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Indoor Air Quality and Overheating in UK Classrooms – an Archetype Stock Modelling Approach

Y. Schwartz¹, I. Korolija,¹ P. Symonds¹, D. Godoy-Shimizu¹, J. Dong¹, S.M. Hong¹, A. Mavrogianni¹, D. Grassie¹ and D. Mumovic¹.

Abstract. Children spend a large part of their waking lives in school buildings. There is substantial evidence that poor indoor air quality (IAQ) and thermal discomfort can have detrimental impacts on the performance, wellbeing and health of schoolchildren and staff. Maintaining good IAQ while avoiding overheating in classrooms is challenging due to the unique occupancy patterns and heat properties of schools. Building stock modelling has been extensively used in recent years to quantify and evaluate performance of large numbers of buildings at various scales. This paper builds on an archetype stock modelling approach which represents the diversity of the school stock in England through an analysis of The Property Data Survey Programme (PDSP) and the Display Energy Certificates (DEC) databases. The model was used for simulating Indoor-to-Outdoor pollution ratios to estimate indoor air pollution levels (NO₂, PM_{2.5} and CO₂) and thermal comfort (overheating) in two climate areas in England: London and the West Pennines. analysis highlighted variations in classrooms' indoor CO₂ levels in different seasons and explored the risk of overheating in relation to a classroom's orientation.

1. Introduction

Children spend a significant amount (around 30%) of their daily lives in schools' premises, 70% inside classrooms [1], subject to unique and dynamic usage patterns [2]. Avoiding compromises in Indoor Environmental Quality (IEQ) due to changes in occupancy patterns, seasonal or outdoor conditions can be a challenging task, even more so in the context of climate change. Exposure to air pollution is a major contributor to mortality in the UK [3] with high concentrations of Particulate Matter (PM) and Nitrogen dioxide (NO₂) believed to be a significant component in increased death rates in England [3], related to illnesses such as Asthma and decreased nasal patency [4]. Though Carbon dioxide (CO₂) cannot be considered an exact analogue of other typical pollutants found in schools, it is perceived as an important indicator for IAQ, especially on occupants cognitive performance [5].

The indoor environment is often evaluated using deterministic models, in which exposure to pollution is modelled as a function of a set of building characteristics (e.g., outdoor concentrations, indoor emissions and indoor use patterns [6], [7]). For estimating the impact of pollutants on indoor air quality on a population-level, variants that represent the stock should be used [8]. To estimate indoor pollution levels from outdoor sources, modelled outdoor pollution levels and building thermal models are combined, and an indoor-to-outdoor pollution ratios (I/O) are calculated [8]–[10]. School buildings in the UK were originally designed to deal with heating demand. As such they largely rely on natural ventilation [11]. To minimise heat loss, windows are often kept shut, which may lead to compromised IEQ. The reliance on outdoor air for natural ventilation – especially in dense urban spaces – has the

¹ UCL IEDE – Institute for Environmental Design and Engineering, WC1H 0NN, London, UK



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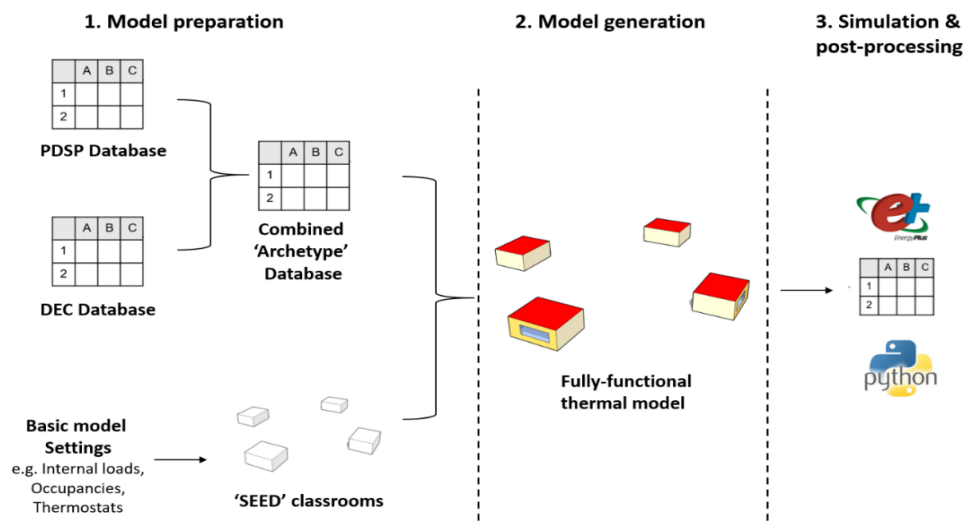
higher risks of contaminants entering the classrooms. Furthermore, as around 80% of the UK school stock was built before 1976 [12], the current UK school stock may not be prepared to cope with the risk of indoor overheating [11]. The evaluation of current and future performance of school buildings has, therefore, become increasingly important [13].

Building stock modelling is widely used to examine the current and future energy and IEQ of large number of buildings at different geographical scales [14]. An Archetype stock model approach uses a number of ‘typical’ buildings to represent the diversity of the building sector. This approach facilitates high-level and quick analysis, helping policymakers promote better-informed policies and regulations. This study forms part of the EPSRC funded project ‘ASPIRE’ (Advancing School Performance: Indoor environmental quality, Resilience and Educational outcomes), which uses DREAMS - Data dRiven Engine for Archetype Models of Schools – a stock model that offers a detailed representation of the English primary school stock – to investigate indoor air quality (CO₂, NO₂, PM_{2.5}) and thermal comfort in English schools, focusing on the analysis of IEQ within classrooms. For this, school classroom archetypes in two UK regions were modelled: the London and the West Pennines [15]. The former is a warmer climate and is also characterised by a dense urban environment with high levels of pollution, whereas the latter is a further north and has a cooler climate, and lower density levels.

2. Methods

The study design is outlined in Figure 1: Based on a detailed analysis of nation-wide schools’ data, classroom-archetype thermal models were developed as representative of the entire schools-classroom stock in the country. Classrooms in the two climate regions were then simulated using EnergyPlus – a dynamic thermal simulation tool which is widely tested and used both in the industry and academia [16], and a set of IEQ indicators were examined and compared.

Figure 1. Study design.



2.1. Stock Data analysis (PDSP / DEC) & Archetype model development

The archetypes in this study were developed following a statistical analysis of two databases: Property Data Survey Programme (PDSP) [17] and Display Energy Certificates (DEC) [18] databases. PDSP is a nation-wide survey of schools’ estates, originally commissioned by the UK Government’s Partnerships for Schools [12]. The PDSP includes information collected between 2012 and 2014 for over 18,000 establishments across England, including primary schools and secondary schools, representing 85% of the stock. For primary schools, this study’s focus, PDSP covers around 90% of the total stock. The data in PDSP is purely descriptive; it is produced through physical inspection of schools’ premises and holds information on physical properties of each school in the database (e.g., footprint area, number of stories,

Window-to-Wall Ratio (WWR), etc). The DEC database provide standardised performance benchmarks for large non-domestic public buildings in England and Wales [18]. The database includes data such as the main ventilation systems, heating fuel and other performance-related information. The DEC data in this study comprises 44,127 certificates for primary schools, lodged between 2010 and 2016. Based on the PDSP and DEC data, schools in this study were classified into archetypes based on the above buildings characteristics with data analysis and classification processes comprising the following:

- Automated address and schools matching procedures, to match schools data from the two databases.
- Based on records in PDSP, five schools' construction eras (pre-1919, inter-war, 1945-1966, 1967-1976 and post-1976) were identified. Typical thermal properties were associated with each era.
- Schools were classified based on their environment (i.e., natural ventilation / mechanical ventilation).
- Schools were classified based on the number of blocks they had: 'Single block' meant schools have one building in the entire premises. 'Multi-block- means schools have more than a single building.
- Thirteen climate-areas were defined, based on the Test Reference Year (TRY) weather files from the Chartered Institution of Building Services Engineers (CIBSE) [19].
- Average WWR were calculated for all entries falling within each archetype.

2.2. Application

2.2.1. Model Description. The modelling procedure started with the generation of a 'seed' thermal model – a classrooms model which contains purely geometrical representation of the examined spaces. The 'seed' model was comprised by four classroom geometries, facing different north-south- east-west orientations, as shown in Figure 2. This model contained inputs on schedules, thermostats, internal gains, and ventilation as described in Table 1, but not windows, specific location, associated weatherfile or construction build-ups. These were assigned before simulation, through automated processing of PDSP

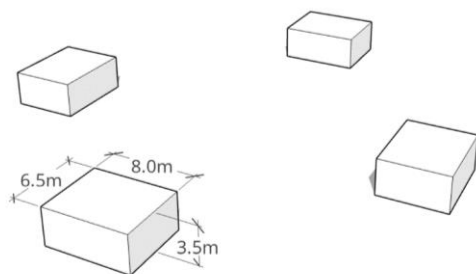


Figure 2. The 'Seed' classroom model.

and DEC data. Classrooms were assumed to be surrounded by other spaces with similar heating demand, therefore, three walls in each classroom, floors and ceilings were assumed to be adiabatic. The build-up and U-values of the external walls were determined by the school's construction era and assigned in the model generation process (between 1.8 – 0.83 W/m²k, from oldest to newest). WWR – as processed and averaged through PDSP – were also assigned at this stage (between 23 – 29% of external wall surfaces). In an automated modelling procedure, programmed in Python 3.9.2 [20] and using EPPY [21], the 'seed' model was manipulated to include relevant archetype data resulting in a set of modes that represent archetype classrooms by climate region, described in Table 2. The model was simulated in both London and West Pennines climate zones using parameterised dataset inputs for outdoor PM_{2.5} and NO₂ and using indoor and outdoor CO₂. The EnergyPlus model had static occupant behaviour assumptions, with windows scheduled to open during occupancy whenever indoor temperature exceeded 21°C, and only if the difference between indoor and outdoor temperature was greater than 2°C, (Table 1). Furthermore, windows were set to open at the first 10 minutes of every lesson during school occupancy times, regardless of temperature. Only naturally ventilated buildings were included in the stock model. modelling only the largest building in case of 'multi-block' schools.

2.2.2. Estimates of indoor concentration of outdoor sourced PM_{2.5} and NO₂. The model was used for estimating monthly and annual average I/O ratio for PM_{2.5}, and annual average I/O ratio for NO₂, due to data availability on average monthly figures for the different pollutants. Deposition velocities were modelled for both PM_{2.5} and NO₂, with calculations presented in literature [8]. The average classroom internal surface area (floor, ceiling, and total wall area) to volume (floor area × ceiling height) ratio was

calculated to be 1.13 m^{-1} , using the estimated classroom dimensions from Figure 2, and based on [22]. Deposition rates for $\text{PM}_{2.5}$ (0.19 h^{-1}) [23] and NO_2 (0.87 h^{-1}) [24] were used to calculate their deposition velocities, $4.67 \times 10^{-5} \text{ ms}^{-1}$ and $2.14 \times 10^{-4} \text{ ms}^{-1}$ respectively. Outside $\text{PM}_{2.5}$ values were modelled with a penetration factor of 0.8 (the fraction of pollutants that infiltrate through the building envelope) during the October to April heating season, and 1 at all other times [8]. NO_2 was modelled with a fixed penetration factor of 1 [25]. The authors acknowledge significant uncertainties in deposition velocities and penetration rates estimations. Monthly and annual average background $\text{PM}_{2.5}$ and NO_2 levels for 2019 were obtained from UK Department for Environment, Food and Rural Affairs [26], [27] publications. DEFRA publications show multiple sensor-sites for pollutant measurements at each climate zones. Therefore, measurements for all 'London' sites were averaged for the London climate area. Pollutant levels for Blackpool and Manchester sites were averaged for the West Pennines climate area. Through the post-processing analysis, outdoor average levels were multiplied by the simulated I/O ratio for each archetype, which resulted in the estimated indoor concentration of each outdoor pollutant.

Table 1. Model inputs.

Ventilation	Value	Time on
Infiltration	1 l/m ² exterior surface area	24 hours
Natural Ventilation	8 l/second/person Fixed (rather than air flow network)	a. 09:00 – 16:00, 10 minutes at the beginning of every hour. b. If internal temperature is above 21°C, and difference between indoor and outdoor temperature is greater than 2°C
Internal loads	Loads	Schedule
Lighting	5.1 W/m ²	09:00 – 16:00: 100%
Occupancy	0.56 ppl/m ² with 110 w/p	09:00 – 16:00: 100%
Electrical equipment	3.3 W/m ²	09:00 – 16:00: 100%
Thermostat	Temperature	Schedule
Heating setpoint	20°C	09:00 – 16:00
	12°C	Otherwise

Table 2. Schools' classification: Primary schools archetypes (Na = Natural Ventilation. Me = Mechanical ventilation).

Era	London										West Pennines															
	Pre-1919		Inter-War		1945-1966		1967-1976		Post 1976		Pre-1919		Inter-War		1945-1966		1967-1976		Post 1976							
Schools	488		240		529		559		390		358		121		310		506		241							
V	Na	Me	Na	Me	Na	Me	Na	Me	Na	Me	Na	Me	Na	Me	Na	Me	Na	Me	Na	Me						
Schools	477	11	234	7	511	18	543	16	358	32	355	3	121	-	302	8	494	12	228	13						
Extensions?	N	Y	-	N	Y	-	N	Y	-	N	Y	-	N	Y	-	N	Y	-	N	Y	-					
Schools	34	443	-	26	207	-	84	427	-	98	445	-	120	238	-	2	353	-	121	-	302	-	494	-	228	-
Average WWR (%)	25	27	-	28	26	-	27	26	-	29	27	-	25	27	-	23	24	-	25	-	23	-	23	-	24	-

2.2.3. *Estimates of indoor concentration of indoor and outdoor CO₂.* Constant outdoor CO₂ value was estimated to be 415 ppm. The source of indoor CO₂ was related to occupants and tied with the occupancy schedule, as described in Table 1. CO₂ generation rate was assumed to be $3.82 \times 10^{-5} \text{ m}^3/\text{s}^{-w}$ [16]. The authors acknowledge the uncertainty in the occupancy schedule, occupants' activities and the associated emission rates which may lead to different indoor CO₂ generation rates.

2.2.4. Overheating analysis. The model does not include air quality-controlled windows. Instead, it investigates overheating potential as a result of the users' window control – as defined in section 2.2.1 above, in attempt to reflect the way natural ventilation in classrooms is used in practice. To calculate overheating, hourly temperatures in each classroom was simulated. Based on CIBSE Guide A's guidance for overheating assessment [28], the percentage of hours exceeding 28°C were calculated by archetype. Similar to other performance proxies, overheating was examined for months when schools' classrooms are occupied; between September and July, excluding weekends and UK bank holidays.

3. Results

All ratios and figures in this section are calculated for the assumed school occupancy hours only (09:00-16:00) as these are the times where pupils may be affected by poor indoor air quality.

3.1. Comparing indoor contamination of outdoor NO₂ – London / West Pennines climate areas

An analysis of DEFRA's average NO₂ levels (Figure 3) shows a steady decrease in average figures over time. For this reason, it was decided to only consider the last five years of data (2015 – 2019) in calculating the static average NO₂ levels. In the five selected years, external NO₂ levels vary from 19.1 – 53.1 µg/m³, and an average of 34.5 µg/m³ for the London climate area, compared to 12.2 – 40.1 µg/m³ and an average of 25.2 µg/m³ in the West Pennines climate area. The modelled I/O ratios and resulting absolute NO₂ concentrations are shown in Table 3. While I/O ratios seem to be very similar (due to similar window opening times and a slightly higher ratio for the warmer region), London area shows significantly higher absolute NO₂ concentration levels, due to higher average ambient outdoor pollution.

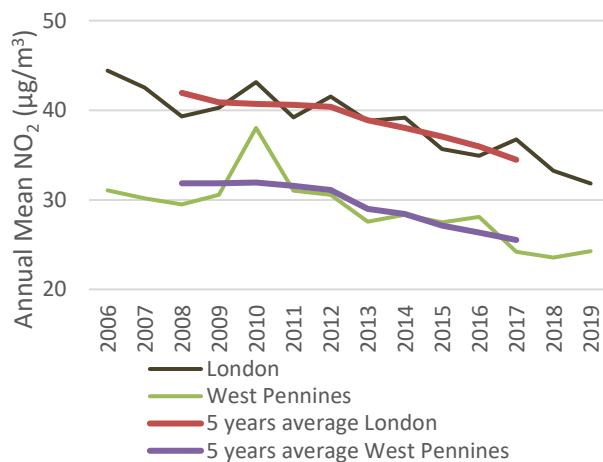


Figure 3. Annual mean outdoor NO₂ concentration – London and West Pennines climate areas.

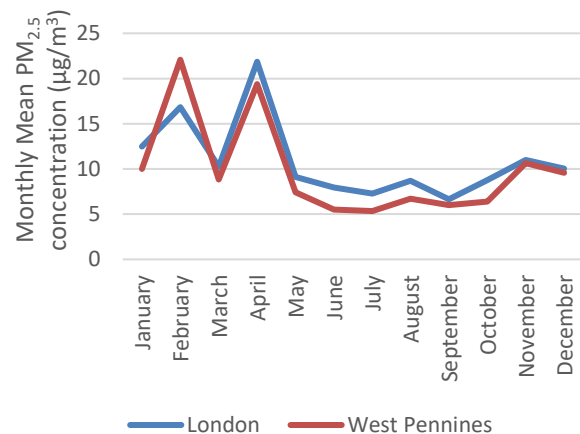


Figure 4. Mean monthly average outdoor PM_{2.5} concentration – London and West Pennines climate areas (2019).

3.2. Comparing indoor contamination of outdoor PM_{2.5} – London and West Pennines climate areas

Detailed monthly averages for PM_{2.5} were available from DEFRA's database for 2019 for both climate areas. PM_{2.5} Monthly average variations is presented in Figure 4. Based on this data, annual average PM_{2.5} for London area was 10.9 µg/m³, while annual average in the West Pennines was 9.8 µg/m³. Table 4 shows the modelled I/O ratios and the absolute PM_{2.5} concentrations figures. Similarly to the NO₂ simulation results, simulated I/O ratios were very similar in the two regions, however, in this case the London area shows a smaller difference of PM_{2.5} concentration values compared to the West Pennines, due to the smaller differences in average background PM_{2.5} levels.

3.3. Comparing indoor CO₂ levels in London / West Pennines

Simulation results for CO₂ concentration show an average of 1,247 ppm for a London-based typical classroom during occupancy, compared to 1,278 ppm in the West Pennines area (2.5% difference). As

the main source of indoor CO₂ levels is occupants, and while occupancy profiles and background emissions are similar in both regions, this difference is attributed to the ventilation control as the result of the indoor air temperature, which allows more frequent ventilation in the warmer climate of London. Tables 5-6 show a breakdown of seasonal indoor CO₂ levels in London. Results show significant fluctuations in indoor CO₂ levels, due to both warmer external temperatures coupled with high indoor occupant densities that bring to an increase in temperature. This allows more frequent window opening and higher ventilation. An analysis of indoor CO₂ levels based on archetype's classroom orientation in London shows that south-facing classrooms have the lowest average hourly CO₂ levels, while north-facing classrooms have the highest. This is, again, attributed to the indoor temperature differences as the result of solar gains, which allow more frequent window openings in south-facing classrooms.

Table 3. Simulated annual NO₂ I/O ratios and absolute average values.

	London area	West Pennines area
I/O ratio	0.74	0.72
µg/m ³	25.3	9.9

Table 4. Simulated annual PM_{2.5} I/O ratios and absolute average values.

	London area	West Pennines area
I/O ratio	0.77	0.78
µg/m ³	8.5	7.45

Table 5. Simulated seasonal hourly average indoor CO₂ (ppm)

	Jan - Mar	Apr - Jun	Sep - Dec
CO ₂ (ppm)	1,695	1,020	1,312

Table 6. Simulated annual hourly average indoor CO₂ (ppm) by classroom orientation

	West	East	South	North
CO ₂ (ppm)	1,249	1,239	1,158	1,310

3.4. Overheating assessment

An overheating analysis was carried out on the London classroom archetype based on CIBSE Guide A [28], where the allowed percentage of occupancy time spent over 28°C is 1%. Table 7 shows the percentage occurrences when indoor temperature exceeds 28°C in classrooms of each archetype in London, showing classrooms with four different orientations. Results show that east, west, and south-facing classrooms have around four times higher risk of failing the overheating criteria. Furthermore, schools built post-1976 are at higher overheating risk, likely due to the envelope's improved thermal performance. Schools built post-war (1945 – 1967) had the lowest risk of overheating.

Table 7. London classrooms Overheating risk – Percentage of occupied hours above 28°C (%).

	West	East	South	North
Pre 1919	2.8	3.4	3.2	0.8
Inter war	3.1	3.8	3.5	0.9
1945-1966	2.6	3.2	2.8	0.8
1967-1976	2.8	3.5	3.2	0.8
Post 1976	3.7	4.5	3.9	1.2

4. Discussion & Conclusion

This paper described the development of a national archetype stock model for school classrooms and its application in estimating indoor environmental quality (indoor exposure of indoor and outdoor pollutants and risk of overheating). The proposed archetype model enabled a rapid comparison of indoor environmental quality proxies in classrooms in two climate regions in England. The model can be used to estimate current exposure levels under current weather and pollution conditions, but also future scenarios, accounting for climate change, reduced indoor emissions or outdoor fuel types.

4.1. I/O Pollution levels (PM_{2.5}, NO₂)

The proposed archetype framework enabled a rapid estimation of I/O pollution ratios. The modelled I/O ratio for PM_{2.5} was around 0.78 – higher than previous studies (0.13-0.86 [8], 0.45-0.62 [29]). This is likely due to the difference in calculating the ratio, which in this study only accounted for ratio during occupancy time. Absolute PM_{2.5} values fell within the wide range of results for previous studies – 8.5

and $7.55 \mu\text{g}/\text{m}^3$, compared to $3.2 - 12.9 \mu\text{g}/\text{m}^3$ [8] and $5.2 - 11.4 \mu\text{g}/\text{m}^3$ [9]. As for NO_2 – the I/O ratio results in this study ($0.74 - 0.72$) are slightly higher than figures calculated in other studies ($0.25-0.64$ [8]) and absolute NO_2 values (25.3 and $9.9 \mu\text{g}/\text{m}^3$) are also generally on the high range of similar studies ($7.3 - 23.3 \mu\text{g}/\text{m}^3$ [8]), again, probably because of the focus on occupancy times and window opening in this study. As for NO_2 , the model was also capable of factoring seasonal variations in outdoor pollution levels. This can be extremely useful in the evaluation of school environments – spaces that are occupied intensively throughout most of the year. It is worth mentioning that existing literature covers housing, which may explain discrepancy due to operational patterns. The analysis could not find significant differences in indoor pollution levels across the different archetypes. It is suggested that the minimal differences are the result of similar ventilation rates and windows opening times, as the result of the internal temperature levels, which is not significantly different when comparing the archetypes. Archetypes' build-ups have an impact on heat-loss. It is therefore expected that these will have a more significant impact on heating energy consumption.

4.2. Indoor & Outdoor CO_2 , Overheating risk

Simulated values of average indoor CO_2 concentration have shown annual variations, with higher CO_2 levels during winter months. A relationship has also been derived between classroom orientation and indoor CO_2 levels – which may be especially useful in the design of new school buildings. Conversely, the study has shown that north-facing schools have the lowest overheating risk compared to any other orientation. This important finding highlights conflicts between ventilating and passive cooling of indoor spaces through ventilation while relying on intake of outdoor air, which may be contaminated.

4.3. Limitations

Occupant behaviour – The proposed model currently uses a fixed occupancy and usage schedules. In practice, classrooms may be used differently and that the window-opening control may vary significantly, for example due to proximity to noisy and busy roads, or any other personal preference.

Pollutant behaviour – The degree of uncertainty in using annual, or even seasonal averages to calculate indoor air quality is acknowledged, especially in light of evidence for hourly variations in pollution. These averages were used due to unavailability of more detailed pollution levels for selected locations. The model, however, can receive any changes in outdoor pollution levels or deposition velocities.

Archetype build-ups – it is acknowledged that there may be a range of variations in the assumed archetypes build-ups. It is also noted that the fabric of many school buildings may have undergone a retrofit over the years, and that the actual fabric's thermal properties may be better than those assumed in the model. However, with better input descriptive data of the stock the modelling accuracy can be improved.

Ventilation rates – To test the models' capability in providing meaningful outputs, the ventilation modelling was simplified in this study, and was set to $8\text{l}/\text{s}/\text{p}$ whenever windows were opened. It is acknowledged that a fixed ventilation rate may not be the most appropriate means of simulating a naturally ventilated environment, however, this was used as a 'proof-of-concept'. More detailed natural ventilation models can be developed for future work to describe the indoor air quality analysis.

A detailed evaluation of the model's sensitivity to various input variables should be carried by using sensitivity analysis. This could help identifying those factors that impact the model outputs most.

Acknowledgments

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