CAN INDOOR AIR QUALITY IN VICTORIAN CLASSROOMS SATISFY GOVERNMENT STIPULATED REQUIREMENTS?

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1. SUMMARY

Research indicates that high carbon dioxide (CO_2) levels in classrooms adversely affect the health and productivity of students. To address this, the government stipulates indoor air quality (IAQ) requirements in Building Bulletin 101 (BB101) as maximum CO_2 concentrations and minimum ventilation rates for classrooms. Due to recent budget cuts, school refurbishments are attracting more attention than new-build.

This work, involving a naturally ventilated Victorian classroom, uses computational fluid dynamics (CFD) simulations to predict the IAQ performance of six refurbishment interventions in order to investigate compliance with BB101 requirements. Furthermore, focusing on the BB101 compliant interventions, it explores their thermal comfort impact in terms of draught and vertical temperature difference, and determines their energy consumption impact by combining output from a parallel dynamic modelling (DTM) study.

Three interventions (parallel windows, plenum, roof-window) satisfy BB101 IAQ requirements. Of these, the parallel window emerges as the intervention achieving the greatest energy savings and causing thermal discomfort to the least number of occupants.

2. AIM AND OBJECTIVES

The aim of the study was to determine the most appropriate intervention for the classroom of the case study, with respect to heating energy consumption and thermal comfort parameters, in order for BB101 requirements to be met throughout the year.

In reaching the above aim the following objectives were pursued:

1. Select the most appropriate IAQ standards and thermal comfort requirements that will be used throughout the study to appraise predictions of CO_2 concentration, ventilation rates, draught and vertical temperature difference.

2. Obtain data on dimensions, location and surroundings, heat gains, occupancy schedules, as well as window opening strategy.
3. Monitor external temperature and indoor CO_2 concentration and temperature, for characterising current IAQ levels and calibrating the base case CFD model.
4. Compile a list of interventions suited to the specific case study, based on: safety, acoustics, maintenance and ease of use, and model them as parametric CFD studies.
5. Using CFD predicted CO_2 concentrations and ventilation rates for each intervention assess compliance with BB101 requirements.

For interventions whose IAQ performance satisfies BB101 requirements:

6. Assess the CFD predicted thermal comfort impact on the occupants in terms of draught and vertical temperature difference.
7. Compare the CFD predicted CO_2 level reductions with the corresponding DTM reductions and obtain the DTM predicted energy savings associated with each intervention.

3. INTRODUCTION

School buildings have an important role in the effort to meet the UK government's emissions targets, as 'almost 15 per cent of carbon emissions (are) attributable to the public sector' (SDC, 2008). The recent abolition of the Building Schools for the Future (BSF) government investment programme puts emphasis on retrofitting existing schools in order to improve energy efficiency, rather than building new ones. Clements-Croome et al. (2008) recognise a 'trend to save energy by reducing ventilation rates'. On the effects of this Bakó-Biró et al. (2012) presented evidence that 'low ventilation rates in classrooms significantly reduce pupils' attention and vigilance, and negatively affect memory and concentration'. To ensure good IAQ in schools the government's BB101: *Ventilation for School Buildings* (DfE, 2006), concentrating on maximum CO_2 concentrations and minimum ventilation rates, provides the regulatory framework.

The work presented here forms the third part of an investigation on the relationship of IAQ levels, energy demand and thermal comfort in a naturally ventilated Victorian classroom in the UK. Simpson (2011) initially quantified the IAQ and energy consumption of the building, while Hallin (2012), concentrating on one classroom, determined the relationship between minimum energy cost, temperature and adequate IAQ for eight interventions using dynamic thermal simulation. This study employed CFD for the simulation of six of these interventions in the same classroom. CFD is a detailed modelling technique increasingly applied in recent years in the investigation of indoor airflows (Chen, 2009). The software tool used was the FLAIR component of the PHOENICS CFD package. The IAQ requirements and thermal comfort recommendations for the appraisal of the CFD predictions are compiled in Table 1.

Table 1: Compilation of IAQ standards and thermal comfort requirements

CO_2 concentration BB101 (DfE, 2006)	**Ventilation Rates** BB101 (DfE, 2006)	**Draught** (ASHRAE, 2009)	**Vertical Temp Difference** (CIBSE, 2006a)	**Temperature Limits** BB101(DfE, 2006) & (DfE, 2013)
mean value ≤ 1500ppm at any occupied time	minimum value ≥3 l/s/person	air velocity ≤0.25m/s	head height and ankle ΔT≤3K	T≤32°C
capacity to lower it to 1000ppm (measured at seated head height)	capability for purge ventilation ≥8 l/s/ person			T≥16°C

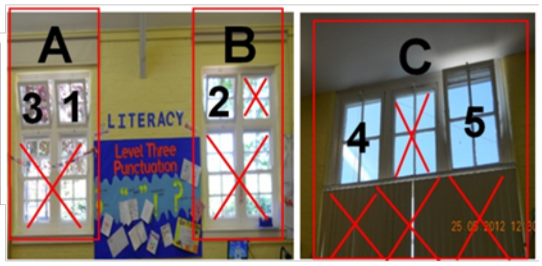
4. DEFINITION OF THE BUILDING AND SYSTEMS

The case study concerns a naturally ventilated primary school located in the East Midlands in a medium-sized village away from urban areas with increased CO_2 levels. The building is comprised of the original 1871 built Victorian section and a post-1968 extension. The classroom investigated (Fig.1) is located at the corner of the Victorian section, has a pitched roof and large Victorian bottom hung, single pane, wood cased windows on 0.35m thick solid brick external walls, facing a light-traffic road on the West and a car park on the North. Space dimensions are 6.5x6.5m and the volume is 169m^3.

In Figure 1, windows noted with ''X'' are sealed with layers of paint, while the numbers represent the preferred window opening pattern. During the heating period (October 1 to March 30), internal heat gains amount to a total of 4415.66W, taking into account a single radiator. During the non-heating period this is reduced to 2995W. Due to orientation and surrounding trees direct sunlight through windows does not affect the space.

Six interventions were selected as parametric CFD studies based on their practical suitability to the specific school in terms of safety and acoustics, as well as

Openings	Dimensions
Small Windows	1.20 x 1.60m
Large Window	2.30 x 2.55m
Corridor Door	1.96 x 1.25m



INTERNAL HEATGAINS				
SOURCE	BREAKDOWN	HEAT (Watts)	SUMM (Watts)	NOTES
Occupants	30 students & a teacher	31 x 70	2170	from CIBSE Guide A Table A6.3, assumed as "seated, very light work"
Heating	Radiator	1345.66	1420.66	data from parallel study
	Convector Fan Motor	75W		data from heating engineer
Equipment	Computer	55	225	from CIBSE Guide A Table A6.7
	Monitor	70		from CIBSE Guide A Table A6.8
	Projector	100		from CIBSE Guide A Table A6.12
Lighting	8 Fluorescent F75W/35 lamps	8 x 75	600	wattage from lamp code
TOTAL: 4415.66 W				

Figure 1: Data on classroom orientation, window measurements and opening pattern, and internal heat gains

maintenance and ease of use. Detailed assessment of these against the corresponding standards was out of the scope of this investigation. However, an empirical and intuitive evaluation was possible. Four of the interventions involve varying the openable sections within the Victorian window frames, while two are structural additions. The interventions are:

- Intervention 1: Low level openings
- Intervention 2: Top openings with low level fully open vents
- Intervention 3: Mixed openings (low on frames A&B, high on frame C)
- Intervention 4: Parallel windows
- Intervention 5: 0.6m high plenum addition
- Intervention 6: 1.0x0.28m roof-window addition

5. MODELLING APPROACH, TOOLS USED AND LIMITATIONS

The base case CFD model (Fig. 2) was comprised of the existing openable areas in the classroom. It was refined by checking the CFD predicted CO_2

concentrations and temperatures against actual values monitored between February 2 and May 25, 2012 for:

• Outdoor temperature in °C (HOBO Pendant® Temperature/Alarm Data Loggers)

• Class CO_2 concentration in ppm (Telaire 7001 Carbon Dioxide Monitor)

• Indoor temperature in °C (HOBO Temperature/Relative humidity/Light External Channel Data Loggers)

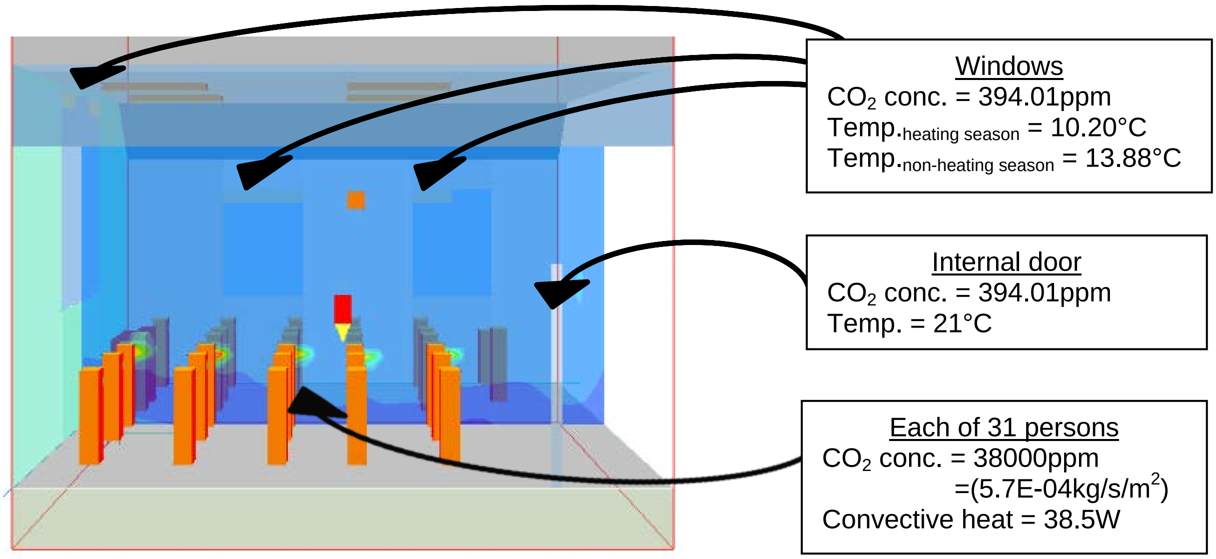


Figure 2: Base case CFD model in PHOENICS with temperature and CO_2 boundary conditions for openings and occupants

The geometry of the base case involved a 6.5x6.5x7.16m domain containing 31 CO_2 exhaling occupants and heat emitting equipment whose dimensions were altered to avoid complexity of the computational grid. A grid of 70x60x50 (210000cells) was derived, as a grid independence test showed temperature and CO_2 concentration, plotted for a point in the domain (x=4, y=6.3, z=1), to be independent of grid density in this cell range. The domain material was specified as standard air, the buoyancy model used was Boussinesq and solar radiation was considered negligible. Considering the high-Reynolds-number k-ε model and its variations have been shown to produce accurate results in previous work (Nielsen et al., 2007), the Kato-Launder variation was used as turbulence model as it provided best convergence of results.

The boundary conditions were as follows.

• at external walls: adiabatic with zero thickness

• at each of the two internal walls and ceiling: 325.5W. This was determined by dividing the total surface heat flux by the three surfaces. The total surface heat flux was calculated as the radiant heat, assumed as 45% of a person's sensible heat (70W), emitted by 31 occupants.

• at heat emitting fixtures and people (modelled as 0.3 x 0.2 x 1.0m volume objects): heat gains (Fig.1) were divided by the number of exposed object surfaces to represent the surface heat flux of each surface. For each person this was 7.7W convective heat, calculated as the remaining 55% of a person's sensible heat, divided by five exposed sides.

• at windows, vents and the internal door opening: window temperature was 10.20°C for the heating season, 13.88°C for the non-heating (averages of monitored external temperature) and door temperature 21°C (heating system installer set point). The CO_2 concentration was assumed to be 394.01ppm (5.986x10-4 kg/kg) (NOAA/ESRL, 2012). The flow direction was unspecified, with a loss coefficient of 2.69 and assumed medium turbulence flow with turbulence intensity at 5%,

• at CO_2 sources from 31 people (modelled as two dimensional 0.1x0.1m mouths): 38000ppm from a CO_2 mass flux equal to 5.7 x10-4 kg/s/m^2. This was computed based on an assumed density of 1.2kg/m^3 and a volume flow rate of 4.75x10-6 m^3/s with the assumption that there are 15 0.5l breaths in 1minute, and that the speed of respiration CO_2 is 0.0125m/s.

In assuring the quality of the simulation outputs, all CFD simulations were checked for convergence of their solution results by means of:

• errors in the balance of mass flow in and out of the domain being less than 1% of each flow

• errors in the balance of heat flow being less than 1% of the total heat gains

• constant monitoring values

The simulations initially failing to pass the above criteria underwent an iterative process involving running the same models for modified under-relaxation factors, or an increased number of cells, until convergence was achieved.

In terms of monitoring, the study was compromised by often having the electricity that supplies one of the two CO_2 and temperature sensors being switched off by cleaning personnel. In terms of the CFD analysis, furniture modelling was omitted as it would complicate the grid composition, and actual dimensions and location of heat emitting objects were altered for simplification of grid density.

Although the number of cells was chosen after a grid independence test, at 210000 it is still only about two thirds the number of cells computed by the equation: ’$N = 44.4 \times 10^3 V^{0.38}$‘, where N is the number of cells and V the space volume in m^3. This equation is used as a rough estimate by the German guideline VDI6019 (Nielsen et al., 2007) and in this case results to 311875cells.

6. RESULTS AND DISCUSSION

Comparing the CFD predictions of CO_2 concentrations for the parametric studies shows that all interventions apart from low level openable windows improve the current CO_2 performance. However, four interventions − mixed level openings, parallel windows, the plenum and the roof-window− meet the BB101 requirements, for both the heating and non-heating seasons. Best results for uniformity of CO_2 distribution are produced for the parallel windows and the roof-window interventions, the latter also resulting to the lowest CO_2 concentration values.

In terms of ventilation rates, the last three interventions meet the BB101 criterion of 3l/s/p, with 8l/s/p purge capacity, the whole year round. The plenum intervention is predicted to provide the highest ventilation rate.

In terms of average draught, all cases satisfy the ASHRAE requirement of being less than 0.25m/s. However, due to uneven distribution of draught, there are locations in the classroom where levels are above those acceptable. Figure 3 shows the plenum intervention producing evenly distributed low value draughts at the level of the ankles and the head, while in the parallel window and roof-window cases up to 16% of the occupants (5 persons, enclosed in white dotted boxes) is affected by discomfort.

The CIBSE recommendation for vertical temperature gradient to be less than 3K is not met by any intervention analysed. The closest achieved is by the roof-window at 3.35°C in the non-heating season. A matrix similar to that of Figure 3 but for temperature, allows checking for discomfort due to extreme temperatures. The plenum intervention generates temperatures below the lower acceptable limit of 16°C at both levels during the heating season. The addition of a roof-window creates temperatures within the comfort limits at all times, while the parallel windows cause discomfort due to temperatures below 16°C to 13% of occupants (4 persons) when all windows are open during the heating period.

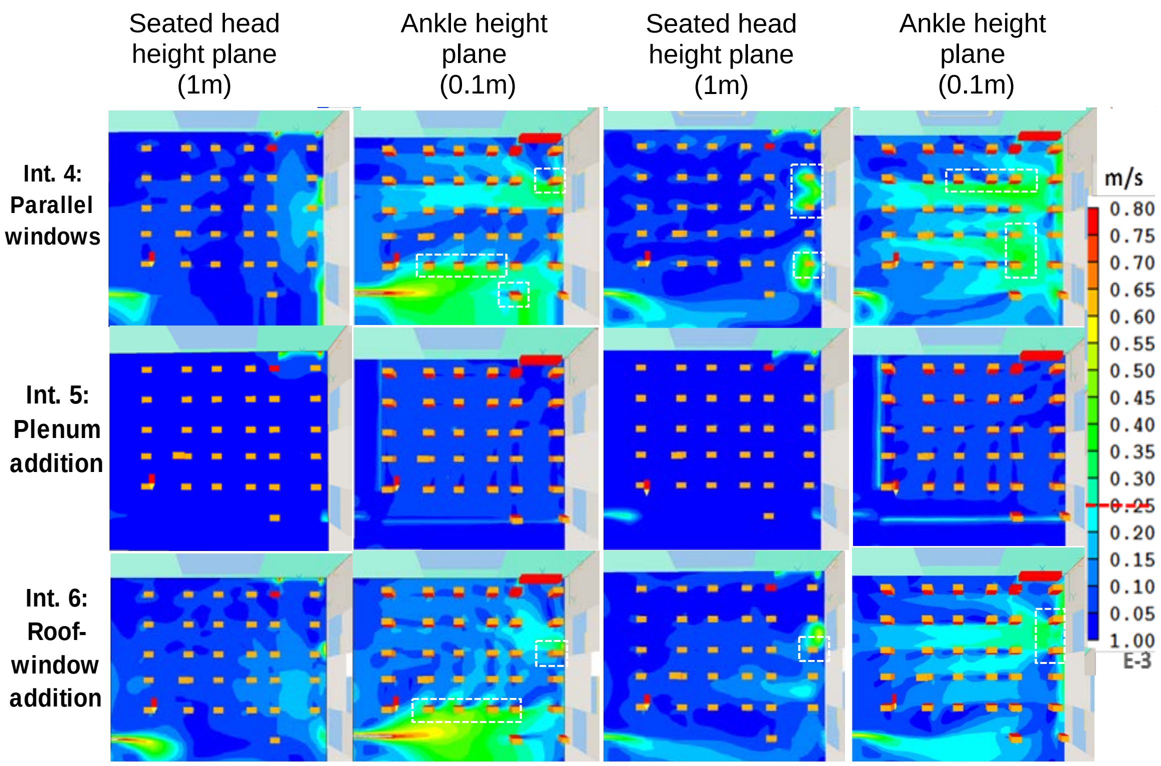


Figure 3: Matrix of top view velocity variation results at ankle and head height levels during the heating season

Finally, three interventions satisfy BB101 IAQ requirements, the parallel windows, the plenum and the roof-window. Taking into consideration their thermal comfort performance (Table 2) it initially appears that the roof-window performs best against the relevant standards. Although none of the three interventions is predicted to meet the CIBSE vertical temperature gradient standard for the minimum opening areas, the roof-window causes discomfort to the least number of occupants, affecting a maximum of 16% with draught.

Adding the factor of potentially improving the energy efficiency of the classroom alters this early conclusion. The third group of columns (Table 2) takes into consideration the parallel dynamic simulation study of Hallin (2012). Although Hallin uses room average CO_2 concentrations, the trend concerning percentage CO_2 level reduction from the base case levels, is the same as that of the CFD study results for the plane of seated head height. For both minimum and maximum window opening areas the CFD simulation predicts the roof-window intervention to lead to the largest CO_2 reductions (33.55% and 46.53% respectively), followed by the parallel windows (14.85% and 43.64%). Hallin's findings follow the same trend (from 59% to 55%). The similarity between CO_2 results sourced from different simulation

Table 2: Comparison of BB101 compliant interventions with respect to thermal comfort and predicted CO_2 and heating energy reductions

		IAQ REQUIREMENTS		THERMAL COMFORT PARAMETER RECOMMENDATIONS			CO_2 & ENERGY DECREASE FROM BASE CASE VALUES		
		BB101: on CO_2 conc.	BB101: on Ventilation rate	ASHRAE: Draught	CIBSE: Vertical temperature difference	BB101 & DOE: Temperature limits	CFD STUDY (PHOENICS): Plane Av. CO_2 conc. @ z=1m	DYNAMIC STUDY (IES): Room Av. CO_2 conc.	DYNAMIC STUDY (IES): Energy savings
Intervention 4: Parallel windows	W_{min}	COMPLIES	COMPLIES	NO agreement (16% of occupants in discomfort)	NO agreement	NO agreement (13% of occupants in discomfort)	14.85%	55%	21%
	W_{max}						43.64%		
Intervention 5: Plenum addition	W_{min}	COMPLIES	COMPLIES	AGREES	NO agreement	NO agreement	8.60%	42%	5%
	W_{max}						35.42%		
Intervention 6: Roof-window addition	W_{min}	COMPLIES	COMPLIES	NO agreement (16% of occupants in discomfort)	NO agreement	AGREES	33.55%	59%	8%
	W_{max}						46.53%		

methods strengthens the confidence in using Hallin's energy savings findings as the predicted energy efficiency improvement. The roof-window only results in an 8% energy saving from the 279kW/m^2/yr of the base case, while the parallel windows reduce heating energy demand by 21%.

Table 3 maps out localised thermal discomfort associated with the parallel window intervention which could be useful to the teacher when deciding the seating arrangement. Alternatively, these locations could provide comfort to students whose tolerance to heat is lower than that of the average.

7. CONCLUSIONS

The parallel windows intervention results to the largest energy savings and causes thermal discomfort to the least number of people while meeting BB101 requirements for IAQ. Compared to the modelled base case it is predicted to:

• reduce CO_2 concentration at seated head height by up to 21.0%

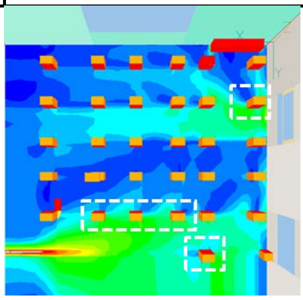
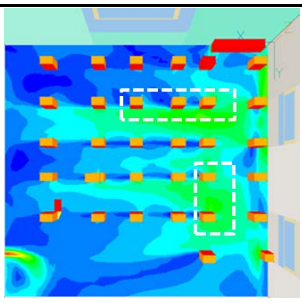
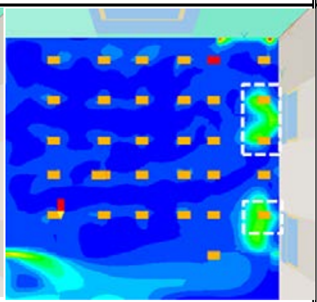
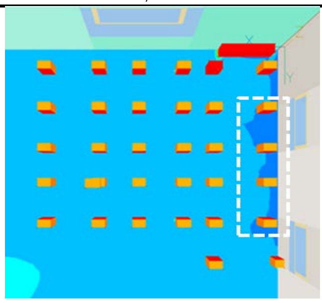
• increase ventilation rate per person by up to 43.3% and purge capacity by up to 47.1%

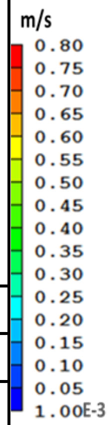
• reduce heating energy consumption by 21%

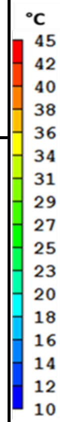
• cause discomfort due to vertical temperature difference only for the minimum openable window area

• cause discomfort due to draught only during the heating season, to a maximum of 16% of occupants, and discomfort due to temperatures less than 16°C to a

Table 3: Localised thermal discomfort predicted for Intervention 4: Parallel windows

			Heating season		Non-heating season	
			Ankle height z=0.1m plane	Seated head height z=1m plane	Ankle height z=0.1m plane	Seated head height z=1m plane
Intervention 4: Parallel windows	Minimum window opening	due to draught:	 16,13%	none	none	none
		due to cold:	none	none	none	none
		due to vert. T diff.:	4.73°C difference in average temperatures		4.14°C difference in average temperatures	
	Maximum window opening	due to draught:	 16,13%	 9,68%	none	none
		due to cold:	 12,9%	none	none	none
		due to vert. T diff.:	none		none	





maximum of 13% of occupants.

Running additional simulations for peak recorded winter and summer external temperatures would be useful in determining a range in values of IAQ and thermal comfort parameters for each intervention.

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