Institution: University College London		
Unit of Assessment: 13 – Architecture, Built Environment and Planning		
Title of case study: Using indoor air quality research to co-create healthy schools in collaboration with policy makers and industry		
Period when the underpinning research was undertaken: 2007-2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Dejan Mumovic	Professor of Building Performance Analysis	2003-present
Esfand Burman	Lecturer	2015-present
Anna Mavrogianni	Associate Professor	2010-present
Clive Shrubsole	Senior Research Associate	2012-2019
Hector Altamirano Medina	Associate Professor	2010-present
Michael Davies	Professor of Building Physics and Environment	2004-present
Samuel Stamp	Lecturer	2015-present
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

The UCL Institute for Environment Design and Engineering (IEDE) has led three major research projects on indoor air quality in schools. This research has: i) provided the evidence base for policymakers in the EU, UK and London to change school designs, thus cost effectively improving indoor air quality; and ii) set the criteria for best practice amongst building engineers and industry partners working on schools across the 27 EU member states and the UK. These impacts have, in turn, reduced the potential risk of respiratory and cardiovascular diseases like asthma among children and teachers due to poor indoor air quality.

2. Underpinning research (indicative maximum 500 words)

Second only to the home, schools are the most important indoor environment for children, and numerous studies have found that the indoor air in schools can often breach World Health Organization (WHO) requirements for quality. Moreover, studies indicate that poor air quality has a negative impact on children, especially their respiratory health, absenteeism and academic performance. For example, poor indoor air quality as indicated by high levels of $PM_{2.5}$ (particulate matter, i.e. particles that have a diameter less than 2.5 micrometres) correlates to the incidence of asthma and asthma symptoms, including cough, wheeze and rhinitis. It is estimated that when extrapolated to a national level, a 50% reduction in average $PM_{2.5}$ concentrations in schools, for the approximately 10,000,000 schoolchildren in the EU, could provide nearly 60,000 additional quality adjusted life years. Furthermore, space heating currently accounts for the largest non-staff cost in school budgets and thus school planners must be equipped with robust data to make decisions that both aid school budgets, and improve indoor air quality. The UCL Institute for Environmental Design and Engineering (IEDE) has worked on three research projects linked to these issues from 2007 to 2019:

'Ventilation in Schools'
Funded by the Office of the Deputy Prime Minister (ODPM) Building Operational Performance Framework (CI 71/6/37, 2008-2009, GBP230,000) 'Ventilation in Schools' was based on a series of field measurements investigating indoor air quality, thermal comfort and acoustic performance of nine recently built secondary schools in England. The study considered 34 natural and mechanical ventilation design strategies. It established: i) that the dynamics of CO_2, as a proxy for indoor air quality in schools is a function of the selected ventilation strategies under typical "performance in use" conditions; and ii) while the acoustic standards are demanding it was possible to achieve natural ventilation designs that met the criteria for

indoor ambient noise levels **[a] [b]**. The study also showed that most classrooms in the sample met the requirement of limiting the daily average CO_2 concentration to below 1,500 parts per million (ppm), but only a minority met the need to readily provide 8 litres per second (l/s) per person of fresh air **[a]**. The research shows that natural ventilation options can be a cheaper and quieter alternative to mechanical ventilation, while keeping within air quality regulations. They are therefore a viable and cost-effective option for school planners.

'School Indoor Pollution and Health: Observatory Network In Europe' (SINPHONIE)
SINPHONIE was a scientific and technical network, created with the aim of improving air quality across EU schools and kindergartens to reduce the incidence and severity of respiratory illnesses among students and teachers caused by air pollution. It involved European universities and research institutes from 23 European countries, 115 schools and 5,175 schoolchildren and was sponsored by the EU Commission (EUR4,000,000) between 2011 and 2020. SINPHONIE used standardised procedures and protocols (taking into account potential confounders) to provide a coherent understanding of the effects of indoor air exposure in schools on the health of schoolchildren. UCL was the only UK partner contributing to all stages of SINPHONIE. IEDE's researchers paid special attention to current indoor air quality guidelines for school buildings including thermal conditions, CO_2 levels, and corresponding ventilation rates taking into account specific indoor pollution levels. Drawing on detailed monitoring data from a sample of 18 classrooms (heating and non-heating seasons) from six London schools, behavioural, health and environmental factors linked to pollution levels were analysed and the adequacy of CO_2 as an overall predictor for indoor air quality in classrooms was evaluated **[c]**. The research showed that schoolchildren exposed to above or equal median concentration of $PM_{2.5}$, benzene, limonene, ozone and radon were significantly more likely to suffer from upper airways, lower airways, eye and systemic disorders. Increased odds were also observed for any symptom among schoolchildren exposed to concentrations of limonene and ozone above median values. Results also showed that increased ventilation rate was significantly associated with decreased odds of suffering from eye and skin disorders whereas similar association was observed between temperature and upper airways symptoms. The research showed that CO_2 measurements alone cannot guarantee a healthy indoor environment in schools **[c] [d]**. Instead, a comprehensive list of indoor air quality parameters is necessary within building design and these were established by the study, including the economic benefits of reducing the levels of nitrogen dioxide (NO2) near primary schools **[e]**.

'Total Operational Performance of Low Carbon Buildings in UK and China' (TOP)
Sponsored by EPSRC (EP/N009703/1 GBP800,000) between 2015 and 2019 and in collaboration with Tsinghua University, TOP conducted field measurements to explore how building design and operation could provide improved indoor air quality whilst delivering low energy and low carbon buildings including schools, offices, hospitals, and large residential buildings. Following a long history of collaboration with industry partner Eltek (specialist data loggers), the 'AQ110' advanced air quality monitor was developed to support this work. The integrated unit was designed to capture temperature, humidity, CO_2, particulates (PM_1, $PM_{2.5}$, PM_{10}), NO_2, CO and TVOCs. This has allowed an understanding of both indoor and external pollutants, as well as their relationship to thermal comfort and ventilation rates **[f]**.

3. References to the research (indicative maximum of six references)

a) Mumovic, D., Palmer, J., Davies, M., Orme, M., Ridley, I., Oreszczyn, T., Way, P. (2009a). Winter Indoor Air Quality, Thermal Comfort and Acoustic Performance of Newly Built Schools in England. *Building and Environment*, 44 (7),1466-1477 https://doi.org/10.1016/j.buildenv.2008.06.014

b) Mumovic, D., Davies, M., Ridley, I., Altamirano-Medina, H., Oreszczyn, T. (2009b). A Methodology for Post-occupancy Evaluation of Ventilation Rates in Schools. *Building Service Engineering Research and Technology*, 30 (2), 143-152. https://doi.org/10.1177/0143624408099175

c) Chatzidiakou, L., Mumovic, D., & Summerfield, A. (2015a). Is CO_2 a good proxy for indoor air quality in classrooms? Part 1: The interrelationships between thermal conditions, CO2 levels, ventilation rates and selected indoor pollutants. *Building Services Engineering & Technology*, 36 (2), 129-161. https://doi.org/10.1177/0143624414566244

d) Chatzidiakou, L., Mumovic, D., & Summerfield, A. (2015b). Is CO_2 a good proxy for indoor air quality in classrooms? Part 2: Health outcomes and perceived indoor air quality in relation to classroom exposure and building characteristics. *Building Services Engineering & Technology*, 36 (2), 162-181. https://doi.org/10.1177/0143624414566245

e) Guerriero, C., Chatzidiakou, L., Cairns, J., & Mumovic, D. (2016). The economic benefits of reducing the levels of nitrogen dioxide (NO_2) near primary schools: The case of London. *Journal of Environmental Management*, 181, 615-622. https://doi.org/10.1016/j.jenvman.2016.06.039

f) Stamp, S., Burman, E., Shrubsole, C., Chatzidiakou, L., Mumovic, D., & Davies, M. (2020). Long-term, continuous air quality monitoring in a cross-sectional study of three UK non-domestic buildings. *Building and Environment*, 180. https://doi.org/10.1016/j.buildenv.2020.107071

4. Details of the impact (indicative maximum 750 words)

4.1 Providing the evidence base for policymakers to improve indoor air quality in schools

Influencing the European Commission

Guidelines for Healthy Environments within European Schools **[1]**, published by the European Commission Directorate General for Health and Consumers in 2014, and sponsored by the European Commission's Directorate-General for Health and Consumers describes the guidelines for healthy environments within European schools. It has been translated into 25 European languages as part of the implementation of Regional Priority Goal III (RPG3) of the Children's Environment and Health Action Plan for Europe (CEHAPE), which aims to prevent and reduce respiratory disease due to outdoor and indoor air pollution. SINPHONIE, as the world's first and largest study reviewing the importance of indoor pollution factors including occupancy behaviour and mechanical design **[c] [d] [e],** was a key foundation for **[1]**. EU member states have adopted sections in their school planning approaches, ensuring that policy makers are equipped to account for indoor air quality in their school design plans.

Providing foundational research for the UK Department of Education

In 2014, the UK government introduced a GBP4,400,000,000 Priority School Building Programme (PSBP) to rebuild and refurbish school buildings in the worst condition. The scheme covers a total of 537 schools across the UK. In the same year (revised in 2018), the UK Department for Education (DfE) published 'Building Bulletin (BB) 101: Ventilation, Thermal Comfort and Indoor Air Quality'. This document describes the factors that affect the indoor environment of schools, setting out the regulatory framework for ventilation in schools. BB101 also gives recommended performance levels for compliance with UK regulations and is mandatory for all new schools built under the PSBP scheme.

The dynamics of CO^2 in classrooms as described in 'Ventilation in Schools' **[a] [b]** differentiated how naturally and mechanically ventilated buildings affect the quality of teaching and learning spaces in the BB101 guidelines **[2]**. Furthermore, SINPHONIE indicators for indoor air quality monitoring form the foundation of Section 6 on Indoor Air Quality and Appendix C, with sources and research on the health effects of pollutants in schools presented in Annex B **[3]**.

As PSBP requires planners to conform to BB101, it is integrated into the design of 537 new and refurbished schools, their budgets, and their carbon footprint planning. A Technical Manager at the Department for Education indicates the importance of **[a] [b]** in the 2014

version of BB101 and **[c] [d] [e]** in the 2018 revision of BB101: "This work was important to change the default mechanical ventilation design that could have significantly increased operational costs and associated carbon emissions, thus burdening school budgets and increasing the carbon footprint of the school building sector […] [the research] underpin[s] the decision-making process of designing healthy schools" **[4]**.

Contributing to the Mayor of London's audit on air pollution in schools

In 2017, Professor Mumovic was commissioned by the Mayor of London's Office, to review the existing evidence and investigate the level of indoor air pollution in London's schools in the report 'Indoor Air Quality in London's Schools' **[5]**. The report found notable differences in the characteristics of indoor air pollution between seasons and classrooms depending on their microenvironment, building characteristics, operation and maintenance, indicating that annual personal exposure to PM in London's classrooms may be higher than WHO 2010 guidelines. The report was published through the Mayor's Office, with the simultaneous announcement of the creation of a GBP1,000,000 fund to help the worst affected schools (200 additional schools across five London boroughs) based on an audit of schools run by global engineering consultancy WSP. Mumovic was on the Project Advisory Board of the GLA Audit. IEDE research continues to provide the scientific basis for the Greater London Authority (GLA)'s indoor air quality initiatives, and the researchers are currently collaborating with GLA on 'Indoor Air Quality in Nurseries'.

4.2 Raising the profile of indoor air quality in schools in collaboration with industry partners

Setting the criteria for best practice for building engineers

The Chartered Institution of Building Services Engineers (CIBSE) is the standard setter and authority on building services engineering in the UK. It publishes 'CIBSE Guides and Codes', which are internationally recognised as authoritative, and sets the criteria for best practice in the profession.

Co-founded by Mumovic (with CIBSE), the 'CIBSE School Building Design Group' is a professional network that shares knowledge on the design, operation, and environmental quality of schools. The network was founded based on IEDE research, with Mumovic a committee member for 12 years. Today, the School Building Design Group has over 10,000 members (including building services engineers, architects and facility managers) in 22 countries worldwide **[6, 11]**.

CIBSE's Technical Memoranda (TMs) offer in-depth technical guidance on specific topics. All 22,000 CIBSE members (including architects, facility managers, and people working in the building industry) in 91 countries across the world are given free access to full texts as electronic files. Mumovic led two Technical Memoranda (TM57 and TM61/64) focusing on ventilation, emission sources and mitigation measures schools. The inclusion of IEDE research in TM57 **[a-e]** and TM61/64 **[a-f]** ensures that insights from research on design and indoor air quality are distributed globally across the profession **[7-10]**. TM57 sold 794 copies between 2016 and July 2020, and this uptake is considered by the Head of Research at CIBSE to be a "significant achievement taking into account that approximately 580 schools [were] built or [underwent] major refurbishment during that period" across the network" **[11]**.

Co-creating impact with industry.

Designing and testing innovative, low-carbon ventilation systems for schools was the focus of a knowledge transfer partnership between IEDE and Ventive **[12]**. Ventive is a London-based company focused on the design of naturally intelligent ventilation systems to deliver fresh air at minimal energy cost. The partnership developed and implemented an engineering design protocol and database. This enabled the embedding of indoor air quality and ventilation effectiveness in Ventive's product development installed in schools. Using insights from **[a-f]**, Ventive's founder highlights how their Passive Ventilation with Heat Recovery (PVHR) technology products "now have better heat exchangers, and our systems are cloud-connected

to enable remote, real-time performance monitoring, system adaptation and proactive maintenance". The founder confirms the importance of this collaboration in the rollout of these products, indicating that it allowed them to "better understand and advance our design and test innovative, low-carbon ventilation systems for schools […] This enabled the embedding of new indoor air quality systems and improved ventilation effectiveness in schools, providing improved air quality for more than 8,000 children in over 40 schools across the UK" **[13]**.

The results of AQ110 Advanced air quality monitors developed with Eltek **[f]** have been published as part of 'CIBSE TM61 Operational Performance of Buildings' and 'CIBSE TM64 Indoor Air Quality: Emission Sources and Mitigation Measures', again sharing IEDE research expertise across the industry **[9, 10]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

1. Stylianos Kephalopoulos, et al. (2014). Guidelines for Healthy Environments within European Schools, European Commission, Directorate General for Health and Consumers and Directorate General Joint Research Centre - Institute for Health and Consumer Protection. https://doi.org/10.2788/89936
2. Building Bulletin (BB) 101: Ventilation, Thermal Comfort and Indoor Air Quality (2014), Department for Education, London, UK
3. Building Bulletin (BB) 101: Ventilation, Thermal Comfort and Indoor Air Quality (2018), Department for Education, London, UK
4. Testimonial: Design Team, Department for Education
5. Mumovic, et al. (2018). Indoor Air Quality in London's Schools, Greater London Authority, London, UK
6. About the School Design Group, CIBSE. https://bit.ly/3qXy7Ji
7. CIBSE SDG (2010) CIBSE School Design Group Bulletin 1
8. CIBSE TM57 (2015) Integrated School Design, CIBSE, London, UK
9. CIBSE TM61 (2020) Operational Performance of Buildings, CIBSE, London, UK
10. CIBSE TM64 Indoor Air Quality (2020): Emission Sources and Mitigation Measures, CIBSE, London, UK
11. Testimonial: Head of Research, CIBSE
12. Innovate UK (2015-2017), Ventilation Effectiveness and Indoor Air Quality, Knowledge Transfer Partnership No.9845, Company Partner: Ventive Limited https://bit.ly/3vCZ8pd
13. Testimonial: Founder of Ventive