Simulating Ventilation for Indoor Air Quality of Non-domestic Environments in London Schools: A Building-based Bottom-up Approach

Shih-Che Hsu,MSc   Ian Hamilton,PhD   Anna Mavrogianni,PhD   Rob Liddiard,PhD

ABSTRACT

In the UK, people spend over 90% of a day indoors. On weekdays, when outdoor air pollution concentrations peak in the morning and in the late afternoon, people are usually either in non-domestic premises or on their way to/from non-domestic premises. Therefore, establishing the distributions of indoor air pollutant concentrations in non-domestic environments is essential to model human exposure to hazardous air pollution, especially for vulnerable populations, such as schoolchildren or patients in hospitals. In the Hazardous Air Pollutant Exposure Model of the US Environmental Protection Agency, microenvironment pollutant concentrations are determined by outdoor pollutant concentrations, penetration of outdoor air indoors, proximity of the microenvironment to the outdoor pollutant emission source, and emission sources within microenvironments. Penetration of outdoor air to indoors is related to building characteristics, such as fabric air tightness and ventilation control, which can be affected by energy efficiency retrofits. The aim of this study is to predict the air penetration rate for London's school buildings (nursery, primary and secondary schools) and enhance our understanding of how energy efficiency improvements will impact indoor air quality modelling so as to prevent potential harmful exposure and improve existing retrofit techniques. The baseline statistics of building physics for school environments in London were aggregated from the building typologies and room uses from 3DStock Model to analyse the effect of built configurations on building ventilation and air tightness. The simulation results show that air change rates due to natural ventilation is low in Post-1980 school buildings, which means recently built or retrofitted buildings that are more airtight and energy efficient need to carefully maintain purpose provided ventilation to ensure adequate air exchange.

1. INTRODUCTION

To achieve the UK's 2050 climate targets of net zero carbon emissions (Climate Change Act 2008), building retrofits are urgently required to improve building energy efficiency and reduce carbon emissions, especially in public buildings. This will result in significant modifications in building envelope characteristics, especially air tightness. There has also been increasing research and policy interest in Indoor Air Quality (IAQ) and the potential health impacts of indoor air pollutant exposure in recent years. Building envelope air change rate plays a significant role in indoor air quality estimation when simulating the infiltration of outdoor air pollutants indoors (Shi et al. 2015).

Starting in 2003, the UK government started a series of school building retrofits under the Building Schools for the Future (BSF) plan and again through the 2011 Priority School Building Programme (PSBP). These programmes focused on improving building energy and environmental performance, and on enhancing the learning environment. There are significant knowledge gaps around the impact of these initiatives on IAQ within the UK schools, and more generally the IAQ conditions in the UK schools is not well described. Therefore, this study aims to understand the

Shih-Che Hsu is a research fellow in the Energy Institute, University College London, London, UK. **Ian Hamilton** is a reader in the Energy Institute, University College London, London, UK. **Anna Mavrogianni** is an associate professor in the Institute for Environmental Design and Engineering, University College London, London, UK. **Rob Liddiard** is a research associate in the Energy Institute, University College London, London, UK.

impact of building physics and energy performance on air penetration rate for ventilation prediction and indoor air quality modelling in London school buildings. London school buildings were retrieved from a 3-dimensional model of London, providing the opportunity to develop bottom-up physics-based models to simulate indoor air quality and energy demand. Nursery, primary and secondary schools were modelled as they accounted for the majority (more than 90%) of educational premises in London.

CONTAM 3.2 was employed to simulate IAQ in London school buildings. CONTAM is a well-validated multizone indoor air quality and ventilation analysis computer program created by the National Institute of Standards and Technology (NIST) of the U.S. Department of Commerce. It can determine (1) airflows, (2) indoor contaminant concentrations and (3) personal exposure to indoor air pollution (NIST 2015). To date, only a few recent studies applied CONTAM to school environments (Silva et al. 2017; Fernandes et al. 2019) and the majority of CONTAM simulations were used for a single building, of which the modelling outputs may be difficult to generalise. This study employs bottom-up large-scale building modelling of schools by using aggregated information from across London.

2. METHOD

2.1 3DStock: aggregation of school environments in London

The London 3DStock is a method for modelling London's whole building stock, which was developed by a team at the UCL Energy Institute led by Professor Philip Steadman. Information from Great Britain Ordnance Survey digital maps, commercial property taxation data from the Valuation Office Agency (VOA), and Light Detection and Ranging (LiDAR) data from the UK Environment Agency, are assembled into a 3D model (Steadman et al. 2020). This is held in a PostgreSQL database containing the characteristics of individual domestic, non-domestic and mixed-use buildings in London, for the simulation and analysis of energy performance in all 33 boroughs of the Greater London Authority. The VOA's non-domestic detailed premises surveys record floor-by-floor activities, room-level sub-activities and floor areas. Using this large building-based dataset, 3DStock can be used in statistical and epidemiological studies of population-level energy demand (Hamilton et al. 2017) and bottom-up building stock indoor air quality modelling.

In this research, 3DStock was used to aggregate basic building statistics of existing school buildings in London. The aggregated properties were used to generate simple archetypes that represent school building typologies for different construction periods. Depending on the building form, different models were created to simulate ventilation and penetration of outdoor air pollution indoors in CONTAM by estimating building air exchange rates (Air Changes per Hour, ACH) for each archetype. The building statistics extracted for CONTAM model development from the 3DStock model were building types; construction periods; floor levels; education types; room functions; total floor area and energy performance ratings. The classes of each building characteristic are listed below:

(1) Building type: Four typical building types were used, which are Detached, Semi-detached, End-terrace and Mid-terrace forms. N.B. these types refer to the attachment of a building to other buildings, and not a reference to residential use.

(2) Construction period: Four periods were used to present the building age in the non-domestic premises survey of VOA, which are Pre-1914, 1918-1939, 1945-1989, Post-1980. Those without a record of construction year, were denoted 'N/A'.

(3) Floor level: Floor level was recorded for each premises in 3DStock up to the fiftieth floor. Number 0 to 50 were used to denote ground floor to fiftieth floor. Basements, lower ground floors and mezzanines are also identified. For those buildings lower than sixth floor (inclusive), 'low-rise' buildings are then assigned, while only 972 premises (less than 6% of all premises) are assigned as high-rise buildings.

(4) Education type: There are ten types of education activities classified in 3DStock: Nursery (including creche, playschool, and childcare); Private school; State school; College (including 6th form, further education, higher education, etc.); University; University ancillary land/buildings; Dance School/Centre; Field study (including Activity and Adventure Centre); Miscellaneous education; Training Centre.

(5) Room function: Detailed sub-activities within each premises are provided in 3DStock, largely based on the VOA's sub-activity classification system. In this research, education sub-activities are grouped into 11 types: Canteen; Classroom; Cloakroom; Hall; Laundry; Lobby; Nursery; Office; Storage; Washroom (WC); Others.
(6) Total floor area was recorded in metre square (m^2) in 3DStock.
(7) Energy performance: 3DStock contains records for Energy Performance Certificates (EPCs), which are a theoretical energy performance indicator based on the building and the standardised use of its fixed services (heating, lighting etc.). EPCs grade performance from 'A' (best) to 'G' (worst). Where the premises does not have an EPC, a 'virtual EPC' (vEPC) has been created, based on nearby premises with similar characteristics. To cope with mixed-use buildings, 3DStock also aligns non-domestic EPCs and vEPCs to their domestic equivalents (Steadman et al. 2020), using a scale of 1 to 100, with 100 being the best performance.

2.2 CONTAM: simulation of ventilation and air pollution in London school environments

CONTAM was used in this research to determine room-to-room natural airflows driven by exterior wind pressures and buoyancy effects of indoor-outdoor temperature differences in school buildings, which were investigated under various ventilation conditions related to room functions and typical building typologies. Natural ventilation usually refers to air exchange through the intentional openings of building envelopes like windows and doors and unintentional leakage areas of building envelopes. Unintentional air exchange is described as infiltration (Shi et al. 2015). This work specifically excludes unintended infiltration rate, simulating only hour-by-hour intentional ventilation rate.

Parameters were adjusted in CONTAM libraries and building variables were set accordingly for typical London school buildings. To simulate the airflows through windows and doors *(flow paths)* in the CONTAM models, building characteristics from 3DStock and typical school building layouts were applied to corresponding models. Summer weather was set as the warmest July and winter weather as the coldest January according to the UK typical meteorological status (Met Office 2020). Based on the typical meteorology features, hourly airflows and time-average natural ventilation rates were subsequently simulated in the building form of three school environments (nursery, primary and secondary schools) for two months in January and July.

The first step of simulation was to set up the floor layout in the sketchpad of CONTAM. After comparing several floor plans of nursery, primary and secondary schools in London, simplified layouts were created, as shown in Figure 1 for (a) primary and secondary schools and for (b) nurseries. The target rooms used in simulation were also noted. The ambient environment surrounding the building was set at 20 ˚C, 101,325 Pa, 70% RH, 4 mph (1.79 m/s) western wind in summer and 10 ˚C, 101,325 Pa, 80% RH, 13 mph (5.81 m/s) western wind in winter for steady-state simulation, and used the weather file converted from Typical Meteorological Year 2 (TMY2) in London for transient analysis. The zones in CONTAM sketchpad were assigned with the aggregate floor areas by room function, construction periods and energy performance. The temperature was set at 18 ˚C for classrooms and 16 ˚C for other spaces in winter and 22 ˚C for classrooms and 20 ˚C for other spaces in summer based on the advice of National Educational Union (NEU 2020).

The openings information was assumed according to a rule of thumb referred to the UK Ministry of Housing, Communities & Local Government building regulations, Approved Documents (MHCLG 2020), which includes the two-way wind flow model of single opening with the size (2 m x 0.8 m for doors and 0.5 m x 2 m for windows), the relative elevation (0 m for doors and 1.5 m for classroom windows and 2.5 m for WC windows), the schedules (24-hour opening and standard school time from 8 am to 6 pm on Monday to Friday) were tested and the wind pressure information based on the wall azimuth angle. The windows were also tested in the one-way flow using powerlaw model of Analysis of Smoke Control Systems (ASCOS) connection method. It is an implementation of the more general orifice flow element built in CONTAM. A flow coefficient of 0.35 was adopted for the urban area. Other settings were kept default when running simulations.

Nursery, primary and secondary schools were the only buildings chosen as they have the greatest diversity of building characteristics and energy performance and form the majority (more than 90%) of the 'Education' class in

3DStock. Therefore, for the primary and secondary school the 3DStock aggregate building information of EPC grade C in Post-1980 category and EPC grade D in 1918-1939 categories were used; for the nursery school the information of EPC grade C in Post-1980 and EPC grade D in Pre-1914 categories were used. Considering the relatively fewer high-rise buildings of London nursery, primary and secondary school, the ground floor was the only focus of the simulation.

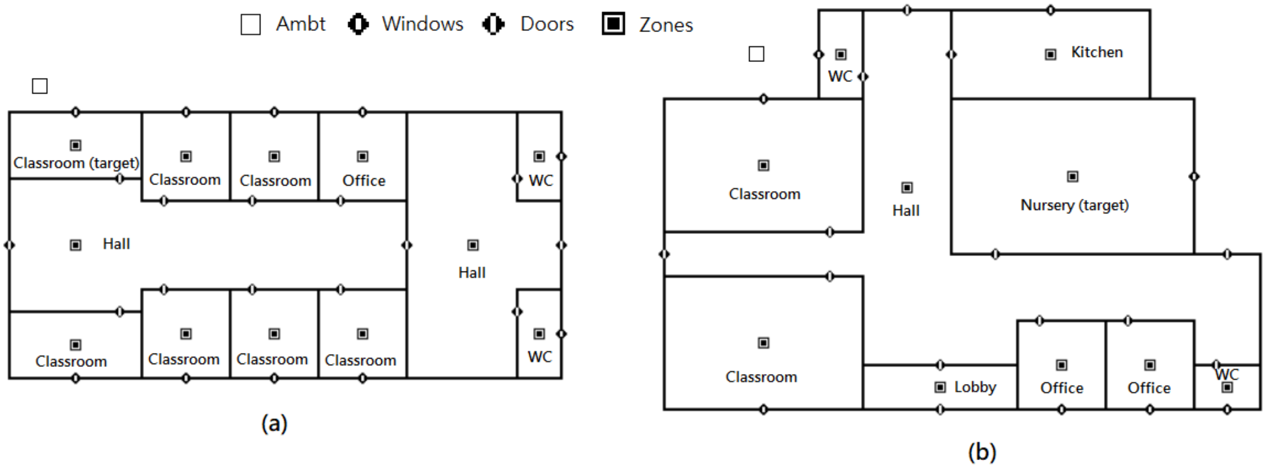

Figure 1 Simplied layouts of London (a) primary and secondary school and (b) nursery school.

3. RESULTS AND DISCUSSION

3.1 3DStock model aggregation results

The building information extracted from the 3DStock model can provide the distribution of education types, building physics and room functions of school buildings in London. The Sankey diagram in Figure 2 illustrates the breakdown of total floor area of school buildings in London by construction period, school activity, space usage and floor level. The majority of school buildings in London were built before 1914 and after 1980 in detached building types. Private schools/colleges and Nurseries are the two dominant education types in the study. Classroom activity dominates the space of private school/college education and is found predominantly at ground, first and second level. Nursery activity is the main function in Nursery premises and is mainly located on the ground floor. Office activity is evenly found in all education types and below fourth floor. When floor levels are ranked by their total floor area, the top four largest are ground, first, second floors and basement level, and very few activities are in the floors higher than fifth floor.

Table 1 shows the number and average floor area of the school room-level units across different education types and building types. Detached buildings account for 62% of the room-level units and occupy 58% of total floor area, which matches the statistics in Figure 2. Nursery accounts for more than half (62%) of the room-level units and double the number (30%) of private school/college, but the total floor area is still a little smaller than private school/college due to the smaller average floor area (36 m^2) of Nursery premises, which is almost half of the average floor area (74 m^2) of private school/college. Although the average floor area of premises in high-rise buildings is larger than ones in low-rise buildings except for Dance School/Centre, the overall average floor area is still around 55 m^2 due to the number of low-rise buildings surpassing high-rise buildings by far. The top three largest average floor areas of premises in low-rise buildings, in order, are College (164 m^2), Training Centre (123 m^2) and University (92 m^2), with the smallest one being Nursery education (35 m^2).

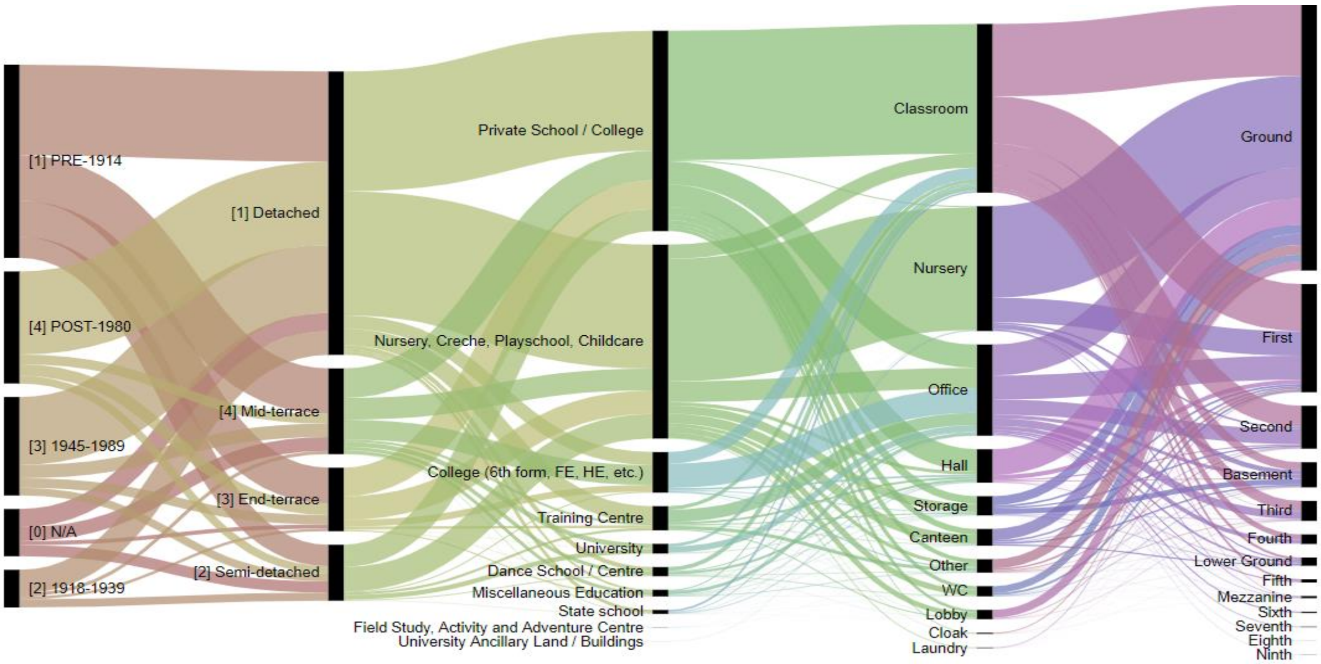

Figure 2 Sanky diagram of London school buildings created by RAWGraphs data visualization framework (Mauri et al. 2017).

Table 1. Summary of Building Typologies of Education in London

Building Type / Education Type[1]	[1] Detached N (%)	[1] Detached Mean Area (m2)	[2] Semi-detached N (%)	[2] Semi-detached Mean Area (m2)	[3] End-terrace N (%)	[3] End-terrace Mean Area (m2)	[4] Mid-terrace N (%)	[4] Mid-terrace Mean Area (m2)	Total N (%)	Total Mean Area (m2)
College	**107 (0.6)**	**242**	**15 (0.1)**	**128**	**39 (0.2)**	**334**	**272 (1.6)**	**141**	**433 (2.5)**	**183**
Dance School	**122 (0.7)**	**73**	**16 (0.1)**	**112**	**11 (0.1)**	**82**	**113 (0.6)**	**66**	**262 (1.5)**	**73**
Nursery	**6926 (39.4)**	**36**	**1500 (8.5)**	**33**	**1400 (8)**	**34**	**1089 (6.2)**	**40**	**10915 (62)**	**36**
Low-rise[2]	6737 (38.3)	36	1483 (8.4)	32	1339 (7.6)	33	1034 (5.9)	40	10593 (60.2)	35
High-rise[2]	189 (1.1)	48	17 (0.1)	99	61 (0.4)	51	55 (0.3)	52	322 (1.8)	52
Private School	**3325 (18.9)**	**69**	**543 (3.1)**	**78**	**794 (4.5)**	**70**	**539 (3.1)**	**106**	**5201 (29.6)**	**74**
Low-rise[2]	3231 (18.4)	68	533 (3)	75	478 (2.7)	73	481 (2.7)	94	4723 (26.8)	72
High-rise[2]	94 (0.5)	106	10 (0.1)	238	316 (1.8)	65	58 (0.3)	197	478 (2.7)	93
Training Centre	**264 (1.5)**	**124**	**28 (0.2)**	**187**	**45 (0.3)**	**130**	**53 (0.3)**	**87**	**390 (2.2)**	**124**
Total	**10919 (62)**	**51**	**2152 (12.2)**	**52**	**2333 (13.3)**	**55**	**2195 (12.5)**	**77**	**17599 (100)**	**55**

[1] Due to the limited space, education types are listed for those more than 1%.

[2] High-rise Building: Total floor >= 6; Low-rise Building: Total floor < 6; only private and nursery school in simulation are listed.

3.2 CONTAM model simulation results

Table 2 summarises the energy performance of school premises of different construction periods and education types. Most London school premises have EPC grade C (32.7%) or grade D (35.4%), and EPC grade D dominates almost all construction periods and education types except for Post-1980 and Private School/Centre. There are higher percentages of both Post-1980 and Private School/Centre premises with EPC (grade C), which are better than the building mode grade D within the 3DStock sample and for the England's existing properties as found in the Live tables on Energy Performance of Buildings Certificate (Smith 2020). The EPC grade of the premises was allocated to that premises' rooms, thus providing energy performance for each education space. This showed that all room purposes in Post-1980 premises have EPC grade C and all room purposes (except lobby) of Private school premises also have EPC grade C. Classrooms especially have better energy performance, not only in Post-1980 but also in Pre-1914 premises.

Table 2. EPC grade of Different Periods and Education in London

EPC	A	B	C	D	E	F	G	N/A	Total
Periods[1]	N(%)	N(%)	N(%)	N(%)	N(%)	N(%)	N(%)	N(%)	N(%)
[1] PRE-1914	40 (0.2)	751 (4.3)	2375 (13.5)	2671 (15.2)	1035 (5.9)	232 (1.3)	88 (0.5)	386 (2.2)	7578 (43.1)
[2] 1918-1939	1 (0)	106 (0.6)	572 (3.3)	747 (4.2)	335 (1.9)	78 (0.4)	9 (0.1)	84 (0.5)	1932 (11)
[4] POST-1980	0 (0)	505 (2.9)	1437 (8.2)	1024 (5.8)	154 (0.9)	100 (0.6)	26 (0.2)	248 (1.4)	3494 (19.9)
Total	**55 (0.31)**	**1754 (10)**	**5748 (32.7)**	**6237 (35.4)**	**2051 (11.7)**	**537 (3.1)**	**157 (0.9)**	**1060 (6)**	**17599 (100)**
Education Types[1]									
Nursery	0 (0)	698 (4)	3386 (19.2)	4437 (25.2)	1610 (9.1)	236 (1.3)	99 (0.6)	449 (2.6)	10915 (62)
Private School	49 (0.3)	890 (5.1)	2052 (11.7)	1420 (8.1)	336 (1.9)	241 (1.4)	8 (0)	205 (1.2)	5201 (29.6)

[1] Due to the limited space, only epochs and education types in simulation are listed.

Based on the 3DStock aggregate information, CONTAM building layouts were created for primary and secondary schools in Post-1980 for EPC grade C and 1918-1939 for EPC grade D, and for nursery schools in Post-1980 for EPC grade C and Pre-1914 for EPC grade D. Table 3 below shows the mean floor area of room purpose in four periods for different education types, which was input in CONTAM zone floor area. For example, the mean of classroom floor area of primary and secondary school in Post-1980 is 128 m^2. Figure 4 below shows an example of simulated airflow rate distribution of target classroom of Post-1980 primary and secondary schools with (a) 24-hour opening and (b) standard school time schedule during 1st July to 7th July, and two opposite lines, red and purple lines, stand for the balanced airflows coming in through windows from outdoors and blowing out the door respectively. The maximum ventilation rate, 6,776.5 m^3/h at 12 pm on 4th July with 24-hour opening schedule, was divided by the volume of classroom 384 m^3 to give 17.6 ACH. For wintertime between 1st January to 7th January, the maximum ventilation rate of the target classroom was 13,905.4 m^3/h at 8am on 3rd January with 24-hour opening schedule and lead to an ACH (36.2), which is almost double that of summer and with the opposite direction of airflow coming in through door and blowing out via windows. Comparing to the results of 1918-1939 for EPC grade D, smaller classroom floor areas lead to higher air change rate, 24 ACH in summer and 49.3 ACH in winter.

Nursery schools in London have same direction pattern of air movements in summer (1st July to 7th July) and in winter (1st January to 7th January) with primary and secondary schools. These scenarios resulted in summer ventilation rate of 3376.3 m³/h and air change rate of 10.9 ACH and winter ventilation rate of 4356.4 m³/h and 14.1 ACH for Post-1980 buildings, whereas Pre-1914 nursery buildings with lower EPC grade had a higher maximum air change rates, 20.8 ACH in summer and 26.9 ACH in winter respectively.

Table 3. Cross Table of Room Purpose Mean Area of Education Types in Different Periods

Room Purpose	Canteen	Classroom	Cloak	Hall	Laundry	Lobby	Nursery	Office	Other	Storage	WC	Total	Total
Periods[1] Edu. Types[2]	Area (m2)	Area (m2)	Area (m2)	Area (m2)	Area (m2)	Area (m2)	Area (m2)	Area (m2)	Area (m2)	Area (m2)	Area (m2)	% of N	Area (m2)
[0] N/A	**16**	**141**	**4**	**174**	**12**	**42**	**88**	**83**	**111**	**14**	**11**	**7.7%**	**70**
[1] PRE-1914	**20**	**86**	**14**	**115**	**12**	**22**	**55**	**47**	**45**	**17**	**11**	**43.1%**	**50**
Nursery	14	40	8	59	12	18	54	21	24	13	8	21.6%	31
[2] 1918-1939	**14**	**77**	**10**	**99**	**7**	**15**	**44**	**41**	**74**	**18**	**10**	**11.0%**	**39**
Private School	24	94	10	124	0	16	20	44	26	30	11	2.0%	62
[3] 1945-1989	**18**	**115**	**22**	**190**	**9**	**40**	**89**	**59**	**79**	**15**	**12**	**18.4%**	**61**
[4] POST-1980	**23**	**112**	**14**	**147**	**10**	**42**	**102**	**79**	**72**	**13**	**16**	**19.9%**	**64**
Nursery	18	50	9	58	10	35	103	31	44	10	13	13.8%	44
Private School	50	128	23	153	7	53	72	78	88	25	19	4.3%	86
Total	**19**	**96**	**15**	**141**	**10**	**34**	**70**	**58**	**66**	**16**	**12**	**100.0%**	**55**

[1] Due to the limited space, only the epochs in simulation are listed. [2] Only the education types in simulation are listed.

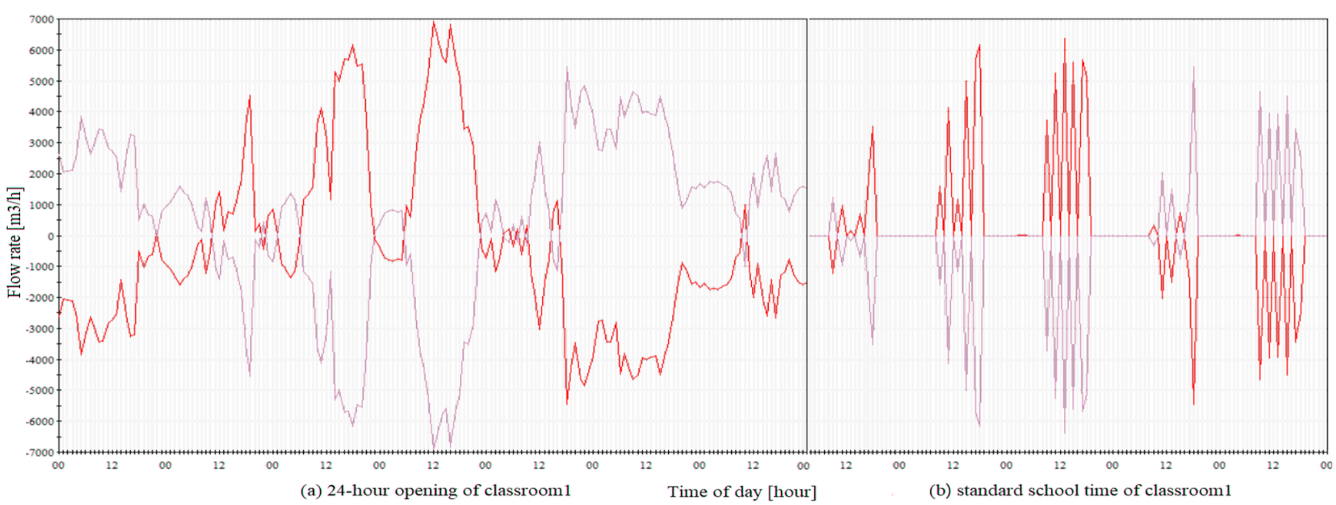

Figure 4 Simulated airflow rate of target classroom of primary and secondary school with (a) 24-hour opening and (b) standard school schedule (Monday to Friday) between 1st July and 7th July. Two opposite lines, red and purple lines, stand for the balanced airflows coming in through windows from outdoors and blowing out through the door.

The CONTAM model also provides the whole building air change rate under conditioned space. The ACH simulation results were as follows (standard deviation shown in parentheses): Post-1980 primary and secondary schools, July 4.5 (1.5), January 6.9 (1.5); Post-1980 nursery schools, July 14.5 (5.2), January 22.3 (8.1); 1918-1939 primary and secondary schools, July 6.1 (2.0), January 9.4 (2.1); Pre-1914 nursery school, July 20.6 (7.3), January 31.7 (11.5).

3.3 Discussion

The air change rate of a building was shown to be affected by not only external ambient conditions but also by building orientation, spatial configuration, floor area, construction year and energy performance. However, both the 3DStock and CONTAM models are still under development, so some building characteristics were not available in 3DStock and were assumed in simulations, for example, the room arrangement, the type and feature of flow paths (openings). The simulation results presented here focus on air change rate, which indicate natural ventilation is low in Post-1980 school buildings and imply recently built or retrofitted buildings are both more airtight and more energy efficient. 3DStock intends to expand across England and Wales providing a source of 3D building characteristics for simulation/evaluation of energy performance. After substituting real data from 3DStock for modelling assumptions, the temperature-driven ventilation and unintentional leakage could be considered accurately, and the mechanical ventilation would be assessed. All model improvements will help future indoor air quality simulation and assessment.

CONCLUSION

The deterioration of IAQ, due to less natural ventilation, may cause adverse exposure to indoor air pollutants, so there is a need to enhance our understanding of how energy performance and efficiency improvement will affect indoor air quality. This study contributes to understanding the relative importance of building energy performance and energy-related features on ventilation. The large-scale inventory of school buildings in London provides the opportunity of bottom-up building stock indoor air quality modelling and the prospect of physics-based modelling on mechanical ventilation to eliminate indoor air pollutants when information is available in the future.

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