VOLUME 1

Is CO_2 a good proxy for Indoor Air Quality in school classrooms?

by

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Declaration

I, Evangelia Chatzidiakou, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed: ______________________________

Date: ______________________________

Abstract

Background The increasing interest in Indoor Air Quality (IAQ) of educational buildings has been underpinned by the rising incidence of asthma and respiratory disease among children, who spend a substantial amount of their lives on the school premises. The susceptibility of children compared with adults has led to the formulation of guidelines regulating IAQ in school buildings. WHO guidelines provide the scientific basis for legally enforceable standards for non-industrial environments. Reflecting the relative difficulty and expense of obtaining measurements of specific pollutants, guidelines for the provision of adequate IAQ in UK schools have been typically framed around thermal conditions, carbon dioxide (CO_2) levels, and estimated ventilation rates as a primary indicator of IAQ.

Aim Drawing on detailed monitoring data from 15 primary and three nursery London classrooms, this thesis sets to evaluate if indoor CO_2 levels in classrooms are a good indicator in ensuring a healthy and satisfactory school environment. To fully answer this question this thesis aims

- to associate levels of specific indoor pollutants with CO_2 levels and ventilation rates after controlling for environmental and behavioural factors;
- to identify specific exposures in the classroom that may affect asthma prevalence, self-reported health symptoms and perceived IAQ.

Method The study was organised as a case-crossover study of the heating and non-heating season, and employed a multi-disciplinary methodology, including direct-reading instrumental sampling, passive sampling for long-term measurements, and determination of microbiological contaminants with molecular methods. The monitored data were matched with school and classroom characteristics, self-reported health symptoms and IAQ perception of 376 primary school students attending 15 classrooms with standardised questionnaires. The integrated database was analysed with Bayesian multilevel models that provide a concordance between theoretical approaches and statistical analysis, while taking into account the hierarchy of the data.

Results Indoor CO_2 levels and estimated ventilation rates were a reliable predictor for some outcomes, such as indoor temperature, Particulate Matter (PM) and Volatile Organic Compounds (VOCs) levels. Overall evidence from this study suggests that limiting CO_2 levels below 1000 ppm (which is lower than current guideline values of BB101 performance standard in England (DfE, 2014)) is necessary in order to achieve indoor PM levels in classrooms below WHO 2010 annual guideline values, after removing indoor furnishing acting as dust reservoirs. A strong relationship between indoor temperatures and Total VOCs (TVOCs) levels emerged,

and the predictive models estimated that after removing indoor TVOCs sources, keeping indoor temperatures below 26 °C, and preferably below 22 °C depending on season, may keep indoor TVOCs levels below 250ppb.

Based on the self-reported satisfaction with IAQ at baseline and follow-up period, it was found that keeping indoor temperatures below 26 °C and CO_2 levels below 1000ppm, may additionally reduce predicted percentage of dissatisfaction with IAQ below 30%. The air was perceived as less acceptable with increasing indoor temperature and CO_2 levels, stressing the importance for an integrated approach for the simultaneous provision of thermal comfort and IAQ.

However, indoor CO_2 levels were a poor predictor of traffic related pollutants, such as indoor NO_2 levels, which were significantly associated with the high asthma prevalence reported in this study (OR: 1.11, 95% CI: 1.04-1.19). Exposure to traffic-related pollution levels was additionally associated with increased IAQ dissatisfaction, and higher prevalence and incidence of Sick Building Syndrome SBS symptoms. SBS describes a constellation of nonspecific health symptoms including mucosal, dermal, respiratory and general, that have no clear aetiology and are attributable to exposure to a particular building environment.

Recommendations for future research The methodological framework used in this study could be potentially applied to large scale investigations enhancing our understanding of the factors affecting indoor pollution levels in educational settings. More research is necessary to validate the predictive model of satisfaction with IAQ in different climatic and geographical areas.

Implications for policy This study shows that complaints about poor air quality and health symptoms were related to deficiencies in the indoor school environment, and identified that management and operation of classrooms are key in creating healthy and comfortable school buildings. Greening programmes around school buildings, simple passive measures of the building envelope, altering ventilation strategies among seasons, and timely control of ventilation may improve perceived IAQ and alleviate SBS symptoms. Together with increasing average and background ventilation rates, elimination of indoor sources that impact IAQ is necessary.

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Contents

VOLUME II

Appendices

List of Figures

List of Tables

Glossary

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

-2 times Log Likelihood	The process of assessing the fit of multilevel models to their data is just like those employed in other statistical procedures, such as logistic regression models. A fully saturated model fits the data perfectly and has a -2LL equal to 0. -2LL is a measure of the deviance from a fully saturated model. The smaller the deviance, the better the model fits the data.
Burn-in length	An important research topic within Markov chain Monte Carlo (MCMC) methods is the estimation of convergence of a simulation. The simulation is divided in to two parts, pre- and post-convergence, where the pre-convergence part known as burn-in is discarded, and the post-convergence part is used for inference. In other words, "burn-in" is an informal term that describes the practise of throwing away some iterations at the beginning of an MCMC run. After the burn-in, the simulation runs normally using each iteration in the MCMC calculations. From the theoretical point of view, burn-in is one way of selecting a starting distribution, and burn-in may allow to start with the chain "in equilibrium".
Chain length	MCMC chain is just one random sample from the true underlying posterior distribution. The default length of an MCMC chain differs from one program to another, ranging from around 2,000 to 10,000 total steps combined across chains (e.g., 3 chains with 1,000 steps each is 3,000 total steps). When the MCMC chain gets very long, then in the limit it approximates the true posterior extremely well.

Contextual effects	Individuals in a group, such as students in a classroom, are usually interdependent. That is, what influences one group member may also influence other group members, either directly (i.e., through direct interactions with other group members) or indirectly (i.e., by creating a group environment that influences individual members). Therefore, there may be gains from examining the individual's outcomes within the framework of a group context.
Ecological fallacy	is a logical fallacy in the interpretation of statistical data where inferences about the nature of individuals are deduced from inference for the group to which those individuals belong.
Handling ties	In this thesis, because *interval censoring* was applied, the health data occur as *tied survival times.* In other words, "tied" survival times refers to more than one individual in the data set with the same recorded survival time. Several approaches have been proposed to handle situations in which there are ties in the time data. Interval censoring is a common method for handling ties in biostatistics and refers to observations performed on a continuous random variable which are then grouped into intervals.
Hazard ratio	Hazard ratios are commonly used in survival analysis to allow hypothesis testing. They are similar to relative risk ratios/reduction.
Incidence	is the number of instances of illness commencing, or of people becoming ill during a given period in a specified population (Last, 2001)
Intraclass Correlation Coefficient (ICC)	describes how strongly units in the same group resemble each other. While it is viewed as a type of correlation, unlike most other correlation measures, it operates on data structured as groups, rather than data structured as paired observations. The ICC is commonly used to quantify the degree to which individuals with a fixed degree of relatedness (e.g. students in a classroom) resemble each other in terms of a quantitative trait (e.g. health outcomes).

Link function	The link function provides the relationship between the linear predictor and the mean of the distribution function. There are many commonly used link functions, and their choice can be somewhat arbitrary. The logit in logistic regression is a special case of a link function in a generalized linear model: it is the canonical link function for the Bernoulli distribution.
MM questionnaire	The development of the MM Questionnaires was initiated at the Department of Occupational and Environmental Medicine, Orebro University Hospital, in 1985. The first standardized questionnaire (MM 040 NA for workplaces) was released in 1989 after more than three years of intense testing regarding validity, reliability and, primarily, its practical application. Since then, different versions have been developed directed at specific environments such as schools, day care centers, offices, hospitals and residential dwellings. The different versions of the questionnaire are based on the same core questions. This allows the possibilities of making comparisons between, for instance, school personnel and students, or tenants and workers. Each version also contains additional questions of a more specific nature, based on feedback from many case studies.

Multi-collinearity	is a statistical phenomenon in which two or more predictor variables in a multiple regression or a multilevel regression model are highly correlated, meaning that one can be linearly predicted from the others with a non-trivial degree of accuracy. In this situation the coefficient estimates of the multiple regression may change erratically in response to small changes in the model or the data. Multi-collinearity does not reduce the predictive power or reliability of the model as a whole, at least within the sample data themselves; it only affects calculations regarding individual predictors. That is, a multiple regression model with correlated predictors can indicate how well the entire bundle of predictors predicts the outcome variable, but it may not give valid results about any individual predictor, or about which predictors are redundant with respect to others. A high degree of multi-collinearity can also prevent computer software packages from performing the matrix inversion required for computing the regression coefficients, or it may make the results of that inversion inaccurate.
Observation dependence	When clustering occurs due to a grouping factor, then the observations are dependent. Independence is an assumption of general linear models, which states that cases are random samples from the population and that scores on the dependent variable are independent of each other.
Prevalence	Prevalence is 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**.

PROC PHREG Conditional logistic regression

There are many types of models that have been used for survival analysis. Survival analysis is concerned with studying the time between entry to a study and a subsequent event. Two of the more popular types of models are the accelerated failure time model (Kalbfleisch & Prentice, 1980) and the Cox proportional hazards model (Cox, 1972). The Cox model is a well-recognised statistical technique for analysing survival data. The PHREG procedure in SAS employed in this thesis performs regression analysis of survival data based on the Cox proportional hazards model, which may improve the estimate of treatment effect by narrowing the confidence interval. A Cox model is a statistical technique for exploring the relationship between the occurrence of an event and several explanatory variables. Briefly, the procedure regresses the survival times (or more specifically, the so-called hazard function) on the explanatory variables. The actual method is much too complex for detailed discussion here.

Interpreting the Cox model involves examining the coefficients for each explanatory variable. A positive regression coefficient for an explanatory variable means that the hazard is higher, and thus the prognosis worse. Conversely, a negative regression coefficient implies a better prognosis for patients with higher values of that variable.

Robust sandwich covariance	In probability theory and statistics, covariance is a measure of how much two random variables change together. If the greater values of one variable mainly correspond with the greater values of the other variable, and the same holds for the smaller values, i.e., the variables tend to show similar behaviour, the covariance is positive. In the opposite case, when the greater values of one variable mainly correspond to the smaller values of the other, i.e., the variables tend to show opposite behaviour, the covariance is negative. The sign of the covariance therefore shows the tendency in the linear relationship between the variables. The magnitude of the covariance is not easy to interpret. The normalized version of the covariance, the correlation coefficient, however, shows by its magnitude the strength of the linear relation. As already stated, SAS software uses the Cox proportional hazards model for survival data. Robust sandwich covariance is a regression calibration estimator in Cox regression. In SAS PHREG procedure this option requests the robust sandwich estimate of Lin & Wei (1989) for the covariance matrix. When this option is specified, this robust sandwich estimate is used in the Wald tests for testing the null hypothesis. In this thesis, robust sandwich covariance for aggregated data COVSANDWICH <(AGGREGATE)>was specified, which requests a summing up of the score residuals for each distinct ID pattern in the computation of the robust sandwich covariance estimate.
Survival time	Survival analysis is concerned with studying the time between entry to a study and a subsequent event. Survival times often refer to the development or relapse of a particular symptom. A significant feature of survival times is that the event of interest is very rarely observed in all subjects. Such survival times are termed **censored**, to indicate that the period of observation was cut off before the event of interest occurred.

Abbreviations

2LL	**2** times the **L**og **L**ikelihood
ACH	**A**ir **C**hanges per **H**our
ANOVA	**An**alysis **O**f **Va**riance
ASHRAE	**A**merican **S**ociety of **H**eating, **R**efrigeration and **A**ir **C**onditioning **E**ngineers
BB101	**B**uilding **B**ulletin 101
BMI	**B**ody **M**ass **I**ndex
BMS	**B**uilding **M**anagement **S**ystem
BS EN	**B**ritish **S**tandard **E**uropean **N**orm
CI	**C**onfidence **I**nterval
CIBSE	**C**hartered **I**nstitute of **B**uilding **S**ervices **E**ngineers
CO$_2$	Carbon Dioxide
CS	**C**entral **S**tation
DNPH	**D**initrophenylhydrazine
EDC	**E**lectrostatic **D**ustfall **C**ollector
ELISA	**E**nzyme **L**inked **I**mmunosorbent **A**ssay
ETS	**E**nvironmental **T**obacco **S**moke
GC-MS	**G**as **C**hromatography - **M**ass **S**pectrometry
HDM	**H**ouse **D**ust **M**ite
HEPA	**H**igh **E**fficiency **P**articulate **A**ir
HPA	**H**ealth **P**rotection **A**gency
HPLC	**H**igh **P**erformance **L**iquid **C**hromatography
HVAC	**H**eating **V**entilating **A**ir **C**onditioning system
IAQ	**I**ndoor **A**ir **Q**uality
ICC	**I**ntraclass **C**orrelation **C**officience

IEQ	**I**ndoor **E**nvironmental **Q**uality
IGLS	**I**terative **G**eneralised **L**east **S**quares
I/O	**I**ndoor/**O**utdoor
ISAAC	**I**nternational **S**tudy of **A**sthma and **A**llergies in **C**hildhood
ISO	**I**nternational **O**rganisation for **S**tandarisation
LOD	**L**imit **O**f **D**etection
LTHW	**L**ow **T**emperature **H**ot **W**ater
MCMC	**M**arkov **C**hain **M**onte **Carlo**
NO$_2$	Nitrogen Dioxide
NDIR	**N**on-Dispersive **I**nfra-**R**ed
O$_3$	Ozone
OR	**O**dds **R**atio
PCF	**P**hotometric **C**alibration **F**actor
PID	**P**hoto-**I**onisation **D**etector
PM	**P**articulate **M**atter
PM$_1$	suspended **P**articulate **M**atter (<1 μm)
PM$_{2.5}$	suspended **P**articulate **M**atter (<2.5 μm)
PM$_{10}$	suspended **P**articulate **M**atter (<10 μm)
PMV	**P**redicted **M**ean **V**ote
ppb	**P**art **P**er **B**illion
PPD	**P**ercentage **P**eople **D**issatisfied
ppm	**P**art **P**er **M**illion
PRISMA	**P**referred **R**eporting **I**tems for **S**ystematic Reviews and **M**eta-**A**nalyses
Q1-Q3	Interquartile range 25% to 75%
qPCR	**q**uantitative **P**olymerase **C**hain **R**eaction
RH	**R**elative **H**umidity
SAS	**S**tatistical **A**nalysis **S**oftware
SBS	**S**ick **B**uilding **S**yndrome
SE	**S**tandard **E**rror
SCF	**S**ize **C**alibration **F**actor
SF$_6$	Sulfur Hexafluoride

SINPHONIE	**S**chool **I**ndoor **P**ollution and **H**ealth: **O**bservatory **N**etwork in **E**urope
SOAs	**S**econdary **O**rganic **A**erosols
SSNTD	**S**olid **S**tate **N**uclear **T**rack **D**etector
T3CE	**T**ri**c**hloro**e**thylene
T4CE	**T**etra**c**hloro**e**thylene
TEA	**T**ri**e**thanol**a**mine
TVOCs	**T**otal **V**olatile **O**rganic **C**ompounds
UV	**U**ltra **V**iolet
VOC	**V**olatile **O**rganic **C**ompound
WHO	**W**orld **H**ealth **O**rganization

Symbols

G	metabolic rate	(cm^3/s)
m	metabolic equivalent of task	W/ m^2 (MET)
Q	ventilation rate	(m^3/s)
V	ventilation rate	(L/s-p)
C$_{in}$	initial indoor CO$_2$ concentrations	(ppm)
C$_{out}$	initial outdoor CO$_2$ concentrations	(ppm)
γ_{00}	overall intercept	(-)
σ	standard deviation	(-)
$\sigma^2{}_u$	between-group variation	(-)
$\sigma^2{}_e$	within-group variation	(-)

Chapter 1

Introduction

1.1 Research background

School buildings pose a complex design challenge as they need to perform well over a wide range of environmental conditions, while accommodating periods of high occupant densities. This results in high internal heat gains, emissions of body odours together with various indoor pollutants (physical, chemical and microbial). According to Eurostat (2011) the average primary school class size in European countries and the US was on average 20.8 pupils (σ: 2.0) corresponding to a density ranging from 2 to 3.1 m^2/p (σ: 0.3). The typical classroom has on average four times as many occupants per square metre as the typical European and US office buildings (Seppänen et al., 2006).

Former meta-analytic reviews (Chatzidiakou et al., 2012; Daisey et al., 2003; Mendell & Heath, 2005) offer a comprehensive overview of air quality and thermal conditions in school settings. It is emphasised that reduced ventilation rates and elevated indoor temperatures in schools are common and frequently much worse than in office buildings (Wargocki & Wyon, 2013). At this developmental stage in their lives, children are vulnerable to a range of environmental exposures that can have long-term adverse consequences, such as respiratory illness and poor cognitive performance (Daisey et al., 2003; Mendell & Heath, 2005; Wargocki et al., 2002). Children are particularly vulnerable to airborne pollution because of their high activity levels and their developing lungs, which intake more air in relation to their body mass. Additionally, children have significantly different respiratory parameters compared with adults facilitating deeper and greater lung deposition of particles and gas per cell membrane interactions (Ciencewicki et al., 2009).

Apart from the home, schools are where children spend most of their time indoors (Eurostat, 2011). They represent a significant exposure environment that can trigger health symptoms among susceptible children. In many countries of the northern hemisphere, asthma-related hospital admissions among children coincide closely with their return to the school environment

(Julious et al., 2007). Asthma is the most common chronic disease and the leading cause of hospitalisation among children in England (WHO, 2012). A study by the International Study of Asthma and Allergies in Childhood (Mallol et al., 2013) concluded that England and Ireland have the highest prevalence rates of childhood asthma among European countries. More specifically, the latest data from the ISAAC study revealed that in these two countries the prevalence rate for children aged 6-7 years ranged from 10.2% to 20.9%, and from 9.7% to 27.8% among children aged 13-14 years. In particular, the study findings revealed that, for the younger age group, the prevalence of asthma is increasing over time (average change per year 0.5%).

It is clear, therefore, that school authorities have a particular duty of care for their pupils in ensuring that appropriate conditions in the indoor environment are maintained. In this context, thermal comfort levels and Indoor Air Quality (IAQ) have a crucial role to play in producing an environment that supports optimal educational and health outcomes. Currently, the performance standard document Building Bulletin 101 ”Ventialtion in School Buildings” (BB101) (DfE, 2014), is introduced as a means of demonstrating compliance with the Building Regulations Part F (Ventilation) (HM Government, 2010) in new and refurbished English and Welsch school buildings. The World Health Organisation (WHO) provides legally enforcable guideline values. Reflecting the relative difficulty and expense of measuring specific pollutants, in BB101, carbon dioxide (CO_2) concentrations have been chosen as the key performance indicator for the assessment of IAQ and ventilation in schools (Section 2.3.3). Similarly, current standards, such as ASHRAE 62.1 and BS EN 15251:2007 applicable in many European and US countries also adopt CO_2 as a basic assessment proxy. While high CO_2 levels in environments with high occupant density, such as classrooms, provide a good indication of ventilation rates, purging and dilution of pollutants, they might be a poor indicator for traffic-related pollutants (Section 2.4.4) which may trigger long-term and acute health responses of the occupants.

Currently, in England there are approximately 4.3 million students aged under 11 in primary and nursery schools. Based on the current birth rate, this number is predicted to increase to 4.8 million by 2020 leading to demand for a large number of schools to be remodelled, refurbished or constructed (Figure 1.1). Namely, the additional 500,000 school places are roughly equivalent to 20,000 new classes of 25 pupils, or an additional 1,700 average-sized primary and nursery schools in the next six years.

Additionally to the fast growing English population and the demand for new schools, retrofitting and maintenance is necessary because of the great age and many years of intensive use of the current school building stock. There are around 5,000 listed school buildings in England built in the Victorian and Edwardian period (1837-1910), representing a significant part of the country’s architectural heritage. All of the above factors indicate the urgent and increasing

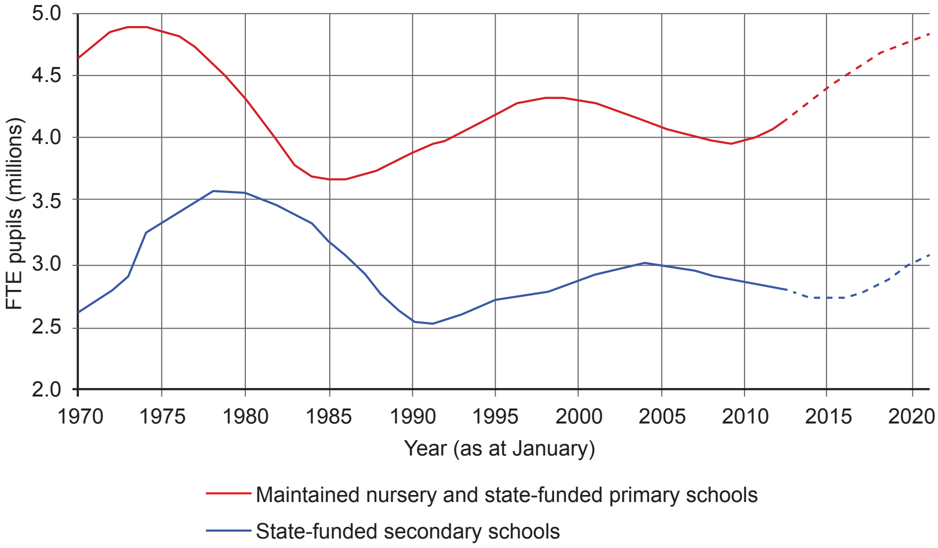

Figure 1.1: Full-time equivalent number of students by type of school in England

Years: January 1970 to 2013 (actual)-January 2014 to 2022 (projection) (DfE, 2013)

demand for design and retrofitting guidelines for healthy and comfortable school buildings. These challenges, and the opportunity to assist teaching personnel and students to achieve their full potential, emphasise the timeliness of this research.

1.2 Research hypothesis and objectives

The previous section highlighted the importance of providing healthy and satisfactory school environments, and the effort of school and government authorities to ensure that adequate conditions in the indoor environment are maintained by means of introducing performance standards, such as the BB101. However, little evidence is currently available from detailed empirical data on the IAQ in schools (Chapter 2). In line with the performance standards, building scientists evaluate IAQ primarily based on ventilation rates and CO_2 levels without considering interactions of specific pollutants, and their impacts on children's health.

On the other hand, epidemiological studies associate health outcomes from school children with pollution data collected from outdoor fixed monitoring stations. Primarily, these studies relied upon exposure measurements from a small number of fixed site monitors which lack spatial and temporal resolution, which may mask exposure variability in the study population (Özkaynak et al., 2013). When these measurements are used as estimates of exposures, there is an inherent assumption that pollutant concentrations are homogeneous over the geographic area covered by the study population. This assumption is not true, particularly for pollutants with localized and heterogeneous sources, such as indoor emissions or traffic, and the modification effect of operational and construction characteristics of buildings.

This thesis investigates the large number of factors involved within classroom IAQ and the acute health outcomes of the occupants based on field data collected from 18 London case study classrooms in six schools, with the intention of exploring the degree to which this primary hypothesis remains true:

Is CO_2 a good proxy for IAQ in school classrooms so as to ensure a healthy indoor environment?

In order to answer this research question, the primary aim of this thesis is (a) to investigate the relation between CO_2 levels and ventilation rates with specific indoor pollution levels taking into consideration operational, behavioural, construction characteristics of school buildings and the role of the microenvironment. The secondary aim is (b) to explore the association between CO_2 levels, ventilation rates and specific pollutants with health outcomes and perceived IAQ.

(a) *CO_2 levels and estimated ventilation rates in relation to classroom pollution levels after controlling for environmental and behavioural factors*

As the current performance standards in England (DfE, 2014) focus on CO_2 levels as the primary indicator of IAQ, this thesis aims to associate indoor CO_2 levels with pollution levels employing statistical modelling, and in doing so, to evaluate whether achieving levels below guideline values of these standards may limit indoor exposure to specific pollutants. As part of energy management practice to assess and evaluate operational performance of non-domestic buildings, a widely adopted method is benchmarking as reference values may be derived based on statistical criteria. The scarce data available from comprehensive monitoring of IAQ have contributed to the lack of a similarly robust IAQ benchmarking methodology for buildings. While comprehensive monitoring of total IAQ performance of classrooms is therefore necessary; apart from the mere collection of field data, a systematic synthesis of a comprehensive database is necessary to identify characteristics of the built environment, the microenvironment and operational and behavioural patterns influencing exposure influence spatial and temporal variation of indoor pollution levels.

(b) *Health risks and satisfaction with IAQ in relation to CO_2 levels and school exposure to specific pollutants.*

The majority of studies associated health responses from school children with pollution data collected from outdoor fixed monitoring stations, which might not represent indoor exposure in the classroom. Few studies have been organised as crossover among seasons; therefore, limited information is available on temporal variation of indoor pollution concentrations and the risk of acute events from transient effects.

Additionally, little evidence is currently available on the association between specific indoor exposures with perceived IAQ and SBS symptoms in schools (section 2.5). To date, most studies on Sick Building Syndrome (SBS) and perceived IAQ have focused on office workers, and only a few employed simultaneously measurements of a large number of pollutants. Addressing these gaps in current knowledge, the secondary aim of this work is to associate indoor exposure in the classroom with the risk of acute health symptoms and to create predictive models of classroom exposure with perceived IAQ.

The extensive systematic review of the literature (Chapter 2) showed that there is a lack of an integrated approach to assess IAQ of school classrooms. This study addresses the need for a comprehensive assessment of IAQ that will simultaneously investigate the interaction between the microenvironment, meteorological parameters, building characteristics, maintenance of school buildings with health and satisfaction of school occupants. In summary, to investigate fully the first point from a building science point of view, an effort to produce a comprehensive IAQ database is necessary, adopting methodological approaches from microbiological and chemical disciplines. For the second point, it is necessary to investigate whether CO_2 is directly related to health outcomes and perceived IAQ; and indirectly, whether CO_2 is a good predictor of indoor pollutants associated with health responses and dissatisfaction of the occupants.

The following objectives relate to the proposed outputs of the thesis:

- to summarise in a systematic way, the range of indoor pollution levels reported from monitoring surveys in classrooms in published literature, and to evaluate the strength and consistency of literature relating indoor pollution levels and thermal conditions in school settings to health and comfort of the occupants;
- to adopt a multidisciplinary methodological framework to assess IAQ performance of non-industrial environments applicable in large-scale surveys;
- to identify new pathways for providing adequate IAQ, including new good practice on designing, refurbishing, managing and using current and future schools.

This thesis focuses on London schools which is taken as a case study. The data analysed in this work were collected by the author during the SINPHONIE project. The following section provides further details of the *School Indoor Pollution and Health: Observatory Network* SINPHONIE project and the role of the author in relation to the originality of this thesis.

1.3 Originality and novelty

The research presented in this thesis is partially based on the extensive EU Commission project SINPHONIE funded by the European Parliament and carried out under a contract with the European Commissions Directorate-General for Health and Consumers (2010-2012).[1] In total,

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[1] DG SANCO/2009/C4/04, contract SI2.570742)

38 partners from 25 countries were involved in the SINPHONIE project. The project required a multidisciplinary approach with expertise in epidemiology, environmental chemistry, microbiology and building science. Analysis of microbiological parameters were carried out centrally for all SINPHONIE partners in specialised laboratories allowing direct comparison between countries according to the harmonised protocol. Similarly, radon etching was performed centrally for all SINPHONIE partners. Chemical analysis of passive sampling of gases was outsourced in accredited laboratories in the UK.

The author of this thesis was the only UK researcher working on the SINPHONIE and carried out all fieldwork, the observational and intervention studies, administered and transcribed questionnaire surveys to school personnel and students of the school sample. UCL colleagues helped with the logistics of the labour-intensive deployment of equipment. The author completed the deliverables and milestones set out by the SINPHONIE project; however, this thesis did not focus on the whole project. The SINPHONIE study was designed as a case-control epidemiological investigation and aimed to prevent and reduce respiratory disease due to outdoor and indoor air pollution in primary and nursery classrooms.

There are significant innovative *methodological* elements aimed to address the specific aims of this work that were independent of the SINPHONIE protocol:

- This thesis was organised as a case-crossover observational study to investigate temporal variation of indoor pollution levels and to examine the transient effects of brief exposures on the onset of acute outcomes. Advantages of case-crossover design over traditional statistical designs are detailed in section 4.2.
- Monitoring methodology included real-time instrumental sampling to capture temporal changes of the dynamic indoor environment. The SINPHONIE protocol included only long-term integrated measurements to capture average classroom exposure.
- The standardised SINPHONIE questionnaires were extended to include perceived IAQ and satisfaction with the classroom environment.
- As the statistical analysis framework was not specified by the SINPHONIE project, multilevel models with Bayesian estimation techniques were employed for the synthesis of the findings (Section 4.5.3).

A detailed description of the methodological design of this thesis can be found in Chapter 3 and Chapter 4. Based on the above methodological decisions, this thesis has made the following contributions to knowledge :

(a) *Integration of building characteristics, microenvironment and behavioural patterns of the occupants with monitored IAQ*

Previous IAQ assessments have mainly focused on indoor temperatures and CO_2 levels. This study comprehensively assesses IAQ of school classrooms. While the present work builds on existing literature on potential building characteristics that may affect indoor pollution levels, one of its innovative elements is the identification of operational patterns on pollutants' levels. The potential benefit of a number of preventive measures and implementation of best practice for school building operation was highlighted.

(b) *Association between school exposure with health responses and satisfaction with IAQ*

Existing epidemiological studies tend to focus on the impact of external rather than internal conditions on health risk. Moreover, limited evidence is currently available on the association between specific pollutants with SBS symptoms and perceived IAQ of school children. The findings presented in this thesis associate prevalence and incidence of SBS symptoms with school based exposure. This is one of the few studies on SBS in educational settings organised as a longitudinal study. A predictive model on IAQ perception was computed, and controlled simultaneously for a large number of specific pollutants and personal factors. While previous predictive models (BS EN 15251: 2007) on perceived IAQ focus on ventilation rates and CO_2, the predictive model created in this thesis highlights the interaction between temperature and ventilation rates on perceived IAQ.

(c) *Transferability of methodological framework*

From a methodological viewpoint the study was designed to determine the effects of building characteristics, microenvironment, operation and maintenance of school buildings on indoor pollution levels, and their association with health responses and satisfaction with IAQ of the occupants. The simultaneous measurements of a large number of parameters allowed for an in-depth investigation of relationships, while controlling for possible confounding factors. Although a small sample of schools and respondents were used as a case study, the methodological approach showcased in this thesis could be easily transferred to large-scale surveys in schools. The validity of the methodological framework adopted in this study is supported by the findings that were in line with and extended previous research.

(d) *Application of novel statistical analysis in building science*

Bayesian estimation methods in multilevel modelling constitute an effective method for analysing small databases. Multilevel modelling provided a robust yet sensitive tool, and an appropriate analytical framework to deal with observation dependence in the data. More importantly, multilevel models permit to explore the nature and extent of the relationships at both micro and macro levels. Finally, multilevel models can be readily expandable to study changes over time using longitudinal data. Multilevel models are now widely applied in epidemiology and social sciences, and their use is expected to extend to the building science.

1.4 Thesis structure

The structure of the thesis is described here by chapter. While held together the parts form a deeper research story, the Chapters 2 through to 7 are based on published papers (Appendix A), and can be read independent of one another.

Chapter 1 briefly introduces the complexity of school building design raising the need for a comprehensive assessment of IAQ. Research aims and objectives are presented, as well as an outline of the hypotheses to be tested.

Chapter 2 employs a systematic approach to evaluate the strength and consistency of current evidence relating thermal conditions and IAQ in school settings to health outcomes and comfort of the occupants. The chapter briefly introduces current standards and guidelines that aim to ensure adequate IAQ in school classrooms, and employs a systematic meta-analytic approach to synthesise evidence on thermal conditions, CO_2 levels, estimated ventilation rates and targeted indoor pollution levels. The chapter discusses the implications of the microenvironment, building design and construction characteristics, occupancy patterns, ventilation strategies and maintenance on IAQ.

Chapter 3 and **Chapter 4** discuss the multidisciplinary methodology adopted in this study to assess IAQ performance of school classrooms comprehensively. **Chapter 3** presents the monitoring approach for the quantification of physical, chemical and microbial parameters. **Chapter 4** provides information collected on school buildings and classrooms through standardised spreadsheets, and describes the sample focusing on microenvironment, building characteristics, heating and ventilation strategies, construction materials and indoor furnishing, daily operation and maintenance that may potentially impact on IAQ. Moreover, **Chapter 4** presents the methodology for collecting self-reported health responses and satisfaction with the school environment, and the novel application of the statistical methods employed in the analysis.

Chapter 5 describes briefly the sample of schools and classrooms, and discusses empirical evidence on indoor and outdoor thermal conditions and pollution levels in the heating and non-heating season, and compares results with current standards, guideline values, and levels reported in the literature in school settings. The Chapter employs descriptive and inferential statistics to investigate factors which may impact IAQ.

Chapter 6 focuses on the interrelationships between indoor pollutants with environmental and behavioural factors employing two-level multilevel regression models.

Chapter 7 identifies specific pollutants that affect prevalence, incidence and remission of asthmatic symptoms, SBS symptoms and satisfaction with IAQ. The analysis employs two-level (classroom and child) multilevel logistic and ordered multinomial regression models.

Chapter 8 and **Chapter 9** discuss good practises for designing, refurbishing, managing and using schools of the future. Following the previous analysis, a response to the hypothesis question is given, framed by an examination of the limitations of this work, implications for policy guidance, and recommendations for future research.

1.5 Academic output of this thesis

In total, seven peer-reviewed journal papers and three peer-reviewed conference papers, a book chapter and four technical reports were derived from this thesis. Copies of all papers are provided in **Appendix** A.

Journal Papers

1. Chatzidiakou, L., Mumovic, D., Summerfield, A.J. Is CO_2 a good proxy for IAQ? Part 1: The interrelationships between thermal conditions, CO_2 levels, ventilation rates and selected indoor pollutants. *Building Services Engineering Research & Technology (BSERT)*, 36(2) 129 - 161

   in Section A.1.1. *Relevant PhD Chapters:* Chapter 2 (Literature Review), Chapter 3 (Methodology for multilevel modelling) and Chapter 6 (Associations between environmental and behavioural factors with indoor pollution levels).

2. Chatzidiakou, L., Mumovic, D., Summerfield, A.J. Is CO_2 a good proxy for IAQ? Part 2: Health outcomes and perceived indoor air quality in relation to classroom exposure and building characteristics *Building Services Engineering Research & Technology (BSERT)*, 36(2) 162 - 181

   in Section A.1.2. *Relevant PhD Chapters:* Chapter 2 (Literature Review), Chapter 3 (Methodology for multilevel modelling) and Chapter 7 (Associations between school exposure with health implications and satisfaction with IAQ).

3.

4. Chatzidiakou, L., Mumovic, D., Summerfield, A.J., Altamirano-Medina, H. 2014. Indoor Air Quality in London Schools. Part 1: Performance in Use . *Intelligent Buildings International*

   in Section A.1.3. *Relevant PhD Chapters:* Chapter 2 (Literature Review), Chapter 3 and Chapter 4 (Methodology and presentation of Case Studies), and Chapter 5 (Results of monitored thermal conditions, CO_2 levels, estimated ventilation rates and airborne particle concentrations).

5. Chatzidiakou, L., Mumovic, D., Summerfield, A.J., Taubel, M., Hyvärinen, A. 2014. Indoor Air Quality in London Schools. Part 2: 'Long-term integrated assessment' *Intelligent Buildings International*

   in Section A.1.4. *Relevant PhD Chapters:* Chapter 2 (Literature Review), Chapter 3 (Methodology) and Chapter 5 (Results of chemical and biological contaminants)

6. Chatzidiakou, L., Summerfield, A.J., Mumovic, D., Hong. S. 2014. Low carbon vs Victorian school design: indoor air quality, energy performance and health responses. *Indoor and Built Environment*, 23 (3), 417-432

   in Section A.1.5. *Relevant PhD Chapters:* Chapter 2 (Literature Review), Chapter 3 and Chapter 4 (Methodology for IAQ monitoring and Case Studies) and Chapter 5 (Results of empirical evidence) and Chapter 7 (Associations between school exposure with health implications and satisfaction with IAQ).

7. 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), pp. 228-259.

   in Section A.1.6. *Relevant PhD Chapters:* Chapter 1 (Background of the topic) and Chapter 2 (Literature Review).

Conference Papers

8. Chatzidiakou, L., Mumovic, D., Summerfield, A., Hong, S. 2013. Low Carbon vs Victorian School Design: Indoor Air Quality, Energy and Health Responses. *Environmental Health in Low Energy Buildings*, Vancouver, Canada, 15-18 Oct 2013. HVAC&R Research.

   in Section A.2.1

9. Chatzidiakou, L., Mumovic, D., Summerfield, A., 2012. Indoor Air Quality and Thermal Comfort Conditions in Three Primary Victorian Schools in Central London. *10th International Conference Healthy Buildings.* Brisbane, Australia, 8-12 July 2012.

   in Section A.2.2

10. Chatzidiakou, L., Mumovic, D., Summerfield, A. 2013. Is CO_2 a good proxy for indoor air quality in school? *CIBSE Technical Symposium.* Liverpool, UK, 11-12 April 2013.

    in Section A.2.3

Book Chapter

11. Chatzidiakou, L., Jones, B., Mumovic, D. 2014. Indoor Air Quality and Ventilation Monitoring. In: D. Mumovic, K. Santamouris, ed.*A handbook of sustainable building design and engineering: an integrated approach to energy, health and operational performance. (in press)*

    Relevant PhD Chapters: Chapter 3 (Methodology for IAQ monitoring)

Technical Reports

12. Chatzidiakou, L., Mumovic, D., 2014. The Effects of Thermal Conditions and Indoor Air Quality on Health, Comfort and Cognitive Performance of Students: A Review of the Literature. Built Offsite, London

13. Palmer, J., Mumovic, D.-Editors, 2014. Integrated School Building Design, CIBSE Technical Memorandum, CIBSE, ISBN: tbc *(in press)*

14. Chatzidiakou, L., Pissani M., Mumovic, D., 2012. Overheating Assessment and Indoor Air Quality in Castle Hill Primary School. Technology Strategy Board: Building Performance Evaluation Programme, London

15. Chatzidiakou, L., Mumovic, D., 2012. Effectiveness of Natural Ventilation in School Classrooms. SINPHONIE, WP3 deliverables

16. Chatzidiakou, L. 2014. The commercial evaluation of PhD research: Creation of healthy indoor environments in schools. emph UCL ADVANCES. The Centre for Enterpreneurship and Business Interaction at UCL

    in Section A.3.1.

Chapter 2

Literature Review

2.1 Outline

This chapter summarises in a systematic way the range of indoor pollution levels reported from monitoring studies in classrooms in published literature, reviews the evidence in a systematic way whether school buildings provide a healthy and satisfactory indoor environment for the occupants, and evaluates the strength and consistency of literature relating indoor pollution levels and thermal conditions in school settings to health and comfort of the occupants, and the implications to building design.

Firstly, Section 2.2 describes the criteria for methods of selection and classification of literature. Current regulatory framework developed to ensure acceptable thermal conditions and adequate IAQ in educational settings and other non-industrial environments is presented in Section 2.3. Since it is increasingly recognised that more systematic evidence is needed to strengthen the base for appropriate IAQ and ventilation guidelines for schools, Section 2.4 presents empirical evidence on the concentration of physical, microbial and chemical levels, and the strength and consistency of the associations with potential health risks. Section 2.5 summarises evidence on the association between indoor exposure in classrooms with perceived air quality and sensory irritations. Section 2.6 investigates factors affecting indoor concentrations of pollutants such as the microenvironment, building characteristics, traffic intensity, operational schedules and occupancy density. The chapter closes with a summary section (Section 2.7) that highlights current gaps in the literature.

2.2 Materials and methods employed in this review

The review and meta-analysis was conducted in a systematic way according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist and flow diagram (Moher et al., 2009). This section describes search strategies, inclusion criteria and methods of literature classification.

2.2.1 Search strategy

Four conceptual themes were developed: *environmental factors, environment, human outcomes* and *publication*, each using a variety of search terms (Table 2.1). Search-terms were developed using combinations of controlled vocabulary and free-text terms. Only papers with title, keywords or abstracts including records in each of the four search categories were selected.

In this chapter, the term *environmental factors* refers to IAQ and thermal conditions. Although noise and light are also important constituents of Indoor Environmental Quality (IEQ), their effects will not be considered in this review as their effects on students' well-being are outside of the scope of this thesis. IAQ was further analysed under two specific terms: *ventilation* and *indoor pollutants*. Indoor pollutants included in this review are known with respect to their health implications, and are often found indoors in concentrations of health concern.

The *human outcomes* of primary interest are *health, absenteeism* and *perceived IAQ*. Potentially adverse health effects in relation to school exposure considered in this review include: asthma and allergy; respiratory infections including colds, lower or upper respiratory symptoms; and neurological symptoms including headache, fatigue, or difficulty concentrating. Health effects are generally assessed with medical tests or self-reported health symptoms through standardised questionnaires.

Absenteeism is the degree to which pupils are absent from school. Some studies separate illness related from non-illness related absenteeism. Since illness related absence from schools may be related to respiratory infections, asthma, allergies, gastrointestinal infections, or other disease, it can serve as an indicator of health effects sufficiently severe to require staying home from school. Additionally, the review collected evidence on factors that may affect school occupants' comfort in relation to thermal conditions and IAQ. Thermal comfort is dependent on hygrothermal conditions of the environment, air velocity as well as personal factors such as activity levels and clothing insulation. Perceived IAQ is generally assessed with questionnaire surveys distributed to school occupants. The questionnaires normally ask subjects to rate air quality on a scale ranging from clearly acceptable to clearly unacceptable. Some questionnaires may include more detailed self-perceived aspects of IAQ, such as 'dryness', 'stuffiness', 'freshness', odour or air movement.

The term *environment* was used to restrict search only on studies dealing with schools, because other environments accommodating adults exclusively may differ significantly in terms of the tasks, motivation, and aspects of the built environment. This review used electronic databases of scientific publications available up to September 2013, including *Medline/PubMed*, the *American Society of Heating, Refrigerating and Air-Conditioning Engineers* (ASHRAE), *ScienceDirect*, *Scopus* and *SpringerLink.* In addition, a manual search was conducted in the journal *Indoor Air.*

Table 2.1: Table with keywords entered

Conceptual themes	**Specific themes**	**N of search terms**	**Typical search terms**
Environmental factors	Thermal conditions	10	temperature, thermal comfort, Relative Humidity, air movement, draught, air temperature, mean radiant temperature, relative air velocity, water vapour pressure, clo-value
	ventilation	25	air change rate, air supply rate, carbon dioxide, natural ventilation, mechanical ventilation, cross ventilation, single-sided ventilation, mixed mode ventilation
	Air quality	80	Particulate Matter, PM_1, $PM_{2.5}$, PM_{10}, airborne particles, respirable fraction, thoracic fraction, fine particles, ultra-fine particles, Volatile Organic Compounds (VOCs), Total VOCs, formaldehyde, pinene, limonene, benzene, toluene, trichloroethylene (T3C4), tetrachloroethylene (T4CE), naphthalene, nitrogen dioxide (NO_2), ozone (O_3), traffic-related pollutants, radon, settled dust, dog allergen, cat allergen, fungal, mould, damp *Penicillium* spp, *Aspergillus* spp., bacterial, endotoxin
Environment		15	Schools, classrooms, educational setting
Human outcomes	Health	91	Symptoms, SBS, diseases, odour, asthma, wheeze, respiratory disease, allergy, sensitisation, nasal patency, nasal obstruction, headache, fatigue, tiredness, malaise, cold, flu, influenza
	Attainment	4	Absenteeism, school attendance, illness-related absenteeism, absences
	IAQ Perception	8	perceived air quality, subjective air quality, odour, olfactory irritations, olf, sensory irritations, bioeffuels, comfort
Publication		3	journal article, journal paper, ASHRAE Transactions

2.2.2 Inclusion and exclusion criteria

Based on the above, inclusion and exclusion criteria were applied in the titles, keywords and abstracts, before obtaining full reports of the studies that appeared to meet the criteria. Inclusion criteria were as follows:

- the most important criterion for inclusion was that the collected air quality data were used to indicate or represent pollutant concentrations in school environments either collected from ground monitors installed in or around the schools, or represented by data collected at the nearest monitoring stations;
- thermal comfort studies in educational settings;
- includes children between 4 years old and 16 years old which is the statutory school-leaving age in England, and younger children are assumed to be at least as vulnerable as older children;

- reports on ventilation rates and CO_2 levels in school classrooms regardless of ventilation strategies (e.g. natural ventilation, mixed mode etc.);
- studies on perceived IAQ and SBS symptoms;
- published up to 2014;
- reports the findings of a primary research study or secondary analysis; and
- published in English.

Moreover, findings of this report were compared with findings from other meta-analytic studies on IAQ, ventilation and health. As already stated, the review primarily focuses on children in school environments, as other environments accommodating adults may differ significantly. However, when evidence was inconclusive (assuming that children are at least as sensitive as adults to environmental exposures) the findings of this review were compared with meta-analytic studies of adult office workers. Particularly strong design studies on adults in controlled laboratory environments were also included as there are no similar laboratory experiments with children.

Exclusion criteria were as follows:

- subjects were recruited from schools, but the assessment was based on exposure at home rather than at school;
- studies by same author that repeat results;
- studies with weak design, such as case studies (small sample) and uncontrolled interventions. The methodological quality of the studies was assessed based on population size, study design, air pollutant exposure measurement, medically-diagnosed current asthma, confounding factors, controls used and statistical methods utilised. Quality of reporting was evaluated by using the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement checklist for cohort, case-control, and cross sectional studies, version 4 (Elm et al., 2007).

2.2.3 Classification and quality assessment of studies

Figure 2.1 outlines the flow of the review process and number of articles involved in this review. Titles and abstracts were reviewed for relevance, and assessed, which were not related to the scope of this study. Relevant papers were then included for full text review (total = 226 articles), and tested against the eligibility criteria presented in Section 2.2.2.

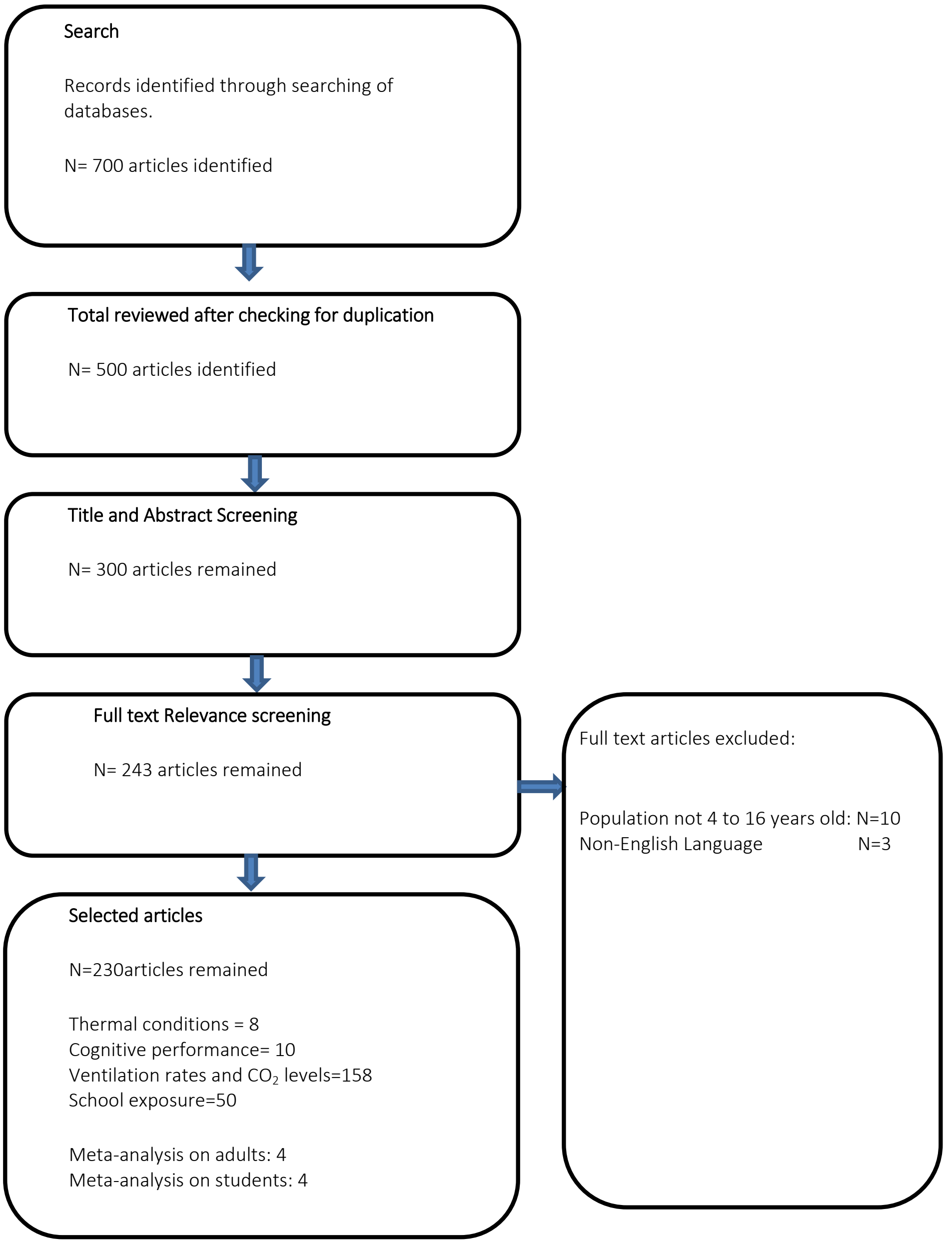


Figure 2.1: Flow diagram of study selection

2.2.4 Data extraction and synthesis of evidence

Full text relevant studies were coded accordingly to address the topic focus of the review: study type (e.g. primary research, meta-analysis), the focus of the study (e.g. health outcomes, pollutant concentrations), the country in which the research was conducted and the study population (e.g. age group). Extracted data from each article included:

- population (age of participants and sample size);
- variables used in analysis;
- outcome measures;
- associations proposed by the study.

Numerical data available in scientific evidence were used to create a quantitative database. Regression models with Confidence Intervals (CI) and prediction limits were produced in SAS 9.3. All reported data points were included regardless of the level of statistical significance, which was more than $p<0.05$ in all studies.

2.3 Indoor air quality guidelines and reference values

The importance of good IAQ for the health of the individual was recognized as long as 150 years ago (Spengler et al., 1999). That period also saw recommendations, which essentially related to questions of ventilation and CO_2 levels. The first evaluation standards for organic and inorganic substances were laid down in the 1970s, often on an empirical basis, but it was not until the mid-1980s that a shift occurred towards systematically deriving guideline and reference values. A guideline or reference value can only be regarded as rational when a strategy for its verification is available on the basis of *toxicological, epidemiological* and *statistical criteria.* Generally, guideline values usually refer to criteria derived on the basis of health aspects while reference values are in most cases statistically based (Salthammer, 2011).

This section is in three subsections:

- As this study focuses on London schools, the first two subsections will focus on the performance standard document Building Bulletin 101 ”Ventilation in School Buildings” (BB101), which is introduced as a means of demonstrating compliance with the new Building Regulations Part F (Ventilation) (HM Government, 2010) in new and refurbished English and Welsh school building stock. In BB101, CO_2 concentrations have been chosen as the key performance indicator for the assessment of IAQ and ventilation in schools. Moreover, relevant standards applicable worldwide(ASHRAE, ISO and EN) will be compared with the performance standard BB101.

- in the third subsection guideline and reference values for organic and inorganic air pollutants are presented. The guideline values reported in this section are derived by expert committees of the World Health Organisation (WHO), an official international organisation, which documents their judgement in accompanying reports. In 2006 the WHO elaborated criteria (identification, format, work plan and existing systematic reviews) for deriving indoor environmental guideline values on the international level (WHO, 2006). WHO guidelines provide a scientific basis for legally enforceable standards for indoor environments.

2.3.1 Thermal conditions

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: 2005, ASHRAE Standard 55: 2010 and at the European level EN 15251: 2007.

The thermo-physiological model was developed by Fanger (1970) based on extensive American and European experiments which involved over 1000 adults exposed to well-controlled environments. The model equation developed is presented in ISO 7730, and can be used to calculate Predicted Mean Vote (PMV). This predicted thermal sensation can be transferred to the predicted thermal comfort in the form of Predicted Percentage Dissatisfied (PPD), which is the predicted percentage of people in a large group that will be dissatisfied at a PMV value. The calculation of PMV takes into account the thermo-physiological properties of humans and their balance with the environment. On a personal level, this includes the activity level and clothing insulation. The thermal environment is determined by the variables air temperature, mean radiant temperature, relative humidity and air velocity. The recommended temperature range lies between 20 °C ±1 and 24.5 °C ±2.5 depending on season.

The latest versions of the standards ASHRAE 55: 2010, ISO 7730: 2005 and EN 15251: 2007 include also an adaptive thermal comfort diagram in the evaluation of thermal comfort of a not 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. Adaptive models have been developed through fieldwork and state that thermal preferences depend on the way people interact with their environment, modifying their own behaviour and adapting their expectations to match the thermal environment.

The Building Bulletin 101 (BB101) (DfE, 2014) was developed to regulate indoor thermal conditions in English classrooms and to assess the risk of overheating at design stage and under operational conditions. Performance in use for the Priority Schools Building Programme specifies that when the external air temperature is above 20 °C, average temperature difference over 30 minute intervals should not exceed 5 °C. Regarding the heating season, regulatory framework focuses on minimum indoor temperatures in the workplace of 16 °C (HSE, 2013).

2.3.2 Ventilation rates and carbon dioxide levels

Ventilation is the process of exchanging indoor polluted air with outdoor (presumably) fresh and clean air and provides simultaneous catering for adequate IAQ and thermal comfort. Recent versions of the standard ASHRAE 62.1-2010 determining IAQ in North America and some other countries recommend minimum ventilation rates in the breathing zone based on the number of occupants and a building's surface area, and aim to dilute bio-effluents from occupants and emissions from building materials to improve perception of IAQ. More specifically, for school classrooms accommodating children younger than nine years old, a minimum of 5 L/s-p is recommended together with 0.6 L/s per m^2. Assuming an occupancy density of 2 m^2/p (Section 1.1), then a minimum airflow rate of 6.2 L/s-p should be provided in primary school classrooms. Maximum recommended CO_2 levels can be inferred from ventilation rates as 856 ppm by using equation 2.1 (ASHRAE 62.1- 2010), assuming outdoor CO_2 levels of 450 ppm, and an occupancy number of 25 pupils (Section 1.1).

$$C_{(\mathrm{in})} = C_{(\mathrm{out})} + m\kappa \frac{P}{V} \tag{2.1}$$

where

$C_{(\mathrm{out})}$	= outdoor CO_2 levels	450 ppm
m	= metabolic rate	1.2 met
κ	= conversion constant	84
P	= number of people	(-)
V	= ventilation rates (L/s-p)	

Similarly to the ASHRAE standard, the European standard EN ISO 15251:2007 also specifies minimum ventilation rates based on occupancy density, emission rates of building materials and comfort criteria (Predicted Percentage of Dissatisfaction (PPD) with IAQ). The standard classifies three categories of buildings based on predicted satisfaction with IAQ: category 1 buildings are expected to have less than 15% of the occupants dissatisfied with IAQ, category 2 buildings less than 20%, while in category 3 buildings, the PPD is expected to be less than 30%. Buildings with predicted percentage of dissatisfaction with IAQ higher than 30% do not meet the comfort criteria. Assuming again a density of 2 m^2/p, recommended ventilation rates range from the lowest required ventilation case scenario (PPD: <30%, very low emitting building) of 2.2 L/s-p up to 7.0 L/s-p for the highest required ventilation case scenario (PPD: <15%, non-low emitting building). These ventilation rates correspond to indoor CO_2 levels from 810 ppm to approximately 1600 ppm using equation 2.1.

In the UK, BB101 (2006) and the updated version Priority School Building Programme (PSBP) (DfE,2014) provide the regulatory framework for the adequate provision of ventilation in UK schools based on Part L and F of Building Regulations. More specifically, for naturally ventilated classrooms both standards recommend:

- the average concentration of CO_2 during the occupied period should not exceed 1500 ppm, and a daily average of 5 L/s-p shall be provided;
- at any occupied time the occupants should be able to reduce the concentration of CO_2 to 1000 ppm, and achieve a minimum of 8 L/s-p;
- minimum ventilation rates shall not fall below 3 L/s-p. According to BB101 (2006) maximum CO_2 concentrations during a typical teaching day shall never exceed 5000 ppm, while the updated version specifies that maximum CO_2 levels shall not exceed 2000 ppm for more than 20 minutes (DfE, 2014).

2.3.3 Guidelines for specific indoor pollutants

The reliance on proxies for IAQ assessment reflects the relative difficulty and expense of obtaining measurements of specific pollutants and identifying any related health effects. The guidelines have been developed allowing for the reduction of health impacts of air pollution based on a comprehensive review and evaluation of the accumulated scientific evidence.

The guidelines are applicable in settings occupied by the general population, such as homes and public spaces. The same guidelines are also applicable in day care settings, although lower limits might be necessary to protect children, who are more susceptible to air pollution. Table 2.2 presents guideline values for chemicals targeted in this study (Table 3.1), which are often found indoors in concentrations of health concern.

Table 2.2: 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

The concentrations of airborne trichloroethylene (T3CE) associated with an excess lifetime cancer risk of 1/10 000, 1/100 000 and 1/1 000 000 are 230, 23 and 2.3 μg/m^3 respectively.

The excess relative risk, based on long-term (30-year) average radon exposure is about 16% per increase of 100 Bq/m^3, and on this relative scale does not vary appreciably between current smokers, ex-smokers and lifelong non-smokers. In view of the latest scientific data, 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. The current Action Level in the UK is set at 200 Bq/m^3 (Health Protection Agency, 2009).

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 VOCs (TVOCs) has been introduced in existing literature. The first exposure-range classification relative to the TVOC level was suggested by a committee of the European Collaborative Action Indoor Air Quality and its Impact on Man (ECA, 1992), which has since then formed the basis for VOC measurement by means of GC/MS following thermal desorption on Tenax TA (Molhave et al., 1997). In this case, the range of VOCs to be included in the TVOC value is defined by the retention window between n-hexane (C6) and n-hexadecane (C16) under clearly defined analytical conditions (BS ISO 16000-6: 2011). Based on the above method, in some countries, thresholds for TVOCs in indoor non-industrial environments have been developed, and most of them are in the magnitude of 200 to 600 μg/m^3 (Salthammer, 2011) to prevent discomfort and acute distinct health issues. In the UK, the recent version of Building Regulations Part F (HM Government, 2010) based on the European Collaborative Action (ECA, 1992) recommends concentrations below 300 μg/m^3 for domestic buildings.

It is also common to measure TVOC by use of direct reading instruments like photo acoustics (PAS), flame ionization (FID) and photo-ionization (PID) (BS ISO 16000-29: 2014). To date, this has caused confusion because TVOC recommendations are often not accompanied by a clear TVOC definition. The concentration given by each detector type when exposed to mixtures in an environment is not equivalent because of the different nature of the detection principles (BS ISO 16000-29: 2014), and therefore the VOC mixture concentration from instrumental sampling would not be equivalent to the TVOCs values determined with the BS ISO 16000-6. Currently, the TVOC value is widely accepted as a screening parameter but is not recommended to be used as an indication of health, as the TVOC concept does not consider indoor chemistry.

Indoor environments with high occupancy density such as schools have high indoor biological concentrations (Salo et al., 2009). Due to the complexity of the fungal exposure assessment, there is a lack of clearly defined threshold levels for fungi and substances derived from fungi. Based on findings from cross-sectional and cohort studies, thresholds associated with allergic sensitisation (Salo et al., 2009) are 1 000 ng/g for cat allergen (Fel d 1) and 2 000 ng/g for dog allergen (Can f 1). The threshold for asthma symptoms in sensitised individuals is 8 000 ng/g and 10 000 ng/g for cat and dog allergens respectively. However, these thresholds are indicative as quantification depends on method of sampling and correlation between different methods has been poor (Karlsson et al., 2002).

2.4 Physical, chemical and microbial parameters in school settings and their effects on health and comfort

While some studies have investigated levels of specific pollutants in school environments, the vast majority have focused on CO_2 levels and ventilation rates. In addition, building regulatory frameworks for the provision of adequate IAQ has also been framed around CO_2 levels and ventilation rates rather than specific pollutants.

Studies assessing the effects of school exposure have typically obtained either broad-scale measurements from central stations, or school-based scales by monitoring pollutants in school buildings and their immediate surroundings, or calculated exposures at the personal scale using monitors attached to a number of children.

Information compared in this section highlights the degraded air quality noticed in monitoring studies, and their critical relationship to health implications addressed in exposure studies in the school environment.

2.4.1 Thermal conditions in school settings

Studies on thermal comfort in schools are scarce and most focus on tropical and sub-tropical settings (Table 2.3) in children over 13 years old. Overall, in warm climates the findings indicate that satisfaction of the occupants with thermal conditions was dependent on season (Corgnati et al., 2009) and ventilation system, as occupants in naturally ventilated classrooms accepted a wider range of temperatures compared with occupants in mechanically ventilated classrooms (Kwok & Chun, 2003; Wong & Khoo, 2003).

In the UK, only one study in secondary (Mumovic et al., 2009) and one in primary schools (Teli et al., 2012) investigated thermal comfort of students. Mumovic et al. (2009) reported a tendency for winter overheating with temperatures as high as 28.9 °C. The most common reason for such high temperatures was that classroom ventilation rates were too low to mitigate overheating caused by high internal heat gains and solar radiation. Suggestive consistent evidence indicates that children 9 to 11 years attending schools in temperate climates (Mors et al., 2011; Teli et al., 2012) may be more sensitive to higher temperatures than adults. When the

Table 2.3: Thermal comfort field studies in school classrooms

Study	**Age Group**	**Country**	**Climate**	**Ventilation Type**
Wong & Khoo (2003)	13 to 17	Singapore	Tropical	NV
Kwok & Chun (2003)	13 to 17	Japan	Sub-tropical	NV, MV
R.-L. Hwang et al. (2006)	11 to 17	Taiwan	Sub-tropical	NV
Liang et al. (2012)	12 to 17	Taiwan	Sub-tropical	NV
Corgnati et al. (2007)	12 to 23	Italy	Mediterranean	NV
Corgnati et al. (2009)	12 to 23	Italy	Mediterranean	NV
Mors et al. (2011)	9 to 11	Netherlands	Temperate	NV
Teli et al. (2012)	9 to 11	UK	Temperate	NV
Mumovic et al. (2009)	12 to 16	UK	Temperate	NV, MM, MV

NV= Natural Ventilation, MM= Mixed Mode, MV= Mechanical Ventilation

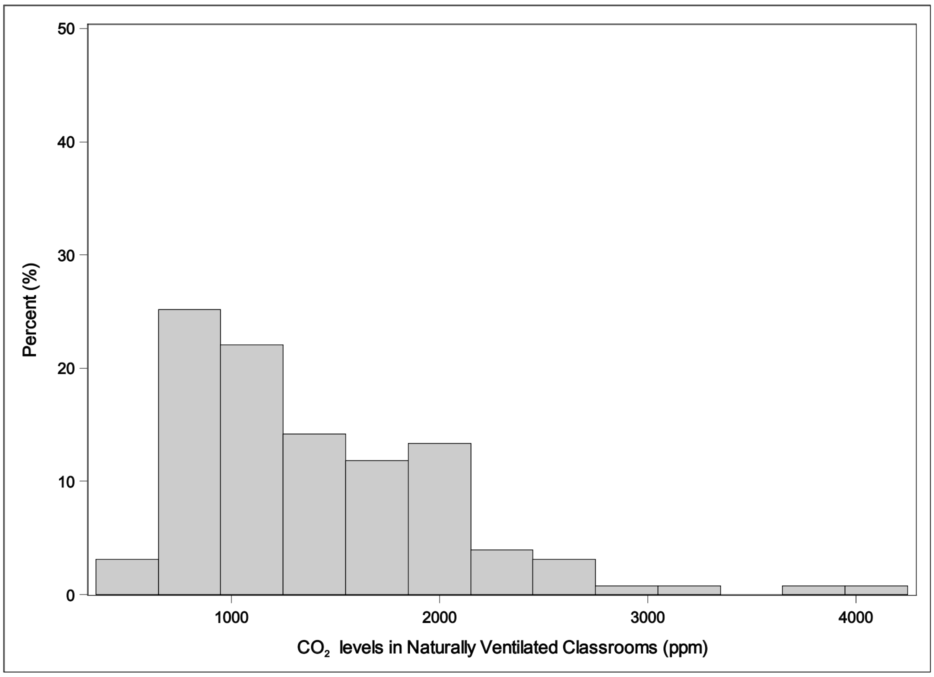
actual thermal sensation votes of children were compared with comfort predictions and adaptive temperature limits, lower temperatures than predicted by these methods were preferred. More specifically, comfort temperatures were found 4 °C lower than the PMV and 2 °C lower than the EN 15251 adaptive comfort model predictions (Teli et al., 2012).

Limited evidence is currently available on the health effects of indoor classroom temperatures on children. One study (Mi et al., 2006) used a relatively large sample of 1414 pupils (age 13-14 years old) attending 30 classrooms in 10 naturally ventilated schools in China, and monitored a large number of pollutants. Recorded average indoor temperatures of 17 °C (range: 13 to 21 °C). The study suggested that lower temperatures in this range may have a protective effect on health by reducing breathlessness among students (OR=1.26 per 1 °C; $p < 0.001$), and the association remained significant after controlling for other exposures. While lower temperatures might be associated with higher ventilation rates purging indoor pollutants, the findings must be interpreted with caution, as the paper does not provide information on the schools' heating systems that could potentially affect exposure. Moreover, the confounding effect of temperature is an inherent limitation in all epidemiological investigations (Reid et al., 2012).

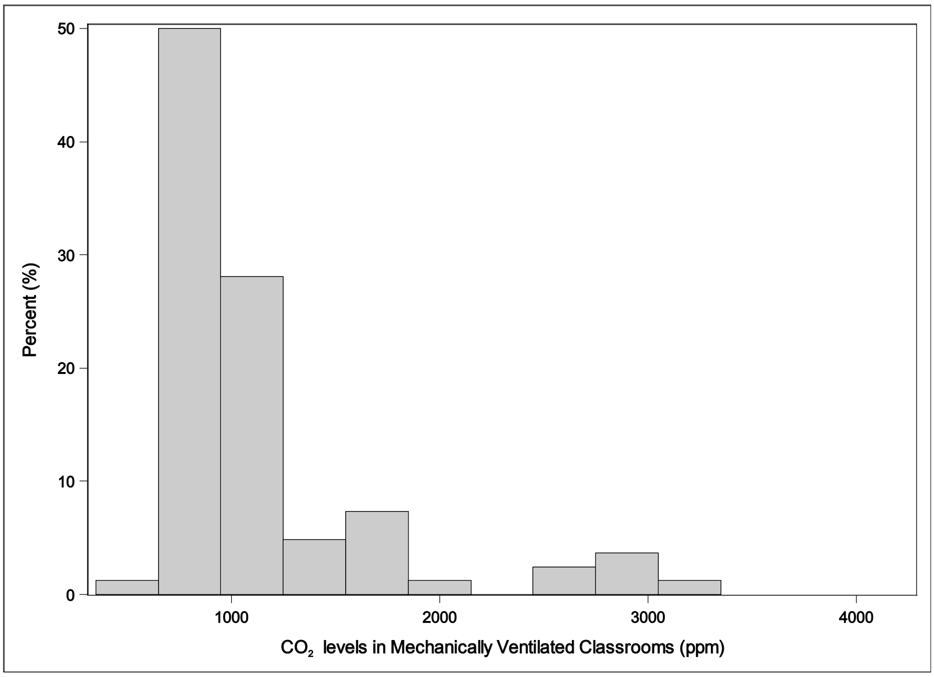
2.4.2 Ventilation rates and carbon dioxide levels

In order to evaluate the existing knowledge on ventilation conditions in school settings, a number of papers (Table 2.4) reporting on both CO_2 levels and ventilation rates in naturally and mechanically ventilated schools were analysed. Eight of the papers on naturally ventilated schools used tracer gas measurements, while the rest used the metabolic CO_2 levels to estimate the ventilation rates. Some papers only reported average values of CO_2 and ventilation rates, while other papers additionally reported minimum and maximum values.

The database created showed that a highly skewed distribution described concentrations of CO_2



(a) Distribution of indoor daily average CO_2 concentrations in 555 naturally ventilated classrooms reported in the literature



(b) Distribution of indoor CO_2 concentrations in 900 mechanically ventilated classrooms reported in the literature

Figure 2.2: Distribution of indoor CO_2 in classrooms in the literature (Table 2.4)

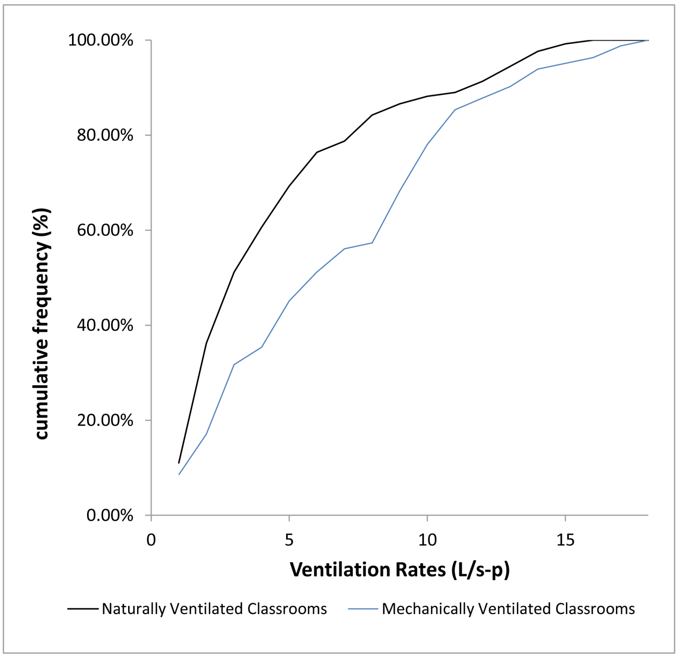


Figure 2.3: Cumulative frequency distribution of the mean ventilation rates (L/s-p) during the teaching period for the naturally and mechanically ventilated schools in theliterature (Table 2.4)

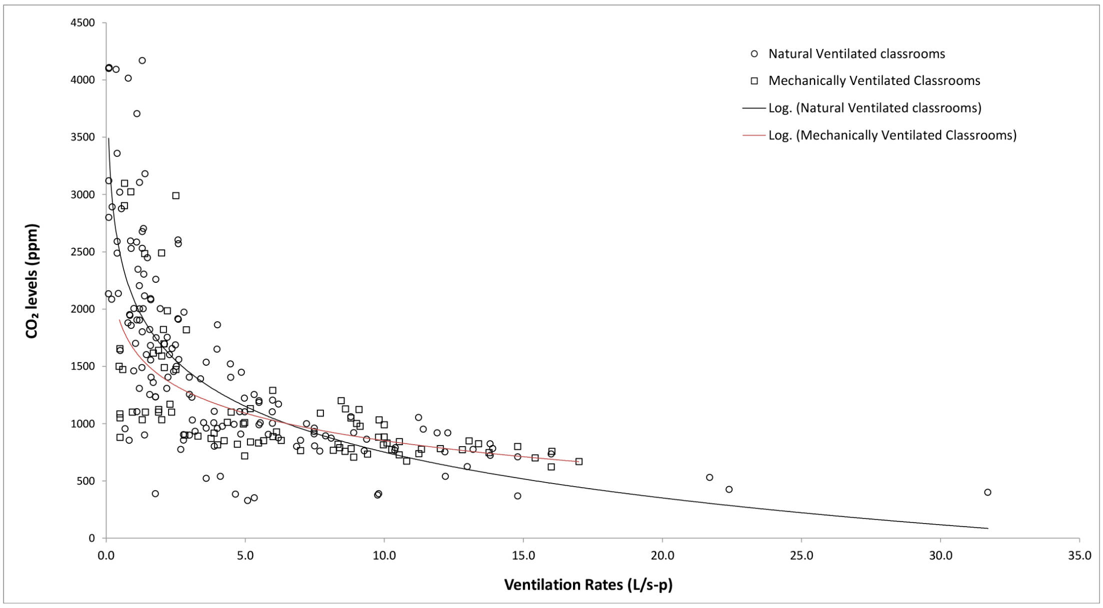


Figure 2.4: Correlation between indoor CO_2 concentrations (ppm) during the teaching and the resulting ventilation rates in naturally and mechanically ventilated schools included in the literature (Table 2.4)

in 555 naturally and 900 mechanically ventilated classrooms (Figure 2.4). It was found that naturally ventilated classrooms had higher indoor median CO_2 levels of 1234 ppm (interquartile range: 920 to 1801 ppm) compared with mechanically ventilated settings which had median indoor CO_2 levels of 922 ppm (interquartile range: 803 to 1128 ppm) (Figure 2.2). Only the 35% of the naturally ventilated classrooms had daily average CO_2 concentrations below 1000 ppm, while for mechanically ventilated schools the figure increases to 55%.

Median ventilation rates provided in naturally ventilated classrooms were 3 L/s-p (interquartile range: 1.5 to 6 L/s-p). Median ventilation rates in mechanically ventilated classrooms were almost twice as high compared with natural settings (median: 5.8 L/s-p, interquartile range: 2.3 to 9.8 L/s-p). The cumulative distribution of ventilation rates showed (Figure 2.3) that 70% of the naturally and 45% of the mechanically ventilated classrooms had mean ventilation rates below 5 L/s-p.

The relation between CO_2 concentrations and the corresponding ventilation rates may be described by an exponential curve (Figure 2.4). Overall, the large number of studies clustered in Figure 2.4 towards the lower end of the range of ventilation rates suggests that low ventilation rates and high CO_2 rates were common, and only a relatively small percentage of classrooms managed to comply with international standards ASHRAE 62.1-2010 and EN ISO 15251:2007 (Section 2.3.2).

Lower ventilation rates have been linked to increased infection risk in a range of environments, including schools, with the Wells-Riley equation since the 1970s. Because airborne communicable infection can only be acquired by inhaling air that has been previously exhaled, a study linked the probability of airborne infection to CO_2 levels directly (Rudnick & Milton, 2003). Previous meta-analytic studies have reported that low ventilation rates in schools are linked to adverse health effects in children and adults (Daisey et al., 2003; Mendell & Heath, 2005; Wargocki et al., 2002).

Four studies (Mendell et al., 2013; Mi et al., 2006; Shendell et al., 2004; Smedje & Norbäck, 2000) aimed to quantify the association between ventilation rates and CO_2 with absenteeism

Table 2.4: Studies providing evidence on CO_2 and ventilation rates in school settings included in the review

Setting	N_{papers}	$N_{schools}$	$N_{classrooms}$	References
Naturally ventilated schools	16	261	555	Mendell et al. (2013), Bakó-Biró et al. (2012), Mumovic et al. (2009), Santamouris et al. (2008), Bakó-Biró et al. (2007), Fromme et al. (2007),HESE (2006), Mi et al. (2006), Zhao et al. (2006), Kim et al. (2005), Beisteiner & Coley (2002), Kolokotroni et al. (2002), Lee & Chang (2000), Scheff et al. (2000), Smedje, Norbäck, & Edling (1997), Walinder et al. (1997)
Mechanically ventilated schools	17	200	900	Mendell et al. (2013), Wargocki & Wyon (2013), Bakó-Biró et al. (2012), Haverinen-Shaughnessy et al. (2011), Morse et al. (2009), Mumovic et al. (2009), Santamouris et al. (2008), Godwin & Batterman (2007), HESE (2006), Ramachandran et al. (2005), Shaughnessy et al. (2006), Fox et al. (2003), Kinshella et al. (2001), Lee & Chang (2000), Scheff et al. (2000), Walinder et al. (1997), Norbäck (1995)

and asthmatic symptoms (which may be triggered by viral infections) (Table 2.5). Increased indoor CO_2 levels were associated with current asthma and asthma medication in children (Mi et al., 2006). One study (Smedje & Norbäck, 2000) was organised as a case-crossover intervention with newly installed mechanical ventilation systems in a sample of 1,476 primary and secondary school pupils in 39 randomly selected Swedish schools. It was found, that the increased outdoor air flow rate from 1.3 to 12.8 L/s-p, with a corresponding decrease of mean indoor CO_2 from 1050 to 780 ppm, resulted in a significant reduction of asthmatic symptoms in pupils from 11.1% to 3.4% over the two-year period. One study (Walinder et al., 1997) that used non-invasive medical tests (acoustic rhinometry) in adult school occupants attending 12 schools associated increased CO_2 levels with inflammatory biomarker response of the nasal mucosa.

Only two strongly designed studies associated ventilation rates and CO_2 levels in the classroom with absenteeism (Table 2.5). Both studies used a large sample size and were organised as case-crossover, where each student served as their own control. These studies (Mendell et al., 2013; Shendell et al., 2004) controlled for socioeconomic and demographic characteristics of the population. An increase in CO_2 concentrations by 1000 ppm was associated ($p<0.05$) with a 0.5 - 0.9% decrease in annual average daily attendance corresponding to a relative 10 - 20% increase in student absence (Shendell et al., 2004). Mendell et al. (2013) used a more robust methodology in a sample of 162 classrooms located in 28 primary schools in three climatic districts over a two-year period, as the study employed a more detailed estimation of ventilation rates inferred from real-time CO_2 monitoring compared with Shendell et al. (2004) that used spot measurements of CO_2 levels which might not reflect indoor conditions accurately. Moreover, Shendell et al. (2004) used *total* absence as an outcome, without separating illness absence from other types

Table 2.5: Information on studies associating indoor CO_2 levels and ventilation rates in schools with health effects of students

Study	Setting	Subjects	Ventilation rates	CO_2 concentrations (ppm)	Methodology	Analysis	Results
Mi et al. (2006)	N_s=10, N_{cl}=30	13-14 years old, N_c= 1414	2.9- 29.4 ACH	1060 (370), range: 530-1910	Self-reported health questionnaire, number of students, T, RH, NO_2, O_3, formaldehyde	Multiple logistic regression	indoor CO_2 was related with current asthma OR= 1.18 for 100 ppm ($p<0.01$) and asthma medication OR= 1.15 for 100 ppm ($p<0.05$)
Smedje & Norbäck (2000)	N_s=39	616 years, N_c= 1476	4.4 vs. 12.8 L/s-p	1050 ppm vs. 780 ppm	Self-administered questionnaire posted to parent	Multiple logistic regression	At least one asthmatic symptom was less common with increased ventilation
Shendell et al. (2004)	N_s=22, N_{cl}=436	3-11 years	No data	range δCO_2: 10 to 4230	Total Absenteeism, Ethnicity, Free School Meals, Room type	multivariate linear regression models between absenteeism and indoor CO_2 levels	10- 20% relative increases in student absence per 1000 ppm
Mendell et al. (2013)	N_s= 28, N_{cl}= 162	8-10 years	mean: 3.51 to 8.98 L/s-p	mean: 1200-2490	Illness-related absenteeism, room type, ventilation strategy, T, RH, Ethnicity, Free School Meals	zero-inflated negative binomial models	for each additional 1 L/s-p, ill-related absenteeism was reduced by 1% to 1.6%

N_s= Number of schools, N_{cl}= Number of classrooms, N_c= Number of children, δCO_2: Difference between indoor and outdoor CO_2 levels of absence unlikely to be influenced by ventilation rates. Mendell et al. (2013) consistently (regardless of climate, season, ventilation strategy) estimated that in the range from 4.0 L/s-p to 7.1 L/s-p for every 1 L/s-p increase in classroom ventilation rates illness related absences were reduced by 1.0 to 1.5% ($p<0.01$). Converting the findings of Shendell et al. (2004) to a comparable metric, each additional 1 L/s-p was associated with a 2.1 - 7.6% relative decrease in illness absence, approximately 2 to 5 times larger than the findings reported in Mendell et al. (2013). Explanation for the discrepancies included the different methods of estimation of ventilation rates, as well as the distinction in the outcome between illness-related and total absenteeism which could inflate results. A similar study in office workers found a 2.9% decrease in short-term illness absence in adults per 1 L/s-p increase in ventilation rates (range: 12 to 24 L/s-p) Milton et al. (2000).

In summary, the association between higher CO_2 levels and lower ventilation rates with increased probability of airborne communicable infection are well-established in the literature. Indoor CO_2 concentrations can be considered a measure of risk of transmission of airborne disease throughout the classroom. The above studies strengthen the evidence for a relationship between reduced ventilation rates and increased CO_2 levels with higher prevalence of health effects that might be explained by the increased risk of contracting viral infections, which are likely to result in school absenteeism and trigger asthmatic symptoms in susceptible individuals (e.g. asthmatic children). It can be hypothesised that decreased ventilation rates in classrooms may be associated with increased illness absences from respiratory infections, due to increased indoor airborne concentrations of respiratory virus. However, as these studies are correlational, causality cannot be established.

2.4.3 Particulate Matter

In addition to its gaseous components, indoor air may contain a variety of contaminants that occur as airborne particles. Conventionally, particles are classified by their aerodynamic diameter (usually referred to as particle size) because these properties govern the transport and time of suspension in the air, their deposition in the lungs, and they are generally related to their chemical composition (Morawska & Salthammer, 2003). The main indoor sources of particles in school environments include human activities, plants and building materials, especially mineral fibres. Particles also penetrate in the classrooms through ventilation and infiltration from the outdoor environment, particularly in urban areas where exhausts from vehicles are the main sources.

Comparison between studies monitoring PM in the classrooms was complicated by large differences in the design of the studies including duration, number of schools monitored and instrumentation used (Table 2.6). Indoor mean PM_{10} concentrations in school classrooms reported in the literature ranged from 30 to 104 $\mu g/m^3$ (minimum-maximum: 12 to 313 $\mu g/m^3$) (Figure 2.5). Indoor mean $PM_{2.5}$ concentrations ranged from 12 to 37 $\mu g/m^3$ (minimum-maximum: 1 to 80 $\mu g/m^3$) (Figure 2.6).

Table 2.6: Information on studies quantifying indoor PM concentrations in school settings

Study	**Location**	**School setting**	**Duration of measurements**	**Method**	**PM fractions**
Goyal & Khare (2009)	New Dehli	N_{cl}=1 in a NV school (Urban)	1 year	Optical Photometer (*Grimm Technologies*)	PM_{10} $PM_{2.5}$ PM_1
Fromme et al. (2007)	Munich	N_s=64, N_{cl}=92	winter/summer	Gravimetric and optical photometers(*Grimm Technologies and TSI model 3034*)	PM_{10} PM_4 $PM_{2.5}$
Branis et al. (2005)	Prague	lecture theatre	1 week (winter season)	Gravimetric (*Harvard impactors, Teflon filters*)	PM_{10} $PM_{2.5}$ PM_1
Patel et al. (2009)	NY	N_s=5, (3 urban, 2 suburban schools)	over 2 years: 4 to 6 weeks in the summer and spring season	Beta Attenuation Monitor	$PM_{2.5}$
Heudorf et al. (2009)	Frankfurt	N_s=1	3 weeks	Gravimetric (DUSTTRACK Aerosol Monitor Typ 5820) and Optical Methods (Grimm Technologies)	PM_{10}
Weichenthal et al. (2008)	Ontario	Ns=2 (Urban), N_{cl}= 37	1 week	Optical counter (*TSI P-TRACK*)	PM_1 (0.02-1 μg)
Guo et al. (2008)	Suburban	N_{cl}=1, MV	2 weeks (September)	Optical Counter (*TSI, Model 3071A*)	PM_1 (0.014-0.8 μg)
Aliboye et al. (2006)	UK	N_s=8, N_{cl}=16	Duration of measurements	Gravimetric method over the occupied period and 24-hr indoors (micro-fiber filters), TSI P-Tack ultrafine particles	PM_{10}, PM_1
HESE (2006)	6 European countries	N_s= 21, N_{cl}=46	Duration of measurements	Gravimetric method over the occupied period indoors and outdoors	PM_{10}

N_s= Number of schools, N_{cl}= Number of classrooms, NV= Naturally ventilated, MV= Mechanically ventilated

Currently, there is still little quantitative information available about the concentration levels of very small particles (PM_1), not only in schools, but also in other indoor and outdoor environments. Concentrations recorded in various countries to date range from 188 n/cm^3 to 14,300 n/cm^3 (Guo et al., 2008; Weichenthal et al., 2008). Branis et al. (2005) recorded average mass PM_1 concentrations with gravimetric methods in a naturally ventilated school gym of 10.9 $\mu g/m^3$ (range: 3.5 to 34.4 $\mu g/m^3$). The measurement process requires the use of particle counters due to the limitations of laser meters in detecting ultrafine particles. Linked to the complexity of assessments of particles in indoor environment related to technical and instrumental limitations, there are limitations in understanding the causal relationships between exposures to particles and resulting health responses. Sub-micrometre particles are generated mainly from combustion, gas to particle conversion, nucleation or photochemical processes, and are typically composed of a mixture of components including soot, acid condensates, sulfates, nitrates and traces of metals and toxins (Fromme et al., 2008).

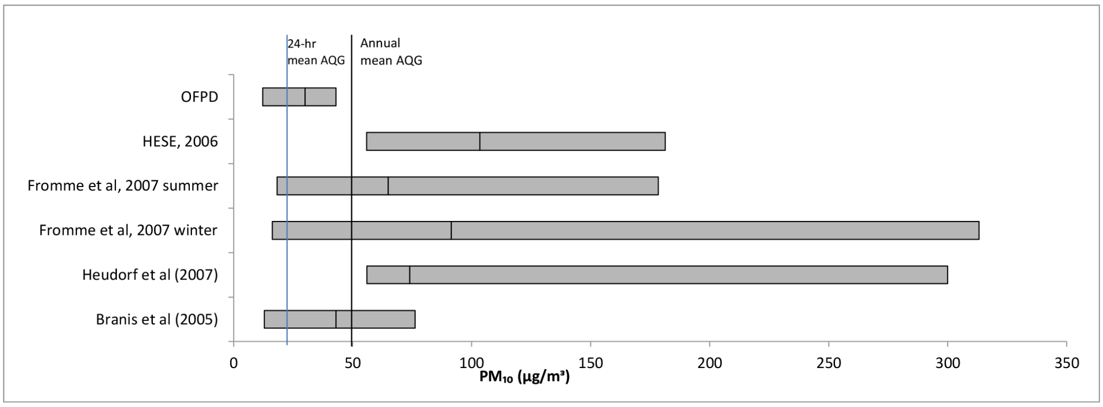


Figure 2.5: Range of PM_{10} in 159 classrooms in 96 schools (Table 2.6). Vertical lines indicate WHO 2010 recommended guidelines (Table 2.2)

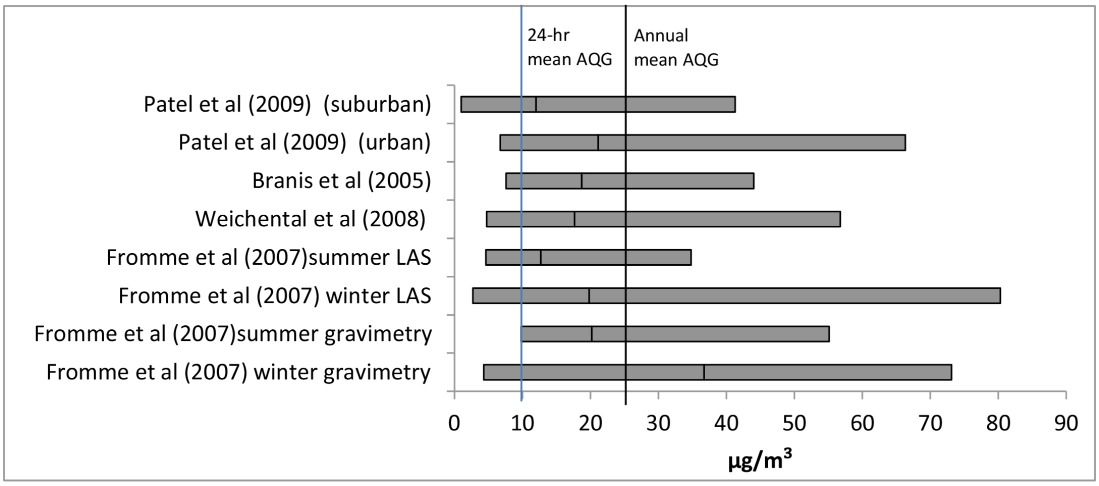


Figure 2.6: Range of $PM_{2.5}$ in 72 schools (Table 2.6). Vertical lines indicate WHO 2010 recommended guidelines (Table 2.2)

One recent systematic meta-analysis (Gasana et al., 2012) included nine studies on the association between PM exposure with asthma in children, but only six were concerned with school-aged children. Five of them used the ISAAC methodological framework (B. F. Hwang et al., 2005; Janssen et al., 2003; Kim et al., 2004; Shima et al., 2010; Zhang et al., 2002) to assess exposure, and only one study (Linares et al., 2010) used non-invasive medical tests (spirometry). All studies collected data from outdoor monitoring stations, which may not represent indoor school exposure accurately. Only one study (Timonen, 2002) in the literature reported toxicological effects from exposure to PM_1 at school mainly related to impairment of baseline lung function in children with chronic respiratory illness. The positive association between PM exposure with incidence of wheeze in children was quantified in the meta-analytic study (Gasana et al., 2012), and the summary effect estimate was meta-OR: 1.05 (95%CI:1.04-1.07). The effects of PM exposure in the development of wheeze and asthma in children are inconsistent: suggestive evidence associates PM exposure and lower respiratory symptoms (wheezing, bronchitis), and the association is stronger for the fine particles (Gasana et al., 2012).

Furthermore, there is indicative evidence that exposure to $PM_{2.5}$ concentrations even at levels commonly monitored in schools (Figure 2.6) may be associated with current conjunctivitis, hay-fever, and sensitisation to outdoor allergens (Janssen et al., 2003). Epidemiological studies failed to detect an association between PM_{10} with prevalence and incidence of asthma (B. F. Hwang et al., 2005; Janssen et al., 2003; Kim et al., 2004; Shima et al., 2010).

Only two recent studies investigated the effect of PM exposure on absenteeism (Chen et al., 2000; Park et al., 2002). Two epidemiological studies associated elevated outdoor PM_{10} levels with school absenteeism (Park et al., 2002; Ransom & Pope, 1992). Ransom & Pope (1992) collected absenteeism data from a nursery and primary school over a five-year period, and estimated that an increase of 40% ($p < 0.01$) in school absences was associated with an increase of outdoor PM_{10} from 50 to 100 $\mu g/m^3$. The effect lagged up to three to four weeks, and with younger children aged 5 to 8 years old primarily affected. Park et al. (2002) estimated that the relative risk for illness-related absenteeism was 1.06 (95%CI: 1.04-1.09) per 42.1 $\mu g/m^3$ increase of PM_{10}. The study was organised as a longitudinal study over a four year period; however the sample was relatively small including only one school. Chen et al. (2000) used a relatively large school sample; however the study failed to separate illness-related from non-illness related absenteeism, which might explain the negative association between PM_{10} exposure and absenteeism.

2.4.4 Nitrogen dioxide and ozone

In total, six studies monitored indoor concentrations of NO_2 in classrooms with mean levels fluctuating from 8.3 to 77.0 $\mu g/m^3$ (Figure 2.7). Blondeau et al. (2005) reported, in eight French schools, mean concentrations of 11.6 $\mu g/m^3$ in the summer (median range: 0.0 to 17.9 $\mu g/m^3$) and 12.8 $\mu g/m^3$ in winter (range: 4.2 to 33.3 $\mu g/m^3$). Similar median results of 10.4 $\mu g/m^3$ (median range: 3.0 -15.1 $\mu g/m^3$) were reported in HESE (2006) study in six European cities in 46 classrooms located in 21 schools. Lowest mean indoor O_3 concentrations were reported in 10 schools in Shanghai (Mi et al., 2006) and ranged from 1.1 to 8.6 $\mu g/m^3$ (average: 5.5 $\mu g/m^3$ ± 3.1) (Figure 2.8).

NO_2 has often been adopted as pollutant surrogate in epidemiology to estimate traffic exposure, as it is generated by fuel combustion. Growing evidence supports the relation between exposure to traffic related pollutants, and especially NO_2, in the school environment with health responses from children. Meta-analytic research (Gasana et al., 2012) included 19 studies on the association between exposure to NO_2 levels and asthma in children, and the synthesis of the findings reported a positive association between exposure to NO_2 with higher prevalence (meta-OR: 1.05, 95% CI: 1.00-1.11) and incidence (meta-OR: 1.14, 95%CI: 1.06-1.24) of childhood asthma. Out of the 19 studies, 11 were recent (post 2000) and focused on school aged children. Out of those studies, 10 employed the ISAAC methodology obtaining data from fixed

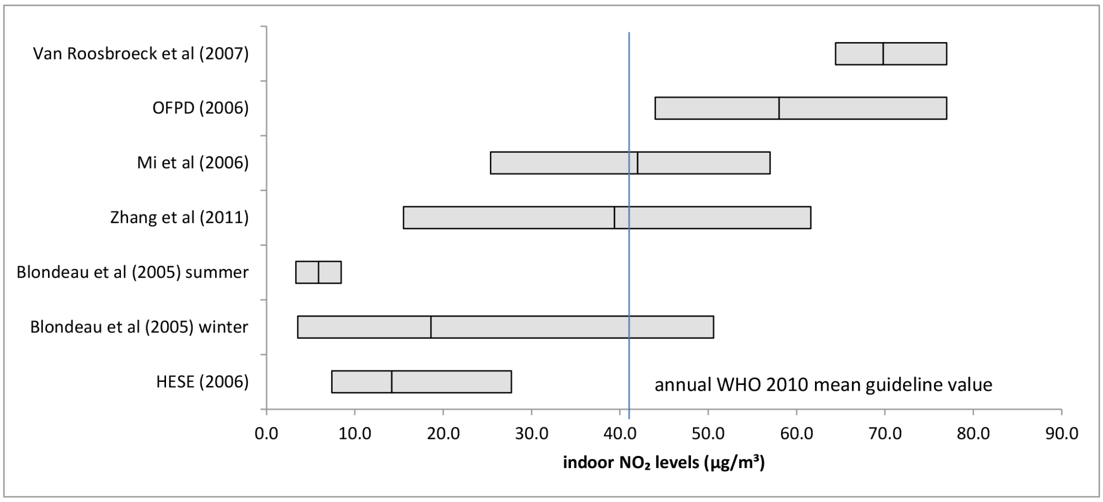


Figure 2.7: Range of NO_2 levels in 102 classrooms in the literature. Vertical line indicates WHO 2010 recommended annual guideline values (Table 2.2).

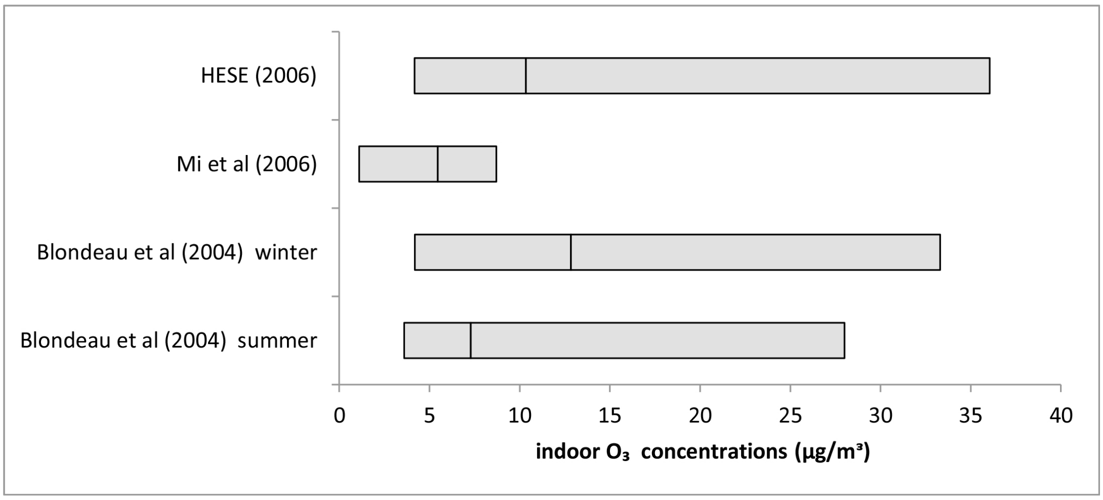


Figure 2.8: Range of O_3 levels in 64 classrooms in the literature

outdoor monitoring sites, which might differ from classroom exposure. Only one study (Linares et al., 2010) employed spirometry tests.

Apart from asthma and asthmatic symptoms, exposures were related to increased respiratory symptoms, allergy exacerbations (especially to indoor allergens), current conjunctivitis, current wheeze and current itchy skin rash compared with children exposed to urban background concentrations (Janssen et al., 2003; Van Roosbroeck et al., 2007). There is some limited evidence suggesting that indoor peak concentrations might be more important than average exposure. Pilotto et al. (1997) found a significant association between absenteeism and hourly school exposure of 150 $\mu g/m^3$, which is below WHO (2010) guidelines of 200 $\mu g/m^3$ for peak concentrations.. That study reported much higher indoor NO_2 concentrations (up to 304 $\mu g/m^3$) than the more recent studies (Figure 2.7) as levels were strongly affected by the heating systems of the classrooms (un-flued gas).

School illness related absenteeism increased at higher outdoor concentrations of O_3 (Park et al., 2002), and could be significantly predicted if lagged effects of exposure were taken into consideration (Chen et al., 2000; Gilliland et al., 2001). Park et al. (2002) estimated that relative risks of illness related absenteeism for O_3 were 1.08 (95% CI: 1.06-1.11) per 32 $\mu g/m^3$, while Gilliland et al. (2001) for a similar increase in exposure quantified an increase of 63% risk of illness related absenteeism with the effects lagged for a period of five days. Chen et al. (2000) reported that an increase of 100 $\mu g/m^3$ in O_3 can increase the risk for illness related absenteeism by 13% with lagged effects taken into consideration. While WHO (2010) recommended ozone concentrations lower than 100 $\mu g/m^3$ over an 8-h period (Table 2.2), overall evidence suggested that minimum increase of 6% in relative risks of ill related absenteeism among children should be expected for an increase in the range of 30-50 $\mu g/m^3$.

Specific health effects accounting for absenteeism at high ozone concentrations were mostly related to respiratory illness. Gilliland et al. (2001) quantified that the relative risk per 40 $\mu g/m^3$ corresponded to an increase by 83% for respiratory illnesses, 45.1% for upper respiratory illnesses, and 174% for lower respiratory illnesses with wet cough. No relationship between respiratory symptoms and lower indoor ozone ranging from 1 to 9 $\mu g/m^3$ (17 to 28 $\mu g/m^3$ outdoors) (Mi et al., 2006) could be established.

2.4.5 Volatile Organic Compounds

VOCs include a variety of organic chemicals that are emitted as gases from certain solids and liquids. Indoor sources may be continuous or intermittent. The most important indoor continuous sources in schools are building construction materials, furniture and textiles. Intermittent sources include occupants and a number of their activities. Outdoor VOCs contribute to indoor air pollution, but concentrations are generally much lower.

There is sufficient evidence from both human and animal studies to believe that some VOCs have carcinogenic and mutagenic effects on human health. For example, benzene is classified as a carcinogen and no safe limit of exposure can be recommended (Table 2.2). VOCs are acutely and chronically toxic at low concentrations, so symptoms may not become completely manifest for years. Identifications of the most commonly reported specific compounds found indoors, in order of magnitude were formaldehyde, toluene, limonene, benzene, xylene, styrene, T3CE and T4CE. The VOC compounds presented in Table 2.7 include the compounds targeted in this study according to the SINPHONIE protocol. All studies used diffusive samplers and analysis was performed with GC-MS, and therefore values are comparable.

Table 2.7: Indoor and outdoor levels of specific VOCs measured in school classrooms according to season

Pollutant	**Season**	**Concentrations (μg/m^3)**	**Reference**
formaldehyde	Heating season indoors:	range: 14-87 , mean:30 (18)	Sofuoglu et al. (2011) Shendell et al. (2005) Zhang et al. (2006)
	Non-heating season indoors:	38	
benzene	Mean indoor winter:	0.6	Adgate et al. (2004)
	Mean outdoor winter:	1.3	
	Mean indoor spring:	0.6	
	Mean outdoor spring:	1.1	
	Mean indoor winter:	19.77	Pekey & Arslanba (2008)
	Mean outdoor winter:	16.41	
	Mean indoor spring:	7.5	
	Mean outdoor spring:	4.77	
	Median indoor:	2.6	Geiss et al. (2011)
	Median outdoor	2.1	
	Mean indoor:	1.4	Aliboye et al. (2006)
	Mean outdoor:	0.8	
	Mean indoor:	0.09	Godwin & Batterman (2007)
	Mean outdoor:	0.06	
toluene	Mean indoor winter:	2.9	Adgate et al. (2004)
	Mean outdoor winter:	2.6	
	Mean indoor spring:	1.6	
	Mean outdoor spring:	2.7	
	Mean indoor winter:	77.77	Pekey & Arslanba (2008)
	Mean outdoor winter:	41.69	
	Mean indoor spring:	55.05	
	Mean outdoor spring:	18.15	
	Mean indoor:	4.9	Aliboye et al. (2006)
	Mean outdoor:	3.8	
	Mean indoor:	2.81	Godwin & Batterman (2007)
	Mean outdoor:	0.52	
T3CE	Mean indoor winter:	0.2	Adgate et al. (2004)
	Mean outdoor winter :	0.3	
	Mean indoor spring:	0.1	
	Mean outdoor spring:	0.3	
	Mean indoor:	0	Aliboye et al. (2006)
	Mean outdoor:	0	
	Mean indoor:	0.02	Godwin & Batterman (2007)
	Mean outdoor:	0	
T4CE	Mean indoor winter:	0.4	Adgate et al. (2004)
	Mean outdoor winter:	0.2	
	Mean indoor spring:	0.3	
	Mean outdoor spring:	0.3	
	Mean indoor:	0	Aliboye et al. (2006)
	Mean outdoor:	0	
	Mean indoor:	0.02	Godwin & Batterman (2007)
	Mean outdoor:	0	
Pinene	Mean indoor winter:	0.2	Adgate et al. (2004)
	Mean outdoor winter:	0	
	Mean indoor spring:	0.2	
	Mean outdoor spring:	0.1	
	Median indoor:	1.5	Geiss et al. (2011)
	Median outdoor	0	
	Mean indoors:	1.35	Godwin & Batterman (2007)
	Mean outdoor:	0.11	
limonene	Mean indoor winter:	4.6	Adgate et al. (2004)
	Mean outdoor winter:	0.1	
	Mean indoor spring:	1.9	
	Mean outdoor spring:	0.4	
	Mean indoors:	4.41	Godwin & Batterman (2007)
	Mean outdoor:	0.29	
	Median indoor:	2.6	Geiss et al. (2011)
	Median outdoor:	0.2	
naphthalene	Mean indoors:	0.82	Godwin & Batterman (2007)
	Mean outdoor:	0.1	

VOCs can be up to 10 times more concentrated in indoor air compared with those in outdoor air. As it is possible to detect 50 different compounds indoors, each at a low concentration but higher than outdoors, the concept of total VOCs (TVOCs) has been introduced in existing literature (Molhave, 2009). Today, the TVOC value is widely accepted as screening parameter but is not recommended to be used as an indicator of health. Because of the relative complexity of associating TVOCs with health outcomes due to individual susceptibility, the unknown interaction of the compounds, and the near infinite possibility of variants in mixture composition with each compound having different toxicity, TVOCs can only be used as an indicator of sensory irritations.

Various studies have employed different analytical approaches (Table 2.8). Some studies reported one average value over the whole classroom sample, while others provided more detailed information. Indoor TVOCs measured in 255 classrooms (Table 2.8) formed a highly skewed

Table 2.8: Information on studies monitoring TVOC concentrations in classrooms

Study	**School setting**	**Duration of measurements**	**Method**
Sofuoglu et al. (2011)	N_s=3, N_{cl}=9	one typical teaching day in spring, winter and fall	diffusive sampling with pump: Tenax TA sorbent analysed with thermal desorption in GC-MS
Godwin & Batterman (2007)	N_s=21, N_{cl}=64	typical teaching week	Passive sampling: Tenax TA sorbent analysed with thermal desorption in GC-MS
Aliboye et al. (2006)	N_s=8, N_{cl}= 80	typical teaching week	no data
Smedje, Norbäck, & Ling (1997)	N_s=38, N_{cl}= 96	one typical teaching day	Selective Ion Monitoring GC-MS
Norbäck (1995)	N_s=6, N_{cl}=6	one typical teaching day	diffusive sampling with pump: Charcoal sorbent analysed with thermal desorption in TD-GC-MS

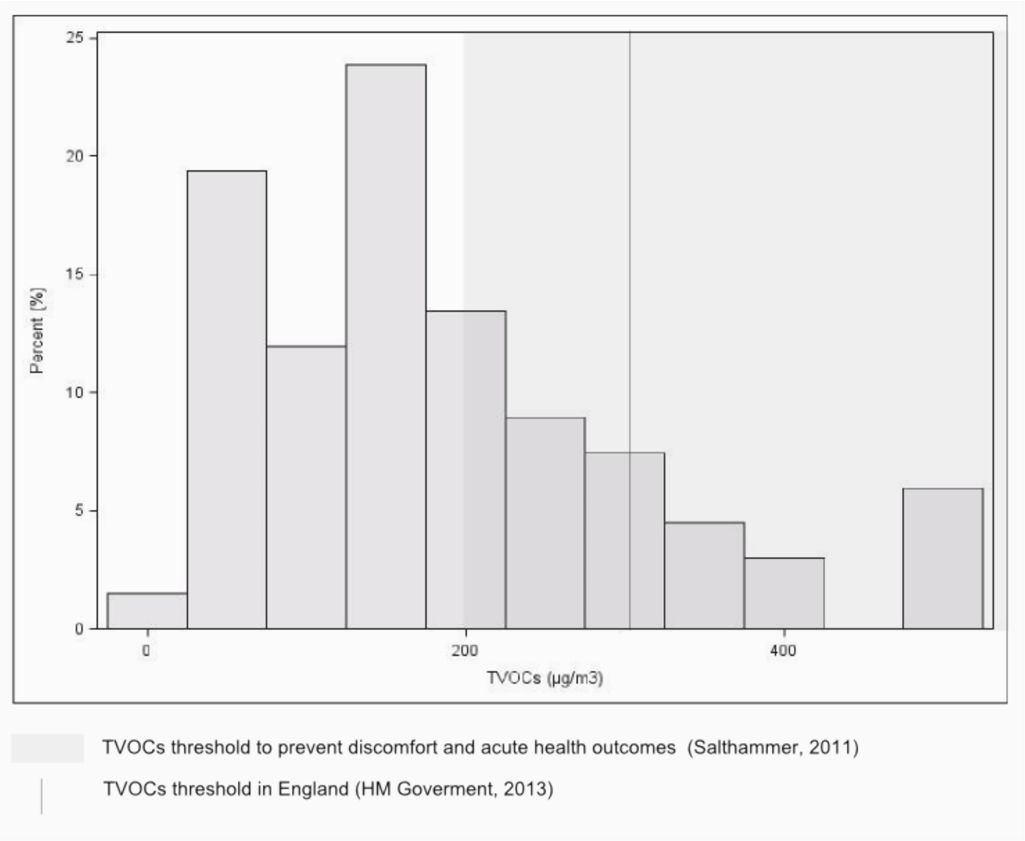


Figure 2.9: Distribution of indoor TVOCs in 255 classrooms (Table 2.8). Indoor exposure thresholds for sensory irritation (section 2.3.3) are indicated

distribution (Figure 2.9), with 40% of the classrooms exceeding 200 μg/m^3, which is the threshold (Section 2.3.3) of discomfort and distinct acute health issues. Daisey et al. (2003) in an extensive review of published evidence reported higher average TVOCs concentrations ranging from 100 to 1600 μg/m^3 in three US and 47 European (Italian, French and Swedish) nursery, primary and secondary schools.

2.4.6 Allergens

In general, studies over the past decade have more often assessed allergens in settled dust than through air sampling; however the correlation between methods has been poor (Karlsson et al., 2002).

Two systematic meta-analytic studies (Salo et al., 2009; Tranter, 2005) on allergen levels in day-care and school settings were found. Evidence from these studies indicated that the school environment may be an important site of allergen exposure for children with no pets at home. The magnitude of exposure differed significantly between classrooms and was dependent on socio-economic and cultural factors regarding pet ownership. Most commonly detected in school classrooms were cat (Fel d 1) and dog (Can f 1) allergens. Sampling from 194 classrooms in five studies (Abramson et al., 2006; Arbes et al., 2005; Kim et al., 2005; Ramachandran et al., 2005; Zhao et al., 2006) detected cat allergen ranging from non-detectable to 2.3 μg/g (mean: 0.8 μg/g, σ:1). Mean dog allergen concentrations sampled in the dust from 62 classrooms in two large studies (Kim et al., 2005; Zhao et al., 2006) ranged up to 3.0 μg/g (mean: 1.3 μg/g, σ:0.9). Studies have also detected cockroach (Chew et al., 2005; Foarde & Berry, 2004), mouse (Chew et al., 2005), horse allergens (Kim et al., 2005; Zhao et al., 2006) and dust mites in low concentrations (Foarde & Berry, 2004).

Findings from cross-sectional and cohort studies suggest that indirect exposure to pet allergens in school environments might influence asthma morbidity (Almqvist et al., 2001; Kim et al., 2005; Langley et al., 2003; Smedje & Norbäck, 2001; Smedje, Norbäck, & Edling, 1997; Zhao et al., 2006). Kim et al. (2005) associated wheeze, daytime breathlessness, asthma and atopic sensitisation with dog allergen above 8 μg/g in settled dust. School exposure to cat allergens at low concentrations of 0.17 μg/g was associated with higher risk for asthma diagnosis compared with 0.14 μg/g (Smedje & Norbäck, 2001).

2.4.7 Fungal and bacterial groups and microbial by-products

Fungi colonies may release individual spores, clusters of spores or small fungal fragments. Fungal spores constitute a significant fraction of bioaerosol microbial particles and are often 100 to 1000 times more numerous than other bio-particles. Similarly to inorganic airborne particles, fractions smaller than 10 μm are of primary concern as they can penetrate deep into the lower airways and lungs and cause allergic reaction or infect tissues. Various species may produce several mycotoxins depending on the substrate, which will not be analysed in this review. Additionally to fungal concentrations, this section will briefly summarise evidence on concentrations of bacterial groups and bacterial by-products (endotoxin).

In general, in indoor air risk assessments, fungal measurements have been used in distinguishing mould problems, and controlling the success of repair, and remedial measures in school buildings (Santilli, 2002; Savilahti et al., 2001; Taskinen et al., 1999). Environmental monitoring of fungal counts is often based on the determination of culturable or total spore concentrations in samples, possibly combined with the identification of fungi on the generic level than on the species level

(Godwin & Batterman, 2007; Jo & Seo, 2005; Scheff et al., 2000). Levels determined ranged from 92 to 505 CFU/m^3 with an average of 305 CFU/m^3. The fungal species determined in indoor school environments were *Penicillium* spp. followed by *Cladosporium* spp., *Aspergillus* spp. and *Alternaria* spp., and they varied with climate and location, in rural or urban areas.

In temperate climates, *Cladosporium* is expected to be the predominant indoor fungus (accounting for 50% of the total), as it has a strong outdoor context, followed by *Penicillium, Aspergillus, Alternaria* spp. and yeasts. The order of the last four groups may vary with location. In buildings with moisture damage *Penicillium* and *Aspergillus* are largely dominant (Cabral, 2010).

A wide spectrum of health effects were reported among occupants of water-damaged buildings including the occurrence of new allergic diseases shortly after the start of the school year (Savilahti et al., 2001), increased incidence of wheezing (16% vs 6%, $p < 0.001$) (Taskinen et al., 1999) and asthmatic attacks (Mi et al., 2006). Severe general symptoms and respiratory symptoms, such as headaches (88%), sore throat (75%), fatigue (67%), coughing (54%), and higher occurrence of respiratory infections were also noticed with exposure to fungal particles at mean concentrations of 260 to 1297 CFU/m^3 (Santilli, 2002). However, clear dose-response relation between indoor levels with health symptoms is missing because of difficulties in the fungal exposure assessment and a lack of standardised protocols for fungal sampling and analyses (Pasanen, 2001).

The airborne bacteria that people are exposed to seldom cause illness; however, high exposure level is potentially harmful to health. Environments with high occupancy density, such as classrooms, should be investigated for bacterial concentrations. Studies of airborne bacteria in schools have referred to total bacteria counts, rather than identifications (HESE, 2006; Jo & Seo, 2005), or determined gram-positive and gram-negative (Godwin & Batterman, 2007; Scheff et al., 2000). Bacterial indoor levels ranged from 577 to 1000 CFU/m^3 with an average of 785 CFU/m^3.

Endotoxin is a component produced by the outer membrane of gram-negative bacteria. Previous studies (Foarde & Berry, 2004; Instanes et al., 2005; Rullo et al., 2002) assessing endotoxin exposure provided data from a very limited number of schools and locations in schools. These studies sampled endotoxin primarily from floor settled dust, and found mean concentrations ranging from 0.1 to 32.2 EU/mg, and were significantly higher in rural school classrooms compared with urban settings. A recent large-scale study characterised endotoxin levels in settled dust using the Electrostatic Dustfall Collector (EDC) (Jacobs et al., 2013). Repeated measurements were performed in a total of 237 classrooms in three countries with different climates. It was found that variability between countries was significant, with highest levels determined in schools in a temperate climate (Netherlands), followed by 20-60% lower levels in a Mediterranean climate (Spain). Lowest levels (85-90%) were determined in a Continental/Subarctic climate (Finland) possibly due to low outdoor temperatures and snow cover that may have reduced the influx of outdoor bacteria (and, therefore, endotoxin levels) into schools. In each country, major sources of variability were the school and the sampling period. Overall, endotoxin levels were on average four times higher in classrooms than in children's bedrooms, and therefore endotoxin exposure at school is likely to contribute considerably to total endotoxin exposure. The same study detected a borderline association between endotoxin exposure and the occurrence of asthmatic symptoms.

Although it is well documented that exposure in damp buildings can increase the relative risk of experiencing health problems, there is a lack of clearly defined thresholds for concentrations of microbial counts and by-products. According to the *hygiene hypothesis*, exposure to low microbial concentrations (Kim et al., 2007) and endotoxin in school may have protective effects from respiratory symptoms and asthma.

2.5 Sick Building Syndrome symptoms and perception of IAQ in relation to school exposure

Most researchers agree that Sick Building Syndrome (SBS) describes a constellation of non-specific health symptoms that have no clear aetiology and are attributable to exposure to a particular building environment (Molhave, 1991). Presently, it is not clear whether SBS consists of symptoms correlated to an exposure or reflects an accumulation of effects of several unrelated indoor exposures (Salthammer, n.d.). Irritations in indoor environments are reported with different frequency; one group of frequent symptoms has been identified as SBS. Since the early 1980s, the WHO has compiled the common symptoms reported in what was defined as SBS (WHO, 1983). These symptoms included: mucosal symptoms (eye, nose and throat irritation, sensation of dry mucous membranes); dermal symptoms (dry, itching and red skin); neurological symptoms (headaches and mental fatigue); respiratory symptoms (high frequency of airway infections and cough, hoarseness and wheezing); and general symptoms (nausea, dizziness and unspecific hypersensitivity). Further, the WHO panel lists odour and taste sensations. WHO suggested that the diagnosis of SBS would require a demonstration of an elevated complaint (or symptom prevalence) associated with a particular building. All these symptoms are common in the general population; the distinguishing feature which makes them part of the sick building syndrome is their temporal relation in a particular building. All except skin symptoms should improve within a few hours of leaving a problem building; apart from dryness of the skin, which may take a few days to improve (Burge, 2004).

A previous systematic review of the literature (Wargocki et al., 2002) on subjective indoor air quality found that the majority of the studies typically deal with office workers, and few of them employ actual measurements of pollution levels. Only five studies were found on the association between school exposure and SBS symptoms (Cooley et al., 1998; Mysen et al., 2005; Smedje, Norbäck, & Ling, 1997; Zhang et al., 2011, 2012). Out of these, only two studies (Zhang et al., 2011, 2012) were organised as longitudinal investigation over a two-year period in school settings.

Overall evidence shows that additionally to improving thermal sensation, keeping the air dry and cool significantly affects IAQ perception directly (Wargocki et al., 2002). Lowering the temperature from 25 to 20 °C reduced SBS symptoms among students (Mysen et al., 2005; Zhang et al., 2012). Higher ventilation rates in non-industrial indoor environments including schools may improve perceived IAQ and health, as indicated by SBS symptoms and inflammation Wargocki et al. (2002). However, two studies in school settings have failed to establish a direct relation between perceived IAQ with CO_2 levels (Smedje, Norbäck, & Ling, 1997; Zhang et al., 2012), possibly because they used spot measurements that might not accurately reflect daily indoor CO_2 levels.

A study in 38 schools administered a questionnaire survey simultaneously with exposure measurements of a large range of indoor pollutants, and related dissatisfaction with IAQ with higher TVOCs and mould concentrations (Smedje, Norbäck, & Ling, 1997). The study quantified that for every 100 $\mu g/m^3$ of TVOCs dissatisfaction increased by OR:1.8 (95%CI: 1.1- 3.0). The most commonly detected VOCs in the study were α-pinene, limonene, toluene and xylene.

In that study (Smedje, Norbäck, & Ling, 1997), apart from TVOCs, total moulds were also a significant predictor of perceived IAQ. More specifically, for every 10-fold increase of moulds, dissatisfaction with IAQ increased by 1.9 (95%CI: 1.3-2.8). Predominant fungal species determined were *Cladosporium* spp., *Mycelia sterilia* and *Penicillium* spp. A study in 48 US schools (Cooley et al., 1998) also associated SBS complaints from occupants with exposure to *Penicillium* spp. and *Stachybotrys* spp. A recent longitudinal study (Zhang et al., 2011) associated bacterial compounds with lower prevalence of mucosal and general symptoms; however, fungal counts were associated with increased incidence of SBS symptoms in the school.

Exposure to higher NO_2 concentrations might be related to SBS, especially mucosal symptoms (OR=1.13 per 10 $\mu g/m^3$) (Zhang et al., 2012) in a sample of 1143 primary school children; however, Smedje, Norbäck, & Ling (1997) did not find an association between perceived IAQ and NO_2 levels.

2.6 Environmental and behavioural factors affecting IAQ and thermal comfort

In this section, the consistency and strength of evidence associating environmental and behavioural factors on pollution levels in the classrooms is investigated.

2.6.1 Envelope permeability and indoor to outdoor ratios

Pollutants from outdoor air penetrate indoors through intended openings (doors, windows) or any cracks and gaps of the building envelope. A fast and straightforward screening method for calculating indoor concentrations from outdoor sources is the indoor to outdoor (I/O) ratio found by statistical regression of experimental data. In the absence of indoor sources, this ratio is also referred to as *infiltration factor* or *penetration efficiency*. Indicative I/O ratios estimated in school environments for different pollutants are presented in this section.

In general, most studies found weak relationships between indoor and outdoor PM_{10} concentrations during unoccupied periods (Fromme et al., 2007; Goyal & Khare, 2009; Poupard et al., 2005). 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 (Goyal & Khare, 2009; Patel et al., 2009; Poupard et al., 2005; Weichenthal et al., 2008). The strong influence of outdoor sources suggested that the building envelope provided little protection from fine and ultra-fine 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 (Branis et al., 2009; Goyal & Khare, 2009; Heudorf et al., 2009; Scheff et al., 2000). Because bioaerosols are governed by the same principles as PMs, their I/O ratio was greater than unity and lay in the range $1.6<I/O<2.7$ (Jo & Seo, 2005; Kim et al., 2007; Scheff et al., 2000).

Little information is currently available on the effect of building airtightness on penetration ability of NO_2 and O_3. Studies have estimated that I/O ratios of NO_2 are close to unity, between $0.77<I/O<1.18$ (HESE, 2006; Norbäck et al., 2011; Poupard et al., 2005). Poupard et al. (2005) investigated I/O ratio of NO_2 levels in the winter and summer season in a sample of school buildings constructed in the 19^{th} Century. The paper suggested that the building envelope provided little protection from outdoor NO_2 pollution regardless of airtightness of investigated buildings (Poupard et al., 2005). The effect of the airtightness of the building envelope on indoor O_3 concentrations is unclear because it is a highly reactive gas. The I/O ratio of ozone has been estimated as being between $0<I/O<0.5$ (HESE, 2006; Mi et al., 2006; Poupard et al., 2005). Poupard et al. (2005) estimated that for airtight buildings the ratio was close to zero and unrelated to outdoor concentrations, but increased for more permeable

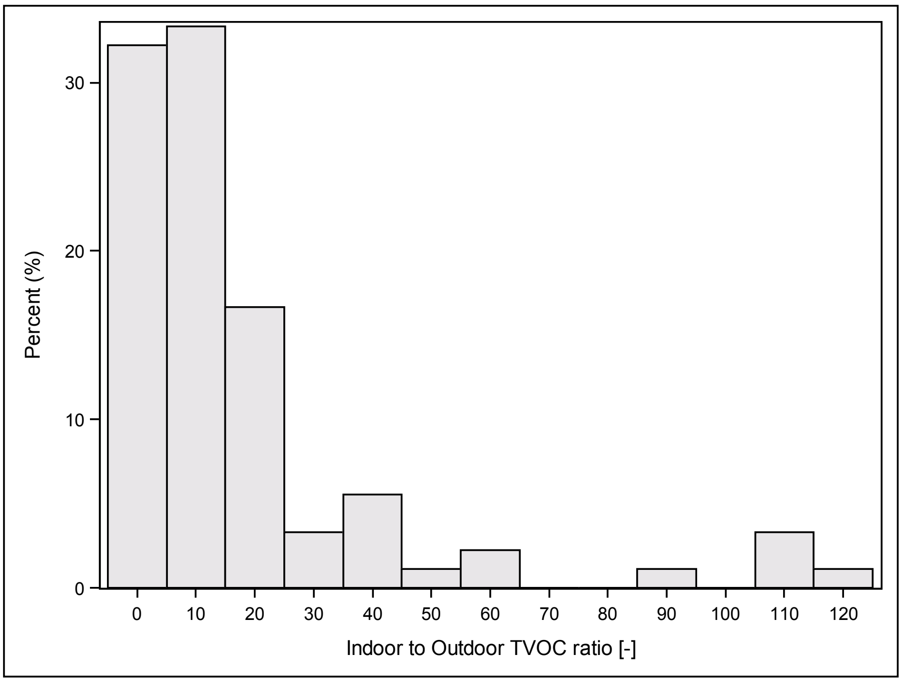


Figure 2.10: Distribution of indoor to outdoor ratio of Volatile Organic Compounds in the literature (Table 2.9)

buildings with decreasing airtightness. However, Weschler (2000) proposed that the lower I/O ratios of O_3 estimated in indoor investigations are likely the result of stronger deposition on solid surfaces, or decomposition in the indoor air rather than differences in the filtering of the ventilation air when crossing the building envelope.

The contribution of strong indoor sources on VOCs concentrations was reflected in high I/O ratios; 65% of monitored classrooms exceeded outdoor concentrations by more than a factor of 10 (Figure 2.10). The independence of indoor VOC concentrations from outdoor levels was reflected in their variability within schools (Godwin & Batterman, 2007).

Overall evidence suggested that traffic related pollutants with outdoor sources, such as NO_2 and PM, had I/O ratios close to unity, as they were able to penetrate the building envelope regardless of airtightness. Lower I/O ratios were recorded for O_3; however the underlying relationship is not clear, as ozone is a secondary pollutant and has no strong primary sources. The relative strength of pollutants with indoor sources such as VOCs was reflected in high I/O ratios, and high variability of I/O ratios among adjacent classrooms.

2.6.2 Carbon dioxide levels and estimated ventilation rates

Average concentrations of indoor TVOCs had a moderate relationship with average CO_2 concentrations (Figure 2.11). Mean indoor TVOCs concentrations of 200 $\mu g/m^3$, which is the lowest

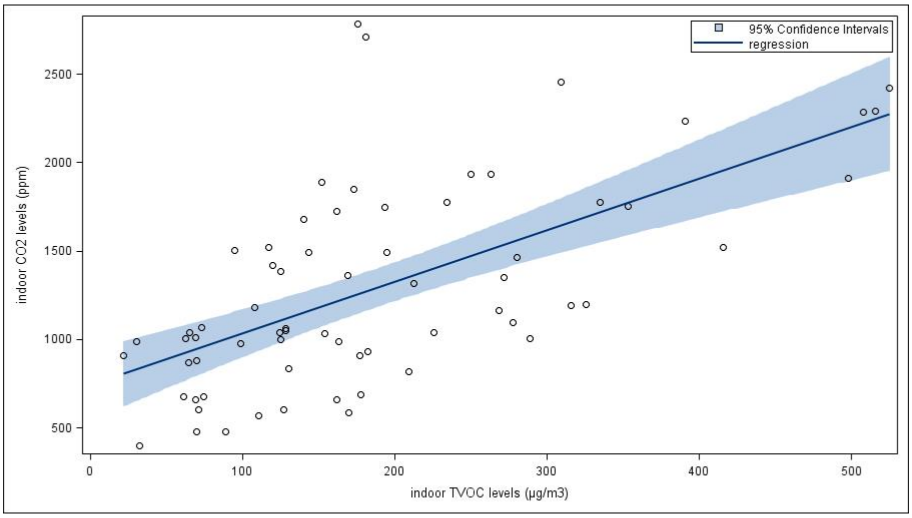


Figure 2.11: Moderate relationship between CO_2 concentrations and TVOCs in 132 classrooms in the literature (Table 2.9)

threshold value to prevent discomfort and sensory irritations (Section 2.3) occurred when indoor CO_2 levels were around 1300 ppm (95%, CI: 1200-1400). The efficiency of ventilation in reducing VOC concentrations was stronger for VOCs with indoor sources, especially *limonene* and *pinene* (Godwin & Batterman, 2007).

Studies in schools generally found a negative correlation between air exchange rates and indoor particle concentrations, and this relationship appeared stronger for the smaller particle sizes (Goyal & Khare, 2009; Guo et al., 2008; HESE, 2006). Only one study noticed elevated PM levels during ventilation periods, most likely due to resuspension from air currents (Heudorf et al., 2009).

A weak positive relationship between air exchange rate and *Aspergillus* was detected and the relation was stronger when total bioaerosols were considered (Godwin & Batterman, 2007). Lower total and viable bacteria, moulds and air allergens were measured in mechanically ventilated classrooms with lower CO_2 levels and humidity (HESE, 2006). CO_2 levels in heavily occupied schools have been found to correlate with the levels of airborne bacterial markers, with an increase of 1 ppm in CO_2 levels corresponding to an increase of 1 CFU/m^3 in airborne fungi (Fox et al., 2003; Ramachandran et al., 2005).

Limited evidence is available on the relationship between NO_2 and O_3 levels and ventilation rates. While no relationship was found for NO_2 (Poupard et al., 2005), suggestive evidence related increased ventilation rates to increased O_3 levels (Poupard et al., 2005). Gold et al. (1996) found I/O of ozone concentrations depended on permeability; in occupied classrooms it was up to 0.71 (σ: 0.03) when cross ventilation took place, and dropped to 0.15 (σ: 0.02) when ventilation was eliminated.

Overall, the evidence suggests that increased ventilation rates are effective in removing airborne particles, air allergens and TVOCs concentrations. No relationship between increased ventilation and NO_2 could be established. Timing of window opening in classrooms might be an important factor affecting indoor O_3 concentrations.

2.6.3 Temporal variations

Variations in pollutant concentrations can be observed on an hourly, daily, weekly, monthly and seasonal basis. Seasonal variations may directly influence the concentrations of pollutants both indoors and outdoors and indirectly through adaptive actions from the occupants. Varying climatic parameters may also indirectly influence the contribution of outdoor pollutants to indoor levels.

While there is limited information on seasonal variation of microbial concentrations in classrooms, two studies reported summer to winter ratio of up to 15 and 10 for fungi and bacteria respectively in subtropical (Jo & Seo, 2005) and continental (Ramachandran et al., 2005) climates, and the concentration order of individual fungi remained unchanged regardless of season (Jo & Seo, 2005). The higher microbial counts in the summer may be explained by the higher temperatures that favoured the growth of fungal and bacterial groups (Jo & Seo, 2005; Ramachandran et al., 2005), while relative humidity was positively associated only with proliferation of specific fungal groups. Microbial counts in these studies were determined with cultivation-based methods, which might affect the results. However, little evidence exists on seasonal microbial variations in temperate climates.

Only one study (Scheff et al., 2000) determined diurnal variations of microbial concentrations with air-sampling measurements during a teaching day, and reported higher levels for all investigated fungal and bacterial groups during the morning hours.

Variation of endotoxin levels among seasons was stronger for countries with large climatic differences, and more stable in temperate and Mediterranean climates (Jacobs et al., 2013). Cat and dog allergens did not significantly vary among seasons (Fromme et al., 2008). Some studies, however, reported seasonal variations of allergens, mostly on mice and cockroaches (Abramson et al., 2006; Chew et al., 2005).

Studies found higher indoor TVOCs concentrations during the heating season than the non-heating season (Adgate et al., 2004; Pekey & Arslanba, 2008; Shendell et al., 2005; Sofuoglu et al., 2011). While most studies attributed the variations in different ventilation patterns (Adgate et al., 2004; Pekey & Arslanba, 2008; Shendell et al., 2005), a study speculated that elevated indoor TVOCs concentrations during the heating season resulted from increased emissions of a freshly painted wall from heating systems (Sofuoglu et al., 2011). Increased ventilation patterns during summer months altered the VOCs profile in the classrooms allowing greater contribution of outdoor VOCs (Pekey & Arslanba, 2008), which may be more harmful to human health.

The method used for PM mass determination may affect the results. Optical methods, for example, may be affected by higher RH. Two studies which investigated indoor and outdoor seasonal PM variations (Fromme et al., 2007; Goyal & Khare, 2009) found two to three times higher concentrations in winter compared with the summer period, and the difference was higher when optical methods were employed compared with gravimetric. Studies performed over shorter periods found no relationship, or a weak negative relationship, with temperatures and a moderate positive relationship with RH (Branis et al., 2005; Goyal & Khare, 2009).

While temperature might influence PM concentrations directly, the temperature difference between exterior and interior might affect penetration ability of the pollutants. Higher I/O ratios were noticed in the non-winter period (Branis et al., 2005; Goyal & Khare, 2009). A possible explanation for the different I/O ratios between seasons might be that when temperature is generally lower than outdoors, the temperature gradient created increased infiltration rates leading PMs into the building.

Seasonality also affected size variations of particles (Goyal & Khare, 2009): PM_{10} dominated indoor PM concentrations in non-winters, representing 70 ± 5% of total respirable particulate matter, followed by 17 ± 3% $PM_{2.5}$ and 13 ± 2% PM_1, while during winters, it was 49 ± 4% followed by 27± 2% and 24 ± 3% for PM_{10}, $PM_{2.5}$ and PM_1 respectively. Rain had wash-out effects on outdoor particle concentrations (Guo et al., 2008). Apart from seasonal variations, weekly and daily variations were also reported and were mainly related to traffic intensity. Increased outdoor particle matter during the start of the school day coincided with the traffic peak hours, and decreased later in the day with the increase of temperature (Goyal & Khare, 2009).

Wind speed and direction were found to be significant predictors of indoor fine and ultrafine particles concentrations (Branis et al., 2005; Goyal & Khare, 2009; Patel et al., 2009; Weichenthal et al., 2008). While lower wind speed from highway traffic elevated indoor $PM_{2.5}$ concentrations, higher wind speeds dispersed outdoor concentrations. Wind direction and proximity to main traffic arteries were mainly affecting NO_2 indoor concentrations in flat terrain, low-rise area (Kim et al., 2004; Van Roosbroeck et al., 2007). A good agreement between fixed stations and indoor concentrations was reported only for schools located more than 300m away from major high traffic areas (background urban schools) or upwind. Measurements in school downwind and in proximity to pollution sources were up to 50% higher compared with background schools. One study (Blondeau et al., 2005) examined seasonality of NO_2 in schools and found higher mean concentrations both indoors and outdoors in the heating season, and I/O ratios remained similar in both seasons.

To summarise, seasonal variations of pollutants were affected both directly and indirectly from complex meteorological phenomena, temperature changes and varying outdoor sources, and indirectly through altered ventilation patterns. More research is necessary on seasonal variations of biological counts in school settings in temperate climates. Varying wind speeds and directions throughout the year were also found to affect penetration ability of traffic generated pollutants, such as PMs (especially the smaller fraction) and NO_2. Increased ventilation rates during the non-winter period reduced TVOCs, but elevated levels of specific VOCs with outdoor sources. Heating sources might also affect emission rates of TVOCs from internal finishing.

2.6.4 Occupancy

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 (Branis et al., 2005; Fromme et al., 2007; Goyal & Khare, 2009; Poupard et al., 2005). The effect of occupancy systematically affected indoor PM_{10} concentrations more than any other physical parameter (Branis et al., 2005; Heudorf et al., 2009; Poupard et al., 2005; Scheff et al., 2000) including meteorological parameters (Fromme et al., 2008; Goyal & Khare, 2009). Fromme et al. (2007) noticed that classrooms with children younger than eight years old, who are physically more active than older children, had statistically significantly higher PM_{10} levels. Although it is likely that occupants may introduce new particles through clothing and shoes indoors, in the absence of data on the size distribution of particles generated indoors by humans or other sources, resuspension is suggested as being the dominant phenomenon behind the increase.

Occupant activity increased bioaerosol concentrations both directly through the presence of children (Aydogdu, 2005; Fox et al., 2003), and indirectly through resuspension of previously deposited particles (Fox et al., 2003; Godwin & Batterman, 2007; Jo & Seo, 2005; Scheff et al., 2000). Meaningful exposure to cat and dog allergens in classrooms transported from home through clothing has been documented; therefore, occupants' pet ownership was found to be the most significant predictor of allergen levels (Almqvist et al., 1999; Zuraimi et al., 2007). Cultural differences in cleaning habits can influence indoor microbial concentrations. For instance, children in Finnish schools generally take off their shoes when entering schools, which is not the common practice in other European countries. It is, therefore, possible that apart from climatic factors, a lower extent of tracked-in soil was associated with lower endotoxin levels (Jacobs et al., 2013). Similarly to PM, the grade of the classroom was inversely associated with microbial counts.

Higher TVOCs concentrations were monitored during occupied periods (Scheff et al., 2000;

Shendell et al., 2005). Different activities in school microenvironment were reflected in large variability among secondary, primary and nursery classrooms (Godwin & Batterman, 2007; Sofuoglu et al., 2011).

In summary, occupancy was found to affect PM and, particularly, the larger fraction due to resuspension of previously deposited matter. Pollutants with indoor sources like VOCs and microbial concentrations were elevated during the occupied period.

2.6.5 Building characteristics and maintenance

Apart from absolute values of physical parameters such as ventilation rates and temperature, the ventilation system itself can affect the perceived environmental quality and health of the occupants. Frequency of symptoms in students in air-conditioned classrooms were higher than in naturally ventilated classrooms (Koo et al., 1997), and included watery and runny eyes although air changes were higher (Kinshella et al., 2001), and occurrence of new allergies (Mysen et al., 2005). The incidence of asthmatic symptoms was lower for children who attended schools with new ventilation systems installed (Smedje & Norbäck, 2000). Potential causes of adverse health effects and dissatisfaction due to HVAC systems comprised improper maintenance of the HVAC systems (Wargocki et al., 2002), which was a significant predictor of high bacterial markers and total bioaerosol counts (Fox et al., 2003; Lee et al., 2002; Mysen et al., 2005; Wong et al., 2008). A centralised HVAC system was associated with significantly higher cat and dust mite allergens than other types of ventilation systems (Tranter, 2005).

The ventilation strategy itself can affect the satisfaction of occupants with IAQ. At the same level of exposure to airborne pollutants, more complaints were reported in mechanically ventilated schools with mixing flow (56%) and mechanical exhaust (61%) compared with naturally ventilated classrooms or classrooms with displacement ventilation (48%) (Smedje, Norbäck, & Ling, 1997). Moreover, air dispersion in the occupied zone may affect satisfaction with IAQ. One study (Norbäck et al., 2011) performed intervention studies that modified the ventilation system in three primary classrooms accommodating a small sample of children (N_c=61). It was found that for similar ventilation rates and indoor operative temperatures, students in classrooms with displacement ventilation systems (both floor master system and front ventilation system) perceived better air quality ($p = 0.006$), reported less dyspnoea ($p = 0.007$), and tear film stability was improved ($p = 0.03$) compared with mixing ceiling ventilation. Although displacement of pollutants from the breathing zone might improve air quality in the occupied zone, temperature difference between the supply and room air temperatures greater than 10 °C may create local discomfort at ankle level (Mumovic et al., 2007).

Interior finishing in the classroom such as furnishings and textiles in the classroom may act as significant reservoirs of irritants and allergens, and have an impact on the school IAQ (Arbes et al., 2005; Foarde & Berry, 2004; Smedje & Norbäck, 2001). Dirty carpets can pollute the indoor environment of the classroom (Bakó-Biró et al., 2012). Carpeting was the only significant factor affecting *Alternaria* spp. (Arbes et al., 2005) and *Aspergillus* spp. concentrations (Godwin & Batterman, 2007). Carpeting also acted as cat and dog allergen reservoir, elevating concentrations 10-fold in day care centres compared with hard floor (Arbes et al., 2005). The highest levels of allergens have been found in upholstery seats (Zhao et al., 2006).

Various abatement measurements focused on reducing dust reservoirs, like introducing special clothing (Karlsson et al., 2002). Intensified cleaning removed deposited re-suspendable dust and reduced indoor PM_{10} concentrations (Heudorf et al., 2009). However, cleaning products used in classrooms should be carefully selected, as they may increase indoor TVOCs levels. Additionally, cleaning products may contain terpenes, which may interact with ozone leading to the formation of secondary organic compounds (SOAs) (Morawska et al., 2009).

Different materials used in buildings of varying age may affect the growth of microbial concentrations and emissions. Increasing age of building has been positively correlated with bioaerosol concentrations (Aydogdu, 2005). In similar conditions of temperature and RH, higher bioaerosol concentrations of *Penicillium* spp. and *Aspergillus* spp. were monitored in portable classrooms compared with conventional classrooms (Godwin & Batterman, 2007), and in below-ground classrooms (Jo & Seo, 2005), which might be related to decreased UV sun radiation levels.

2.7 Summary

This chapter used a systematic approach to collect and synthesise evidence from peer-reviewed scientific studies focusing on empirical data on indoor thermal conditions, CO_2 levels, estimated ventilation rates, and indoor pollution levels in school settings, and health implications on children between 6 to 16 years old. The review has been conducted in accordance with key systematic review principles to ensure that it is transparent, replicable and updateable. The regulatory framework developed to ensure acceptable thermal conditions and adequate IAQ in UK classrooms was presented. Additionally, environmental and behavioural factors affecting pollution levels in school buildings were examined.

Some limitations of this review are inherent in most review studies that tend to be prone to publication bias towards positive findings (Sterne et al., 2001). As negative studies performed are less likely to be submitted or accepted for publication, they are less likely to be identified and included in reviews. This review did not include possible important effects of noise and light, which are not considered in this thesis, and specific pollutants, such as carbon monoxide (CO) and sulfur oxides (SO_x), which have not been identified as the main problem in the UK.

The review identified low ventilation rates and high CO_2 levels in a sample of 555 naturally and 900 mechanically ventilated school classrooms. Further work is required to establish evidence based guidelines for average temperatures and CO_2 levels in classrooms.

A striking feature of the published evidence is the high indoor concentrations of traffic related pollutants above current guidelines reported in many European classrooms. Little evidence is available on the association of SBS symptoms in the classroom with specific pollutants. Moreover, few studies have been organised as case-crossover of the heating and non-heating season; therefore, limited information is available on seasonal variation of indoor pollution concentrations, and prevalence and incidence of health symptoms.

Chapter 3

Methodology: Monitoring Approach

Measurements of physical, chemical and microbiological parameters

3.1 Outline

The extensive literature review (Chapter 2) has highlighted the need for an integrated approach to assess total IAQ performance of classrooms. This chapter together with Chapter 4 present the multidisciplinary methodology adopted to measure comprehensively IAQ in classrooms.

In the first section 3.2 an overview of the study design is presented. This Chapter presents the monitoring approach in four separate sections and provides a detailed description of the materials and analysis for the determination of physical parameters (§3.3), particulate matter (§3.4), radon (§3.5), chemical concentrations (§3.6), and microbiological (§3.7) contaminants.

3.2 Overview of the methodological design of the study

As illustrated in section 1.3, this PhD was carried out as part of the SINPHONIE project, where the author was the only UK researcher. In line with the SINPHONIE protocol, a sample of one nursery and five primary state schools in the Greater London area was recruited from a number of consenting school authorities.

Headteachers were contacted initially by phone and e-mail (Appendix C.2), and offered a small financial recompense for their involvement. There were no reports of health complaints or environmental problems from any of the schools before the investigations. Priority was given to selecting schools with motivated school managers, teachers and students, as their approval and support was crucial for the successful completion of the field studies. A sample of urban and suburban, contemporary and historical school buildings was selected to ensure high variability facilitating meaningful analysis.

While the SINPHONIE study was designed as a case-control epidemiological investigation, this thesis employed a case-crossover design. Fieldwork was conducted during the heating season (October 2011 - January 2012) with a monitoring period of five consecutive working days at each school. This was repeated in the non-heating season (March - June of 2012). Due to availability of equipment monitoring was performed in consecutive weeks (Table 5.1).

For each school, three classrooms and one outdoor site were selected. The classrooms in primary schools were selected according to the following criteria: as representative of the school in terms of their geometrical characteristics; classrooms used by children aged between nine and eleven; classrooms occupied by the same class of pupils for the whole school year, if possible with full occupation per weekday; classrooms with varying orientation (facing the street or the yard); and classrooms in use for at least the last six months, to avoid encountering emissions from new building materials. In the case of classrooms with equivalent conditions, those with a higher number of pupils were chosen.

Monitoring was carried out according to the general aspects of sampling strategy described in EN ISO 16000-1:2006. The centre of the room is generally considered the most suitable location for sampling. However, considerations regarding interfering with normal occupants' activities and health and safety regulations in schools resulted in an alternative strategy for the placement of equipment. In all cases, equipment was placed away from external walls and at sited-head height. Placement of equipment in each classroom can be found in the Appendix Section D.2. Outdoor equipment was deployed on the roofs of school buildings (Appendix D.1) to avoid occupants' interference, microclimate effects and the influence of pollutants from buildings. This labour-intensive task was assisted by a colleague. A summary of the methodology followed for monitoring of physical, chemical and microbial parameters is given in Table 3.1 and Table 3.2, providing information on selected equipment, duration of measurements and relevant standards and guidelines followed.

The monitoring approach included passive and direct-reading instrumental methods. Passive sampling measurements obtained average concentrations over the investigated period and were specified by the SINPHONIE protocol. The main advantages of passive sampling are their independence from the main power supply, the noise-free operation and the low detection limits achieved. Samplers that required exposure periods longer than one week were installed at the first day of the fieldwork, and collected when achieving the limit of quantification as specified by the manufacturer.

Instrumental sampling was not specified by the SINPHONIE protocol, and was developed as part of the framework of this thesis. Continuous sampling aimed to capture variations in the dynamic indoor environment constantly influenced by fluctuating strength of sources, human activity, ventilation rates and externalities. Equipment was chosen after considering size, robustness and low noise operation to minimise disturbance of the occupants. Sensitivity and lower detectable limits were selected based on the anticipated concentrations obtained from the literature review presented in chapter 2. Equipment was calibrated by the manufacturer.

Descriptors of the physical environment were collected to enable the characterisation and comparison of school buildings for the interpretation of the fieldwork measurements. The school and classroom checklists were an extended version of the SINPHONIE questionnaires (Section 4.3). The questionnaire on health symptoms and perceived IAQ was an extended version of the SINPHONIE questionnaire, and was administered to primary school children twice; once in the heating (baseline) and once in the non-heating season (follow-up) at the same week as the monitoring of pollutant levels (Section 4.4). Only the 15 classrooms accommodating older primary school children (9-11 years old) were included, as their responses to surveys are considered more accurate than those of younger children (Engvall et al., 2004). The ISAAC Phase II (Weiland et al., 2004) showed that children of this age group participated and performed satisfactorily in all proposed tests.

Analysis of the integrated database was performed with multilevel modelling which allows a concordance between theoretical hypotheses and statistical methods with a Bayesian estimation method, which is suitable for small datasets (Section 4.5).

Table 3.1: Summary of methodology used for monitoring of physical and chemical parameters

Monitored Parameters	Method	Duration of measurements	Monitoring intervals	Accuracy/ Detection limit	Equipment	Standards/ Publications
T (°C)	Rotronic sensor	5 working days	1 min	±0.5 °C (range −30 °C to 65 °C)		BS EN ISO 7726:2001
RH (%)				±1.5%		
Weather station					Eltek Ltd	
CO_2 (ppm)	Non-Dispersive Infrared Spectrometry (NDIR)	5 working days	1 min	3% (range 0 - 20000 ppm) or 50pppm		BS EN 16000-26
PM_1, $PM_{2.5}$, PM_{10} ($\mu g/m^3$)	Optical method	5 working days	1 min	range 1$\mu g/m^3$	TSI DUSTTRAK DRX Model 8533	
NO_2 ($\mu g/m^3$)	TEA principle	2 weeks	.	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	.	3.4 $\mu g/m^3$	DIF 300 RTU, Gradko International, Ltd	Ozden & Döerolu (2012)
Radon (Bq/m^3)	α-track	4 weeks	.	10Bq/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*	Passive Diffusive Sampling analysed with GC-MS	5 working days	.	0.10$\mu g/m^3$	*Radiello* samplers, analysis Health&Safety Labs	BS ISO 16017-2: 2012
Formaldehyde ($\mu g/m^3$)	Passive 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

Table 3.2: Summary of methodology used for monitoring 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)

3.3 Monitoring of physical parameters

3.3.1 Temperature, relative humidity and weather data

Temperature, RH (Figure 3.1) and weather data (rainfall, wind velocity (Figure 3.2) and solar radiation) were monitored with a wireless installation for five consecutive days in 1-minute intervals. Indoor dry bulb temperature was measured with a thermistor sensor with an accuracy of ±0.5 °C (range: −30 °C to 65 °C). Relative humidity was measured using a rotronic sensor with an accuracy of ± 1.5%. The transmitters were placed at sitting head height, and telemetry was used to transmit the data to receiver-loggers where data could be accessed online (via a GSM modem) (Figure 3.1).

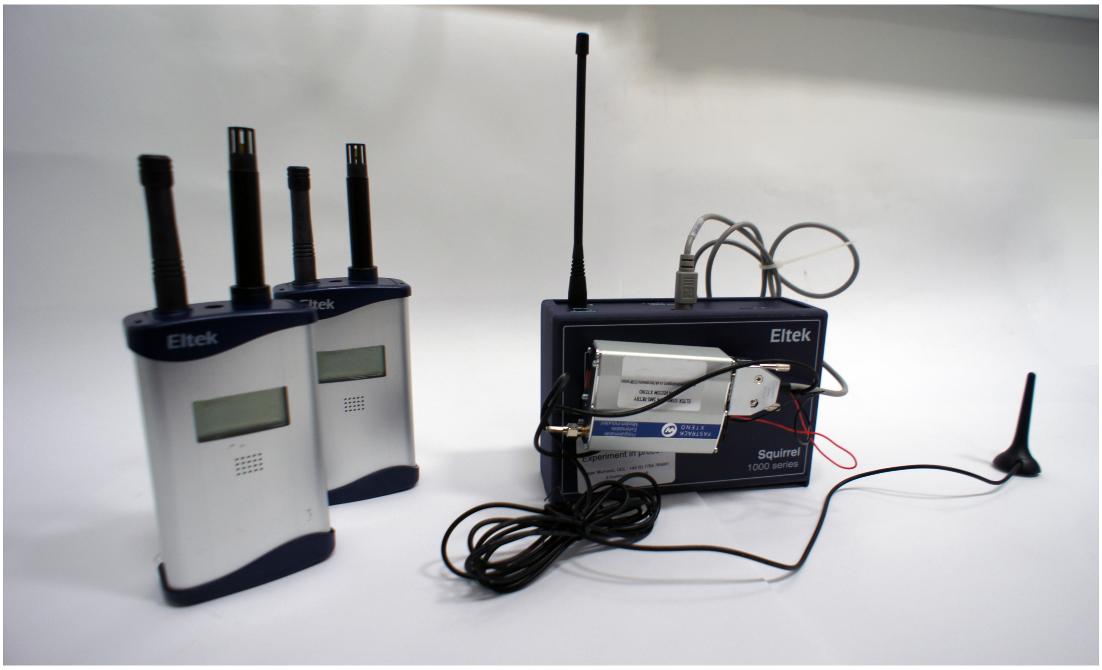


Figure 3.1: Wireless installation for temperature, RH, and CO_2 monitoring

3.3.2 Carbon dioxide and estimation of ventilation rates

Indoor and outdoor CO_2 concentrations were monitored with Non-Dispersive Infrared Spectrometry (NDIR) according to BS EN ISO 16000-26 standards. The CO_2 sensor was incorporated in the data loggers (GenII, GD-11) with an accuracy of 3% in the range of 0 to 20000 ppm or 50 ppm (whichever is greater). According to the standards (BS EN ISO 16000- 26:2012), one sampling point per room is sufficient in spaces smaller than 50 m^2. Although some classrooms were larger, previous work (Mahyuddin et al., 2013) showed that spatial variation of CO_2 levels in larger naturally ventilated classrooms monitored away from the external wall is smaller than the NDIR sensor sensitivity. The sampling point was located with a sufficient separation (of at

Figure 3.2: Weather station installed in a school yard during fieldwork

least 1.5 m) from where air was exhaled by the occupants.

Ventilation rates can be estimated using the decrease rate of a tracer gas dispersed uniformly into the space. In this study, the decay of metabolic CO_2 generated by the occupants was used to estimate ventilation rates under normal conditions and during intervention studies for the estimation of infiltration and purge ventilation rates. The alternative method that uses sulfur hexafluoride (SF_6) as a tracer gas was not applied in this study as SF_6 is a major contributor to GHG emission and its use is banned in the UK. Moreover, previous studies of schools have found that the SF_6 method tends to overestimate ventilation rates since it does not correctly account for exchanges with other rooms as it may only estimate aggregated ventilation rates over a suitable period (Beisteiner & Coley, 2002). The technique requires an almost linear semi-log plot, which means that the driving forces determining the flow rate remain constant during the experiment. Because classrooms are dynamic, transient environments, tracer gas techniques in schools in the literature were used primarily for the estimation of non-varying infiltration rates during unoccupied periods with static conditions.

Although mass-balance equation requires steady state conditions, such conditions rarely happen in occupied classrooms due to constant adjustment of openings and changing number of occupants. Use of non-steady state values in a time invariant mass balance equation may overestimate the ventilation rates (Beisteiner & Coley, 2002; Mumovic et al., 2009; Santamouris et al., 2007). Therefore, the study adopted an adjusted form of non-steady state equation (3.1) to estimate normal performance of naturally and mixed mode ventilated classrooms under normal conditions, previously used in school classrooms (Beisteiner & Coley, 2002; Mumovic et al., 2009).

Daily observational data collected during the investigated week focused on occupant density, activity levels and openings' adjustment. Observations were performed manually immediately before and after breaks, and every 20 minutes depending on the duration of the session during the occupied period. These observations were used for the estimation of ventilation rates. After inspection of the data, ventilation rates were estimated over 20-minute intervals.

$$C_{(t)} = C_{(ex)} + \frac{G}{Q} + \left(C_{(in)} - C_{(ex)} - \frac{G}{Q} \right) e^{-\frac{Q}{V}t} \tag{3.1}$$

where:

$C_{(t)}$	Internal concentrations of CO_2 at time t (ppm)
$C_{(ex)}$	External concentration of CO_2 at (ppm)
$C_{(in)}$	Initial concentration of CO_2 (ppm)
G	Generation rate of CO_2 in the space (cm^3/s)
V	Room volume (m^3)
t	Time (s)

The equation 3.1 can be applied under the following assumptions:

- internal-exchange rate Q and generation rate G are constant over an analysed period (i.e. a class session),
- the initial concentration C_{in} has to be in a steady state, and
- there are no inter-zone air flows from adjacent rooms.

Further uncertainties related to this method include:

- the difficulty in estimating the CO_2 emission rate per person;
- precise estimation of the volume of the classroom;
- inaccuracies caused by instrumental errors; and
- assumption of homogenous distribution of the CO_2 in the space (Santamouris et al., 2008).

During the unoccupied period, the capabilities of the design under intervention studies (purge ventilation rates/ infiltration rates) were estimated with equation 3.1. Infiltration rates were estimated during the unoccupied period assuming that generation of CO_2 in the space (G) was 0, and keeping all openings closed. Purge ventilation rates were estimated during the unoccupied period when all windows were kept open.

Estimation of generation rate of CO_2 in the space

The metabolic rate depends on surface area of the person and the level of activity (Beisteiner & Coley, 2002). In this study, a figure of 65 W/m^2 was assumed for primary school children, 70 W/m^2 for nursery school children and 80 W/m^2 for teachers derived from the work of Coley & Beisteiner, 2002.

The CO_2 generation rate (G) was adjusted for gender and age, and was calculated (Table 3.3) as described in ASHRAE Handbook of fundamentals (ASHRAE, 2009). A detailed description of the calculation method can be found in Appendix B.1.

Table 3.3: CO_2 generation details used for the estimation of ventilation rates

classroom	Age of occupants	Assumed average CO_2 generation per person (L/h)
Nursery school (Early Years)	3 to 4	9.14
Year 4	8 to 9	13.38
Year 5	9 to 10	13.58
Year 6	10 to 11	14.36
Teacher (Female)	.	20.62
Teacher (Male)	.	22.90

3.4 Particulate Matter

Particulate Matter (PM) was monitored using optical methods with four TSI DUSTTRAK DRX Model 8533 (TSI Incorporated, St. Paul, MN) (Figure 3.3). The exterior equipment was fitted in an environmental enclosure (TSI, model 8535) (Figure 3.4).

The detection of temporal changes on a time scale of a few minutes is the main advantage of optical methods over traditional gravimetric samplers. The selected instrument employs a method to measure size segregated mass fraction concentrations of PM_1, $PM_{2.5}$, PM_4, PM_{10}, and Total Particulate Matter over a concentration range of 0.001 to 150 mg/m^3 in real time. The correlation between laser meters was tested prior to fieldwork in a control environment, and was very high (R^2= 0.71 to 0.76 for all fractions) (Appendix, Figure B.2).

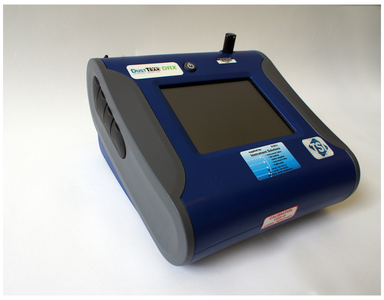


Figure 3.3: Laser photometer for Particulate Matter monitoring

Principle of operation

The principle of optical operation of the selected equipment is different from a typical photometer because it can simultaneously cover the mass concentration range and detect single particles. While photometers can be used at high mass concentrations, they do not give any size information (unless used with size selective inlet conditioners) and significantly underestimate particle mass contributed by large particles. On the other hand, Optical Particle Counters (OPC) provide size information, but cannot be used at high mass concentration. The DUSTTRAK DRX Aerosol Monitor is able to combine the advantages of both measurement techniques to improve the overall accuracy of the mass measurement. The signal processing is different from a typical photometer because the photodiode signal is separated into two components: the photometric signal; and the single particle pulses. Therefore, in laboratory conditions when

Figure 3.4: Environmental enclosure for laser Particulate Matter photometer

measuring known aerosol, the selected photometer manages to achieve high correlation. A detailed description of the detection process of the particles in the optical chamber can be found in Appendix B.2.

3.5 Radon

The advantages of α-track method (Figure 3.5) used in the study included the low cost, the unlimited shelf and post-storage life and the simplicity of installation. Integrated measurement method for determining average activity concentration of Rn-222 and its decay products using passive sampling and delayed analysis is described in BS ISO 11665-4: 2012.

The sensor is a Solid-State Nuclear Track Detector (SSNTD) film placed in an accumulation chamber made of conductive plastic material allowing air to diffuse through a filter. Alpha particles from Rn-222 and its decay products strike the detector causing damage tracks. The detectors were exposed for a period of four weeks allowing a lowest detectable limit of 10 Bq/m^3 (Yushui et al., 1993). Before and after exposure detectors were wrapped in tinfoil. Outdoor samplers were exposed in a Stevenson screen (Figures 3.6 and 3.7). Because radon is largely a ground contaminant, indoor concentrations were sampled in the lowest occupied floor, normally an office where the occupants were briefed to avoid interference. Sensors were placed in a clear place to avoid the influence of potential thoron exhalation from walls.

Figure 3.5: An α-track radon detector

Similarly to the rest of the samplers, exposure to extreme temperature, humidity, direct sunlight and increased air movement were avoided.

Exposed detectors together with field blanks were posted to a specialised lab (Hungary, ‘Frederic Loliot-Curie’ National Research Institute for Radiology and Radiohygiene) for analysis. The sensors were developed by etching with a chemical treatment. The ‘latent tracks’ caused by the alpha particles produced by the disintegration of the radon and its short-lived decay products were converted into ‘etched tracks’. The number of tracks per area counted was used to calculate the radon concentration of the investigated schools. Laboratory blanks and one field blank were used per school to identify background noise. Radon measurements for the non-heating season were excluded from the analysis because of very high blank values. Samplers posted from the specialised laboratory during the non-heating season were enclosed in a different plastic case which might have resulted to an incidental damage of the protective aluminium foil.

Figure 3.6: Stevenson screen

Figure 3.7: Stevenson screens installed in a school yard

3.6 Chemical parameters

3.6.1 Nitrogen dioxide

Passive sampling of NO_2 was performed with Palmes type diffusive acrylic tubes fitted with thermoplastic rubber caps (Figure 3.8). Most passive sampling evaluation studies have reported a good agreement of the method with alternative measurement methods in field inter-comparisons (BS EN 13528-3: 2003). The majority of the studies compared NO_2 diffusion tubes with co-located chemiluminescence analysers (Vardoulakis et al., 2009). The method is applicable to the determination of the mass concentration of NO_2 present in the range of 3 to 2000μg/m^3 for sampling times between two to four weeks. The passive sampling principle is based on the reaction of NO_2 with the compound TEA (Tri-Ethanol-Amine) placed in the inert bed of one cap (BS EN ISO 16000-15:2008). A stainless grid is firmly attached on the adsorbent end of the coloured cap to hold the 20% TEA solution (Figure 3.9). Samplers were prepared and analysed in a specialised lab (Gradko International Ltd, UK).

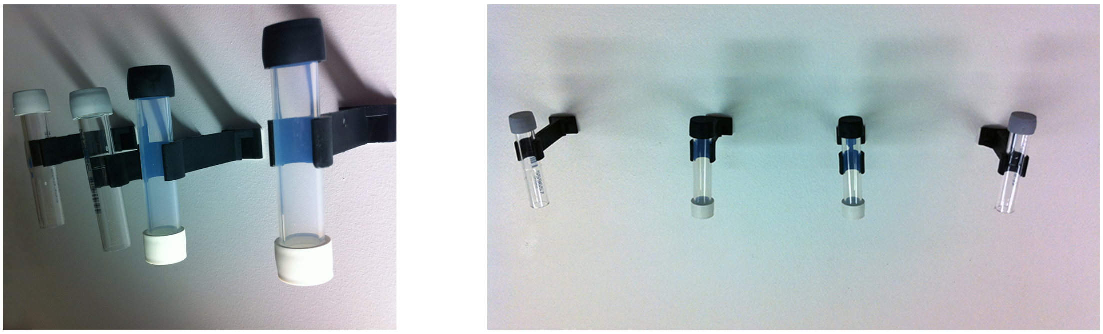


Figure 3.8: Palmes' type tubes for the passive diffusive sampling of ozone and nitrogen dioxide installed in a school

The samplers were stored in temperatures between 5 and 10 °C for periods of time shorter than 12 weeks, which is the recommended shelf-life by the manufacturer. Samplers were carried in cooling bags on-site. The second end cap was removed immediately before exposure to allow chemical adsorption of NO_2 onto the adsorbent medium. Tubes were adjusted on plastic holders and attached on the wall (Figure 3.8) at around 2m height vertically with the open end downwards during sampling. Height of sampling and placement of the sampler in the room was not considered important as spatial variability of NO_2 levels in large single-zone spaces were found negligible (Janhäll et al., 2003). After the two weeks exposure period, tubes were sealed with the second end cap, placed in coded airtight bags and posted overnight to the lab for analysis. Concentrations of nitrite ions and hence NO_2 chemically adsorbed were quantitatively determined by UV/ Visible Spectrophotometry with reference to a calibration curve derived from the analysis of standard nitrite solutions (U.K.A.S. Accredited Methods).

Figure 3.9: Palmes' type tubes for the passive diffusive sampling of ozone and nitrogen dioxide

The method showed a high reproducibility. As part of the quality assurance, 36 sites were sampled in duplicates and a high correlation (R^2=0.99) between the two samplers was noticed (Appendix B, Figure B.4). Results downloaded from Central Stations (CS) in proximity to the urban schools showed a good agreement with values obtained with passive sampling outdoors in the school premises (Appendix B, Figure B.3). Apart from a laboratory blank, a fieldwork blank per school was used and stored in an airtight bag in a dark cool place with minimum temperature fluctuations. Blanks were generally very low (Appendix B, Table B.1), and the results presented are blank subtracted.

Although passive sampling of NO_2 is a validated method, (BS EN 16339: 2013) several factors may affect the accuracy of measurements (Vardoulakis et al., 2009), and, therefore, actions were taken to eliminate inaccuracies. Such factors include: (1) interference from other pollutants; (2) the material of the tube, length of exposure period, and different concentration levels; (3) the absorbent solution; and (4) certain environmental conditions, such as wind speed, air temperature and humidity.

1. TEA sampling may result in some absorption of SO_2 which can reduce the collection efficiency of the sampler by acidifying the absorbent (Cox, 2003). Moreover, interference with ozone may be noticed at concentrations above $200\mu g/m^3$.

2. Previous research has shown that because the body of the acrylic tube is almost totally opaque to UV light, over-estimation of ambient NO_2 concentration may occur due to the reaction of NO with O_3 inside the tube (Heal et al., 1999). Because the overestimation can be minimised at longer sampling periods, exposure was extended to two weeks.

3. The 20% TEA - water solution was preferred over the 50% solution because it had higher uptake rates and was more closely correlated to chemiluminescence analysers (Kirby et al., 2000), as sufficient hydration of TEA is necessary for complete adsorption of NO_2.
4. Effect of environmental factors on outdoor passive samplers can be controlled to a certain extent by the use of specially designed protective screens and shelters. Therefore, outdoor samplers were kept in Stevenson screens (Figure 3.6, 3.7), which provided protection from solar radiation and high winds (Glasius et al., 1999).

3.6.2 Ozone

Passive sampling with Palmes' type tubes was used for O_3 quantification. Tubes are made of fluorinated ethylene polymer fitted with thermoplastic rubber caps. One cap (black) contains the adsorbent, while the second cap (white) allows diffusion of sampled air through a micron porosity filter to prevent the ingress of airborne particulate nitrate (Figure 3.9). This method is suitable for the determination of mass of ozone concentrations from 3.4 to 200 $\mu g/m^3$ for exposure from two to four weeks.

Diffusive tubes were prepared in a specialised lab and analysed by Ion Chromatography (Gradko International Ltd, UK) with reference to a calibration curve derived from the analysis of standard nitrite solutions (U.K.A.S. Accredited Methods). Previous research found a high correlation between the Gradko nitrite passive analyser and an automatic analyser (Ozden & Döerolu, 2012; Vardoulakis et al., 2009), which is considered the most accurate method.

The samplers were stored in temperatures between 5 and 10 °C for periods of time shorter than 12 weeks and carried in cooling bags onsite. Ozone samplers were stored in designated airtight containers immediately before and after sampling (Figure 3.9). Tubes were adjusted on plastic holders and attached to the wall at around 2 m height vertically with the micron filter downwards during sampling (Figure 3.8).

As part of the quality assurance, 19 out of 46 samplers exposed were taken in duplicates (40%) in the heating and non-heating season, and a very high reproducibility of the method was noticed (Appendix B, Figure B.5). Laboratory and fieldwork blanks per school were used, and values were very low (Appendix B, Table B.2). One field blank per school was used and it was stored in a dark cool place with small temperature fluctuations. Detected concentrations of 0.05 μg on the tube roughly correspond to 7 $\mu g/m^3$ for an exposure period of 400 hours.

Limitations of O_3 passive sampling

Chemical reaction between O_3 and NO within diffusion tubes may lead to formation and overestimation of NO_2 as well as underestimation of O_3 (Vardoulakis et al., 2009). The effect is higher near busy motorways where NO concentrations are higher. In order to minimise the interference, the sampler incorporates a micron-porosity filter.

3.6.3 Total Volatile Organic Compounds

Active sampling of total VOCs (TVOCs) was performed with a Photo-Ionisation Detector (PID), which provides a light and simple method with very low detectable limits according to (BS ISO 16000-29: 2014). The instrument (Figure 3.10)(Pho Check Tiger, Ionscience) provides a detection range of 1 ppb to 20,000 ppm (±5% display reading). A custom-built outdoor enclosure for TVOCs monitoring was used (Figure 3.11) built by the instrument supplier company. A good agreement (R^2 =0.98) was found among instruments when tested simultaneously in a controlled environment prior to fieldwork (Appendix, Figure B.8).

Although PID method can provide useful information on overall exposure to organic and some inorganic vapours, it cannot distinguish between detectable compounds in a mixture of gases. The monitor detects VOCs by breaking them into electrically charged fragments with a 10.6eV UV lamp and detects the ions on a metal screen. Therefore, compounds detected include those with an ionisation potential less or equal to that supplied by the lamp. Gases with ionisation potentials higher than that of the lamp (such as aldehydes) will not be detected, while the PID responds more selectively to aromatic hydrocarbons.

Threshold values for TVOCs indoors range between 200 to 600μg/m^3 (Section 2.3.3) when TVOCs measurements are performed by means of GC/MS following thermal desorption on Tenax TA (BS ISO 16000-6: 2011). The PIDs give results in parts per million (ppm) or parts per billion (ppb) based on the molecular weight of isobutylene, which is used to calibrate these instruments. Based on this conversion, the threshold values correspond to concentrations between 87 and 260 ppb. As there are no defined thresholds for TVOC levels monitored with a PID detector, the above thresholds will be used. However, the comparison must be interpreted with caution because the concentrations measured by the PID detector are not equivalent to concentrations measured with passive sampling (BS ISO 16000-6: 2011) due to the different nature of the detection principles (BS ISO 16000-29: 2014).

3.6.4 Targeted Volatile Organic Compounds

The list of priority substances included VOCs commonly present in educational environments that have shown adverse health effects and hence are a potential hazard. Targeted VOCs were benzene, toluene, trichloroethylene (T3CE), tetrachloroethylene (T4CE), pinene, limonene, naphthalene and formaldehyde. *Radiello* passive diffusive samplers were installed on Monday mornings and were collected on Friday afternoons of the investigated week (Figure 3.12).

Figure 3.10: Direct reading Photo-Ionisation Detector for continuous monitoring of TVOCs

Figure 3.11: External installation for TVOCs detector

Among different types of axial diffusive samplers, the radial type was preferred as it improves significantly geometrical constant and therefore sampling rate and analytical sensitivity. Selected samplers consist of three parts (Figure 3.13):

- The diffusive body, which is opaque to light, and is suited for the sampling of light-sensitive compounds. It is made of polycarbonate micro-porous polyethylene;
- the adsorbent activated graphitised charcoal cartridge inside a stainless steel mesh;
- the polycarbonate supporting triangle, with designated area for coding. Coding was always performed with pencil to avoid interference of marker solvents with sampling.

Cartridges were transported on-site in cooling bags, separately from NO_2 and O_3 samplers, to avoid risk of contamination. Contact with the cartridge with bare hands was avoided. Immediately before exposure adsorbing cartridges were removed from the glass vial (Figure 3.14) and inserted fully in the diffusive body (Figure 3.13). After the five-day exposure, the cartridge was removed from the diffusive body, placed into a labelled glass vial and sealed in a metal container. Cartridges were kept in the fridge for a period of one to six weeks before posting to the lab for analysis (Health and Safety Laboratories, UK) for logistic purposes, which is in line with the manufacturer's recommendations. This was cost-effective because the laboratory analysis is performed in batches of 10 samplers with thermal desorption (BS ISO 16017-2: 2012) in a Gas Chromatographer-Mass Spectrometer (GC-MS).

Before fieldwork in the non-heating season, cartridges were conditioned and recovered with thermal desorption. Diffusive bodies were used for five samplings before discarding as adsorbed dust may penetrate the pores and affect sampling rates.

Formaldehyde was sampled separately from the other VOCs with a similar procedure (BS ISO 16000-4:2011). The method is suitable for measurement of formaldehyde in indoor air over the range from 1 $\mu g/m^3$ to 1000 $\mu g/m^3$. *Radiello* sampler for formaldehyde is similar to VOC sampler (Figure 3.12), as it consists of a cartridge inserted in a diffusive body secured on the supporting triangle. However, the diffusive body is of different porosity to allow lower sampling rates. Moreover, additionally to physical adsorption, formaldehyde is sampled with chemical adsorption. The chemiadsorbing cartridge is impregnated with 2,4-Dinitrophenylhydrazine (DNPH) (Appendix B, Figure B.6). Analysis was performed with High Performance Liquid Chromatography (HPLC) coupled with UV detector in a lab (Health and Safety labs, UK). Although the method is designed to eliminate potential interference from other compounds, the risk of ozonolysis is increased at ozone concentrations above 200 $\mu g/m^3$, which were not noticed in the school sample in both seasons (Table D.7 and D.8).

Field blanks identical to those used for sampling were subjected to the same handling procedure apart from exposure and enclosed in the samples so any discrepancies could be identified. One VOC blank per school was used, and, generally, field blank values were very low (Appendix B, Table B.3). Formaldehyde blank values were lower than the instrumental noise (below detection limit). As part of the quality assurance a 10% of the samples was taken in duplicates in both seasons and the correlation was very high (Appendix B, Figure B.7).

Figure 3.12: Passive diffusive VOC and formaldehyde samplers installed in duplicates in a classroom

Figure 3.13: VOC passive sampler

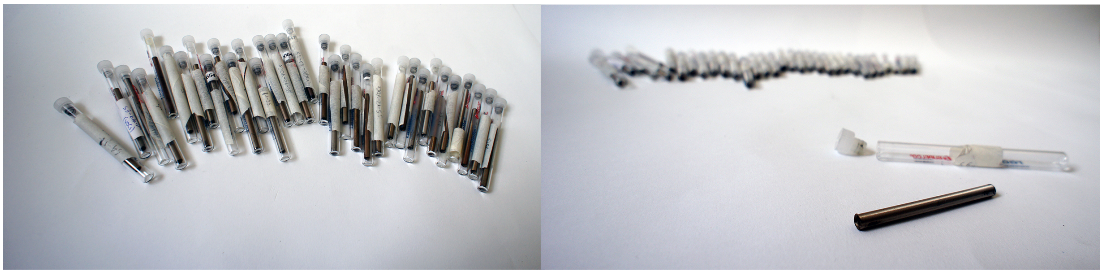


Figure 3.14: Adsorbing cartridges stored in labelled glass vials

3.7 Biological Sampling

Recent versions of ISO standards include sampling strategies for mould (BS ISO 16000-19:2012) by filtration and impaction, and analysis with culturable methods. Commonly used methods for sampling of bacteria and allergen levels are yet to be standardised. Although standards consider active sampling of airborne dust as the most valid method, the approach described in this section for the determination of biological levels in indoor environments has many advantages including the applicability to large-scale surveys, simplicity of investigation compared with cumbersome active air sampling equipment and high reproducibility.

Indoor dust was collected with suction-based methods for determination of fungal and bacterial groups and allergens, and with natural deposition for endotoxin measurements (Table 3.2) in all three classrooms of each investigated school. Analysis was performed with molecular, cultivation-independent methods. Fungal and bacterial groups were sampled both in the heating and non-heating season, while allergens and endotoxin levels were sampled only in the heating season. Previous investigations on seasonal variations of endotoxin levels in schools detected a high correlation between repeated measurements (Jacobs et al., 2013); therefore single endotoxin measurements form a reasonable basis for estimating annual endotoxin levels in schools.

The large surface area to mass ratio of indoor dust provides opportunities for particles forming dust to serve as sinks for a variety of organic species. Indoor dust is a complex mixture of biologically derived materials, particulate matter deposited from the indoor aerosol and soil particles brought in through shoes and clothing of the occupants. In this investigation, both **old dust** and **fresh dust** was sampled from three classrooms in each school. Old dust is settled dust of unknown age, and is a secondary source of airborne particles as they can get re-suspended and become airborne. Old dust can be found settled on indoor undisturbed surfaces, and reflects the composition of the air over a period of time, and can be used for detecting particles that have been released to the indoor air in an unpredictable or episodic way, such as fungal spores. Fresh dust is defined as dust of which the age is exactly known and can be determined by measurement planning.

In all cases, areas with visible chalk deposition were avoided to prevent contamination of the sample. When suction-based methods were used, the vacuum nozzle was rinsed with 70% ethanol solution before sampling different spaces to avoid contamination, as high variability of microbial concentrations between adjacent classrooms was identified in the literature review (Chapter 2).

A description of the analytical methods of the dust samples in the specialised analysing centres is presented in Section B.5.

3.7.1 Fungal and bacterial groups

The microbial investigation included *Cladosporium herbarum*, which is present in healthy buildings (Cabral, 2010) as an indicator of outdoor concentrations. However, the investigation targeted primarily fungal and bacterial groups that indicate moisture damage in buildings. *Trichoderma viride* and *Alternaria alternata*, both require high moisture levels (equilibrium RH >90%) on construction, finishing and furnishing materials in order to grow (WHO, 2009). PenAsp (*Paecilomyces varioti*) and *Aspergillus versicolor* require lower moisture to grow (equilibrium RH <80%) (WHO, 2009), and *Penicillium* spp and *Aspergillus* spp. are largely dominant in sick buildings. The presence of *Mycobacterium* spp. has been common in moisture damaged buildings; their presence increasing with the degree of moisture damage (Torvinen et al., 2006). Similarly, *Streptomycetes* spp. are not normal flora in urban environments, and their presence may indicate damp or wet material (Bischof et al., 2002).

Dust collection method

Old dust was collected from surfaces above floor level which are cleaned less frequently, such as skirting boards, top of bookshelves and window and door frames, and can be considered as long-term integrated airborne exposure. The microbial taxa to be assayed were chosen based on knowledge of their allergenic properties or previous investigations, where they have shown indications to be associated with adverse health effects, conditions of moisture damage and dampness, or based on their known prevalence in outdoor and indoor environment. Analysis of fungal and bacterial groups were analysed in the heating and non-heating season from settled dust collected from the same surfaces following the protocol described below.

A conical nylon bag (Allied Filter Fabrics, Hornsby, Australia, 25 μm pore size) was mounted with masking tape on the suction pipe of a household 400 W vacuum cleaner for 10 minutes at maximum airflow. Immediately after sampling the sock was firmly sealed with a twist tie, put in an airtight press-sealed coded bag and transported in opaque envelopes to avoid light exposure. Particular care was taken to avoid touching the internal surface of the sock with bare hands. Collected samples and one blank were stored in a dark, dry space at room temperature until shipment to the analysing laboratory at the Department Environmental Health, National Institute for Health and Welfare, Kuopio, Finland. In line with the SINPHONIE protocol, all samples from participating countries were analysed in the same laboratory (Section B.5.1), so the microbial counts can be comparable.

3.7.2 Allergens

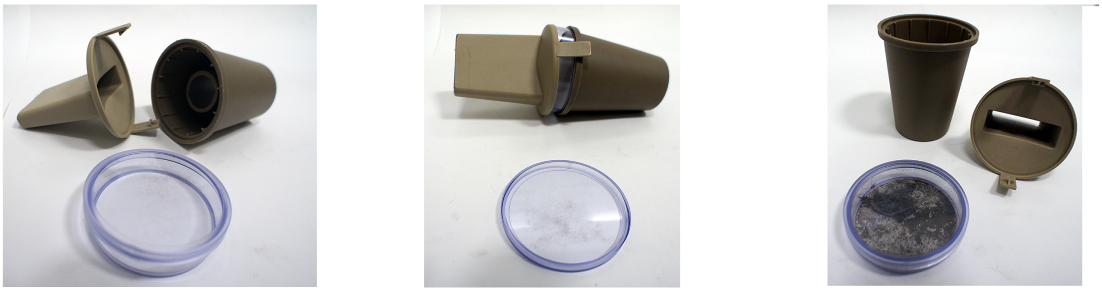


Figure 3.15: The Allergology Filter Cassette fitted on the plastic sampling mouth piece

Several allergen methods are used to assess level of personal or indirect exposure to allergens in schools and in general correlations between different methods have been poor (Karlsson et al., 2002). In this study, allergen sampling in settled dust was performed with the 90 mm Allergology Laboratory Copenhagen (ALK) filter cassette (P-B Miljo A/S) fitted with a disposable nozzle on the hose of the same 400 W household vacuum cleaner used for the microbial sampling. The ALK cassette (Figure 3.15) consists of a Petri-dish like filter holder with a lid. A filter of 0.6μm pore size at the bottom collects sampled dust supported by a plastic grid at the bottom. This method has been widely used in environmental exposure assessments in school buildings (HESE, 2006; Immonen et al., 2001; Kim et al., 2005; Smedje & Norbäck, 2001; Smedje, Norbäck, & Edling, 1997; Tranter, 2005; Zhao et al., 2006).

Dust collection method

The time length of dust collection was standardised by the protocol. Dust was collected for four minutes at maximum air flow, equally divided between floor and other horizontal surfaces, such as desks and chairs, as previous researchers detected higher allergen levels in upholstered furniture (Salo et al., 2009). The aim of the sampling was to maximise the surface area, and therefore be representative of the classroom microenvironment. Sampled areas are indicated in the classroom plans (Appendix D.2).

In line with the SINPHONIE protocol, two filter cassettes were used per classroom (Appendix B.5.2), because the classroom was divided arbitrary into two parallel zones:

- One zone included the area close to the window, exposed to direct sunlight. This filter cassette was stored in room temperature in a dark place until analysis.
- The second zone included the zone away from the window, and the filter cassette was stored in the freezer in -20 °C.

The harmonised analysis of samples from all participating institutions, including UCL, was performed at the Institute for Occupational and Environmental Medicine, University Hospital, Uppsala, Sweden (Appendix B.5.2).

3.7.3 Endotoxin

Although no clear association was found in microbiological studies, it has been proposed, that endotoxin from Gramm-negative bacteria occurs at higher moisture damage (Bischof et al., 2002).

Dust collection method

Electrostatic Dust Fall Collector (EDC) is a validated method for the average airborne Endotoxin exposure with high reproducibility (Noss et al., 2008). In this investigation, EDC consisted of four electrostatic clothes exposed to the air horizontally mounted on a plastic 42 by 29.6 cm sized folder. The samplers were exposed for a period of four weeks on an undisturbed surface at 1.5 to 2.2 m, away from air velocities and heat sources (Figure 3.16).

The EDC was transported in airtight plastic bags before and after sampling. Contact with the wipes with bare hands was avoided. Extraction and analysis of the dust took place at National Institute for Environmental Health, Hungary (Section B.5.3).

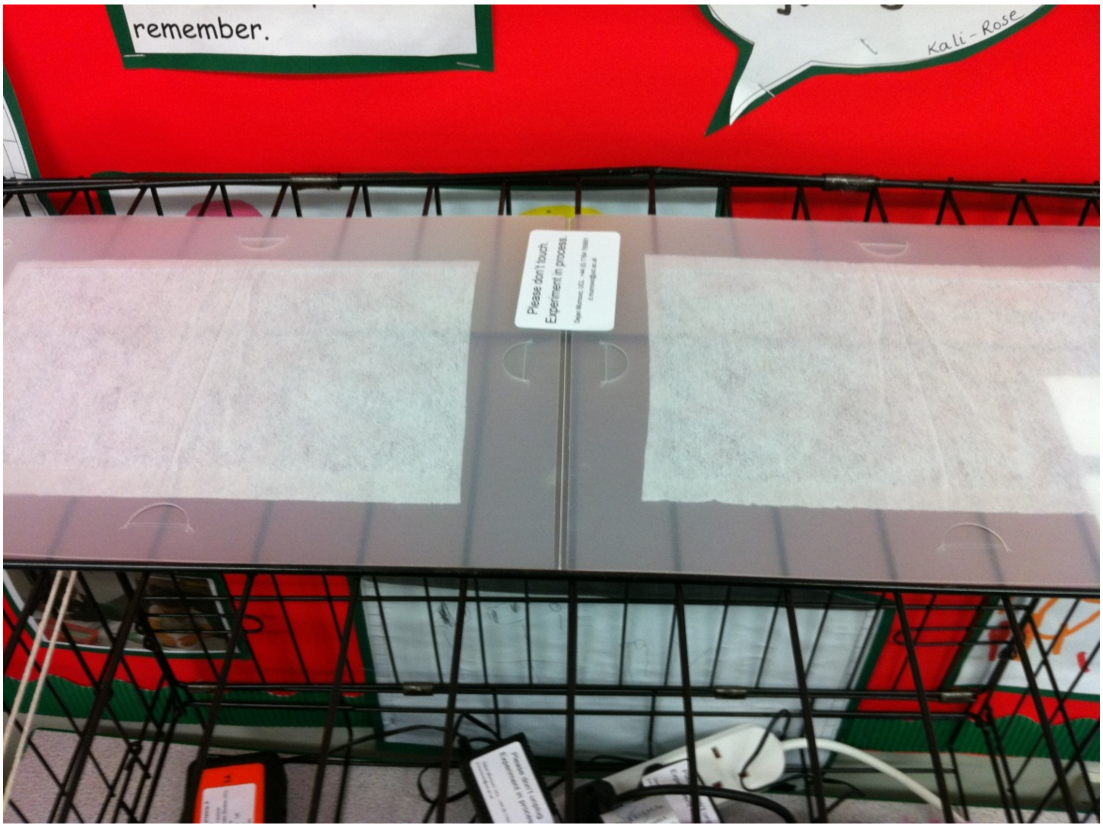


Figure 3.16: Electrostatic Dustfall Collector installed in a school

3.8 Summary

This chapter presented the methodology for determination of physical, chemical and microbial parameters, which can be extended in many non-industrial indoor environments, as it is cost-effective and is applicable in large-scale surveys. The limitations and potential interferences of the selected methods were documented in detail. The study was organised as a longitudinal study of the heating and non-heating season. Direct-reading instrumental sampling was employed for temperature, RH, CO_2, PM, TVOCs to capture indoor variations in relation to fluctuating strength of sources, occupants' activities and ventilation patterns. Passive sampling was employed for quantification of NO_2, O_3, identification of VOCs, PM and radon, which all have long-term effects on the health of occupants. Microbial assessment used long-term integrated samples analysed with molecular methods.

This chapter together with Chapter 4, present the multidisciplinary methodology adapted to create the integrated database of health responses of the occupants matched with building characteristics, the microenvironment and daily maintenance and operation of school buildings. The next chapter also presents the methodology for developing multilevel statistical models.

Chapter 4

Methodology: Surveys and Statistical Analysis

Collection of building characteristics, occupant surveys and statistical analysis

4.1 Outline

The extensive literature review in Chapter 2 identified that IAQ depends strongly, on the one hand, on the interaction between the building and the outdoor environment. Indoor air is an extension of ambient air, as outdoor pollution can penetrate indoors through intended openings and unintended cracks in the building envelope. On the other hand, IAQ depends on the way the building is used, as indoor chemistry is a complex interaction of various factors, such as indoor sources and sinks, and pollutant depletions. With this in mind, descriptors of the physical environment were collected to enable the characterisation and comparison of school buildings for the interpretation of the fieldwork measurements.

In this chapter four main elements are addressed:

- The first part (Section 4.2)
- The second part (Section 4.3) offers a description of the standardised checklists used to collect information on the microenvironment, school buildings' and classrooms' characteristics, which may impact on IAQ.
- The third part (Section 4.4) presents the questionnaire survey employed to collect prevalence, incidence and remission of health symptoms, personal factors and students satisfaction with the school environment. The research methodology received approval from UCL Ethics Committee (3357/001).
- The fourth part lays out the descriptive and inferential statistics, and the multilevel models employed to analyse the integrated database (Section 4.5). Multilevel modelling provides a convenient analytical framework with concordance between theoretical approaches

and statistical analysis. While multilevel modelling has gained popularity over the last two decades in various research fields, such as social science and epidemiology, the use in building science is still limited to a few recent studies. Section 4.5 presents detailed steps for building two-level multilevel regression, logistic and multinomial models, as well as the advantages, limitations, considerations, and assumptions of the method.

4.2 Sample size and power considerations

Sample size determination is an important step in the design of a research study. Appropriately-sized samples are essential to infer with confidence that sample estimated are reflective of underlying population parameters. This study has a relatively small sample size; therefore results need to be interpreted carefully. The statistical efficiency was maximised by the following estimators and procedures:

Multilevel hierarchy

Sample size determination in multilevel designs requires attention to the fact that statistical power depends on the total sample sizes for each level. It is usually desirable to have as many units as possible at the top level of the multilevel hierarchy. With this consideration in mind, classrooms were inserted as the higher level in the random part of the model, while the effect of the school was controlled in the fixed part.

Bayesian estimation

Multilevel modelling is a particularly useful analytical approach when data are sparse. The empirical Bayes estimator is a shrinkage estimator approach as it borrows information from all the groups to support statistical estimation for the groups with insufficient observations (Gelman et al., 2013), and, therefore, provides an appealing option for small datasets. Bayesian model averaging is advantageous because it accounts for model uncertainty and minimises the risk of over-fitting.

Case cross-over design

The case - crossover design was introduced in 1991 as a new epidemiologic technique for examining the transient effects of brief exposures on the onset of acute outcomes (Maclure, 1991). This technique allows testing for an acute health effect of an exposure to air pollution with restriction in time to remove seasonal confounding. Moreover, use of subjects as their own controls eliminates confounding by subject characteristics that remain constant. Self- matching of cases eliminates the threat of control- selection bias and increases efficiency. Use of cases as their own self-matched controls guarantees representativeness and generalisability, in principle, to all acute-onset outcomes hypothesised to be caused by brief exposures with transient effects.

In practice, its utility relative to the traditional case-control design will depend on the relative susceptibilities of each design to selection bias and information bias, which will depend on the particular exposures of interest.

4.3 Standardised checklists used to characterise buildings and classrooms

This section presents on-site surveys, observational studies and standardised checklists used to collect information on factors that potentially impact on IAQ. The summarising Table 4.1 presents all parameters considered in the analysis.

4.3.1 On-site survey of school buildings

The checklist (Appendix, Section C.1.1) was used to collect information on the microenvironment of the surrounding area, construction characteristics, ventilation and heating strategy and potential indoor pollution sources (water leakage, visible mould, infestation, use of pesticides, cleaning schedule, presence of kitchen, presence of photocopiers, special use rooms) (Table 4.2). The checklist was completed after consulting with the facility managers of the schools.

Table 4.1: Summary of Level-2 predictors of the physical environment

Group	Predictor variable	Explanation
Microenvironment		
	Location (binary)	0: Suburban 1: Urban
	Proximity to traffic (Categorical)	1: Urban in immediate proximity to high traffic intensity street 2: Urban background 3: Residential with a high traffic street less than 400m away 4: Residential more than 400m away from high traffic street
School and classroom characteristics		
	Thermal mass (binary)	0: Mixture of high and low thermal mass walls 1: High thermal mass building
	Ceiling (binary)	0: exposed ceiling 1: suspended panels on ceiling
	Natural Ventilation (binary)	0: Mixed-mode ventilation 1: Natural Ventilation
	Ventilation strategy (categorical)	1: Single-sided natural ventilation 2: Mixed-mode ventilation 3:Infiltration (restricted windows) 4:Cross-sided natural ventilation
	Heating System (binary)	0: LTHW radiators 1: underfloor heating
	Airtightness of building envelope (Continuous)	Based on estimated infiltration rates
	Glazing (binary)	0: Single glazing 1: Double or triple glazing
	Window type (Categorical)	1:side pivot 2: sash window 3: top-hang inwards 4: bottom-hang outwards
	Openable area (m^2)	Continuous
	Exposure to wind direction (Categorical)	1: windward side 2: parallel to the wind direction 3: leeward side
	Area (m^2) and Volume of classroom (m^3)	Continuous
Maintenance/ Operation		
	Blackboard (binary)	0: Control 1: Presence of chalkboard in the classrooms
	Cleaning schedule (binary)	0: Classrooms cleaned in the morning (before occupied period) 1: Classrooms cleaned in the evening (after occupied period)

Continued on next page

Table 4.1 – *Continued from previous page*

Group	Predictor variable	Explanation
	Cleaning product	0: Low-emitting cleaning products 1: Non low-emitting cleaning products
	Pest control (binary)	0: Control 1: Use of pesticides during the academic year
	Carpet	0: Control 1: Presence of wall-to-wall carpeting
	Carpet (m^2)	Continuous variable of total carpeted area in the classroom
	Curtain (m^2)	Continuous variable of total curtain area in the classroom
	Fleecy factor (m^2/m^3)	Continuous variable. Estimated as the area of fleecy surfaces (e.g., textile floor coverings, curtains, and textile chair covers) divided by the volume of the room
	Furniture (binary)	0: Control 1: Furniture introduced in the classroom less than two years before sampling period
Occupancy		
	Number of occupants	Continuous variable of students in classroom
	Density	estimated based on the enrolled students per floor area (m^2/p) and per cubic metre (m^3/p) of classroom

4.3.2 Questionnaire administered to headteachers and teachers on building and classroom characteristics

The questionnaire was directed as a semi-structured interview to the headteachers (Appendix, Section C.1.2) and teachers (Appendix, Section C.1.3) of the monitored classrooms, where the respondents could make additional comments.

This questionnaire obtained information on: general characteristics of the school building (construction years, restoration history, maintenance authority); comments on the microenvironment of the surrounding area (emitting establishments in vicinity, green spaces, activities in the schoolyard, traffic intensity of surrounding streets); building systems (heating system and ventilation strategies); potential indoor pollution sources (cleaning products during occupancy period, dust, infestation sources, such as mould, rodents, cockroaches) and self-reported satisfaction with IEQ in the school.

The questionnaires administered to teachers aimed to collect information on the interior finish-

Table 4.2: Structure of the checklists used for the on-site survey of schools and selected classrooms

Cheklists for the characterisation of school buildings			
General characteristics	**Construction characteristics**	**IEQ provision**	**Potential indoor pollution sources**
Geographical location	Construction year	Ventilation strategies	Rodents, cockroaches, mould, pets
Microclimate of surrounding area	School area and number of enrolled students	HVAC system maintenance	Indoor facilities and activities
Outdoor pollution sources	Wall construction and roof structure	Heating system	
Noise pollution sources	Maintenance and Legislation		
	Radon mitigation		
Cheklists for the characterisation of classrooms			
General Characteristics		**IEQ provision**	**Potential indoor pollution sources**
Physical characteristics		Heating system	Blackboard
Occupancy patterns		Ventilation strategies	Electronic Equipment
Lighting and Daylight			Furniture
Controls			Fleecy materials
Indoor Materials			Furniture
			Artwork materials
			Cleaning frequency and products
			Risk of mould infestation

ing of the classroom, ventilation strategies and typical window adjustment and thermal comfort during typical days in the heating and non-heating season, cleaning frequency, emitting products introduced in the classroom (presence of blackboard, artwork and cleaning products), risk of mould infestation, overall satisfaction with the environmental quality of the classroom and number of asthmatic children. The number of asthmatic children was cross-checked with the self-reported questionnaire administered to children.

4.4 Students' self-reported questionnaire

In this section, the methodology for collecting self-reported health symptoms and satisfaction with the school environmental quality is presented.

The study is a follow-up during an academic year of a cohort consisting of a volunteer sample of students. The same questionnaire was administered in the heating (baseline) and non-heating (follow-up) season, and performed the same week as the monitoring of pollutant levels. The pen-and-paper questionnaires were transcribed in protected excel sheets with locked cells by the author. After the transcription, the numeric data were plotted in boxplots, and outliers were cross-checked with the questionnaires. As part of the quality assurance, the Principal Investigator of the project checked a random 10% of the transcribed data.

Children were generally able to complete the questionnaire with little or no help from the researcher and the teachers. Students with learning disabilities and with limited use of the English language were excluded from the study. It was made clear to all students that choosing not to participate in the study would not disadvantage them in any way. A short presentation on the aim of the research, the importance of adequate air quality and sources of pollution in the school environment was given after the completion of the questionnaire. The students were attending a fixed classroom throughout the academic year for the majority of teaching activities, except for sports. Each student participated in two clusters of measurements; one in the heating and one in the non-heating season. There were no reports of health complaints or environmental problems from any school before the investigation. At baseline the questionnaire was distributed to 430 students attending five schools.

The questionnaire is based on a version of the MM questionnaires (Orebro Model) (Andersson, 1998), which have set a standard for the phrasing of questions on SBS (Engvall et al., 2004), and their validity is similar to medical interviews (Malo et al., 2013). Versions of the questionnaire have been used in epidemiological studies among children and adults in dwellings (Norlen & Andersson, 1993; Stridh & Andersson, 1995), and among both pupils and school personnel in schools (Andersson et al., 2008; HESE, 2006; Mysen et al., 2005). The author extended the SINPHONIE questionnaire by including questions on perception and satisfaction with the indoor environmental quality, including IAQ which was outside of the scope of the SINPHONIE project. The questionnaire administered in both seasons of this investigation can be found in the Appendix C.3.3. Because the questionnaires involved sensitive personal data, informed consent from students (Appendix C.3.1) and their carers (Appendix C.3.2) was necessary for the participation.

Questions were presented in a rational order, and the philosophy behind the construction of the questionnaire was that it should resemble a dialogue rather than a checklist. The idea is that the respondent makes a visual and emotional mind map of the environment before proceeding to more general judgement. This structure is often called the *'inverted-funnel principle'* and is commonly used to obtain reliable specific and general information in questionnaires (Engvall et al., 2004). Sensitive personal information, such as health related questions, was embedded in the middle of the questionnaire, surrounded with more neutral' questions. Students were asked to recall aspects of indoor environmental quality and health symptoms during the investigated week. If perception varied, they were asked to make a judgement on the usual air quality during that period. The questionnaire collected information on personal factors, self-reported health symptoms and perception of indoor air quality:

- Personal factors collected included gender, age and exposure to environmental tobacco smoke. Three questions evaluated psychosocial climate in the school regarding overall satisfaction with the school environment, stress levels and climate of co-operation on an 11-point scale. A literature review (Frontczak & Wargocki, 2011) indicated that these personal factors may influence human comfort in indoor environments, and should, therefore, be controlled.
- Health questions on SBS symptoms had binary responses (1: symptom was present, 0: symptom was not present). As SBS symptoms are acute, students were asked whether they experienced SBS symptoms during the investigation week in the school, home or other indoor environments. In the analysis, only SBS symptoms experienced in the school environment were considered. There were 29 questions on SBS symptoms. Five categories of symptoms were determined: dermal, general, ocular, nasal and throat. The last three categories were grouped further as mucosal symptoms (Table 7.1). For each person, symptoms belonging to the same category were grouped together and coded as 1 if at least one symptom was present. Incidence of any symptom was defined as the presence of a symptom at the end of the follow-up period, and absence in the beginning. Remission of a particular group of symptoms (mucosal, dermal or general) was defined as the presence of a symptom in the beginning and absence of the symptom at the end of the follow-up. The same definitions of incidence and remission have been used in other longitudinal SBS studies (Zhang et al., 2011).
- Students were asked whether they ever had an asthma attack or asthmatic symptoms in the school environment. Asthmatic symptoms included wheezing or whistling in the chest while at school. Asthma attacks and asthmatic symptoms self-reported from students were cross-validated with the classroom teachers, who were aware of asthmatic children. The question on asthma attacks and asthmatic symptoms was a single question; therefore no grouping of the responses was necessary. The incidence of asthma attacks and asthmatic symptoms in the school environment was estimated during the follow-up period.
- Satisfaction with IAQ investigated in this thesis was evaluated in a bipolar and semantic differential 7-point scale.

4.5 Statistical analysis

4.5.1 Inferential statistics

Descriptive statistics (mean, standard deviation, median, interquartile range and minimum and maximum concentrations) were calculated over the occupied period (09:00am-15:00pm) for each classroom using the MEANS command in SAS 9.3. Descriptive and inferential statistics were performed using SAS system version 9.3 (SAS Institute Inc., Cary, NC, USA), and statistical significance was set to 95% ($p < 0.05$). As the inferential statistics cannot be performed with null values, non-detects (values below the diffusive sampling detection limits) were set to half the detection limit (0.02 $\mu g/m^3$ for most compounds), as in previous publications (Godwin & Batterman, 2007). Inferential statistical tests used in the thesis can be summarised as follows:

- *Mann-Whitney U test* (also referred to as Wilcoxon rank-sum test). This test is the non-parametric equivalent of the independent t-test, and is used to test the null hypothesis that two populations are the same against an alternative hypothesis. It was employed, in this thesis, to determine whether there was a significant difference in pollutants' concentrations (continuous outcome) measured in urban and suburban schools in one season. For example, *Mann-Whitney U test* was used to determine whether outdoor NO_2 concentrations sampled in urban and suburban school premises in the heating season was significantly different. *Mann-Whitney U test* has been previously used extensively in schools to detect differences in pollution levels between two groups (Abramson et al., 2006; Branis et al., 2009; Godwin & Batterman, 2007; Karlsson et al., 2002; Rullo et al., 2002; Smedje & Norbäck, 2001; Torvinen et al., 2006; Zhao et al., 2006).

- *Wilcoxon signed-rank test* is the alternative to the paired Student's t-test (t-test for matched pairs, or the t-test for dependent samples) when the population cannot be assumed to be normally distributed. The *Wilcoxon signed-rank test* is a non-parametric statistical hypothesis test used when comparing repeated continuous measurements on a single sample to assess whether their population mean ranks differ (it is a paired difference test). In this thesis, *Wilcoxon signed-rank test* was used to test whether pollution levels were significantly different between seasons. For example, this test was used to determine whether outdoor NO_2 levels measured in urban schools were significantly higher in the heating compared with the non-heating season. The test has been used to investigate seasonal variations of pollutants' concentrations in previous environmental investigations in school settings (Norbäck et al., 2011).

- *McNemar test* is a statistical test used on paired nominal data (basically a paired version of Chi-square test). In this thesis, it was used to test changes in prevalence of health symptoms (collected as binary responses) between seasons. The occurrence of the responses collected in the heating season from each student (case) was paired with the responses collected in the non-heating season (control). Therefore, each student served as his or her own control.

- *Pearson's chi square (χ^2)* test is a statistical test used to evaluate how likely is that the difference arose by chance in unpaired categorical data. In this thesis it was used to compare whether the prevalence of symptoms was significantly different between urban and suburban schools.

4.5.2 Types of multilevel models employed

While multilevel modelling has been used in epidemiological and social research, application on building science has been limited (Banerjee & Annesi-Maesano, 2012; Zhang et al., 2012). Collected data had a hierarchical structure, because units at a lower level were nested within units at a higher level with students nested in classrooms, and classrooms nested in schools. Moreover, repeated measurements were nested in classrooms creating longitudinal model or *growth curve models*. Conventional single-level statistical methods are inappropriate because observations are dependent and the contextual effects cannot be addressed. In this work, students attending the same classroom would be expected to have more similar health outcomes than students attending different classrooms, because they are exposed to similar exposures. Therefore, six types of models were employed:

Model I

Two-level multilevel regression models (classroom and season level) were used to analyse factors affecting indoor pollutants concentrations. The outcome variable in these models was a specific indoor pollutant (continuous outcome), and the predictors included binary, categorical and continuous variables, of both school and classroom characteristics (Level-2 predictors), as well as continuous data that fluctuated over time (Level-1 predictors).

Time measurements were expressed on the same measurement scale, as all continuous measurements were averaged over 20-minute intervals. A separate database with average exposure was created to analyse long-term integrated measurements. Using longitudinal multilevel modelling with variables that are not measured on an interval scale can result in misleading analysis results and erroneous conclusions (Peugh, 2010). The effect of the school was controlled in the fixed part of the model. A detailed description of the steps followed to build these type of models is presented in Section 4.5.4.

Model II

Two-level logistic models (classroom and student level) were used to associate health responses (Section 4.4) with specific exposures in the school environment at baseline conditions (in the heating season). Because health responses (outcome variable) were obtained as binary variables, multilevel logistic regression was necessary. Multilevel logistic models are an extension of fixed effects logistic regression incorporating random effects into the model to deal with the Intraclass Correlation Coefficient that arises in multilevel data.

Predictor variables were indoor pollutants (continuous variables) measured at classroom level. Each exposure was tested in isolation in a separate model as pollutants may autocorrelate (Chapter 6). All models controlled for personal factors at student level (such as age, gender and exposure to ETS in other environments). The models also controlled for the effect of the school.

While several link functions can be fitted, in this work the logit model was used, which is the most common choice in epidemiological studies.

Model III

Two-level ordered multinomial logistic models (classroom and student level) were used to associate satisfaction with IAQ with specific exposures to pollution, personal factors and building characteristics. Satisfaction with IAQ was the outcome variable, and was expressed in a 7-point scale (Section 4.4). While many researchers treat ordinal variables as if they were continuous, and analyse them using ordinary least squares regression, this is not recommended for two main reasons: (i) the differences between numeric codes assigned to categories have no meaning (only their relative values can be interpreted); and (ii) ordinal values in this work had skewed distributions.

Similarly to the binary logistic Model II, each predictor variable was entered separately into the model. The models that aimed to associate personal variables with perceived IAQ used binary (e.g., gender), continuous (e.g., age) and ordered categorical variables (overall satisfaction with school environment) as predictor variables. The categorical predictor variables were treated as continuous. The models controlled for the effects of school and season. The ordered multinomial logistic models that aimed to associate perceived IAQ with building characteristics also used binary (e.g., visible mould), categorical (e.g., location) and continuous variables (e.g., number of occupants), which were entered separately into the model.

Indoor pollution levels (continuous variables) measured at classroom level in both seasons, were also inserted separately into the models, which controlled for the effects of school, season and personal factors (age, gender, exposure to ETS). The models aimed to determine predictors consistently affecting satisfaction with IAQ in both seasons.

Model IV

Similarly to Model III, this model is a two-level (classroom and student levels) ordered multinomial logistic model that investigates indoor pollution levels which may affect satisfaction with IAQ, and each exposure was inserted separately in to the model controlling for the effects of school and personal factors (age, gender and exposure to ETS). Contrary to Model III, this model was repeated separately in the heating and non-heating season, as factors varying among seasons (such as differences in occupants expectations) may affect the associations.

Model V

In this step, all factors which were significant in Model III were simultaneously entered into the multilevel (classroom amd student level) ordered multinomial logistic model. Two models were constructed: one for physical and chemical parameters; and one for microbial parameters. The aim of these models was to identify the most significant predictors from each category that may influence overall satisfaction with IAQ in both seasons.

Models I to V were fitted in MLwiN version 2.30, (Centre for Multilevel Modelling, University of Bristol), a special-purpose computer programme for multilevel modelling. All models presented in this thesis had successfully converged in Iterative Generalised Least Squares (IGLS) estimation method (deterministic estimator), before applying the Markov Chain Monte Carlo (MCMC) estimator (stochastic estimator). MCMC is a Bayesian estimation method suitable for small datasets (Stegmueller, 2013). Burn-in length was set to 5 000, chain length to 50 000, and visual diagnostics were applied to check for convergence (Appendix Section C.4). A two-tailored test and a 5% level of significance were applied (β coefficient/ standard error (SE) >1.96). The odds ratio (OR), with a 95% Confidence Interval (95%CI) was calculated.

Model VI

Conditional logistic regression is a suitable method for sparse data, and is used to investigate the relationship between an outcome and a set of prognostic factors in matched case-control studies. Conditional logistic regression is suitable for repeated measurements in survival analysis (or time to event analysis), and works in nearly the same way as regular logistic regression, except for the need to specify which individuals belong to which pair or stratum.

In this study, conditional logistic regression models were employed to associate exposure with specific indoor pollutants (prognostic factor) with incidence or remission of symptoms in the non-heating season (outcome), where each student was used as his or her own control (matched case-control). Essentially, conditional logistic regression was used to estimate the hazard ratio of incidence and remission in health symptoms in relation to seasonal variations of indoor pollution concentrations.

The conditional logistic regression models were developed by the PHREG procedure in SAS 9.3 with robust sandwich covariance for aggregated data. Ties were handled with the DICRETE method. While PHREG procedure includes four methods for handling ties, only the DISCRETE logistic model is available for discrete time-scale data, and was, therefore, applied in the analysis. The other three methods apply to continuous time-scale data.

In addition, dummy survival time variables were created, so that all the cases in a matched set have the same event time value, and the corresponding controls are censored at a later interval time. Therefore, dummy time intervals were set to 2010-2011 and 2011-2012. The code for the logistic model can be found in Appendix Section C.5.

Similarly to Model II, each exposure was inserted separately in the model. The Hazard Ratio (HR) with 95% CI was calculated in SAS version 9.3.

A previous meta-analytic study (Dedrick et al., 2009) reported methodological shortcomings in a sample of 99 published journal papers employing multilevel models for the analysis. Analysis of reporting practices indicated some clear problems, with many articles not reporting enough information for a reader to critique the reported analysis. The complexity of multilevel models precludes rigid rules for methodological decisions and reporting practices; however, Dedrick et al. (2009) proposed a checklist consistent with the standards for reporting on empirical social science research in American Educational Research Association (AERA, 2006). Taking this into account, this section reports methodological decisions for the development of multilevel models, as well as a detailed description of the theoretical background of multilevel modelling.

4.5.3 Advantages of multilevel modelling

Prior to the availability of multilevel analytical techniques and computer programs, multilevel data were analysed separately at a single level, either at individual (Equation 4.1) or at group level (Equation 4.2).

Individual level model:

$$y_{ij} = \beta_0 + \beta_1 \chi_{ij} + e_{ij} \tag{4.1}$$

where y_{ij} is the outcome at individual level, β_0 represents mean outcome of group j, and e_{ij} is the random individual variation around this mean.

Group level model:

$$y_j = \gamma_0 + \gamma_1 \chi_j + u_j \tag{4.2}$$

where γ_0 denotes the overall intercept representing the grand mean of y_{ij}, and u_{0j} captures the variation between group means.

Model 4.1 ignores the within observation dependence, and, therefore, violates the basic assumption underlying traditional regression models. As a result, standard errors of parameter estimates would be biased downwards resulting in a *Type I* error producing misleading regression. Model 4.2 focuses exclusively on the inter-group variation and on the data aggregated to the group level. While group level model eliminates observation dependence problem, it ignores the role of individual-level outcomes in shaping the outcome and also reduces statistical power by using a much smaller sample size.

Model 4.2 eliminates the observational dependence, but ignores the role of individual-level variables in shaping the outcome; and by using a group-level sample greatly reduces the statistical power.

Traditionally, researchers tended to use model results at one level to draw statistical inferences at another level, which has proven incorrect. The relationships found at group level are not reliable predictors for the relationships at the individual level and vice versa. This phenomenon is known as *ecological fallacy* or *Robinson effect.* In multilevel modelling the ecological fallacy is eliminated because data obtained at individual and contextual level are simultaneously analysed (Wang et al., 2011).

The ecological fallacy is caused because model 4.2 analyses y_{ij} at the group level. Aggregating individual measures changes their meaning. If χ_{ij} is a continuous variable then χ_j is the average of χ_{ij} in group *j.* If χ_{ij} is a binary variable (e.g 1: female, 0:male), the χ_j would be the proportion of females in j^{th} group. Clearly χ_{ij} and χ_j are different measures, and they will have different effects in separate models.

In this thesis, the use of multilevel statistics provides quantitative information between and within spatial units (e.g. classroom). For example, measured pollution levels in a classroom might be dependent on contextual effects of the school, such as strength of outdoor sources, but also on individual characteristics of the classroom, such as frequency and timing of window opening. Similarly, health of the student may be influenced by contextual effects of the school environment, but also by individual level factors, such as exposure of the student to environmental tobacco smoke (ETS) at home. Multilevel models allow exploring the nature and extending of the relationships at both micro and macro levels, as well as across levels.

4.5.4 Steps for building two-level multilevel models

The purpose of model development is to find a parsimonious model that not only fits the data, but also provides interpretable results. Therefore, model development is an exploratory process that is driven by theory, hypothesis, statistical tests of the hypotheses and model comparisons.

Multilevel models are complex because the outcome variance consists of micro and macro components and variance occurs at both levels. This section presents the methodology for the development of a two-level multilevel regression model using a combination of approaches from Hox (1995) and Singer (1998). The first step was to create an empty model, and then sequentially examine the effects of macro and micro explanatory variables.

Empty model

Empty model or *intercept-only model* or *unconditional means model* is fundamental in multilevel development. The empty model allows: (a) decomposing the total outcome variation into within-group and between-group variations; (b) provides information about the grand mean of the outcome measure, reliability of each groups mean outcome measure as an estimate of its population mean; and (c) is the baseline model with which other complex models can be compared. The empty model is identical to a *one-way random effect of variance* (ANOVA), where no explanatory variables are included in level-1, or level-2 models:

$$y_{ij} = \beta_{0j} + e_{ij} \tag{4.3}$$

$$\beta_{0j} = \gamma_{00} + u_{0j} \tag{4.4}$$

$$y_{ij} = \gamma_{00} + u_{0j} + e_{ij} \tag{4.5}$$

i=1,.r, where r = number of level-2 units, and

j=1,.s, where s = number of level-1 units

$u_{0j} \sim N\ (0,\ \sigma^2{}_{u0})$

$e_{ij} \sim N\ (0,\ \sigma^2{}_{e})$

In model 4.3 $\beta_{0\mathrm{j}}$ represents mean outcome of group j, and e_{ij} is the random individual variation around this mean. In equation 4.4 γ_{00} denotes the overall intercept representing the grand

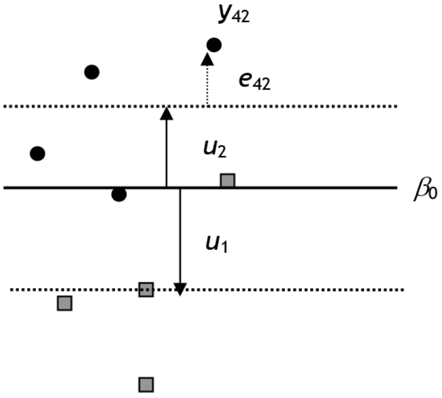


Figure 4.1: Individual and group residuals in a two-level empty model. The figure shows y values for eight individuals in two groups, with individuals in group 2 denoted by black circles and those in group 1 denoted by grey squares. The overall mean is represented by the solid line and the means for groups 1 and 2 are shown as dashed lines. Also shown are the group residuals and the individual residual for the 4^{th} individual in the 2^{nd} group (e_{42}). Group 1 has a below-average mean (negative u_j), while group 2 is above average (negative u_j)

mean of y_{ij}, and u_{0j} captures the variation between group means. Model 4.5 is a *combined model* in which the outcome y_{ij} is a combination of two parts: the fixed part (γ_{00}); and the random part consisting of two random effects, the group variation (u_{0j}) from the overall mean, and the individual variation (e_{ij}) around group-specific means (Figure 4.1).

Because no covariates are involved, the variance in the *empty model* is not explained, and can be decomposed into two components: within-group and between-group variance. The total variance can be described as:

$$\begin{aligned} \text{var } y_{ij} &= \text{var}(\gamma_{00} + u_{0j} + e_{ij}) \\ &= \text{var } (u_{0j}) + \text{var } (e_{ij}) \\ &= \sigma^2{}_{u0} + \sigma^2{}_{e} \end{aligned}$$

Within and between-group variance can be used to calculate the Intraclass Correlation Coefficient (ICC) using equation 4.6.

$$ICC = \frac{\sigma^2{}_{u0}}{\sigma^2{}_{u0} + \sigma^2{}_{e}} \tag{4.6}$$

As within-group homogeneity is an indication of between-group heterogeneity, significant testing of ICC is equivalent to testing for the null hypothesis that the between-group variance is zero (all groups have the same outcome mean). ICC can be considered a correlation among individuals within the same group and ranges between 0 and 1. A statistically significant ICC close to 1 indicates that multilevel regression is necessary, while a non-significant ICC close to 0 means that a multiple regression model is appropriate for data analysis, with the multilevel model reduced to a fixed-effect model. As an example, in this thesis it is expected that a large

ICC will be computed for pollutants with large spatial variability, such as NO_2, indicating that classrooms in proximity will be more similar than classrooms located in remote locations (within-group variability will be small compared with between-group variability). On the other hand, a small ICC is expected for transboundary pollutants, indicating that the variability between classrooms in different schools (between-group variability) will be small. Even a small ICC can lead to substantial *Type-I* errors in statistical testing leading to falsely rejecting a true null hypothesis. If ${\sigma^2}_{u0}$ is statistically significant then ICC is statistically significant too.

Adding level-2 explanatory variables into the empty model (predicting between-group variation)

The next step of model development expands the empty model by adding explanatory variables. As there are no level-1 explanatory variables, the within-group variation is not explained in this model.

This thesis adopted an approach supported by Singer (1998) to expand the model by adding level-2 variables contrary to alternative approaches of including level-1 variables first (Hox, 1995). As already discussed, the empty model indicates significant unexplained variation in the mean outcome across groups, and it is, therefore, logical to add group-level variables in the model to explain the variation.

Level-2 variables are macro-level variables and can be aggregate measures (such as mean values of individual measures), characteristics unique to groups that cannot be captured at an individual level or categorical measures. In this thesis, level-2 variables were classified in categories focusing on the main factors affecting indoor concentrations (Section 4.3, Table 4.1), namely microenvironment (outdoor concentrations, orientation of the facade, wind speed and direction), building characteristics (airtightness, ventilation strategy, potential indoor sources), maintenance and operation of buildings and occupancy. In this step, all relevant level-2 parameters, as indicated in the methodological guidance for building multilevel models (Dedrick et al., 2009), were considered. However, the number of group-level variables must not be greater than the number of the groups. A similar rule applies to multi-linear regression that the number of independent variables must not be greater than the number of observations in a regression model. In practice, a limited number of level-2 variables are used in multilevel model applications.

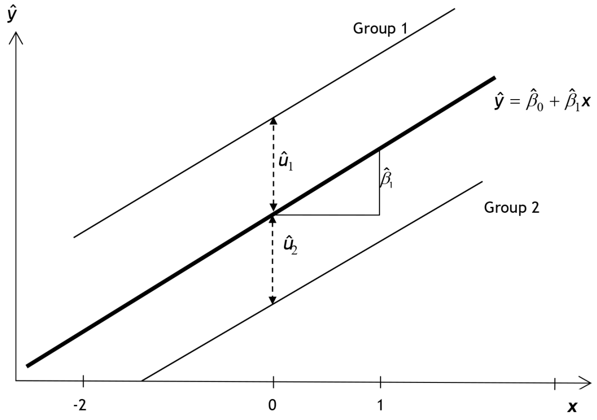


Figure 4.2: Prediction lines from a random intercept model. This figure shows the overall predicted regression line and the predicted lines for two groups. The estimated residual for group 1 (u_1) is greater than zero leading to a predicted line with an above-average intercept, while group 2 has a below average intercept.

For simplicity, a model with one level-2 explanatory variable w_{1j} is presented:

$$y_{ij} = \beta_{0j} + e_{ij} \tag{4.7}$$

$$\beta_{0j} = \gamma_{00} + \gamma_{01} w_{1j} + u_{0j} \tag{4.8}$$

$$y_{ij} = \gamma_{00} + \gamma_{01} w_{1j} + (u_{0j} + e_{ij}) \tag{4.9}$$

This tentative model with main effects of macro explanatory variables only can be called a *random intercept* model. Compared with the *empty model*, this model has the same random effect, but differing only by one fixed effect (Figure 4.2). The random effects part (u_{0j} + e_{ij}) is the same in both models.

The process of assessing the fit of the data is similar to those employed in other statistical procedures such as logistic regression models. Testing of significance of the level-2 variables can be based on the comparison of the deviances (-2 times the Log Likelihood, or -2LL). Significant factors cause a significant decrease in the -2LL deviance ($p < 0.05$) because a smaller deviance indicates that a model fits the data better.

$$ModelFit = \frac{\mid 2LL_{empty\ model} \mid - \mid 2LL_{specified\ model} \mid}{differenceindegreesoffreedom(Df)} \tag{4.10}$$

In this thesis, all relevant level-2 parameters were considered in the analysis, and progressively entered into the model:

- Each factor was inserted independently in the empty model, and the new deviance was compared with the deviance of the empty model. A significant reduction in the model (Equation 4.10) indicated that the tested factor may be a significant predictor.
- All relevant parameters tested *in isolation* that remained significant were entered *simultaneously* into the model.
- Then, each factor was *removed* to test whether the removal of the factor caused the -2LL deviance to reduce significantly. These parameters were kept in the *random intercept* model.

Generally, adding level-2 variables decreases the between-group variation ($\sigma^2{}_u$), while within-group variation ($\sigma^2{}_e$) remains almost identical. The proportion of explained between group variation in the average outcome was estimated using Raudenbush & Bryk (2003) (Raudenbush & Bryk, 2002) method described in the following equation:

$$RB(\%) of explained level-2 variance = 1 - \frac{\sigma^2{}_{u\ \textit{(specified model)}}}{\sigma^2{}_{u\ \textit{(empty model)}}} \tag{4.11}$$

Adding level-1 explanatory variables in the model (predicting level-1 variation)

While in a two-level multilevel model all group-level regression coefficients are fixed, level-1 regression coefficients may be fixed or random. In this step, level-1 explanatory variables are added to the model; however, the slope coefficients in this thesis are treated as fixed. The model 4.14 is a *random intercept model with fixed main effects.* For simplicity, one level-1 explanatory variables (χ_{ij}) was introduced in the following model:

$$y_{ij} = \beta_{0j} + \beta_1 \chi_{ij} + e_{ij} \tag{4.12}$$

$$\beta_{0j} = \gamma_{00} + \gamma_{01} w_{1j} + u_{0j} \tag{4.13}$$

$$y_{ij} = \gamma_{00} + \gamma_{01} w_{1j} + \beta_1 x_{1ij} + (u_{0j} + e_{ij}) \tag{4.14}$$

Similarly to the procedure followed in the previous step, level-1 variables were selected in the basis of theory and classified categories. In this step, all relevant indoor environmental conditions measured at Level-1 (seasonal level and time-dependent measurements) were entered separately into the tentative model 4.9. The factors that reduced within - classroom variation (σ_e^2) significantly were kept in the final model. Similarly to the Level-2 model, each factor was removed to test the change of the model deviance statistics.

Continuous predictor level-1 variables were centred. The selected approach was to subtract the grand- mean of the predictor variable from each score (x_{ij} - $\bar{x}$). Raudenbush & Bryk (2002) have suggested that grand mean centring has the advantage of reducing multi-collinearity when level-2 interactions are introduced in the model. In some cases, a steady meaningful variable was subtracted, which has the same effect as grand-mean centring.

Further steps that can be addressed in multilevel modelling are *level-1 random slope coefficients*, which allow the effect of a level-1 explanatory variable to vary across groups, and *cross-level interactions*, which show how the effects of level-1 variables can be moderated by the group-level variables. However, these models are not applied in this thesis because the data need to be very large in order to prevent instability of model estimation with many random coefficients.

4.5.5 Assumptions and considerations

Like traditional regression, the following assumptions were made:

1. Individuals are mobile, and it is reasonable to expect that members of the group have not entered the group at the same time. Length of exposure to classroom pollution levels may have systematic effects upon individuals. However, information on enrolment in school was not collected, and, therefore, it was assumed that every pupil was affected in the same way and to the same degree.
2. All students were assumed to be completely nested (that is each individual belongs to only one classroom). In some schools, students may join adjacent classrooms for limited amount of type; however, it was not taken into consideration.
3. Like traditional regression analysis, all explanatory variables were assumed without errors.
4. Normality of the data was assessed using level-1 residuals.
5. Data were missing at random.

4.6 Summary

This chapter summarised the methodological framework for the collection of physical environmental parameters for the characterisation of school buildings and classrooms with standardised checklists. Overall, it was shown that the school sample provided large variation to facilitate meaningful analysis.

This chapter additionally presented the methodology for collecting self-reported health symptoms from the students. Asthma and asthmatic symptoms experienced in the school environment were validated by the classroom teachers for the quality assurance of the data. Previous investigations reported that phrasing of the questions may affect the results. This study adopted a standardised validated questionnaire on SBS symptoms, which has been used in previous school investigations on children.

A key innovative element of the methodology includes the multilevel statistical analysis. Collected data were not independent (with students nested in classrooms, and classrooms nested in schools), and therefore conventional regression would not appropriately address contextual effects. The relationships detected at individual level are not reliable predictors of relationships at group-level and vice versa. Model development is driven by theory, statistical tests of the hypotheses, and model comparisons to derive a parsimonious statistical regression model.

Together with the previous chapter, this chapter presented the multidisciplinary methodology of the comprehensive assessment of IAQ under operational conditions. In the next chapter, fieldwork measurements will be presented with descriptive and inferential statistics.

Chapter 5

Results

Performance in use

5.1 Outline

The term *performance in use* has been introduced in England and Wales to describe the assessment of the school building, and its services, by measuring the parameters of interest under the designed conditions of occupancy (DfE, 2014). The performance in use criteria in the current building regulatory frameworks for the provision of adequate IAQ and ventilation in the school environment have been developed around thermal conditions, CO_2 levels, and estimated ventilation rates, but do not reference exposure limits to pollutants associated with the health outcomes of occupants (Section 2.3).

While it is widely recognised that poor IAQ can have detrimental effects on the health of the occupants, the scarcity of performance in use data from comprehensive monitoring of IAQ may explain the lack of a robust IAQ benchmarking methodology for buildings. The systematic review of the literature (Chapter 2) identified only one study that had measured a wide-range of indoor pollutants in UK school classrooms, but without considering seasonal variation of indoor pollution levels in classrooms. Comprehensive evaluation of IAQ and pollutant levels poses considerable methodological challenges. Apart from spatial variation of pollution levels in classrooms, which may be related to fluctuation of strength of indoor and outdoor sources, temporal variation of pollutants might be observed in an hourly, daily or seasonal basis. The spatial and temporal variability of pollution may significantly affect exposure, and, consequently, the health outcomes of the occupants.

This chapter aims to present empirical data on indoor pollution levels and thermal conditions in schools, which can assist IAQ benchmarking of real buildings, and improve operational performance in the heating and non-heating season. The first section of 5.3 presents evidence on thermal conditions during a typical teaching week in the heating and non-heating season.

Section 5.5 presents findings on indoor and outdoor PM concentrations sampled with optical methods, and concentrations of radioactive particles detected with passive sampling. In Section 5.9 spatial and temporal variations of indoor and outdoor concentrations of nitrogen dioxide, ozone and VOCs sampled with passive and direct-reading instrumental sampling are investigated. Section 5.10 presents indoor concentrations of allergens, fungal and bacterial groups, and by-products (endotoxin).

5.2 Case studies

This section is in two parts and presents a short description of the recruited schools (§5.2.1) and selected classrooms (§5.2.2).

5.2.1 School sample

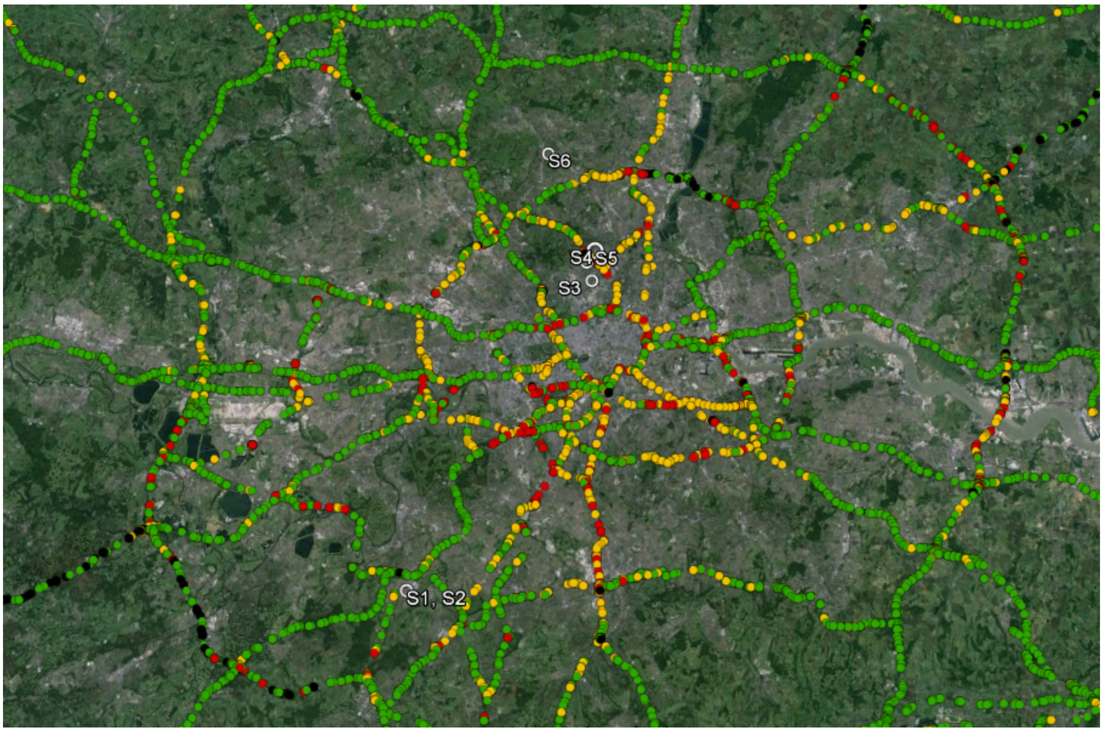


Figure 5.1: Placement of the school sample in the Greater London area with traffic intensity indication *Source: (Google Earth 7.1.2, 2013)*

The school sample (Table 5.1) 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 (Appendix D.1, Figure 5.1). 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 5.1). Urban school S3 (Appendix D.1, Figure D.2) was located in immediate proximity to a main street with high traffic intensity, while urban S4 and S5 were surrounded by pedestrian streets and vegetation (urban background) 150 to 500m away from main traffic arteries (Appendix D.1, Figure D.3 and D.4). In suburban schools S1 and S2 (Appendix D.1, Figure D.1), traffic was related to the operation of the school and coincided with the start and the end of the occupied period. Although S6 was located in a residential area, the school was less than 400m away from a high traffic street (Appendix D.1, Figure D.5). The high percentage of Free School Meals (FSM) reported in S5 (Table 5.1) was related to a school policy offering FSM to all students regardless income through an indepedent supplier.

The suburban schools S1, S2 and S6 were single-storey buildings, and classrooms had direct access to the playground. In these schools a long corridor provided access to the classrooms. The corridors were also used as teaching spaces for "one-to-one" and small groups' tutorials. The general floor plan of Victorian schools was organised around a main hall used for physical education, assembly, school celebrations and as a dining hall. Monitored classrooms in the Victorian school were located on the second floor of the three-storey buildings.

Construction characteristics of the schools varied widely and reflected common contemporary building methods (Table 5.1). S2 was built as a low carbon school building, an airtight construction with high U-Values (BREAM: Very Good). Victorian schools are historically high thermal mass buildings without insulation. In S2 heating was provided with an underfloor system with local controls. The heating strategy employed by the rest of the school sample was Low Temperature Hot Water radiators (LTHW). In most classrooms, radiators were installed below the windows; however, in the nursery school S1 radiators were installed at a high level above breathing zone as a protective measure for the safety of very young children.

Table 5.1: School construction characteristics and aggregated socio-economic information

School code	Area	Investigation Heating Season	Investigation Non-Heating Season	FSM (%)	Construction Year	Construction Materials	Ventilation Strategy	Window design and glazing	Cleaning activities/ products
S1	Suburban	7 Nov 2011-11 Nov 2011	16 Apr 2012-20 Apr 2012	.	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	Evening Bleach
S2	Suburban	14 Nov 2011-18 Nov 2011	23 Apr 2012-27 April 2012	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	Evening Bleach
S3	Urban in immediate proximity to main traffic artery	21 Nov 2011-25 Nov 2011	30 Apr 2012-04 May 2012	53%	1896	high thermal mass uninsulated walls and ridge roofs	NV	Wooden frame Vertical sash windows Single Gazing	Evening Low emitting cleaning products
S4	Urban background	28 Nov 2011-02 Dec 2011	28 May 2012-01 June 2012	13%	1870	high thermal mass uninsulated walls and ridge roofs	NV	Wooden frame Bottom-hung inward windows Single Glazing	Morning
S5	Urban background in proximity to a carpentry industry	5 Dec 2011- 09 Dec 2011	18 June 2012-22 June 2012	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	Morning
S6	Suburban high traffic street less than 400m away	9 Jan 2012- 13 Jan 2012	21 May 2012-25 May 2012	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	Evening Low emitting cleaning products

NV: Natural Ventilation; MM: Mixed Mode; FSM=Free School Meals

5.2.2 Classroom sample

For each school, three classrooms accommodating older children (9-11 years old) were selected. Detailed plans and sections of the classrooms were produced with the help of a laser meter so that area, volume, glazed area and openable area could be estimated (Appendix D, Section D.2).

The classrooms used four ventilation strategies:

- classrooms using single sided natural ventilation;
- classrooms using cross-sided natural ventilation;
- classrooms with restricted windows relying on infiltration (uncontrolled background ventilation); and
- classrooms employing mixed mode ventilation strategies (natural inlet, mechanical extract at ceiling height).

Night cooling ventilation strategies were avoided for safety reasons (Table 5.2) in most schools. However, classrooms located at higher floors (in S3 and S4) used night cooling, as well as S6 which incorporated in the design windows at high level.

Table 5.2: Physical characteristics of classrooms

classroom	Floor material	Orientation	Volume (m^3)	Occupants density (m^3/p)	Fleecy factor (m^2/m^3)	Openable (m^2)	area	Night cooling	Visible mould
S1_r1	Wall-to wall	NW	209	7.5	0.33	2.2		0	0
S1_r2	carpet and	NW	198	7.1	0.39	2.2		0	0
S1_r3	smooth synthetic	SE	163	6.8	0.24	2.2		0	0
S2_r1	Wall-to wall	NE	380	13.6	0.26	2.7		0	0
S2_r2	carpet and	E	380	15.2	0.26	2.7		0	0
S2_r3	smooth synthetic	E	380	15.2	0.26	2.7		0	0
S3_r1	Wall-to wall	SW	270	10.4	0.38	1.2		1	0
S3_r2	carpet and	NW	243	8.7	0.4	3.4		1	0
S3_r3	smooth synthetic	NE/SE	327	7.4	0.52	2.2		1	0
S4_r1	Smooth synthetic	NE/SE	265	9.1	0.2	4		0	1
S4_r2	Wood	NE	312	11.3	0.11	4.4		1	1
S4_r3	Wood	NE	328	11.3	0.1	4		0	0
S5_r1		E	240	7.5	0.16	0		0	0
S5_r2	Smooth synthetic	NW/SW	262	8.2	0.18	0		0	1
S5_r3		NE/SE	280	8.8	0.17	0		0	1
S6_r1	Wall-to wall	W	209	9.1	0.64	2.1		1	0
S6_r2	carpet and	W	244	11.1	0.54	2		1	0
S6_r3	smooth synthetic	S	265	11	0.48	2		1	0

Potential indoor pollution sources previously reported in the literature were identified in all classrooms. Ridge roofs in Victorian schools had incidences of water leakages resulting in visible mould growth in some classrooms (Table 5.2). In Victorian schools, the kitchen and dining area were co-located with classrooms inside the main building, while in suburban contemporary schools the kitchen was located in a detached building. In all schools, toilet facilities were located in the main building. As part of the educational process, all classrooms provided reading corners with fleecy material, such as rugs and cushions, and were equipped with a sink. Glues and paints commonly used for students' artwork were kept in open containers inside all classrooms. Finally, all classrooms used whiteboards with solvent markers in addition to electronic interactive boards, while chalk blackboards were used only in S4 classrooms.

5.3 Temperature and relative humidity

A summary of temperature, RH, CO_2 levels and estimated ventilation rates in the heating season (Table D.1) and non-heating season (Table D.2) can be found in the Appendix D. Air changes ($h^{-}1$) were converted to ventilation rates (L/s-p) based on maximum occupancy levels noticed and volume of the classroom using the equation 3.1 presented in Section 3.3.2.

The climate in London is temperate maritime that rarely sees extremely high or low temperatures. The meteorological years 2011 and 2012 when this research was conducted were typical compared with the last 30 year period (1981-2010) (Metoffice, 2015) in terms of mean (Figure D.24), maximum (Figure D.22) and minimum (Figure D.23) temperatures and solar radiation levels (Figure D.25). Lowest outdoor temperatures were recorded in January (Figure D.26), while highest outdoor temperatures were recorded during August when schools are closed (Figure D.27). Outdoor maximum temperatures in June and July were similar (Figure D.27).

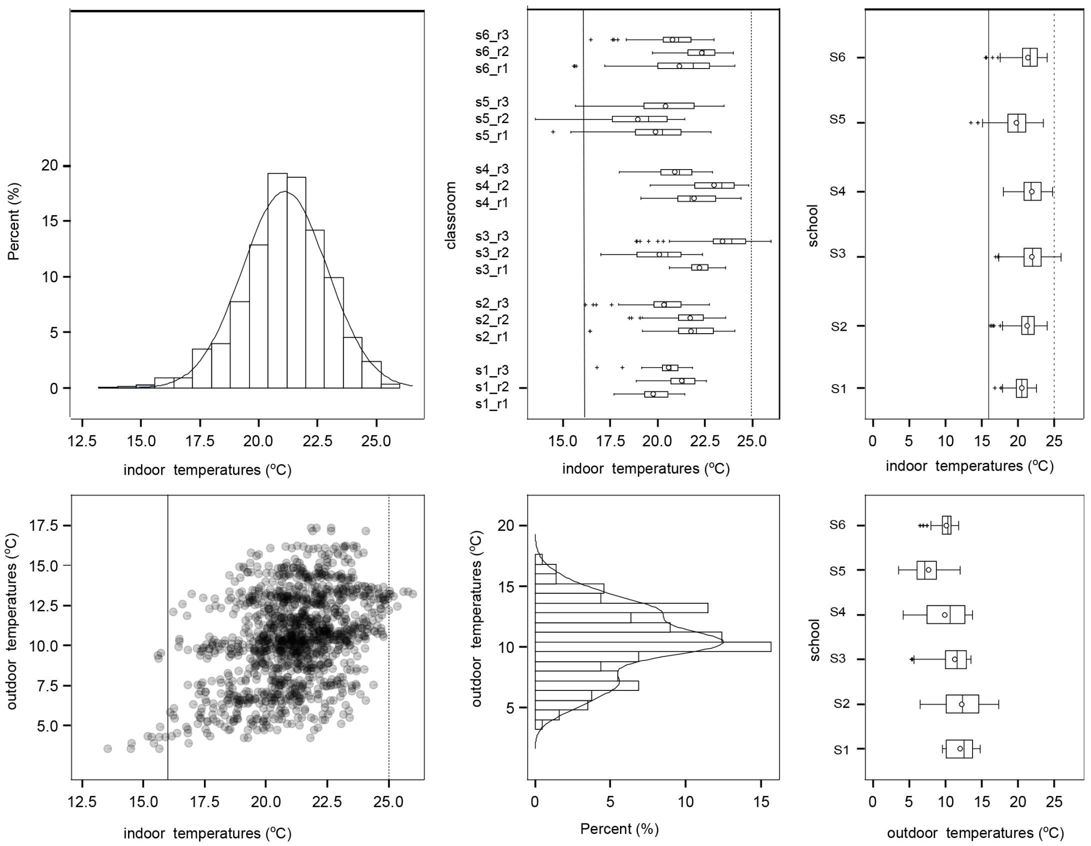


Figure 5.2: Indoor and outdoor temperatures during the occupied period of the heating season

Outdoor temperatures monitored during the heating season were $T_{o\ mean}$ =10.5 °C (σ: 0.7) (Table D.1), and during the non-heating season were $T_{o\ mean}$ = 14.5 °C (σ: 0.5) (Table D.2). Mean indoor temperatures in the occupied period in the heating season were 21.3 °C (range: 13.0 to 26.4 °C), and indoor temperatures in the non-heating season were 22.8 °C (range: 15.9 to 28.9 °C).

Lowest outdoor temperatures during the monitored weeks in the heating season were noticed in S5. When outdoor temperatures fell below 6 °C , indoor temperatures below 16 °C were recorded in all classrooms of this school (Figure 5.2) in the beginning of the teaching days before internal gains build-up, which is below the guidelines of acceptable indoor temperatures in classrooms (Section 2.3.1). These observations indicate that pre-heating of the classrooms when outdoor temperatures fall below 6 °C might be necessary. A tendency for overheating (e.g. above 25 °C) in the heating season was noticed in one South-East classroom (S3_r3) in Victorian S3.

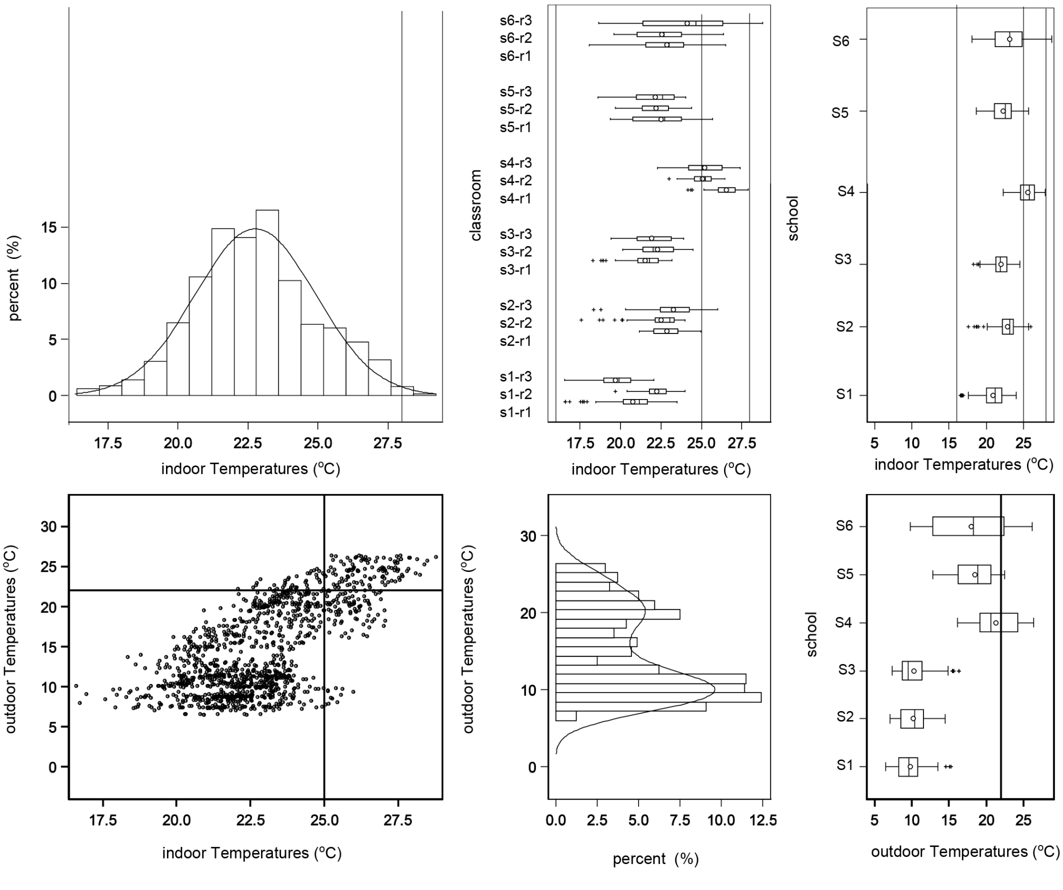


Figure 5.3: Indoor and outdoor temperatures during the occupied period of the non-heating season. Vertical lines indicate thresholds for overheating (DfE, 2014) and minimum indoor temperatures (Health Safety and Welfare, 1992)

In the non-heating season outdoor temperatures were above 6 °C (Figure 5.3) and no instances were detected where indoor temperatures fell below acceptable levels. During the investigation weeks of the non-heating season higher outdoor temperatures were noticed during the monitoring period in S4, S5 and S6 (Figure 5.3). When outdoor temperatures drifted above 20 °C all classrooms in S4 particularly in one South-East facing classroom (S4_ r1) and one South facing classroom in S6 (S6_ r3) did not comply with current specifications, as is evident from the top right quadrant of the scatter plot indicating a temperature difference above 5 °C (Figure 5.3). A tendency for overheating (above 25 °C) was particularly evident in two East facing classrooms of S2 and S5.

5.4 Carbon dioxide levels and estimated ventilation rates

A typical profile of CO_2 levels during a teaching day in the heating season is presented in Figure 5.4 for three classrooms applying different ventilation strategies in two Victorian schools (S3 and S5) and one recently constructed school (S2). The classrooms were operated under normal conditions.

It can be noticed that CO_2 profiles are similar for all schools as they had similar occupancy schedule during the day (Figure 5.4). Indoor CO_2 levels increased rapidly from the start of the day reaching the first peak before the morning break. The morning break is short and children were not asked to leave the classroom, so indoor levels did not reach equilibrium with outdoor levels. Concentrations of CO_2 increased until lunch break and then decreased as classrooms were mostly unoccupied. A third peak is noticed in the afternoon session before children leave the building.

The two Victorian schools S3 and S5 had similar occupancy patterns and construction characteristics apart from window frame and glazing. Historically, Victorian classrooms have relied on infiltration to provide fresh air. In S5 original wooden sash single glazed windows were replaced with PVC double glazing increasing the airtightness of the building envelope with estimated infiltration rates from 0.2 to 0.3 h^{-1} compared with S3 with maintained glazing ranging from 0.3 to 0.6 h^{-1} (Table 5.3). Moreover, to save energy, window opening was restricted in S5 during the heating season (Table 5.1).

Table 5.3: Infiltration rates (ACH_{inf}), ventilation rates under normal teaching conditions (ACH_{usual}) and maximum ventilation rates (ACH_{purge}) achieved under intervention studies estimated from CO_2 levels in both seasons

	Heating Season			Non-heating Season	
School	ACH_{inf} h^{-1} (L/s-p)	ACH_{usual} h^{-1} (L/s-p)	ACH_{purge} h^{-1} (L/s-p)	ACH_{inf} h^{-1} (L/s-p)	ACH_{usual} h^{-1} (L/s-p)
S1	.	.		.	.
S2	0.2 (0.7)	1.2 (4.7)	2.2 (8.2)	0.4 (1.5)	0.7 (2.8)
S3	0.4 (1.2)	1.9 (5.1)	2.6 (6.8)	0.3 (0.8)	2.3 (6.0)
S4	0.3 (0.7)	0.9 (2.3)	1.4 (3.8)	0.3 (0.8)	2.2 (6.3)
S5	0.2 (0.5)	.	.	0.4 (0.8)	2.5 (5.7)
S6	0.6 (1.7)	1.0 (3.0)	2.2 (6.5)	0.4 (1.0)	1.8(5.4)

Figure 5.5 presents the range of indoor CO_2 concentrations recorded in the three classrooms

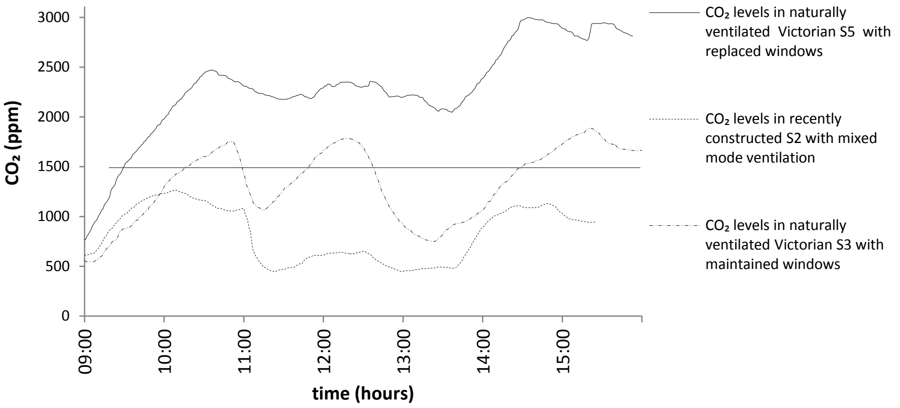


Figure 5.4: Concentrations of CO_2 in three classrooms with different ventilation strategies during a typical teaching day in the heating season. Daily average guideline value (DfE, 2014) is indicated

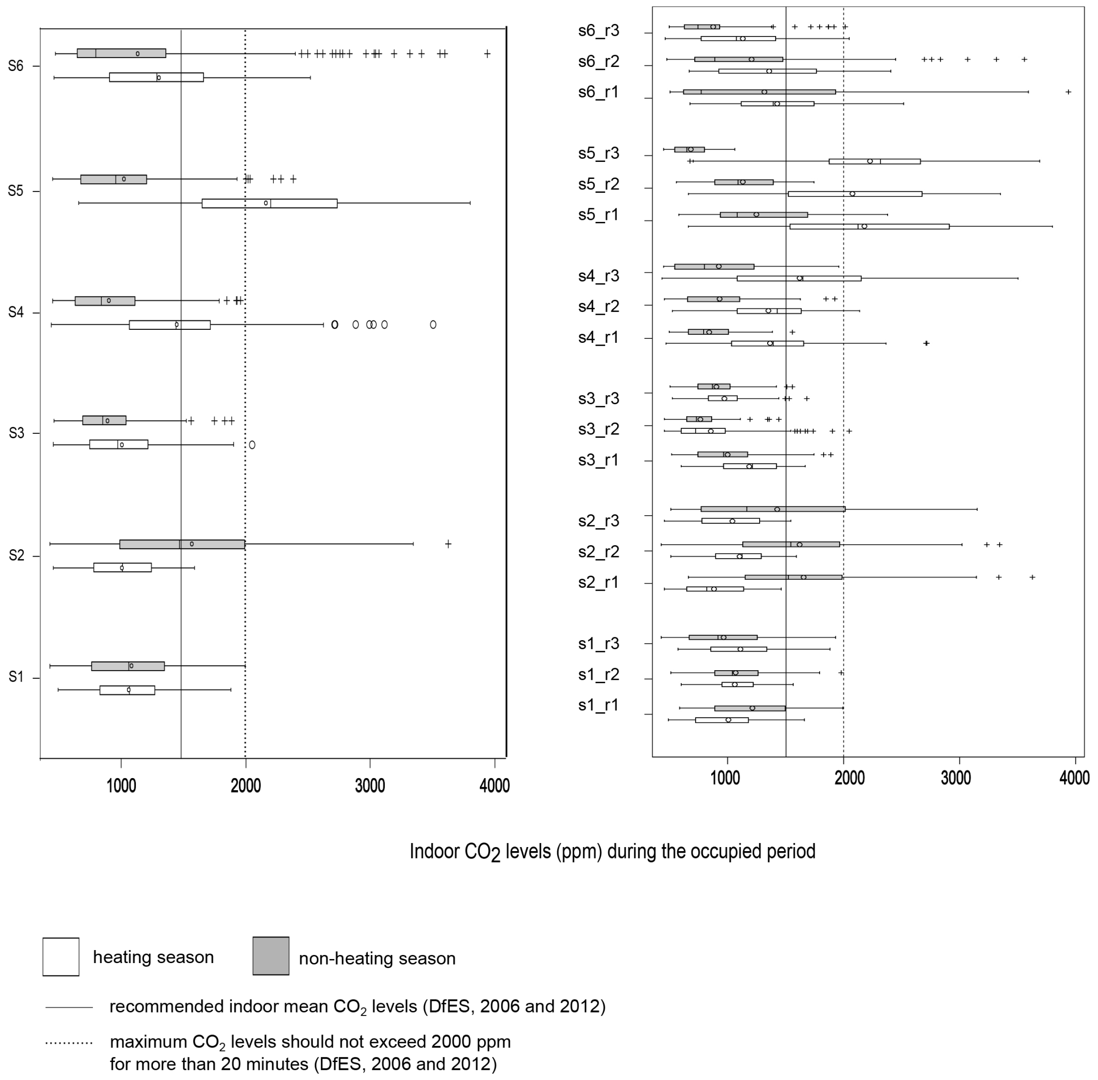


Figure 5.5: Range of indoor CO_2 levels in the heating and non-heating season, and recommended levels

of each school in both seasons, and Table 5.3 presents mean infiltration rates, ventilation rates during a typical teaching day and maximum ventilation capability of the classrooms estimated using CO_2 as a proxy as described in Section 3.3.2.

Overall, mean indoor CO_2 levels in the heating season were 1296 ppm (σ: 420), and slightly higher than mean concentrations in the non-heating season of 1040 ppm (σ: 488). Concentrations recorded in this study were within the range reported in peer-reviewed studies in the literature (Figure 2.2).

For the heating season, the highest mean indoor CO_2 levels were recorded in all three classrooms of S5, which exceeded the daily average guideline value of 1500 ppm and ranged between 2083 ppm and 2188 ppm reflecting the restricted ventilation patterns during the heating season (Table 5.3). While the Victorian S3 was also clearly not designed to meet current guidelines, its single sash windows could be opened fully. As expected, therefore, S3 classrooms had high ventilation rates and low CO_2 levels in both seasons (Figure 5.5).

One classroom in Victorian S4 exceeded daily average guidelines in the heating season (mean: 1619 ppm), and two classrooms were above maximum CO_2 levels in the non-heating season (Figure 5.5). S4 had maintained original wooden bottom-hung inward opening windows. During the study period, it was noticed that poorly maintained window frames were difficult to adjust resulting in limited openable area. Moreover, the classrooms in S4 relied on single sided ventilation and could not achieve maximum ventilation rates of 8 L/s-p (Table 5.3).

Adaptive actions of the occupants appeared to correspond with the design characteristics of the openings. Although classrooms in S1 had restricted windows, indoor concentrations of CO_2 were the lowest recorded among the studied classrooms. During the monitoring period, and from semi-structured interviews (Appendix C.1.3), it was noticed that school personnel rarely used the windows and instead used alternative ventilation patterns. Teachers kept the door leading directly to the playground open for the longest part of the occupied period, also to accommodate the needs of younger children who are generally more physically active than older children.

In contrast, design of S6 incorporated top-hung outwards windows both at low and high level providing conditions for cross-ventilation of the classroom. However, window design provided poor thermal comfort control, since openings on the low level were kept shut due to risk of draught in the heating season. Estimated ventilation rates under normal use of the classrooms in s6 ranged from 2.3 to 3.7 L/s-p, although higher rates of 5.0 to 7.7 L/s-p could be easily achieved. As a result, maximum CO_2 levels in both season exceeded DfES, 2014 recommendations in all classrooms of S6.

The ventilation strategy in the newly built school S2 included a mixed mode approach incorporating a mechanical exhaust controlled through a CO_2 sensor (Table 5.3). Contrary to the good performance of S2 in the heating season, an inadequate setting of the BMS system resulted in the failure of the mixed mode system in the non-heating season. Among all the classrooms in the study, only the two S2 classrooms failed to achieve daily average concentrations below 1500 ppm (Figure 5.5). Although the system provided a manual override, school personnel were not aware of the use due to lack of briefing. Openable area alone was not able to provide adequate ventilation rates (2.3-3.5 L/s-p), and, therefore, mean CO_2 concentrations monitored in S2 in the non-heating season (Figure 5.5) were 389 to 774 ppm higher than during the heating season.

Minimum ventilation rates were below 3 L/s-p specified by the standards (Table 5.3). Comparison of estimated ventilation rates during the occupied period at normal usage with purge ventilation rates achieved as a result of further investigation and intervention, indicated that all classrooms could be easily ventilated at a higher ventilation rate (Table 5.3). Highest ventilation rates in the heating season were reported in S2 that used mixed mode strategy (7.2-10.0 L/s-p). The mechanical extract installed at ceiling height at the back of the room provided ideal conditions for mechanically assisted ventilation. Additionally, classrooms in S3 that employed natural ventilation strategies and had the ability to open windows fully, also achieved high ventilation rates of 5.0 L/s-p to 9.3 L/s-p.

To summarise, while most classrooms managed to comply with current guidelines regulating IAQ regarding average and maximum CO_2 levels, only a few classrooms managed to provide 8 L/s-p of fresh air under the easy control of the occupants. Main hindering factors for successful application of natural ventilation included management and operation of school buildings, including sub-optimal operation of the windows and severely restricted openable areas. Lowest ventilation rates were reported in classrooms with limited openable areas (S4), classrooms that were affected by sub-optimal occupant operation due to the risk of draught in the heating season (S6) and classrooms subject to sub-optimal operation as a result of school management practice (such as restricted window ventilation in the heating season in S5 and inadequate settings in S2 in the non-heating season).

5.5 Particulate Matter

PM concentrations monitored with optical methods during the occupied period in both seasons in urban and suburban schools are compared with guidelines in Figure 5.7, and a numerical descriptive summary can be found in Appendix D, Table D.3.

Figure 5.6 presents I/O ratios for levels of PM_{10}, $PM_{2.5}$ and PM_1 based on hourly average measures over a typical week in the non-heating season. Outdoor PM concentrations showed distinctive peaks at the beginning and the end of the school day, and appeared to be related to school operation (such as parents picking up students by car). Hourly I/O ratios of PM_{10} were higher than unity during the occupied period with a sharp increase in the beginning of the teaching day when occupants enter the classroom. A second sharp peak evident during the lunch break when intense activities by the students are thought to re-suspend previously deposited particles and thereby increasing airborne concentrations. At the end of the occupied period and consistent with the natural deposition of particles on surfaces, I/O ratios decreased below unity. The I/O ratio of PM_{10} decreased rapidly at this time consistent with higher deposition rates. Larger particle size (Figure 5.6) had faster deposition rates. Indoor PM_1 levels were closely correlated to indoor $PM_{2.5}$ as they are determined by similar physical properties. PM_1 and $PM_{2.5}$ also had similar mean I/O ratios during the occupied period of 1.4 and 1.5 respectively, which were lower than PM_{10}, as occupancy affects smaller PM fractions to a lesser extent.

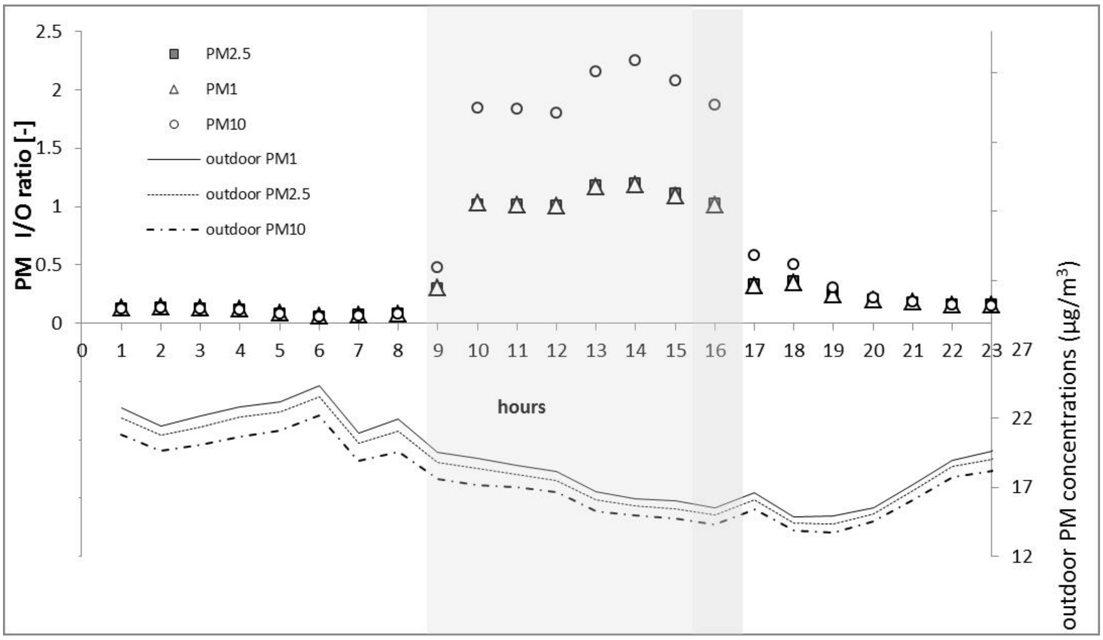


Figure 5.6: Hourly average of I/O ratio and outdoor concentrations of three PM fractions in a school over a week in the non-heating season

Outdoor PM_{10} concentrations monitored for a typical week in proximity to the urban schools in the heating and non-heating season exceeded 20 $\mu g/m^3$. It is likely, therefore, that concentrations were above annual WHO 2010 guidelines over the academic year. Higher outdoor PM_{10} concentrations were monitored in the heating compared with the non-heating season. Outdoor PM_{10} concentrations were significantly higher in urban (mean: 41 $\mu g/m^3$, σ: 29) than in suburban (mean: 29 $\mu g/m^3$, σ: 16) schools in the non-heating season (S= 304224, p <0.001). Limited evidence is available on indoor PM_{10} levels in UK classrooms. One study of 16 UK classrooms (Aliboye et al., 2006)reported similar indoor PM_{10} concentrations of 30

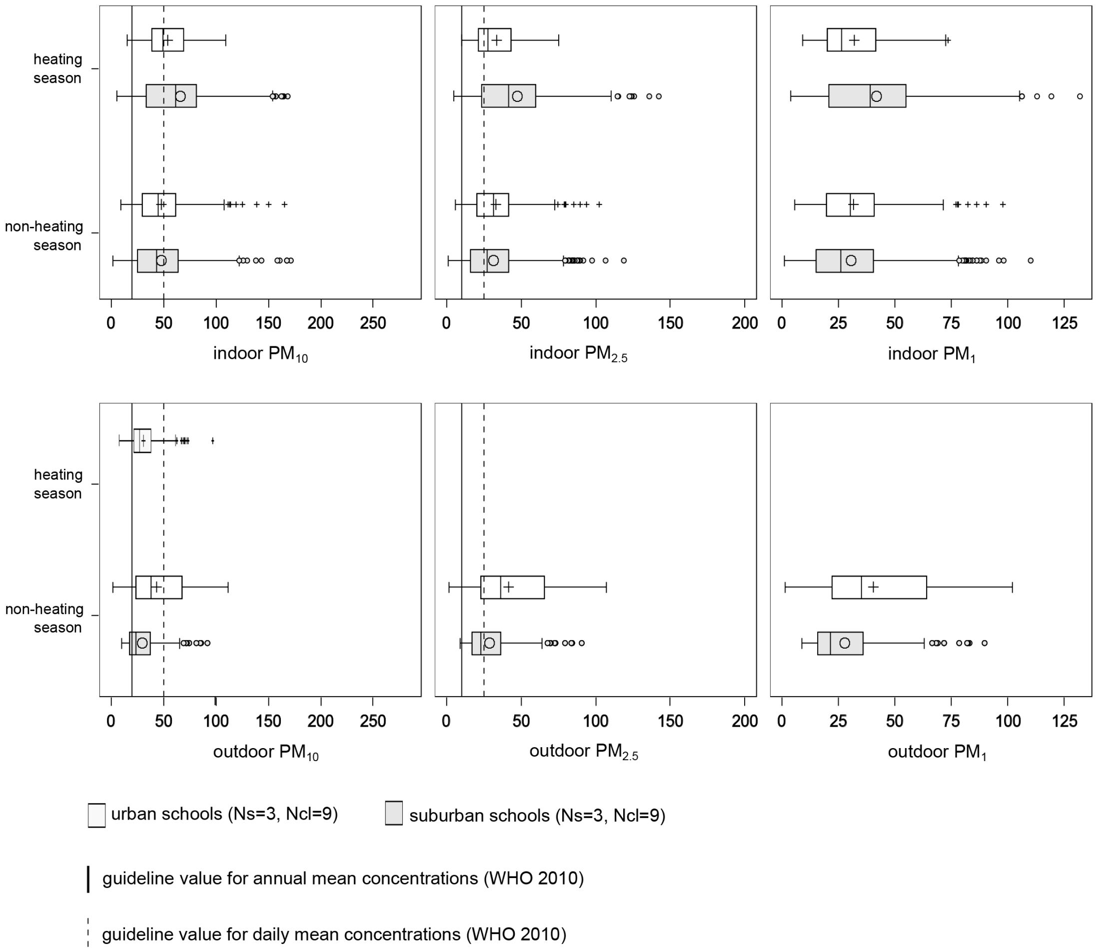


Figure 5.7: Range of indoor and outdoor concentrations of PM_{10}, $PM_{2.5}$ and PM_1 in urban and suburban schools in the heating and non-heating season

$\mu g/m^3$ (range: 12 to 43 $\mu g/m^3$). Higher mean indoor PM_{10} concentrations were reported in four European studies (Section 2.4.3, (Figure 2.5) with mean concentrations ranging from 43 to 104 $\mu g/m^3$.

Mean outdoor $PM_{2.5}$ concentrations monitored during the occupied period of the non-heating season with optical methods in immediate school premises were 32 $\mu g/m^3$ (σ: 22), exceeding daily WHO 2010 guidelines in all schools. Outdoor mean PM_1 concentrations in the non-heating season were 31 $\mu g/m^3$ (σ: 22). Similarly to outdoor PM_{10}, monitored outdoor $PM_{2.5}$ and PM_1 concentrations outside of urban schools were significantly higher than for suburban locations (S=302020, $p < 0.001$).

In this study, mean indoor concentrations of $PM_{2.5}$ and PM_1 monitored with optical methods ranged from 18 to 62 $\mu g/m^3$ and 17 to 61 $\mu g/m^3$ respectively in both seasons. Mean indoor $PM_{2.5}$ in this study were higher than levels reported in monitoring studies (Figure 2.6) using optical methods in urban and suburban schools that ranged from 12 to 23 $\mu g/m^3$ (min-max range: 1 to 80 $\mu g/m^3$).

All PM fractions indoors were higher in the heating compared with the non-heating season. Unlike outdoor concentrations, however, the difference in indoor PM levels between urban and suburban schools was not statistically significant. It was also found that indoor PM_{10} concentrations during the occupied period was consistently higher than outdoors (Figure 5.6).

5.6 Radon

Radon levels in the schools were below 200 Bq/m^3, the Action Level above which mitigation measures should be taken HPA, 2009). In most schools I/O ratio of concentrations was greater than unity (Figure 5.8) indicating the build-up of radioactive particles, and is related to ventilation rates of the investigated space. In one school (S5) indoor radon levels were lower than unity and may be related to increased ventilation patterns in the school office.

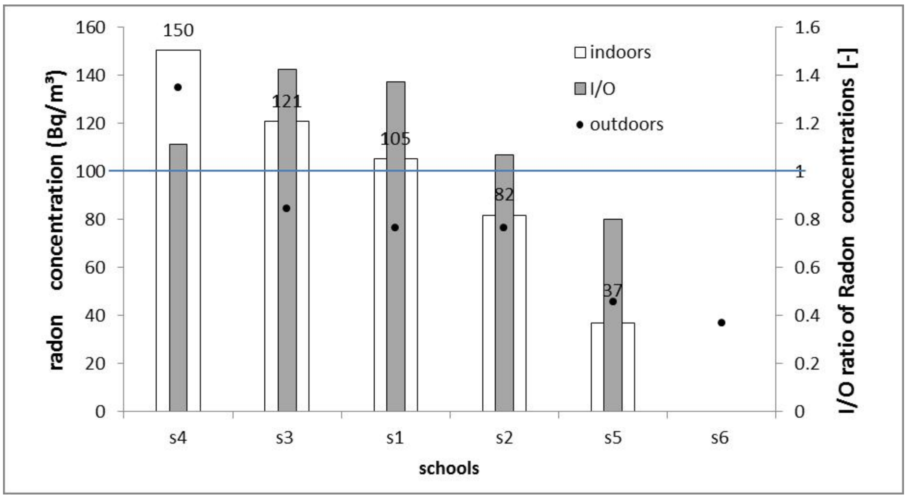


Figure 5.8: Indoor, outdoor and I/O ratio of radon levels measured with passive sampling in the heating season

Because radon is a ground contaminant a high spatial variability of outdoor radon levels can be noticed in the diverse concentrations monitored in S3, S4 and S5 located in close proximity (Figure 5.8). There are no large UK campaigns monitoring radon levels in schools, and levels vary significantly by country. For example, out of the 890 schools investigated in Slovenia 77 exceeded the value of 400 Bq/m^3 (Vaupotic et al., 2000), while 86% of 512 Greek schools were between 60 and 250 Bq/m^3 (Clouvas et al., 2011).

5.7 Total Volatile Organic Compounds monitored with direct-reading instrumental sampling

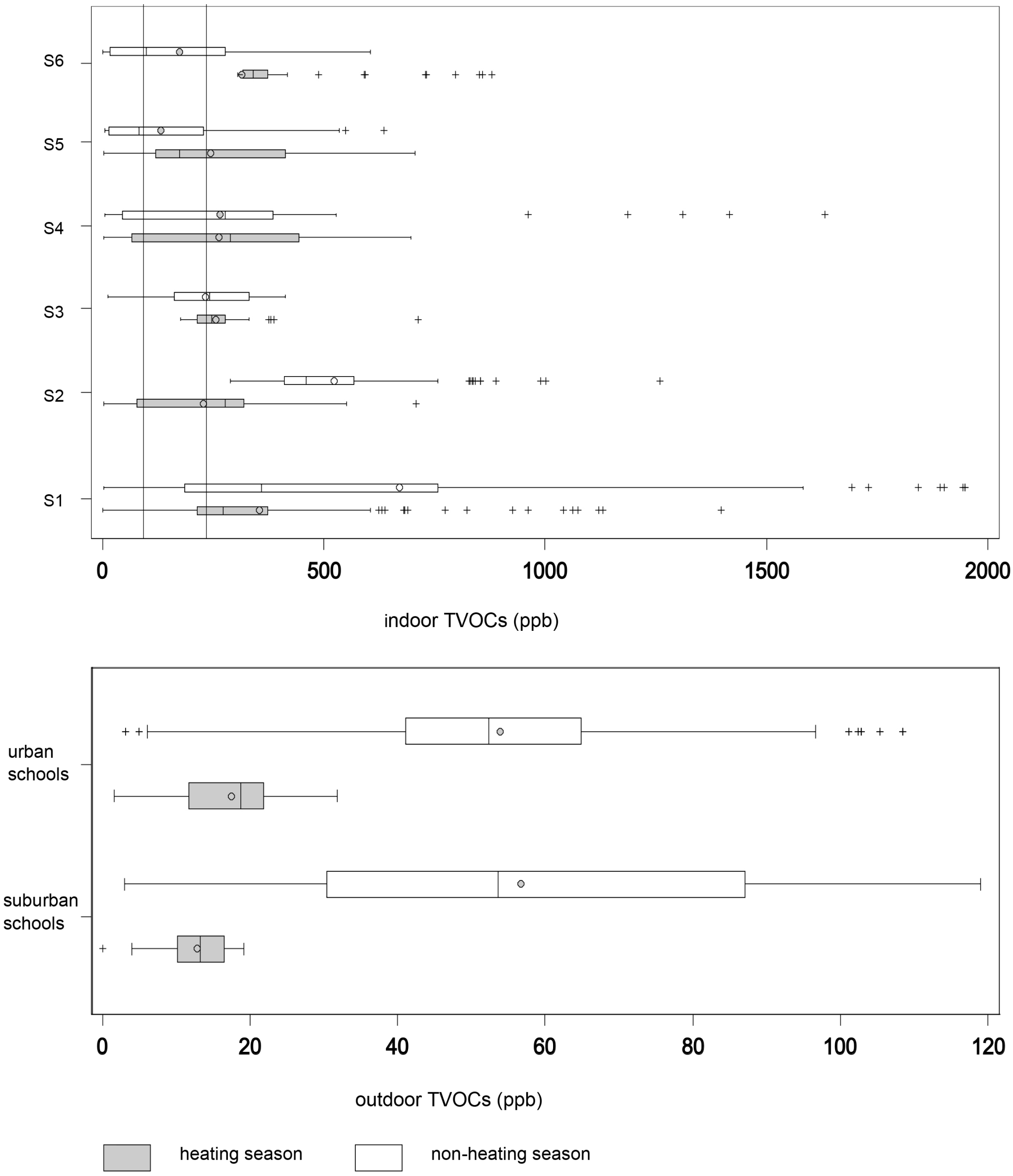


Figure 5.9: Range of indoor and outdoor TVOCs levels monitored with direct-reading instruments in the heating and non-heating season. Thresholds associated with sensory irritations are indicated

Outdoor TVOCs levels (Figure 5.9) were similar in urban and suburban schools (median: 49 ppb, interquartile range (Q1-Q3): 34-81 ppb), and as expected were significantly lower than indoor levels due to the presence of significant indoor sources (median: 269 ppb, Q1-Q3: 64-408 ppb). While outdoor levels were slightly elevated during the non-heating season, there was no statistically significant seasonal difference in indoor levels (Figure 5.9). Mean and median indoor TVOCs exceeded guideline value of 300 μg/m^3 (129 ppb) in all classrooms in both seasons. Although these TVOCs concentrations indicate that there might be some sensory discomfort among students, the comparison is only indicative as there are no threshold values for TVOCs levels monitored with PID detectors (Section 3.6.3). In both seasons, average indoor TVOCs levels in the three nursery classrooms were 550 ppb (Q1-Q3: 202 to 621 ppb) higher than levels monitored in 15 primary school classrooms of 253 ppb (Q1-Q3: 81 to 367 ppb).

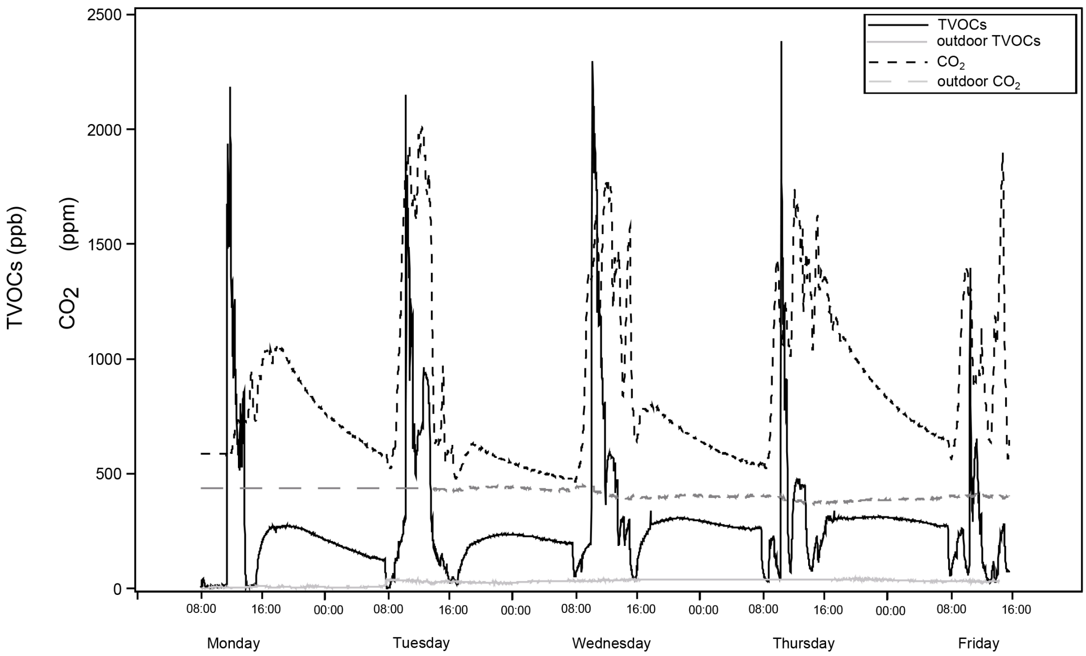


Figure 5.10: Indoor and outdoor CO_2 and TVOCs levels during a typical monitoring week in the non-heating season

Indoor TVOCs profiles during the study period, and representative of a typical teaching week, in a nursery classroom are presented in Figure 5.10. When a classroom was fully occupied, TVOCs and CO_2 levels increased sharply as occupants introduced transient VOCs sources. The ability of ventilation to reduce indoor TVOCs levels was reflected in the high correlation between TVOCs and CO_2 levels during breaks, and at the end of the occupied period when indoor levels reached the low values of outdoors. The peak noticed during the unoccupied period appears likely to have resulted from emissions of cleaning products. Levels during the unoccupied period remained elevated because windows remained restricted for security reasons. A sharp decrease of TVOCs was noticed in the beginning of the teaching period, when the teacher enters the classroom and opens the windows, increasing the ventilation rates and diluting indoor VOC concentrations. A numerical descriptive summary of the results can be found in the Appendix Table D.4.

5.8 Targeted Volatile Organic Compounds determined with passive sampling

In this section, indoor and outdoor concentrations of the eight targeted VOCs determined with passive sampling for a five-day period in the heating and non-heating season are compared with current guideline values and concentrations monitored in school classrooms in previous studies (Table 2.7). A numerical descriptive summary of the results can be found in the Appendix Tables D.5 and D.6 for the heating and non-heating season respectively.

Measured outdoor VOCs concentrations were low (generally lower than 1 μg/m^3) with the exception of formaldehyde (Figure 5.13), which was the most abundant outdoor compound detected in both seasons. As expected, indoor VOCs concentrations were much higher than outdoor levels. Generally, outdoor VOC concentrations did not differ significantly between urban and suburban schools in both seasons (Table 5.4).

Table 5.4: Statistical testing for the difference in indoor and outdoor VOC concentrations measured in urban and suburban schools in the heating and non-heating season

	Obs	HCHO	benzene	toluene	T3CE	T4CE	pinene	limonene	naphthalene
Urban vs Suburban (Mann-Whitney Test)									
Indoor (Z)	N=18	-2.6**	\	\	\	3.4**	\	\	1.8*
Outdoor (Z)	N=6	\	\	\	\	-1.9*	-2.1*	\	\
Heating vs Non-Heating Season (Wilcoxon signed-rank Test)									
Indoor (S)	N=23	85.0**	116.5***	138.0***	-108.0***	\	90.0***	70.0*	-122.0***
Outdoor (S)	N=6	10.5*	\	10.5*	-10.5*	\	\	\	-10.5*

[*] \denotes insignificance, * significant at p<0.05, ** significant at p<0.01, *** significant at p<0.001

5.8.1 Limonene and pinene

Outdoor concentrations of limonene were significantly higher (Table 5.4) in the non-heating compared with the heating season. Ten-fold higher outdoor limonene levels from 0.05 μg/m^3 to 3.44 μg/m^3 were sampled in the schools compared with 0.10 to 0.29 μg/m^3 reported in previous investigations (Figure 5.11). Outdoor pinene concentrations were 0.03 μg/m^3 (σ: 0.02) in the heating season and lower than levels measured in the non-heating season of 0.18 μg/m^3 (σ: 0.24), but the difference was not statistically significant (Table 2.7). These levels were generally within anticipated concentrations reported in the literature, which ranged from below detectable concentrations to 0.11 μg/m^3 (Figure 5.11).

Indoor limonene concentrations measured in this study in both seasons ranged from 0.42 to 50.83 μg/m^3 (Figure 5.11), and were markedly higher than concentrations reported in previous

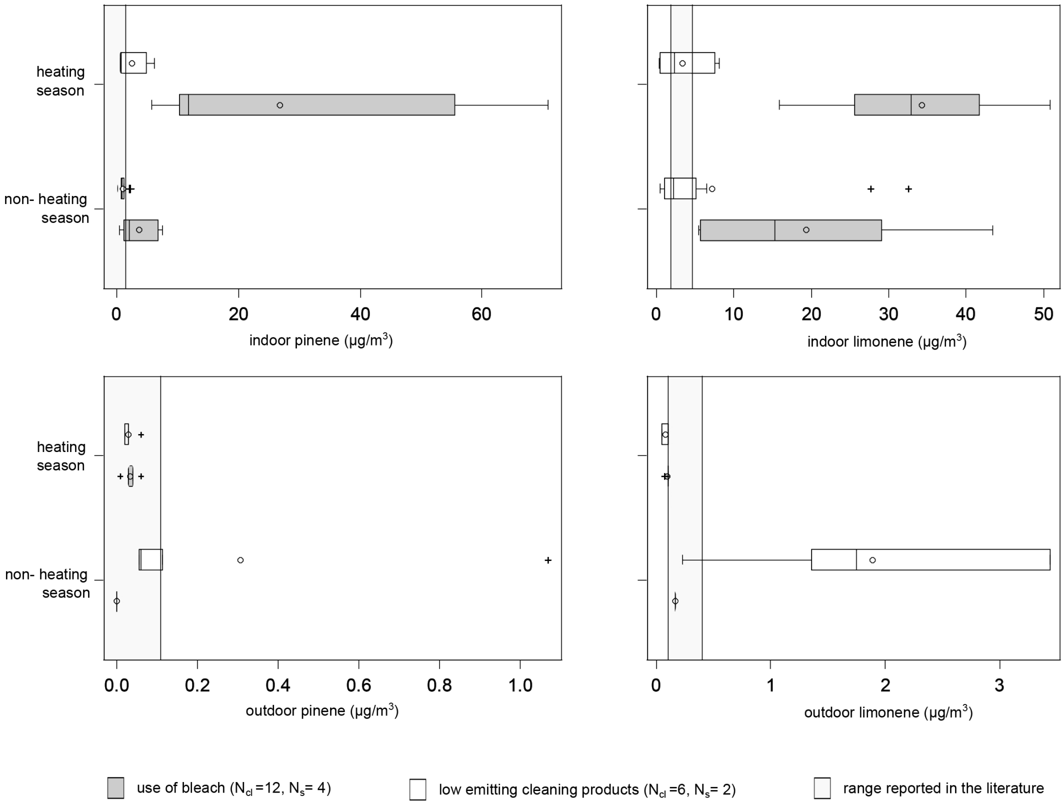


Figure 5.11: Indoor and outdoor levels of limonene and pinene in schools using bleach (N_{cl}=12, N_s=4) compared with schools using low emitting cleaning products (N_{cl}=6, N_s=2)

studies that ranged from 1.90-4.41 μg/m^3 (Table 2.7). Similarly, indoor pinene concentrations in the schools ranged from 0.45 to 70.83 μg/m^3 (Figure 5.11), which were higher compared with 0.20-1.35 μg/m^3 reported in the literature (Table 2.7).

The low outdoor levels and high I/O ratios (Figure 5.15) indicated that the primary indoor sources of limonene and pinene compounds were most likely commercially available cleaning products introduced in the classrooms. In this investigation, the use of bleach (Table 5.1) in the cleaning supplies was a significant predictor ($p<0.001$) of high indoor limonene and pinene concentrations (Figure 5.11).

5.8.2 Benzene, toluene and naphthalene

Indoor and outdoor benzene and toluene concentrations sampled in this investigation (Figure 5.12) were within the range of concentrations reported in previous research in school buildings premises. Four-fold higher levels were reported in Turkish schools for both benzene and toluene (Pekey & Arslanba, 2008).

One proposed method of determining VOC sources in urban areas is to examine the relative ratio of aromatic hydrocarbons. Aromatic hydrocarbons (toluene and benzene) are ideal candidates

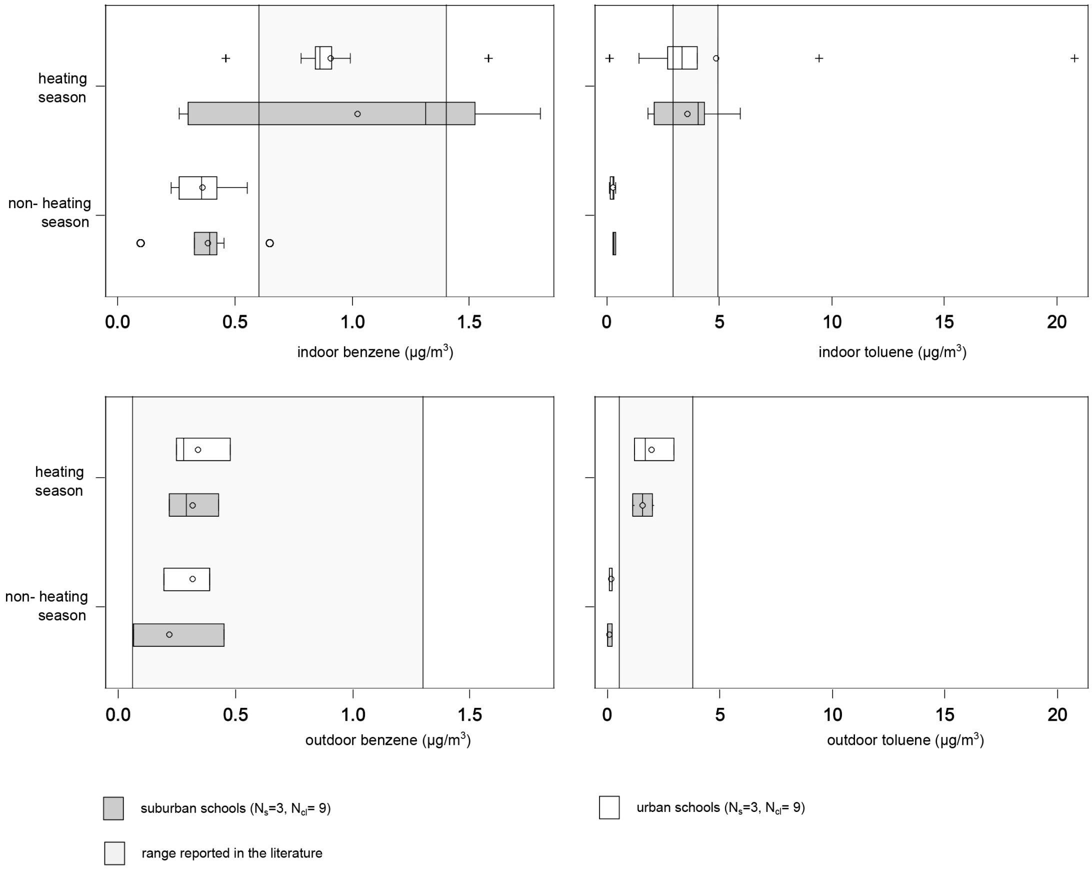


Figure 5.12: Range of indoor and outdoor benzene and toluene concentrations determined with passive sampling in urban and suburban schools in the heating and non-heating season

for sources investigations, as they are less reactive in the atmosphere. Benzene is predominantly emitted from traffic, whereas toluene is generated from both traffic and solvents. The ratio between toluene and benzene (T/B) can act as an indicator of traffic emissions when this ratio is within the range of 1.5-4.3, as reported by previous studies (Sofuoglu et al., 2011). In the heating season, outdoor ratios in suburban school premises ranged from 4.7 to 5.3, while in urban areas from 4.8 to 6.2 indicating that apart from traffic emission sources, solvent source impacts were likely present. A change of outdoor sources was noticed in the non-heating season as outdoor T/B ratio was between 0.7 to 2.2 in all classrooms, and was a good predictor of distance from traffic with a ratio higher than 1.6 for urban schools and lower than 1.6 for suburban schools. Significantly higher outdoor levels of toluene were monitored in the heating season (Table 5.4), possibly due to additional outdoor sources. Higher winter levels of terpenes were also reported in previous investigations (Pekey & Arslanba, 2008; Sofuoglu et al., 2011).

Indoor benzene concentrations in both seasons ranged from 0.10 to 1.80 μg/m^3, and were significantly higher in the heating season (Table 5.4). Mean concentrations reported in school classrooms in the literature ranged from 0.09 to 1.40 μg/m^3 (Figure 5.12), and were within the range reported in this study. Mean indoor toluene concentrations in the heating season were

4.74 μg/m^3 (σ: 4.29), and were significantly higher (Table 5.4) than levels in the non-heating season, which were 1.03 μg/m^3 (σ: 0.44). Additional indoor toluene sources were detected in two urban classrooms in the heating season with levels five-fold higher (Figure 5.12).

Limited evidence is available on naphthalene concentrations in school premises. Outdoor concentrations of naphthalene were significantly (Table 5.4) higher in the non-heating (1.25 μg/m^3, σ:1.17) than the heating season (0.06 μg/m^3, σ: 0.01), and three-fold higher than levels reported in a study in 26 school premises (Godwin & Batterman, 2007) of mean values of 0.10 μg/m^3 (max: 0.90 μg/m^3). Indoor mean values sampled in that study were 0.82 μg/m^3 (Godwin & Batterman, 2007), and in good agreement with levels sampled in this study (range: 0.06 to 3.05 μg/m^3, mean: 0.85 μg/m^3).

5.8.3 Formaldehyde

Significantly higher outdoor levels of formaldehyde (Table 5.4) were sampled in the heating season compared with the non-heating season. Highest outdoor formaldehyde levels (14.57 μg/m^3) were detected in urban S5 located in proximity to a carpentry industry (Table 5.1) compared with an average of 3.10 μg/m^3 sampled in the rest of the school sample stressing the importance of local emission sources on VOCs outdoor concentrations.

Construction materials and furniture containing formaldehyde-based adhesives are well-known indoor persistent formaldehyde sources. Consistent with the decline in indoor formaldehyde concentrations with the age of this emission source, higher levels of formaldehyde were recorded in classrooms with furniture introduced in the last two years (Figure 5.13).

A significant variation (Table 5.4) was noticed in indoor formaldehyde levels between seasons, with higher levels recorded indoors in the winter season (mean: 18 μg/m^3, σ: 10) compared with the non-heating season (mean: 15 μg/m^3, σ: 10). Similar seasonal variation of indoor formaldehyde levels was noticed in previous studies in schools (Table 2.7). Formaldehyde investigations are often performed in schools, and reported mean values ranged from below detectable limit to 109 μg/m^3 (Table 2.7). Although WHO guidelines set limits for 30-minute exposure (Table 2.2), it is expected that because of the presence of persistent sources (e.g., emitting materials), indoor concentrations in the sample were below recommendations.

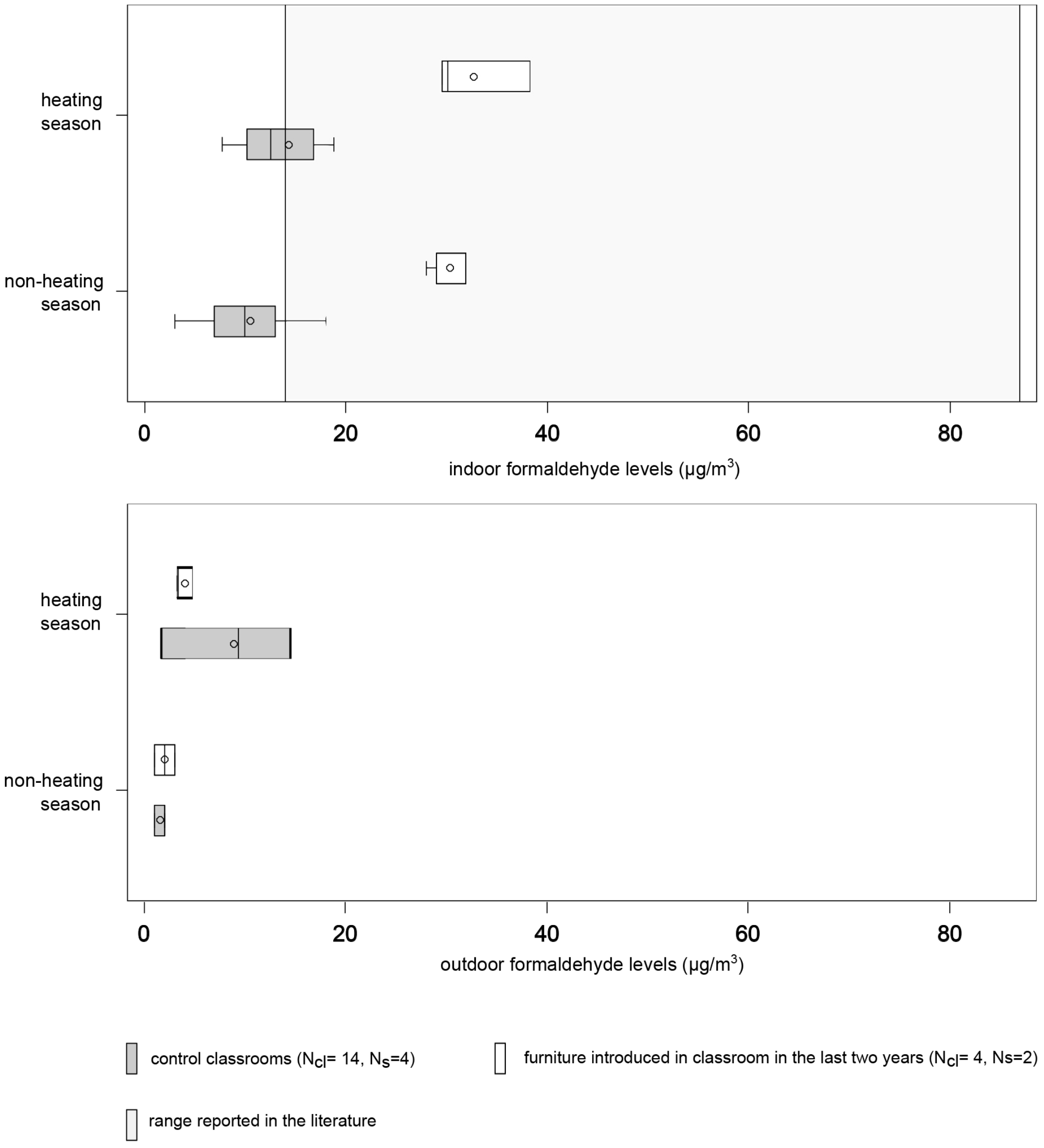


Figure 5.13: Formaldehyde concentrations measured in classrooms with furniture introduced in the last two years compared with the control group

5.8.4 Trichloroethylene and tetrachloroethylene

Outdoor T3CE and T4CE ranged from below detectable limit up to 0.49 μg/m^3 (Figure 5.14) and were marginally higher than levels measured in previous campaigns ranging from below detectable limit up to 0.30 μg/m^3 (Table 2.7).

In this study, indoor T4C3 levels were lower in the non-heating season ranging from 0.07 to 0.41 μg/m^3 (av: 0.24 μg/m^3, σ: 0.09) compared with the heating season ranging from 0.01 to 0.94 μg/m^3 (av: 0.34 μg/m^3, σ:0.27). Indoor T3CE levels ranged from 0.01 to 2.37 μg/m^3. Similarly to outdoor concentrations, previous studies reported significantly lower indoor T4CE and T3CE concentrations ranging from 0.02 to 0.20 μg/m^3 (Table 2.7).

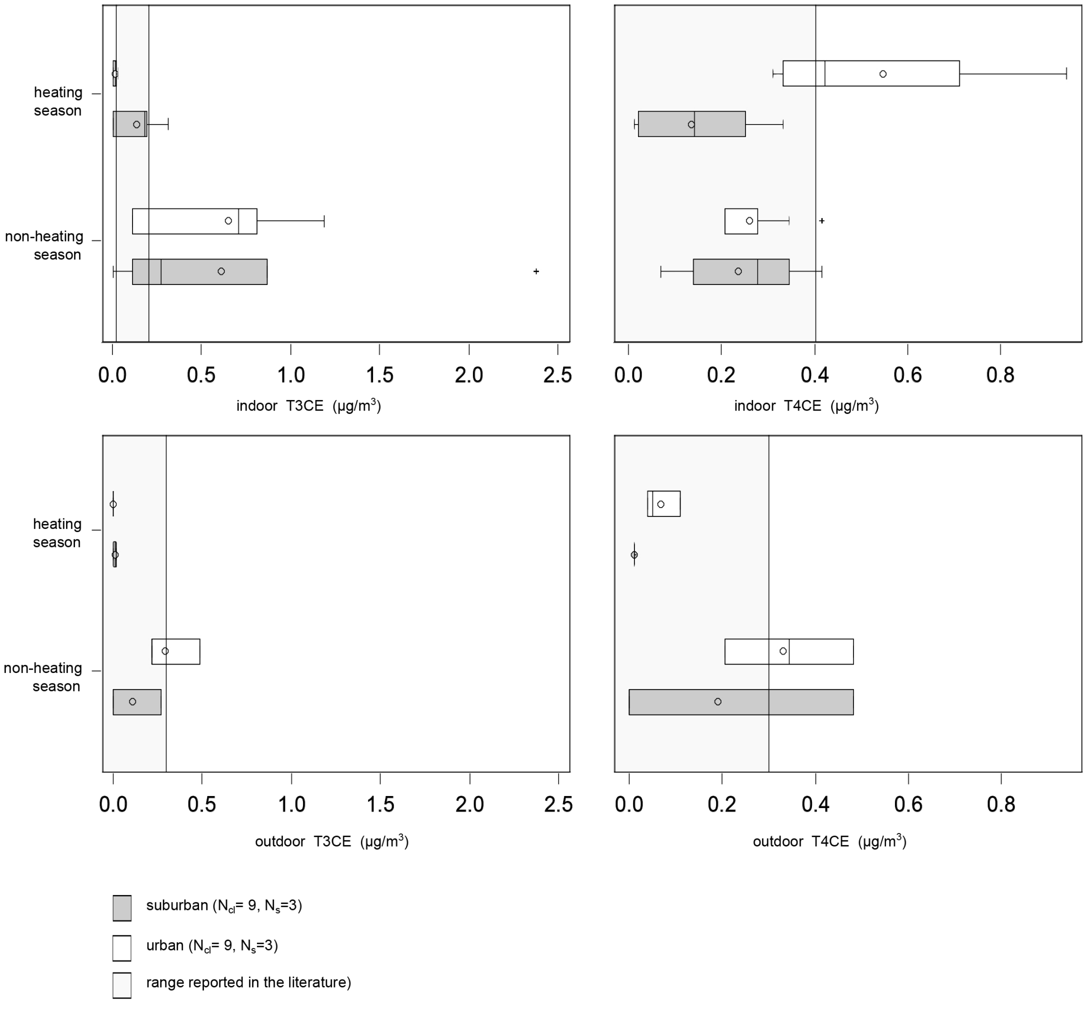


Figure 5.14: Indoor and outdoor concentrations of T3CE and T4CE levels determined with passive sampling in urban and suburban schools in the heating and non-heating season

5.8.5 Indoor to outdoor ratios of VOCs

Estimated I/O ratios of VOCs were consistently higher than unity reflecting the presence of indoor sources and low ventilation rates (Figure 5.15). I/O ratios were higher in the heating season compared with the non-heating season due to the significantly higher indoor VOC concentrations recorded in the heating season compared with the non-heating season (Table 2.7).

Highest I/O ratios were calculated for VOCs with strong indoor sources, such as pinene, limonene and T3CE. Indoor concentrations of pinene were on average nearly 300 times higher than outdoor (range I/O ratio: 20-2361) in the heating season, and 11 times higher in non-heating season (range: 1.4-1490). Limonene I/O ratio was on average 242 in the heating (range I/O: 8.4-550) and 4.7 in the non-heating season (I/O ratio: 0.2-255). I/O ratio of T3CE ranged from 1 to 30 in heating season and 0.5<I/O <118 in the non-heating season showing that there are substantial indoor sources varying between seasons. High I/O ratios of benzene ranging from 2 to 11 in nursery schools indicate that in the absence of other likely indoor sources this harmful pollutant was introduced in the classrooms with artwork products.

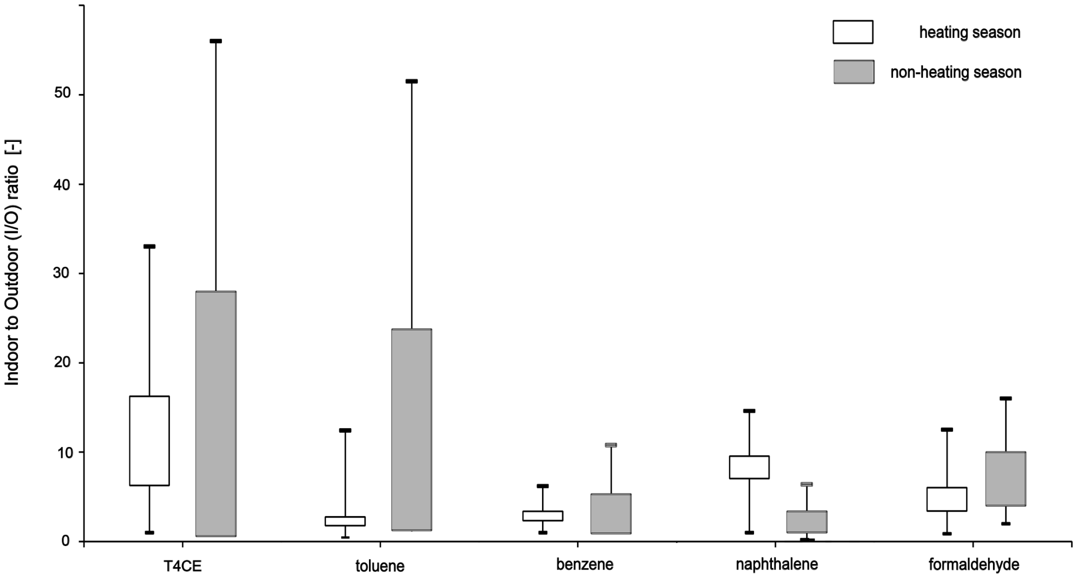


Figure 5.15: Indoor to Outdoor (I/O) ratio of selected compounds in the heating and non-heating season

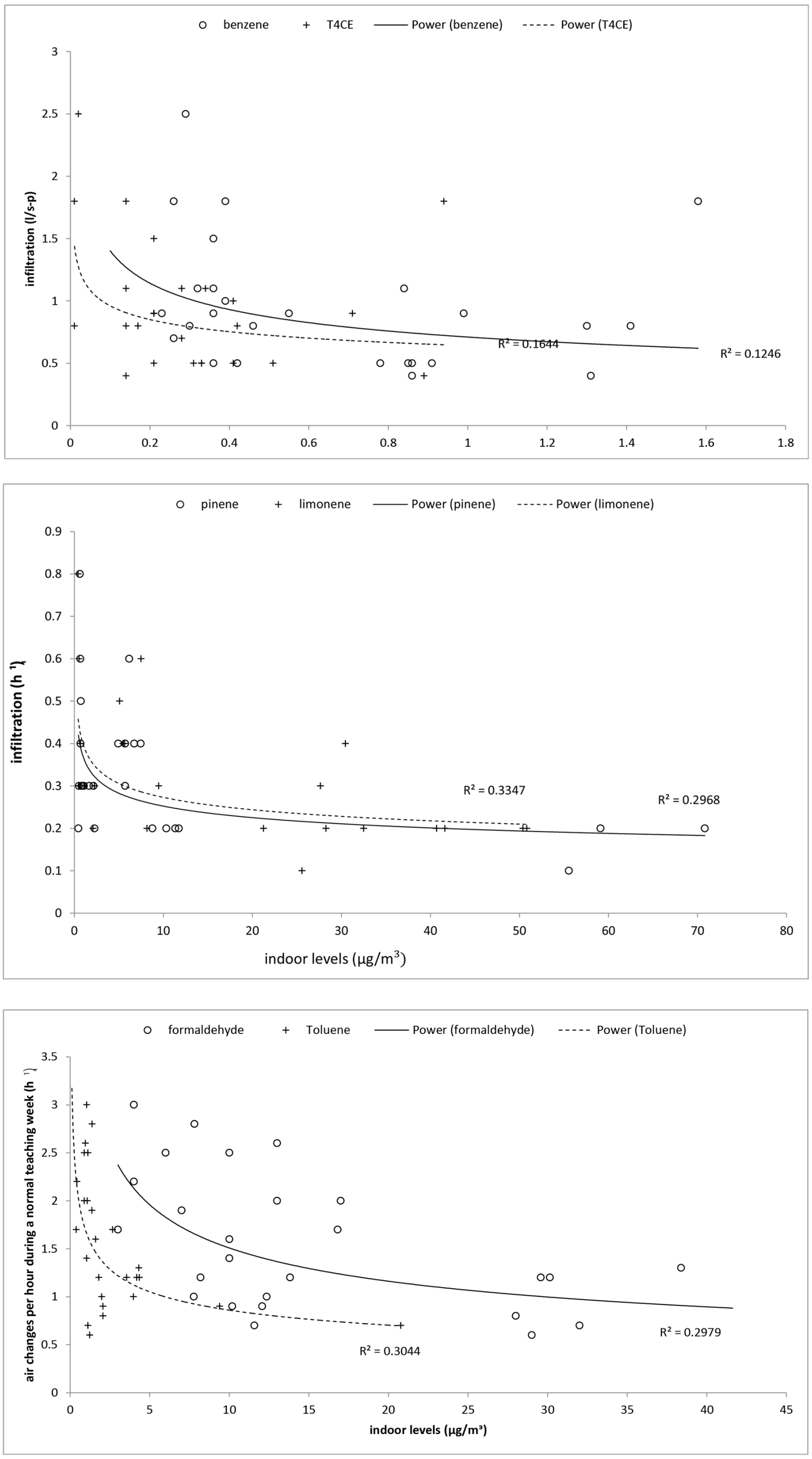


Figure 5.16: The correlation between indoor VOC concentrations with average infiltration and ventilation rates over a five-day period in the heating and non-heating season

A preliminary investigation of possible correlations between indoor VOC levels with ventilation and infiltration rates is presented in Figure 5.16. A negative exponential correlation was detected between formaldehyde and toluene concentrations (R^2=0.30) with average ventilation rates. A weak to moderate negative relationship was also noticed between pinene (R^2=0.30), limonene (R^2=0.33), benzene (R^2=0.12) and T3CE (R^2=0.16) with infiltration rates.

5.9 Nitrogen dioxide and ozone

The descriptive numerical summary of NO_2 and O_3 measurements can be found in the Appendix Tables D.7 and D.8 for the heating and non-heating season respectively.

NO_2 is generally considered a measure of traffic intensity; therefore, outdoor concentrations measured in urban school premises were significantly higher than values in suburban school premises in both seasons (Z=174.6, $p<0.001$). Apart from spatial variations, strong seasonal variations were observed in outdoor NO_2 levels with higher concentrations measured in the heating season ($p<0.001$), and especially in proximity to urban schools ranging from 40.2 to 49.4 $\mu g/m^3$ (Figure 5.17).

Indoor NO_2 concentrations ranged from 6.6 to 41.2 μg/m^3 in both seasons (Figure 5.17) and were within the range reported in six studies in a sample of 102 classrooms (min-max: 3.3-77 μg/m^3) (Figure 2.7). Proximity to pollution sources strongly affected exposure to NO_2 concentrations; highest levels were reported in urban schools and particularly (Table D.7) in a case study (S3) in close proximity to a high traffic intensity street (Table 5.1). In the absence of indoor NO_2 sources, outdoor levels are the main contributors to indoor levels, therefore mean NO_2 levels in urban classrooms were two-fold higher than suburban classrooms in both the heating (mean: 31.2 vs 14.9 $\mu g/m^3$) and the non-heating season (mean: 19.1 vs 10.2 $\mu g/m^3$) (Figure 5.17). The two-fold increase of NO_2 noticed in urban compared with suburban classrooms in both seasons was similar to the increase reported in a previous study (Van Roosbroeck et al., 2007).

Strong seasonal variation of outdoor NO_2 levels affected indoor levels raising concerns on the degraded IAQ noticed in the heating season in school classrooms. Influenced by seasonal variations of outdoor NO_2 levels, indoor levels sampled in the heating season (mean: 23.0 $\mu g/m^3$, σ: 9.7) were higher compared with the non-heating season (mean: 14.7 $\mu g/m^3$, σ: 5.4). Although limited evidence is available on seasonal variation of NO_2 concentrations in school classrooms, a study (Blondeau et al., 2005) in eight French schools found a similar difference with higher indoor mean levels in the heating season of 18.6 $\mu g/m^3$ (range: 3.5 - 50.6 $\mu g/m^3$) compared with 5.9 $\mu g/m^3$ (min-max range: 3.3 - 8.5 $\mu g/m^3$) in the non-heating season.

Indoor O_3 levels ranged from below detectable limits to 27.3 $\mu g/m^3$, and were within the range

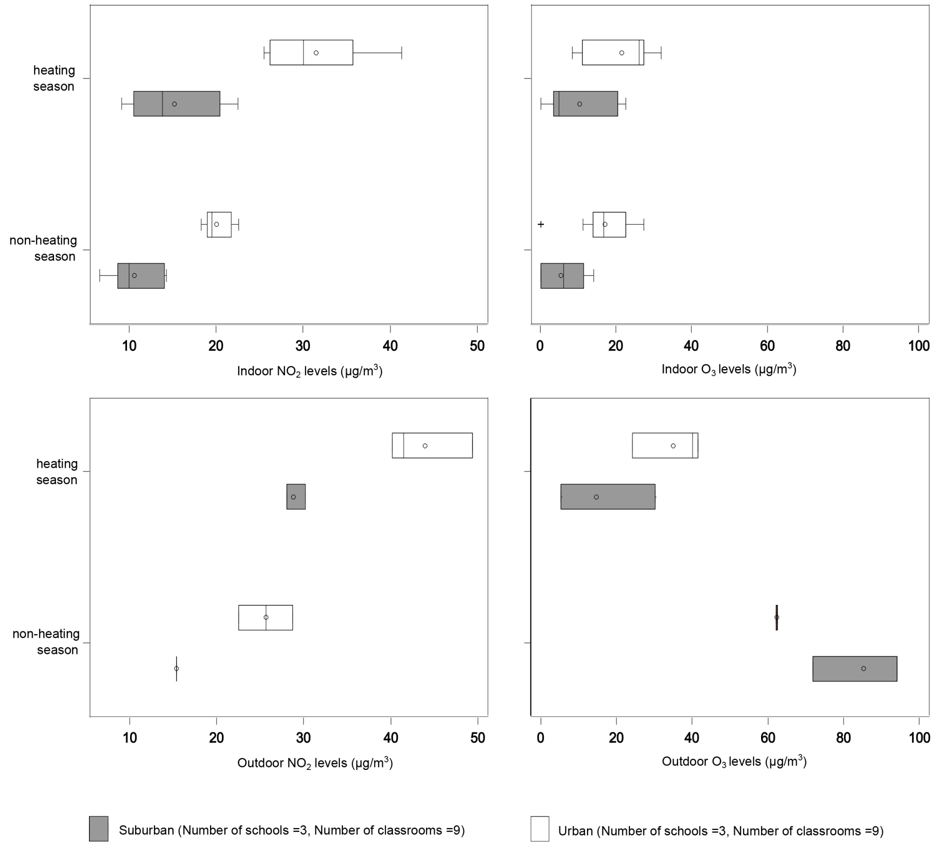


Figure 5.17: Range of indoor and outdoor levels of NO_2 and O_3 levels in the heating and non-heating season in urban and suburban schools

(1.1 to 48.5 $\mu g/m^3$) reported in the literature (Figure 5.17) in 37 European schools. Similarly to outdoor levels, indoor ozone levels were higher in the non-heating season (mean: 15.9 $\mu g/m^3$, σ: 6.4) compared with the heating season (mean: 8.3 $\mu g/m^3$, σ: 3.5) (Figure 5.17).

In contrast to NO_2 seasonal variations, outdoor O_3 concentrations were significantly higher ($p < 0.001$) in the non-heating season (mean: 77.0 $\mu g/m^3$, σ: 14.4) compared with the heating season (mean: 24.2 $\mu g/m^3$, σ: 14.1), most likely related to increased solar radiation that assists the formation of the photo-reactive gas. Limited evidence is available on seasonal variation of ozone in school classrooms. One study conducted in eight French schools (Blondeau et al., 2005) ranged from 3.6 to 28 $\mu g/m^3$(mean: 7.3 $\mu g/m^3$) in the non-heating season, and 4.2 to 33.3 $\mu g/m^3$(mean: 5.5 $\mu g/m^3$) in the heating season, and the difference was not significant.

Estimated I/O ratios of NO_2 suggest that penetration ability of the pollutant indoors may depend on airtightness of the building envelope. This relationship was reflected in the lower ratios estimated in contemporary more airtight S1 and S2 ranging from 0.3 to 0.5 compared with 0.6 to 0.8 in the rest of the sample (Appendix D, Table D.7). The ability of more airtight buildings to filter NO_2 and protect the occupants, was further strengthened by the higher I/O ratios of NO_2 estimated in the non-heating season that ranged from 0.8 to 0.9 as increased ventilation rates increased the permeability of the building envelope (Table 5.3). Previous research reported that a relationship between increased permeability of the building envelope and lower I/O ratios (Blondeau et al., 2005) could not be established. However, the sample included in that study consisted of eight schools constructed in the 19^{th} Century, lacking information on contemporary more airtight buildings.

An inverse relationship was noticed between I/O ratios of O_3 and I/O of NO_2 ($R^2 = 0.67$). Highest I/O ratio of O_3 was recorded in most airtight schools S1 and S2 in the heating season (0.6 to 0.9), while in the rest of the sample I/O ratios of O_3 were from 0.2 to 0.5. In the non-heating season I/O ratio of O_3 ranged from 0.1 to 0.4 in all schools. Lower I/O ratios of ozone compared with NO_2 ratios are likely the result of stronger deposition on solid surfaces, or decomposition in the indoor air (Weschler, 2000), rather than differences in the filtering of the ventilation air when crossing the building envelope.

5.10 Microbiological parameters

The complexity of the microbial exposure assessments and the lack of generally applicable threshold levels for fungi and bacteria in indoor environments have probably contributed to the limited availability of studies on such exposures in day cares and school settings (Section 2.4.7). Moreover, as different methods were used for sampling and analyses in the studies conducted, it is mostly not possible to compare findings. Traditionally, cultivation based methods, typically in combination with short-term air sampling have been used, but recently efforts in indoor microbial exposure assessment have developed towards using long-term integrated samples (Jacobs et al., 2013), such as settled dust, and cultivation-independent analyses methods. In this thesis, various fungal and bacterial groups and allergens were determined with qPCR from dust settled on elevated surfaces (Section 3.7.1), thus considered to represent airborne exposure.

5.10.1 Fungal and bacterial groups

There was not a statistically significant difference in fungal and bacterial levels determined in settled dust between urban with suburban schools (Table 5.5), with the exception of *Mycobacterium* spp., which was higher in suburban schools ($Z = 2.5$, $p < 0.01$) in both seasons. Regardless of season, the ranking by concentration of individual fungi species and bacteria genera remained unchanged.

Little evidence exists on seasonal microbial variations in classrooms in temperate climates (Section 2.4.7). In this investigation, higher microbial concentrations were sampled in the heating season (Table 5.5) possibly because of the small difference in indoor operative temperatures

Table 5.5: Significance testing of indoor fungal and bacterial concentrations determined in settled dust of urban and suburban schools

	PenAsp	*Cladosporium herbarum*	*Trichoderma viride*	*Alternaria alternata*	*Alternaria versicolor*	*Streptomyces* spp.	*Mycobacterium* spp.
Urban vs Suburban: Mann Whitney U test (Z)							
	\	\	\	\	\	\	2.5**
Heating vs Non-Heating Season: Wilcoxon signed-rank test (s)							
	63.5**	84.5***	53.5**	\	\	81.5***	68.5**

\denotes insignificance, * significant at $p<0.05$, ** significant at $p<0.01$, *** significant at $p<0.001$

between seasons, and the positive effect of heating systems on microbial growth. As already discussed (section 3.7.1), determinants were DNA-based and not restricted to viable microbes, which means that also dead cells and cell fragments that contain DNA are enumerated, unlike in cultivation-based approaches, where only viable and culturable microbes are detected. Also, the sample material used was airborne dust settled on elevated surfaces that are less regularly cleaned. Settled dust samples are integrated samples of longer sample accumulation time periods; if the last cleaning of these surfaces has been several weeks or months back then the microbial material accumulated over this period is enumerated from settled dust. In that sense, airborne settled dust as collected in this study is less representative of one specific season, as heating season determinations might also reflect microbial exposure of the non-heating season.

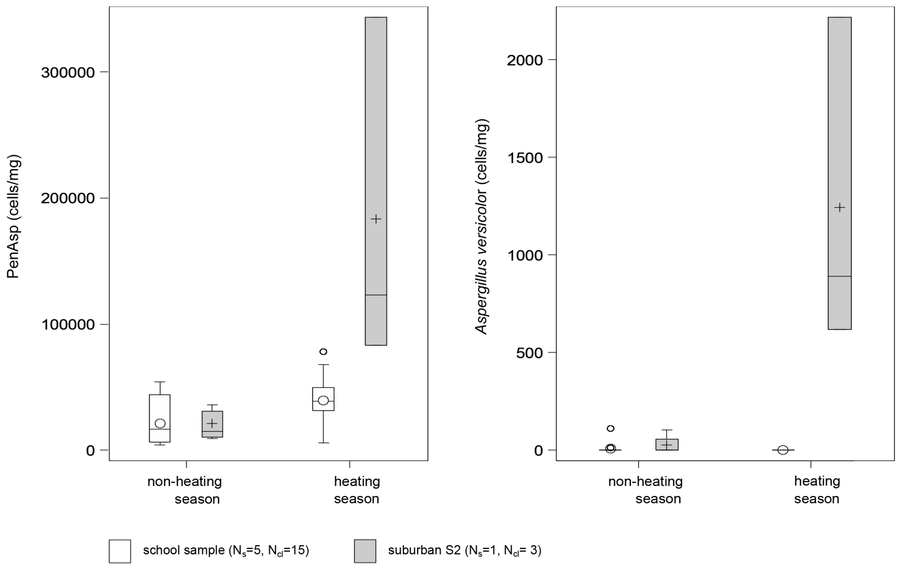


Figure 5.18: Counts of indoor *Penicillium* spp./ *Aspergillus* spp. and *Aspergillus versicolor* determined in settled dust of schools applying different heating strategies

Highest fungal concentrations in settled dust sampled in the study classrooms were *Penicillium* spp. /*Aspergillus* spp. / *Paecilomyces variotii* (PenAsp), followed by *Cladosporium herbarum.* The highest levels observed for the PenAsp groups is not surprising, as the qPCR assay used for enumeration of this group of fungi targets a large number of different *Penicillium* and *Aspergillus* species, whereas for example qPCR assays for the detection of *Cladosporium herbarum* or *Aspergillus versicolor* target only one single fungal species.

Apart from this more methodological reason, *Cladosporium* and *Penicillium, Aspergillus* are those fungal species most frequently encountered in indoor environments (accounting for at least 50% of the total) based on results of cultivation based studies (Cabral, 2010; Godwin & Batterman, 2007; Scheff et al., 2000). Generally, in healthy buildings it is expected that *Cladosporium* spp. are the predominant fungal species, as they have strong outdoor context. Therefore, it is expected that in healthy indoor environments the majority of indoor fungi present come from outdoor sources (Section 2.4.7). Concentrations of *Trichoderma viride, Aspergillus versicolor* and *Alternaria alternata*, which require high levels of equilibrium relative humidity (>90%), were very low, and not present in all classrooms.

Indoor microbial concentrations of schools employing different heating systems were compared. The highest concentrations of *Penicillium* spp./ *Aspergillus* spp. during the heating season were found in the three classrooms of suburban S2 using underfloor heating (83510 to 343520 cells/mg), compared with 5811 to 78066 cells/mg (av: 35450 cells/mg) for the remaining 15 classrooms (Figure 5.18)). In the non-heating season, indoor *Penicillium* spp./ *Aspergillus* spp. concentrations in S2 (average: 25348 cells/mg, range: 10593 to 35975 cells/mg) were within the range determined for the rest of the school sample (average: 20250 cells/mg, range: 4228 to 54453 cells/mg).

Further insight into this variation can be gained from the concentrations determined in S1 classrooms, which can be considered as control classrooms, as they were located in the same building complex as S2, and had similar cleaning schedules. The levels of indoor *Penicillium* spp./ *Aspergillus* spp. concentrations measured in S1 were significantly lower than S2 and within the range reported for the rest of the sample in both seasons. It is highly likely, therefore, that the five-fold higher levels of *Penicillium* spp./ *Aspergillus* spp. sampled in S2 classrooms in the heating season (Figure 5.18) can be attributed to the combined effect of the under-floor heating system with the presence of carpet (Table 5.1), which provided favourable conditions for microbial growth.

In the heating season, *Aspergillus versicolor* were below detection limit in all classrooms, while elevated concentrations were determined in S2 classrooms (av: 1242, range: 612 to 2217 cells/mg). In the non-heating season, *Aspergillus versicolor* concentrations were also below limit of detection in most classrooms but sporadically detected in low concentrations in some classrooms. In S2 concentrations detected in the non-heating season were (av: 62 cells/mg, range: 28 to 103 cells/mg), which was significantly lower than in the heating season. Similarly to *Penicillium* spp./ *Aspergillus* spp. concentrations, *Aspergillus versicolor* concentrations determined in settled dust differed significantly between S2 and the rest of school sample (Figure 5.18) in the heating season, but not in the non-heating season indicating that the combination of underfloor heating with carpet elevated indoor concentrations of this species.

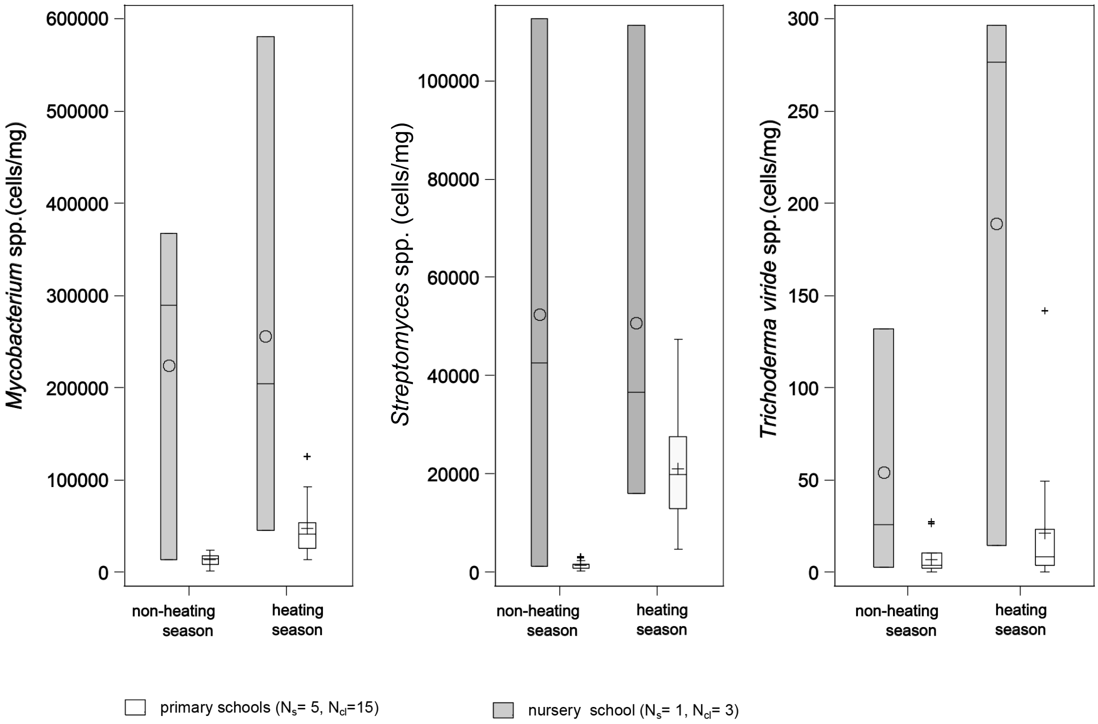


Figure 5.19: Counts of *Mycobacterium* spp., *Streptomyces* spp. and *Trichoderma viride* detected in settled dust of primary and nursery schools in both seasons

Alternaria alternata concentrations were below limit of detection in most classrooms in both seasons.

High numbers of bacterial counts can be found in environments with high occupancy density, such as classrooms. *Mycobacterium* spp ($Z= 2.61$, $p <0.01$) and *Streptomyces* spp. ($Z=2.23$, $p<0.01$) concentrations were significantly higher in nursery classrooms than primary classrooms (Figure 5.19) and the difference was larger in the non-heating season. *Mycobacterium* spp determined in settled dust in the heating season in the nursery classrooms was on average 276 720 cells/mg (range: 45 604 to 580 782 cells/mg), which was on average six-fold higher than levels determined in primary classrooms (av: 47 196 cells/mg range: 13 088 to 125 273 cells/mg). In the non-heating season, the difference between levels of *Mycobacterium* spp sampled in nursery classrooms (av: 223 294 cells/mg, range: 13 619 to 367 398 cells/mg) were on average 17 times higher than average levels recorded in primary classrooms (av: 12 616 cells/mg, range: 1 619 to 23 399 cells/mg).

Streptomyces spp. levels determined in settled dust of nursery schools (av:54 660 cells/mg, range: 16 026 to 111 288 cells/mg) in the heating season were on average 2.6 times higher than levels determined in the primary classrooms (av: 21 018 cells/mg, range: 4 718 to 47 455 cells/mg) (Figure 5.19). In the non-heating season, the difference in *Streptomyces* spp. levels between nursery (av: 52 100 cells/mg, range:1 161 to 112 631 cells/mg) and primary schools (av:1 481 cells/mg, range: 261 to 3 052 cells/mg) was larger, as levels were on average 35 times higher.

Similarly, concentrations of *Trichoderma viride* were significantly higher in S1 nursery school classrooms (Z=2.36, $p < 0.01$) than primary classrooms in both seasons (Figure 5.19). Generally, levels of *Trichoderma viride* detected in primary classrooms were very low in both seasons. In the heating season levels were on average 21 cells/mg, which was nine-fold lower than average levels detected in nursery schools (av: 196 cells/mg, range: 14 to 296 cells/mg). In the non-heating season, average levels in primary schools were 8 cells/mg, which were seven-fold lower than levels in nursery classrooms (average: 54 cells/mg, range: 3 to 132 cells/mg).

A possible explanation for the higher bacterial and *Trichoderma viride* counts in nursery schools may be related to teachers keeping the door leading to the playground open during the teaching day. Higher counts may be related to the higher extent of tracked-in soil by shoes, as younger children were generally more physically active frequently moving between indoors and outdoors.

Endotoxin, a component of the layer of gram-negative bacterial cell walls, is ubiquitous in many indoor environments. In this study median levels were 4 412 EU/m^2 (range: 1 580 to 13 842 EU/m^2). A high positive correlation (R^2=0.39) was identified between endotoxin concentrations and *Penicillium* spp./ *Aspergillus* spp. levels in classrooms in the heating season.

5.10.2 Allergens

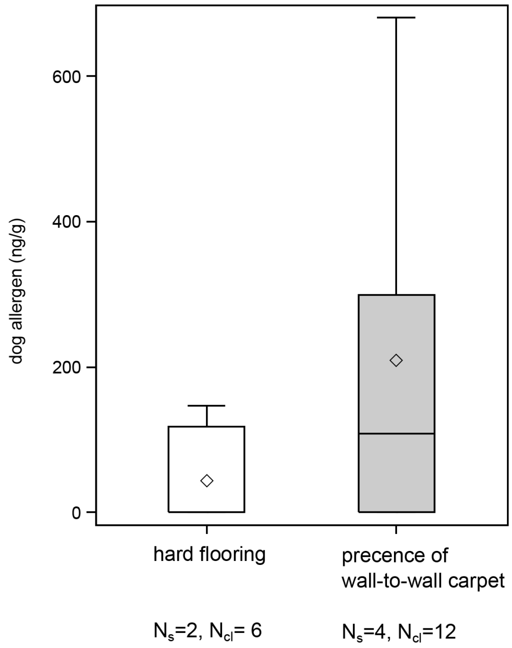


Figure 5.20: Dog allergen contaminants in hard floor and carpeted school classrooms

The magnitude of exposure to allergens differed between classrooms as it is dependent on socioeconomic and cultural factors regarding pet ownership. Exposure to cat allergen in the school environment was significant with median concentrations of 268 ng/g (range:0 to 1762 ng/g). Thresholds associated with allergic sensitisation are 1 000 ng/g (Section 2.3.3) for cat allergen (Fel d 1) and were exceeded in a nursery classroom (S1_r3) and one Victorian classroom (S4_r1). Published investigations also identified school classrooms as a significant site of indirect exposure to allergens (Section 2.4.6).

Levels of dog allergens were below the threshold for allergic sensitisation of 2000 ng/g in all classrooms, and ranged from below detectable limit to 680 ng/g (median: 50 ng/g). The presence of wall-to-wall carpeting elevated indoor dog allergens in school classrooms (Figure 5.20) but not cat allergens. Horse allergens were not detected in any of the schools (<100 ng/g) while dust mites allergen (Der f 1) was found only in S4 at low concentrations (167 ng/g).

5.11 Summary

A systematic approach is needed to strengthen the evidence base for appropriate IAQ and ventilation guidelines for schools; however, to date there has been a lack of empirical data from comprehensive monitoring of IAQ. The overall aim of this chapter was to provide empirical evidence on indoor pollution levels to assist the formation of IAQ benchmarking of school buildings under operational conditions. Additionally, this chapter provided evidence on seasonal variation of IAQ, the impact of potential outdoor sources of pollutants, and large variations in the concentration of indoor pollutants reflective of issues with building operation and management.

Thermal conditions were within acceptable comfort range for most of the occupied period and within the specifications of relevant regulations (Section 2.3.1). Minimum temperatures at the beginning of the teaching day during the heating season fell below health and comfort requirements, indicating the potential need for preheating of classrooms when outdoor temperatures fall below 6 °C. When outdoor temperatures drifted above 20 °C, schools were unable to comply with current guidelines. A tendency for overheating (above 25 °C) in the non-heating season was noticed in South, South-East and East facing classrooms indicating the need for passive measures, such as external shading.

Indoor CO_2 levels and ventilation rates estimated in the classrooms were within the range reported in the literature (Section 2.4.2). While most classrooms managed to comply with current guidelines regulating IAQ regarding average and maximum CO_2 levels, only a few classrooms managed to provide 8 L/s-p of fresh air under the easy control of the occupants. The main hindering factors for successful application of natural ventilation included management and operation of school buildings, besides sub-optimal operation of the windows and ventilation systems, and severely restricted openable areas. Mixed mode ventilated classroom presented a new set of challenges for the occupants, who were unaware of manual override settings.

Results are in line with and extend findings of previous studies on PM levels in indoor air of school buildings and provide evidence that exposure in the classroom to PM is high. 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 classroom may be higher than WHO 2010 guidelines (Section 2.3.3). In most classrooms, PM concentrations were above daily guideline values.

Large radon variability between neighbouring school buildings was detected, and it may be necessary that large scale campaigns in UK school buildings are conducted in new school building locations and existing building stock. As radon is largely a soil contaminant, remediation works in existing buildings and protective measures in new buildings should be seriously considered if radon concentrations are between the Target Levels (100 Bq/m^3) and Action Levels (200 Bq/m^3).

A small spatial variability between urban and suburban schools was noticed for outdoor VOCs concentrations indicating the transboundary nature of these pollutants. However, seasonal variation of outdoor levels was detected indicating varying outdoor solvent sources. The seasonal variation of specific indoor VOCs was large, and more likely related to altered ventilation patterns among seasons. A strong finding of this work was the higher VOCs levels detected in this study compared with the literature. The high indoor VOCs and TVOCs levels were most likely associated with sub-optimal management practices, such as storage and use of cleaning products, and construction materials introduced in the classrooms.

Proximity to pollution sources strongly affected exposure to NO_2 concentrations; highest levels were reported in urban schools, and particularly in one case study by close proximity to a high traffic intensity street. The two-fold increase of NO_2 noticed in urban compared with suburban classrooms in both seasons was similar to the increase reported in a previous study (Van Roosbroeck et al., 2007). This study provided indicative evidence that increased airtightness of the building envelope may protect the occupants from harmful traffic related pollutants such as NO_2. Higher O_3 were measured in the non-heating season, as higher solar radiation assisted the formation of this photo-reactive gas. Lower I/O ratios of ozone compared with NO_2 ratios are likely the result of stronger deposition on solid surfaces, or decomposition in the indoor air (Weschler, 2000), rather than differences in the filtering of the ventilation air when crossing the building envelope.

The classrooms were a relevant site of indirect exposure to cat and dog allergens, also identified in previous studies. The findings indicate that increased ventilation rates may reduce indoor cat allergens levels, possibly because they remain airborne for longer. Higher indoor microbial counts were detected in the heating season compared with the non-heating season. *Penicillium* spp./ *Aspergillus* spp. fungi were found on average six-fold higher in classrooms that had wall-to-wall carpets combined with underfloor heating. The findings strongly suggest that the combination provided favourable conditions for microbial proliferation. Additionally, findings indicate that carpeting elevates dog allergen concentrations compared with hard floor in classrooms. Tracked-in soil from younger children, who are generally more active between indoors and outdoors, was suspected to be the source of significantly elevated indoor bacterial counts in nursery classrooms.

Using the database presented in this chapter, a detailed analysis with multilevel regression modelling will be presented to investigate further environmental and behavioural factors, which may affect indoor pollution levels in the next chapter.

Chapter 6

Is CO_2 a good proxy for Indoor Air Quality?

Environmental and behavioural factors affecting indoor pollution levels: A multilevel approach

6.1 Outline

The lack of empirical data for indoor levels of pollution in classrooms has important implications for the formulation of regulatory framework for the provision of adequate air quality in school environments. In order to overcome this challenge, apart from the collection of more experimental data, a systematic synthesis effort is necessary to identify parameters influencing exposure. Previous researchers employed various statistical regression techniques, such as principal components analysis (Blondeau et al., 2005; Poupard et al., 2005), bivariate linear regression (Fromme et al., 2007), and multiple linear regression (Godwin & Batterman, 2007) to investigate factors affecting IAQ in schools.

This chapter uses the database presented in the previous Chapter 5 to identify environmental and behavioural parameters which may influence indoor pollution levels by employing two-level multilevel models. The chapter is organised in six parts: the most influential factors affecting indoor thermal conditions (§6.2) , PM (§6.3), NO_2 (§6.4), TVOCs (§6.5), specific VOCs levels (§6.6) and indoor biological counts (§6.7) are investigated. All models employed here are Model I as defined in Section 4.5, and were developed according to the methodology presented in Section 4.5.4.

6.2 Factors affecting indoor thermal conditions

Environmental and behavioural factors affecting indoor temperatures during the occupied period were investigated with a two-level model where classrooms and season were treated as random effects (Table 6.1). The computed ICC (Section 4.5.4, Equation 4.6) is 0.48 indicating that the variation of thermal conditions between classrooms was large.

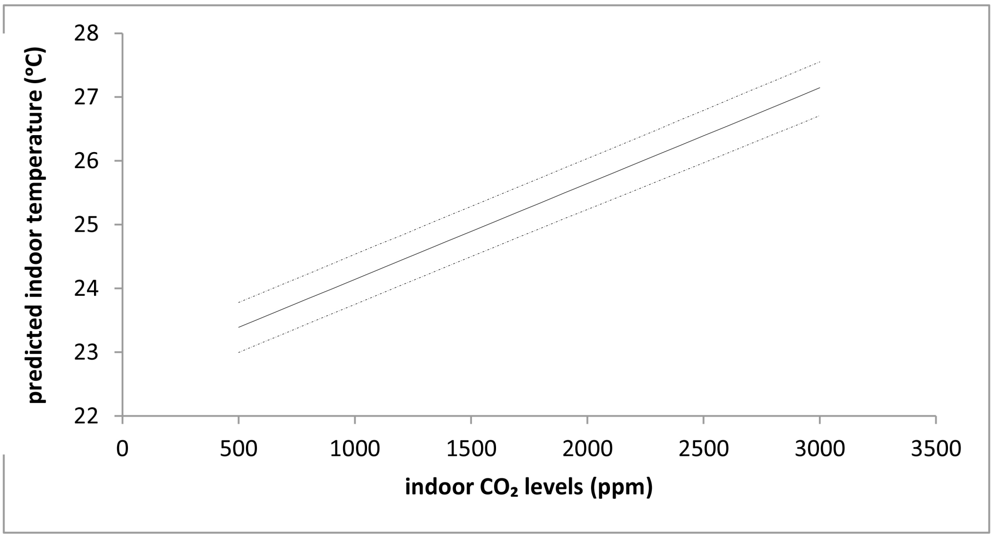


Figure 6.1: Predicted indoor temperatures with 95% Confidence Interval from indoor CO_2 levels when outdoor temperatures are 20 °C in high thermal mass classrooms with exposed ceiling applying cross-ventilation and night cooling with occupancy of 30 people and controlling for RH (Table 6.1)

The classroom level proportion reduction of variance estimated with R&B method (Section 4.5.4, Equation 4.11), shows that Level-2 model, which included construction characteristics (thermal mass, exposed ceiling and glazing of windows), ventilation strategies (night cooling) and occupancy density explained 34% of the total variation in classrooms.

The parameter estimates shown in Table 6.1 determine how influential a factor is on indoor temperatures, with larger estimates (regardless of sign) indicating the more effective factors. The most influential factors mitigating overheating were double glazing, high thermal mass of the building and ventilation strategy (cross-ventilation, single-sided and mixed mode). More specifically, cross-ventilation strategies were more effective in mitigating overheating compared with classrooms applying single-sided and mixed mode ventilation, which were around 2 °C warmer.

In the next step, environmental parameters were inserted in the model, which further increased the proportion of explained variance between classrooms up to 90%. The model shows that indoor temperatures will rise by 1 °C for every 4 °C increase in the outdoor temperatures. As expected, higher indoor CO_2 levels were associated with higher indoor temperatures as both increase in the presence of occupants through metabolic breathing, and increased sensible and latent heat gains respectively. However, it is worth noting that the association between CO_2 levels and indoor temperatures remained significant after controlling for occupancy density and occupants' numbers, indicating that reduced ventilation rates contributed to overheating.

The relationship between predicted indoor temperatures and indoor CO_2 levels can be described by a linear relationship (Figure 6.1). It is expected, that when outdoor temperatures reach 20 °C, a tendency for overheating is expected at CO_2 levels above 1500 ppm. It was assumed that classrooms applied passive measures (high thermal mass, exposed ceiling and application of night cooling, single glazing) under normal occupancy density (30 people).

Table 6.1: Determinants affecting indoor temperatures during the occupied period using a two-level model (classroom and season level controlling for the effect of the school)

	Empty model	Level -2 model	Final model	Parameters estimates (%)
	β^a (SE)	β^a (SE)	β^a (SE)	
Intercept	22.0 (0.37)	23.6 (0.45)	23.4 (0.24)	
Construction characteristics				
Thermal mass (binary)		0.5 (0.4)	-1.7 (0.2)	17.6
Exposed ceiling (binary)		-0.6 (0.1)	-0.8 (0.1)	8.6
Single glazing (binary)		-2.4 (0.3)	-2.6 (0.2)	26.9
Operation of Buildings				
Ventilation strategy				
(reference category: cross-sided natural ventilation)				
Mixed-mode		1.5 (0.5)	1.6 (0.3)	16.1
Single-sided natural ventilation		2.3 (0.5)	1.1 (0.3)	10.9
Night ventilation (binary)		-1.4 (0.02)	-0.1 (0.1)	1.5
Occupants number		0.04 (0.01)	0.07 (0.01)	0.8
Occupancy density (m^3/p)		0.005 (0.058)	-0.2 (0.04)	1.6
Environmental Parameters				
Outdoor temperature (°C)			0.4 (0.006)	3.9
(centred around 10 °C)				
Indoor CO_2 levels (ppm)			0.001 (0.000)	10.3
(centred around 1000 ppm)				(per 1000 ppm)
Indoor RH levels (%)			-0.2 (0.004)	1.7
(centred around 50%)				
Model Summary				
Between classroom variation (σ_u^2)	2.453 (0.823)	1.621(0.544)	0.223 (0.076)	
Within classroom variation (σ_e^2)	2.7 (0.064)	2.473 (0.058)	1.042 (0.025)	
Deviance statistic (-2LL)	13953.79	13630.71	9825.53	
Units: Classroom	18	18	18	
Units: season	3618	3618	3390	

a Regression coefficient from linear regression, change in temperature per change in unit determinant, SE= standard error

6.3 Factors affecting indoor Particulate Matter concentrations

Factors affecting indoor PM_{10} and PM_1 concentrations during the occupied period in the heating and non-heating season were investigated using two-level models (classroom and season level) (Table 6.4) controlling for the effect of the school. $PM_{2.5}$ profile was very similar to the PM_1, and concentrations were closely correlated because they are determined by similar physical properties, and therefore only the predictive model for PM_1 is presented here. The computed ICC for PM_{10} and PM_1 was 0.12 and 0.20 respectively, indicating that the between classroom variation is relatively small.

It was first shown that the orientation of the classroom facade to the wind direction affected indoor PM concentrations. Classrooms located parallel to the wind direction had the highest indoor PM concentrations (Table 6.4) possibly because lower pressure coefficients limit the driving forces for natural ventilation, and, therefore, cannot purge indoor concentrations. Classrooms located in the windward side of the schools had higher indoor PM levels compared with classrooms in the leeward side of the school buildings, as positive wind pressures might have increased infiltration rates of particles. The effect of wind on increasing infiltration ability of PM levels, and especially the smaller fraction has been reported in previous studies (Section 2.6.3).

The effect of wall-to-wall carpeting on elevating indoor organic and inorganic airborne particle concentrations was the most significant predictor in this study, and the strong effect was also detected in previous studies in school classrooms (Section 2.6.5). In this study, carpeted classrooms had on average 38 $\mu g/m^3$ and 29 $\mu g/m^3$ higher indoor PM_{10} and PM_1 levels respectively during teaching activities than classrooms with hard flooring (Table 6.4).

Timing of cleaning activities in the classroom also affected indoor PM concentrations during the occupied period, possibly because particles may get re-suspended during cleaning activities of the classrooms. More specifically, in classrooms that cleaning took place in the beginning of the occupied period had on average 16 $\mu g/m^3$ and 25 $\mu g/m^3$ higher levels of PM_{10} and PM_1 respectively.

The effect of occupancy on elevating indoor PM_{10} levels, further revealed re-suspension of previously deposited matter in the classroom, and is in agreement with findings in previous investigations (Section 2.6.4). Increased occupancy density was, therefore, a significant predictor of indoor PM_{10} levels. Smaller fraction was not as strongly affected by re-suspension as the effect of occupancy density was not significant, which was also reported in previous studies. Moreover, nursery classrooms had on average 15 $\mu g/m^3$ higher indoor PM_{10} levels than primary classrooms, possibly because younger children are more physically active. The effect of classroom year on indoor PM_{10} levels was also reported in a study using bivariate analysis

(Fromme et al., 2007), although the difference between year 5-7 was greater (25 to 56 μg/m^3 lower) compared with year 1-4.

Indoor environmental parameters, such as temperature and RH, which are also affected by occupancy, were reliable predictors of indoor PM_{10} levels (Table 6.4). More specifically, the model predicts that for every 1000 ppm increase of indoor CO_2 levels, an increase of 8 to 10 μg/m^3 is expected. A similar relationship was noticed in an investigation in 75 German schools (Fromme et al., 2007). A positive relationship was found between indoor RH and indoor PM_{10} levels in both seasons, and results agree with previous research (Goyal & Khare, 2009). However, the results between indoor temperatures and PM levels have been inconsistent in previous studies (Section 2.6.3). In this study, a positive relationship between indoor PM and higher indoor temperatures was estimated after controlling for meteorological parameters, building, maintenance and operational characteristics and indoor environmental conditions. Available continuous outdoor PM data were inserted in the final model, and it was shown that the contribution of outdoor levels to indoor concentrations was relatively small.

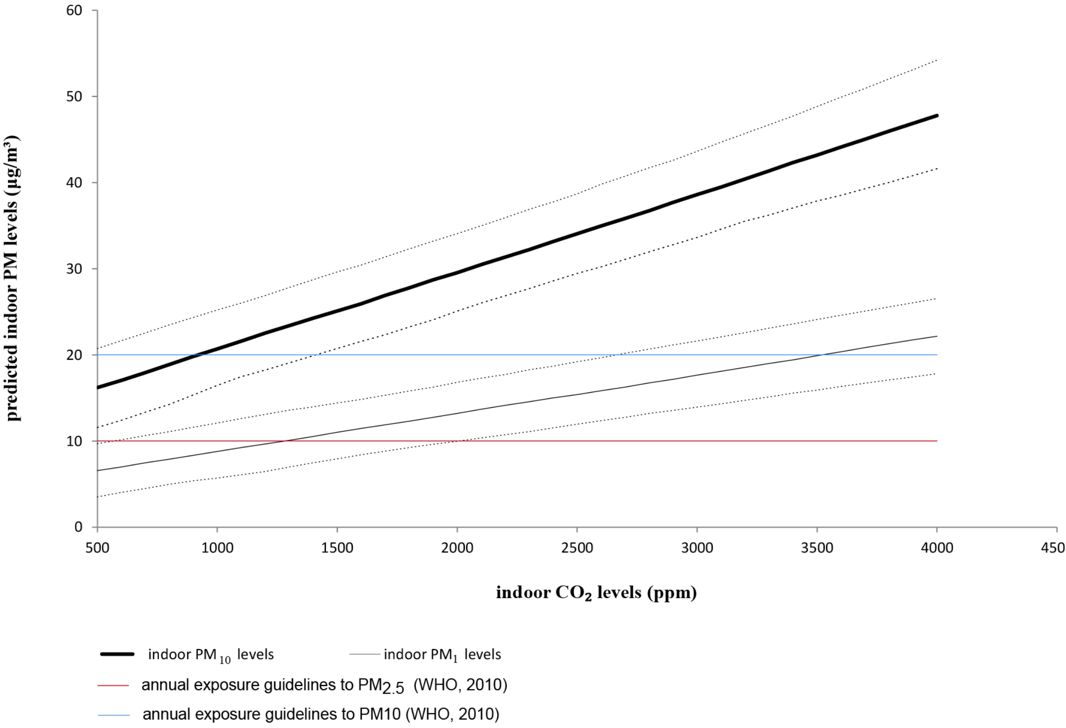


Figure 6.2: Predicted indoor PM levels with 95% Confidence Intervals from indoor CO_2 levels at indoor temperature of 20 °C when wall-to-wall carpeting is removed controlling for the effect of the school, wind direction, occupancy density and RH (Table 6.4)

Indoor CO_2 concentrations remained a significant predictor for indoor PM levels after controlling for the effect of occupancy; therefore, the relation between CO_2 and PM extends beyond the re-suspension of particles, and is possibly related to low ventilation rates. The predictive models (Figure 6.2) show that in order to maintain indoor PM levels below daily guideline values (WHO, 2010), it is necessary to remove firstly indoor sources from classrooms, and, secondly, ensure average indoor CO_2 levels below current guidelines. It was predicted that when indoor CO_2 levels reach 1000 ppm, indoor PM_{10} levels will be 21 μg/m^3 (95%CI: 16 to 25 μg/m^3) exceeding the 20 μg/m^3 WHO 2010 guideline value of annual exposure (Section 2.3.3). Although there are no guidelines formed for PM_1 exposure (Salthammer, 2011), $PM_{2.5}$ annual concentrations should not exceed 10 μg/m^3. As indoor PM_1 and $PM_{2.5}$ were closely correlated, when indoor CO_2 levels were 1200 ppm, average indoor PM_1 prediction was 10 μg/m^3 (95%CI: 6 to 13 μg/m^3) (Figure 6.2).

6.4 Factors affecting indoor nitrogen dioxide concentrations

Estimated ICC from the variance components of the random part of the model was 84%, and indicates that there is strong spatial variability between classrooms (Table 6.2). A similar ICC coefficient equal to 81% was estimated for indoor NO_2 variability in 400 classrooms of 109 schools in six French cities using a three-level multilevel model (Banerjee & Annesi-Maesano, 2012). The findings indicate that uncontrolled background ventilation may increase indoor concentration. More airtight building envelopes had on average 12.7 μg/m^3 lower indoor levels than leaky buildings, and may, therefore, protect occupants from outdoor concentrations. Outdoor concentrations and airtightness of the building envelope explained 70% of the variation between classrooms (Table 6.2). As the I/O ratios were smaller than unity, the presence of indoor sources might be negligible.

Table 6.2: Determinants of indoor NO_2 concentrations using a two-level model (classroom season level)

	Empty model	Level-2 model	Final model
Intercept	19.0 (2.0)	21.6 (1.2)	22.7 (0.6)
Microenvironment			
Outdoor NO_2 (μg/m^3)		0.8 (0.1)	0.6 (0.0)
Building Characteristics			
Airtightness			
Reference category (0.2<ACH_{inf} <0.4 h^{-1})			
Leaky buildings (ACH_{inf} >0.4 (h^{-1})			3.6 (1.3)
Airtight buildings (ACH_{inf} <0.2 h^{-1})			- 9.1 (1.1)
Random Part of the model			
Between classroom variation (σ_u^2)	64.9 (23.9)	19.4 (8.0)	1.4 (1.2)
Between season variation (σ_e^2)	12.5 (4.3)	3.4 (1.4)	2.7 (1.1)
Deviance statistic (-2LL):	230.9	139.6	109.0
Units: Classroom	18	14	14
Units: season	35	26	26

6.5 Factors affecting indoor Total Volatile Organic Compounds concentrations

The computed ICC was 0.25, therefore, the variation between classrooms was moderate. As expected, the most influential operational and maintenance characteristics of classrooms on indoor TVOCs concentrations during performance in use were cleaning products introduced in the classrooms, occupancy density and fleecy factor (Table 6.3). The use of bleach elevated indoor levels by 118 ppb on average compared with the control group after taking into account all influential parameters. Fleecy materials introduced in classrooms had a negative impact on IAQ elevating indoor levels by 473 ppb for each square metre per cubic metre of classroom volume, possibly through off-gassing, or cleaning products used to maintain these materials (such as wall-to-wall carpets).

After controlling for number of occupants and associated possible bio-effluents, indoor temperature and CO_2 levels remained significant predictors of indoor TVOCs levels. Because indoor temperatures correlated with CO_2 levels (Table 6.1), temperature explained most of the variation of indoor TVOCs levels (Figure 6.3). It was predicted that in classrooms using low emitting cleaning products, and with fleecy materials removed, when indoor temperatures exceed 22 °C, mean indoor TVOCs levels will be above UK recommendations (111 ppb, 95% CI: 71-157 ppb). At indoor temperatures above 26 °C, indoor TVOCs levels will exceed highest thresholds of discomfort (254 ppb, 95%CI: 209-301 ppb) (Section 2.3.3) (Figure 6.3).

6.6 Factors affecting targeted indoor Volatile Organic Compounds concentrations

Naphthalene, benzene and T3CE were the VOCs whose outdoor concentrations were strong predictors of indoor levels (Table 6.5). Classroom level predictors of indoor VOCs levels included the introduction of new furniture for formaldehyde (Figure 5.13), use of pesticide in the school predicted higher indoor naphthalene levels, and cleaning agent T4CE was associated with increased curtain area. 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.

After controlling for the effect of the school , the models investigated the effect of ventilation and infiltration rates, and indoor CO_2 levels on indoor VOCs concentrations (Figure 6.4). It was found that higher infiltration rates may remove VOCs with indoor intermittent sources, such as toluene and limonene. Lowering indoor CO_2 levels during teaching activities may control VOCs levels emitted from continuous sources, such as formaldehyde and toluene, and prevent the build-up of VOCs with outdoor sources, such as benzene (Table 6.5).

Table 6.3: Determinants of indoor TVOCs concentrations during the occupied period using a two-level multilevel model (classroom-season level)

	empty model Section 4.3	Level-2 model Section 4.5.4	Tentative model Section 4.5.4	Final model Section 4.5.4
	β (SE)	β (SE)	β (SE)	β (SE)
Intercept	318.6 (36.9)	256.7 (35.5)	263.7	258.5 (39.0)
Operation and Maintenance of Building				
Use of bleach (binary)		123.9 (25.0)	111.7 (25.5)	118.3 (25.2)
Number of occupants		0.6 (2.1)	0.8 (2.1)	6.6 (2.2)
Fleecy factor (m^2/m^3)		409.0 (64.3)	398.2 (67.1)	472.9 (66.4)
Environmental Parameters				
Indoor CO_2 levels (1000 ppm)			0.04 (0.01)	0.02 (0.01)
Indoor temperature (°C)				35.7 (3.2)
Model summary				
Between classroom variation (σ_u^2)	23951 (8172)	19266 (6599)	19953(6850)	23935 (8173)
Between season variation (σ_e^2)	71174 (1923)	69974 (1891)	71678 (2004)	68348 (1911)
Deviance statistic (-2LL):	38697	38646	36189	36070
Units: Classroom	18	18	18	18
Units: season	2757	2757	2577	2577

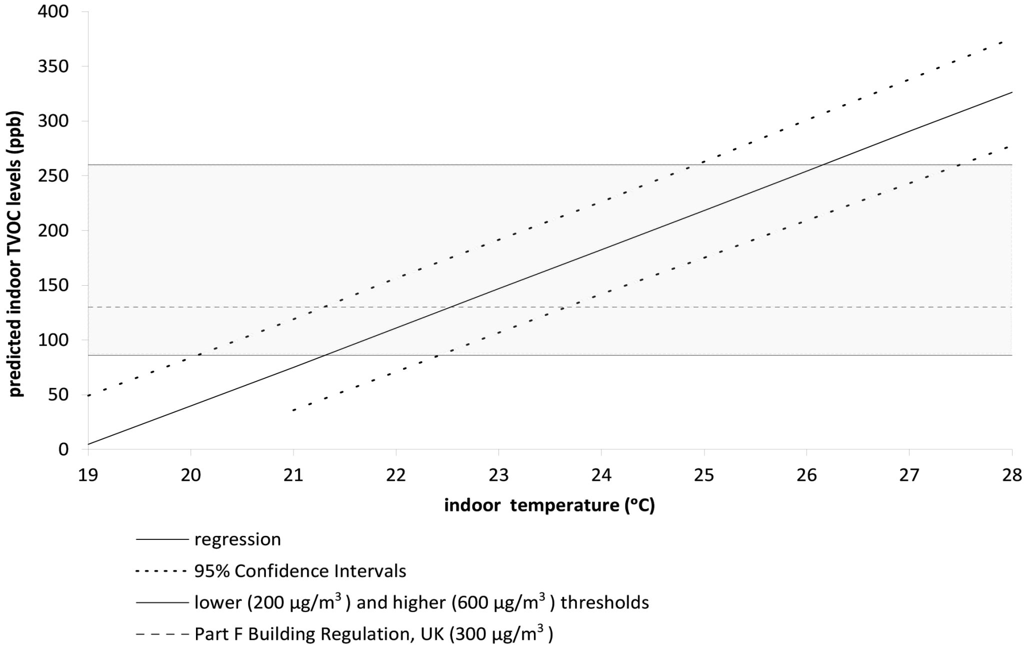


Figure 6.3: Predicted indoor TVOCs levels with 95% Confidence Interval from indoor temperatures when fleecy factor and use of bleach have been eliminated, and CO_2 levels are 1000 ppm controlling for the effect of the school (Table 6.3). Recommended range and UK threshold levels are indicated in the graph

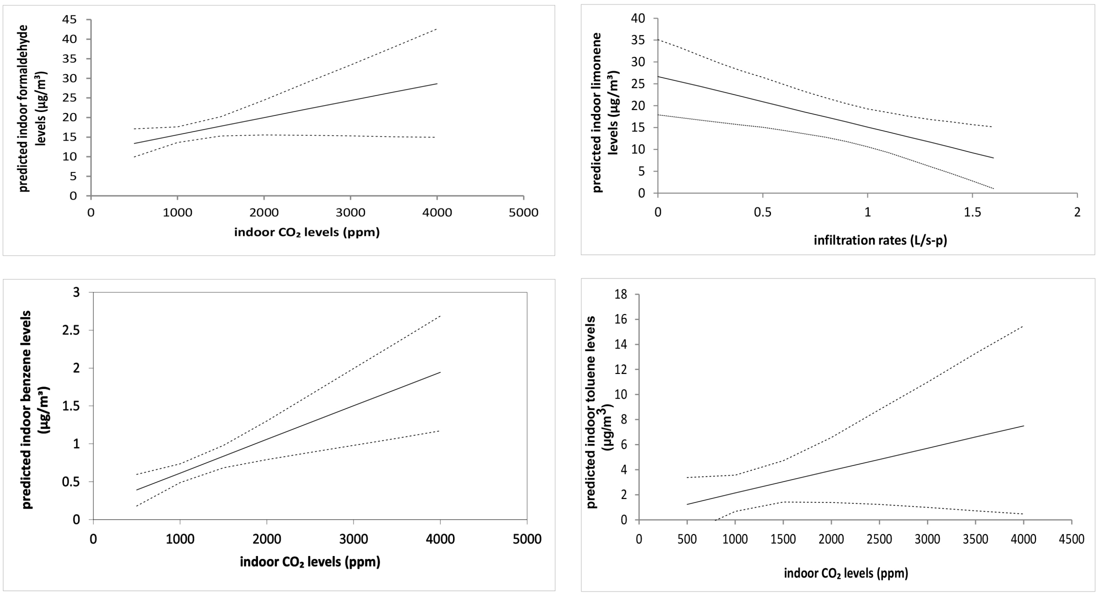


Figure 6.4: Predicted indoor VOCs levels with 95% Confidence Interval from indoor CO_2 levels controlling for the effect of the school Table 6.5

6.7 Factors affecting indoor microbial counts

The empty models revealed that there was a large variation between indoor exposure to *Cladosporium herbarum* in the classrooms (Table 6.6), as this species is strongly affected by outdoor context varying between urban and suburban schools. After controlling for the effect of the school and temperature, it was computed that classrooms with higher ventilation rates during teaching activities had lower counts of *Cladosporium herbarum* (Figure 6.5). These findings indicate temporary contamination of the buildings from outside, and that higher ventilation rates may dilute microbial counts. Similar results have been reported in a previous study in school buildings (Ejdys, 2007).

Trichoderma viride, and bacterial groups *Mycobacterium* spp. and *Streptomyces* spp. exhibited strong spatial variation among classrooms. Higher infiltration rates were associated with increased counts of bacterial genera *Mycobacterium* spp. and *Streptomyces* spp., and fungal species *Alternaria alternata* and *Trichoderma viride* (Figure 6.6). A possible explanation of the finding is, that uncontrolled infiltration or exfiltration of warm, moist air can cause condensation in wall cavities (and ceiling or attic spaces) providing favourable conditions for microbial species and groups that require high equilibrium relative humidity to grow (Section 3.7.1).

The variability of indoor PenAsp and *Aspergillus versicolor* between classrooms was relatively small, and lower in classrooms employing natural ventilation and LTHW heating system (Table 6.6).

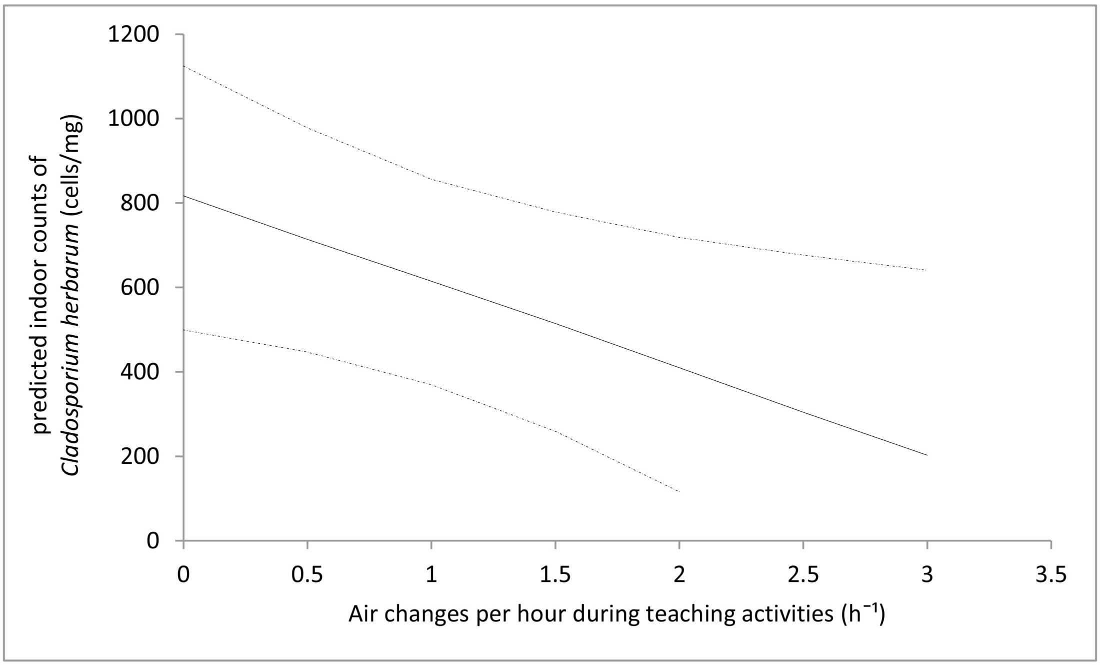


Figure 6.5: Predicted indoor *Cladosporium herbarum* counts (cells/mg) with 95% Confidence Interval from air changes per hour during normal teaching activities when indoor temperatures are 20 °C and controlling for the effect of the school

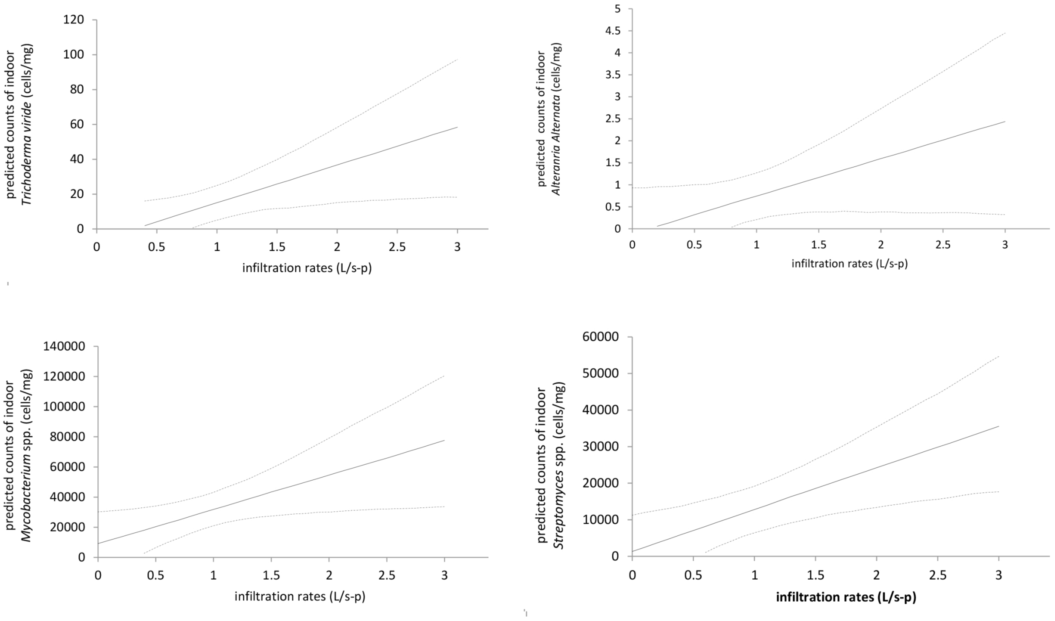


Figure 6.6: Predicted indoor microbial counts with 95% Confidence Interval from infiltration rates (L/s-p) controlling for the effect of the school

Table 6.4: Determinants of indoor PM concentrations during the occupied period using a two-level multilevel model (classroom-season) and controlling for the effect of the school

	PM_{10}				PM_1			
	Empty model	Level-2 model	Final model	Final model including outdoor PM_{10} levels	Empty model	Level-2	Final model	Final model including outdoor PM_1 levels
	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)
Intercept	46.5 (2.7)	49.7 (6.5)	44.2 (6.7)	42.9 (9.0)	30.0 (2.1)	39.3 (2.5)	28.6 (3.2)	28.1 (2.5)
Microenvironment								
Wind direction in relation to building faade								
(Reference category: facade parallel to wind direction)								
Classroom facade on windward side		-6.1 (1.9)	-5.7 (2.2)	-6.7 (3.9)		-6.8 (1.2)	-6.5 (1.3)	-7.1 (2.0)
Classroom facade on the leeward side		-8.0 (2.3)	-6.8 (2.3)	-10.7 (3.4)		-5.1 (1.4)	-5.9 (1.3)	-7.6 (1.7)
Building Characteristics and Operation								
Presence of carpet (binary)		16.4 (8.5)	38.2 (9.1)	34.2 (15.4)		47.6 (6.1)	29.3 (5.2)	-4.5 (7.2)
School type (binary)		-1.9 (4.7)	-13.4 (4.8)	-8.2 (4.7)		\	\	\
Cleaning Schedule (binary)		-15.9 (6.0)	-16.1 (6.7)	-21.4 (10.6)		-36.5 (4.0)	-25.5 (3.9)	-6.9 (2.7)
Occupancy density (m^2/ p)		-1.2 (4.3)	-10.0 (4.3)	-12.7 (8.5)		\	\	\
Environmental parameters								
T (°C)			3.1 (0.4)	\			\	\
RH (%)			1.2 (0.1)	\			\	\
Centred around 50%								
CO_2 (ppm)			0.009 (0.001)	0.011 (0.002)			0.004 (0.001)	0.004 (0.001)
Centred around 1000 ppm								
Outdoor PM concentrations ($\mu g/m^3$)				0.31 (0.05)				0.27 (0.03)
Random Part of the model								
Between classroom variation (σ_u^2)	116.2 (41.9)	82.3 (30.5)	104.0 (38.0)	55.4 (28.0)	77.0 (26.5)	66.2 (22.8)	69.0 (23.8)	27.8 (13.2)
Between season variation (σ_e^2)	865.2 (24.0)	850.9 (23.6)	745.4 (21.5)	563.3 (27.8)	304.5 (8.2)	296.5 (8.0)	275.0 (7.7)	136.9 (6.8)
Deviance statistic (-2LL)	25099.2	25050.3	23008.6	7624.9	23578.1	23502.2	21774.8	6458.9
Units: Classroom	17	17	17	17	18	18	18	17
Units: season	2609	2609	2429	829	2748	2748	2568	829

Table 6.5: Determinants of indoor VOCs (μg/m^3) concentrations using a two-level multilevel model (classroom-season level) controlling for the effect of the school

EMPTY MODEL	**formaldehyde** β (SE)	**naphthalene** β (SE)	**benzene** β (SE)	**toluene** β (SE)	**T3CE** β (SE)	**T4CE** β (SE)	**limonene** β (SE)	**pinene** β (SE)
Intercept	16.1 (2.3)	0.9 (0.2)	0.7 (0.1)	2.9 (1.8)	0.3 (0.1)	0.3 (0.0)	16.9 (3.0)	9.2 (3.8)
Random Part								
Between classroom variability (σ_u^2)	85.8 (31.2)	0.4 (0.2)	0.2 (0.1)	10.2 (4.2)	0.1 (0.1)	0.0 (0.0)	61.7 (65.8)	227.5 (85.5)
Between season variability (σ_e^2)	14.3 (4.9)	0.1 (0.0)	0.1 (0.0)	4.1 (1.4)	0.1 (0.0)	0.0 (0.0)	203.5 (69.0)	52.2 (18.5)
Deviance statistic (-2LL):	238.0	58.8	32.8	180.5	40.5	-15.5	293.0	270.7
Units: Classroom	18	18	18	18	18	18	18	18
Units: season	35	35	35	35	35	35	35	34
FINAL MODEL								
Intercept	13.7 (3.4)	1.1 (0.2)	0.7 (0.1)	2.6 (1.5)	0.1 (0.1)	0.3 (0.0)	16.5 (5.4)	3.4 (4.3)
Microenvironment (outdoor pollution levels)								
outdoor naphthalene (μg/m^3)		0.5 (0.1)						
outdoor benzene (μg/m^3)			2.3 (0.5)					
outdoor T3CE (μg/m^3)					1.8 (0.6)			
Level-2 characteristics (maintenance and operation of classroom)								
Furniture introduced in the classroom in the last 2 years (binary)	17.6 (2.7)							
Use of pesticides in the school		0.4 (0.2)						
Curtain area (m^2)						0.007 (0.002)		
Use of bleach in the classroom (binary)							21.6 (5.0)	11.7 (5.5)
Ventilation efficiency								
Air Changes per hour during normal teaching activities (h^{-1})	- 2.3 (1.0)							
Indoor CO_2 levels (per 1000 ppm increase)			0.4 (0.1)			0.2 (0.1)		
Infiltration rates (L/s-p)				-0.7 (0.2)			-11.6 (4.2)	
Random Part								
Between classroom variability (σ_u^2)	0.0 (0.0)	0.1 (0.1)	0.0 (0.0)	25.5 (9.0)	0.0 (0.0)	0.0 (0.0)	11.4 (33.0)	171.3 (67.2)
Between season variability (σ_e^2)	13.6 (3.6)	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)	0.0 (0.0)	102.6 (40.7)	51.1 (18.0)
Deviance statistic (-2LL):	152	38	10	106	28	-28	212	266
Units: Classroom	16	18	18	16	18	18	16	18
Units: season	28	35	35	28	35	35	28	34

Table 6.6: Determinants of indoor microbial counts (cells/mg) using a two-level model (classroom and season level) after controlling for the effect of the school

	Cladosporium herbarum	PenAsp	*Aspergillus versicolor*	*Alternaria alternata*	*Trichoderma viride*	*Mycobacterium* spp.	*Streptomyces* spp.
EMPTY MODEL	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)
Intercept	339 (102)	42292 (10588)	112 (70)	0.7 (0.3)	33 (16)	66590 (25092)	18271 (5394)
Random Part							
Between classroom variability (σ_u^2)	135960 (65233)	620204096 (818587864)	18197 (37336)	0.1 (0.5)	3919 (1448)	9095543808 (3850588520)	346014240 (184343402)
Between season variability (σ_e^2)	105100 (35034)	2704323072 (923392668)	139160 (46387)	2.2 (0.7)	812 (271)	4474925056 (1491641883)	355383616 (118461215)
ICC	0.56	0.19	0.12	0.04	0.83	0.67	0.49
Deviance statistic (-2LL):	541	866	533	132	386	931	830
Units: Classroom	18	18	18	18	18	18	18
Units: season	36	35	36	36	36	36	36
FINAL MODEL							
Intercept	-142 (224)	120565 (23053)	703 (143)	1.6 (0.7)	21.0 (13.8)	36484 (15745)	16061 (8250)
Ventilation efficiency							
Natural ventilation (binary)		-94509 (24885)	-710 (157)				
Heating system (binary)							
Indoor temperature (oC)	-118 (46)						
Air changes during normal teaching activities (h^{-1})	- 201 (95)						
Infiltration rates (L/s-p)				0.9 (0.4)	21.4 (9.3)	22964 (9996)	11436 (4315)
Random Part							
Between classroom variability (σ_u^2)	21982 (41227)	1079966592 (672034764)	21836 (239836)	0.4 (0.4)	101 (155)	278669056 (188224309)	132060800 (55176046)
Between season variability (σ_e^2)	125724 (48410)	1499765632 (513731784)	775936 (258926)	1.2 (0.5)	453 (175)	365245024 (142138799)	38904584 (153149456)
Deviance statistic (-2LL)	427	855	516	94	931	668	620
Units: Classroom	16	18	18	16	18	16	16
Units: season	29	35	36	29	36	29	29

6.8 Summary

This chapter used multilevel statistical modelling to quantify the variability in indoor air quality of classrooms, and to evaluate the adequacy of CO_2 as a proxy for adequate IAQ in classrooms. The results of this study demonstrated marked differences in the characteristics of indoor air pollution between seasons and classrooms depending on their microenvironment, building characteristics, operation and maintenance.

Overall the model shows that increased CO_2 levels in the classroom indicate that high internal gains and reduced ventilation patterns may result in overheating. It was found that current recommendations on average indoor CO_2 levels during a teaching day may also prevent overheating. Predicted indoor temperatures during a teaching day will exceed 25 °C , when indoor CO_2 levels exceed 1500 ppm, assuming that buildings have applied passive measures (external shading, exposed ceiling and night cooling), and outdoor temperatures are 20 °C.

The results suggested that there are two main mechanisms that increase indoor PM concentrations in the classroom. On the one hand, indoor PM, 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. Classrooms parallel to the wind direction had smaller potential of enhancing natural ventilation strategies, and, therefore, the highest concentrations. Together with 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 1000 ppm for the coarse fraction, and 1200 ppm for the fine fraction to ensure annual mean exposure below WHO 2010 guidelines.

The introduction in classrooms of non-low emitting cleaning products and wall-to-wall carpeting elevated indoor TVOCs concentrations, possibly due to off-gassing of carpets, or cleaning products used for maintenance. After eliminating indoor sources, the predictive models indicated that keeping the temperature below 26 °C is necessary to prevent the build-up of TVOCs below the range of discomfort, and preferably below 22 °C depending on season. An association between specific VOCs and higher ventilation rates emerged. It was shown that higher ventilation rates may prevent the build-up indoors of harmful VOCs with outdoor sources (such as benzene), and may remove specific VOCs, especially when continuous indoor sources are present. Higher ventilation rates in naturally ventilated classrooms may also dilute microbial counts.

Uncontrolled infiltration rates may increase indoor NO_2 concentrations, which were strongly predicted by outdoor levels, and may also encourage microbial growth of species, whose presence indicates damp or wet material. Apart from its entry during occasional events (such as water leaks, heavy rain and flooding), most moisture enters a building infiltrating the building envelope, or resulting from the occupants' activities. Both infiltration and exfiltration of warm, moist air can cause condensation in wall cavities, which may encourage microbial growth.

In the next chapter, the effect of building characteristics, indoor physical, chemical parameters and microbial counts on health outcomes and perceived IAQ of the students will be investigated with multilevel logistic and ordered multinomial models.

Chapter 7

Self-reported Health Responses

Asthmatic Symptoms, Sick Building Syndrome symptoms and perceived IAQ among students in relation to school exposure and building characteristics

7.1 Outline

As already stated (Section 1.1), the prevalence of asthma has increased over the past decades making it the most common chronic illness in children, and the leading cause of hospitalisation among children (WHO, 2012) with the UK and Ireland having the highest prevalence rates of childhood asthma among European countries (Mallol et al., 2013) as reported by the ISAAC study. Apart from asthmatic symptoms, other health symptoms and irritations in indoor environments are frequently reported. The validity of such complaints as an indicator of exposure is potentially of great interest, and highlights the need to investigate the extent at which such perceptions can be related to objectively established factors.

The extensive literature review (Section 2.4) summarised findings from epidemiological and toxicological studies primarily on the association between respiratory disease and school exposure. The majority of these studies obtained data from fixed monitoring stations while indoor exposure may significantly differ. Most studies on SBS symptoms and perceived IAQ typically deal with office workers and few of them employ actual measurements of pollution levels. Only a few studies investigated the association between indoor exposure to specific pollutants and asthma exacerbation, SBS symptoms and dissatisfaction with IAQ of the occupants, while controlling simultaneously for a large number of indoor air pollutants (Section 2.5).

This chapter aims to associate exposure to specific pollutants, with prevalence, incidence and remission of self-reported health symptoms, and in so doing, evaluate the adequacy of current regulatory framework. Moreover, this chapter aims to relate personal factors, building characteristics and classroom exposure to perceived IAQ, and whether perception may vary among seasons. This longitudinal study of the heating and non-heating season draws on survey responses from children and detailed monitoring of pollutants and the IAQ of 15 primary school classrooms in five schools located in the London area.

The chapter is organised in four parts. The first part (Section 7.2 presents the prevalence of asthma, asthmatic and SBS symptoms in the school environment. The association between prevalence of symptoms at baseline conditions (heating season) with specific exposures are investigated in Section 7.3, while exposures affecting incidence and remission in the follow-up period (non-heating season) is analysed in Section 7.4. In the last section 7.5, perceived IAQ in relation to personal factors, the microenvironment, operation and maintenance, school building characteristics and classroom exposure is investigated with a longitudinal model, and season-based ordered multinomial multilevel models. The chapter closes with a summary.

7.2 Prevalence of health data

In total, 376 students of 430 (Response Rate: 87%) participated in the baseline and follow-up 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. Percentage of girls was lower in the suburban schools (50.4%) compared with urban schools (61.2%). A detailed summary of information on the participants by classroom can be found in the Appendix D.12.

The prevalence of groups of SBS symptoms in the school environment is presented in Figure 7.1, and a detailed breakdown of all SBS symptoms is presented in Table 7.1. Prevalence of all SBS symptoms in the school environment was higher in the heating season compared with the non-heating season. Influenza epidemics in temperate regions tend to be higher in the heating season and may create SBS-like symptoms (Ginsberg et al., 2009); however, the difference in influenza prevalence between seasons in this study was not significant (Table 7.1). The remission of symptoms in the non-heating season was significant for throat ($p < 0.001$), nasal symptoms ($p < 0.05$) and respiratory symptoms ($p < 0.05$) as calculated by the McNemar test (Section 4.5). Prevalence of general, ocular and dermal symptoms was not significantly different between seasons during the academic year. Apart from dermal symptoms in the non-heating season, all reported SBS symptoms were higher in the urban schools compared with the suburban schools in both seasons (Figure 7.1).

The prevalence of asthma was significantly ($p < 0.001$) different between urban and suburban schools. More specifically, prevalence of asthma attacks and asthmatic symptoms in the urban schools ranged from 7.9 to 12.5% (average: 10.2%), while in the suburban schools it was 1.5 to

1.6% (av: 1.5%). Highest asthma prevalence was reported in S3, which is situated in immediate proximity to a high intensity street. There was no new incidence of asthma reported during the academic year. Additionally, the prevalence of respiratory symptoms that could potentially be asthmatic symptoms (such as wheezing and/or difficulty breathing), was not significantly different among seasons.

7.3 Associations between prevalence of asthma, asthmatic and Sick Building Syndrome symptoms with classroom exposures at baseline conditions

The analysis at baseline using multilevel logistic regression Model II (Section 4.5) showed some statistically significant associations between indoor exposures with health symptoms while controlling for age, gender, exposure to ETS at home and overall satisfaction with the school environment. While age and gender were not identified as risk factors, exposure to tobacco smoke at home was a significant predictor for asthma prevalence.

Prevalence of asthma attacks and asthmatic symptoms in the school environment were associated only with school exposure to indoor NO_2 levels (Figure 7.2). Respiratory symptoms during the investigated week were not significantly associated with any exposure.

All SBS symptoms were inversely associated with higher infiltration rates (Table 7.2). Higher prevalence of ocular symptoms was associated with pollutants with predominantly outdoor sources, specifically, NO_2, PM_{10}, benzene and naphthalene. Additionally, prevalence of throat symptoms was positively associated with higher indoor exposure to PM_{10}.

Among all microbial exposures, only *Mycobacterium* spp. was associated with health outcomes at baseline conditions. Although *Mycobacterium* spp. had a protective effect on dermal symptoms, higher counts were associated with higher prevalence of nasal symptoms.

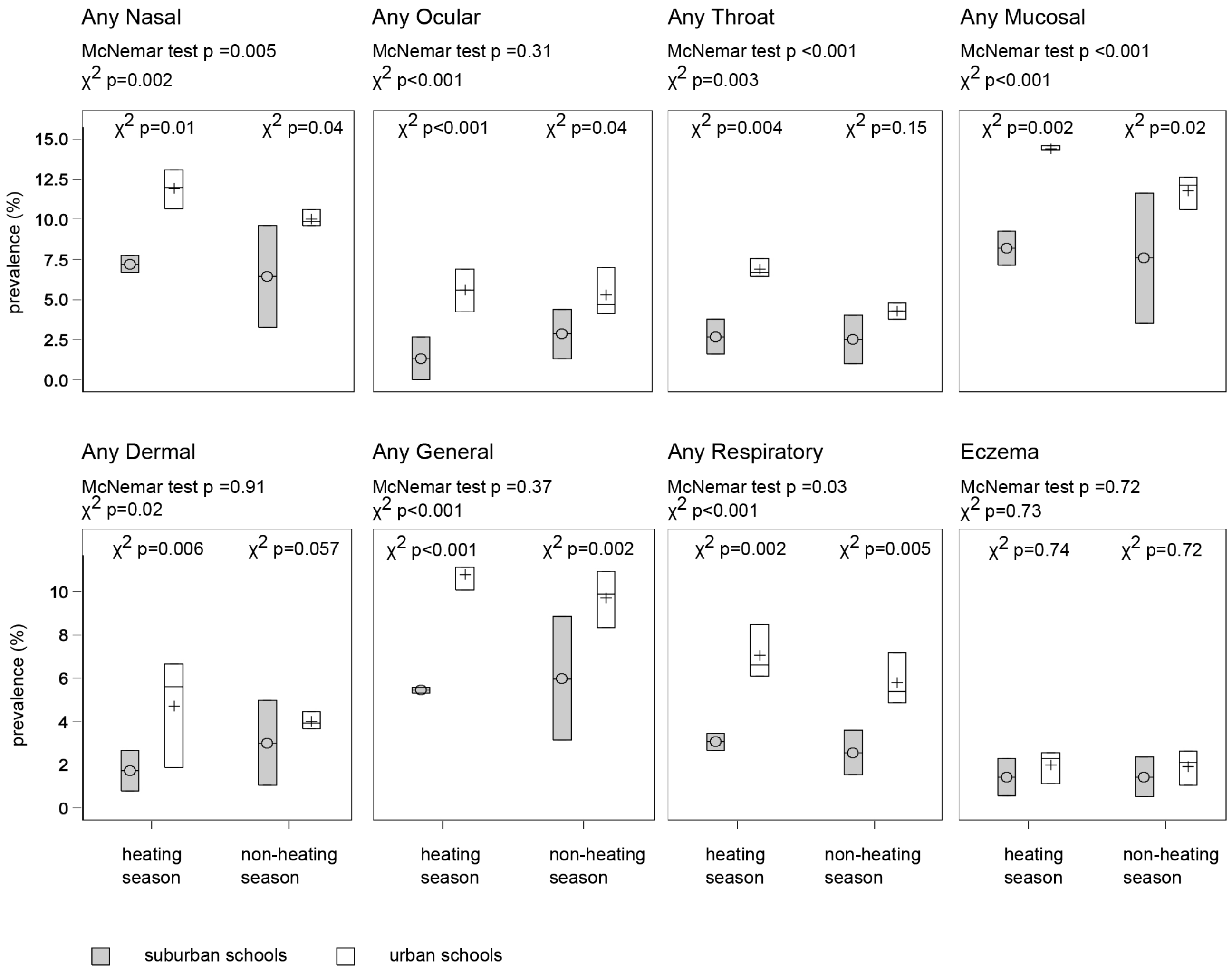


Figure 7.1: The prevalence of asthma, asthmatic and self-reported health symptoms during the investigated week in urban and suburban schools in the heating and non-heating season of 2011 2012

Table 7.1: The prevalence of SBS symptoms in the investigated weeks of the heating and non-heating season

	Prevalence (%)		$p - value^a$
	Heating season N=370	Non-heating season N=370	
Type of symptom			
Ever Asthma	7.3	7.3	1
Eczema	5.1	8.6	0.72
Rashes on the hands	8	6.1	0.3
Itching on the hands	10.9	11.2	0.89
Facial rash	3.4	3.7	0.81
Facial itching	9	8	0.63
Any dermal[b]	**18.5**	**18.2**	**0.91**
Burning Sensation in the Eyes	5.5	6.7	0.48
Itching Eyes	12	11.4	0.89
Dry Eyes	4	3.4	0.82
Sensation of Sand in the Eyes	6.5	7.4	0.88
Red Eyes	5.9	4	0.29
Swollen Eyes	1.6	3.4	0.21
Any Ocular[b]	**19.7**	**22.7**	**0.31**
Irritated Nose	9.9	12.7	0.26
Sneezes	23.4	28.7	1
Nasal obstruction	25	15.2	<0.001
Nasal catarrh	30.9	21.8	0.004
Bleeding Nose	4.7	2.5	0.16
Any Nasal[b]	**50.7**	**40.7**	**0.005**
Dryness in the throat	16.3	10.7	0.025
Sore throat	15.6	8.2	0.002
Irritating cough	13.35	7.1	0.005
Any Throat[b]	**26.8**	**17**	**<0.001**
Any Mucosal[b]	**60.7**	**49**	**<0.001**
Sensation of getting a cold	18.1	12.2	0.02
Getting a cold	16.2	8.4	0.002
Influenza	3.8	2.2	0.3
Wheezing	4.7	4.4	1
Difficult Breathing	9.1	5.9	0.12
Difficult Breathing with Wheezing	3.1	3.4	0.63
Any Respiratory[b]	**28.2**	**22.1**	**0.03**
Headache	22.1	18.6	0.27
Malaise	9.3	7.4	0.47
Fatigue	32.4	28.7	0.24
Muscle pain	12.7	13.9	0.68
Any general[b]	**43.6**	**40.7**	**0.37**

a: Differences tested by McNemar statistical test,
b: prevalence of at least one weekly symptom.

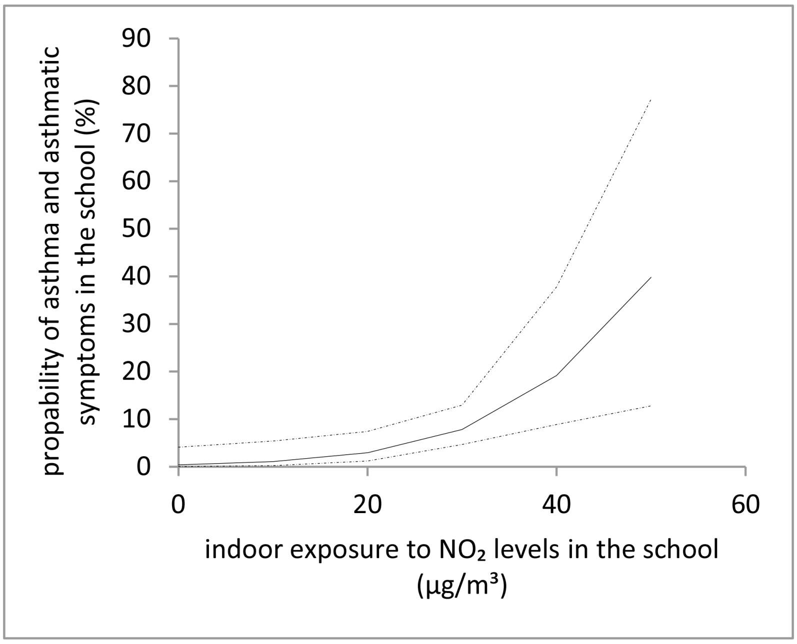


Figure 7.2: Probability of asthma and asthmatic symptoms in relation to classroom exposure to NO_2 controlling for the effect of the school, gender, age, and exposure to environmental tobacco smoke at home

Table 7.2: Association between exposure in the classroom with prevalence of SBS symptoms in the heating season among 376 students using Model II controlling for the effect of the school and personal factors (age, gender, exposure to ETS at home and overall satisfaction with the school)

Type of symptoms (OR 95%CI)						
Predictor	Asthma	Any Dermal	Any Ocular	Any Nasal	Any Throat	Any General
ACH_{inf}	\	0.33 (0.17-0.66)	0.43 (0.23-0.81)	0.43 (0.23-0.81)	0.53 (0.29-0.98)	0.53 (0.30-0.94)
PM_{10}	\	\	1.06 (1.00-1.12)	\	1.03 (1.00-1.06)	\
NO_2	1.11 (1.00-1.19)	\	1.05 (1.00-1.11)	\	\	\
Benzene	\	\	4.49 (1.01-20.00)	\	\	\
Naphthalene	\	\	13.81 (1.58-120.54)	\	\	\
Mycobacterium spp.[a]	\	0.99 (0.97-1.00)	\	1.16 (1.01-1.33)	\	\

OR 95%CI: Odds Ratio with 95% Confidence Interval (CI) calculated by multilevel logistic regression (Model II). Control for school, age, gender and exposure to tobacco smoke analysing each exposure separately. \ denotes insignificance. ACH_{inf}: Infiltration rates (h^{-1}). a: odds ratio expressed as change of coefficient per 10^3 cells/mg,

7.4 Associations between incidence and remission of Sick Building Syndrome symptoms with classroom exposures in the follow-up period

Table 7.3: Association between exposure in the classroom with incidence and remission of SBS symptoms among 376 students in the follow-up period using Model VI

Type of symptoms (HR 95%CI)						
Predictor	Any Dermal	Any Ocular	Any Nasal	Any Throat	Any Respiratory	Any General
ACH_{inf}	0.05 (0.01-0.21)	0.17 (0.05-0.54)	0.13 (0.05-0.33)	0.23 (0.07-0.78)	0.65 (0.45-0.93)	0.20 (0.08-0.54)
PM_{10}	\	1.02 (1.01-1.03)	1.02 (1.01-1.03)	1.01 (1.00-1.03)	\	1.01 (1.00-1.03)
NO_2	\	1.06 (1.03-1.10)	\	1.03 (1.01-1.06)	1.04 (1.02-1.07)	1.03 (1.01-1.06)
O_3	\	\	1.02 (1.00-1.03)	\		1.02 (1.00-1.03)
Benzene	\	2.20 (1.30-3.71)	\	\	\	\
T4CE	\	3.96 (1.95-8.07)	\	\	\	\

HR 95%CI: Hazard Ratio with 95% confidence interval calculated by conditional logistic regression (Model VI). Adjustment for school, age, gender and exposure to tobacco smoke analysing each exposure separately. \ denotes insignificance. ACH_{inf}: Infiltration rates (h^{-1})

Additional analysis of incidence and remission of SBS symptoms in relation to indoor exposures were investigated with conditional logistic regression Model VI, controlling for the effect of school and personal factors (Table 7.3). The aim of this model is to associate new occurrences of SBS symptoms (or absence of symptoms in the follow-up period) with seasonal variation of indoor pollution levels.

Similarly to baseline conditions (Table 7.2), it was found that the hazard ratio for all SBS symptoms decreased at lower infiltration rates.

The conditional logistic regression model associated incidence of ocular symptoms with NO_2 and benzene, which were also significant predictors of ocular symptoms at baseline conditions. Additionally, T4CE was found to increase incidence of ocular symptoms. In contrast, naphthalene was not a significant risk factor in the follow-up period for incidence of ocular symptoms. While at baseline conditions exposure to PM_{10} was associated with ocular and throat symptoms, in the follow up period PM_{10} exposure was associated with all mucosal and general symptoms.

Exposure to indoor O_3 levels in the heating season was not significantly related to any SBS symptoms (Table 7.2); however, in the non-heating season exposure increased the hazard ratio of nasal and general symptoms (Table 7.3).

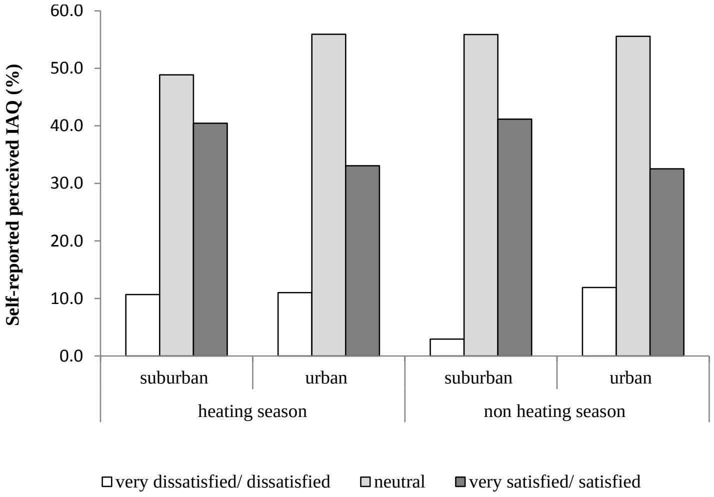


Figure 7.3: Perceived air quality reported by 376 students in urban and suburban schools during the investigated weeks in the heating and non-heating season

7.5 Associations between perceived IAQ with personal and environmental parameters in the heating and non-heating season

There was no statistically significant difference in dissatisfaction with IAQ between the heating and non-heating seasons. The percentage of students dissatisfied or very dissatisfied with IAQ in the classroom in the heating season was 13.2% in the heating season, and 15.9% in the non-heating season (Figure 7.3).

7.5.1 Perceived IAQ in relation to personal factors

The multilevel (classroom and student level) ordered multinomial logistic regression Model III was employed to investigate personal factors and psychosocial climate at school associated with perception of IAQ (Table 7.4). Each predictor was entered separately into the model, while controlling for the effect of the school. It was found that IAQ was more likely to be perceived as worse by younger students, and by those who found schoolwork stressful. Air quality tended to be perceived as better by students who reported increased satisfaction with the psychosocial climate in the school. Compared with other students, those who were exposed to environmental tobacco smoke at home were also more likely to report higher satisfaction with IAQ in the classroom.

Table 7.4: Personal factors, domestic exposures and psychosocial work climate significantly associated with perceived IAQ using Model III

Factor	Odds Ratio (95% CI)
Season (binary)	/
Age (range 9-11 years old)	0.79 (0.67-0.94)
Gender (binary)	/
Exposure to Environmental Tobacco Smoke (ETS) (binary)	1.36 (1.05-1.77)
Stress at School (11-point scale)	1.06 (1.02-1.11)
(How stressful is the school work to you?)	
Cooperative environment at School (11-point scale)	0.80 (0.76-0.84)
(How friendly is your school?)	

Odds Ratio (OR) with 95% confidence interval (CI) calculated by multilevel ordinal multinomial regression. Adjustment for school, age, gender and exposure to tobacco smoke analysing each exposure separately. \ denotes insignificance

7.5.2 Perceived IAQ in relation to the microenvironment and school building characteristics

The association between the microenvironment and school buildings characteristics with IAQ perception was investigated using ordered multinomial logistic Model III (Table 7.5). Proximity to high intensity street may increase traffic-related pollutants, and increase, therefore, dissatisfaction with IAQ. Timing of cleaning activities affected satisfaction with IAQ, with higher satisfaction tending to be reported in schools where cleaning activities were scheduled after the end of the occupied period compared with schools where these activities were performed at the start of the teaching day. Occupants attending classrooms with visible mould growth were more likely to report higher dissatisfaction with IAQ. In addition to occupancy density, smaller openable window area and excessive curtain area impacted negatively perceived IAQ.

Table 7.5: School building characteristics and daily maintenance significantly related to perceived IAQ using Model III

Factor	Odds Ratio (95%CI)
Proximity to traffic: (reference category residential suburban)	
1: urban on a high intensity street	5.52 (3.13-9.72)
2: urban background	3.70 (2.17-6.29)
3: residential in proximity to a high intensity street	2.47 (1.39-4.41)
Cleaning	0.75 (0.58-0.97)
0: cleaning activities took place before the start of school day	
1: cleaning activities took place after the occupied period	
Visible mould	1.35 (1.00-1.82)
0: no sign of visible mould in the classroom	
1: visible mould was detected in the classrooms	
Number of occupants	1.02 (1.00-1.04)
Occupancy density (m^2/p)	0.65 (0.45-0.95)
Occupancy density (m^3/p)	0.88 (0.83-0.93)
Curtain area (m^2)	1.02 (1.01-1.03)
Openable area (m^2)	0.81 (0.74-0.88)

7.5.3 Perceived IAQ in relation to classroom exposure

The longitudinal Model III investigating indoor school exposures and satisfaction with IAQ (Table 7.6) showed that the air quality was likely to be perceived better at lower indoor temperatures, and the association was consistent in both the heating and non-heating season. Moreover, lower RH, higher ventilation rates and lower indoor CO_2 levels improved perceived IAQ.

Apart from indoor physical parameters, higher measured concentrations of traffic related pollutants (NO_2, O_3 and benzene) impacted negatively on perceived IAQ. A small negative impact of airborne dust (all PM fractions) on perceived IAQ emerged in the non-heating season, and the association remained significant in the longitudinal model. Students in classrooms with higher concentrations of VOCs with indoor sources (limonene, pinene and formaldehyde) were more likely to perceive IAQ worse in the non-heating season, and the association remained significant in the longitudinal model.

Among all microbial exposures, the presence of *Cladosporium herbarum* was not associated with IAQ dissatisfaction. The negative effect of *Trichoderma viride* and *Alternaria alternata* on perceived IAQ was consistent in the longitudinal study. Among bacterial groups, *Mycobacterium* spp., a marker for the presence of moisture, was significant in the longitudinal model. PenAsp (*Penicillium* spp. /*Aspergillus* spp., *Paecilomyces varioti*), *Aspergillus versicolor* and *Streptomyces* spp. counts were associated with increased IAQ dissatisfaction in the heating season when levels were higher. Endotoxin data were collected only in the heating season, and their presence impacted on IAQ negatively.

When all the physical and chemical exposures were introduced in the longitudinal Model V simultaneously, only CO_2 (OR: 3.42, 95%CI: 1.78-6.58, per 1000 ppm increase), and temperature (OR: 1.36, 95%CI: 1.34 -1.37) remained significant predictors of perceived IAQ. The model controlled for the effect of the school, personal factors, and other indoor exposures (RH, TVOCs, NO_2, O_3 and T4CE). Based on this ordered logistic multinomial model, the predicted percentage of responses of perceived IAQ was estimated in relation to indoor temperature in the range from 19 to 26 °C and indoor CO_2 levels in the range between 500 to 2000 ppm, so the model does not extrapolate beyond the range of the predictor variables.

According to EN 15251: 2007 (Section 2.3.2) predicted percentage of dissatisfaction among occupants may be estimated based on provided ventilation rates and corresponding CO_2 levels. However, indoor temperatures are crucially important for the estimation of PPD (Figure 7.4). The percentage of students assumed to be dissatisfied with IAQ was set to votes of 3 or lower in the 7-point scale. It was found that lowest dissatisfaction reported was 4.9% (95%CI: 1.3-18.3%) when indoor CO_2 levels (500 ppm) and indoor temperatures were lowest (19 °C) in the range

Table 7.6: School exposure significantly related to perceived IAQ using Model III and Model IV controlling for the effect of the school and personal factors (age, gender, exposure to ETS at home and overall satisfaction with the school)

Factor	Longitudinal study (Model III)	Heating season (Model IV)	Non-heating season (Model IV)
	Odds ratio (95%CI)	Odds ratio (95%CI)	Odds ratio (95%CI)
T_{mean}	1.26 (1.15- 1.38)	1.22 (1.05- 1.40)	1.25 (1.12- 1.41)
RH_{max}	1.02 (1.00-1.04)	\	1.02 (1.00-1.05)
CO^{a}_{2mean}	\	1.63 (1.12-2.37)	2.9 (1.57-5.34)
ACH_{norm}	0.85 (0.73-0.99)	\	0.66 (0.51-0.84)
NO_2	1.05 (1.03-1.07)	1.02 (1.00-1.04)	1.08 (1.04-1.12)
O_3	1.04 (1.02-1.05)	1.02 (1.00-1.04)	1.04 (1.02-1.06)
PM_1	1.02 (1.00-1.03)	\	1.02 (1.00-1.04)
PM_{10}	1.01 (1.00-1.02)	\	1.02 (1.00-1.04)
Volatile Organic Compounds			
TVOCs[b]	1.22 (1.00-1.49)	1.35 (1.11-1.64)	1.16 (1.01-1.32)
T4CE	1.12 (1.05-1.19)	\	1.30 (1.05-1.62)
benzene	1.74 (1.07-2.83)	\	1.72 (1.06-2.77)
formaldehyde	1.05 (1.03-1.07)	1.04 (1.02-1.06)	1.05 (1.03-1.07)
pinene	1.02 (1.00-1.03)	\	1.17 (1.08-1.27)
limonene	1.01 (1.00-1.02)	\	1.03 (1.01- 1.05)
Microbial Parameters			
PenAsp[b]	1.04 (1.03-1.06)	1.03 (1.01-1.05)	\
Trichoderma viride[d]	1.07 (1.02-1.13)	1.06 (1.01-1.12)	1.02 (1.00-1.04)
Streptomyces spp.[c]	\	1.18 (1.01-1.38)	\
Mycobacterium spp.[c]	1.05 (1.00-1.11)	\	1.03 (1.00-1.06)
Alternaria alternata	1.12 (1.01-1.25)	\	\
Aspergillus versicolor[d]	1.09 (1.05-1.13)	1.06 (1.02-1.10)	\
Endotoxin	ND	1.80 (1.02-3.18)	ND

ND: data are not available,
95%CI= 95% confidence intervals, \ denotes insignificance, a: odds ratio expressed as change of coefficient per 10^3 ppm, b: odds ratio expressed as change of coefficient per $10^2 \mu g/m^3$ c: odds ratio expressed as change of coefficient per 10^4 cells/mg, d: odds ratio expressed as change of coefficient per 10^2 cells/mg.

(Figure 7.4). Dissatisfaction with perceived IAQ increased at higher temperatures and indoor CO_2 levels. Highest levels of 56.8 % were, therefore, recorded at 2000 ppm and 26 °C (Figure 7.4). When indoor CO_2 levels reach 1500 ppm, indoor temperatures shall be kept below 24 °C (PPD= 29.6%) to maintain a category 3 building. It was predicted that at indoor CO_2 levels of 1000 ppm, indoor temperatures shall be kept below 24 °C to meet comfort criteria for category 2 building (PPD =18.6%), or below 22 °C to meet category 1 building (PPD = 13.8%).

When all microbial parameters were entered simultaneously in a longitudinal Model V, only *Trichoderma viride* remained significant (OR: 1.02, 95%CI: 1.00-1.05). The model controlled for exposure to all microbial groups and species, personal factors and the effect of the school. Predicted percentage of dissatisfaction was estimated to be above 30% even at very low indoor *Trichoderma viride* counts of 10 cells/mg.

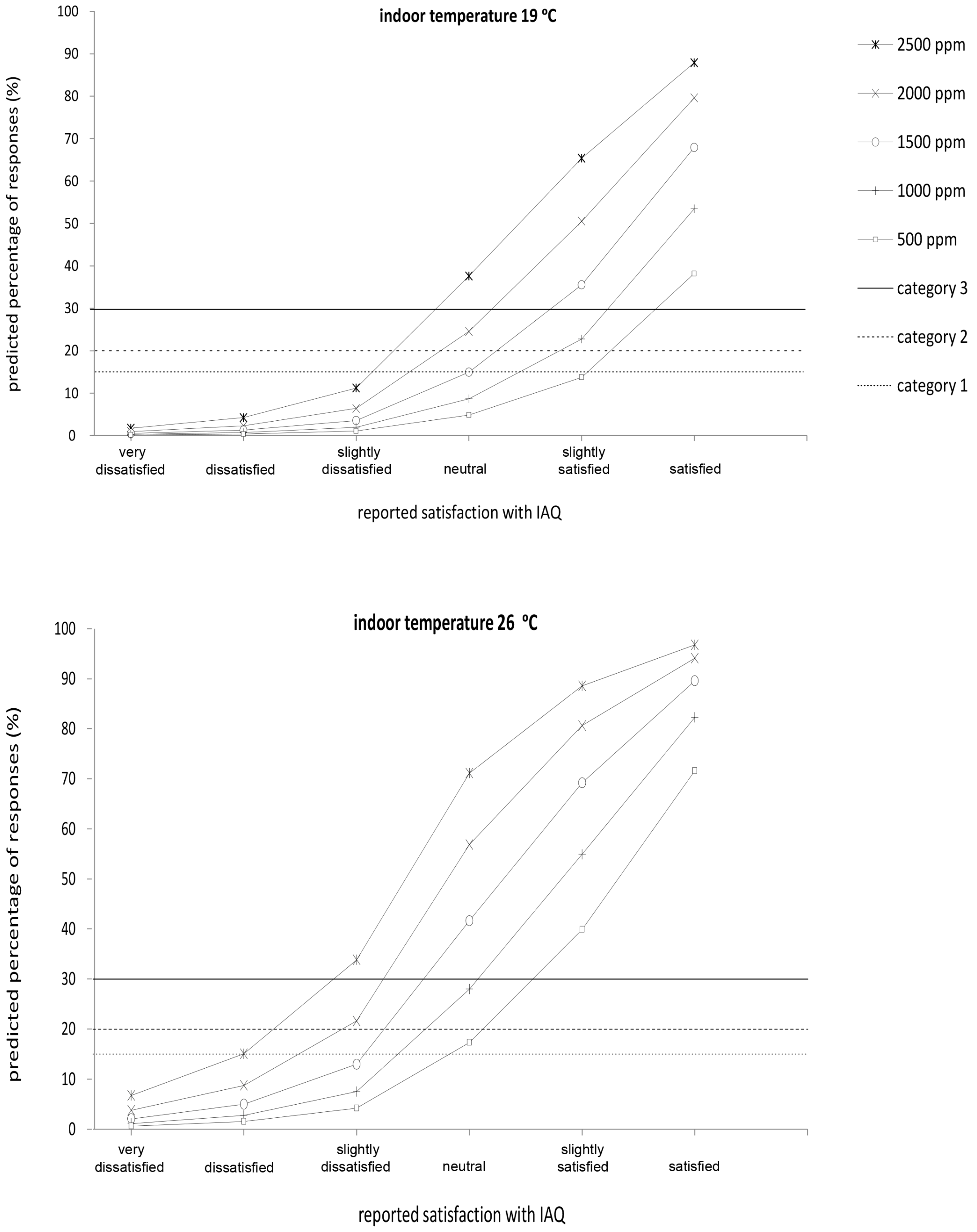


Figure 7.4: Percentage of students predicted to be satisfied with IAQ in relation to indoor CO_2 levels at 19 °C and at 26 °C indoor temperatures after controlling for the effect of the school, personal factors and exposure to specific indoor chemicals. Categories of buildings in terms of comfort provided according to the BS EN 15251: 2007 (Section 2.3.2) are specified

7.6 Summary

This chapter investigated factors affecting health symptoms of students and perceived air quality in London school classrooms. The study is one of the few (Zhang et al., 2011, 2012) organised as a longitudinal study on SBS symptoms in the school environment, taking into account a large number of measured pollutants simultaneously.

The prevalence of asthma attacks and asthmatic symptoms (wheezing or whistling) ever experienced in the school environment was markedly higher for students at urban schools (10.2%) compared with those attending suburban schools (1.5%). The association between prevalence of asthma with indoor exposure was performed with multilevel logistic regression at classroom and student level, controlling for personal factors (age, gender, exposure to ETS at home) and the effect of the school. The only significant pollutant related to asthma attacks and asthmatic symptoms in the school environment was indoor NO_2 levels. Although the association might not be causal as other socio-economic factors may affect health outcomes, it is consistent with recent systematic meta-analytic study (Gasana et al., 2012) that reported 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).

In both baseline and follow-up study, dermal, mucosal and general symptoms increased at lower infiltration rates. Higher prevalence and incidence of SBS symptoms, particularly ocular, was associated with higher levels of traffic-related pollutants, more specifically PM_{10}, NO_2, benzene, naphthalene, O_3 and T4CE. In a comprehensive review of the relationship between ocular symptoms and indoor exposure in office-like environments, Wolkoff (2008) concluded that few pollutants reach high enough concentrations to create irritations, and include specific VOCs (such as benzene and T4CE), and particle settlement on surfaces. The results presented here are also consistent with toxicological evidence. It is well known that benzene and naphthalene are human carcinogens, and classified as moderate eye irritants (WHO, 2010). Similarly, NO_2 is an irritant to all mucosal membranes, including the eyes, as the gas reacts with water to form nitric acid. Although the chemical composition of PM was not known, previous studies associated mucosal symptoms with indoor PM exposure (Morawska & Salthammer, 2003).

Traffic-related pollutants associated with higher prevalence and incidence of SBS symptoms were also associated with increased dissatisfaction with IAQ. It is likely that the irritation caused in the mucosal membranes affected perceived IAQ indicating that dissatisfaction with IAQ is a first indication of exposure.

TVOCs levels in most classrooms were above thresholds associated with irritation (Table 5.9). Therefore, it is not surprising that the association remained significant in both seasons and the longitudinal model. Moreover, pollutants with indoor pollution sources, such as terpenes (pinene and limonene) increased dissatisfaction with IAQ in the non-heating season. Formaldehyde is a well-known irritant of the mucosal membrane, and increased dissatisfaction with IAQ was consistent in both seasons.

In order to investigate which exposures are the most significant in affecting IAQ satisfaction, a model controlling for all significant exposures and personal factors was created. Indoor temperatures (OR: 1.36, 95%CI: 1.34 - 1.37) and CO_2 levels (OR: 3.42, 95%CI: 1.78 - 6.58, per 1000 ppm increase) remained significant in the longitudinal model, when controlling for all chemical and physical parameters. The predictive model estimated that classrooms in this study could achieve percentages of dissatisfaction with IAQ lower than 15% (category 1) by keeping indoor CO_2 levels below 1000 ppm and indoor temperatures below 22 °C, stressing the importance of an integrated approach to provide adequate thermal comfort and IAQ simultaneously.

In this study, species associated with increased IAQ dissatisfaction included fungal and bacterial species that need high equilibrium RH (>90%) for growth, and their presence indoors indicates moisture damage. Presence of *Trichoderma viride* even at very low concentrations in both seasons increased dissatisfaction with IAQ consistently, and remained significant (OR: 1.02, 95% CI: 1.00-1.05) when controlling for all microbial exposures in the model.

Personal factors affecting perceived IAQ of students were similar to those reported in adult studies (Frontczak & Wargocki, 2011): stress levels, overall satisfaction with the school environment and age, which has also been reported in pervious school studies (Smedje, Norbäck, & Ling, 1997). Students exposed to ETS at home perceived school IAQ as better, possibly because of their lower relative expectations of indoor air. In adult investigations, gender was a significant predictor of perceived IAQ, with females generally reporting higher percentage of dissatisfaction; however, in this study on prepubescent population the difference between males' and females' IAQ perception was not significant.

Building characteristics that affected perceived IAQ included factors that may affect indoor pollution levels. Findings indicated that air quality was more likely to be perceived better in schools away from direct traffic and worse in schools in proximity to high traffic intensity, which may elevate levels of traffic-related indoor pollutants through infiltration. Similarly, timing of cleaning, occupants' density, visible mould and curtain area may increase indoor airborne particles through re-suspension, microbial concentrations and indoor TVOCs which may impact negatively on perceived IAQ. Higher openable area may increase the potential for natural ventilation that may purge indoor concentrations, and was inversely associated with IAQ dissatisfaction.

Chapter 8

Discussion: Guidance for healthy and satisfactory school buildings

8.1 Interpretation of key findings

The work described in this thesis identified a range of issues for the management and operation of school classrooms in adhering to IAQ regulations in the UK, as well as the need to go beyond current regulations to examine the concentrations of specific pollutants to ensure a healthy environment. This study drew on detailed monitoring data from a sample of 18 classrooms from six London schools, and employed a multidisciplinary methodology that is applicable in large scale surveys. The study was organised as a case crossover of the heating and non-heating season. Multilevel modelling was employed to systematically synthesise the data, and highlighted the degraded IAQ in school classrooms especially in the heating season, the impact of potential outdoor sources of pollutants, and large variations in the concentration of indoor pollutants reflective of issues with building operation and management.

The *first research question* of this thesis was to investigate whether CO_2 levels and estimated ventilation rates can ensure low indoor concentrations of specific pollutants. A key finding was that CO_2 levels were a reliable predictor for some outcomes, which are affected by occupants' activities and ventilation rates, such as indoor temperatures, Particulate Matter and VOCs levels. Overall evidence from this study suggests that limiting CO_2 levels below 1000 ppm (which is lower than current recommendations) is necessary in order to achieve indoor pollution levels in classrooms below limits associated with health outcomes. Findings suggest that increasing ventilation rates may improve IAQ through:

1. Mitigating overheating.

   The study was performed during a typical meteorological year. The monitoring weeks during the non-heating season were performed during the hottest period of the operational school year. It was first shown that together with the application of passive measures (such as external shading, night cooling and exposed high thermal mass) controlling daily average CO_2 levels was effective in mitigating overheating, as higher ventilation rates may remove excessive heat gains. Overall, the predictive model shows that higher CO_2 levels (e.g. above 1500 ppm) indicate a tendency for overheating (e.g. above 25 °C) especially in the non-heating season when outdoor temperatures exceed 20 °C. However, as outdoor temperatures may drift above 20 °C schools may be thermally challenged and fail to meet comfort criteria during these periods.

2. Purging indoor PM concentrations.

   Indoor PM concentrations monitored in representative weeks of the academic year suggested that annual personal exposure to PM_{10} and $PM_{2.5}$ in the classrooms were higher than the annual recommended WHO 2010 guideline values. Because monitoring was performed over representative weeks of the heating and non-heating season, findings suggest that concentrations may exceed annual recommendations. Indoor CO_2 levels were a significant predictor of indoor elevated airborne concentrations, after controlling for the effect of occupancy. Therefore, the relationship between CO_2 levels extends beyond re-suspension of previously deposited matter indicating indoor airborne PM build-up at low ventilation rates. In classrooms without indoor dust reservoirs, such as wall-to wall carpets, the predictive models suggested that in order to limit exposure to PM_{10} in classroom below annual recommended concentrations, indoor CO_2 levels shall be kept below 1000 ppm. Increasing ventilation rates above current recommendations can therefore, lower classroom exposure to PM below annual WHO guidelines.

3. Diluting indoor TVOCs levels.

   Apart from reducing indoor PM levels, higher ventilation rates can dilute indoor TVOCs levels, and dilute specific VOCs, especially with continuous indoor sources, such as formaldehyde. Although indoor temperatures were within the specifications of relevant regulations for most of the occupied period, a positive association between indoor temperatures and TVOCs levels emerged after controlling for the effect of potential indoor sources and ventilation rates. After removing indoor sources (such as fleecy factor and low-emitting cleaning materials) keeping the indoor temperature in the classroom below 26 °C (or preferably below 22 °C depending on season) and indoor CO_2 levels below1000 ppm, may limit indoor TVOC levels to below thresholds of 254 ppb (95% CI: 209-301 ppb) and 111 ppb (95%CI: 71-157 ppb). Although there are no guidelines values for TVOCs levels monitored with PID methods, these levels correspond to approximately the thresholds associated with sensory irritations. However, as the thresholds have been set based on GC-MS levels, this comparison should be interpreted with caution.

4. Purging indoor microbiological counts

   Higher air changes during normal teaching activities reduced indoor levels of cat allergens and *Cladosporium herbarum. Cladosporium* species in temperate climates are the most common encountered indoors (accounting for 50% of the total).

It must be kept in mind that while higher ventilation rates during the occupied period improved the indoor environment, IAQ was found to deteriorate at higher uncontrolled infiltration rates on indoor pollutants' concentrations. It was shown that infiltration rates were associated with increased indoor NO_2 levels, and microbial counts of fungal species and bacterial genera, whose presence indicates wet or moistened surfaces. The association between increased microbial counts with uncontrolled airflow rates might be explained by warm and moist air condensing on walls when infiltrating or exfiltrating.

The *second research question* of this thesis was to investigate the association between classroom exposure with health outcomes, SBS symptoms and perceived IAQ.

Findings indicate the need for an integrated approach providing simultaneously adequate IAQ and thermal comfort. The air was perceived as less acceptable with increasing temperature, but the impact of temperature was less significant at higher indoor CO_2 levels. Keeping indoor temperatures within 22 to 26 °C and CO_2 levels below 1000 ppm may improve perceived IAQ. More specifically, the predictive model estimated that keeping indoor CO_2 levels below 1000 ppm, and indoor temperatures below 22 °C may reduce the predicted percentage of dissatisfied occupants below 15% (category 1 building). At the same indoor CO_2 levels, higher temperatures of 26 °C predicted percentage of dissatisfaction will rise at 25% (category 3 building). This effect of improved perception at lower indoor temperatures is probably due to stimulation of thermal sense as a result of convective and evaporative cooling of the respiratory tract when the temperature is lower than the mucosal temperature which is approximately 30 to 32 °C. Indoor CO_2 levels remained also a significant predictor of perceived IAQ, possibly because levels correlate with pollution emitted from the person (odour and other bioeffluents), but also because CO_2 levels explained most of the variation caused by other parameters, such as RH.

As the above findings on perceived IAQ in relation to temperature and odour confirm and extend previous research performed on adults (Fang, Clausen & Fanger, 1998) in a controlled laboratory environment, it is strongly suggested that the methodology employed in this study allows collecting reliable self-reported perceptions and health symptoms from students 9 to 11 years old. This study is the first to establish this association while simultaneously controlling for specific indoor chemical exposures. Moreover, for the first time, this study employs advanced statistical analytical techniques controlling for contextual effects (such as effect that depend on school, classroom and season) that might affect the predictions (Section 4.5.3. The range of mean indoor temperatures ranged from 19.0 to 26.5 °C, and mean indoor CO_2 levels ranged from 613 to 2074 ppm, so predictions of the multilevel ordered multinomial regression models were within this range. Like traditional regression, extrapolating results beyond the range of predictor variables can lead to seriously biased estimates.

Apart from the corresponding energy savings of keeping the temperature low, the literature review supported that lower indoor temperatures in classrooms may also improve cognitive performance and thermal comfort. Emerging evidence (Wargocki & Wyon, 2013) suggests that lower temperatures in the range between 20 and 25 °C may improve academic performance of children. Previous research in educational settings suggested that children aged 9 to 11 prefer lower temperatures (Teli et al., 2012) by 4 °C than that predicted from the standard PMV model, and by 2 °C than the adaptive comfort model. Possible explanations for this may be the higher metabolic rate per kg body weight, the limited available adaptive opportunities in classrooms, the fact that children do not always adapt their clothing to their thermal sensation, and also because children are generally more physically active than adults in offices.

Confirming ISAAC findings (Section 1.1), the results show that the prevalence of asthma among children in primary schools in England is 7.18%, which is the highest among participating European studies when compared to the SINPHONIE results (Csobod et al., 2014). The percentages obtained on asthma and asthmatic symptoms prevalence in the school environment are robust, as students' responses were cross-validated with the classroom teachers, who were aware of asthmatic children as part of the school protocol. Asthma prevalence in suburban schools was 1.54%, almost seven times lower than in urban schools at 10.16%, which ranged from 7.89% to 12.50%, and increased with proximity to high intensity traffic. Health surveys at national level (US) found that children living in an urban setting were at increased risk for asthma after controlling or ethnicity and economic status (Andrew Aligne et al., 2000).

The multilevel analysis revealed that among all investigated pollutants, only exposure to indoor NO_2 concentrations was significantly related to asthma attacks and asthmatic symptoms in the school environment after controlling for personal factors and school classroom characteristics. The quantification of the relationship was OR: 1.11 (95% CI: 1.04-1.19), which lies within the range reported in a previous meta-analytic study (Gasana et al., 2012). Although results are in line with previous research, 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 of other traffic-related pollutants which may have significant health implications. Additionally, it is possible that students attending urban schools may also 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).

It is difficult to separate the contribution of school-based from non school-based exposure to health outcomes. To overcome this challenge, the questionnaire separated SBS symptoms experienced in the school, home, and other environments. In the analysis, only symptoms experienced in the school were considered, and, for that reason, more likely to be related to school exposure than exposure in other environments. The reported symptoms included predominantly mucosal symptoms, which are considered generally of transient nature, i.e decline or disappear completely when leaving the building (Wolkoff, 2008). The symptoms, however, impact on the quality of life.

Prevalence and incidence of SBS symptoms, particularly ocular, were associated with higher levels of traffic-related pollutants, such as NO_2, O_3, benzene, naphthalene, T4CE and PM_{10}, at baseline and follow-up period, which confirmed previous research in office-like environments (Wolkoff, 2008). These field data support the proposed causality in toxicological studies. The variability of indoor PM between classrooms was small (10%) indicating the transboundary nature of Particulate Matter. The small variability may explain the lack of association between indoor PM exposure and prevalence of asthmatic symptoms and wheezing among children, which was detected in previous studies (Gasana et al., 2012). However, even when the difference in indoor PM exposure was small, higher airborne PM levels were found to increase the hazard ratio for new mucosal and general symptoms, and increased dissatisfaction with IAQ.

An affirmative finding of this work, was that the pollutants causing SBS symptoms (NO_2, O_3, benzene, T4CE and PM_{10}) also increased percentages of dissatisfaction indicating that perceived IAQ is a first indicator of exposure. The term perceived IAQ often refers to the olfactory sense (odour intensity), which in this study also remained the most significant predictor together with the stimulation of the thermal sense of the respiratory tract. Present knowledge indicates that airborne chemicals are sensed by three sensory systems: odour; taste; and the trigeminal chemosensory system. Molhave (1991) also supported the involvement of all three sensory systems on the overall IAQ perception in relation to low level VOC exposure. The trigeminal chemosensory system provides information about irritating or harmful molecules that come into contact with skin or mucous membranes of the eyes, nose and mouth. These nerves can respond to many different types of stimuli, and the receptors react to environmental chemicals following a chemical reaction or a physical adsorption of the compounds to the receptors proteins. Therefore, this study suggests that stimulation of at least one of the sensory systems seems to result in a combined perception of what may be called perceived IAQ.

VOCs with indoor sources, such as formaldehyde, pinene and limonene were associated with increased IAQ dissatisfaction, especially in the non-heating season. Previous research in office buildings (Apte & Erdmann, 2002) has also established the important role that VOCs may play in both directly causing mucosal symptoms, and being indirectly involved in indoor chemical reactions with O_3 producing irritating Secondary Organic Aerosols (SOAs) that can cause SBS symptoms. Exposure to O_3 in the baseline conditions was not associated with any health symptoms, possibly because monitored concentrations were very low in the heating season. However, as outdoor concentrations increased in the follow-up period, a small increase in indoor concentrations was noticed, which increased the hazard ratio for the development of new SBS mucosal symptoms. The extent of the synergy between O_3 and VOCs (pinene and limonene in particular) in the development of SBS symptoms could not be established, as it involves complex interactions of the highly photo-reactive gas influenced by meteorological phenomena, deposition on indoor surfaces or decomposition in the indoor air.

In both seasons, dermal, mucosal and general symptoms increased at lower infiltration rates, but were not associated with ventilation rates during teaching activities. While the mitigation of SBS symptoms with increased ventilation rates has been proposed in meta-analytic systematic reviews in schools and other non-industrial environments (Wargocki et al., 2002), a possible explanation might be that indoor pollution sources present in all classrooms limit the effectiveness of higher ventilation rates (Bakó-Biró, 2004). The association suggested in the literature was for ventilation rates up to 25 L/s-p. In this study, indoor ventilation rates during teaching activities were in the range from 2.3 to 6.3 L/s-p in both seasons. It is possible, that the effects could not be detected because of the small variability between classrooms.

Only a weak association between increased microbial counts with prevalence of SBS symptoms could be assumed, although previous work found a strong relation between health outcomes and exposure to microbial concentrations. More often, these studies employ total mould or total bacterial investigation based on culturable methods without considering microbial species or groups. This work employed molecular method for detailed microbial determination, which can detect much lower concentrations compared with culturable methods by 1000 times. Therefore, even at very low concentrations, *Trichoderma viride* counts were identified as the most significant predictor of dissatisfaction with IAQ. Among the investigated microbial genera, *Trichoderma* (Polizzi et al., 2011) is known to produce allergens, strong sensitisers and eukaryotic membrane-damaging substances that can cause allergic fungal sinusitis and provoke immediate hypersensitivity. Moreover, *Trichoderma* may induce histamine release from human broncho-alveolar cells (Polizzi et al., 2011). It is also possible that the presence of *Trichoderma viride* might be a reliable proxy for increased dissatisfaction with IAQ, as it might be an indicator of other microbial groups that are present in classrooms under similar hygrothermal conditions.

Mycobacterium spp. associated with SBS symptoms in this study has not been reported in previous investigations. It is not surprising, as the use of cultivation-independent methods employed here allowed identifying groups, which are difficult to identify with culturable methods from samples rich with other microbes due to their slow growth rate hampering previous investigations on their role in indoor human exposure. Another reason for the lack of strong association between indoor microbial school exposure and SBS symptoms might be the generally low counts of microbial counts in the sample with the exception of the newly built school in the heating season, where indoor levels were ten-fold higher compared with the rest of the sample. The investigation in this school took place in the first week of November, while the heating season in London starts generally in late September/ October. It is, therefore, possible that the occupants were not exposed for a significantly large period to high indoor microbial concentrations to trigger SBS symptoms.

8.2 Significance and implications of findings for IAQ regulation in UK schools

While it is increasingly recognised that a systematic approach is needed to strengthen the evidence base for appropriate IAQ and ventilation guidelines for schools, to date there has been scarce empirical data from comprehensive monitoring of IAQ. The lack of empirical data for indoor levels of pollution in classrooms has important implications for the formulation of regulatory framework for the provision of adequate air quality in school environments.

This study shows that SBS symptoms and dissatisfaction with IAQ were related to deficiencies in the indoor school environment. The findings highlight the role and responsibility of stakeholders, from regulators to designers and school authorities, to account for the external environment and take the steps needed to ensure that schools provide a healthy indoor environment for their students. 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.

Recommendation 1: Selection of sites for new school buildings and

This study found an association between school exposure to traffic related pollutants and increased prevalence of health outcomes. Prevalence and incidence of ocular symptoms increased at higher indoor exposure of traffic related pollutants. Classroom exposure to NO_2 was associated with increased prevalence of asthma, asthmatic and SBS symptoms, and increased the hazard ratio for SBS symptoms in the follow-up period.

Indoor levels of NO_2, benzene, naphthalene and T3CE were strongly affected by outdoor levels. NO_2 in particular exhibited a high spatial variability of 84%. The highest indoor NO_2 levels were sampled in an urban school in immediate proximity to a high traffic intensity street. It was shown, both from the school sample and the literature, that urban schools should be located at least 150 to 400 m away from main traffic arteries. Designers, engineers, policymakers and stakeholders need to consider the high spatial variability of outdoor pollution levels in urban locations before selecting sites for new school buildings. Such consideration prior to construction may involve extensive monitoring efforts of external air quality in proximity to a proposed school site, or collaboration with the local council to introduce greening or pedestrianisation schemes in the school vicinity.

More broadly, policy should be directed towards city-wide level planning, such as urban greening programmes around school buildings, which are likely to decrease outdoor pollution levels, thus improving health of the students and reducing the prevalence of respiratory illness.

Recommendation 2: Passive design

Simple operation and design improvements are likely to help school classrooms meet guidelines and improve IAQ. Passive measures, such as shading of South, South-East and East facing classrooms, application of night cooling, exposed thermal mass and reducing occupancy density may prevent overheating, as higher ventilation rates may remove excessive heat gains.

Successful application of natural ventilation strategies may mitigate overheating. Cross-ventilation of classrooms had on average 2 °C lower temperatures compared with mixed mode and single-sided ventilation strategies. In this sense, integration of ventilation strategy should be applied as early as possible in the design stage.

Orientation of building facade to prevailing wind direction may enhance the potential for wind-driven natural ventilation. Additionally to enhancing wind-driven natural ventilation, orientation may affect indoor concentration of PM. Higher ventilation rates may purge indoor concentrations, while wind-driven infiltration may affect penetration ability of the pollutant. Placement of classrooms or spaces where students spend most of their time while at school in the leeward side of the buildings may decrease personal exposure to PM, and may decrease prevalence and incidence of mucosal and general symptoms. Detailed investigation of air pollution dispersion inside a school building may be necessary at design stage.

Recommendation 3: An integrated approach to catering for thermal comfort and IAQ

The strong relationship between indoor temperatures and CO_2 levels stresses the importance of an integrated approach for the simultaneous provision of thermal comfort and IAQ in classrooms. After controlling for the effect of occupancy, indoor CO_2 levels remained a significant predictor of indoor temperatures, indicating that the relation between these two parameters extends beyond the effect of occupancy.

Indoor temperature and CO_2 levels remained the only significant predictors when all physical and chemical exposures were simultaneously entered into the model, which further strengthened the importance of simultaneously catering for these parameters. Current standards set comfort criteria based on the predicted percentage of dissatisfaction among occupants. The standards estimate percentage of dissatisfaction with thermal comfort based on indoor temperatures and other hydrothermal and personal factors, and predict dissatisfaction with IAQ based on ventilation rates and indoor CO_2 levels alone. However, this work shows that indoor temperatures together with indoor CO_2 levels simultaneously affect perceived IAQ. Lowest dissatisfaction with IAQ was reported in classrooms with the lowest mean indoor temperatures and CO_2 levels within the monitored range. Keeping low indoor CO_2 levels alone without controlling for indoor temperature, is not enough to ensure a low percentage of dissatisfaction with IAQ, and vice versa.

Recommendation 4: Ventilation effectiveness

The term ventilation effectiveness represents an attempt to quantify the rate at which pollutants are removed from the occupied zone. In this work high ventilation rates were more effective in reducing indoor pollution levels. While most classrooms managed to comply with current guidelines regulating IAQ achieving average and maximum indoor CO_2 levels below 1500ppm and 2000 ppm respectively, only a few classrooms provided maximum ventilation rates of 8 L/s-p during the occupied period. In the study sample, all classrooms could provide higher ventilation rates than those provided under normal teaching periods. Main hindering factors for successful application of natural ventilation strategies included management and operation of school buildings, as well as limited openable areas from poorly maintained windows, and adaptive actions of the occupants to prevent thermal discomfort. It is, therefore, necessary to ensure that ventilation efficiency of classrooms is improved by achieving high ventilation rates under the easy control of the occupants, which can be facilitated by improved maintenance and design of windows. For example, inwards bottom-hung windows at high level eliminated the risk of draughts, especially in the heating season allowing cross-ventilation of the classrooms, and additionally provided opportunities for night cooling overcoming safety concerns.

Mechanical systems appeared to present different challenges to occupants, who were unaware of manual override settings. Because of the transient occupancy in school buildings, briefing of the occupants by facility management on the appropriate use of passive and active systems is essential for the successful application of any ventilation strategy and heating system.

Recommendation 5: Timely control of ventilation and heating systems

Altering ventilation strategies across seasons may improve IAQ and also optimise the energy performance of classrooms. Outdoor NO_2 levels were significantly higher in the heating season, and higher infiltration rates may have contributed to elevated indoor levels. Moreover, as condensation is more likely to occur in the heating season minimising infiltration rates may reduce microbial growth in building materials. Purge ventilation in the heating season before children enter the classroom and during breaks may provide a way to dilute indoor VOCs concentrations (formaldehyde, benzene, T4CE) which build-up at lower air changes and cause SBS symptoms and increase IAQ dissatisfaction, without cooling the building fabric leading to increased energy consumption for heating. Additionally, high ventilation rates in the heating season are easier to achieve because of higher wind-speeds, which are the main driving forces for natural ventilation. Pre-heating of the classrooms when outdoor temperatures fall below 6 °C may improve the thermal comfort of the occupants.

On the other hand, night cooling in the non-heating season may increase the thermal capacity of the building envelope preventing overheating. Higher background ventilation (such as airflow through trickle vents) in the non-heating season may decrease percentage of dissatisfaction among occupants, reduce indoor terpenes and their interaction with O_3 which is higher in the non-heating season.

The inclusion of sensors in classrooms may also help raise awareness among students and staff about local environmental conditions. CO_2 sensors installed in the classrooms would potentially motivate occupants to increase ventilation rates. For instance, there is a negative detection bias towards occupants only becoming aware of indoor environmental quality when they perceive discomfort or health symptoms.

Recommendation 6: Selection of interior finishing and construction materials

Findings suggest the use of wall-to-wall carpeting and fleecy materials in schools should be reconsidered and replacement with hard flooring, which is easier to clean and is not prone to becoming a source of allergens and microbes. Unsuitable finishing in the classroom elevated indoor PM levels of inorganic and specific biological concentrations (such as dog allergens) predominantly through re-suspension of previously deposited particles compared with classrooms with hard floor where particles could be removed more efficiently through cleaning.

Additionally, occupants' behavioural patterns of frequently moving between outdoors and indoors without removing their shoes resulted in higher amounts of tracked-in soil, and, consequently, in higher microbial counts in ground floor carpeted classrooms. Reducing indoor exposure to microbiological counts could be achieved by removing clothes and shoes that may introduce allergens and bacteria. Carpeting in combination with underfloor heating was suspected to facilitate indoor microbial growth.

The presence of carpeting further deteriorated IAQ, as it was associated with higher indoor TVOCs compared with classrooms with hard floor. The observed difference might be related to off-gassing of carpets and fleecy materials or products used to maintain these materials.

Recommendation 7: Elimination of indoor pollution sources

The findings suggest that inadequate ventilation rates combined with sub-optimal management practices, such as storage and use of cleaning products, can lead to concentrations of pollutants that are orders of magnitude above safe levels of exposure, and above outdoor levels. A striking feature of this work was the much higher levels of measured VOCs compared with levels reported in the literature, and TVOCs levels higher than thresholds associated with sensory irritations. Thus, together with higher ventilation rates, control of indoor sources is necessary to reduce indoor VOC levels.

Nursery school classrooms might require higher ventilation rates, as stronger indoor sources exposed younger, more vulnerable children to higher TVOC levels and microbial counts.

Recommendation 8: Targeted long-term investigations in school buildings

Indoor CO_2 levels provided a first indication of exposure, health outcomes of the occupants and perceived IAQ. However, other pollutants harmful to health, such as radon, may not be sensed by humans. For example, large radon variability between neighbouring school buildings was detected, and it may be necessary that large scale campaigns in UK school buildings are conducted in new school building locations and existing building stock. Similarly, targeted microbial investigations and outdoor pollution concentrations (possibly using NO_2 as a proxy) might be necessary to ensure healthy and satisfactory buildings.

In the near future, IAQ investigations in school buildings should be part of the standard requirements of Building Regulations. Currently, indoor environmental investigations are conducted by universities and educational institutions, while industry focuses mostly on energy performance of buildings and has limited knowledge on IAQ and the relation with health responses of the occupants. It is recommended that long-term investigations of pollutants known to affect health are routinely performed in schools, and when necessary remedial measures introduced. Finally, it is important through national campaigns to provide simple advice and raise awareness among school personnel involved with daily maintenance of current building stock to maintain and use buildings better.

Chapter 9

Conclusion

9.1 Key findings

This thesis adopted a multidisciplinary approach to evaluate whether low CO_2 levels and corresponding high ventilation rates can ensure low indoor concentrations of specific pollutants. The study investigated the potential impact of environmental and behavioural factors on indoor pollution levels, and the association with health effects of the occupants employing multilevel modelling. The following conclusions were drawn from the study:

- It was first found that indoor CO_2 levels and corresponding ventilation rates are useful for indoor IAQ investigations, as they provide a first indication of exposure. Keeping average CO_2 levels within current guideline limits may prevent overheating; however, limiting indoor CO_2 levels below 1000 ppm is necessary to achieve annual PM concentrations below annual WHO 2010 guideline values.

- A simultaneous provision for adequate thermal conditions and IAQ is necessary to achieve a satisfactory indoor school environment. It was predicted that lowest predicted percentage of dissatisfaction among students can be achieved when CO_2 levels are below 1000 ppm, and indoor temperatures lie in the range from 22 to 26 °C. Indoor temperatures were a strong predictor of indoor TVOCs concentrations; therefore, indoor temperatures within this range may additionally limit indoor TVOCs below thresholds associated with sensory irritations.

- Proper maintenance and management of the building is decisive for the indoor environment. Thus, together with higher ventilation rates, control of indoor sources is necessary to reduce indoor VOC levels. It is important that construction materials and cleaning products introduced in the classrooms do not significantly impact classroom IAQ. Achieving maximum ventilation capacity of classrooms, together with timely control of ventilation may reduce health outcomes, increase satisfaction of the occupants and improve the energy performance of buildings.

- Findings highlight the inadequacy of the current regulatory framework heavily relying on CO_2 levels (DfE, 2014) to provide healthy and satisfactory school environments, as this study underscores the degraded level of IAQ in a school sample. This was indicated, for example, by the high indoor NO_2 levels recorded in urban classrooms, which were associated with asthma and asthmatic symptoms, increased SBS symptoms and dissatisfaction with IAQ.

9.2 Limitations of this research and recommendations for future work

A larger sample with schools being representative of a well-defined population is necessary for the generalisability of findings. Although sample size is an important consideration, main findings of this work including indoor pollution levels and the association with prevalence of health symptoms were within the range reported in the literature indicating that the school sample was not significantly different from the population. This study employed statistically efficient methods including: a Bayesian shrinkage estimator, multilevel modelling and a case-crossover design. Additionally, compared with previous epidemiological studies, this study offered a more spatially and temporally refined estimation of indoor pollution levels in schools, and a better insight of the factors affecting IAQ.

Regarding methods used for the quantification of physical and chemical parameters, certain limitations were related to the availability of low sensitivity, cost-effective, robust, mobile and low-noise operation sensors:

- This work focused on CO_2 levels and estimated ventilation rates. The estimation of ventilation rates presented challenges, as it might have been influenced primarily by interzonal air flows from adjacent rooms, the approximation of CO_2 emission rates per person and the low sensitivity of the commercially available NDIR sensor.
- The most important school exposure that influences asthma prevalence identified in the research was NO_2. Continuous instrumental monitoring can, therefore, advance understanding of the effect of airtightness on penetration ability of this traffic-related pollutant, and contribute to more informed decisions of applied ventilation strategies and timing of window opening. Current progress in developing low-cost micro-scale sensing technology is radically changing the conventional approach to allow real-time information with a fine spatio-temporal resolution.
- PM concentrations were monitored with optical methods. Although optical methods may provide an indication of PM variation, concentrations might over - or underestimated as the estimation may be affected by RH and size and distribution of the specific aerosol. These limitations can be addressed by gravimetric methods, which may additionally offer

> further insights into the composition and sources of these particles are needed using chemical analysis of gravimetric filters to investigate their varying toxicity.

Significant challenges have hindered the development of generally applicable thresholds for microbial exposure, including complexity of assessment and lack of empirical data in school settings. Therefore, benchmarking of schools regarding microbial exposure can be a robust, alternative approach to thresholds. This research employed molecular methods for determination of biological contamination suitable for large-scale campaigns focusing on fungal and bacterial groups that indicate moisture damage. Such an approach yielded some interesting results associating uncontrolled infiltration rates with these microbial genera and species. While findings advanced the understanding of indoor school environments, the collection of dust from various classroom locations did not allow identification of specific sources of microbial infestation in classrooms. The method also could not accurately separate exposure between seasons, as old settled dust might reflect sample accumulation over longer time periods. Determination of allergen levels focused on cat and dog allergens, while previous campaigns have often detected rodent and cockroach allergens especially in inner-city schools in areas with lower socio-economic indicators. Future research should specifically investigate the combination of carpeting with heating on microbial levels in classrooms.

The case-crossover design of the study allowed for the control of personal characteristics, as each student was acting as their own control. However, the study did not manage to capture asthma exacerbations, possibly due to the relatively short timeframe between the baseline and follow-up period. Although collection of self-reported health symptoms among students is a validated approach often adopted in building epidemiological studies, future investigation should include detailed outcomes from medical tests, such as tear film stability, skin-prick, and exhaled nitrogen monoxide (NO).

The predictive model on perceived IAQ in association with indoor exposures was in line with models developed based on adults in controlled laboratory environments and office-like environments indicating that the methodology employed in this work was adequate to extract reliable information from primary school children (9-11 years old), and can be used in future investigations. However, one of the limitations of the method was that children with learning disabilities and non-English speakers were excluded from the study. Also, some children were absent in the non-heating, potentially due to illness. Therefore, it is likely that this study underestimated the prevalence and incidence of health symptoms by excluding the most vulnerable children. This study did not investigate perception of IAQ of very young children which is potentially of great interest.

The methodological framework used in this study could be potentially applied to large scale investigations enhancing our understanding of the factors affecting indoor pollution levels in educational settings. More research is necessary to confirm the associations between health symptoms and indoor exposure, as well as, the validation of a predictive model of satisfaction with IAQ including both temperature and indoor exposure. As this study used a sample of London primary schools, findings might not apply to different climatic or geographical zones, and therefore further research is necessary.

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