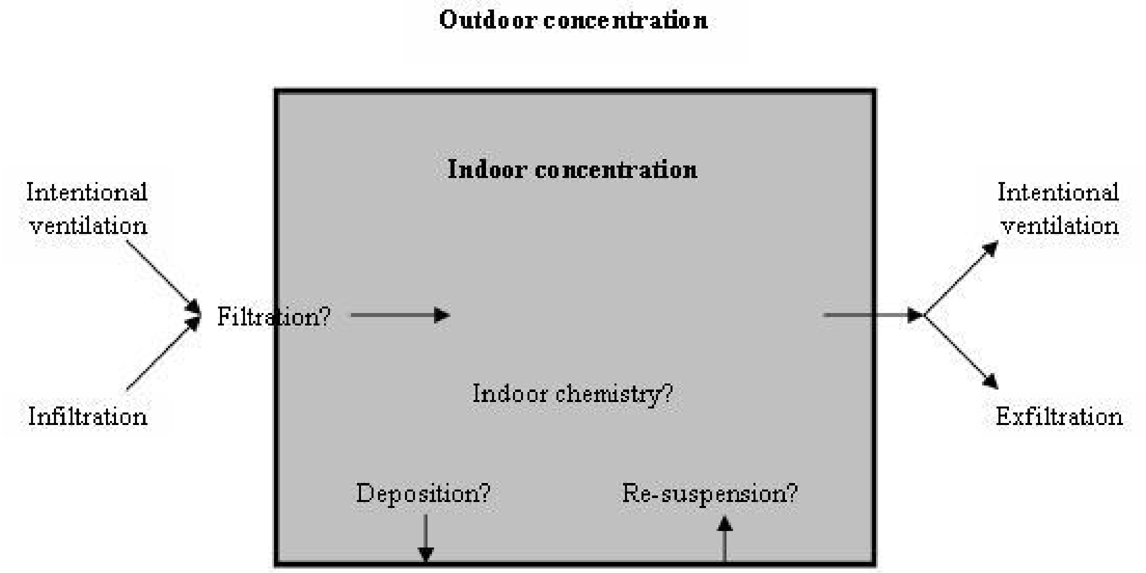

Figure 3: Factors determining indoor air pollution concentrations

Both indoor and outdoor concentrations measured at single, fixed locations may not be sufficiently representative of the overall distribution of concentrations and the actual exposure experienced by the occupants of the building (Milner et al. 2006).

The relationship between the indoor (I) and outdoor (O) air pollution level for a building at a given time is usually expressed in terms of the I/O ratio. The I/O ratio gives an indication of the protective effect of a building for a given pollutant. However, I/O ratios are affected by many factors, such as ventilation rates and the local meteorology. In fact, I/O ratios have been shown to vary greatly, even for an individual building.

Since monitoring work can be technically difficult and expensive, it is often not practical to sample in multiple locations. For single or relatively few sampling locations, it is therefore important to give careful consideration to the siting of equipment. The aim is to find a location that is as representative of the exposure of building occupants as possible. Depending on the situation, this is likely to be in the centre of the room, at head height of a seated adult and away from internal pollution sources (unless the source is of particular interest). In reality, it is often necessary to compromise when choosing a suitable location.

Ideally, multiple measurement locations will give a clearer picture. An example of this is provided by Milner et al. (2006) who monitored CO concentrations in different locations within an office building in central London and at an external location close to the building. The building was flanked by two heavily-trafficked streets and two quiet streets. In general, the data suggested that:

- Indoor CO concentrations were greater on the lower floors of the building;
- Indoor CO concentrations on the same floors were greater closer to the busier roads;
- Correlation between the outdoor and indoor data decreased within the building with distance from the outdoor site, but was found to increase with the introduction of a time lag.

These findings imply that the protection offered by the building shell may be increased further away from the busiest roads. For this particular building, the highest I/O ratios were observed for north-westerly winds, although the highest internal and external concentrations were for south-easterly winds. This suggests that a higher rate of penetration of low ambient concentrations occurred during north-westerly winds and demonstrates how complex the situation may be in an urban setting.

Differences in I/O ratios for a particular building will also occur depending upon the type of pollutant. The I/O ratios of three of the most common indoor pollutants with outdoor sources will now be discussed in more detail: NO_2 and three fractions of particulate matter (PM_{10}, $PM_{2.5}$, PM_1).

Indoor sources of NO_2, such as gas cookers, lead to considerably raised indoors levels and also to increased variation in these levels. However, in schools, when no strong internal sources are present, indoor NO_2 is usually below ambient levels. Studies have estimated that I/O ratios of NO_2 are close to unity, between $0.77 < I/O < 1.18$ (Chatzidiakou et al. 2012).

A detailed description of published evidence on particulate matter in naturally ventilated schools can be found in the systematic review by Chatzidiakou et al. (2012). In summary, great variations in I/O ratios for particulate matter are reported in the literature. There is strong evidence that the presence of occupants and intense activities of students resulted in elevated concentrations of PM and affected the larger size fraction to a greater extent (PM_{10}). Most studies in schools found weak relationships between indoor and outdoor PM_{10} concentrations during unoccupied periods. Indoor concentrations of $PM_{2.5}$ and PM_1 in classrooms were significantly correlated to outdoors; the average rate of diesel traffic was the only significant predictor of average fine and ultrafine indoor concentrations. The strong influence of outdoor sources suggested that the building envelope provided little protection from fine and ultrafine particles. I/O ratio of all PM fractions were always greater than unity during school hours and ranged between 1.1-3.6 for PM_{10} and 1.6-2.8 for $PM_{2.5}$ and 1.5-2.2 for PM_1.

Empirical evidence of indoor PM levels in schools is particularly useful, because predicting indoor levels based on observed outdoor concentrations is complicated by the sizes of the particles, since the penetration and deposition rates of smaller and larger particles will vary. The I/O ratios for NO_2 and

PM reported in the SINPHONIE and UCL database over the occupied period can be found at Section 6.

In summary, monitoring studies report a wide range of indoor concentrations and I/O ratios due to the complexity of indoor-outdoor transport, indoor sources and the wide range of variable parameters that may have an effect.

3 UCL Building Performance Evaluation studies

UCL Building Performance Evaluation (BPE) database contains data collected through a number of different initiatives for conventional and energy-efficiency school buildings, including energy use for heating and equipment, IEQ data, and occupant satisfaction surveys (Table 4).

Table 4: Data available for initial analysis of UK buildings

Building Type	Data Type	Parameter	Temporal Resolution	Granularity	Period	Sample Size	Reference
Conventional Schools	Electricity & Fossil-thermal energy	Measured energy consumption (kWh/m^2)	Annual	Whole Building	2008-2012	6,600 Primary and 1,000 Secondary	(Hong et al. 2013)
	Electricity & Fossil-thermal energy	Calculated and measured energy consumption (kWh/m^2))	Annual	Whole Building	Post-2010	244 Schools	As yet unpublished
BSF Low Carbon Schools*	IEQ	T, RH, CO_2	1 minute (CO_2), 10 minutes (T, RH)	Whole Building	Post-2010	16 Secondary (full IAQ data 4 schools)	(Burman et al. 2014, Williams et al. 2015, Mumovic et al. 2009)
		BUS survey	NA	NA			

** denotes an energy-efficient building*

3.1 General findings in modern schools located within the GLA

Typically, the ventilation (and indirectly IAQ) strategies are developed to cope with two scenarios (CIBSE, 2015):

1. the provision of adequate IAQ in winter without excessive heat loss (this is based on CO_2 as a proxy for IAQ, Section 1.3);
2. the need to prevent overheating in summer (Section 1.4)

In practice the minimum capacity of a ventilation system should be based on ventilation rates to maintain satisfactory IAQ, the maximum should be based on ventilation rates required to limit the risk of overheating during the summer period. Although used as proxy for IAQ, CO_2 concentrations indicate only specific and limited aspects of IAQ, not the overall level of IAQ. There are currently no established good practice guidelines which would help to the building industry and planning authorities to deal robustly with either external or internal pollutants. Similarly, there are no guidelines on how to deal with assessment of IAQ once the schools are commissioned.

A project by the Department for Communities and Local Government (Isanska-Cwiek et al. 2008) evaluated 34 natural and mechanical ventilation design strategies for school classrooms in the context of winter IAQ performance, thermal comfort in winter (including cold draughts and temperature asymmetry), summer overheating and summer IAQ performance. CIBSE's best practice guidelines TM57 *"Integrated School Design"* (CIBSE, 2015) indicates that well implemented natural ventilation strategy hold be the default design solution for the ventilation of school teaching spaces when the ingress of external noise levels can be avoided assuming that external pollution levels are not exceeding well established health IAQ guidelines.

Mechanical air distribution systems are susceptible to poor construction and management practices, with the efficiency of these systems often worse than designers expect due to various factors, such as the underestimation of system pressure drop, fan inefficiency, poor ductwork installation, increased ductwork leakage, and poor system maintenance. Furthermore, air fans are variable torque machines and substantial reductions in power demand and energy consumption can be achieved at part load if fan speed is reduced in response to the actual ventilation demand, for example, when a space is not fully occupied. Design, installation, commissioning, and fine-tuning of such a demand-controlled strategy is crucial to ensure the energy performance of the system is optimised. The evidence collated from operational buildings points to a huge performance gap in the operation of these systems (Bordass et al. 2001, Burman et al. 2014).

Table 5: Key procurement and operational issues that compromise IAQ and overheating resilience (and energy performance) in modern schools

Procurement issues (Design & Construction)	**Operational issues**
Motorised vents and roof lights were critical in achieving effective cross & stack ventilation. However, they were not protected from value engineering and not subjected to seasonal commissioning.	BPE studies identified a number of malfunctioning motorised vents that were stuck open in winter or closed in summer with implications for energy use (heat loss in winter) and overheating resilience.
Motorised vents had been designed to respond to carbon dioxide concentrations in classrooms and summer temperature control settings. However, thermal triggers were not defined and programmed in the BMS.	The cross and stack ventilation strategy is compromised during summer since the motorised vents and roof lights are not responsive to temperature. Night-time ventilation strategy is also currently not followed by the School.
Fresh air rates specified for the air handling units were much higher than minimum requirements. Furthermore, based on the commissioning data, total specific fan power of the installed air distribution system was 53% higher than the regulatory limit.	Panel and bag air filters are not necessarily cleaned or replaced before they reach their final pressure drop. This can increase total system pressure drop by 20% and lead to Specific Fan Powers even worse than what was achieved at the commissioning stage.
There is no effective demand-controlled ventilation. Fan inverters were installed and used at the commissioning stage to balance the system. However, no CO_2 or temperature sensor was installed in the classrooms or extract ductwork to control the air flow. The inverters can only be controlled manually through panel switch operation.	Operational schedules of the air distribution system do not take into account the zoning arrangements to isolate unoccupied zones. This, combined with the procurement issues, means the system provides full fresh air when there is no real demand for it and leads to huge waste of energy.

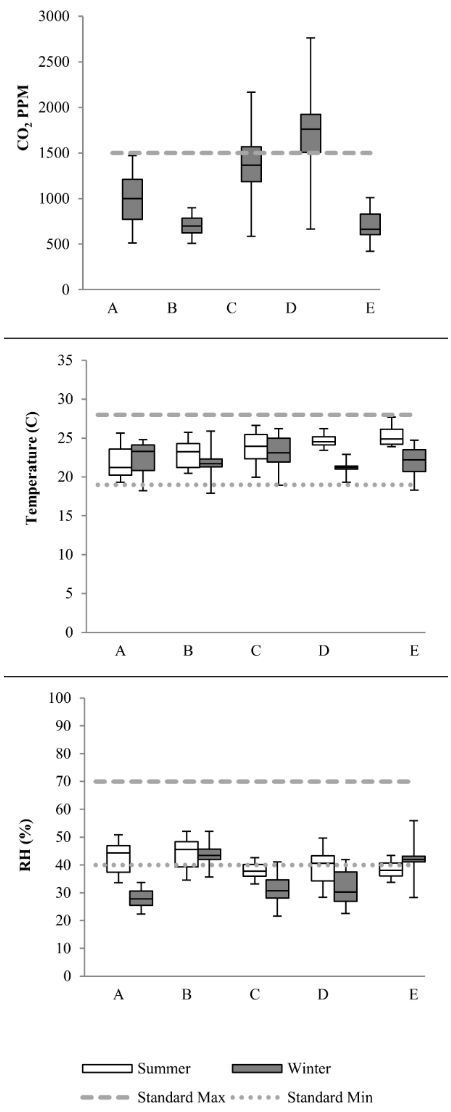

Figure 4: Distributions of monitored IEQ variables for five BSF school buildings, aggregated seasonally. Dashed lines show the target static maximum and minimum criteria as defined by Building Regulations

With the long life of buildings, the failure mode of mechanical ventilation systems must also be taken into account. It is important to ensure operable windows with a reasonable opening area are available in case the air handling units fail to operate as a result of part failure. Value engineering of window openings or adoption of a sealed envelope design without a proactive and preventative maintenance regime (rarely found in schools) can severely compromise the indoor environmental quality where air handling units are not functional. Table 5 summarise key procurement and operational issues affecting IAQ and overheating resilience in BSF schools. Ranges of monitored CO_2, temperatures and RH levels can also be seen in Figure 4. In the UK, RH in buildings is often close to or below the lower limit of the 40-70% comfort range recommended by CIBSE, with RH levels below 40% not unusual during the heating season as humidification is rare.

3.2 Indoor air quality results in a sample of modern BPE schools

A key school analysed within the BPE studies is a recently completed secondary school located in west London, close to the congestion charging zone (Section 6.7, Figure 18). This school, completed in 2009, is ventilated predominantly using centralised mechanical ventilation from air handling units located on the roof, with supplementary ventilation through openable windows in the teaching spaces. The usage of mechanical ventilation was driven by the necessity of attenuating the high external noise levels throughout the day, with the additional attenuation available through the mechanical system enabling a simpler façade over attenuated louvres. Openable windows were provided to assist with purge ventilation at the discretion of the teachers, giving them explicit control over the amount of external noise entering the classroom, balancing the distractions of air quality and noise as needed.

As noted in the other BPE studies (Table 5) there were apparent issues with the commissioning of the mechanical ventilation, with the poor air quality and overheating reported. In response to these complaints, the system was re-commissioned in 2014 prior to the air quality monitoring, including filter replacement/cleaning, rebalancing of dampers, and cleaning of ducts. The value of recommissioning of the mechanical ventilation system is immediately apparent in the good indoor air quality measured within the selected classrooms, with no classroom exceeding 1,500 ppm CO_2 during the monitored period, and two of the rooms averaging below 1,000 ppm (Table 78).

The I/O ratios of NO_2 and O_3 were found 0.6-0.7 and 0.1-0.3 respectively (Table 79), and were within the range estimated in the SINPHONIE project (Chapters 5 and 6).

Clear within the monitored data is the reduction in particulates inside compared to the outside air, with I/O $PM_{2.5}$ ratios between 0.6 and 0.9 (Table 75), assisted by the bag-filters within the air handling units.

Specific VOCs, such as benzene and formaldehyde levels were notably higher indoors than outdoors, indicating the presence of indoor sources (Table 76).

4 Associations between environmental exposure with health outcomes and cognitive performance of students

Children are more vulnerable to airborne pollutants than adults not only because of their narrower airways, but also because they generally breathe more air per kilogram of body weight. Exposure of the developing lung to air pollution reduces the maximal functional capacity achieved as the child enters adulthood, and thus reduces the functional reserve. While children have an underdeveloped ability to communicate concerns in response to pollutant levels, the school environment is a significant site of exposure for them.

Asthma is the most common chronic disease and is the leading cause of hospitalisation among children (World Health Organization 2008). The UK has one of the highest prevalence rates of childhood asthma among European countries, with almost 10% of children (1.1 million) suffering from symptoms (ISAAC, 1998). In many countries there is a significant increase in asthma hospital admissions among asthmatic children peak in September, and coincides closely with their return to the school environment (Julious et al. 2007). These studies indicate that a sub-population of school-aged children with asthma receive challenges when returning back to school that trigger their asthma, such as viral infections and exposure to allergens.

4.1 Health effects of classroom exposure to traffic-related pollutants

Exposure to traffic-related pollutants has been associated with asthma and asthmatic symptoms in children. The systematic meta-analysis (Gasana et al. 2012) included 19 studies and evaluated the strength and consistency of the current evidence. The two forest plots (Figure 5 and Figure 6) are a graphical representation of the estimated results from current scientific studies on the association between prevalence and incidence of childhood asthma/asthmatic symptoms with exposure to traffic-related pollutants. The forest plots present the effect estimates in a natural logarithmic scale using Odds Ratio (OR) (black circles) and 95% Confidence Intervals (95%CI)(horizontal lines). When the CI crosses 1 (vertical line in Figures 5 and 6), the association reported in the study is not significant, as it is not clear if the exposure has a protective effect or increases the risk of illness. The meta-analysis estimates the pooled (i.e. combined) estimate (meta-OR) (diamond in Figures 5 and 6) of previous studies by applying a weight on each study. When the heterogeneity (I-squared) of the subtotal is small (<50%) and the p-value is not significant (p >0.05), the evidence between studies is consistent.

Exposure to NO_2 (Figure 5) was associated with a higher incidence of childhood asthma (meta-OR: 1.14, 95%CI: 1.06–1.24), and exposures to particulate matter was associated with a higher incidence of wheeze in children (meta-OR: 1.05, 95%CI: 1.04–1.07). Figure 6 shows that the prevalence of childhood asthma was associated with exposure to NO_2 (meta-OR: 1.05, 95%CI: 1.00–1.11), NO (meta-OR: 1.02, 95%CI: 1.00–1.04), and CO (meta-OR: 1.06, 95% CI: 1.01–1.12).

The studies included in the meta-analytic study (Gasana et al. 2012) employed measurements from the closest fixed monitoring stations (FS), which might not reflect personal exposure of children, as those measurements did not account for the air pollution heterogeneity. In the case studies outlined in this report, we approximated exposure in the classroom with greater accuracy, as measurements were performed in the breathing zone of the students. Recent advancements in low-cost miniaturised sensors on portable platforms (Mead et al. 2013) can be used for quantification of personal exposure.

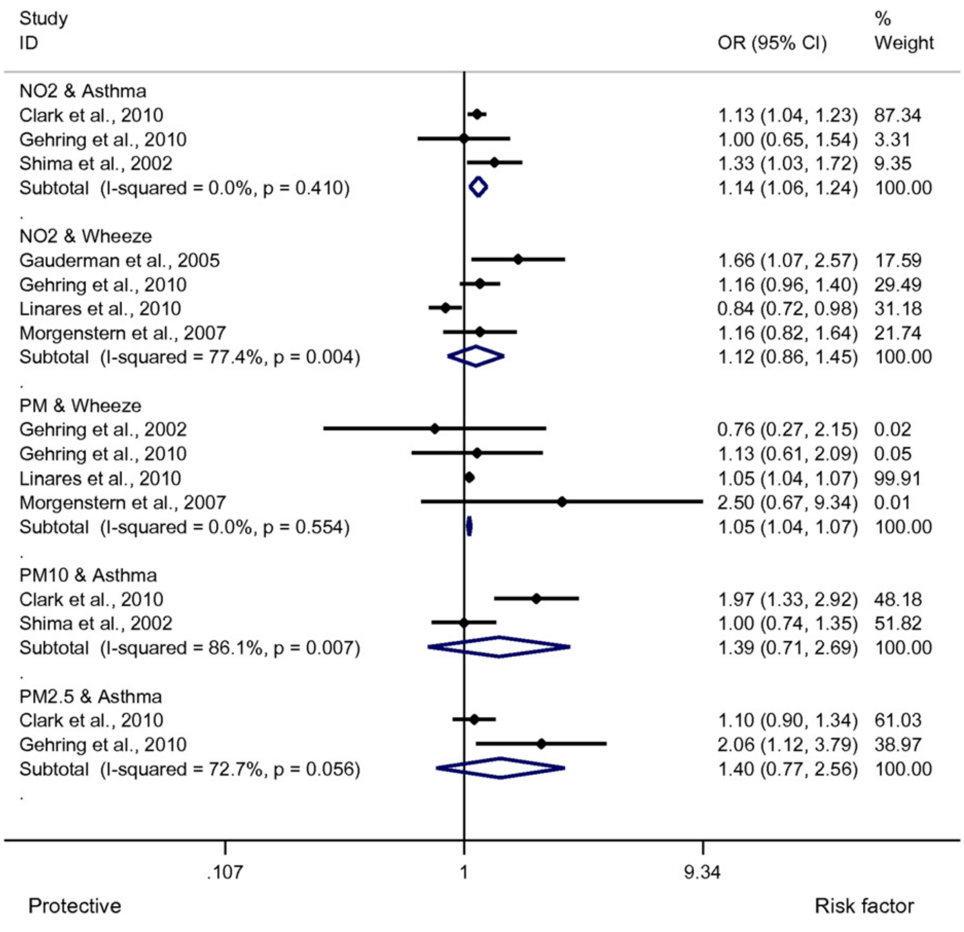

Figure 5: Forest plot of the association between traffic-related air pollutants and the incidence of asthma and wheeze using a random effect model. The pooled effect sizes for each exposure were obtained by a weighted average of adjusted odds ratios for a 10 $\mu g/m^3$ increase in pollutants (Gasana et al. 2012)

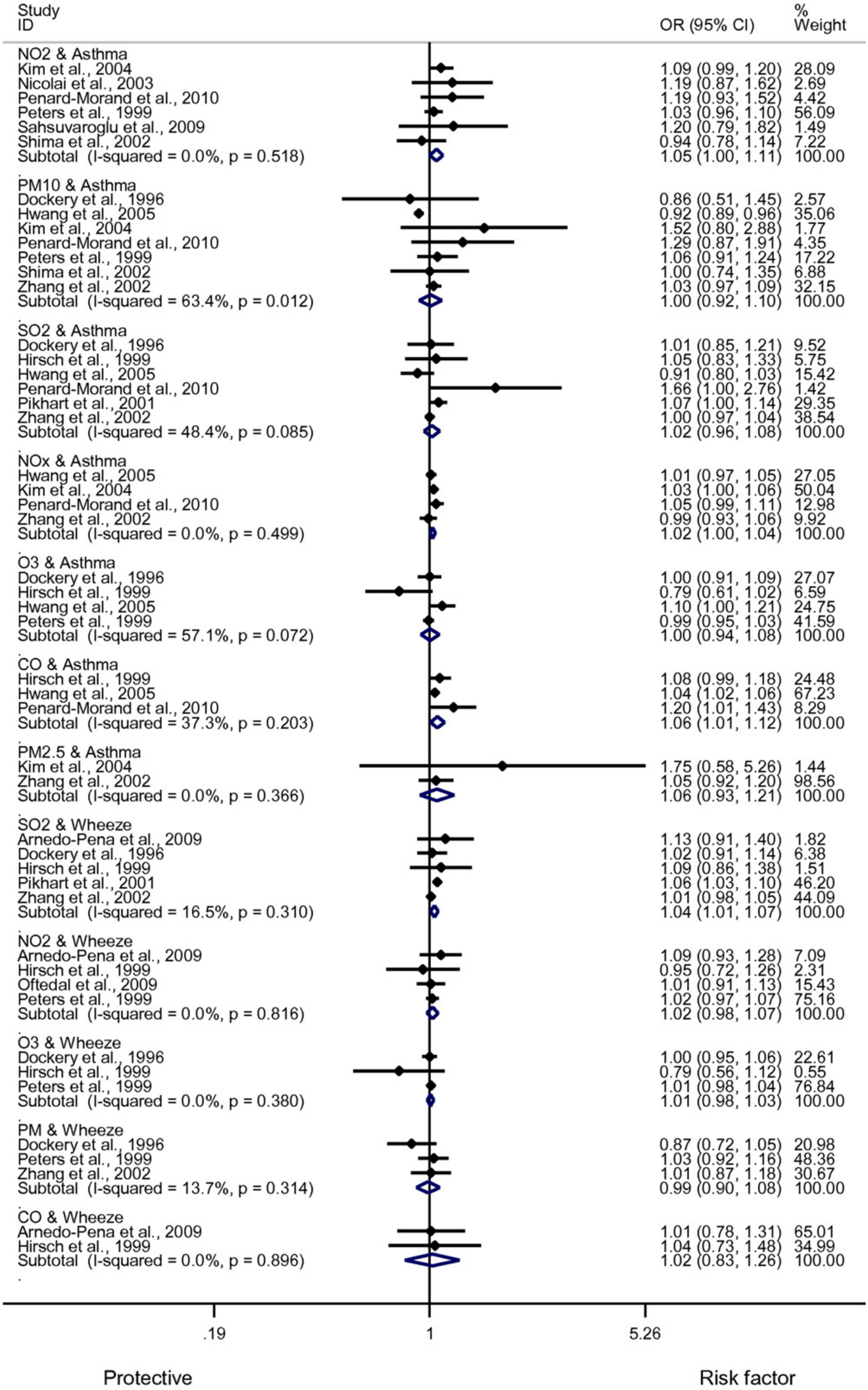

Figure 6: Forest plot of the association between traffic-related air pollutants and the prevalence of asthma and wheeze using a random effect model. The pooled effect sizes for each exposure were obtained by a weighted average of adjusted odds ratios for a 10 μg/m^3 increase in pollutants (Gasana et al. 2012)

4.2 Effects of thermal comfort and ventilation rates on cognitive performance of students

Cognitive performance evaluations focus mainly on two aspects of human performance: speed (how quickly each pupil worked per unit time) and accuracy (expressed as a percentage of possible errors). Much of the current IEQ research focuses on the association between cognitive performance with temperature and ventilation rates/CO_2 levels, with very little evidence currently available on the links between cognitive performance and specific pollutants in the school environment.

The systematic review by Chatzidiakou et al. (2012) offers a comprehensive picture of indoor conditions in school settings, emphasising that reduced ventilation rates and elevated indoor temperatures in schools are common, frequently worse than those found in office buildings (Wargocki & Wyon 2013). At the concentrations found in classrooms, CO_2 is not considered a harmful pollutant, however, it is a well documented (Wells-Riley equation) that it increases the probability of airborne communicable infection (Sze To & Chao 2010).

Further evidence in a meta-analytic review by Chatzidiakou et al. (2014b) investigates the effects of thermal environment and ventilation rates on cognitive performance of students. Generally, current evidence on the association between thermal conditions and cognitive performance of students is limited. Wargocki & Wyon (2013) and Bakó-Biró et al. (2012) employed a relatively large sample with a robust experimental design based on cross-sectional blind interventions. Both studies controlled for personal factors that may affect cognitive performance, as well as $PM_{2.5}$ levels and noise levels. Using a linear fixed effects the findings from Wargocki & Wyon (2013) and Bakó-Biró et al. (2012) were pooled together to estimate the effect of the thermal environment on cognitive performance of students (Figure 7). Overall, this relationship shows that an improvement of 11.0% (95% CI: 10.0% to 11.2%) in cognitive performance may be expected when the indoor air temperature drops from 25 °C to 20 °C.

Using the same meta-analytic technique, the relationship between ventilation rates and improvement in students' performance was estimated (Chatzidiakou et al. 2014b) from six studies (Wargocki & Wyon 2013, Bakó-Biró et al. 2012, 2007, Haverinen-Shaughnessy et al. 2011, Shaughnessy et al. 2006, Coley et al. 2007) in the range from 0.3 L/s-p to 16 L/s-p (Figure 8). This synthesis suggests that an increase of ventilation rates from 5 L/s-p to 15 L/s-p will result in an improvement in performance by 7% (95%CI: 4 to 10%). It should be noted that there is limited data available for higher ventilation rates. At this stage we would recommend designing to achieve ventilation rates between 8-12 L/s-p under the easy control of the occupants.

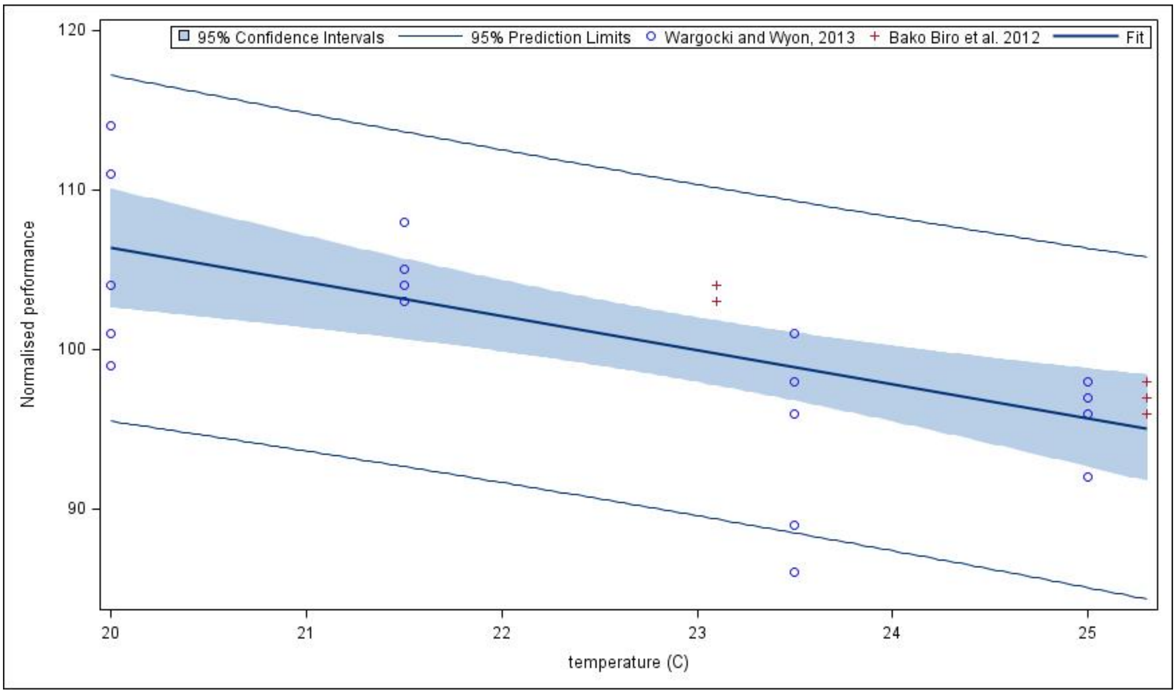

Figure 7: Normalised performance as a function of classroom temperature. The pooled effect estimate was based on two peer-reviewed publications (Wargocki & Wyon 2013, Bakó-Biró et al. 2012)

5 Indoor air pollutants in GLA schools: the SINPHONIE project

The "Schools Indoor Pollution and Health Observatory Network in Europe" (SINPHONIE) (`http://www.sinphonie.eu/`) project was initiated and funded by the European Parliament, through the European Commission's Directorate-General for Health and Consumers (DG SANCO). The overall aims of SINPHONIE were to:

(a) contribute to the better characterisation of IAQ in schools in the EU;

(b) produce recommendations and guidelines on remedial measures in the school environment to cover a wide range of situations in Europe;

(c) disseminate these guidelines to policy makers and other stakeholders who are able to take action in European countries.

The SINPHONIE consortium involved 38 partners from 25 countries and ran for two years between 2010-2012. Overall, 114 primary schools in 23 European countries participated in the environment and health monitoring and assessment. Four geographical clusters were defined within the project (Figure 9) assessing the exposure levels among 5,175 schoolchildren (including 264 children at preschools).

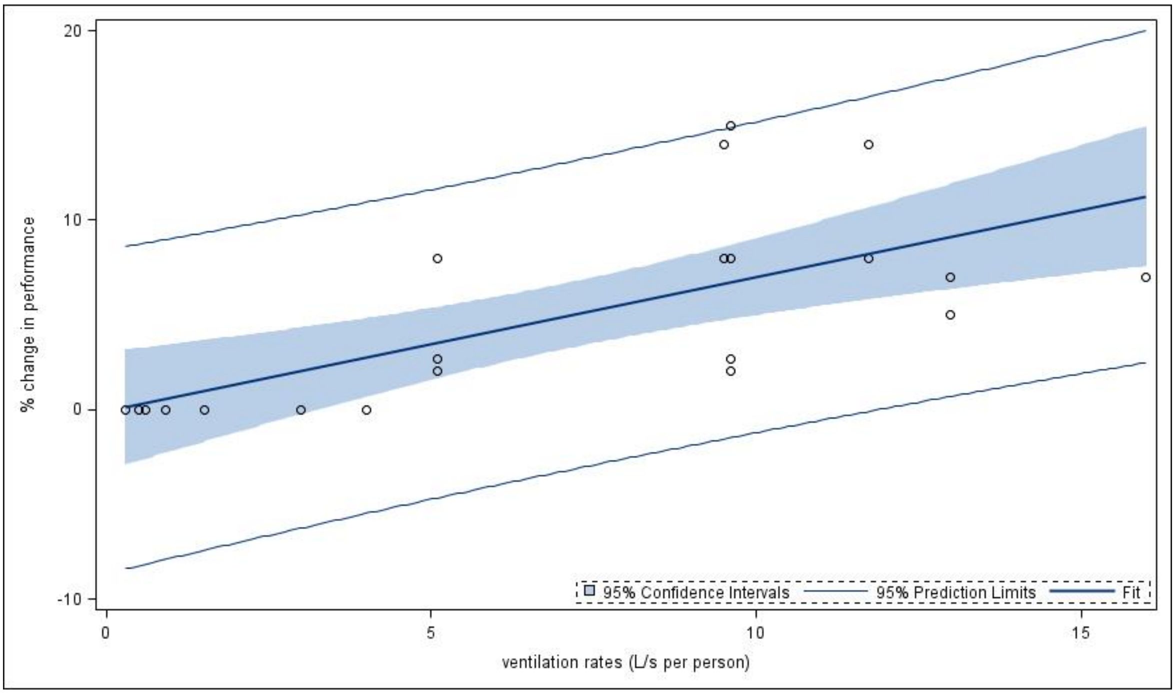

Figure 8: Percentage change in performance vs. average ventilation rate, fitted with a linear regression model derived from six studies (Wargocki & Wyon 2013, Bakó-Biró et al. 2012, 2007, Haverinen-Shaughnessy et al. 2011, Shaughnessy et al. 2006, Coley et al. 2007)

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The SINPHONIE project employed a multidisciplinary methodology with expertise in epidemiology, medicine, environmental chemistry, microbiology and building science. A harmonised protocol was developed, with all 80 researchers participating in the project were trained on environmental monitoring techniques and clinical tests by the scientific and technical staff at the European Commission's Joint Research Centre (JRC) in Ispra, Italy. An integrated database of physical, chemical and microbial parameters in the school environment was created matched with health outcomes of the students.

The UK contribution of the SINPHONIE project

UCL was the UK partner in the SINPHONIE project, additionally updating the methodological framework to include continuous instrumental monitoring of selected IAQ parameters. While SINPHONIE was conducted in the heating season, the UK study design was extended as a case-crossover investigation of the heating and non-heating season.

5.1 The UK school sample

Each school was monitored for a period of five consecutive working days in both the heating (October 2011 - January 2012) and the non-heating seasons (March - June of 2012).

Countries included	Participating schools, N (%)
Cluster 1. Northern Europe [a)] Sweden, Finland, Estonia, Lithuania	13 (11)
Cluster 2. Western Europe [b)] Belgium, UK, France, Austria, Germany	26 (23)
Cluster 3. Central-Eastern Europe [c)] Poland, Slovakia, Czech Republic, Hungary, Romania, Bulgaria, Serbia, Bosnia and Herzegovina	44 (39)
Cluster 4. Southern Europe [d)] Italy, Portugal, Malta, Greece, Cyprus, Albania	31 (27)

[a)] Cold climate (cold winters), large differences between old and new buildings, well-insulated rooms, mechanical ventilation systems.
[b)] Moderate climate (moderately cold winters), differences between old and new buildings (ventilation, insulation, passive and low-energy construction).
[c)] Colder climate (cold winters), moderate to low insulation, no ventilation systems.
[d)] Warm (warmer winters), Mediterranean climate, moderate to low insulation, natural ventilation.

Figure 9: The four geographical clusters in the SINPHONIE project (Csobod et al. 2014)
.

A detailed description of the monitoring strategy and empirical data on indoor pollution levels in classrooms can be found in two peer-reviewed papers (Chatzidiakou et al. 2015a, Chatzidiakou et al. 2015b).

In line with the SINPHONIE protocol, a sample of one nursery and five primary state schools in the Greater London Authority (GLA) were selected from a number of consenting school authorities. The school sample (Table 6) consisted of three schools built in the 19^{th} Century (Victorian) located in the vicinity of central London, and three contemporary schools in suburban areas. The schools were of similar size (mean: 2650 m^2, σ: 530) and similar occupancy (mean: 432 students, σ: 50), but varied considerably in terms of their proximity to likely external pollution sources (Table 6). The descriptive results of the monitoring campaign can be found in Section 6, Case studies 1 - 6.

In each school, three classrooms were investigated which were selected as representative of the school in terms of their geometrical characteristics and occupancy schedule. Classrooms accommodating older children were preferred, as their responses to surveys are considered more accurate than those of younger children. Pollution levels and meteorological parameters were monitored in the school premises simultaneously.

Table 6: School construction characteristics and aggregated socio-economic information

School code	Area	FSM (%)	Construction Year	Construction Materials	Ventilation Strategy	Window design and glazing
S1	Suburban	.	1950 (extension 1999)	mixture of insulated walls of high and low thermal mass Exposed ceiling slab	NV single sided Restricted windows	PVC frame Vertical sash windows Double glazing
S2	Suburban	22%	2010	Low energy school: High U-Values Mixture of insulated walls of high and low thermal mass	MM NV Assisted with Mechanical Exhaust	Wooden frame Vertical pivot windows Double glazing
S3	Urban in immediate proximity to main traffic artery	53%	1896	high thermal mass uninsulated walls and ridge roofs	NV	Wooden frame Vertical sash windows Single Gazing
S4	Urban background	13%	1870	high thermal mass uninsulated walls and ridge roofs	NV	Wooden frame Bottom-hung inward windows Single Glazing
S5	Urban background in proximity to a carpentry industry	95%	1866	high thermal mass uninsulated walls and ridge roofs	NV Restricted windows in the heating season	PVC frame Bottom-hung inward windows Double glazing
S6	Suburban high traffic street less than 400 m away	37%	2000	mixture of insulated walls of high and low thermal mass	NV cross-ventilation with windows on high level	Aluminium frame Top hung outward Double glazing

5.2 Overview of methodological design of the study

The monitoring approach included diffusive and automatic monitoring methods (Table 7). Chemical analysis of the diffusive samplers was undertaken in accredited laboratories in the UK. Analysis of microbiological parameters and radon quantification were carried out centrally for all SINPHONIE partners in specialised laboratories allowing direct comparison between countries. Indoor dust was collected using natural deposition for endotoxin measurements (Table 8) and suction-based methods for fungal groups, bacterial species and allergens in each classroom. Analysis was performed with molecular, cultivation-independent methods.

Self-reported health outcomes were collected through standardised questionnaires and non-invasive clinical tests. These self-reported asthma attacks and asthmatic symptoms were cross-validated with the classroom teachers.

Table 7: Summary of methodology used for monitoring of physical and chemical parameters

Monitored Parameters	Method	Duration of measurements	Monitoring intervals	Precision/ Detection limit	Equipment	Standards/ Publications
T (°C) RH (%) Weather station	electronic resistance sensor	5 working days	1 min	±0.5°C (range −30°C to 65°C) ±1.5%	Eltek Ltd custom-made platform	BS EN ISO 7726:2001
CO_2 (ppm)	Non-Dispersive Infrared Spectrometry (NDIR)	5 working days	1 min	3% (range 0 - 20,000 ppm) or ± 50 ppm		BS EN 16000-26
PM_1, $PM_{2.5}$, PM_{10} ($\mu g/m^3$)	Optical method	5 working days	1 min	precision 1$\mu g/m^3$	TSI DUSTTRAK DRX Model 8533	
NO_2 ($\mu g/m^3$)	TEA principle	2 weeks	.	LOD: 0.57 $\mu g/m^3$	DIF 100 RTU, Gradko International, Ltd	BS EN 13528-3:2003, BS EN ISO 16000-15:2008
O_3 ($\mu g/m^3$)	Palmes' type tubes: Nitrate method	2 weeks	.	LOD: 3.4 $\mu g/m^3$	DIF 300 RTU, Gradko International, Ltd	
Radon (Bq/m^3)	α-track	4 weeks	.	$S\pm$ 10 Bq/m^3	"Frederic Loliot-Curie" National Research Institute for Radiology and Radiohygiene, Hungary	BS ISO 11665-4: 2012
TVOCs (ppb)	Photo-Ionisation Detector (PID)	5 working days	1 min	±5% (range 1ppb-20000ppm)	Tiger Pho Check, Ionscience	BS ISO 16000-29: 2014
VOCs ($\mu g/m^3$): • *Benzene*, • *toluene*, • *limonene*, • *pinene*, • *T3CE*, • *T4CE*, • *naphthalene*	Diffusive Sampling analysed with GC-MS	5 working days	.	LOD: 0.10$\mu g/m^3$	*Radiello* samplers, analysis Health&Safety Labs	BS ISO 16017-2: 2012
Formaldehyde ($\mu g/m^3$)	Diffusive samplers impregnated with DNHP analysis with HPLC	5 working days	.	0.10$\mu g/m^3$	*Radiello* samplers, analysis Health&Safety Labs	BS ISO 16000-4:2011

LOD: Limit of detection

Table 8: Summary of methodology used for quantification of biological parameters

Monitored Parameters	Method	Analysis	Duration of Measurements	Location	Equipment
Endotoxin (EU/m_2)	Natural dust deposition	qPCR	4 weeks	Breathing zone	Electrostatic Dustfall Collector (EDC) (Zeeman, Utrecht, the Netherlands).
Fungal Groups (cells/mg): • *Penicillium* spp. *Aspergillus* spp./ *Paecilomyces variotii* group • *Aspergillus versicolor* • *Trichoderma viride* • *Alternaria alternata* • *Cladosporium herbarum*	Suction based method	qPCR	10 minutes	Dust from undisturbed surfaces above floor level	“Sock“ sampling (Allied Filter Fabrics, Hornsby, Australia)
Bacterial Species (cells/mg): • *Streptomyces* spp. • *Mycobacterium* spp.	Suction based method	qPCR	10 minutes	Dust from undisturbed surfaces above floor level	“Sock“ sampling (Allied Filter Fabrics, Hornsby, Australia)
Allergens (ng/sampler): • Cat allergen (Fel d1) • Dog Allergen (Can f1) • Horse Allergen (Equ c1) • House dust mites (Der p1 and Der f1)	Suction based method	ELISA sandwich monoclonal antibodies	4 minutes	Desks, chairs, upholstery furniture and floor	ALK filter cassette (P-B Miljo A/S, Copenhagen, Denmark)

qPCR: quantitative polymerase chain reaction

5.3 Main findings in schools located within the Great London Authority

This study found notable differences in the characteristics of indoor air pollution between seasons and classrooms depending on their microenvironment, building characteristics, operation and maintenance. The following Section presents findings of indoor environmental conditions in this context and establishes association with CO_2 levels, ventilation and infiltration rates. Detailed description of the multilevel models developed to investigate the associations can be found in a previous publication (Chatzidiakou et al. 2015c).

5.3.1 Associations between indoor NO_2 levels with infiltration rates

Source apportionment for NO_x in the GLA boundaries shows that major and minor roads account for approximately 70% of the total NO_x emissions, with diesel vehicles the primary sources of outdoor NO_2 in London. Concentrations during the heating season were two-fold higher compared with the non-heating season in both the urban and suburban schools (Figure 10). The strong seasonal variation of outdoor NO_2 levels also influenced indoor levels resulting in the degraded IAQ recorded in the heating season.

Outdoor NO_2 concentrations and the airtightness of the building envelope explained 84% of the NO_2 variation between classrooms, indicating the influence of strong outdoor pollution sources and the importance of the building envelope. Overall, I/O ratios in both seasons ranged from 0.3-0.5 in an airtight, contemporary school compared with 0.7-0.9 in Victorian schools that have original wooden window frames. As the I/O ratios of the integrated measurements were smaller than unity, that indicates that the presence of indoor sources was negligible (Chapter 2). While more research is necessary to understand the effect of building characteristics, these findings indicate that uncontrolled infiltration rates may increase indoor concentrations of this harmful pollutant. Suggestive evidence shows that more airtight buildings may offer greater protection to the occupants.

5.3.2 Associations between Particulate Matter with indoor CO_2 levels

Higher levels of all PM fractions were recorded during the heating season (Figure 11). The difference in indoor PM levels between urban and suburban schools was not statistically significant. Indoor PM_{10} concentrations during the occupied period were consistently higher than outdoors.

These results are in line with, and extend, findings of previous studies (Chapter 2) on PM levels in indoor air of school buildings and provide evidence that there is high exposure in the classroom to PM. Mean indoor PM_{10} and $PM_{2.5}$ levels recorded in all classrooms in both seasons were higher than 20 $\mu g/m^3$ and 10 $\mu g/m^3$ respectively, indicating that annual personal exposure to PM in the

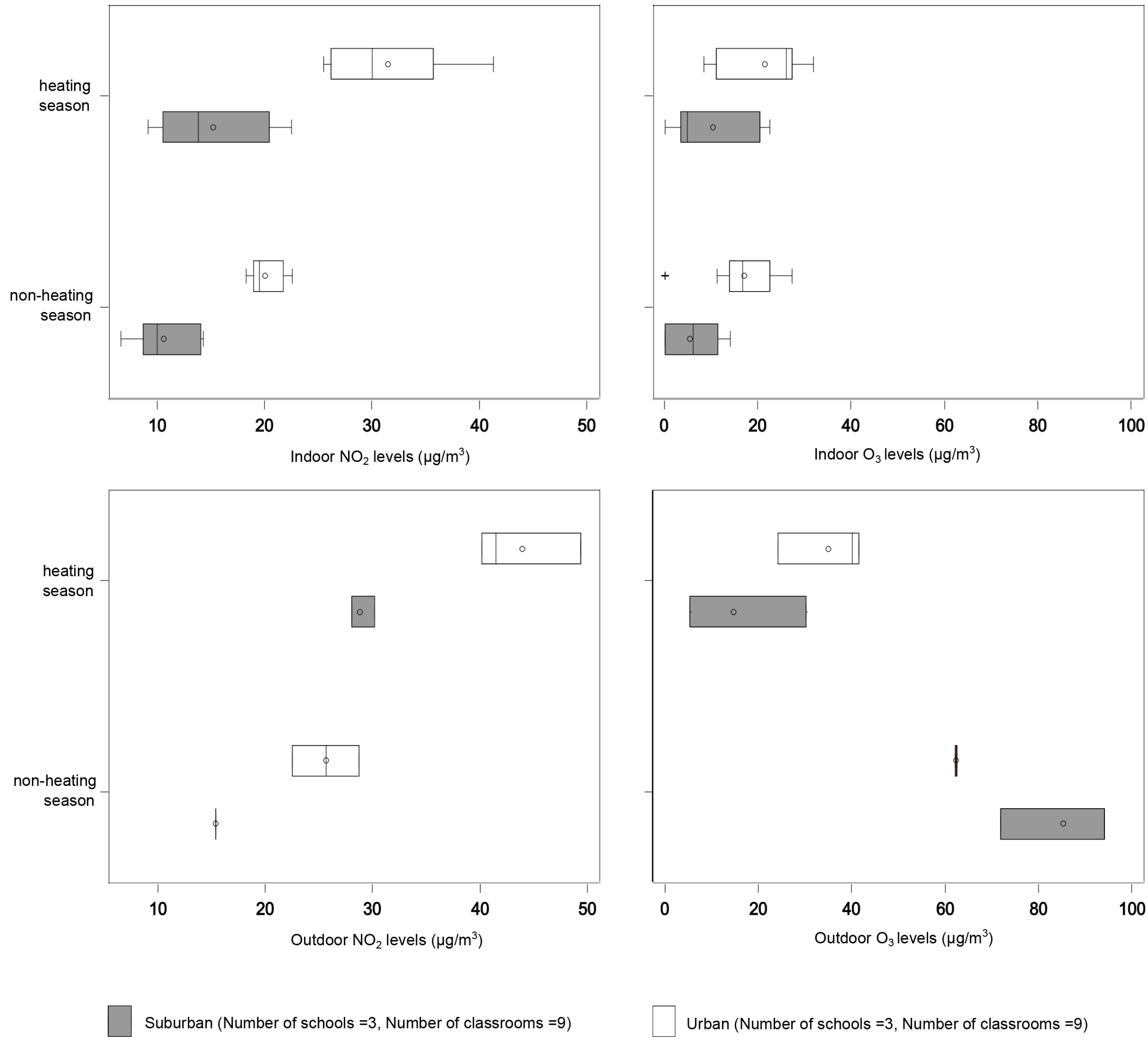

Figure 10: Range of indoor and outdoor levels of NO_2 and O_3 levels in the heating and non-heating season in urban and suburban schools

classroom may be higher than WHO 2010 guidelines (Section 1.2, Table 1). In most classrooms, PM concentrations were above daily guideline values (Section 6).

The results of the multilevel models suggest that there are two main mechanisms that increase indoor PM concentrations in the classroom. On the one hand, indoor PM concentrations, and especially the larger fraction, are strongly affected by unsuitable finishing in the classroom, such as wall-to-wall carpeting, acting as a dust reservoir, which was then re-suspended during occupants' activities. On the other hand, indoor CO_2 concentrations were a significant predictor of indoor PM levels and especially the smaller fraction, after controlling for occupancy indicating that insufficient ventilation rates may result in the build-up of indoor PM levels. Orientation of the building facade to the prevailing wind direction was a significant predictor of indoor PM levels, and especially the smaller fraction.

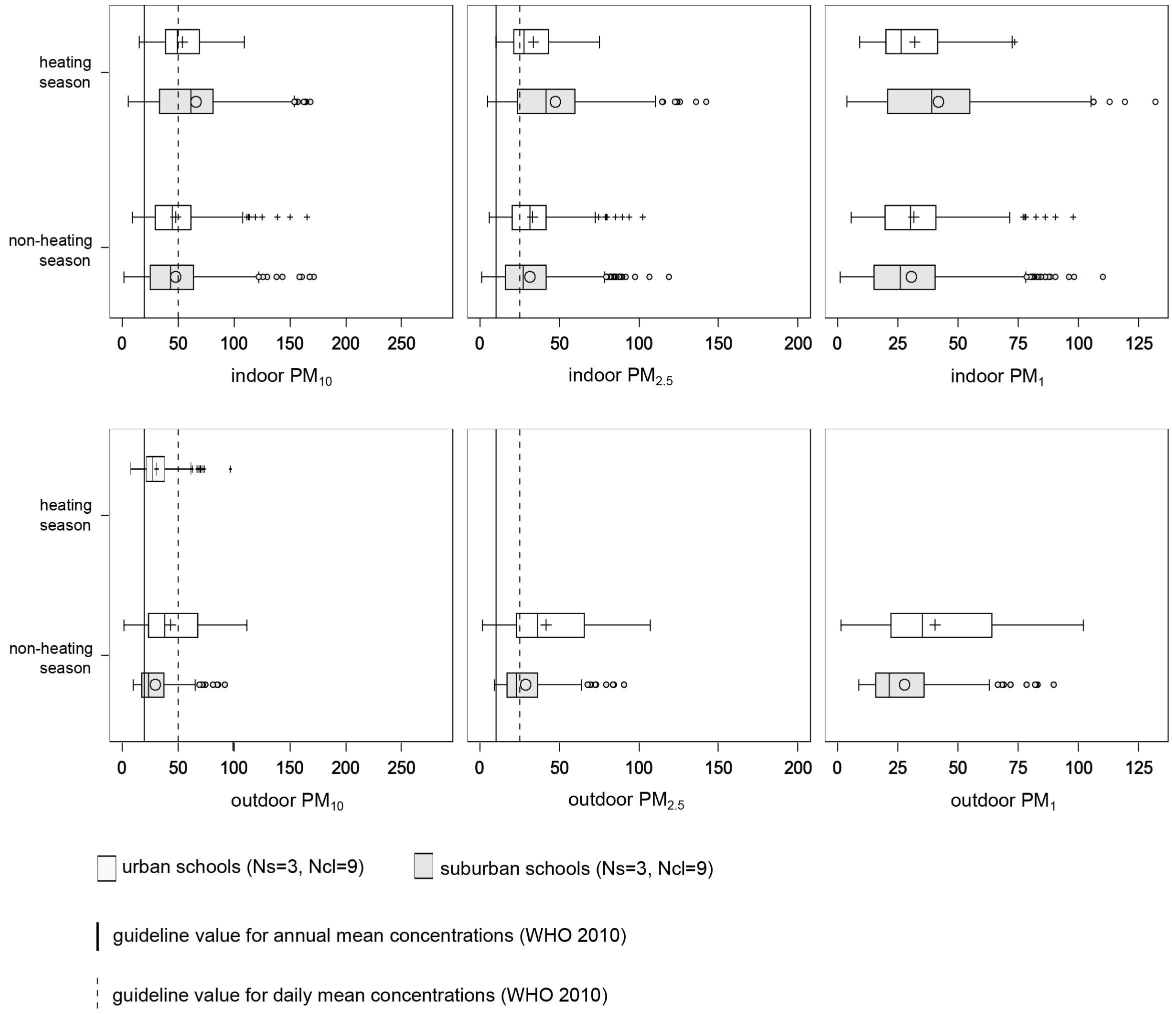

Figure 11: Range of indoor and outdoor concentrations of PM_{10}, $PM_{2.5}$ and PM_1 in urban and suburban schools in the heating and non-heating season

Classrooms parallel to the wind direction had smaller potential of enhancing natural ventilation strategies, and, therefore, the highest concentrations. Together with the elimination of indoor sources in the classrooms, the predictive models estimated that average indoor CO_2 levels during a teaching day should be limited to below 1,000 ppm for the coarse fraction (PM_{10}), and 1,200 ppm for the fine fraction ($PM_{2.5}$) to ensure annual mean exposure remains below WHO 2010 guidelines.

5.3.3 Associations between indoor VOCs with ventilation rates

Higher ventilation rates were negatively associated with concentrations of indoor VOCs with continuous sources. Elevated *naphthalene* levels, a known carcinogen, were associated with the use of pesticides in the school, while higher *formaldehyde* levels were found when new furniture were introduced in the classroom. Among the investigated factors, two operational and maintenance characteristics of classrooms had the biggest effect on elevating indoor TVOCs concentrations, namely (a) the introduction of non-low emitting cleaning products; and, (b) occupancy density. For example, the use of bleach in the school elevated indoor levels of *pinene* and *limonene* by 12 $\mu g/m^3$ and 22 $\mu g/m^3$ respectively compared with the schools using low-emitting cleaning products. Larger areas of carpet and textiles were also positively associated with higher TVOC levels, possibly due to off-gassing of such materials, or cleaning products used for their maintenance.

5.3.4 Risk of overheating and indoor CO_2 levels

Most classrooms managed to comply with current guidelines regarding average and maximum CO_2 levels; however, only a few classrooms managed to provide 8 L/s-p of fresh air under simple control of the occupants (Section 1.3). The main factors hindering successful application of natural ventilation were poor management and operation of school buildings, insufficient understanding of the windows and ventilation systems' operation, and severely restricted openable areas.

Thermal conditions were within acceptable comfort range for most of the occupied period and within the specifications of relevant regulations (Section 1.4). Minimum temperatures at the beginning of the teaching day during the heating season fell below health and comfort requirements, indicating a potential need for preheating of classrooms when lower outdoor temperatures occur. Overall, the increased CO_2 levels in the classroom indicate that high internal gains and reduced ventilation patterns may result in overheating.

5.3.5 Associations between microbial counts with ventilation and infiltration rates

The classrooms were a relevant site of exposure to cat and dog allergens.

Compared with the classroom sample, fungal species (*Penicillium* spp./ *Aspergillus* spp.) were found on average six-fold higher in three classrooms that had wall-to-wall carpets combined with underfloor heating (Figure 12). The findings strongly suggest that the combination provided favourable conditions for microbial proliferation. Higher ventilation rates in naturally ventilated classrooms may dilute microbial counts (further details please see (Chatzidiakou et al. 2015c).

5.4 Asthma attacks and asthmatic symptoms in the school environment

In total, 376 students (Response Rate: 87%) participated in the baseline (heating season) and follow-up (non-heating season) study. Of these, 50.7% were girls, and the average age was 10 years (range: 9 to 11). In total, 131 students attended two suburban schools, and 245 attended three urban Victorian Schools.

The prevalence of asthma was significantly different between the urban and suburban schools ($p<0.001$). More specifically, prevalence of asthma attacks and asthmatic symptoms in the urban schools ranged

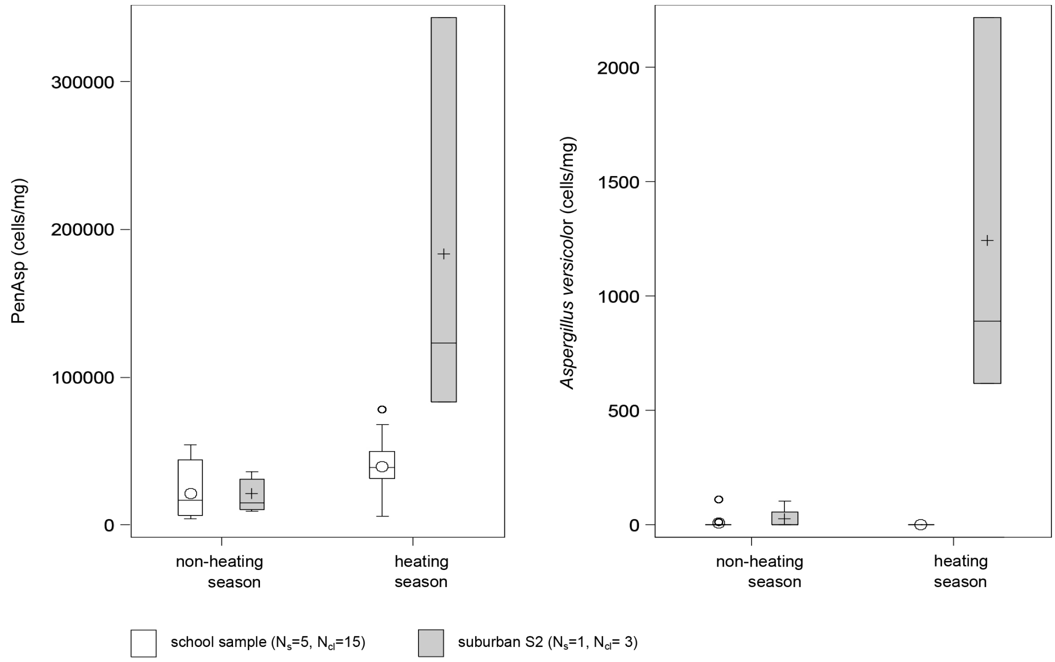

Figure 12: Counts of indoor *Penicillium* spp./ *Aspergillus* spp. and *Aspergillus versicolor* determined in settled dust of schools applying different heating strategies

from 7.9 to 12.5% (average: 10.2%), while in the suburban schools it was from 1.5 to 1.6% (average: 1.5%). Highest asthma prevalence was reported in the school, which is situated in immediate proximity to a street with heavy traffic (Section 6.3).

The only significant pollutant related to asthma attacks and asthmatic symptoms in the school environment was indoor NO_2 levels. These findings are consistent with recent evidence (Section4.1 Figure 6) that estimated a meta-OR of 1.05 (95%CI: 1.00-1.11), which was within the range reported in this study OR: 1.11 (95%CI: 1.00-1.19). A detailed analysis of the associations between classroom exposure with health symptoms and perceived IAQ can be found in a previous publication (Chatzidiakou et al. 2015d).

Although this relationship is in line with previous evidence in a meta-analytical study (Gasana et al. 2012), the association might not be causal, since there may be other confounding factors which would explain the observed association. For example, it might be possible that NO_2 is only a proxy for other traffic-related pollutants which may have significant health implications. Additionally, it is likely that students attending urban schools live in proximity to the school building, and are therefore exposed to higher pollution levels at home too. Exposure to high levels of traffic-related pollutants is quite possibly a specific element of a broader picture of inequalities in health, as there were significant differences between indications of deprivation in the schools, and disadvantaged socio-economic groups tend to have poorer health outcomes (WHO, 2003).

6 Case studies

6.1 Case study nursery school S1 and primary school S2

Location: Suburban contemporary school away from high traffic streets (Table 6)

Figure 13: Plan of nursery S1 and primary S2 and surrounding microenvironment. Selected classrooms and outdoor monitoring site are indicated. Predominant wind directions are presented in two wind roses in the heating and non-heating season

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Table 9: Descriptive summary of PM concentrations ($\mu g/m^3$) during the heating and non-heating season (occupied period, optical laser method)

	Non-heating season										Heating season				
	Indoor concentrations			Outdoor concentrations			FS	I/O ratio [-]			Indoor concentrations			FS	I/O ratio [-]
room	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_1	$PM_{2.5}$	PM_{10}	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_{10}
S1_r1	26 (20)	28 (26)	61 (55)	20 (18)	20 (18)	21 (19)		1.4	1.5	3.1	36 (29)	37 (30)	55 (59)		
S1_r2	27 (13)	28 (14)	31 (17)					1.4	1.4	1.5					
S1_r3	16 (11)	17 (12)	35 (27)					0.9	0.9	1.5	41 (22)	54 (36)	60 (27)		

Table 10: Indoor and outdoor concentrations of VOCs ($\mu g/m^3$) measured with diffusing sampling during the heating season in S1

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S1_r1	18.64		1.58		4.01		0.18		0.27		10.28		32.92		0.49	
S1_r2	17.06	3.33	1.80	0.29	5.89	1.55	0.19	0.01	0.33	0.01	12.99	0.01	38.48	0.07	0.69	0.06
S1_r3	41.62		1.52		5.60		0.16		0.25		18.34		15.93		0.59	

Table 11: Indoor and outdoor concentrations of VOCs ($\mu g/m^3$) measured with diffusive sampling during the non-heating season in S1

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S1_r1	18		0.65		0.95		0.11		0.28		1.24		29.06		0.37	
S1_r2	16	2	0.10	0.06	0.11	0.04	0.00	0.00	0.07	0.00	0.45	0.00	15.29	0.17	0.21	0.11
S1_r3	32		0.32		1.34		0.27		0.14		2.09		43.4		0.64	

Table 12: Descriptive summary of TVOCs concentrations (ppb) during the heating and non-heating season in S1 (occupied period, PID method)

	Heating season				Non-heating season			
Classroom	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**
S1_r1	ND	ND	ND		220	111-531	8-1948	
S1_r2	290	263-383	177-2363	ND	586	300-1504	3-3930	31 (11-35)
S1_r3	218	178-248	105-806		317	309-331	281-442	

Table 13: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the heating season in S1 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S1_r1	19.1	15.6	21.6	10.7	60	55	66	91	739 (241)	604-750	1677	
S1_r2	19.8	16.4	22.7	(9.4-15.0)	59	53	64	(69-95)	737 (280)	541-803	1754	435 (21)
S1_r3	20.2	16.3	22.0		57	51	66		775 (307)	522-938	1935	

Table 14: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the non-heating season in S1 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S1_r1	21.2	16.5	23.8	9.5	46	29	53	80	1218 (390)	881-1515	2006	
S1_r2	22.2	18.6	24.2	(6.4-15.4)	44	21	47	(32-90)	1070 (294)	867-1252	2011	404 (19)
S1_r3	19.8	15.9	22.2		48	25	55		964 (390)	648-1254	2133	

Table 15: Indoor and outdoor NO_2 and O_3 concentrations during the heating season in S1 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ FS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S1_r1	10.5			0.4	LOD		.
S1_r2	12.3	28.0	.	0.4	3.4	5.4	0.6
S1_r3	13.8			0.5	3.4		0.6

Table 16: NO_2 and O_3 concentrations during the non-heating season in S1 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ CS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S1_r1	8.8				<LOD		.
S1_r2	8.8	.	.		6.0	94.1	0.1
S1_r3	9.9				<LOD		.

Table 17: Counts of fungal and bacterial groups sampled in settled dust of S1 during the heating season and analysed with molecular methods (cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S1_r1	31395	347	277	0	0	203774	36665
S1_r2	40974	602	296	0	6	580782	111288
S1_r3	49902	246	14	0	1	45604	16026

Table 18: Counts of fungal and bacterial groups sampled in settled dust of S1 during the non-heating season and analysed with molecular methods collected(cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S1_r1	54453	133	26	<LOD	<LOD	367398	42508
S1_r2	44179	421	132	<LOD	<LOD	288864	112631
S1_r3	16425	16	3	11	<LOD	13619	1161

Table 19: Counts of cat and dog allergens and endotoxin levels in S1

code	**Cat allergen**	**Dog allergen**	**Endotoxin**
	Fel d 1 (ng/g)	Can f 1 (ng/g)	(EU/m^2)
S1_r1	64	<LOD	9637
S1_r2	<LOD	<LOD	8234
S1_r3	**1285**	132	3938

6.2 Case study primary school S2

Table 20: Descriptive summary of PM concentrations during the heating and non-heating season (occupied period, optical laser method)

Non-heating season											Heating season				
	Indoor concentrations			Outdoor concentrations			FS	I/O ratio [-]			Indoor concentrations			FS	I/O ratio [-]
room	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_1	$PM_{2.5}$	PM_{10}	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_{10}
S2_r1	20 (11)	21 (11)	36 (21)	20 (7)	21 (7)	21 (7)		1.2	1.2	2.0	42 (18)	43 (18)	58 (21)		
S2_r2	27 (9)	28 (9)	43 (18)					1.6	1.5	2.3					
S2_r3	21 (9)	22 (9)	44 (20)					1.2	1.1	2.1	41 (18)	42 (18)	60 (21)		

Table 21: Indoor and outdoor concentrations of VOCs ($\mu g/m^3$) measured with diffusive sampling during the heating season in S2

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S2_r1	30.14		1.31		3.55		0.19		0.14		55.55		25.56		0.53	
S2_r2	38.38	4.01	1.3	0.43	4.31	2	0.22	0.02	0.14	0.01	59.1	0.03	50.83	0.1	0.55	0.07
S2_r3	29.57		1.41		4.18		0.31		0.17		70.83		28.26		0.61	

Table 22: Indoor and outdoor concentrations of VOCs ($\mu g/m^3$) measured with diffusive sampling during the non-heating season in S2

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S2_r1	29		0.36		1.22		0.11		0.21		6.72		5.47		0.64	
S2_r2	32	2	0.32	0.06	1.11	0.04	0.22	0.00	0.14	0.00	5.7	0.00	9.48	0.17	0.59	0.11
S2_r3	28		0.39		2.06		0.59		0.14		7.45		5.64		0.70	

Table 23: Descriptive summary of TVOCs concentrations (ppb) during the heating and non-heating season in S2 (occupied period, PID method)

	Heating season				Non-heating season			
Classroom	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**
S2_r1	314	284-353	1-857		479	435-713	401-1258	
S2_r3	181	59-259	1-361	ND	372	328-456	288-577	89 (84-92)

Table 24: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the heating season in S2 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S2_r1	22.1	14.5	24.5	12.4	50	41	63	82	882 (295)	632-1132	1789	
S2_r2	21.8	15.0	23.7	(6.5-17.9)	53	44	63	(69.2-90)	1101 (247)	895-1232	1667	434 (17))
S2_r3	20.5	15.1	22.8		55	49	61		1037 (307)	797-1291	1581	

Table 25: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the non-heating season in S2 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S2_r1	22.9	20.0	25.1	10.3	51	37	58	81	1656 (705)	1177-2010	3742	
S2_r2	23	16.5	24.2	(6.9-14.8)	52	35	59	(45-90)	1614(691)	1120-1982	3395	415 (10)
S2_r3	23.4	18.1	26.4		49	33	64		1426 (799)	743-2037	3254	

Table 26: Indoor and outdoor NO_2 and O_3 concentrations during the heating season in S2 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ FS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S2_r1	13.9			0.5	<LOD		.
S2_r2	9.6	28.0	.	0.3	4.8	5.4	0.9
S2_r3	9.1			0.3	4.8		0.9

Table 27: NO_2 and O_3 concentrations during the non-heating season in S2 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ CS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S2_r1	8.7				< LOD		.
S2_r2	7.5	.	.		<LOD	94.1	.
S2_r3	6.6				<LOD		.

Table 28: Counts of fungal and bacterial groups sampled in settled dust of S2 during the heating season and analysed with molecular methods (cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S2_r1	343520	347	8	2217	0	48763	12990
S2_r2	83510	107	4	617	1	67351	19765
S2_r3	123245	380	5	891	2	92074	23780

Table 29: Counts of fungal and bacterial groups sampled in settled dust of S2 during the non-heating season and analysed with molecular methods collected(cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S2_r1	35975	48	2	56	0	17620	1529
S2_r2	10593	38	5	103	0	11631	1256
S2_r3	29476	36	2	28	0	18332	3052

Table 30: Counts of cat and dog allergens and endotoxin levels in S2

code	**Cat allergen**	**Dog allergen**	**Endotoxin**
	Fel d 1 (ng/g)	Can f 1 (ng/g)	(EU/m^2)
S2_r1	368	681	
S2_r2	639	465	3785
S2_r3	461	147	13842

6.3 Case study primary school S3

Location: Urban Victorian school next to a high traffic street (Table 6)

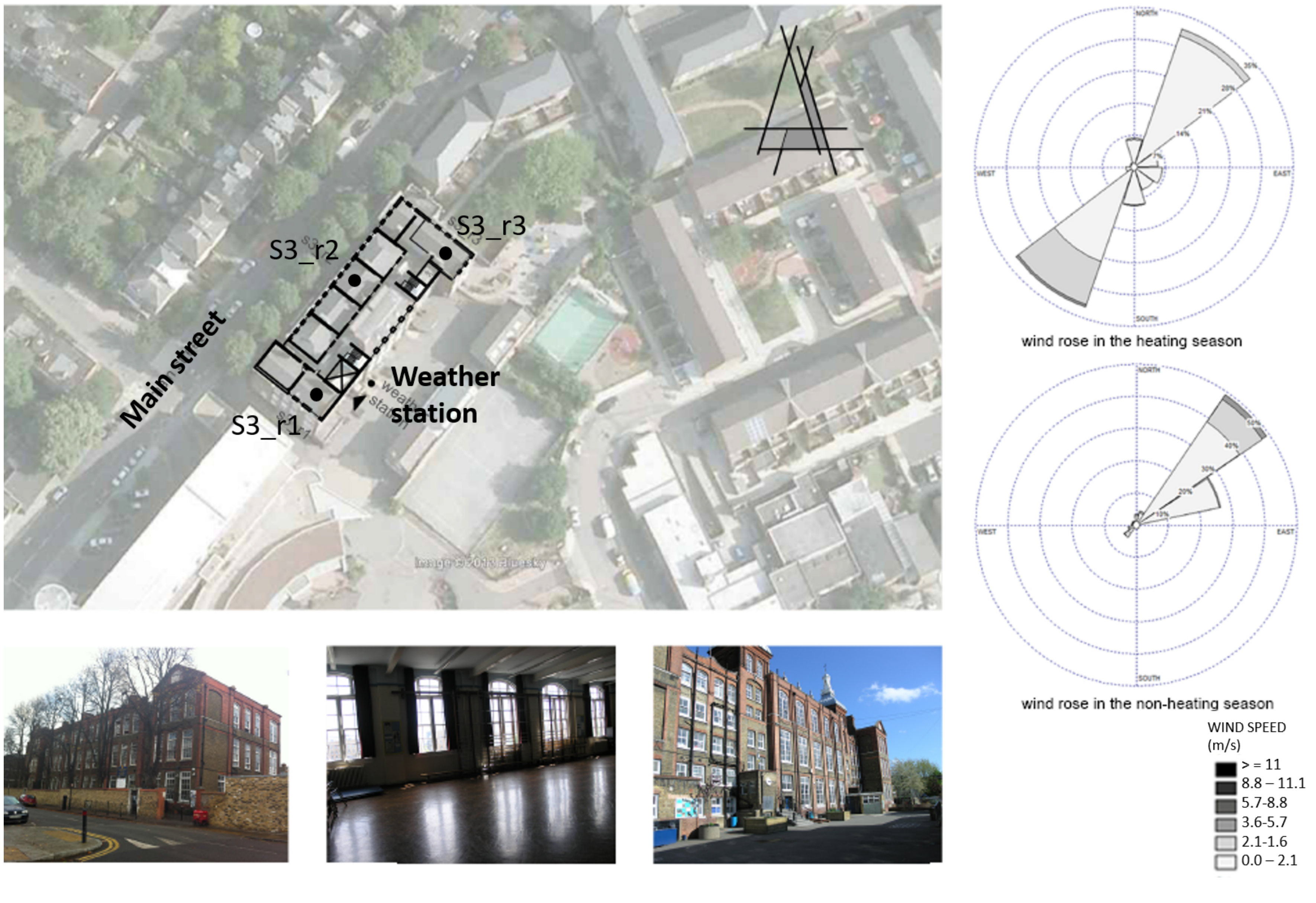

Figure 14: Plan of primary school S3 and surrounding microenvironment. Selected classrooms and outdoor monitoring site are indicated. Predominant wind directions are presented in two wind roses in the heating and non-heating season

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Table 31: Descriptive summary of PM concentrations during the heating and non-heating season (occupied period, optical laser method)

	Non-heating season										Heating season				
	Indoor concentrations			Outdoor concentrations			FS	I/O ratio			Indoor concentrations			FS	I/O ratio
room	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_1	$PM_{2.5}$	PM_{10}	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_{10}
S3_r1	25 (13)	26 (14)	37 (22)	52 (24)	54 (25)	55 (26)	31 (12)	0.5	0.5	0.7	39 (18)	40 (19)	61 (23)	42 (10)	1.5
S3_r3	21 (8)	21 (8)	30 (11)					0.4	0.4	0.6	39 (18)	40 (18)	56 (23)		1.3

Table 32: Indoor and outdoor concentrations of VOCs (μg/m^3) measured with diffusive sampling during the heating season in S3

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S3_r1	13.82		1.58		4.35		0.03		0.94		6.15		7.49		0.91	
S3_r2	7.81	3.29	0.46	0.48	1.38	2.96	0.00	0.00	0.42	0.11	1.65	0.02	2.28	0.10	0.08	0.08
S3_r3	16.81		0.99		2.66		0.02		0.71		4.92		5.50		0.55	

Table 33: Indoor and outdoor concentrations of VOCs (μg/m^3) measured with diffusive sampling during the non-heating season in S3

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S3_r1	3	1	0.23	0.19	0.38	0.31	0.11	0.22	0.21	0.21	1.07	0.23	1.07	0.23	1.77	0.75
S3_r3	4		0.26		0.42		0.11		0.28		0.51		0.51		1.12	

Table 34: Descriptive summary of TVOCs concentrations (ppb) during the heating and non-heating season in S3 (occupied period, PID method)

	Heating season				Non-heating season			
Classroom	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**
S3_r1	268	253-288	226-1181		332	321-346	50-412	
S3_r2	223	205-259	166-2418	20 (10-25)				52 (43-56)
S3_r3					236	221-250	12-281	

Table 35: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the heating season in S3 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S3_r1	22.2	20.4	23.7	11.6	52	37	61	79	1179 (292)	970-1414	1730	
S3_r2	20.5	15.8	22.6	(5.3-13.9)	49	39	60	(51-96)	857 (377)	597-964	2061	454 (42)
S3_r3	23.9	18.8	26.1		47	36	58		976 (218)	842-1079	1691	

Table 36: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the non-heating season in S3 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S3_r1	21.7	18.0	23.4	10.6	46	33	59	79	936 (319)	675-1138	2389	
S3_r2	21.9	19.9	28.6	(7.4-17.8)	43	25	54	(38-92)	711 (213)	556-818	1449	425 (16)
S3_r3	21.8	18.9	24.0		46	38	56		890 (215)	743-1005	1607	

Table 37: Indoor and outdoor NO_2 and O_3 concentrations during the heating season in S3 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ FS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S3_r1	35.6			0.7	10.9		0.5
S3_r2	37.0	49.4	58.0	0.8	10.1	24.2	0.4
S3_r3	41.2			0.8	8.4		0.3

Table 38: NO_2 and O_3 concentrations during the non-heating season in S3 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ CS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S3_r1	21.7			0.8	22.4		0.4
S3_r2	21.8	28.8	51.0	0.8	18.9	62.2	0.3
S3_r3	.			.	13.8		0.2

Table 39: Counts of fungal and bacterial groups sampled in settled dust of S3 during the heating season and analysed with molecular methods (cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S3_r1	67902	240	141	0	7	53325	47455
S3_r2	35138	80	23	0	1	24799	22025
S3_r3	16522	112	19	0	1	44374	16960

Table 40: Counts of fungal and bacterial groups sampled in settled dust of S3 during the non-heating season and analysed with molecular methods collected(cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S3_r1	6518	20	2	<LOD	<LOD	1619	430
S3_r2	11859	32	4	<LOD	<LOD	8058	1543
S3_r3	4345	23	9	<LOD	1	3040	261

Table 41: Counts of cat and dog allergens and endotoxin levels in S3

code	**Cat allergen**	**Dog allergen**	**Endotoxin**
	Fel d 1 (ng/g)	Can f 1 (ng/g)	(EU/m^2)
S3_r1	181	0	6211
S3_r2	323	101	1580
S3_r3	145	108	2626

6.4 Case study primary school S4

Location: Urban Victorian school away from high traffic streets (Table 6)

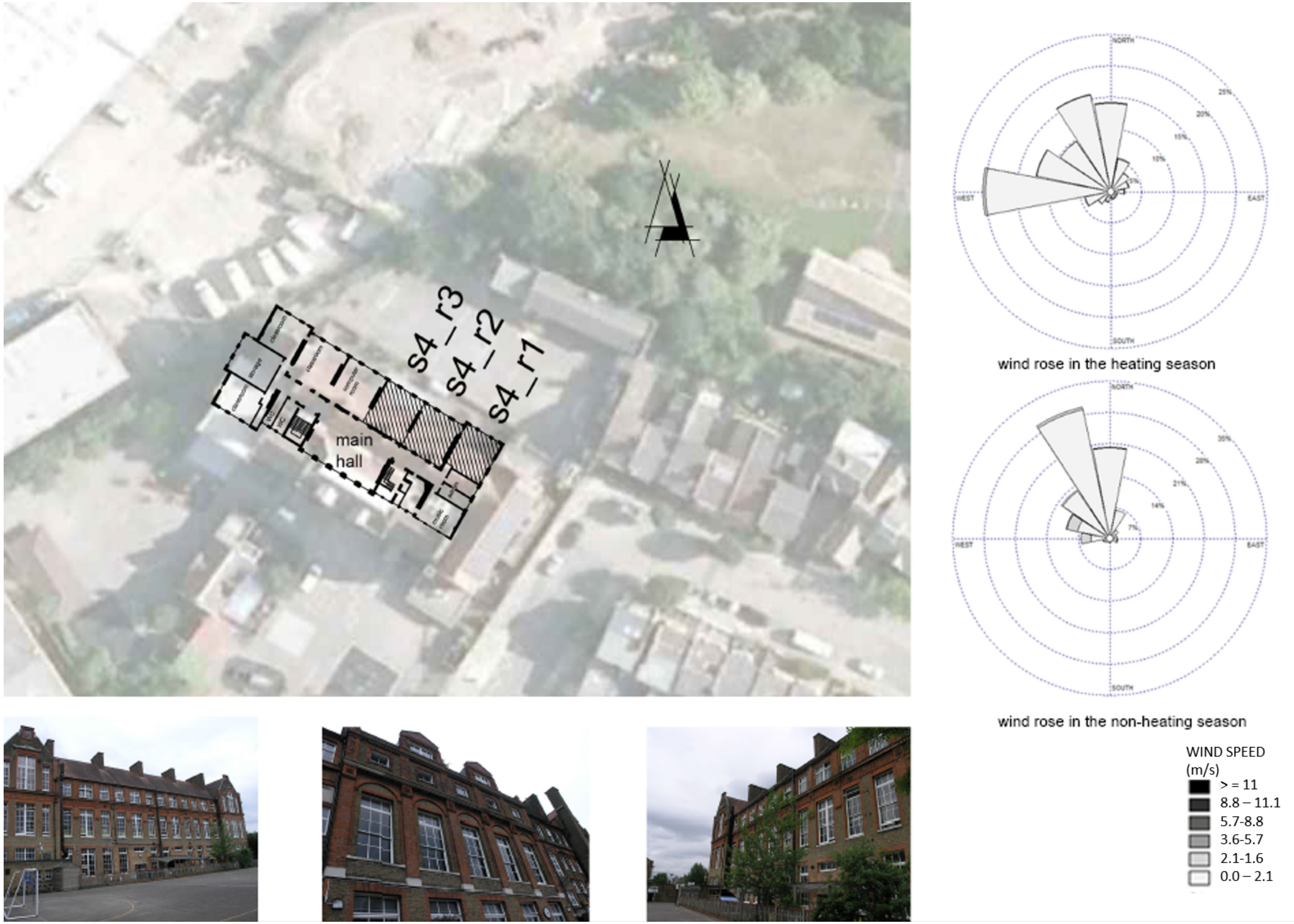

Figure 15: Plan of primary school S4 and surrounding microenvironment. Selected classrooms and outdoor monitoring site are indicated. Predominant wind directions are presented in two wind roses in the heating and non-heating season

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Table 42: Descriptive summary of PM concentrations ($\mu g/m^3$) during the heating and non-heating season (occupied period, optical laser method)

	Non-heating season										Heating season				
	Indoor concentrations			Outdoor concentrations			FS	I/O ratio			Indoor concentrations			FS	I/O ratio
room	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_1	$PM_{2.5}$	PM_{10}	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_{10}
S4_r1	32 (10)	33 (10)	44 (14)	31 (7)	31 (7)	34 (7)	36 (9)	1.3	1.3	1.5	32 (16)	34 (16)	54 (23)	41 (14)	1.3
S4_r2	47 (17)	49 (18)	71 (32)					2.1	2.1	2.9					
S4_r3	44 (15)	45 (15)	60 (22)					1.3	1.4	1.7	39 (14)	41 (14)	66 (22)		1.6

Table 43: Indoor and outdoor concentrations of VOCs ($\mu g/m^3$) measured with diffusive sampling during the heating season in S4

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S4_r1	12.35		0.85		3.97		0.00		0.31		8.77		50.39		0.45	
S4_r2	12.06	3.42	0.84	0.28	9.39	1.67	0.02	0.00	0.34	0.05	5.7	0.06	30.46	0.10	0.49	0.06
S4_r3	11.57		0.91		20.77		0.00		0.33		.		8.16		0.52	

Table 44: Indoor and outdoor concentrations of VOCs ($\mu g/m^3$) measured with diffusive sampling during the non-heating season in S4

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S4_r1	13		0.42		0.95		0.76		0.21		2.26		32.50		1.39	
S4_r2	17	3	0.55	0.39	1.07	0.76	0.70	0.22	0.21	0.34	2.14	0.68	27.65	1.35	2.52	0.91
S4_r3	13		0.36		0.88		1.19		0.21		0.96		2.26		1.18	

Table 45: Descriptive summary of TVOCs concentrations (ppb) during the heating and non-heating season in S4 (occupied period, PID method)

	Heating season				Non-heating season			
Classroom	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**
S4_r1	463	420-502	2-1047		283	61-314	6-348	
S4_r2	216	74-286	17-394	17 (10-24)	427	271-489	21-2254	46 (26-76)
S4_r3	284	26-377	2-542		47	18-100	5-633	

Table 46: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the heating season in S4 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S4_r1	21.8	18.8	26.4	10.7	47	40	52	73	1369 (489)	1010-1645	2902	
S4_r2	23.4	19.6	24.9	(4-13.8)	44	38	50	(57-88)	1353 (364)	1064-1627	2167	461 (59)
S4_r3	21.2	17.5	23.0		52	45	57		1619 (728)	1038-2134	3588	

Table 47: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the non-heating season in S4 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S4_r1	26.5	23.4	28.2	20.7	45	38	49	55	843 (256)	644-983	1645	
S4_r2	25.2	22.9	26.5	(15.8-26.5)	49	39	59	(35-70)	932 (343)	624-1097	2023	407 (24)
S4_r3	25	22.1	27.5		49	39	55		920 (423)	539-1248	1984	

Table 48: Indoor and outdoor NO_2 and O_3 concentrations during the heating season in S4 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ FS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S4_r1	25.5			0.6	6.6		0.2
S4_r2	27.2	40.2	61	0.7	<LOD	37.3	.
S4_r3	30.0			0.8	7.5		0.2

Table 49: NO_2 and O_3 concentrations during the non-heating season in S4 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ CS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S4_r1	18.2			0.8	11.2		0.2
S4_r2	19	22.6	46.0	0.9	14.4	62.56	0.2
S4_r3	19.5			0.9	27.3		0.4

Table 50: Counts of fungal and bacterial groups sampled in settled dust of S4 during the heating season and analysed with molecular methods (cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S4_r1	31515	205	11	<LOD	1	41603	12464
S4_r2	52167	890	49	<LOD	<LOD	40826	8615
S4_r3	47005	451	5	<LOD	<LOD	38869	34789

Table 51: Counts of fungal and bacterial groups sampled in settled dust of S4 during the non-heating season and analysed with molecular methods collected(cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S4_r1	4228	19	1	<LOD	<LOD	2547	322
S4_r2	4804	38	26	<LOD	1	7904	1022
S4_r3	7341	53	1	<LOD	<LOD	23399	2352

Table 52: Counts of cat and dog allergens and endotoxin levels in S4

code	**Cat allergen**	**Dog allergen**	**Endotoxin**
	Fel d 1 (ng/g)	Can f 1 (ng/g)	(EU/m^2)
S4_r1	**1762**	<LOD	6803
S4_r2	77	<LOD	ND
S4_r3	161	147	7917

6.5 Case study primary school S5

Location: Urban Victorian school away from high traffic streets (Table 6)

Figure 16: Plan of primary school S5 and surrounding microenvironment. Selected classrooms and outdoor monitoring site are indicated. Predominant wind directions are presented in two wind roses in the heating and non-heating season

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Table 53: Descriptive summary of PM concentrations during the heating and non-heating season (occupied period, optical laser method)

	Non-heating season										Heating season				
	Indoor concentrations			Outdoor concentrations			FS	I/O ratio			Indoor concentrations			FS	I/O ratio
room	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_1	$PM_{2.5}$	PM_{10}	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_{10}
S5_r1	32 (12)	33 (12)	57 (24)	20 (5)	20 (50)	24 (5)	23 (7)	1.8	1.9	2.5				26 (4)	
S5_r2	23 (10)	24 (11)	43 (21)					1.3	1.4	1.8	20 (7)	21 (7)	42 (15)		1.6
S5_r3	20 (70	21 (7)	30 (12)					1.3	1.3	1.5	23 (6)	24 (6)	43 (13)		1.7

Table 54: Indoor and outdoor concentrations of VOCs ($\mu g/m^3$) measured with diffusive sampling during the heating season in S5

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S5_r1	18.83		0.86		3.36		0.01		0.89		11.74		41.63		0.44	
S5_r2	12.52	14.57	0.86	0.25	3.33	1.21	0.00	0.00	0.51	0.04	11.33	0.04	40.70	0.10	0.73	0.05
S5_r3	13.75		0.78		2.70		0.01		0.33		10.33		21.25		0.68	

Table 55: Indoor and outdoor concentrations of VOCs ($\mu g/m^3$) measured with diffusive sampling during the non-heating season in S5

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S5_r1	7		0.36		1.37		1.08		0.34		1.02		6.49		2.52	
S5_r2	6	2	0.36	0.39	1.11	0.84	0.81	0.49	0.28	0.48	0.73	0.11	5.08	1.75	3.05	2.41
S5_r3	4		0.36		1.03		0.54		0.41		0.45		2.09		1.07	

Table 56: Descriptive summary of TVOCs concentrations (ppb) during the heating and non-heating season in S5 (occupied period, PID method)

	Heating season				Non-heating season			
Classroom	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**
S5_r1	276	127-458	9-745		155	98-268	4-1468	
S5_r2	142	102-450	2-556	14 (4-18)	47	12-16	4-187	45 (36-51)
S5_r3	165	124-279	46-494		178	13-308	6-634	

Table 57: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the heating season in S5 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S5_r1	20.3	14.0	23.3	7.1	56	42	60	65	2187 (804)	1539-2893	4029	
S5_r2	19.5	13.0	21.7	(3.4-12.2)	56	43	63	(45-85)	2083 (687)	1573-2660	3415	402 (11)
S5_r3	20.4	14.9	23.6		53	47	62		2232 (641)	1860-2661	3879	

Table 58: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the non-heating season in S5 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S5_r1	22.3	18.4	25.8	17.6	57	42	68	59	1214 (458)	887-1508	2600	
S5_r2	21.7	16.1	24.5	(12.6-22.7)	56	41	70	(35-88)	1067 (354)	776-1375	1925	403 (12)
S5_r3	20.9	16.1	24.4		53	35	78		613 (562)	502-679	1084	

Table 59: Indoor and outdoor NO_2 and O_3 concentrations during the heating season in S5 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ FS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S5_r1	26.1			0.6	11.5		0.3
S5_r2	26.0	41.5	62.8	0.6	15.9	33.6	0.5
S5_r3	31.9			0.8	13		0.4

Table 60: NO_2 and O_3 concentrations during the non-heating season in S5 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ CS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S5_r1	18.9						.
S5_r2	17	ND	ND	ND	< LOD	ND	ND
S5_r3	22.7			ND	25.3		ND

Table 61: Counts of fungal and bacterial groups sampled in settled dust of S5 during the heating season and analysed with molecular methods (cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S5_r1	39109	1445	2	< LOD	< LOD	48706	7580
S5_r2	22728	1734	< LOD	< LOD	< LOD	13088	27531
S5_r3	10250	531	7	0	< LOD	15987	15305

Table 62: Counts of fungal and bacterial groups sampled in settled dust of S5 during the non-heating season and analysed with molecular methods collected(cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S5_r1	21918	99	10	< LOD	< LOD	16561	1563
S5_r2	50846	67	5	110	< LOD	12369	2890
S5_r3	22439	201	27	< LOD	1	14271	1992

Table 63: Counts of cat and dog allergens and endotoxin levels in S5

code	**Cat allergen**	**Dog allergen**	**Endotoxin**
	Fel d 1 (ng/g)	Can f 1 (ng/g)	(EU/m^2)
S5_r1	490	<LOD	ND
S5_r2	585	118	3081
S5_r3	542	<LOD	3714

6.6 Case study primary school S6

Location: Suburban contemporary school close to a major street 6)

Figure 17: Plan of primary school S6 and surrounding microenvironment. Selected classrooms and outdoor monitoring site are indicated. Predominant wind directions are presented in two wind roses in the heating and non-heating season

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Table 64: Descriptive summary of PM concentrations during the heating and non-heating season (occupied period, optical laser method)

	Non-heating season										Heating season				
	Indoor concentrations			Outdoor concentrations			FS	I/O ratio			Indoor concentrations			FS	I/O ratio
room	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_1	$PM_{2.5}$	PM_{10}	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_{10} (σ)	PM_{10}
S6_r1	23	17.6	26.7	18.4	59	54	65	68	1319 (920)	624-1876	4052		0.4 (1.0)	1.4 (3.5)	
S6_r2	22.7	19.3	26.5	(9.6-26.6)	58	51	64	(50-88)	1205 (727)	715-1496	3642	411 (20)		1.6 (4.9)	
S6_r3	24.6	18.3	28.9		52	48	55		874 (379)	629-915	2043			2.5 (7.7)	

Table 65: Indoor and outdoor concentrations of VOCs ($\mu g/m^3$) measured with diffusive sampling during the heating season in S6

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S6_r1	10.18	1.64	0.30	0.22	2.06		0.00		0.01		0.8		0.52		0.06	
S6_r2	7.77		0.26		1.98	1.1	0.00	0.00	0.01	0.01	0.67	0.03	0.53	0.05	0.06	0.04
S6_r3	8.19		0.29		1.80		0.00		0.02		0.61		0.42		0.06	

Table 66: Indoor and outdoor concentrations of VOCs ($\mu g/m^3$) measured with diffusive sampling during the non-heating season in S6

Code	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
S6_r1	10		0.39		1.03		0.43		0.41		0.68		0.68		0.91	
S6_r2	10	1	0.42	0.45	1.6	0.73	2.37	0.27	0.34	0.48	1.24	0.06	4.40	3.44	1.87	3.21
S6_r3	10		0.45		0.88		0.86		0.28		0.85		1.41		1.82	

Table 67: Descriptive summary of TVOCs concentrations (ppb) during the heating and non-heating season in S6 (occupied period, PID method)

	Heating season				Non-heating season			
Classroom	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**	**Median**	**Q1-Q3**	**Min- Max**	**Outdoor (Q1-Q3)**
S6_r1	340	322-368	22-1068		49	30-81	6-220	
S6_r2	341	312-373	47-416	10 (8-12)	380	16-467	1-606	
S6_r3	ND	ND	ND		247	6-274	1-234	

Table 68: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the heating season in S6 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S6_r1	21.8	15.5	24.2	10.3	52	43	59	80	1425 (477)	1085-1754	2589	
S6_r2	22.5	19.5	24.3	(6.4-11.9)	47	41	53	(69-89)	1354 (477)	927-1766	2506	440 (25)
S6_r3	21.2	15.3	23.1		51	40	59		1425 (423)	766-1419	2707	

Table 69: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the non-heating season in S6 (occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
S6_r1	23	17.6	26.7	18.4	59	54	65	68	1319 (920)	624-1876	4052	
S6_r2	22.7	19.3	26.5	(9.6-26.6)	58	51	64	(50-88)	1205 (727)	715-1496	3642	411 (20)
S6_r3	24.6	18.3	28.9		52	48	55		874 (379)	629-915	2043	

Table 70: Indoor and outdoor NO_2 and O_3 concentrations during the heating season in S6 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ FS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S6_r1	22.5			0.7	7		0.2
S6_r2	20.4	30.2	.	0.7	10.1	39	0.3
S6_r3	22.0			0.7	6.6		0.2

Table 71: NO_2 and O_3 concentrations during the non-heating season in S6 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	$NO_{2\ CS}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	[-]	$\mu g/m^3$	$\mu g/m^3$	[-]
S6_r1	14.0			0.9	11.4		0.2
S6_r2	13.1	15.4	34.8	0.9	14.0	71.9	0.2
S6_r3	14.2			0.9	10.3		0.1

Table 72: Counts of fungal and bacterial groups sampled in settled dust of S6 during the heating season and analysed with molecular methods (cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S6_r1	5811	107	0	0	0	25548	4718
S6_r2	38706	474	28	0	0	27356	20510
S6_r3	78066	2222	20	0	0	125273	40783

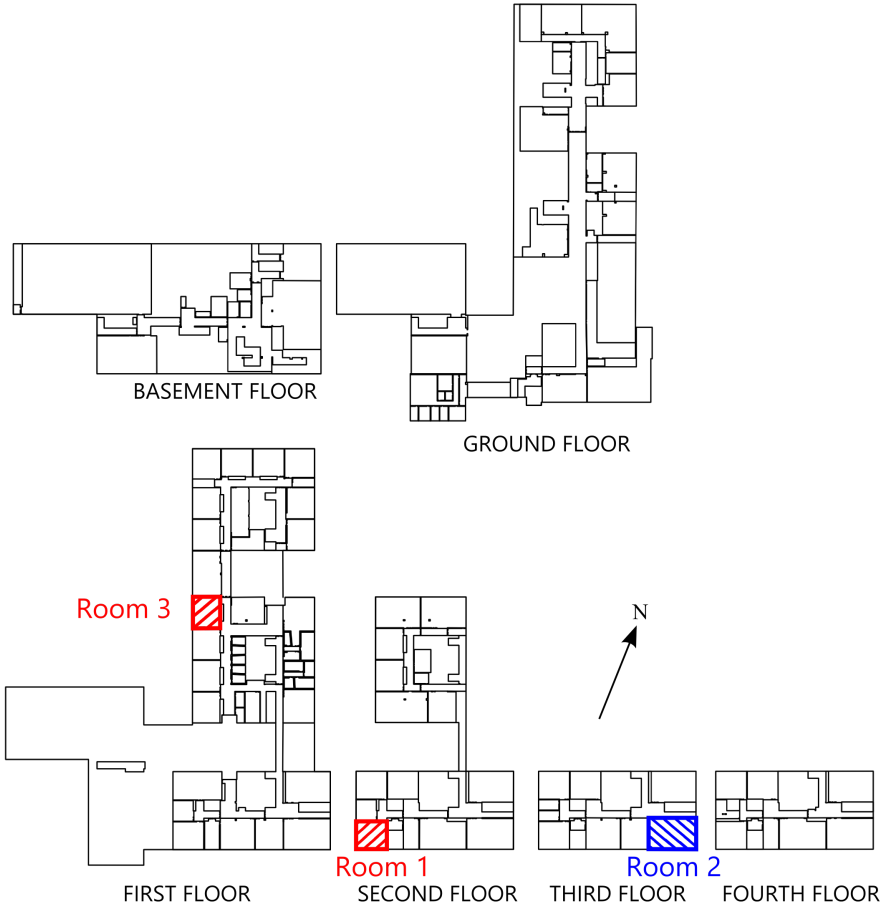
Table 73: Counts of fungal and bacterial groups sampled in settled dust of S6 during the non-heating season and analysed with molecular methods collected(cells/mg)

	Fungal groups					**Bacterial groups**	
room	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Aspergillus versicolor*	*Alternaria alternata*	*Mycobacterium* spp.	*Streptomyces* spp.
S6_r1	14614	144	<LOD	<LOD	<LOD	15810	889
S6_r2	9118	141	3	<LOD	<LOD	14974	1626
S6_r3	30676	143	10	<LOD	<LOD	21107	1489

Table 74: Counts of cat and dog allergens and endotoxin levels in S6

code	**Cat allergen**	**Dog allergen**	**Endotoxin**
	Fel d 1 (ng/g)	Can f 1 (ng/g)	(EU/m^2)
S6_r1	212	299	4886
S6_r2	0	0	2768
S6_r3	58	0	12395

6.7 Case study secondary school S7



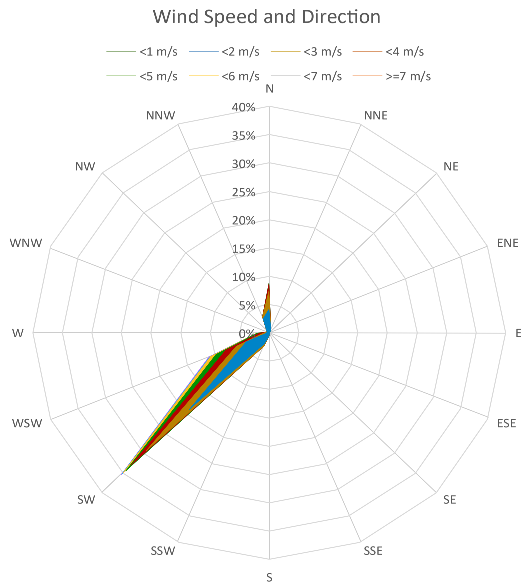


Figure 18: Plan of secondary school S7. Selected classrooms and predominant wind directions in the non-heating season are presented (Images: Tim Crocker/ Feilden Clegg Bradley Studios)

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Table 75: Descriptive summary of PM concentrations during the heating and non-heating season (occupied period, optical laser method)

	Indoor Concentrations (μg/m^3)			Outdoor Concentrations (μg/m^3)			I/O ratios		
code	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_1 (σ)	$PM_{2.5}$ (σ)	PM_{10} (σ)	PM_1	$PM_{2.5}$	PM_{10} (σ)
S7_r1	26 (3)	26 (3)	26 (6)	29 (5)	30 (5)	31 (5)	0.9	0.9	1
S7_r2	17 (44)	18 (44)	21 (45)				0.5	0.6	0.7
S7_r3	20 (3)	21 (3)	21 (5)				0.7	0.7	0.8

Table 76: Indoor and outdoor concentrations of VOCs (μg/m^3) measured with passive sampling during the non-heating season in S7

	HCHO		benzene		toluene		T3CE		T4CE		pinene		limonene		naphthalene	
code	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
s7_r1	5		0.31		0.73		0.17		0.22		0.3		2.1		2.77	
s7_r2	13	<LOD	0.24	0.28	0.65	0.57	0.17	<LOD	0.22	<LOD	0.6	0.12	2.22	0.24	2.2	1.86
s7_r3	4		0.24		0.69		<LOD		0.44		0.42		1.8		3.16	

Table 77: Descriptive summary of TVOCs concentrations (ppb) during the non-heating season in S7 (occupied period, PID method)

code	Median	Q1-Q3	Min-Max	Outdoor (Q1-Q3)
S7_r1	17	10-22	3-29	
S7_r2	69	44-104	0-866	148-286
S7_r3	75	63-95	36-284	

Table 78: Descriptive summary of indoor and outdoor temperature, RH, CO_2 levels during the non-heating season in S7(occupied period)

Room	T_{mean}	T_{min}	T_{max}	$T_{o\ mean}$	RH_{mean}	RH_{min}	RH_{max}	$RH_{o\ mean}$	$CO_{2\ mean}$ (σ)	$CO_{2\ int}$	$CO_{2\ max}$	$CO_{2\ o}$ (σ)
	°C	°C	°C	°C	%	%	%	%	ppm	ppm	ppm	ppm
s7_r1	23.9	18.6	26.4		40	32	57		1035 (212)	650	1497	
s7_r2	24	19.1	26.7	13.4	39	32	56	54	948 (156)	652	1404	566 (23)
s7_r3	23.2	18.5	25.2		38	30	55		891 (159)	648	1336	

Table 79: NO_2 and O_3 concentrations during the non-heating season in S7 (diffusive sampling)

room code	NO_2	$NO_{2\ outdoors}$	(I/O) NO_2	O_3	$O_{3\ outdoors}$	(I/O) O_3
	μg/m^3	μg/m^3	[-]	μg/m^3	μg/m^3	[-]
s7_r1	28.6		0.7	11.3		0.2
s7_r2	27.5	40.4	0.7	5.8	48.2	0.1
s7_r3	25.4		0.6	12.5		0.3

References

American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) (2013), 'ANSI/ASHRAE 55-2013: Thermal Environmental Conditions for Human Occupancy'.

American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) (2016), 'ASHRAE STANDARD 62.1-2016: Ventilation for Acceptable Indoor Air Quality'.

Bakó-Biró, Z., Clements-Croome, D., Kochhar, N., Awbi, H. & Williams, M. (2012), 'Ventilation rates in schools and pupils' performance', *Building and Environment* **48**, 215–223.

Bakó-Biró, Z., Kochhar, N., Awbi, H. B. & Williams, M. (2007), Ventilation Rates in Schools and Learning Performance, *in* 'Proceedings of Clima -Wellbeing indoors', FINVAC, Helsinki.

Bordass, B., Cohen, R., Standeven, M. & Leaman, A. (2001), 'Assessing building performance in use 2: technical performance of the Probe buildings', *Building Research & Information* **29**(2), 103–113.

British Standard Institution (2005), 'BS EN ISO 7730: 2005. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. London, BSI'.

British Standard Institution (2007*a*), 'BS EN 13779: 2007. Ventilation for non-residential buildings. Performance requirements for ventilation and room-conditioning systems. London, BSI'.

British Standard Institution (2007*b*), 'BS EN 15251: 2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. London, BSI'.

Burman, E., Mumovic, D. & Kimpian, J. (2014), 'Towards measurement and verification of energy performance under the framework of the European Directive for energy performance of buildings', *Energy* **77**, 153–163.

Chartered Institution of Building Services Engineers (CIBSE) (2013), ' TM52: The limits of thermal comfort : avoiding overheating in European buildings'.

Chartered Institution of Building Services Engineers (CIBSE) (2015), ' TM57: Integrated School Design'.

Chatzidiakou, L., Mumovic, D. & Dockrell, J. (2014b), 'The effects of thermal conditions and indoor air quality on health comfort and cognitive performance of students', *The Bartlett, UCL Faculty of the Built Environment UCL Institute for Environmental Design and Engineering London* .

Chatzidiakou, L., Mumovic, D. & Summerfield, A. (2015c), 'Is co_2 a good proxy for indoor air quality in classrooms? part 1: The interrelationships between thermal conditions, co2 levels, ventilation rates and selected indoor pollutants', *Building Services Engineering Research and Technology* **36**(2), 129–161.

Chatzidiakou, L., Mumovic, D. & Summerfield, A. (2015d), 'Is co_2 a good proxy for indoor air quality in classrooms? part 2: Health outcomes and perceived indoor air quality in relation to classroom exposure and building characteristics', *Building Services Engineering Research and Technology* **36**(2), 162–181.

Chatzidiakou, L., Mumovic, D. & Summerfield, A. J. (2012), 'What do we know about indoor air quality in school classrooms? a critical review of the literature', *Intelligent Buildings International* **4**(4), 228–259.

Chatzidiakou, L., Mumovic, D., Summerfield, A. J. & Altamirano, H. M. (2015a), 'Indoor air quality in london schools. part 1: Performance in use', *Intelligent Buildings International* **7**(2-3), 101–129.

Chatzidiakou, L., Mumovic, D., Summerfield, A. J., Hong, S. M. & Altamirano-Medina, H. (2014a), 'A victorian school and a low carbon designed school: comparison of indoor air quality, energy performance, and student health', *Indoor and Built Environment* **23**(3), 417–432.

Chatzidiakou, L., Mumovic, D., Summerfield, A. J., Tàubel, M. & Hyvärinen, A. (2015b), 'Indoor air quality in london schools. part 2: Long-term integrated assessment', *Intelligent Buildings International* **7**(2-3), 130–146.

Coley, D. A., Greeves, R. & Saxby, B. K. (2007), 'The effect of low ventilation rates on the cognitive function of a primary school class', *International Journal of Ventilation* **6**(2), 107–112.

Croxford, B. & Penn, A. (1998), 'Siting considerations for urban pollution monitors', *Atmospheric Environment* **32**(6), 1049–1057.

Csobod, E., Annesi-Maesano, I., Carrer, P., Kephalopoulos, S., Madureira, J., Rudnai, P., Fernandes, E. O., Barrero-Moreno, J., Beregszaszi, T., Hyvärinen, A. et al. (2014), 'Sinphonie schools indoor pollution and health observatory network in europe final report'.

Department for Education (DfE) (2016), 'Building Bulletin 101: Ventilation of School Buildings'.

Gasana, J., Dillikar, D., Mendy, A., Forno, E. & Ramos Vieira, E. (2012), 'Motor vehicle air pollution and asthma in children: a meta-analysis', *Environmental research* **117**, 36–45.

Haverinen-Shaughnessy, U., Moschandreas, D. J. & Shaughnessy, R. J. (2011), 'Association between substandard classroom ventilation rates and students' academic achievement', *Indoor air* **21**(2), 121–31.

Health and Safety Executive (HSE) (2013), 'Workplace Health, Safety and Welfare Regulations 1992: Approved Code of Practice and guidance'.

Higgins, J. P. & Green, S. (2011), *Cochrane handbook for systematic reviews of interventions*, Vol. 4, John Wiley & Sons.

HM Government (2010), 'Ventilation: Approved Document F'.
URL: *https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-f*

HM Government (2016*a*), 'Conservation of fuel and power - Approved Document L'.
URL: *https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l*

HM Government (2016*b*), 'Part C - Site preparation and resistance to contaminates and moisture'.
URL: *https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-c*

Hong, S.-M., Paterson, G., Burman, E., Steadman, P. & Mumovic, D. (2013), 'A comparative study of benchmarking approaches for non-domestic buildings: Part 1: Top-down approach', *International Journal of Sustainable Built Environment* **2**(2), 119–130.

Indoor Air Quality and the impact on Man. Report No. 11: Guidelines for Ventilation Requirements in Buildings (n.d.).

Isanska-Cwiek, A., Palmer, J. & Mumovic, D. (2008), 'School design guidance: Integrating ventilation, thermal comfort, and daylighting in support of building bulletin 101'.

Julious, S. A., Osman, L. M. & Jiwa, M. (2007), 'Increases in asthma hospital admissions associated with the end of the summer vacation for school-age children with asthma in two cities from England and Scotland', *Public health* **121**(6), 482–484.

Mead, M., Popoola, O., Stewart, G., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J., McLeod, M., Hodgson, T., Dicks, J., Lewis, A., Cohen, J., . Baron, R., Saffell, J. & Jones, R. (2013), 'The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks', *Atmospheric Environment* **70**, 186–203.

Milner, J. T., ApSimon, H. M. & Croxford, B. (2006), 'Spatial variation of co concentrations within an office building and outdoor influences', *Atmospheric Environment* **40**(33), 6338–6348.

Molhave, L. (2009), *Human responses to Organic Air pollutants in Organic Indoor Air Pollutants: Occurrence, Measurement, Evaluation*, second edn, WILEY-VCH Verlag GmbH& Co.KGaA, Weinheim.

Mumovic, D., Crowther, J. & Stevanovic, Z. (2006), 'Integrated air quality modelling for a designated air quality management area in glasgow', *Building and Environment* **41**(12), 1703–1712.

Mumovic, D., Palmer, J., Davies, M., Orme, M., Ridley, I., Oreszczyn, T., Judd, C., Critchlow, R., Medina, H., Pilmoor, G., Pearson, C. & Way, P. (2009), 'Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in England', *Building and Environment* **44**(7), 1466–1477.

Shaughnessy, R., Haverinen-Shaughnessy, U., Nevalainen, A. & Moschandreas, D. (2006), 'A preliminary study on the association between ventilation rates in classrooms and student performance', *Indoor air* **16**(6), 465–468.

Sze To, G. & Chao, C. (2010), 'Review and comparison between the wells–riley and dose-response approaches to risk assessment of infectious respiratory diseases', *Indoor Air* **20**(1), 2–16.

The International Study of Asthma and Allergies in Childhood (ISAAC) Steering Committee (1998), 'Worldwide variation in the prevalence of symptoms of asthma, allergic rhinoconjunctivitis, and atopic eczema: Isaac', *Lancet* **351**(9111), 1225–1232.

Vardoulakis, S., Gonzalez-Flesca, N., Fisher, B. E. & Pericleous, K. (2005), ‘Spatial variability of air pollution in the vicinity of a permanent monitoring station in central paris’, *Atmospheric Environment* **39**(15), 2725–2736.

Wargocki, P. & Wyon, D. P. (2013), ‘Providing better thermal and air quality conditions in school classrooms would be cost-effective’, *Building and Environment* **59**, 581–589.

Williams, J. J., Hong, S. M., Mumovic, D. & Taylor, I. (2015), ‘Using a unified school database to understand the effect of new school buildings on school performance in england’, *Intelligent Buildings International* **7**(2–3), 83–100.

World Health Organization (2008), ‘Global alliance against chronic respiratory diseases action plan 2008-2013’, *Geneva* .

World Health Organization (WHO) (2003), Social determinants of health: The solid facts, *in* R. Wilkinson & M. Marmont, eds, ‘Healthy cities: Health for all’, 2 edn, World Health Organisation, pp. 89–116.

World Health Organization (WHO) (2006), *Air quality guidelines: global update 2005. Particulate matter, ozone, nitrogen dioxide, and sulfur dioxide*, WHO Regional Office for Europe, Copenhagen.

World Health Organization (WHO) (2010), *WHO guidelines for indoor air quality: selected pollutants*, WHO Regional Office for Europe, Copenhagen.