pollutants

Article

Indoor CO$_2$ and Thermal Conditions in Twenty Scottish Primary School Classrooms with Different Ventilation Systems during the COVID-19 Pandemic

Natalie Bain-Reguis [1,*] , Andrew Smith [1] , Caroline Hollins Martin [2] and John Currie [1]

[1] School of Engineering and the Built Environment, Edinburgh Napier University, Edinburgh EH10 5DT, UK; a.smith7@napier.ac.uk (A.S.); j.currie@napier.ac.uk (J.C.)
[2] School of Health and Social Care, Edinburgh Napier University, Edinburgh EH11 4BN, UK; c.hollinsmartin@napier.ac.uk
* Correspondence: n.reguis@napier.ac.uk

Abstract: Healthy indoor environments influence the comfort, health and wellbeing of the occupants. Monitoring the indoor temperature, relative humidity and CO$_2$ levels in primary schools during the COVID-19 pandemic was mandated by a local authority in Scotland. The aim was to investigate the comfort and safety of the teachers and their pupils. This paper presents the measurements of indoor climate in 20 classrooms in four different primary schools in Scotland. The schools were of different architypes. The classrooms were of different sizes, orientations and occupancy, and had different ventilation systems. Ventilation was achieved either by manually opening the windows, or by a mechanical ventilation system. Indoor air temperature, relative humidity and carbon dioxide (CO$_2$) concentrations were continuously monitored for one week during the heating season 2020/21. Occupancy and opening of the windows were logged in by the teachers. The ventilation rates in the classrooms were estimated by measuring the CO$_2$ concentrations. On the 20 classrooms of the study, data of 19 were analysed. The results show that four of the five mechanically ventilated classrooms performed better than natural ventilation, which indicates that opening the windows depended on the customs and habits. Classrooms in naturally ventilated Victorian buildings have the worst average ventilation rate (4.38 L/s per person) compared to the other classrooms (5.8 L/s per person for the more recent naturally ventilated ones, and 6.08 L/s per person for the mechanically ventilated ones). The results of this preliminary study will be used as the basis to find ways to ensure adequate ventilation in natural ventilated classrooms.

Keywords: school; classroom; ventilation system type; indoor temperature; relative humidity; carbon dioxide; IEQ; IAQ

1. Introduction

The quality of the indoor environment (IEQ) has been shown to have an impact on the health and wellbeing of workers [1], who mostly complain about poor indoor air quality (IAQ) [2] and inadequate indoor temperature [3]. Schools are not exempt from these issues, being places where pupils and teachers spend hours in an overcrowded enclosed space, often with poor ventilation [4].

Multiple studies [4–15] have shown the importance of maintaining appropriate IAQ in classrooms for the comfort, health and wellbeing of both pupils and teachers. The World Green Building Council has published a factsheet about IAQ for schools, and how bad air affects children [16]. According to this report, a 1000 parts per million (ppm) increase above ambient levels of CO$_2$ has been linked to a 10%–20% increase in days away from school.

Keeping healthy IAQ in schools will help children stay healthier, more focused and more productive [8,17]; it will help reduce health and wellbeing issues among pupils [9,10,18,19] and

teachers [11,12,20–22] while maintaining a comfortable and healthy working environment to enhance pupils' learning [6,7,13–15,23,24].

Furthermore, schools are known to be places where viruses can spread easily, from noroviruses to the seasonal flu [25], due to occupants being in close proximity to each other [26]. The SARS-COVID-19 virus is not different, being an airborne virus [27,28] and thriving in dark, dry and crowded places [29].

To evaluate the IAQ, an assessment of the ventilation rates of the rooms can be undertaken. Measuring metabolic respiration evolved carbon dioxide (CO_2) concentrations in occupied rooms has historically been shown to be a good proxy for ventilation assessment [30–32] and is proposed as part of ASHRAE Standards 62.2 [33] and the COVID-19 Education Recovery Group CERG (2020) guidance [34]. Since background (ambient) CO_2 level is relatively stable and indoor excess CO_2 is usually only from living beings' exhalation, measurements of indoor CO_2 concentration by low-cost CO_2 sensors can often be good indicators of ventilation adequacy and thus suitable for mass deployment [35,36].

Keeping schools open is essential for the mental, social and physical development of the children, but cannot be to the detriment of their own health and wellbeing nor that of their teachers. While it is paramount to ensure good ventilation in schools, the comfort of the occupants is also important. It is therefore necessary to monitor the indoor climate of the classrooms, which includes indoor temperature and relative humidity (RH).

Thus, monitoring indoor temperature, RH and CO_2 concentrations have become the guidance to ensure a safe indoor environment [37].

In Scottish schools, the latest guidance suggests CO_2 levels should not exceed 1500 ppm in classrooms and 800 ppm in music rooms and gym halls [35]. The ASHRAE standard 62.2 [33] recommends that indoor CO_2 levels should not be higher than 700 ppm compared to outside. If outdoor CO_2 is assumed to be around 420 ppm, this would mean that ASHRAE recommends a maximum of 1120 ppm for indoor CO_2. Other regulations have imposed stricter limits, down to 800 ppm for some European Countries [38], like in France [39] or in Ireland [40]. The Chartered Institute of Building Services Engineers (CIBSE) has published a new guide stipulating that the ventilation rate should be 10 L/s/person minimum, which is equivalent to 2 air changes/h [41].

The indoor temperature in Scottish classrooms should be kept above 17 °C, according to current regulations [35].

There is a close physical relationship between air temperature and RH levels (psychrometry), which makes the control of humidity in naturally ventilated spaces difficult through simple ventilation measures alone, and in the UK lower levels of RH as a trade-off are often accepted. There is currently no mandatory legal requirement to control RH and the relative risk posed by this parameter alone has not yet been fully ascertained in research. However, some studies have identified an RH 'sweet spot' between 40% and 60%, adding that air that is too dry would allow viruses to thrive and be more active [42,43].

Therefore, the main objective of the present work was to evaluate the environmental conditions of Scottish schools by monitoring the indoor temperature, RH and CO_2 levels of their classrooms, from different building architypes, different sizes, orientations and occupancy and with different ventilation strategies.

2. Materials and Methods

The study was at the request of a Local Authority in Scotland during the heating season of the COVID-19 pandemic (winter 2020/21) to assess the CO_2 levels, ventilation rates and thermal comfort in their classrooms. The study was performed in four urban primary schools all chosen by the local authority after receiving the approval to participate from the headteachers. The 20 classrooms were selected by the business managers of the schools in which the study was performed. Overall, 15 of the 20 classrooms were naturally ventilated, whereas 5 used a mechanical ventilation system.

The typology of all classrooms is presented in Table 1.

Table 1. Classroom's typology where the measurements were performed.

School	Classroom	Storey	Ventilation System	Orientation	Space Volume (m^3)	Space Area (m^2)	Year Built/Last Renovation	Occupancy (Teachers and Pupils)	
								Min	Max
A	A1	Ground	Natural	SSE-E	71.8	28.0	1964	23	27
	A2	Ground	Natural	SSE	94.3	36.3	1964	11	26
	A3	Ground	Natural	SSE	116.8	38.9	1964	24	28
	A4	1st	Natural	E-NNE	145.1	48.4	1964	23	24
	A5	2nd (Top)	Natural	SSE-W	145.1	48.4	1964	19	22
B	B1	Ground	Mechanical	E-W	142.8	47.6	1968	30	33
	B2	2nd (Top)	Natural	NE-SW	148.1	51.9	1968	27	29
	B3	1st	Natural	NE-SW	61.2	23.5	1968	22	29
	B4	Ground	Mechanical	NW	126.8	42.3	2013	23	27
	B5	Ground	Mechanical	N-S-E-W	432.0	154.3	2017	47	51
C	C1	Ground	Natural	W	196.0	38.2	1891	22	30
	C2	2nd(Top)	Natural	SW-W	184.3	40.0	1891	33	34
	C3	2nd (Top)	Natural	W	173.4	38.2	1891	22	31
	C4	2nd (Top)	Natural	NE	250.7	54.5	1891	22	30
	C5	2nd (Top)	Natural	NE-W	250.6	54.5	1891	32	33
D	D1	Ground	Mechanical	W	168.0	42	2015	24	35
	D2	Ground	Natural	SW	210.0	42	1902	30	34
	D3	1st	Natural	NE	192.0	48	1902	29	34
	D4	2nd (Top)	Natural	SW	165.0	33	1902	24	30
	D5	Ground	Mechanical	S	162.0	40.5	2007	23	31

School A, having been built in the early 1960s, is poorly insulated [44] and naturally ventilated, with classrooms on the ground floor having double doors opening directly into the playground.

Schools B and D are composed of different buildings built over the years with different ventilation systems.

School C is a typical Victorian school that is naturally ventilated.

Figures 1–17 show the locations and the floorplans of the schools (classrooms identified and devices localised by a red dot .) and illustrate the different architypes and ventilation systems of classrooms of the school buildings. Note: The floorplans are for illustration purpose and are not to scale.

Due to the emergency of the situation during the COVID-19 pandemic, the local authority granted access to each school buildings for a period of one week maximum over the heating season (November–December 2020), during which the measurements were performed (November–December 2020). They included the measurements of CO_2 concentration using TinyTag TGE-0010 and TGE-0011 loggers (accuracy $\pm$ 50 ppm, $\pm 2\%$ of reading). Other TinyTag TGU-4500 loggers recorded the indoor temperature (-25 to $+85\,^{\circ}C$) and RH (0% to 95%). All the data loggers were provided by the local authority.

Logging intervals were set to every minute with min, max and actual readings. Sample collection began by setting up all sensors for a fixed start time on their deployment date.

Once in the classrooms, the CO_2 monitors were plugged in to an available power socket and made safe with the logger mounted in the 'occupied zone' at approximately 1.5 m above floor level.

The temperature and RH sensors were located next to the CO_2 monitors, placed either on the teachers' desks or on shelves (as shown on Figure 18). Both monitors were positioned away from direct sunlight, radiators, doors and windows.

At the end of the one week of monitoring, all monitors were retrieved, and the data were downloaded onto the Tinytag Explorer platform via a USB cable. The data were then output to Microsoft Excel for analysis.

Figure 1. School A.

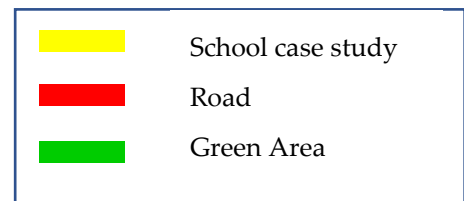**Figure 2.** Picture of school A.

Figure 3. Picture of classroom A2.
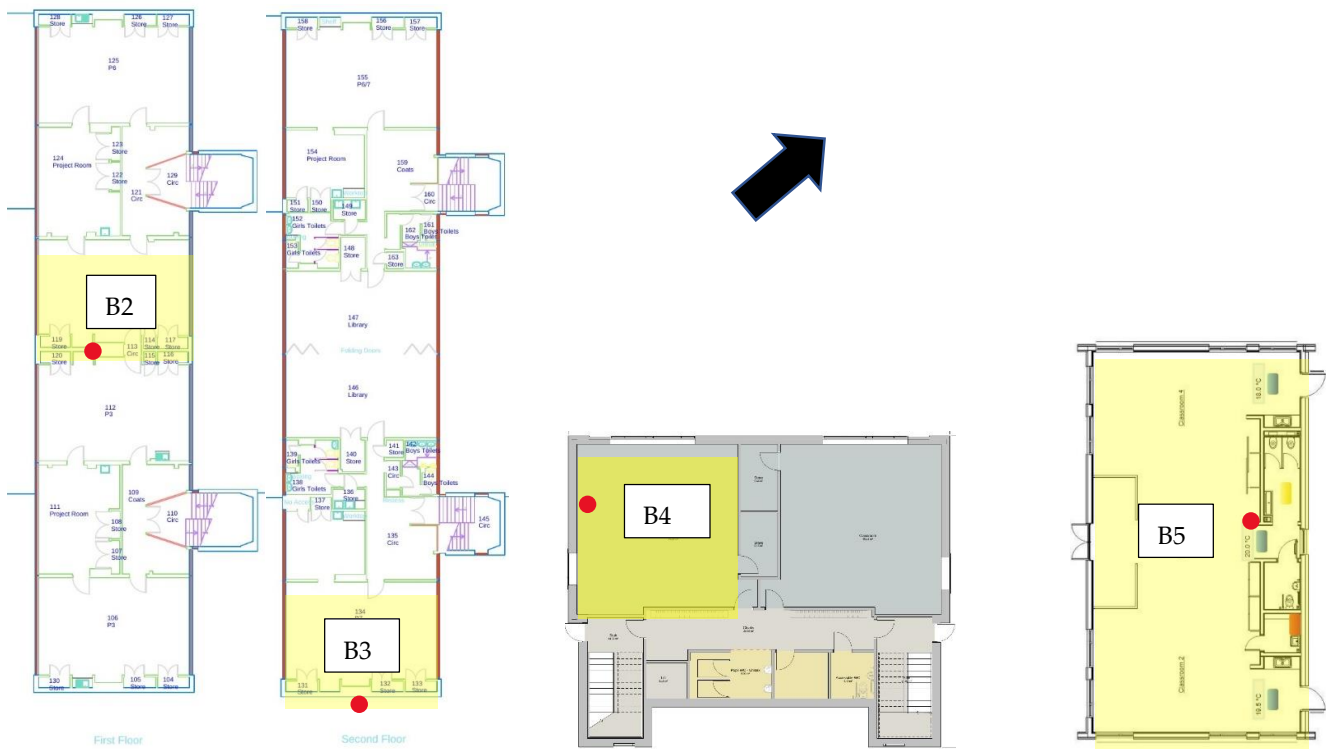

Figure 4. *Cont.*

Figure 4. School B.

Figure 5. Picture of school B.

Figure 6. Picture of classroom B1.

As any indoor environment is impacted by outdoor climatic conditions, the outdoor temperature, RH, wind speed and direction were also studied alongside the internal measured elements. The purpose was to identify potential correlation between the variations of the indoor and the outdoor conditions. The outdoor climate was monitored through the website https://www.wunderground.com/ (last accessed on the 20 November 2021) from different weather stations, located close to the schools monitored. Values were also

recorded from a centrally located weather station owned by Edinburgh Napier University, to validate the data from the Wunderground website.

Opening of the windows and doors and the occupancy were logged in by the teachers.

The average of the peak values of CO_2 concentration measured during school hours was used to estimate the classrooms ventilation rates. Batterman recently reviewed different methods to assess the ventilation rates, using occupant-generated CO_2 [45]. He described four main methods: the steady-state method, the concentration decay, the built-up method and the transient mass balance equation method. Allen and colleagues published a quick five-step guide to evaluate the ventilation rates in classrooms [46], one of which follows the steady-state method described by Batterman.

Figure 7. Picture of classroom B3.

Figure 8. Picture of classroom B5.
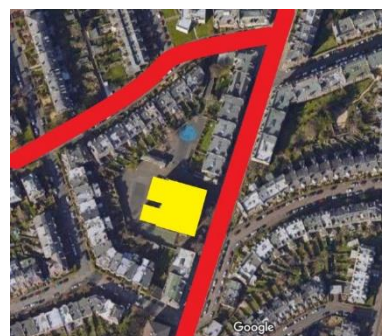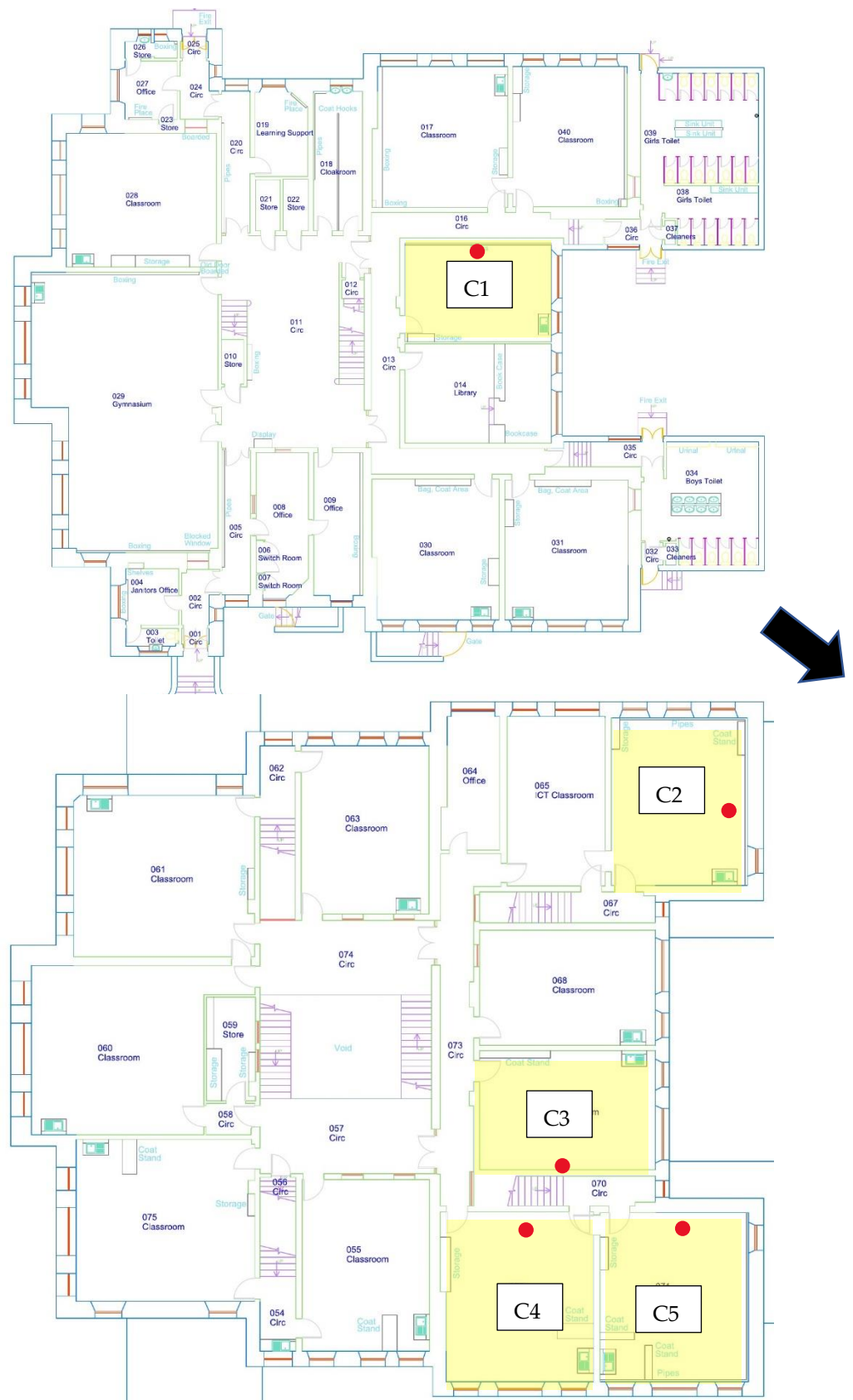

**Figure 9.** *Cont*.

Figure 9. School C.

Figure 10. Picture of school C.

Figure 11. Picture of classroom C3.

Logarithmic decay was used in early experiments in an attempt to evaluate room ventilation rates, but the transitory nature of occupancy experienced, combined with a limited range of concentration decay between occupancy events (flushing), gave inconsistent results. A method for mapping time integrated CO_2 evolution through resolving the first-order partial differential equation for a room ventilated at a specific rate was also undertaken but found to be very time intensive. It was thus decided to utilise time integrated metabolic CO_2 mass balancing to establish comparable metrics.

Considering the pros and cons of each method, and assuming the peak CO_2 is indicative of steady-state CO_2 concentration levels, it could therefore be used to estimate the minimum ventilation rate [41]. The CO_2 generation rate per pupil was assumed to be 0.004 L/s and 0.0054 L/s per teacher [47–49]. The outdoor CO_2 was assumed to be 420 ppm for the City of Edinburgh, considering the global average atmospheric CO_2 for 2020 was estimated to be 412.5 ppm (NOAA, 2021).
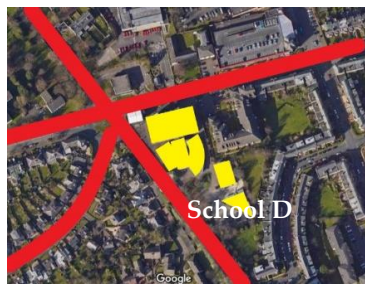
Figure 12. School D.

Figure 13. Picture of school D.

Figure 14. Picture of classroom D1.

Figure 15. Picture of classroom D3.

Figure 16. Picture of classroom D5.

Figure 17. Picture of classroom D5.

Figure 18. Monitors' positioning sample.

3. Results

In the following paragraphs, the indoor temperature, the RH and the CO_2 concentrations measured during the monitored weeks as well as the ventilation rates are discussed. **The patterned bars on the different graphs show the results for the classrooms with mechanical ventilation.** The monitor in the classroom B3 was unplugged shortly after deployment. Therefore, no data were analysed for this classroom.

3.1. Link between Outdoor and Indoor Climate (Temperature and RH)

No evident correlation could be found between outdoor conditions recorded and indoor monitored data. Longer periods of sampling might be necessary to verify the trend.

From the returned log sheets and data recorded therein, it was difficult to quantify exactly how often and for how long the window apertures were opened. Mechanisms for automatically recording window opening and room occupancy should be considered for further studies of this nature.

3.2. Indoor Climate (Temperature and RH)

This section details the indoor temperature and RH in all the monitored classrooms, alongside the 17 °C temperature threshold and the 40%–60% 'sweet spot' of RH levels.

3.2.1. Indoor Temperature

To assess the indoor temperature of the classrooms according to the 17 °C threshold, the minimum and the average indoor temperature of each classroom are shown on Figure 19. It shows that school A, room A5 (16.4 °C) and school B, room B4 (16.9 °C) recorded an average indoor temperature below 17 °C:
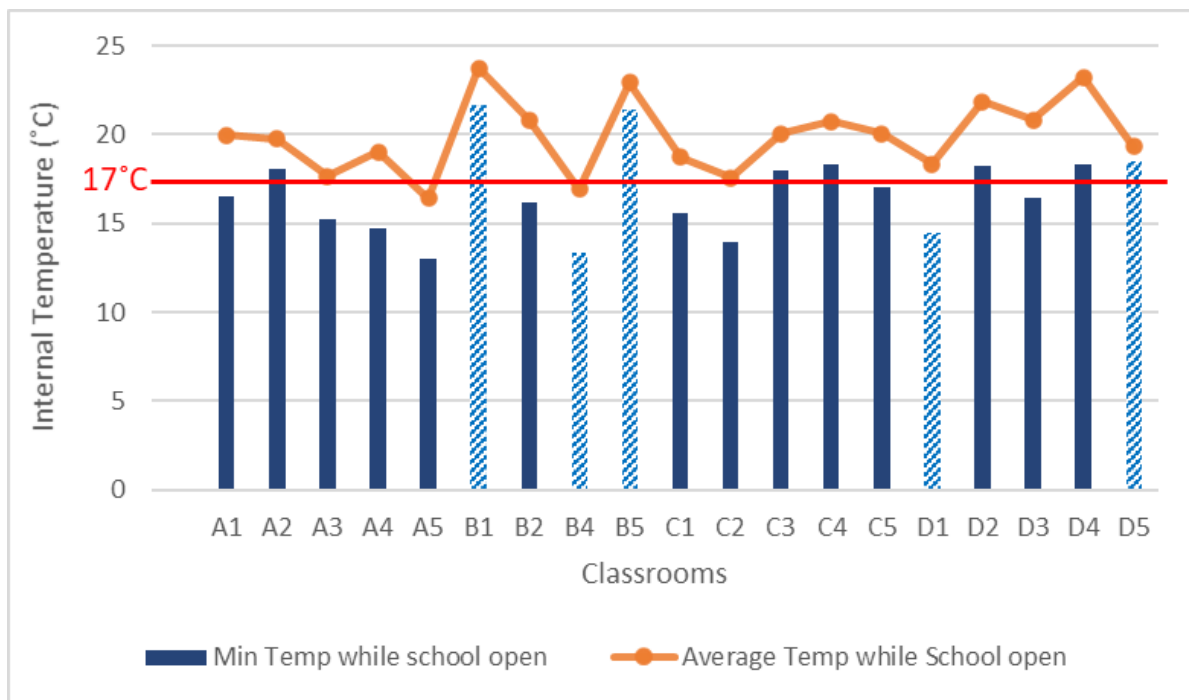
Figure 19. Indoor temperature in the classrooms during school hours, with classrooms B1, B4, B5, D1 and D5 having mechanical ventilation.

To highlight the classrooms with lower than acceptable indoor temperatures, Figure 20 shows the classrooms having an indoor temperature below the 17 °C threshold by % of time and in hours.
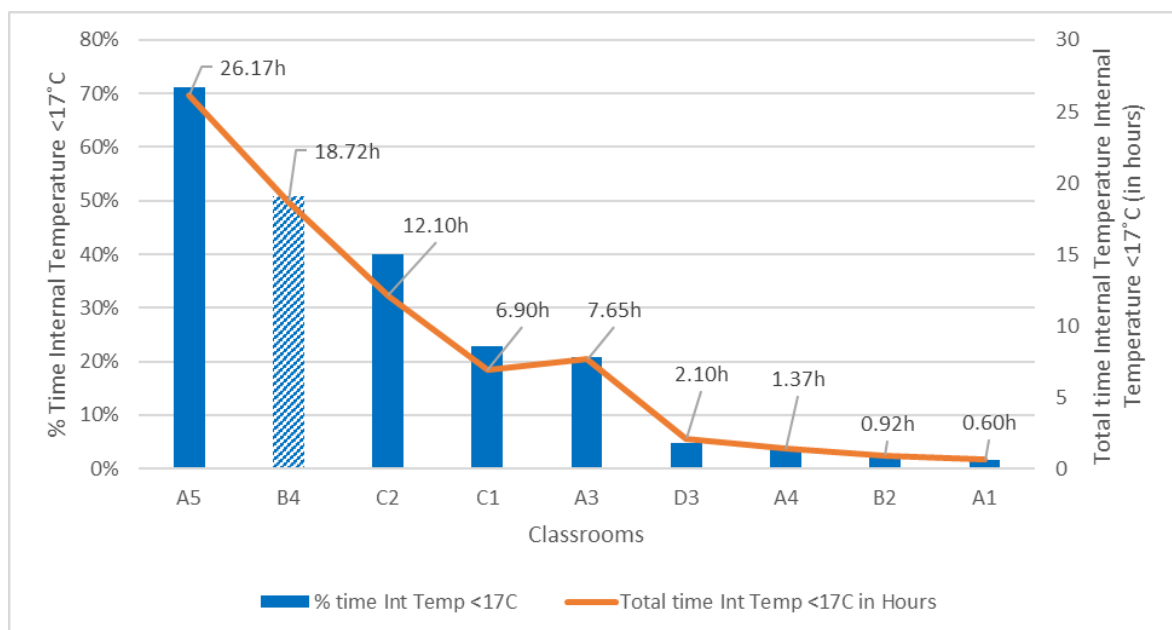
Figure 20. Classrooms with indoor temperature below the 17 °C threshold, with classrooms B1, B4, B5, D1 and D5 having mechanical ventilation.

Studying Figures 19 and 20 alongside the information on Table 2 shows the following. A5 and B4 are either situated on the ground or the top floor, with less potential heat gain from the neighbouring classrooms.

Both A5 and B4 have lower occupancy compared to the other classrooms of the study: 22 and 25 persons (pupils and teachers), respectively, compared to 31 on average, with less heat gain from their occupants.

Table 2. Classrooms with orientation, location, occupancy and window surface areas.

Classroom	Storey	Orientation	Windows Area (m²)	Occupancy (Teachers and Pupils)	
				Min	Max
A1	Ground	SSE-E	22.99	23	27
A2	Ground	SSE	41.47	11	26
A3	Ground	SSE	10.44	24	28
A4	1st	E-NNE	17.48	23	24
A5	2nd (Top)	SSE-W	33.70	19	22
B1	Ground	E-W	4.34	30	33
B2	2nd (Top)	NE-SW	9.63	27	29
B3	1st	NE-SW	2.10	22	29
B4	Ground	NW	12.87	23	27
B5	Ground	N-S-E-W	7.68	47	51
C1	Ground	W	5.21	22	30
C2	2nd(Top)	SW-W	8.83	33	34
C3	2nd (Top)	W	10.47	22	31
C4	2nd (Top)	NE	8.83	22	30
C5	2nd (Top)	NE-W	2.30	32	33
D1	Ground	W	4.00	24	35
D2	Ground	SW	5.00	30	34
D3	1st	NE	4.22	29	34
D4	2nd (Top)	SW	4.40	24	30
D5	Ground	S	22.99	23	31

A5 has one of the largest openable window areas of the study (33 m² compared to 11 m² on average) with more heat loss through the windows, while B4 is facing northwest (where the wind was predominantly blowing during the study week).

In addition to A5 and B4, three other classrooms had an indoor temperature below the 17 °C threshold for at least 10% of the time when pupils are in class: C1, C2 and A3, which are either on the ground or top floor and are facing West (C1 and C2).

To summarise, for this study, factors influencing the indoor temperature in classrooms are the occupancy and the openable surface areas of the windows, as well as their orientation (North and West) and the location (ground or top floor) in the buildings.

3.2.2. Indoor RH

Whereas there are no regulations for RH in Scottish schools, it has been shown in other indoor environments that levels below 40% are favourable for the spreading of viruses [42,43], and levels above 60% tend to increase the development of mould. Therefore, a threshold of 40%–60% was set for this study.

According to Figure 21, the classroom B1 from school B has average RH levels of less than 40% (39%RH), and room A5 from school A has an RH above 60% (60.9%).

The room B1 recorded lower RH values and had a higher average indoor temperature, above 20 °C as shown on Figure 19, with fewer windows recorded as being open compared to other classrooms in the same school. Depending on outside environmental conditions, lowering the room temperature through increased use of natural ventilation would generally increase relative humidity in these spaces.

Figure 22 shows for how long the RH is either less than 40% or more than 60%, while the pupils are in school.
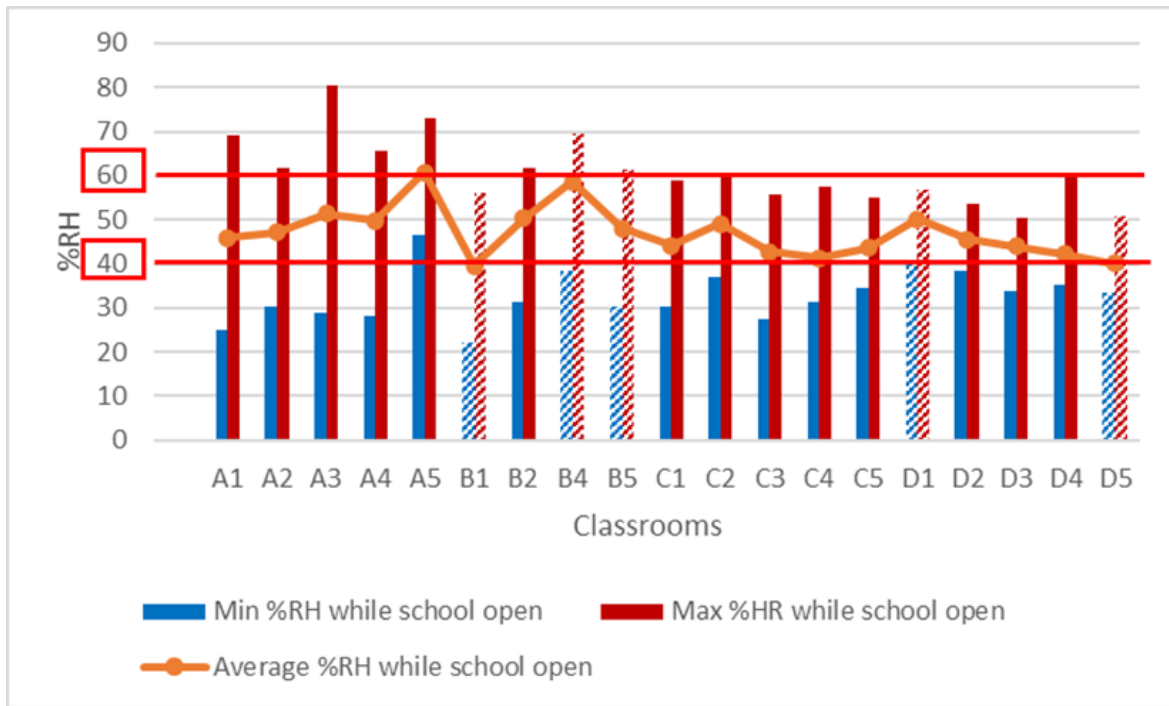
Figure 21. Indoor relative humidity in the classrooms during school hours, with classrooms B1, B4, B5, D1 and D5 having mechanical ventilation.

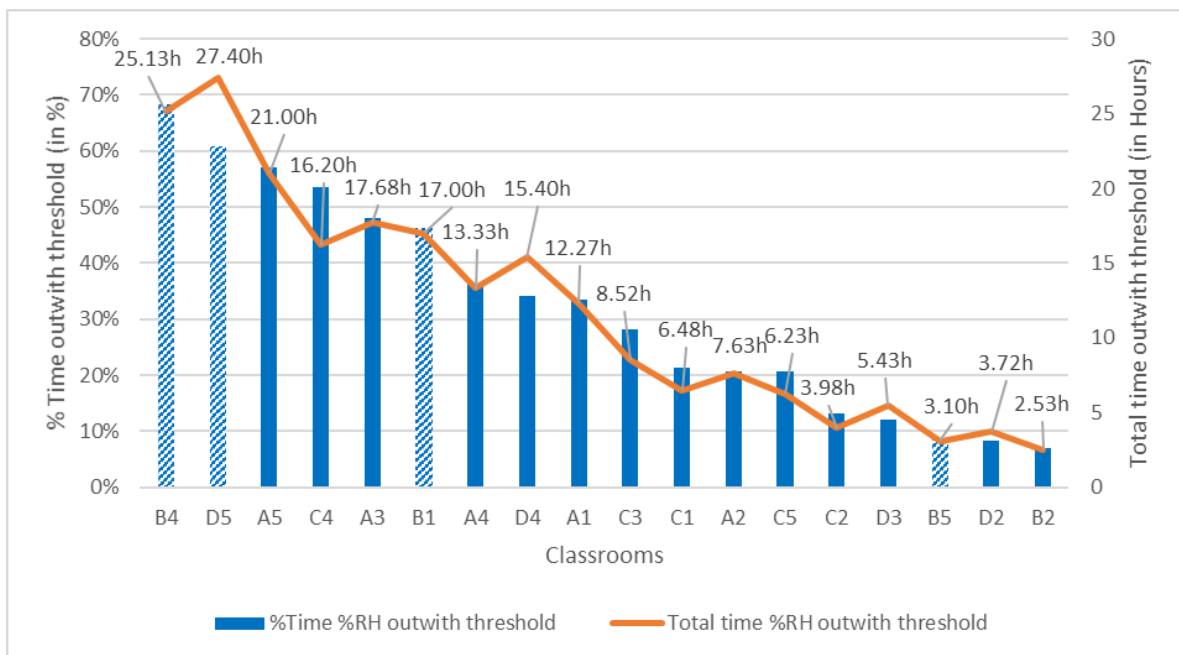**Figure 22.** Total time when RH out with threshold (in % and in hours), with classrooms B1, B4, B5, D1 and D5 having mechanical ventilation.

In total, 18 of the 20 classrooms monitored had an RH out of the 40%–60% threshold, either being lower or higher, with B4 and D5 having the highest number of hours performing out with the threshold, and both classrooms being mechanically ventilated.

3.3. CO$_2$ Concentration and Ventilation Rates

3.3.1. Carbon Dioxide Concentration

The recommended thresholds for room occupancy as provided by Scottish Government advice were 1500 ppm for normal teaching classrooms and 800 ppm for music, drama and gym [35]. Unsurprisingly, the maximum CO$_2$ levels occurred during school time, when the pupils were present in the class, as it has been shown in other studies [50].

Maximum CO$_2$ Levels and % of Time above Threshold

From Figure 23, 79% of the schools monitored demonstrated periods where the maximum recorded CO$_2$ concentrations exceeded threshold values identified above, except for school A:

–   All the rooms at school B were between 1863 and 2810 ppm;
–   Almost all the classrooms at school C (except room C2) were from 1560 to 1862 ppm;
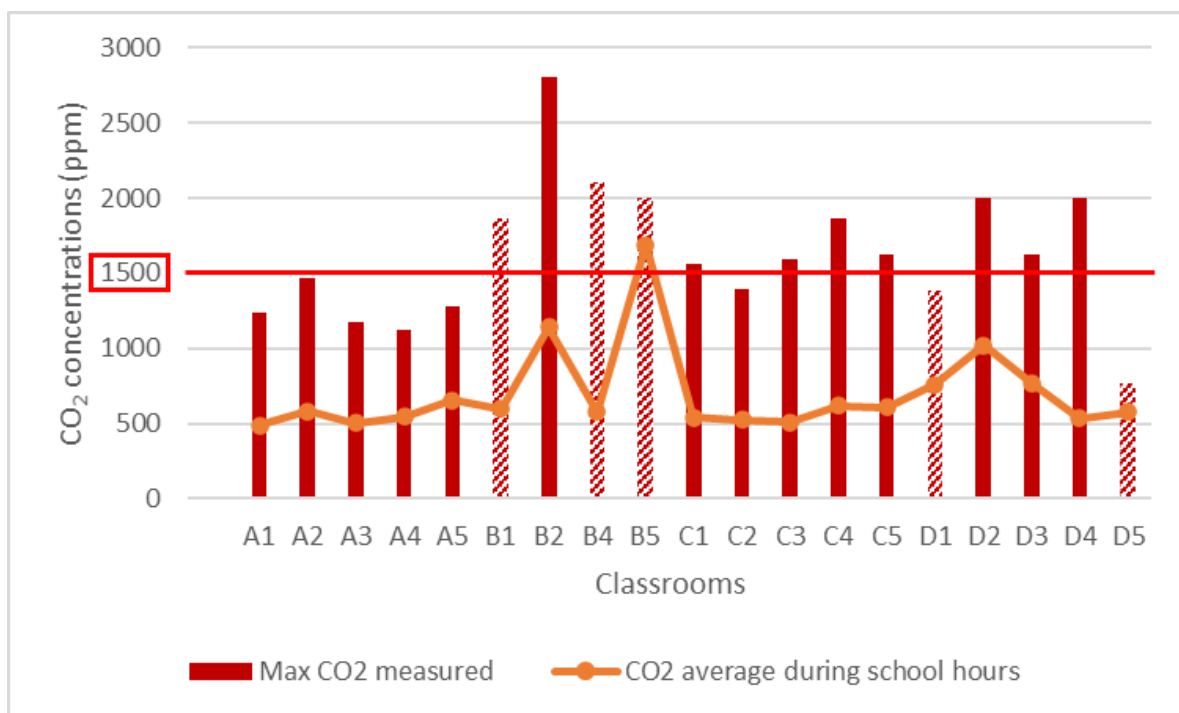–   At school D, classrooms D2 (2001 ppm), D3 (1620 ppm) and D4 (1999 ppm) exceeded threshold values.

Figure 23. CO$_2$ concentrations in the classrooms during school hours.

School A, where all classrooms have natural ventilation, has never recorded values going above the threshold, indicating adequate ventilation to achieve guideline levels.

Peak values going beyond the thresholds, and their duration at such levels, are an important consideration. However, when the CO$_2$ levels reach very high concentration for very short periods of time (less than 20 consecutive minutes), it might be assumed a change in the physical environment occurred, such as opening of more windows and doors, or changes in occupancy, such as pupils sent outside for breaks. When looking at data in more detail, most of these episodes evidenced CO$_2$ concentrations above the Scottish Government thresholds for only short periods of time and can be put into perspective when comparing these with classrooms that evidenced CO$_2$ concentrations above the threshold for more than 20 consecutive minutes (as per regulation in place).

The following school classrooms, representing 42% of all classrooms, were recorded with CO$_2$ concentrations above the threshold (1500 ppm for normal subjects and 800 ppm for music, drama and gym) for more than 20 consecutive minutes:

- School B: rooms B1 (2% above 1500 ppm), B2 (18% of the time above 1500 ppm), B4 (2% of the time above 1500 ppm) and B5 (69% of the time above 1500 ppm);
- School C in rooms C1 (1%), C4 (9% of the time above 1500 ppm) and C5 (4%);
- School D in room D2 (22% of the time above 1500 ppm).

Figure 24 shows the classrooms that have CO_2 concentrations above the thresholds for more than 20 min, and how many hours that represents.
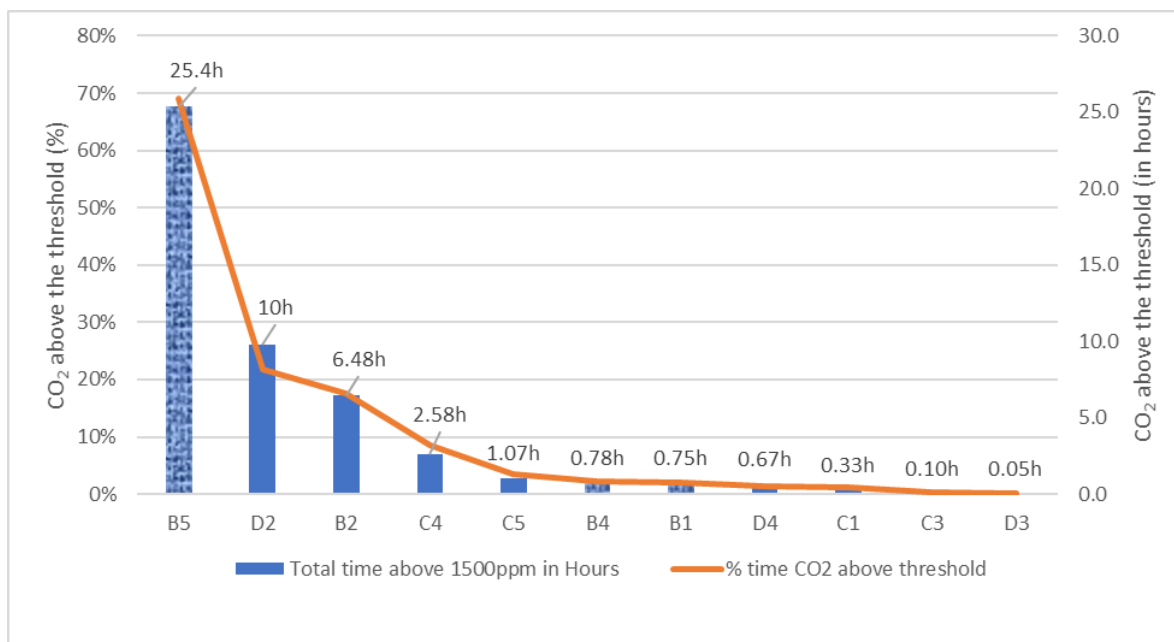

Figure 24. Classrooms with CO_2 concentrations above the threshold for more than 20 consecutives minutes.

Three classrooms (B2, B5 and D2) in two different schools had CO_2 levels above the threshold for more than 10% of the occupied time. B2 and D2 are naturally ventilated, while B5 is mechanically ventilated, which can suggest B5 ventilation system is not supplying enough fresh air (hypothesis will be confirmed in Section Analysis of the CO_2 Concentration for B5).

The following paragraphs analyse the potential reasons for these highest concentrations.

Analysis of the CO_2 Concentration for B5

The CO_2 concentration in B5 (illustrated in Figure 25) was concerning, considering the peak levels were not recorded due to the operating range of the CO_2 sensor installed (2000 ppm), assuming the accurate CO_2 levels were higher. The space is serviced by a recirculatory HVAC system serviced by a heat pump. When considering the ventilation openings recorded on that same day, it was shown that little to no adventitious ventilation support (through openable windows/louvres) was enabled in the room. The Council has since sent technical staff to the site to evaluate issues. In fact, the windows have full height opening sashes that open inwards and are free to swing once open with no restriction on how far it can open. The windows also have the capability to tilt. However, staff did not have keys to enable these functionalities and therefore relied only on the HVAC system. This issue was raised by the local authority directly with the school.

Figure 25. Location, floorplan and pictures of classroom B5.

Analysis of the CO_2 Concentration for B2 and D2

Both classrooms are situated in a Victorian building and are naturally ventilated (Figure 26).

Figure 27 shows the temperature and CO_2 concentration monitored in B2 over the duration of the study while the school was open for the pupils, alongside the number of occupants and windows openings.

The number of pupils present was almost constant throughout the study days (minimum 26, maximum 27).

The teacher left the maximum windows open during two full days of the week, opening half of the windows for the remaining days.

It is noticeable the peaks of CO_2 concentrations build up throughout the week even though the CO_2 concentrations at the start of each day are the same: the levels are higher at

the end of the week than at the start, with a peak on the Friday. The lower levels correspond to a break when the children are leaving the classroom (either mid-morning, for lunch or at the end of the school day). This phenomenon may be caused by residual CO_2 from the other part of the building: corridors, halls, etc., where the ventilation strategies are unknown.

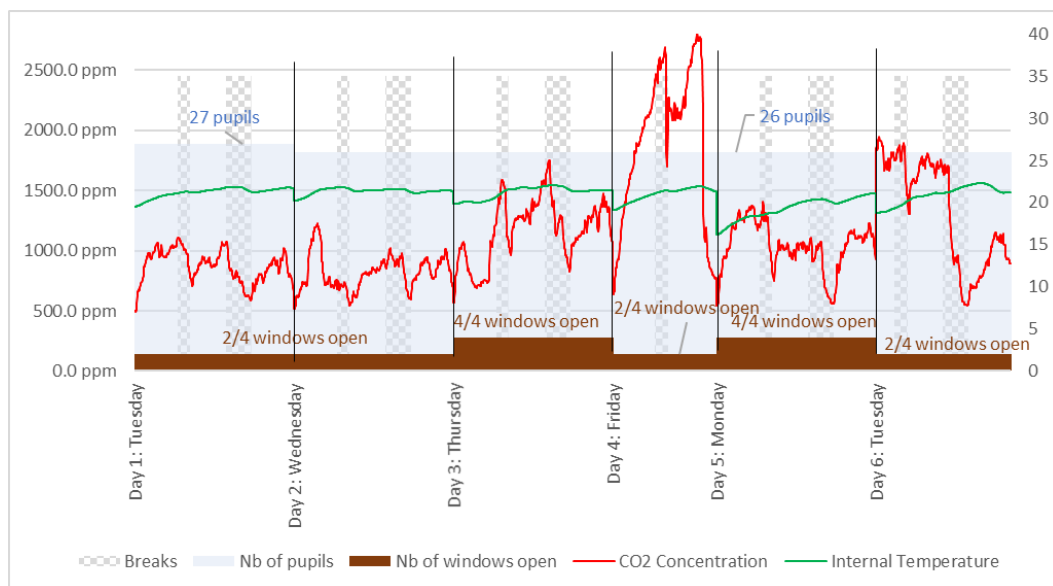**Figure 26.** Classroom B2 on first floor of school B.

Figure 27. Temperature and CO_2 in B2 over the study week (pupils in school: 6 h 30 min per day Monday to Thursday and 4 h 30 min on Fridays).

Having more windows open impacts the CO_2 concentration in two ways: the level decreases quicker and takes longer to increase.

Considering the number of pupils in the classroom is almost constant, pupils leaving the classroom has a direct impact on the CO_2 levels: less occupancy implies lower CO_2 levels.

Figure 28 shows the CO_2 concentrations and the indoor temperature over the study week for the classroom D2. However, the openings and occupancy were reported accurately for this classroom, which is a limitation, and therefore will not be discussed.
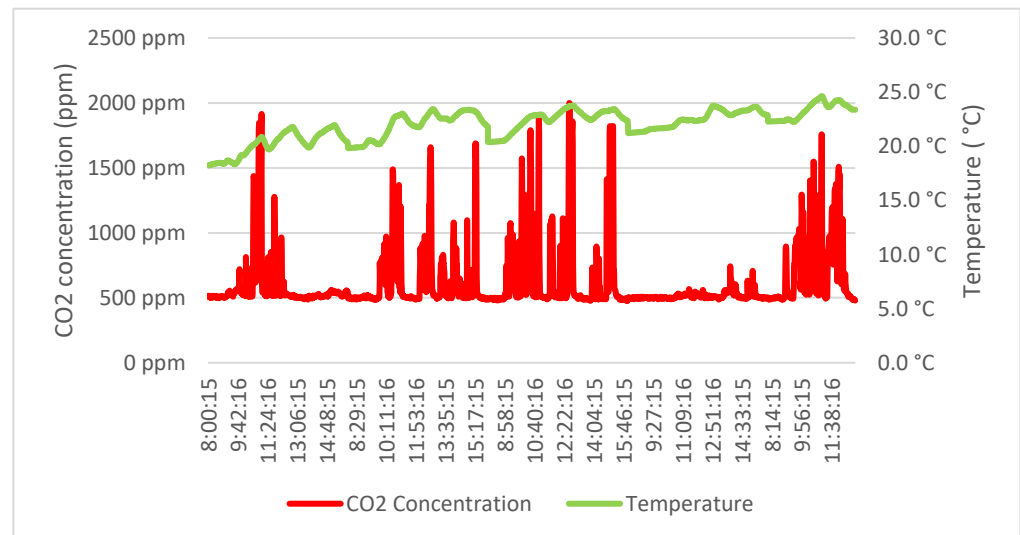

Figure 28. Temperature and CO_2 concentrations in D2 over the four days study week.

The variation in the CO_2 concentrations is more important for this classroom. It is assumed no pupils came in class on day 4, as very low levels were recorded.

When the classroom is occupied consecutively for full days, the same observation as for B2 can be made: the CO_2 concentrations are getting higher over the days, but when the classroom is empty for a longer period, the concentrations tend to be lower.

3.3.2. Ventilation Rates

As detailed in paragraph 2, the ventilation rate calculation technique does not rely on the decay method. Table 3 shows the average ventilation rates in the classrooms, estimated using the measured peak CO_2 concentrations during school hours.

In total, 80% of the mechanically ventilated classrooms had an ACH above the recommended $2\ h^{-1}$, compared to 71% of the naturally ventilated ones. Mechanically ventilated classrooms had a higher ACH except for B5, due to the issue with the HVAC. The high ACH in school A is likely to be a result of the architype of the school building (as detailed in Table 1). It can be assumed the classrooms with mechanical ventilation relied only on the system when the naturally ventilated classrooms had the instructions to open windows and doors as much as possible during the pandemic. This can explain high ACH in some of the naturally ventilated classrooms.

Only the classroom D5 had ventilation rates above the threshold of 10 L/s per person, which suggests that windows and doors should have been open more often.

Except for classroom B5, ventilation rates were lowest where the classrooms were naturally ventilated (average of 4.9 L/s per person) and the highest in the classrooms with a mechanical ventilation system (average of 6.08 L/s per person).

For naturally ventilated buildings, the average of the ventilation rates of Victorian buildings was lower (4.38 L/s per person) compared to more recent ones (5.8 L/s per person).

Table 3. Peak CO_2 concentration and the estimated ventilation rates in classrooms with different ventilation systems.

	Naturally Ventilated Classrooms														Mechanically Ventilated Classrooms				
Class Number	**A1**	**A2**	**A3**	**A4**	**A5**	**B2**	**C1**	**C2**	**C3**	**C4**	**C5**	**D2**	**D3**	**D4**	**B1**	**B4**	**B5**	**D1**	**D5**
Average Peak CO_2 (ppm)	945	1186	982	1043	1137	1710	1192	1032	1396	1028	1343	1624	1410	1704	1459	1413	2001	1213	664
ACH (h^{-1})	10.2	5.4	6.3	3.6	2.9	2.2	2.7	4.1	2.6	2.7	1.9	1.8	2.4	1.9	3.2	2.7	1.0	3.7	10.6
Ventilation rate per person (l/s/pers.)	7.54	5.44	7.35	6.09	5.32	3.05	4.86	6.1	4.01	6.18	4.05	3.1	3.77	2.92	3.89	3.81	2.39	4.88	15.39
average ACH							3.6										4.2		
average Ventilation rate							4.99										6.08		
average ACH Victorian buildings only									2.5										
average Ventilation rate Victorian only									4.38										
average ACH newer buildings only			5.1																
average Ventilation rate newer only			5.80																

It was assumed that the mechanical ventilation in room B5 underperformed as discussed in Section Maximum CO_2 Levels and % of Time above Threshold.

4. Discussion

Of the 20 school classrooms monitored and studied, 19 were studied, as 1 had its monitors unplugged.

On the 19 primary classrooms analysed, this study shows that the peaks of CO_2 concentrations are shown to increase during the day and over the week: the later in the day, the higher the peak CO_2 concentration recorded, and the later in the week, the higher the peak concentrations recorded in classrooms.

As previously anticipated and shown in Section 3.3.2, older Victorian naturally ventilated classrooms (in school C and classrooms D2 to D4) have the lowest ventilation rates. As discussed in Section 3.2, the location and orientation of the classrooms within the school building as well as the occupancy have a direct impact on the indoor temperature.

As expected, this study confirms that mechanically ventilated classrooms, if operated properly, perform better in terms of CO_2 concentrations than naturally ventilated ones [51,52].

Therefore, this study can imply some recommendations. Firstly, all mechanical heating and ventilation systems and manually operated windows servicing classrooms should be checked to ensure correct operation.

Secondly, flush the air by opening fully windows and doors at the start and at the end of the school days.

Thirdly, ensure adequate ventilation (windows and doors) during class time to stimulate cross-ventilation.

Fourthly, windows and doors should be open fully during break and lunch time when pupils are leaving the classroom.

Finally, try to reduce the number of occupants per classrooms or promote outdoor activities.

5. Limitations and Further Work

5.1. Limitations

Some limitations apply to this study and can be divided into three categories.

First, the limitations are related to human behaviour. The equipment was unplugged for short periods of time or for the whole week. Some teachers did not engage in the study or gave imprecise/incomplete information, including classroom D2.

Secondly, the limitations related to the length of the study and the monitors used. The short period of monitoring and of the memory of the data loggers at high resolution enabled only a snapshot of the data. No remote access to the data implied the need to go onsite to upload the results and we only noticed potential issues once they were uploaded.

Finally, due to the transitory nature of occupancy experienced, combined with a limited range of concentration decay between occupancy events (flushing), the often used decay method to calculate ventilation rates gave inconsistent results. Therefore, an adaptation of the steady-state method was adopted.

5.2. Further Development

Following this study, some further development should be envisaged.

More research studies on the impact of RH in schools should be considered.

Primary school classrooms of Victorian buildings have been shown to have the lowest ventilation rates. A longer and more in-depth study targeting these schools would help confirm the trends found during this study.

Measuring the CO_2 concentrations levels alongside the tVOCs may confirm a correlation already noticed during other studies performed in naturally ventilated classrooms [53].

In that context, raising awareness of the importance of IAQ in schools, to teachers, pupils, headteachers and janitorial staff should enable them to grasp the importance of good indoor air quality. In addition, providing each classroom with visual feedback from

monitors for occupants to have the option to act could empower them to feel more in charge of their indoor environment. The use of wireless sensors with remotely accessible data will enable the monitoring to solve any issues as soon as they arise.

References

1. World Green Building Council. *Health, Wellbeing & Productivity in Offices*; World Green Building Council: London, UK, 2014; p. 46.
2. Building Engineering Services Association (BESA). 70% of Office Workers Complain about Poor Air Quality. Available online: https://www.thebesa.com/news/70-of-office-workers-complain-about-poor-air-quality/ (accessed on 19 August 2021).
3. Edem, M.; Akpan, E.; Pepple, N. Impact of Workplace Environment on Health Workers. *Occup. Med. Health Aff.* **2017**, *5*, 1–5. [CrossRef]
4. Chatzidiakou, L.; Mumovic, D.; Summerfield, A.J. What do we know about indoor air quality in school classrooms? A critical review of the literature. *Intell. Build. Int.* **2012**, *4*, 228–259. [CrossRef]
5. Tak, S.; Groenewold, M.; Alterman, T.; Park, R.M.; Calvert, G.M. Excess risk of head and chest colds among teachers and other school workers. *J. Sch. Health* **2011**, *81*, 560–565. [CrossRef] [PubMed]
6. Allen, J.G.; MacNaughton, P.; Satish, U.; Santanam, S.; Vallarino, J.; Spengler, J.D. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. *Environ. Health Perspect.* **2016**, *124*, 805–812. [CrossRef] [PubMed]
7. Toyinbo, O.; Shaughnessy, R.; Turunen, M.; Putus, T.; Metsämuuronen, J.; Kurnitski, J.; Haverinen-Shaughnessy, U. Building characteristics, indoor environmental quality, and mathematics achievement in Finnish elementary schools. *Build. Environ.* **2016**, *104*, 114–121. [CrossRef]
8. Fisk, W.J.; Chan, W.R.; Johnson, A.L. Does dampness and mold in schools affect health? Results of a meta-analysis. *Indoor Air* **2019**, *29*, 895–902. [CrossRef]
9. Annesi-Maesano, I.; Baiz, N.; Banerjee, S.; Rudnai, P.; Rive, S. Indoor air quality and sources in schools and related health effects. *J. Toxicol. Environ. Health Part B Crit. Rev.* **2013**, *16*, 491–550. [CrossRef]
10. Coley, D.A.; Greeves, R.; Saxby, B.K. The Effect of Low Ventilation Rates on the Cognitive Function of a Primary School Class. *Int. J. Vent.* **2007**, *6*, 107–112. [CrossRef]
11. Kielb, C.; Lin, S.; Muscatiello, N.; Hord, W.; Rogers-Harrington, J.; Healy, J. Building-related health symptoms and classroom indoor air quality: A survey of school teachers in New York State. *Indoor Air* **2015**, *25*, 371–380. [CrossRef]
12. Mazurek, J.M.; Filios, M.; Willis, R.; Rosenman, K.D.; Reilly, M.J.; McGreevy, K.; Schill, D.P.; Valiante, D.; Pechter, E.; Davis, L.; et al. Work-related asthma in the educational services industry: California, Massachusetts, Michigan, and New Jersey, 1993–2000. *Am. J. Ind. Med.* **2008**, *51*, 47–59. [CrossRef]
13. Bakó-Biró, Z.; Clements-Croome, D.J.; Kochhar, N.; Awbi, H.B.; Williams, M.J. Ventilation rates in schools and pupils' performance. *Build. Environ.* **2012**, *48*, 215–223. [CrossRef]
14. Haverinen-Shaughnessy, U.; Moschandreas, D.J.; Shaughnessy, R.J. Association between substandard classroom ventilation rates and students' academic achievement. *Indoor Air* **2011**, *21*, 121–131. [CrossRef] [PubMed]
15. Haverinen-Shaughnessy, U.; Shaughnessy, R.J. Effects of classroom ventilation rate and temperature on students' test scores. *PLoS ONE* **2015**, *10*, e0136165. [CrossRef] [PubMed]
16. World Green Building Council. Indoor Air Quality in Schools. 2020. Available online: https://www.worldgbc.org/sites/default/files/BetterPlacesforPeople-SchoolsBriefingNotes-IAQ.pdf (accessed on 28 May 2021).
17. Mendell, M.J.; Heath, G.A. Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air* **2005**, *15*, 27–52. [CrossRef] [PubMed]
18. Bluyssen, P.M.; Kim, D.H.; Eijkelenboom, A.; Ortiz-Sanchez, M. Workshop with 335 primary school children in The Netherlands: What is needed to improve the IEQ in their classrooms? *Build. Environ.* **2020**, *168*, 106486. [CrossRef]
19. Sundell, J.; Levin, H.; Nazaroff, W.W.; Cain, W.S.; Fisk, W.J.; Grimsrud, D.T.; Gyntelberg, F.; Li, Y.; Persily, A.K.; Pickering, A.C.; et al. Ventilation rates and health: Multidisciplinary review of the scientific literature. *Indoor Air* **2011**, *21*, 191–204. [CrossRef] [PubMed]

20. Angelon-Gaetz, K.A.; Richardson, D.B.; Marshall, S.W.; Hernandez, M.L. Exploration of the effects of classroom humidity levels on teachers' respiratory symptoms. *Int. Arch. Occup. Environ. Health* **2016**, *89*, 729–737. [CrossRef]

21. Eng, A.; Mannetje, T.; Douwes, J.; Cheng, S.; Mclean, D.; Ellison-loschmann, L.; Pearce, N. The New Zealand Workforce Survey II: Occupational Risk Factors for Asthma. *Ann. Occup. Hyg.* **2010**, *54*, 154–164. [CrossRef]

22. Whelan, E.A.; Lawson, C.C.; Grajewski, B.; Petersen, M.R.; Pinkerton, L.E.; Ward, E.M.; Schnorr, T.M. Prevalence of respiratory symptoms among female flight attendants and teachers. *Occup. Environ. Med.* **2003**, *60*, 929–934. [CrossRef]

23. Mendell, M.J.; Eliseeva, E.A.; Davies, M.M.; Lobscheid, A. Do classroom ventilation rates in California elementary schools influence standardized test scores? Results from a prospective study. *Indoor Air* **2016**, *26*, 546–557. [CrossRef]

24. Maddalena, R.; Mendell, M.J.; Eliseeva, K.; Chan, W.R.; Sullivan, D.P.; Russell, M.; Satish, U.; Fisk, W.J. Effects of ventilation rate per person and per floor area on perceived air quality, sick building syndrome symptoms, and decision-making. *Indoor Air* **2015**, *25*, 362–370. [CrossRef] [PubMed]

25. Barker, J.; Stevens, D.; Bloomfield, S.F. Spread and prevention of some common viral infections in community facilities and domestic homes. *J. Appl. Microbiol.* **2001**, *91*, 7–21. [CrossRef] [PubMed]

26. Cutler, R. Promoting hygiene in schools: Breaking the chain of infection. *Br. J. Sch. Nurs.* **2010**, *5*, 187–190. [CrossRef]

27. CDC. How Coronavirus Spreads CDC. 2020. Available online: https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html (accessed on 19 August 2021).

28. World Health Organisation Coronavirus Disease (COVID-19): How Is It Transmitted? Coronavirus Disease (COVID-19) Pandemic. *Q A Detail* **2020**. Available online: https://www.who.int/news-room/q-a-detail/coronavirus-disease-covid-19-how-is-it-transmitted (accessed on 19 August 2021).

29. Morawska, L.; Tang, J.W.; Bahnfleth, W.; Bluyssen, P.M.; Boerstra, A.; Buonanno, G.; Cao, J.; Dancer, S.; Floto, A.; Franchimon, F.; et al. How can airborne transmission of COVID-19 indoors be minimised? *Environ. Int.* **2020**, *142*, 105832. [CrossRef]

30. Rudnick, S.N.; Milton, D.K. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air* **2003**, *13*, 237–245. [CrossRef]

31. Chatzidiakou, L.; Mumovic, D.; Summerfield, A. Is CO_2 a good proxy for indoor air quality in classrooms? Part 1: The interrelationships between thermal conditions, CO_2 levels, ventilation rates and selected indoor pollutants. *Build. Serv. Eng. Res. Technol.* **2015**, *36*, 129–161. [CrossRef]

32. Sage-Emg. *Role of Ventilation in Controlling SARS-CoV-2 Transmission*; Sage-Emg: High Wycombe, UK, 2020; pp. 2–33.

33. *ANSI/ASHRAE Standard 62.1-2019*; Ventilation for Acceptable Indoor Air Quality. ASHRAE: Atlanta, GA, USA, 2019. Available online: www.ashrae.org/technology (accessed on 18 January 2022).

34. Scottish Government. *Coronavirus (COVID-19): Guidance on Reducing the Risks from COVID-19 in Schools Non-Statutory Guidance to Ensure a Safe and Supportive Environment for Learning and Teaching*; Scottish Government: Edinburgh, UK, 2022.

35. Scottish Government. Coronavirus (COVID-19): Guidance on Reducing the Risks in Schools. 2021. Available online: https://www.gov.scot/publications/coronavirus-covid-19-guidance-on-reducing-the-risks-in-schools/pages/overview/ (accessed on 19 August 2021).

36. CIBSE. COVID-19 Ventilation Guidance. 2020; Version 4; pp. 1–26. Available online: https://www.cdc.gov/coronavirus/2019-ncov/more/scientific-brief-sars-cov-2.html (accessed on 10 May 2021).

37. World Health Organization. *Methods for Monitoring Indoor Air Quality in Schools*; World Health Organization: Bonn, Germany, 2011.

38. REHVA. *COVID-19 Ventilation and Building SERVICES Guidance for School Personnel*; REHVA: Brussels, Belgium, 2020; pp. 1–5.

39. HCSP COVID-19: Aération, Ventilation et Mesure du CO_2 Dans les ERP. Available online: https://www.hcsp.fr/Explore.cgi/AvisRapportsDomaine?clefr=1009 (accessed on 10 September 2021).

40. HPSC Guidance on Non-Healthcare Building Ventilation during. 2020, pp. 1–10. Available online: www.hpsc.ie (accessed on 10 September 2021).

41. CIBSE. CIBSE COVID-19 Ventilation Guidance, Version 4. 2020; p. 26. Available online: https://www.cdc.gov/coronavirus/2019-ncov/more/scientific-brief-sars-cov-2.html%0Ahttps://www.cibse.org/knowledge/knowledge-items/detail?id=a0q3Y00000HsaFtQAJ# (accessed on 22 November 2021).

42. Azuma, K.; Yanagi, U.; Kagi, N.; Kim, H.; Ogata, M.; Hayashi, M. Environmental factors involved in SARS-CoV-2 transmission: Effect and role of indoor environmental quality in the strategy for COVID-19 infection control. *Environ. Health Prev. Med.* **2020**, *25*, 66. [CrossRef]

43. ASHRAE. ASHRAE Epidemic Task Force. *Ashrae* **2020**. Available online: www.ashrae.org/covid19 (accessed on 18 November 2021).

44. Montazami, A.; Gaterell, M.; Nicol, F. A comprehensive review of environmental design in UK schools: History, conflicts and solutions. *Renew. Sustain. Energy Rev.* **2015**, *46*, 249–264. [CrossRef]

45. Batterman, S. Review and extension of CO_2-based methods to determine ventilation rates with application to school classrooms. *Int. J. Environ. Res. Public Health* **2017**, *14*, 145. [CrossRef]

46. Allen, J.; Spengler, J.; Jones, E. 5-Step Guide to Checking Ventilation Rates in Classrooms; Harvard Healthy Buildings Program: 2020. Available online: www.ForHealth.org (accessed on 18 January 2022).

47. Zhang, D.; Ding, E.; Bluyssen, P.M. Guidance to assess ventilation performance of a classroom based on CO_2 monitoring. *Indoor Built. Environ.* **2022**, 1420326X2110587. [CrossRef]

48. Coley, D.A.; Beisteiner, A. Carbon Dioxide Levels and Ventilation Rates in Schools. *Int. J. Vent.* **2002**, *1*, 45–52. [CrossRef]
49. Beisteiner, A.; Coley, D.A. Carbon Dioxide Levels and Summertime Ventilation Rates in UK Schools. *Int. J. Vent.* **2003**, *1*, 181–187. [CrossRef]
50. Settimo, G.; Indinnimeo, L.; Inglessis, M.; De Felice, M.; Morlino, R.; Di Coste, A.; Fratianni, A.; Avino, P. Indoor air quality levels in schools: Role of student activities and no activities. *Int. J. Environ. Res. Public Health* **2020**, *17*, 6695. [CrossRef] [PubMed]
51. Bannister, P. Why Good Buildings Go Bad, While Some Are Just Born That Way. *Ecolibrium. J. Aust. Inst. Refrig. AC Heat. 2009, 24–32.* Available online: https://iifiir.org/en/fridoc/why-good-buildings-go-bad-while-some-are-just-born-that-way-131023 (accessed on 19 January 2022).
52. Burman, E.; Kimpian, J.; Mumovic, D. Building schools for the future: Lessons learned from performance evaluations of five secondary schools and academies in england. *Front. Built Environ.* **2018**, *4*, 22. [CrossRef]
53. Vassura, I.; Venturini, E.; Bernardi, E.; Passarini, F.; Settimo, G. Assessment of indoor pollution in a school environment through both passive and continuous samplings. *Environ. Eng. Manag. J.* **2015**, *14*, 1761–1770. [CrossRef]