Indoor Air quality in Primary Schools: Final Report

A project funded by the EPSRC IAA

Report produced by

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1 Summary of EPSRC IAA Indoor Air quality in Primary Schools Project

This EPSRC IAA Indoor Air Quality in Primary Schools Project is an interdisciplinary impact project led by Dr Gabriela Zapata-Lancaster from the Welsh School of Architecture as Principal Investigator, Dr Thomas Smith from the School of Geography and Planning as Co-Investigator and Mr Miltiadis Ionas as research assistant. It is funded by the Engineering and Physical Sciences Research Council (ESPRSC) as an Impact Acceleration Account project.

This pilot project aims to support Councils and primary schools in maintaining good indoor environmental conditions in classrooms and indoor spaces. A secondary aim is to produce learning resources for children and teachers and guidance for schools and councils to maintain good indoor environmental conditions classrooms and indoor spaces. The project has proposed and deployed a visual monitoring toolkit to measure indoor air quality in school buildings and provide feedback to occupants. Moreover, it will propose supporting guidance to promote good indoor environmental conditions through behaviours and operational practices in buildings.

This research team partnered with the local council and is working closely with teachers and children in two primary schools towards providing a means for councils and schools to manage the indoor air quality in school buildings. As a secondary aim, it is developing learning resources and engaging in hands-on workshops with pupils to reflect about indoor environmental conditions in schools, focusing on the nexus between behaviours and the resulting indoor environmental conditions.

1.1 Project highlights

The study proposed a monitoring approach to identify indoor air quality and thermal comfort in classrooms and engaged with pupils to explore the use of monitoring data and building performance concepts to learn about sustainability.

Monitoring data highlights

- Study analysed six classrooms' temperature and CO_2, looking at seasonal variations. Other parameters such as relative humidity, ppm, regime of opening/closing windows were also monitored and the results are presented in the following sections.
- Monitoring data suggest that monitored classrooms are within acceptable temperature levels during occupied hours in autumn and winter.
- Monitoring data suggest that CO_2 concentration levels in most of the classrooms were managed effectively through simple behavioural actions and adaptations (windows, doors, flexible use of classrooms).
- The data suggest that the balance between CO_2 and temperature requirements is achievable in autumn but is likely to be more challenging in winter.

Hands-on STEM workshop highlights

- Pupils from six classes (three in each schools) participated in two workshops: 'Building Doctors' and 'Healthy Comfortable classrooms in energy efficient ways' . The workshops were tailored to Foundation & Key stage 2 and included hands-on activities led by pupils.
- During the workshops, pupils practiced numeracy skills and discussed building performance concepts. Pupils measured and discussed monitoring data from their own classrooms, suggesting ideas to improve classrooms' comfort and ventilation. Pupils in all year groups were able to engage with monitoring data (both data collected by Cardiff University team as well as data collected by themselves in the workshop) and reflect about building performance concepts of different complexity in relation to what they do in their classrooms and in relation to sustainability implications.
- Hands-on activities led by pupils using monitoring data of their classrooms and schools offer the opportunity for experiential and practical learning about

sustainability to integrate the six areas of learning and experience as per New Welsh Curriculum. The activities of this project directly focused on (1) maths and numeracy and (2) science and technology; and had indirect links to (3) literacy and communication. There is potential for resources to include arts and health and wellbeing in relation to sustainability and citizenship aspirations. The use of monitoring data from their own schools could potentially contribute to schools delivering the aspirations of the UK Policy Paper 'Sustainability and climate change: a strategy for the education and children's services systems'[1] in relation to Action area 3: Education estate and digital infrastructure and Action area 4: Operations and supply chains; which aims to prepare 'children and young people to face climate change challenges and opportunities with appropriate knowledge, skills and pastoral care'.

The report has been structured as follows: Section 2 presents the monitoring approach; Section 3 describes the monitoring instrumentation; Section 4 outlines the results of the monitoring illustrating general trends in the indoor environmental condition of the monitoring classrooms; Section 5 presents qualitative user studies that identified actions to promote ventilation and thermal comfort, reporting on the satisfaction levels of teachers and pupils in relation to the existing conditions; Section 6 outlines the student's engagement and learning activities during the hands-on STEM workshops delivered by Cardiff University team; and, Section 7 summarises some recommendations based on lessons learned from the project.

[1] UK Policy Paper 'Sustainability and climate change: a strategy for the education and children's services systems' published in April 2022 available at https://www.gov.uk/government/publications/sustainability-and-climate-change-strategy/sustainability-and-climate-change-a-strategy-for-the-education-and-childrens-services-systems

2 Monitoring approach

This pilot project is testing and fine-tuning a monitoring approach to identify the indoor environmental conditions in different types of spaces in Primary schools (1) Classrooms; and (2) Communal spaces. In order to understand better the context of the monitoring data from the schools, the project is also monitoring outdoor temperature and relative humidity in the school grounds.

2.1 Classrooms

We are monitoring indoor environmental conditions in three classrooms that include different age groups and located in different orientations within the school building in each of the two primary schools (six classrooms in total). The monitoring exercise is measuring the temperature, humidity and CO_2 as proxy of air quality. Classrooms were selected on the basis of feedback by Head Teachers and teachers in the schools.

One ‘open/close status’ monitoring devices have been installed in each classroom to understand patterns of use of windows and doors.

2.2 Communal spaces

In addition to monitoring the selected classrooms, the project is monitoring at least one additional ‘communal space’ used for non-educational purposes where different age groups and classes mix: a dining hall (School A) and a communal reading area (School B). The communal space is primarily a space where non-learning activities take place; thus, it is likely to have a different pattern of occupancy than classrooms. In order to provide an additional layer of understanding to characterise the indoor air quality, the project is also measuring the concentration of Particulate Matter 2.5 and 10 in the air indoors to identify exposure to particulate matter (which is associated to outdoor pollution or pollutant activities). PM2.5 and PM10 are particles that are less than 2.5 and less than 10 microns in width. Those with a diameter of 10 microns or less (PM10) are inhalable into the lungs and can induce adverse health effects. Fine particulate matter is defined as particles that are 2.5 microns or less in diameter (PM2.5). Therefore, PM2.5 comprises a portion of PM10. Since PM concentration is associated to outdoor pollution, the sensors are placed near the entrance of the school, at the space closer to the outdoor environment.

3 Monitoring Plan and Monitoring instrumentation

The monitoring instruments were installed in July 2021. The initial interval of readings is one hour. The study is comparing the indoor environmental conditions during unoccupied times (summer) as a baseline to conditions in autumn (shoulder season) and in winter (heating season) with the aim to explore variations due to seasonal differences, changes of occupancy patterns and different regimes of building operation. The understanding of seasonal variations and occupancy patterns variations could inform behavioural based interventions to balance the need to reduce CO_2 levels (as proxy of indoor air quality and ventilation) while maintaining adequate thermal comfort conditions indoors.

The monitoring plans in the figures 1 and 2 represent in a schematic representation the types of sensors installed in each school and their location, which include:

(1) Indoor Temperature and Relative Humidity (T/RH): long term monitoring of three classrooms and one communal space in each school, using two types of sensors per classroom (ALTA wireless sensors and Tinytags sensors/dataloggers).

(2) Outdoor Ambient Temperature and Relative Humidity long term monitoring using one sensor outdoors in the school grounds, one per school (Tinytag sensors/dataloggers).

(3) CO_2 concentration: long term monitoring using one sensor in each one of the three classrooms per school (ALTA wireless sensor). In addition to this long-term monitoring exercise, CO_2 concentration is monitored using HOBO sensors to capture more granular data to characterise the patterns of CO_2 variations during an in-depth short-term monitoring study. This in-depth short-term study has two main purposes: (1) to further validate the measurements of the long-term CO_2 sensor and (2) to get data with the highest possible resolution (minimum time interval).

(4) Particulate Matter (PM) 2.5 and 10: one ALTA wireless sensor has been placed in each school, in an indoor space nearby the main access point. Particulate matter tends to be exacerbated by activities such as cooking, traffic pollution, and smoke. We want to explore to what extent, if any, potential outdoor pollution enters the school premises. This aligns to efforts by the local council to address and limit outdoor pollution. There has been no concerns prior to starting the project about pollution risks; however, this sensor is testing a potential approach that can be taken in the future for investigating sites or buildings located nearly heavily polluted areas (i.e., industrial estates) or adjacent to roads with heavy traffic conditions.

(5) Open/close status of window sensor: one ALTA wireless sensor in one window in each one of the classrooms under study, as indication of the natural ventilation of the classrooms. This sensor displays the state of one window, whether they are open or closed.

All the indoor sensors described above are wireless providing the ability for remote monitoring. The sensors transmit the data through a gateway, which needs power supply and internet access, in order to receive the data and transmit it to the main platform, where it can be accessible by the user.

In addition, the project is deploying two types of user-friendly low-cost sensors in the three classrooms per school (1) to measure CO_2, temperature and relative humidity indoors (Envisense) and (2) to measure outdoor temperature and relative humidity. These user-friendly devices enable real-time visualisation and feedback for teachers and pupils to identify the indoor conditions in their classrooms and to empower them to adopt behaviours that foster good indoor environmental conditions. Notice that the CO_2 Envisense device has similar capabilities and grade than the monitoring sensors issued as part of the Welsh Government initiative to monitor CO_2 in educational settings with guidance published in October 2021.

Figure 1: *A schematic Monitoring Plan of school A, illustrating the location of sensors*

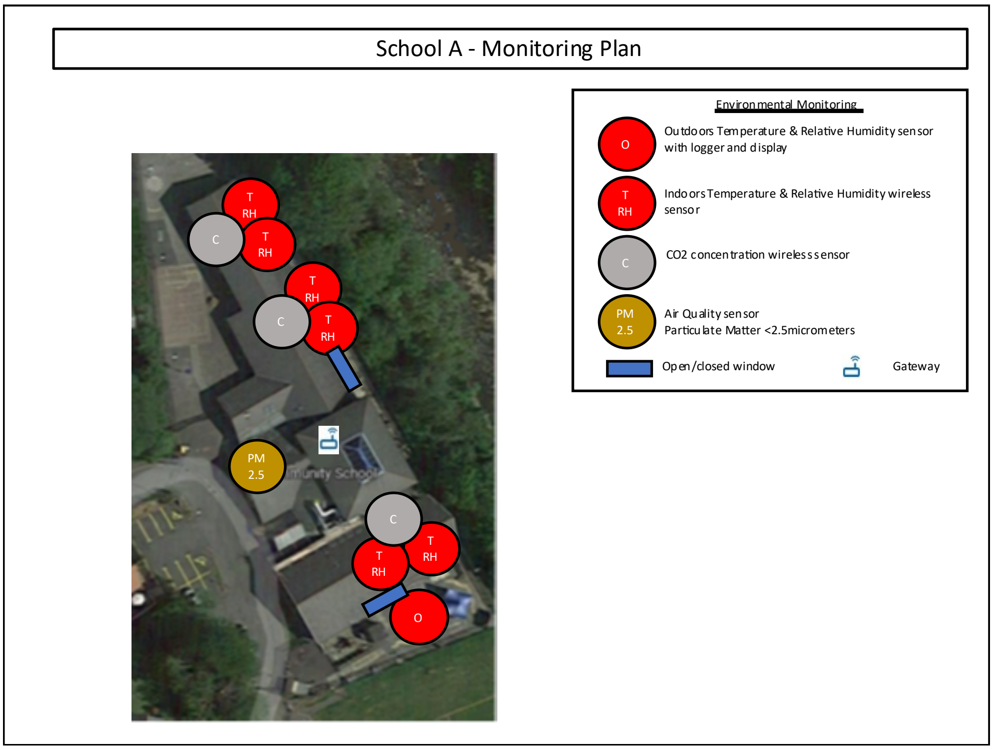
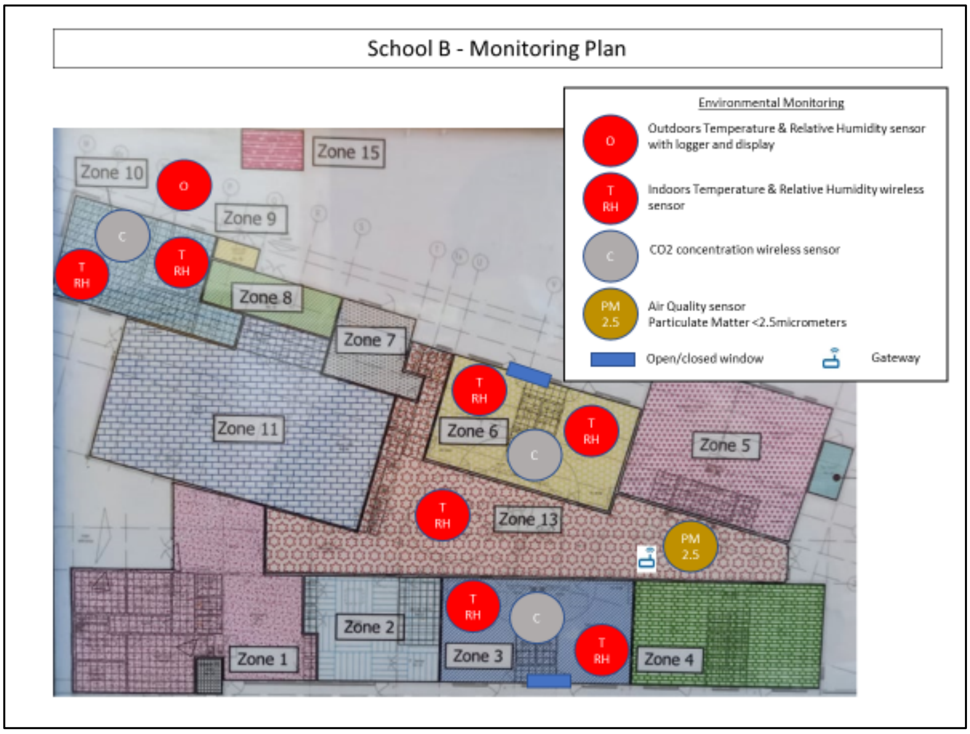


Figure 2: A schematic Monitoring Plan of scool B, illustrating the location of sensors



All the sensors, including those located indoors and outdoors, the wireless transmission system deployed for indoor sensors, and the user-friendly low-cost devices, are further described in Appendix 1: "Monitoring Instrumentation". Moreover, Appendix 2: "Monitoring sensor location" includes pictures illustrating the location of different types of devices in the participating schools.

4 Preliminary analysis of monitoring data: Autumn & Winter 2021-22

A preliminary analysis has been conducted, based on the monitoring data that has been collected during Autumn and Winter of school year 2021-22. Following the weather conditions, this monitoring period has been divided in two sub-periods: the first one is Autumn 2021, from the beginning of the school year until the first half term break, and the second one is Winter 2021-22, from November until the second half term closure in February. The results of the analysis are presented below, grouped according to the monitored parameters.

4.1 Natural ventilation (windows opening pattern)

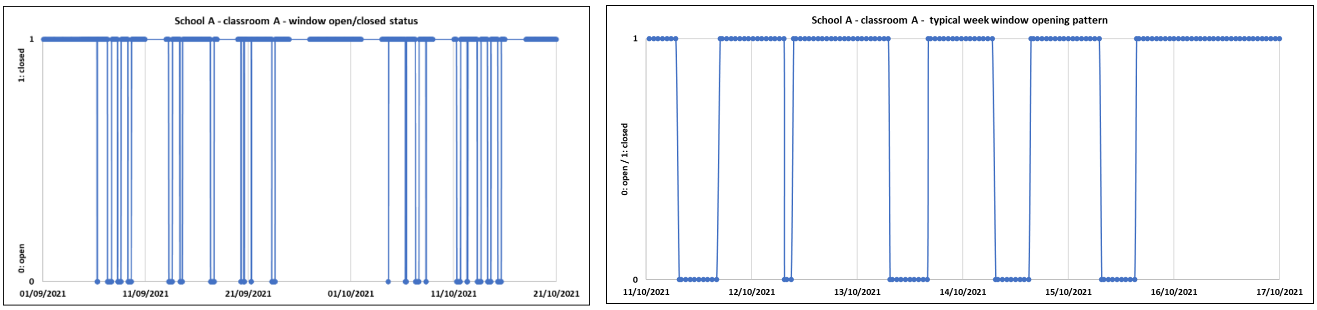
The first category is the natural ventilation of the classrooms. Natural ventilation occurs through doors and windows, so the status of windows (open/closed) is the monitoring parameter to quantify natural ventilation of the classrooms. The results of this study are indicative of the natural ventilation strategies that the two schools follow. At this point, two limitations of the study need to be highlighted. Due to those limitations, the results of this preliminary study could be characterised as indicative and not exhaustive.

Firstly, depending on the design of the buildings, each school has more than ten spaces (used as classrooms or communal spaces) and each classroom has at least three windows and one external door. Thus, it was not feasible for the research team to monitor all openings in both schools. A decision was made as part of the research team's monitoring approach, to focus on classrooms because pupils spend most of their time in them. Moreover, the monitoring approach included the monitoring two classrooms in each school and one window in each classroom, based on the assumptions that all classrooms follow the same ventilation strategies and that all windows in each classroom would be either closed or open.

The second limitation of the study is the lack of detailed data on the occupancy of the classrooms throughout the monitoring period. The research team has obtained a generic schedule of the classes under study. However, the monitoring period covers the whole school year and throughout this period there are discrepancies comparing to that schedule, due to several different school activities. Thus, the schedule may vary, and the research team cannot be sure of the occupancy of each classroom. The results are based on general occupancy patterns that apply throughout the school year, rather than on diary observations.

After having discussed the limitations of the study, the results of the study are presented in the following graphs. For each classroom a variation of the window's status (open/closed) is presented and based on that, a daily pattern is identified. The analysis is divided in Autumn and Winter period, to stress potential differences in the pattern. The results from monitoring school A are presented in Figures 3 and 4.

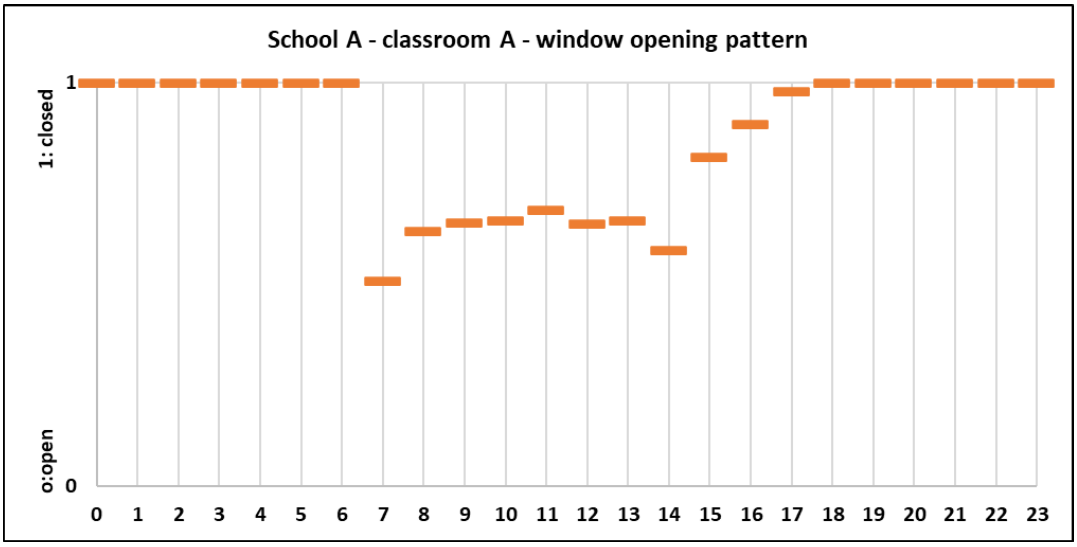
Figure 3: *Window open/closed status variation in school A, classroom A (Autumn 2021)*



In Figure 3, the left hand graph shows the variation of the window open/closed status, illustrated from the beginning of the school year until the half term break (1/9/2021 – 23/10/2022). To make more sense of the data, a week of this period is magnified on the right hand side graph (11-17/10/2021). The pattern is more noticeable in this second graph, in each weekday the window is open for several consecutive hours, whilst the window is constantly closed during the rest of the 24 hour period.

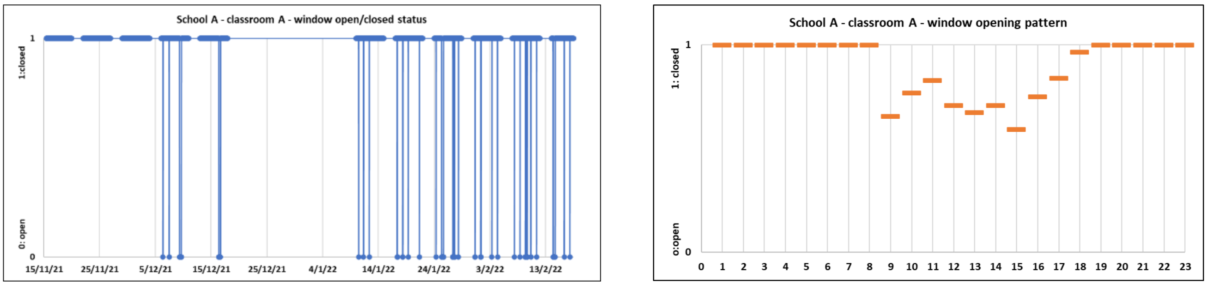
To idenitify a pattern in this variation, the status is hourly averaged to create a daily profile, after all weekend and bank holidays are exlcuded. The results is presented in Figure 4, where the daily pattern of window opening is illustrated. The identified pattern is that during the evening hours, from 17:00 until 06:00 the window is constantly closed, whilst from 07:00 to 14:00, there is a trend of keeping the window open for almost half of the hours. At 15:00-17:00, windows are most probably closed, 70-80% of the times.

Figure 4: Window opening daily pattern in school A, classroom A (Autumn 2021)



Following the same analysis for the same classroom, during the winter period, we have the graphs illustrated in Figure 5. The weekends and the Christmas break days are excluded from the analysis. In the graph on the left-hand side in Figure 5, the results seem to have a specific pattern after the first half of January. By averaging this period on an hourly basis, the daily pattern is identified, and it is illustrated in the graph on the right-hand side of Figure 5. A comparison between Figure 5 to Figure 4 shows that during Winter 2021-2 the windows are opening less than during Autumn 2021.

Figure 5: Window opening variation and daily pattern in School A (Winter 2021-22)



Following the same analysis in school B, we have the results represented in Figures 6 and 7. The data has been hourly averaged to produce daily patterns, after excluding weekends and Christmas break days. In Figure 6 we observe that the guidance regarding open windows during school hours is being followed exclusively in the Autumn, whilst in Winter the pattern is followed almost half of the times.

Figure 6: Window open/closed status variation and hourly averaged daily pattern (Autumn 2021)

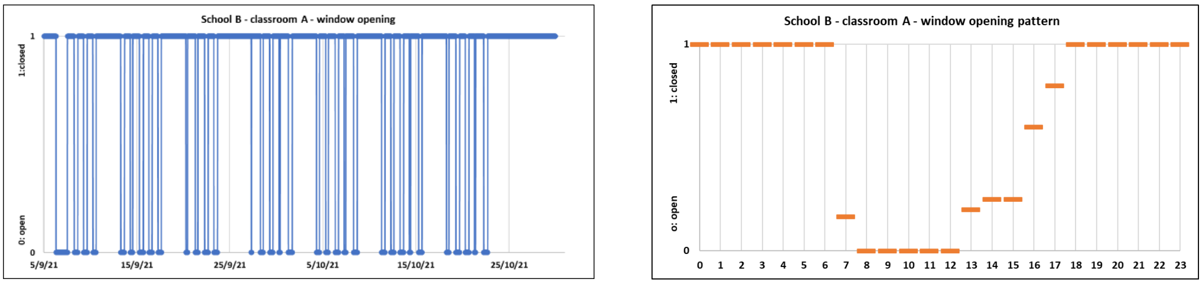
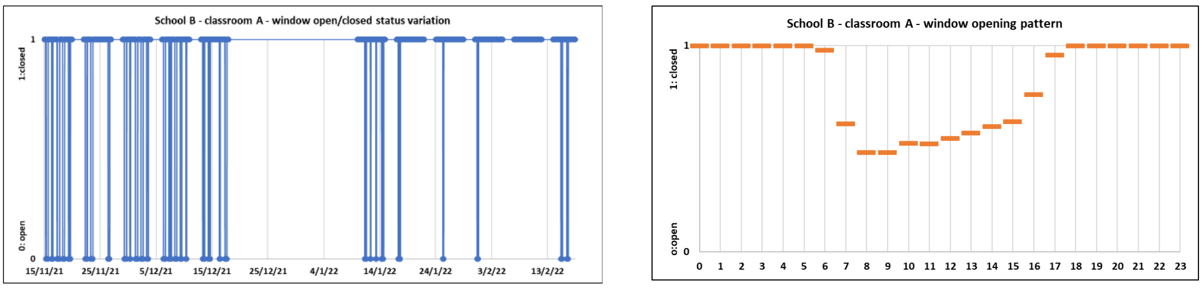
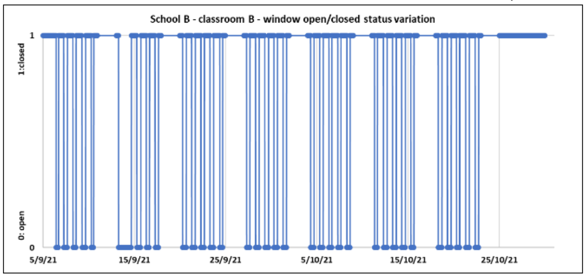


Figure 7: Window open/closed status variation and hourly averaged daily pattern (Winter 2021-22)



The second classroom of school B had been monitored in the same way and the results are represented in Figures 8 and 9. A similar pattern as before has been identified, with the difference that the opening hours during the winter period were almost as frequent as the opening hours during the Autumn.

Figure 8: Window open/closed status variation and hourly averaged daily pattern (Autumn 2021)



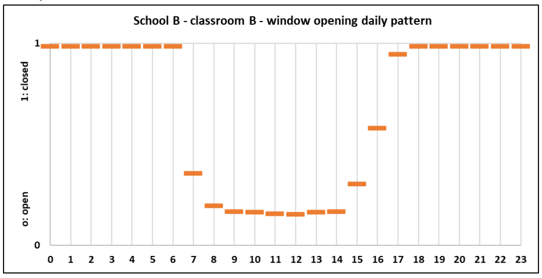
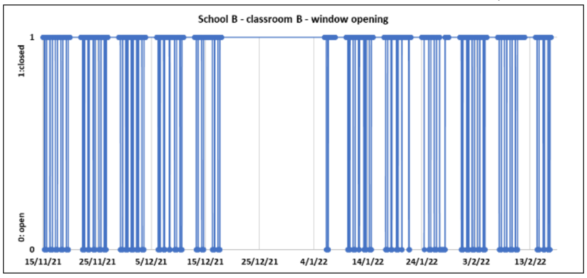
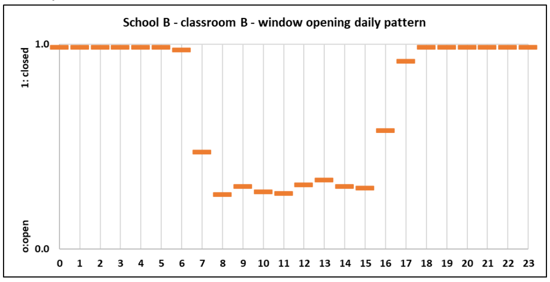


Figure 9: Window open/closed status variation and hourly averaged daily pattern (Winter 2021-22)





4.2 Air Temperature

There are two main observations from the data analysis regarding air temperature. Both observations appear as consequences of the requirement for increased natural ventilation of the classrooms. Normally, classrooms are expected to have a constant air temperature, which would be uniform across the classroom. However, due to the need for constant natural ventilation of the spaces, this is not the case.

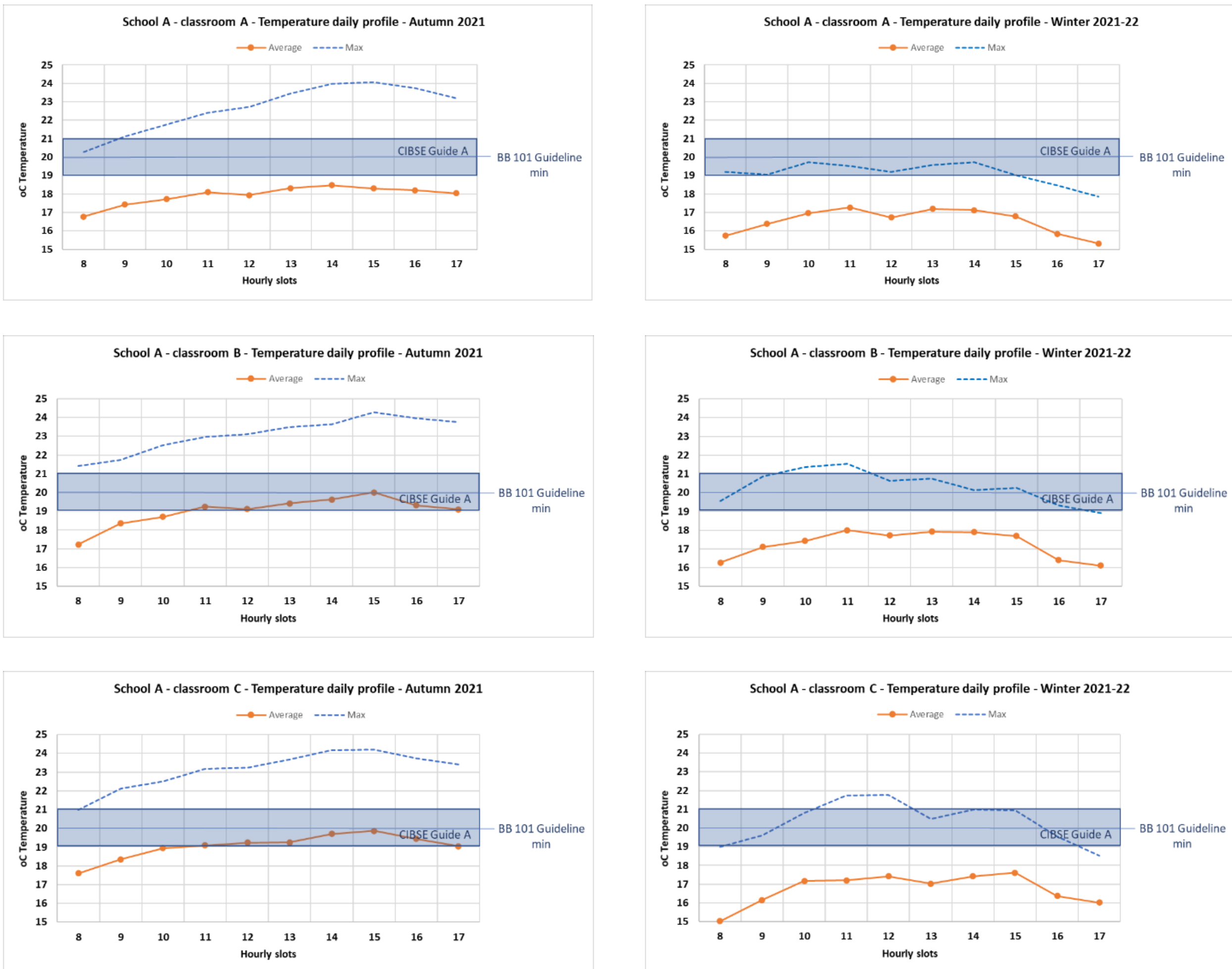
Firstly, the air temperature variation in the classrooms appears to be affected by the ambient air temperature. It is apparent that the variation of air temperature of the classroom throughout the day starts from a certain value as the windows have been closed during the night, it drops with the beginning of the lessons, and then it has a tendency to follow the variation of the ambient temperature. However, each week the average temperature is lower, resulting to an air temperature less than 20°C. Projecting this tendency to the winter months, the indoor air temperature could potentially be too cold and uncomfortable if the opening window regime adopted in autumn is applied in winter.

Secondly, there is a significant temperature difference within the classroom. The graph of an indicative week shows that there is a constant temperature of 2°C between the location near the window and away from the window.

The first set of graphs (Figure 10) show the temperature daily profile in the three classrooms under study in school A. For each classroom, the data for Autumn 2021 are represented in the graph on the left-hand side, while the graph on the right-hand side shows the data for the winter. The scale on the vertical axis is kept the same, to allow for direct comparison.

Analysing the graphs in Figure 10, it is apparent that there are similar observations across all three classrooms of school A. During the autumn of 2021 the average temperature is within the acceptable range by the CIBSE Guide A for classrooms and up to 1ºC below the minimum threshold set by the Building Bulleting Guideline. Moreover, the line that represents the daily profile of the maximum temperature is well above the acceptable range, meaning that in many circumstances the temperature has been higher than the required one by both CIBSE and BB 101.

Figure 10: *Temperature daily profile comparison Autumn 2021 and Winter 2021-22, school A*



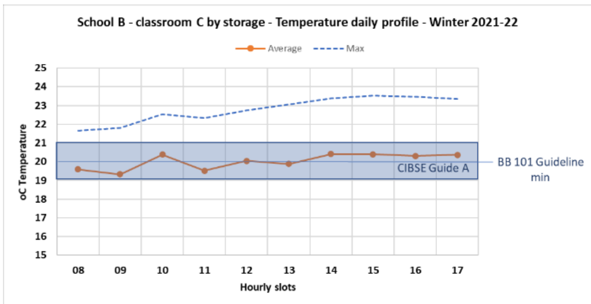
Regarding the comparison between autumn and winter data in Figure 10, there is a noticeable temperature drop in all three classrooms during the winter period. In classroom

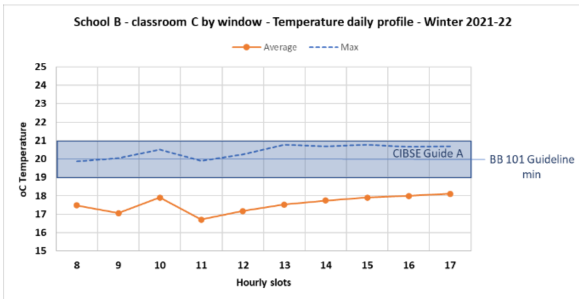
A, the temperature drop is less than 1ºC, in classroom B the temperature drop is around 1ºC, and in classroom C it is 1.5-2ºC. Meanwhile, in all three classrooms the maximum temperature is significantly lower than the one in the autumn. Regarding the comparison against the benchmarks, during the winter the average temperature is 1.5-2ºC below the acceptable range, while the maximum temperature is within the acceptable range.

Overall, the data shows a significant temperature drop during the winter. To reach to a conclusion whether this temperature drop causes discomfort, a deeper analysis is required with a more frequent time interval (60-min interval was used) and a diary study to take into consideration the timing of the activities that take place in each classroom.

Following the same analysis for school B, the results are shown in Figure 11. In school B the temperature remains within the acceptable range both in autumn and in winter 2021-22, with only a minor drop during the winter period.

Figure 11: *Temperature daily profile comparison Autumn 2021 and Winter 2021-22, school B*





At this point it is interesting to mention that in addition to the temperature decrease depending on the weather, there is a significant temperature difference inside each classroom. The last two graphs in Figure 11 are added to show the comparison between the two temperature sensors installed in classroom C, the one near the window and one near the storage. The temperature in the classroom, away from the window is within the acceptable range, while the temperature near the window is at least two degrees lower. This observation is quite compatible with the increased natural ventilation which has been confirmed by the data regarding the window opening patterns. Due to the requirement for increased natural ventilation the windows are left open as much possible and there is a noticeable difference in the classroom, between the areas near and away from the window.

The same observation has been repeated in all classrooms. However, to avoid the unnecessary repetition only one case is illustrated in the report, as a representative case.

Simple behavioural interventions to balance the need of increased natural ventilation and thermal comfort could include (1) reducing the number of hours windows are open to match times when CO_2 levels are likely to be higher during the occupancy hours; (2) locate sitting and learning areas, if possible, farther away from windows so occupants using the spaces are primarily located towards the inner end of the classrooms. This strategy, however, could compromise efforts to maintain social distance or bubble arrangements within classrooms adopted as safety provision in the light of COVID-19 guidance.

4.3 Relative Humidity

The variation of the relative humidity follows the same tendency as described in the section for the air temperature, due to the constant natural ventilation. The fresh air that enters the building is critical to ensure the ventilation of the space. However, the humidity of the air cannot be controlled, resulting to an increased humidity in the classroom. The levels of humidity keep increasing, following the seasonal change of the weather. Moreover, the areas next to the window appear to have higher relative humidity, as the fresh air that enters the building is colder and more humid than the indoor air. The graphs below (Figures

12-17) show the average relative humidity in the classroom, during autumn and winter 2021-22.

Figure 12: Relative Humidity hourly averaged daily profile in school A, classroom A

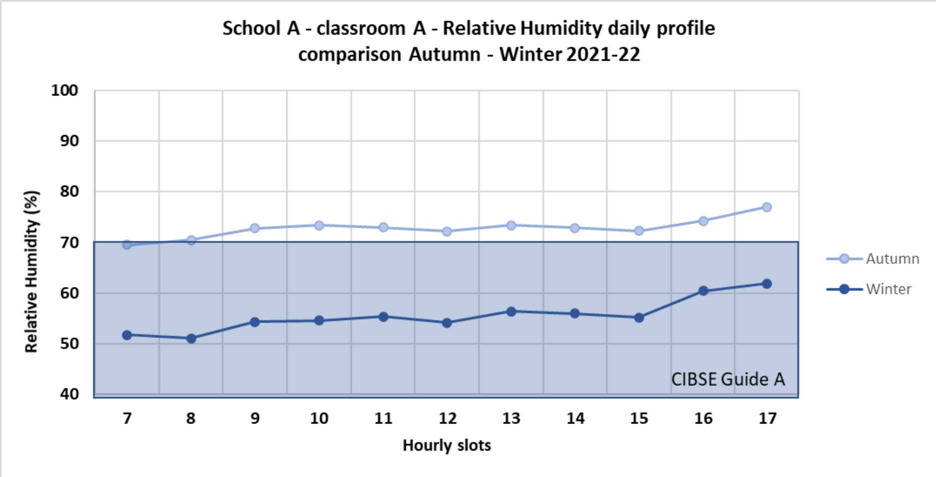


Figure 13: Relative Humidity hourly averaged daily profile in school A, classroom B

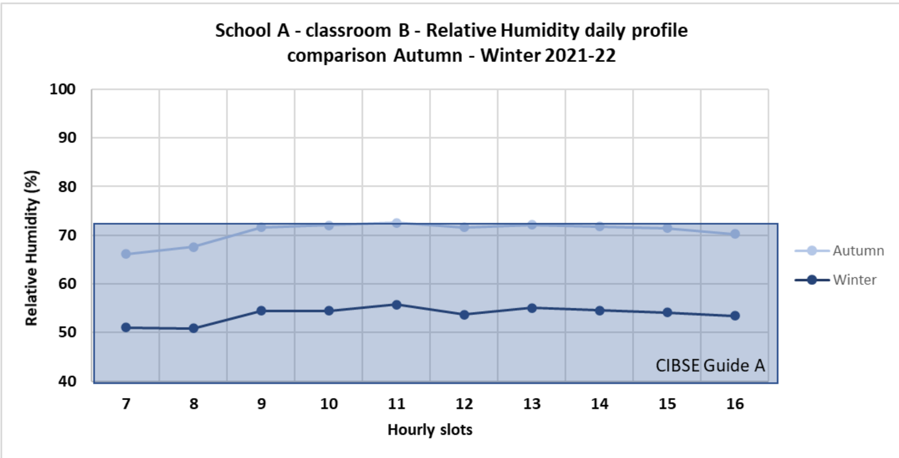


Figure 14: Relative Humidity hourly averaged daily profile in school A, classroom C

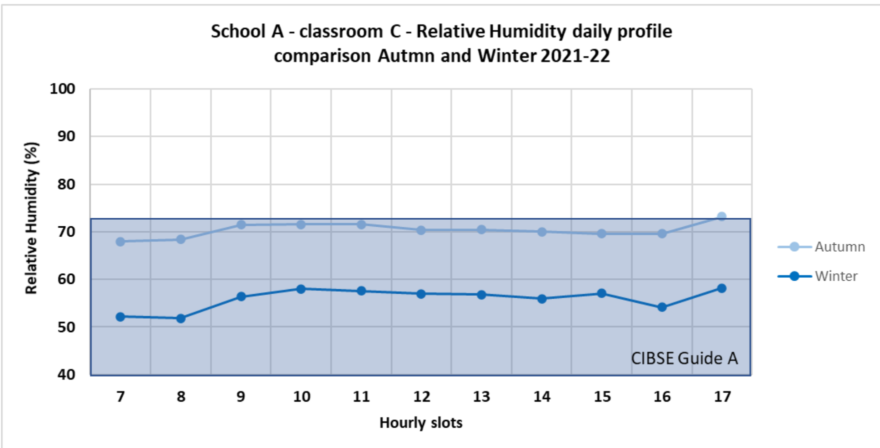


Figure 15: *Relative Humidity hourly averaged daily profile in school B, classroom A*

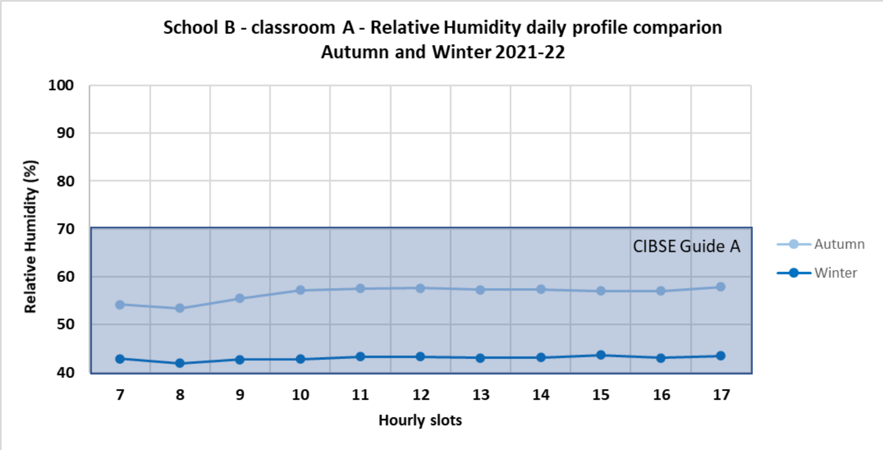


Figure 16: *Relative Humidity hourly averaged daily profile in school B, classroom B*

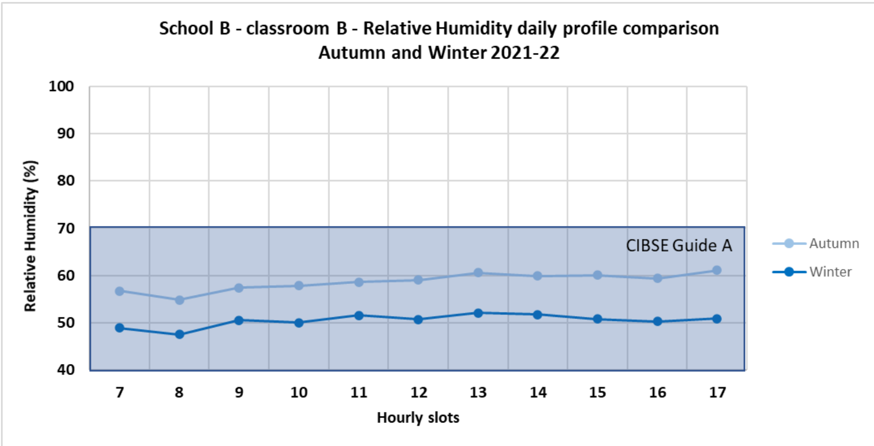
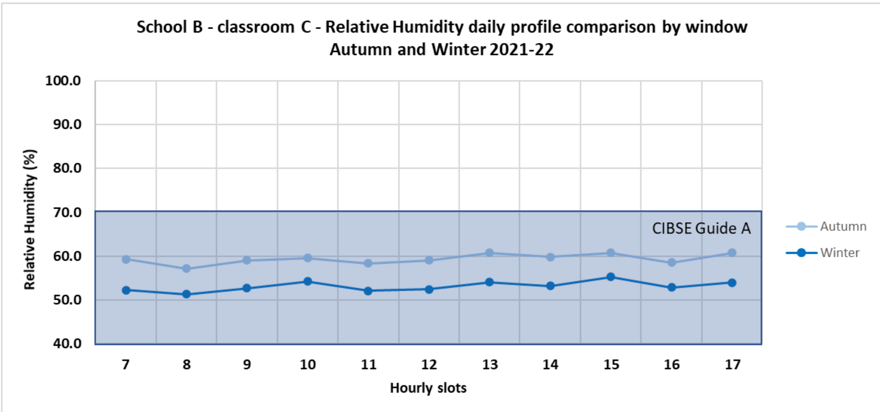


Figure 17: *Relative Humidity hourly averaged daily profile in school B, classroom C*



4.4 CO_2 concentration

The graphs below (Figures 18-23) illustrate the analysis of the data regarding CO_2 concentration in the classrooms under study in two schools, during Autumn and Winter of school year 2021-22.

To describe the following graphs, Figures 18-23 show the CO_2 concentration in school A. Figure 18 shows the CO_2 concentration variation in classroom A, during autumn 2021 at the left-hand side and during winter 2021-22 at the right-hand side. The interval of the measurements has been changed from 60min to 10min, hence the points are more condense in the winter graph. Figure 19 shows the hourly averaged daily profile of CO_2 concentration, including the comparison between autumn and winter. Similarly, Figure 20 and Figure 21 are referring to classroom B , while Figure 22 and Figure 23 are referring to classroom C.

In School A, the data suggests that the CO_2 concentration in the classrooms lies in general within the acceptable range. For the majority of the occupied hours the classrooms are at the lower edge of the amber light zone (800-1500ppm) as per Welsh Government Guidance issued in October 2021. There are instances where the CO_2 concentration is within the red light zone; however, these seem to be short-lived instances. As the time interval is 10-min, the CO_2 concentration is suggested to be further investigated using the in-depth short-term monitoring approach with HOBO CO_2 instruments with higher reading interval (1-min).

Figure 18: *CO_2 concentration variation in school A, classroom A, Autumn and Winter 2021-22*

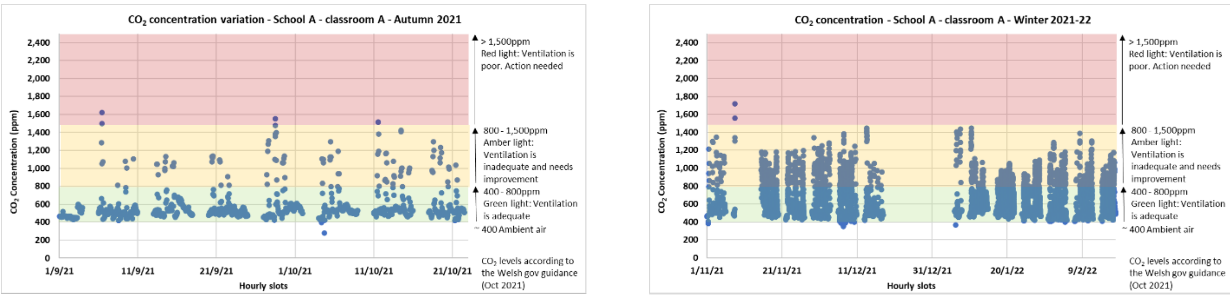


Figure 19: Hourly average CO_2 concentration in school A, classroom A, Autumn and Winter 2021-22

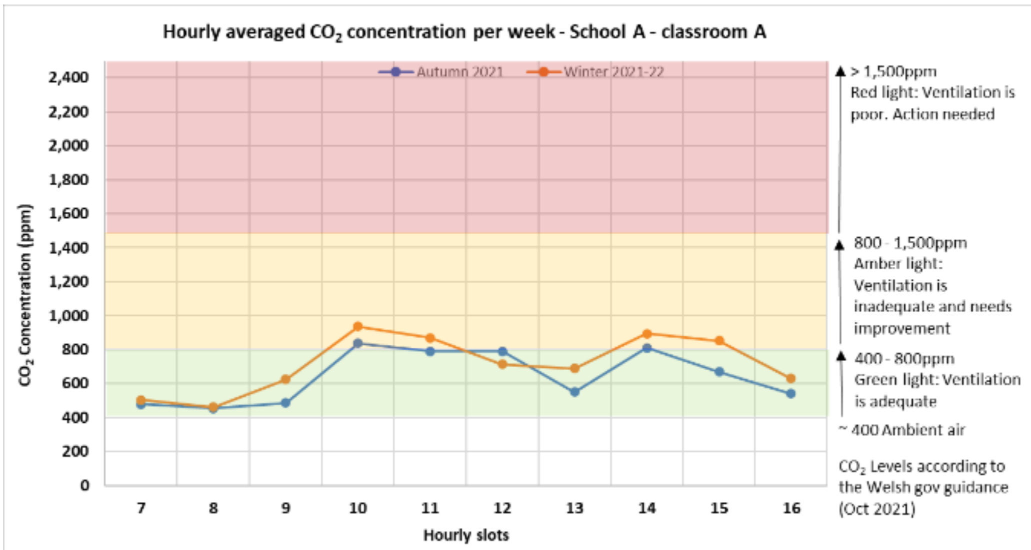


Figure 20: CO_2 concentration variation in school A, classroom B, Autumn and Winter 2021-22

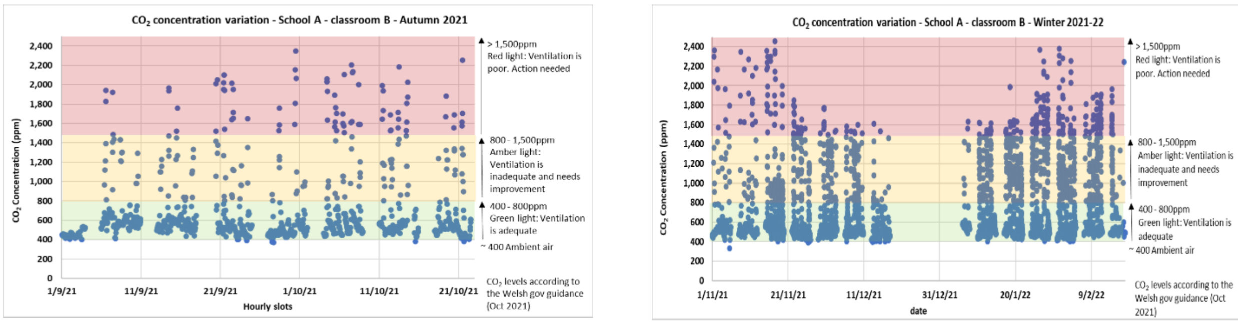


Figure 21: Hourly average CO_2 concentration in school A, classroom B, Autumn and Winter 2021-22

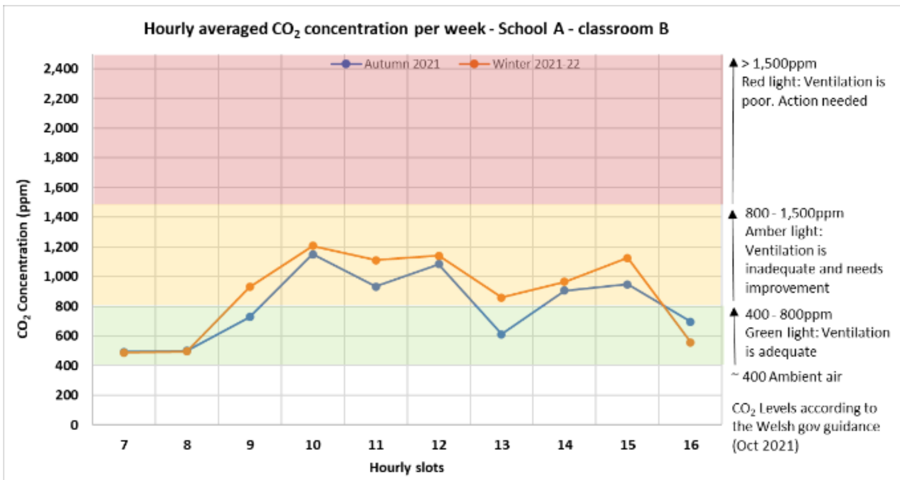
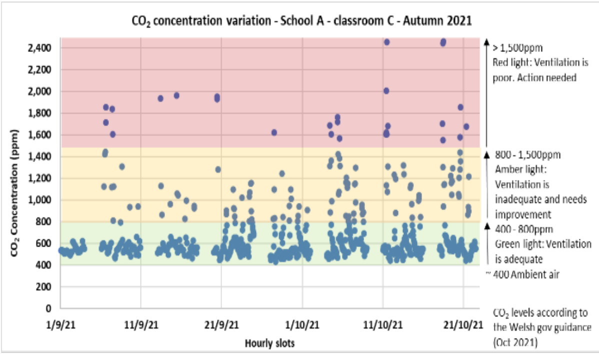


Figure 22: CO_2 concentration variation in school A, classroom C, Autumn and Winter 2021-22



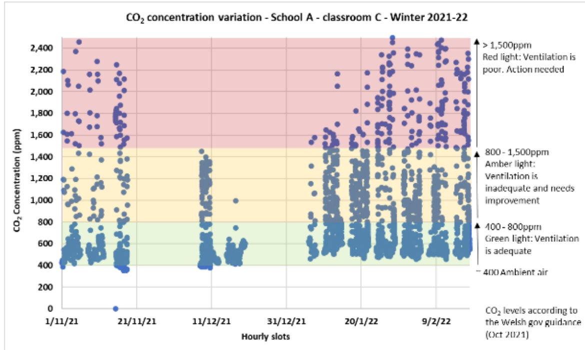
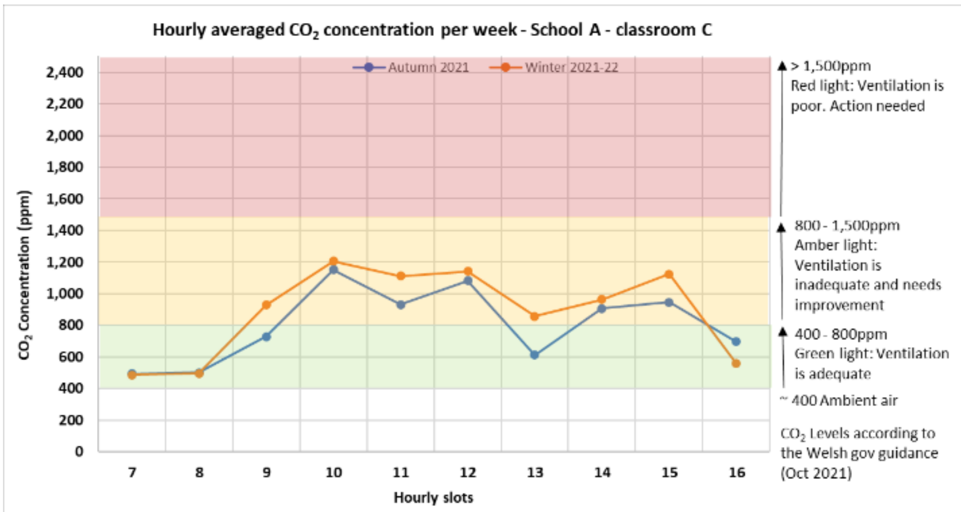


Figure 23: Hourly average CO_2 concentration in school A, classroom C, Autumn and Winter 2021-22



To introduce the following graphs regarding school B, Figure 24 illustrates the variation of CO_2 concentration in classroom A, during Autumn 2021 at the left-hand side and during Winter 2021-22 at the right-hand side. Weekends and holidays have been excluded. The points are more condensed during winter, due to the change of the time interval to 10min, from 60min during autumn. Figure 25 shows the hourly averaged daily profile of the CO_2 concentration in classroom A. The left-hand side graph shows the average CO_2 concentration for each hour of the day, while the right-hand graph shows the maximum recorded CO_2 concentration for each hour of the day.

The same reasoning is followed for the next graphs, Figure 26 and Figure 27 illustrate CO_2 concentration in classroom B, Figure 28 and Figure 29 illustrate CO_2 concentration in classroom C.

Figure 24: *CO_2 concentration variation in school B, classroom A, Autumn and Winter 2021-22*

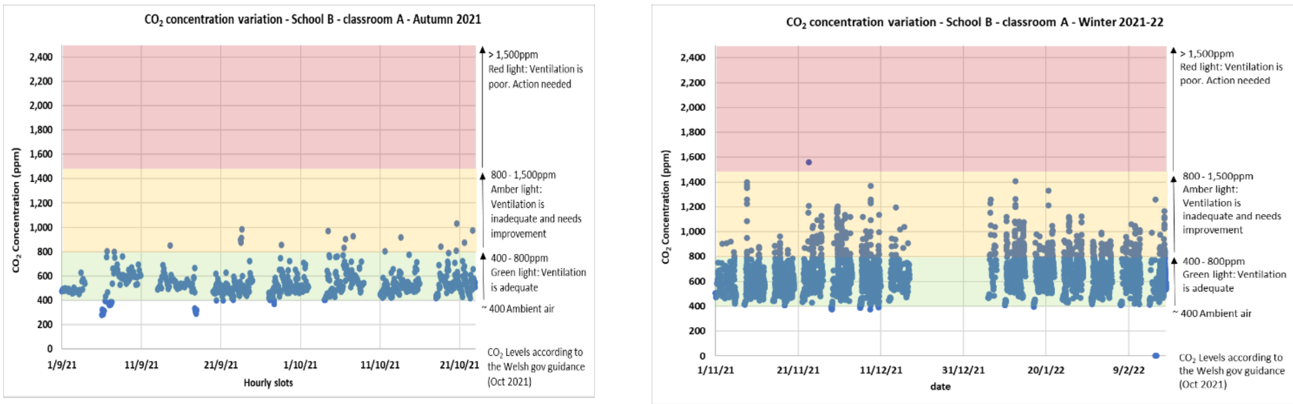


Figure 25: *Hourly average and max CO_2 concentration in school B, classroom A*

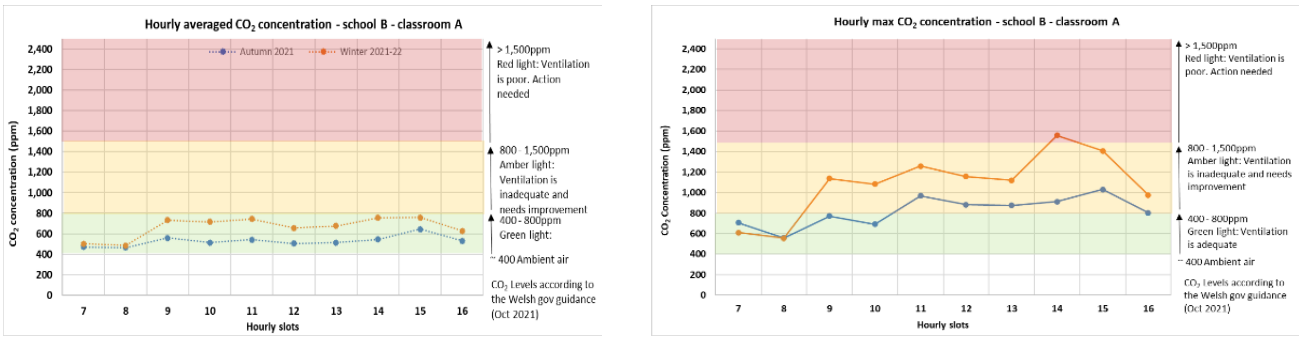


Figure 26: *CO_2 concentration variation in school B, classroom B, Autumn and Winter 2021-22*

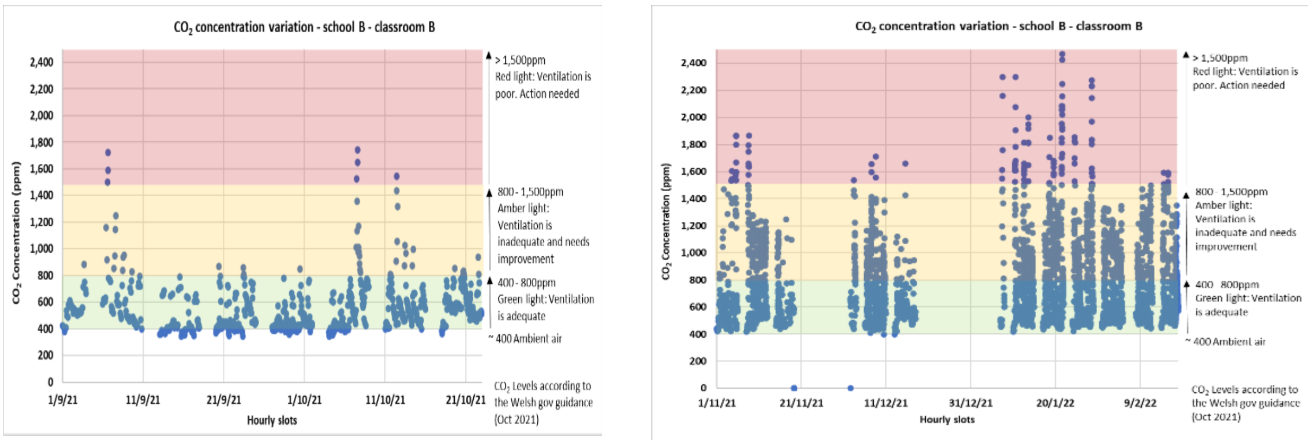


Figure 27: *Hourly average and max CO_2 concentration in school B, classroom A*

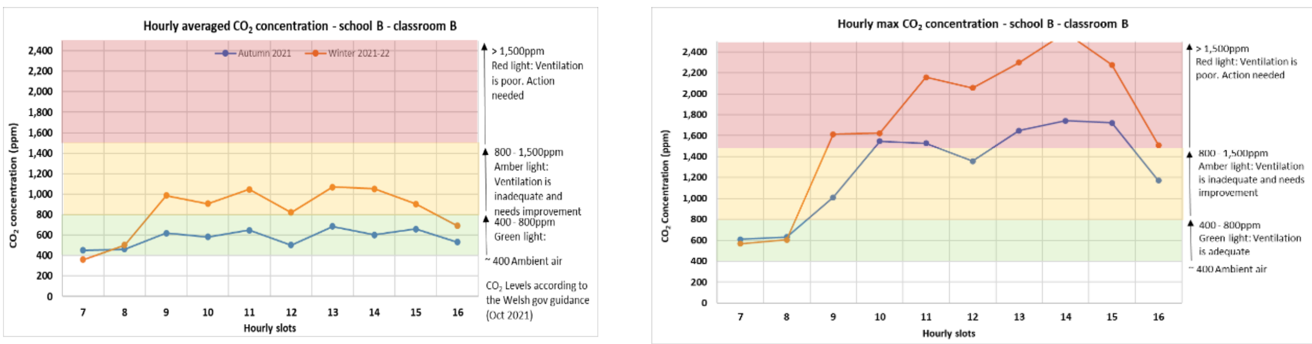


Figure 28: *CO2 concentration* variation *in school B, classroom B, Autumn and Winter 2021-22*

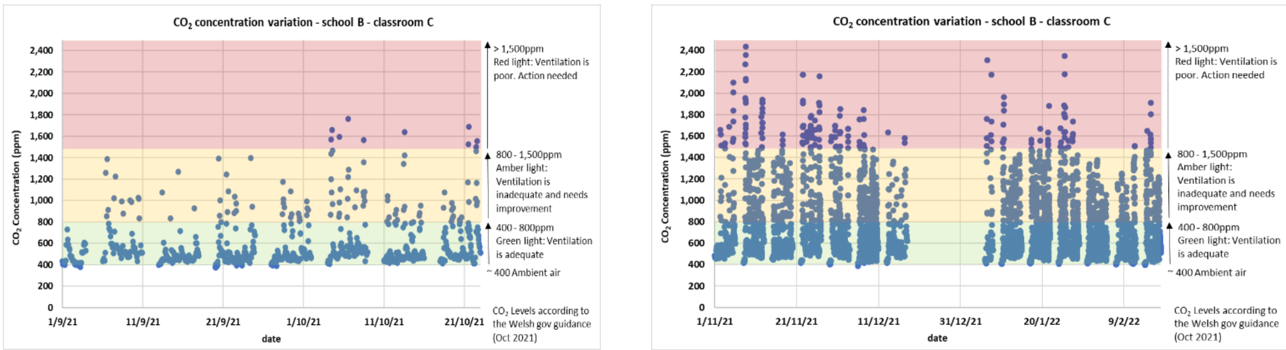
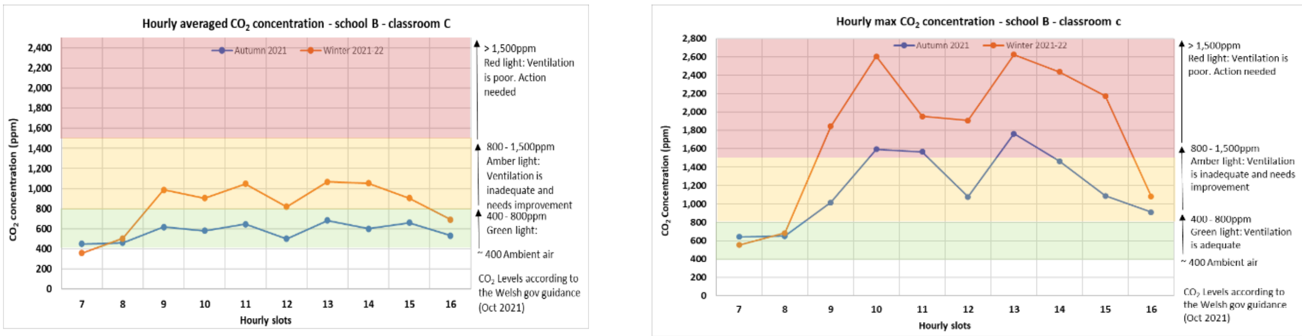


Figure 29: *Hourly average and max CO2 concentration in school B, classroom A*

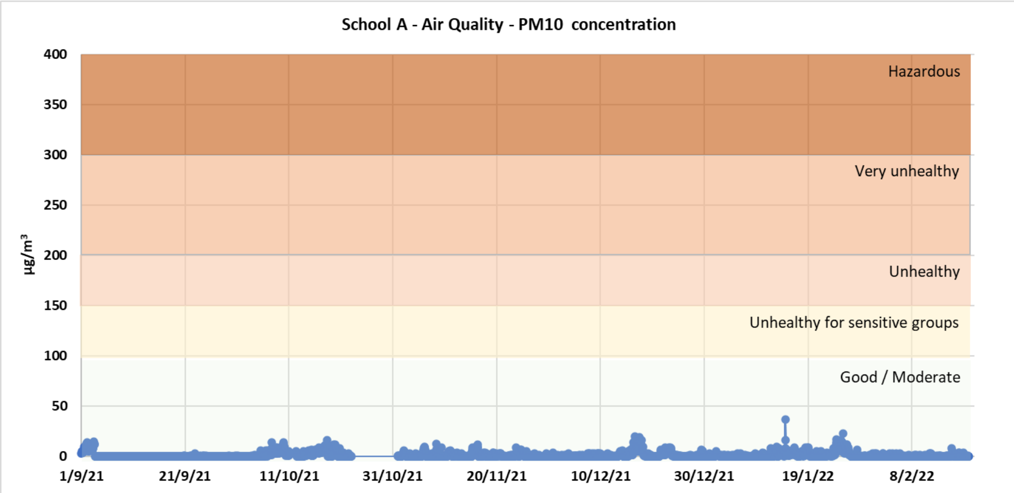


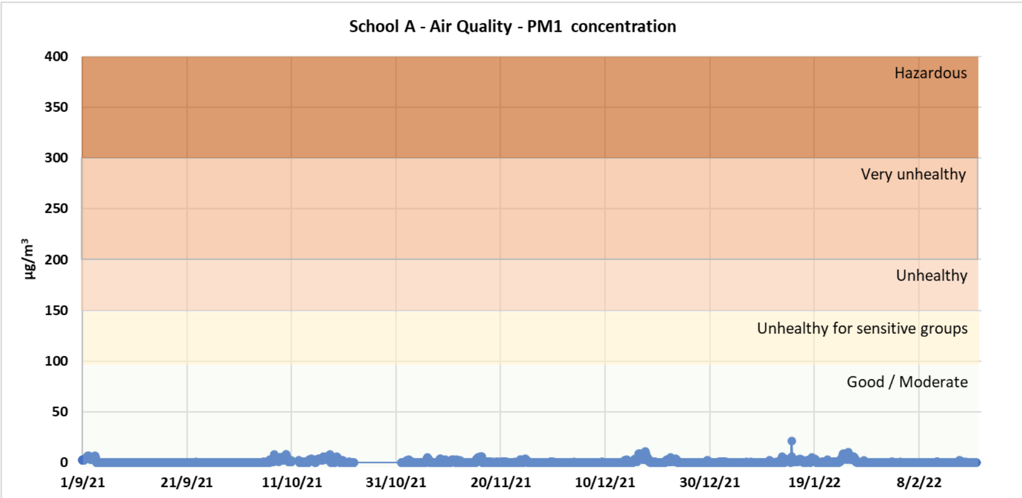
The data suggests that during autumn and winter 2021-22 the CO_2 concentration in the classrooms was generally within the acceptable range. The vast majority of occupied hours the classrooms are on average within a good range of CO_2 concentrations (400-800ppm), which corresponds to 'green light' zone as per Welsh Government Guidance issued in October 2021. The graphs that illustrate maximum CO_2 concentration show that there are very infrequent instances with short-lived peaks where the CO_2 concentration is in the lower end of the amber light zone (800-1500ppm).

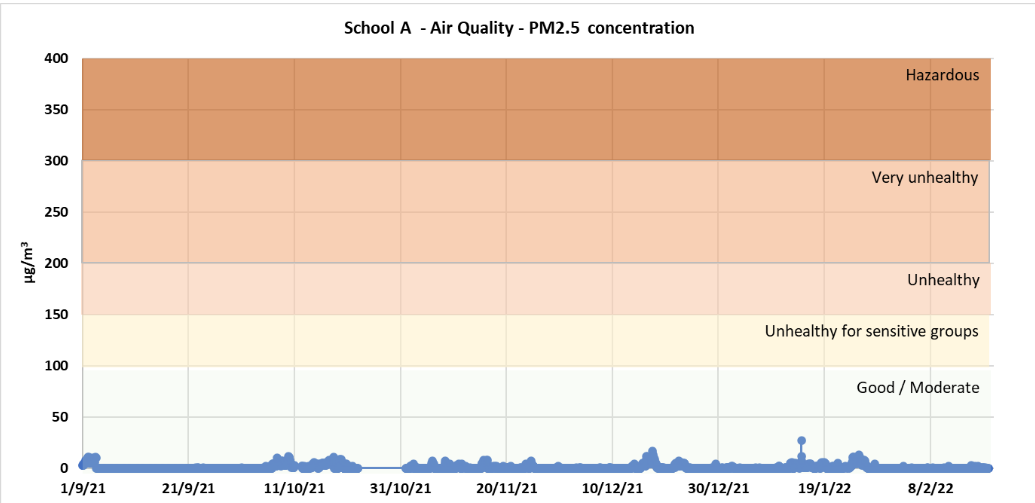
During the winter of 2021-22, data shows increased CO_2 in all three classrooms compared to the autumn of 2021. This is an indication of less natural ventilation due to colder weather during the winter. However, across all graphs of CO_2 concentration it is apparent that the levels remain within the acceptable range, or they increase for short periods.

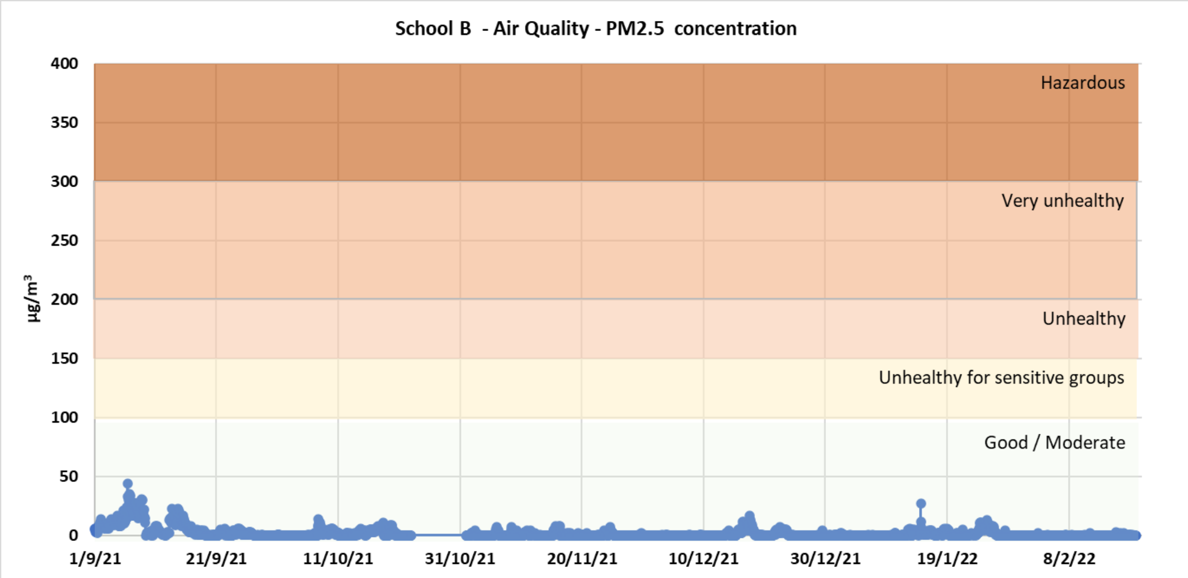
4.5 Air Quality

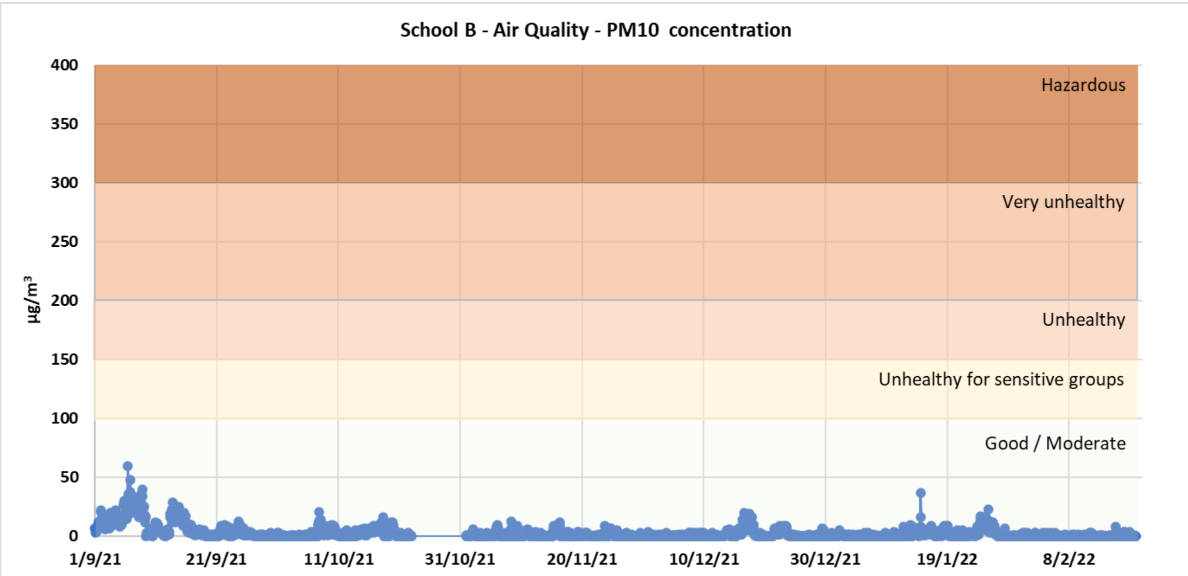
The concentration of PM2.5 and PM10 suggests that both school A and B are within a good air quality zone. This suggests that possible pollutants, if any, from outdoor sources such as nearby road are not entering the schools. This result was expected as both schools are located in relatively safe, non-polluted outdoor zones.

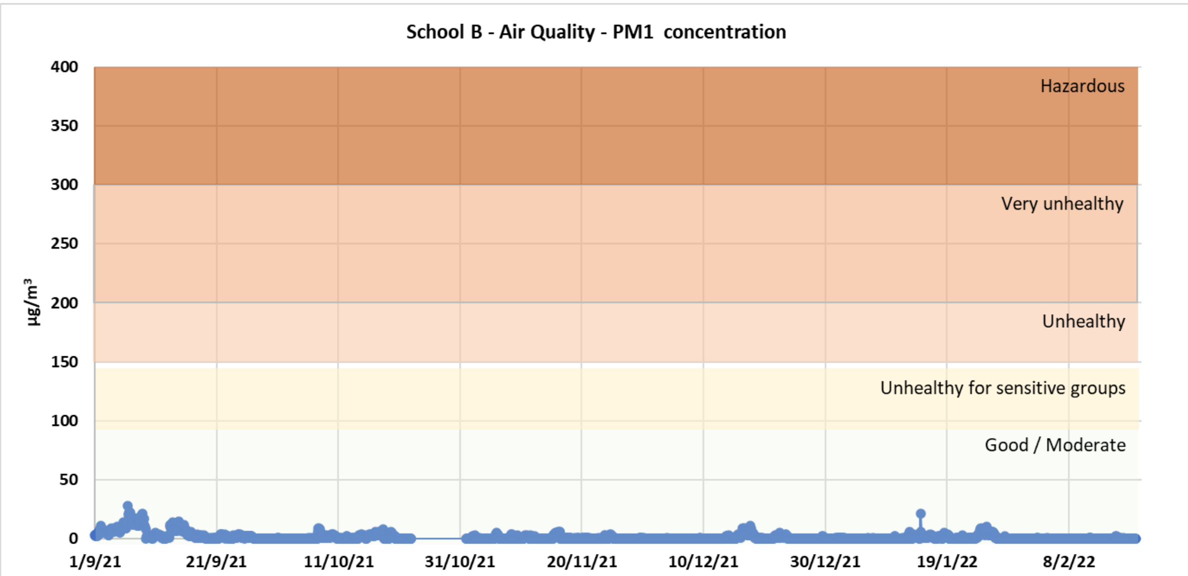

School A - Air Quality - PM10 concentration
µg/m³
400
350
300
250
200
150
100
50
0
Hazardous
Very unhealthy
Unhealthy
Unhealthy for sensitive groups
Good / Moderate
1/9/21
21/9/21
11/10/21
31/10/21
20/11/21
10/12/21
30/12/21
19/1/22
8/2/22


School A - Air Quality - PM1 concentration
µg/m³
400
350
300
250
200
150
100
50
0
Hazardous
Very unhealthy
Unhealthy
Unhealthy for sensitive groups
Good / Moderate
1/9/21
21/9/21
11/10/21
31/10/21
20/11/21
10/12/21
30/12/21
19/1/22
8/2/22


School A - Air Quality - PM2.5 concentration
µg/m³
400
350
300
250
200
150
100
50
0
Hazardous
Very unhealthy
Unhealthy
Unhealthy for sensitive groups
Good / Moderate
1/9/21
21/9/21
11/10/21
31/10/21
20/11/21
10/12/21
30/12/21
19/1/22
8/2/22


School B - Air Quality - PM2.5 concentration
400
350
300
250
200
150
100
50
0
µg/m³
Hazardous
Very unhealthy
Unhealthy
Unhealthy for sensitive groups
Good / Moderate
1/9/21
21/9/21
11/10/21
31/10/21
20/11/21
10/12/21
30/12/21
19/1/22
8/2/22


School B - Air Quality - PM10 concentration
400
350
300
250
200
150
100
50
0
µg/m³
Hazardous
Very unhealthy
Unhealthy
Unhealthy for sensitive groups
Good / Moderate
1/9/21
21/9/21
11/10/21
31/10/21
20/11/21
10/12/21
30/12/21
19/1/22
8/2/22


School B - Air Quality - PM1 concentration
400
350
300
250
200
150
100
50
0
µg/m³
Hazardous
Very unhealthy
Unhealthy
Unhealthy for sensitive groups
Good / Moderate
1/9/21
21/9/21
11/10/21
31/10/21
20/11/21
10/12/21
30/12/21
19/1/22
8/2/22

6. Lessons learnt from monitoring studies

Monitoring CO_2 as a proxy of the ventilation level is crucial for maintaining the desired level of indoor air quality in schools. To make sure that the monitoring process produces meaningful data there are a few parameters that should be taken in consideration.

Depending on the type of the monitoring devices, they might need calibration before their use. This process should be done carefully and following the manufacturer's instructions. This should be taken into consideration when choosing monitoring equipment, as the equipment should be able to be used by non-specialists, such as teachers.

Baseline ambient CO_2 levels should be monitored before the actual monitoring of the CO_2 of the classrooms. The ambient CO_2 levels might be different depending on the area where the school is located, so initial measurements give reference points for the monitoring process.

The location of the CO_2 sensors should be changed periodically to give more indicative mapping of the room. Especially due to the requirement for open windows, the air inside the classroom is not homogenous and the CO_2 percentage is not the same throughout the whole room. Moreover, the sensors collect air from a certain area around them, depending on their technology and quality. By changing the location of the sensors, the measurement is more indicative.

In case of logging CO_2 meter data, the interval is very important. For example, an interval of 60min would give an indicative value only when the levels of CO_2 are steady and will track long-term changes. In the case of classrooms, the changes are often and an interval of at least 10min should be used.

5 Qualitative user studies

The research included user studies with teachers and pupils to explore their satisfaction levels with the indoor environment and the actions adopted to promote ventilated and thermally comfortable classrooms. The research methods with teachers included two questionnaires (1) to identify their comfort perceptions about indoor environmental conditions and (2) to explore with teachers' adaptations in response to health and safety requirements to foster good indoor environmental conditions in the schools. The research methods with pupils comprised (1) drawing to reflect about their comfort perception of the indoor environment in their classrooms, and actions to modify the thermal experience with all pupils participating in the study (age range between 7-11 years old); and, (2) questionnaires only to children aged between 9-11 years old using traditional thermal comfort surveys instruments for this age group.

The questionnaires with teachers in relation to adaptation in schools explored changes in the use of the school buildings including spatial adaptation in classrooms and changes in everyday operation and use of building controls in classrooms; changes in use of school/classroom as response to COVID-19; provision of guidance and advise; and prompted teachers to provide examples of actions adopted and to identify opportunities for flexible use of teaching spaces both inside and outside their classrooms. The questionnaires to report satisfaction levels were primarily retrospective self-accounts of comfort perception related to temperature and air quality in the classroom where respondent teaches worked, and actions that are taken to change the indoor environmental conditions in different seasons. The children's questionnaires and drawings explored how their classroom felt in terms of temperature, humidity and air freshness at the moment of the survey.

Teachers reported that the main strategy adopted to foster well-ventilated classrooms was increasing the number of hours that windows and doors connecting to the outdoors were open during school time. However, this strategy is problematic in winter as it leads to discomfort due to low temperatures indoors. In order to minimise cold indoor temperatures during occupied hours, windows and doors are open during times when pupils are not in the classroom (i.e. during breaks and during outdoor learning time). The CO_2 monitors helped teachers to identify times to operate windows to maintain CO_2 concentration within recommended levels.

In some instances, teachers reported new layouts and spatial configurations in the classrooms where they primarily teach; for example, distances between desks and working stations, and the zoning of activities inside the classrooms. In younger year groups, teachers reported that learning activities are promoting more hours of outdoor learning, using covered areas connecting classrooms and in the outdoor open spaces available to the school. Teachers consider that there are opportunities to use outdoor spaces, and spaces immediately outside the classroom for younger year groups flexibly in alignment with pedagogical needs. Communal spaces used for breaks or for flexible learning by different year groups have been timetabled more systematically to avoid mix of year groups.

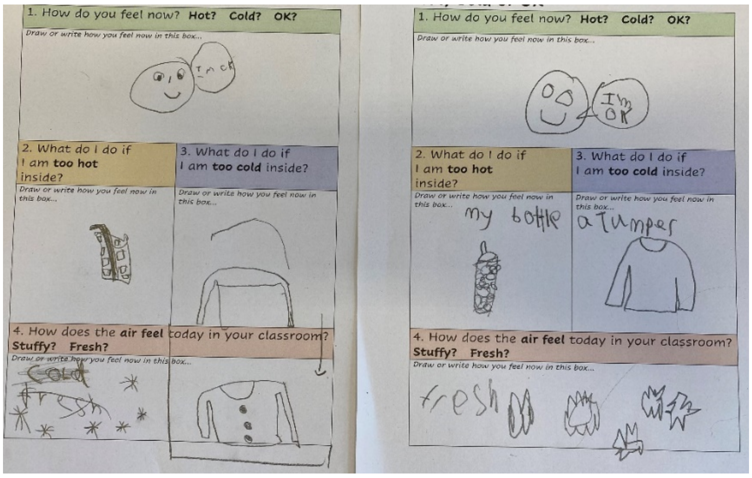
Teachers reported that advice has been provided in relation to mitigation risk for COVID-19. This advice has focused on cleaning, hygiene and social distancing. Other strategies included staggered drop-off and collecting times, designated access for different year groups using different access points to the school, and one way circulation systems.

In terms of thermal experience in the monitored classrooms, the study undertook studies of thermal comfort and perception of air freshness among pupils in December. All pupils used drawings to reflect about their thermal experience in the classroom and actions taken to achieve thermal comfort (Figure 30 provides an example). Questionnaires were administered to pupils older than nine years old to rate their perceptions of temperature and air freshness in their classrooms.

In terms of the drawings, younger children were able to express concepts related to their thermal experience in general; however, it is unclear if their responses were a reflection of their perceived experience "right here, right now". Typically, drawings by younger children involved responses about their thermal experiences inside and outside the classroom, including the home environment. Younger children were able to identify a broad range of actions they can take to improve their thermal comfort, referring primarily to personal adaptation actions such as changing clothing levels (e.g. extra layers when cold).

Drawings by older children (>nine years old) who also completed questionnaires showed a good understanding of concepts related to thermal experience but there seemed to be less clarity in relation to the understanding of concepts related to air freshness and ventilation. It was noticed that the general trends expressed in relation to thermal experience via drawings and the responses in questionnaires were aligned for data collected among older children through different instruments (drawings and questionnaires). Older children were able to express visually their thermal experience in the classroom. Actions to modify their thermal experience included examples of actions taken in the classroom setting as well as outside the classroom in other environments (i.e. at home, in the playground). This could be explained by the limited agency of children to take action to modify the thermal environment in their classroom and a wider recognition of thermal experiences in the most common settings they use.

Figure 30: Examples of drawings of pupils capturing their views about thermal comfort and air freshness in their classrooms



The results in School A (Figure 31 and 32) show that in terms of temperature perception, 26% of pupils felt very cold, 67% felt comfortable and 7% felt very hot. In relation to pupil's reported perception of air freshness, 71% considered the air in the classroom to be fresh, 7% considered the air to be unfresh and 22% thought the air was neither fresh or unfresh.

Figure 31. School A Responses related to temperature perception by the participating classrooms

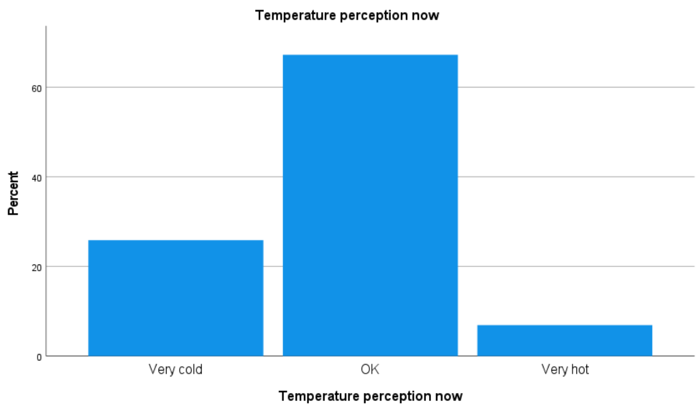
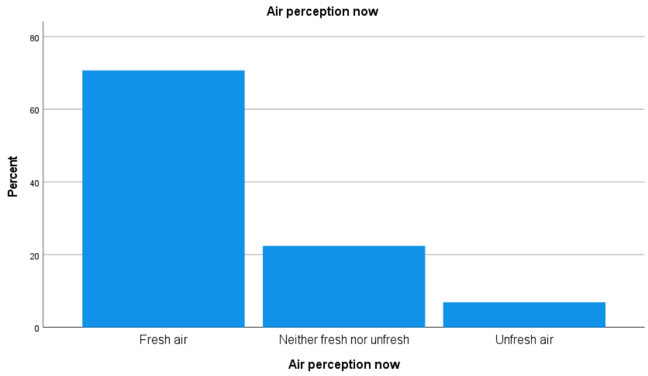


Figure 32. School A Responses related to perception of air freshness by the participating classrooms



The results in School B (Figures 33 and 34) show that in terms of temperature perception, 34% of pupils felt very cold, 26% felt comfortable and 40% felt very hot. In relation to pupil's reported perception of air freshness, 30% considered the air in the classroom to be fresh, 30% considered the air to be unfresh and 40% thought the air was neither fresh or unfresh.

Figure 33. School B Responses related to temperature perception by the participating classrooms

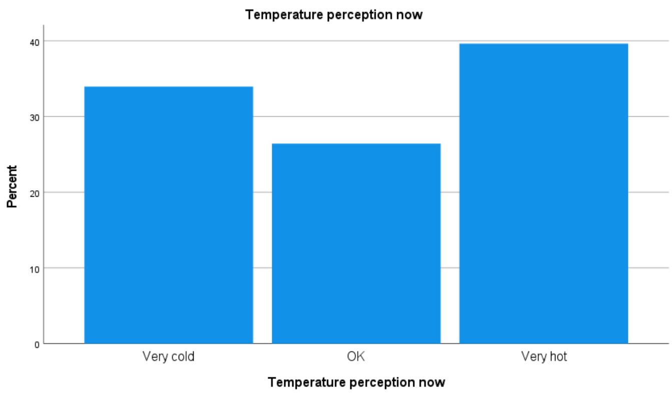
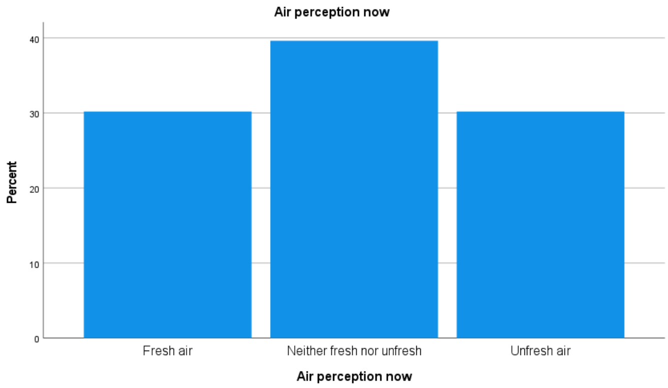


Figure 34. School B Responses related to perception of air freshness by the participating classrooms



The user studies suggest that the participating schools have been implementing guidance to promote fresh air and ventilation by keeping windows and doors open during occupied hours. This strategy, however, has been adapted in relation to the needs to maintain thermal comfort in different seasons. During winter season, when outdoor temperature drops, window opening times have concentrated, whenever possibly, to times when pupils are not in the classroom to avoid discomfort due to cold temperatures. For example, windows and external doors in classrooms are open before the start of the school day, during lunch breaks and outdoor play times and after the end of the school day. The patterns of CO_2 concentration suggest trends around opening/closing of windows and doors to promote ventilation. The monitored classrooms show that CO_2 concentration levels tend to be within green and amber light zone as per Welsh Government guideline in autumn and in winter. It should be noted that the strategy of opening windows more frequently and for longer hours is likely to be problematic for energy conservation during the heating season and may lead to increased heating demand.

Qualitative studies to identify the thermal experience and the perception of air freshness in classrooms show mix results. Pupils from School A where monitoring data in winter shows that classrooms are between 16-18^{o}C show good satisfaction levels with the temperature of their classrooms (67% of pupils reporting to feel comfortable). There is, however, a significant proportion of pupils in this school (26%) who felt very cold. In School B where the monitoring data suggest winter temperatures between 17-19^{o}C there were mix responses both in terms of temperature and air freshness in the classroom without a clear majority of pupils reporting any predominant perception trend.

6 School's engagement: development of educational resources and hands-on workshops with pupils

A second strand of this project is focused on developing learning resources and engaging in hands-on workshops with pupils to reflect about indoor environmental conditions in schools, focusing on the nexus between behaviours and the resulting indoor environmental conditions.

A series of workshops are being developed with the support of teachers of monitored classrooms which include a mix of age groups from Foundation Phase and Key Stage 2. The resources are tailored to the knowledge and skills of different age groups and the complexity of concepts related to building performance, indoor environment and comfort in buildings and energy in buildings, and wider concerns about energy use and sustainability. We are designing practical STEM workshops with children to discuss concepts related to temperature, indoor air and building parameters while practicing numeracy skills. Children are producing materials such as drawings, tables, crafts and charts as part of the workshop activities and encouraged to use monitoring devices to understand concepts about building performance using their own schools as Living Labs.

As a result of our work on engagement we delivered two workshops: 'Building Doctors' and 'Healthy comfortable classrooms in Energy efficient ways'. Each workshop has lesson plans tailored to Foundation phase and to Key Stage 2; teaching/learning resources to deliver the workshop and templates to run practical children-led hands-on activities. The learning resources used during these workshops were developed with the feedback of teachers and in response to pupils' interest, needs and knowledge of the topics discussed. The workshops offer the opportunity for kids to discuss what they know about buildings and sustainability as a way to empower them to take actions that foster good indoor environments in sustainable ways. The workshops include hands-on activities where kids use monitoring instruments to develop numeracy skills and explore concepts about building performance. The estimated time allocation per workshops is 60-75 minutes.

Pupils had the opportunity to practice Maths and numeracy skills as well as Science and Technology skills as part of the hands-on workshops. They explored concepts related to the building performance and sustainability of their own school using monitoring data collected by Cardiff University as well as data collected by themselves in their own classroom:

‘We enjoyed drawing our ideas [about keeping comfortable] and collecting [building performance] readings independently around our school’

Pupil from Foundation phase

Sections 6.1. and 6.2 summarise the workshops, describing the topics and aims for Foundation Phase and for Key Stage 2. Appendix 3 illustrates the monitoring devices used by pupils during the workshops.

6.1. BUILDING DOCTORS

The general aim of this workshop is to discuss with children what they understand about the concepts related to ‘temperature’, ‘thermal experience’, ‘thermal comfort’ and what the implication are in terms of school energy use and sustainability**.** Workshops for Key Stage 2 also included the concepts of ‘indoor air quality’ ‘ventilation’ ‘air freshness’.

6.1.1. BUILDING DOCTORS - Lesson Plan Foundation phase

Topic: What do children understand about ‘temperature’, ‘thermal experience’ and ‘thermal comfort’?

Aims of workshop 1 – *what the Cardiff team and teachers can learn as result of the workshop:*

1) To explore children’s understanding of building performance concepts (thermal comfort).

2) To identify children’s perception of thermal comfort in their classroom in the light of monitoring data.

3) To compare differences/similarities of understanding of concepts per age groups which can inform learning materials/instruments to collect data about perception/experience in buildings (cross comparison of data collected, specific ‘research aim exploration’ per age group/key stage)

Learning aims of visit 1 (foundation phase)- what the pupils learn as result of the workshop:

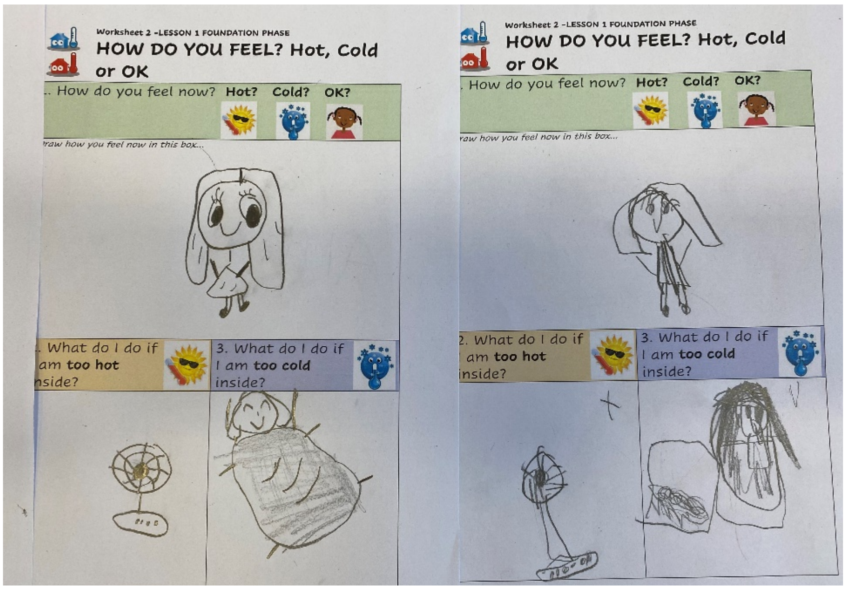
1. To understand how you feel now in the building, and when you are hot or cold, and what you would do if you were too hot or too cold when inside a building.

2. Building doctors and Feverish buildings: how to take the temperature of the air inside and outside a building, how to record it and compare the temperature in different locations (hands-on activity by pupils using monitoring instruments).

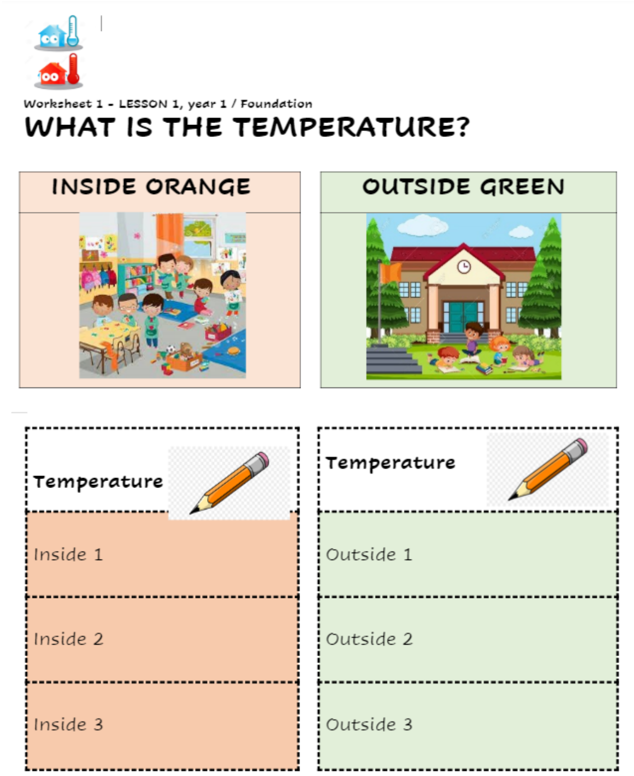
3. To understand how buildings use energy to keep you warm, and how you can do to make your classroom comfortable

Suggested extension activity (after the workshop)

Making buildings warm or cold: Monitoring the temperature - Can we measure the temperature over time? – Looking at monitoring device left in the classroom and demonstrating what they can do. – Recording the temperature at different times of day – do they notice any difference (e.g. morning of schools day, and home-time?) - Do they notice the classroom being a different temperature when it is hotter or colder outside?



Example of Worksheet used in Workshop 1 completed by Foundation Phase pupils



Worksheet 1 - LESSON 1, year 1 / Foundation

WHAT IS THE TEMPERATURE?

INSIDE ORANGE	OUTSIDE GREEN
Temperature	Temperature
Inside 1	Outside 1
Inside 2	Outside 2
Inside 3	Outside 3

Example of Worksheet used in Workshop 1 for Foundation Phase pupils to record data about their school using monitoring devices

6.1.2. BUILDING DOCTORS- Lesson Plan Key Stage 2 phase

Topic What do children understand about 'temperature', 'thermal experience' and 'thermal comfort' AND indoor ventilation?

Aims of workshop 1 - *what Cardiff team and teachers can learn as result of the workshop:*

1) To explore children's understanding of building performance concepts (thermal comfort, ventilation/CO_2).

2) To identify children's perception of thermal comfort and ventilation in their classroom in the light of monitoring data that they collect in hands-on workshop.

3) To compare differences/similarities of understanding of concepts per age groups which can inform learning materials/instruments to collect data about perception/experience in buildings.

4) Optional aim for upper Key Stage 2 level: to identify children's understanding of energy in buildings and sustainability impact of energy sources in buildings.

Learning aims of visit 1 (Key Stage 2 phase)- what the pupils learn as result of the workshop:

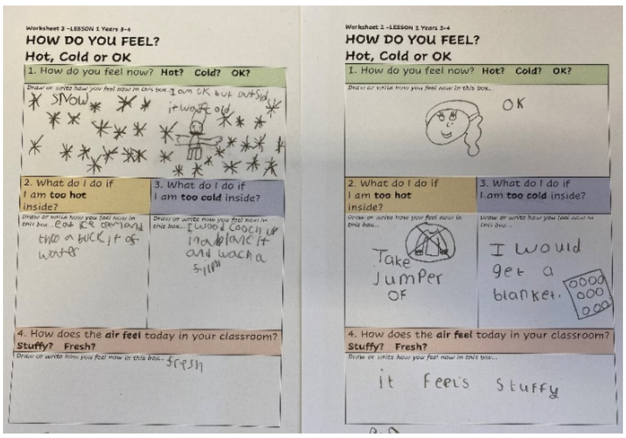
1. To understand how you feel now in the building, and when you are hot or cold, and what you would do if you were too hot or too cold when inside a building. With upper Key stage 2 children the concept of ventilation is also explored - how does the classroom feels now in terms of ventilation, what do you do if it feels airy, if it feels unfresh?

2. Building doctors and Feverish buildings: how to take the temperature of the air inside and outside a building, how to record it and compare the temperature in different locations (hands-on activity by pupils using monitoring instruments). With upper Key stage 2 children the concept of ventilation is also explored - how to record CO_2 and compare it in different locations.

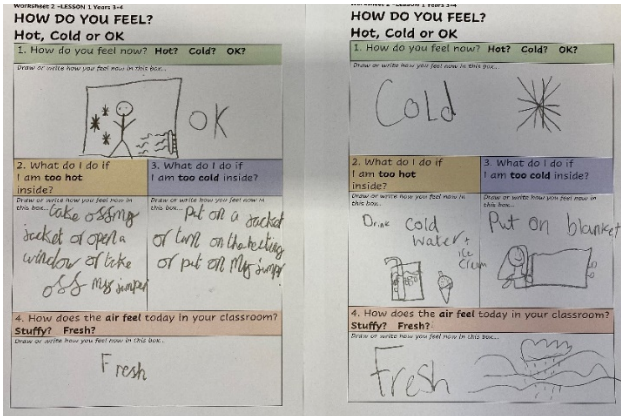
3. To understand how buildings use energy to keep you warm, and how you can do to make your classroom comfortable. With upper Key stage 2 children the concept of sustainable energy in buildings is also explored - including a discussion about energy in buildings and the sustainability impacts of energy sources in buildings.

Suggested extension activity (after the workshop)

Making buildings warm or cold: Monitoring the temperature - Can we measure the temperature over time? – Looking at monitoring device left in the classroom. – Recording the temperature and CO_2 concentrations at different times of day – do you notice any differences (e.g. morning of schools day, and home-time?) - Do you notice the classroom being a different temperature when it is hotter or colder outside? Do you notice how CO_2 changes if you open windows? At different times of the day? During school days and during weekends?



Example of Worksheet Workshop 1 completed by Key Stage 2 Phase pupils (Year 3)



Example of Worksheet Workshop 1 completed by Key Stage 2 Phase pupils (Year 6)

ENVIRONMENTAL DATA LOG BOOK					
		CLASSROOM /INDOORS			OUTDOORS
Week 1	Time	Classroom Temperature (oC)	Relative Humidity (%)	CO2 concentration (ppm)	Outdoor Temperature (oC)
Monday date :	Morning _______				
Tuesday date :	Morning _______				
Wednesday date :	Morning _______				
Thursday date :	Morning _______				
Friday date :	Morning _______				

Example of 'Environmental Data Log book' to be used as extension activity of Workshop 1 for Key Stage 2 Phase pupils to record data about their school using monitoring devices

6.2. WORKSHOP 2: 'HEALTHY AND COMFORTABLE CLASSROOMS IN ENERGY EFFICIENT WAYS'

Building upon Workshop 1 'Building Doctors', this workshop explored how energy is used in the context of the classroom and to consider how to promote warm and comfortable classrooms while using less energy. This workshop enabled Cardiff University team to explore how monitoring data from the schools can be used to discuss with pupils about concepts related to energy efficiency, saving energy and sustainability. Children from all year groups used and interpreted monitoring data collected by the Cardiff University team and also used monitoring instruments to record temperature, lighting levels and air quality in their classrooms.

Learning aims of visit 2 (Foundation Phase and Key Stage 2):

1. To understand how energy is used in the context of the classroom (heating, lighting and ventilation), and how buildings contribute to energy use and climate change.

2. To understand how being comfortable in the classroom requires energy.

3. To identify different ways that we can save energy in the classroom

In addition to Learning aims above, **Key Stage 2 workshops** have the following aims:

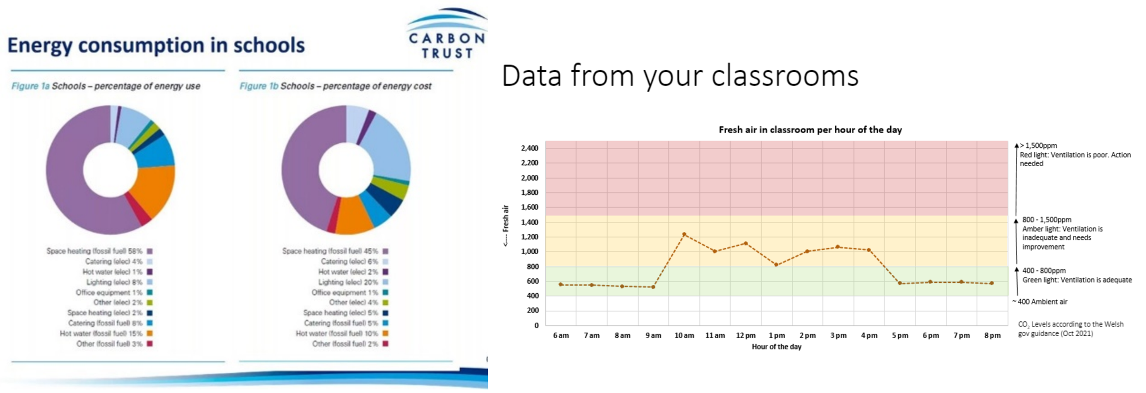
1. To understand how we balance the need for using less energy (heating) and that we need fresh air for ventilation.

2. To develop a more detailed understanding of where energy used in the school comes from, and the different ways energy is produced more generally, and how these are linked to climate change.

A number of resources were developed to facilitate the workshops including:

Power point presentation to facilitate discussions and to encourage pupils to connect concepts of temperature to heating to energy use in their schools (Foundation and Key Stage 2). Key Stage 2 workshop also included the concept of ventilation.

Monitoring data and building performance data of schools (included their own school's data): (1) Energy consumption in schools - energy used for different type of activities in school buildings (heating, lighting, hot water, etc) (Source: Carbon Trust); (2) Display Energy Certificate (DEC) with Energy data of the schools; (3) Monitoring data (classroom average temperature and CO2 levels).



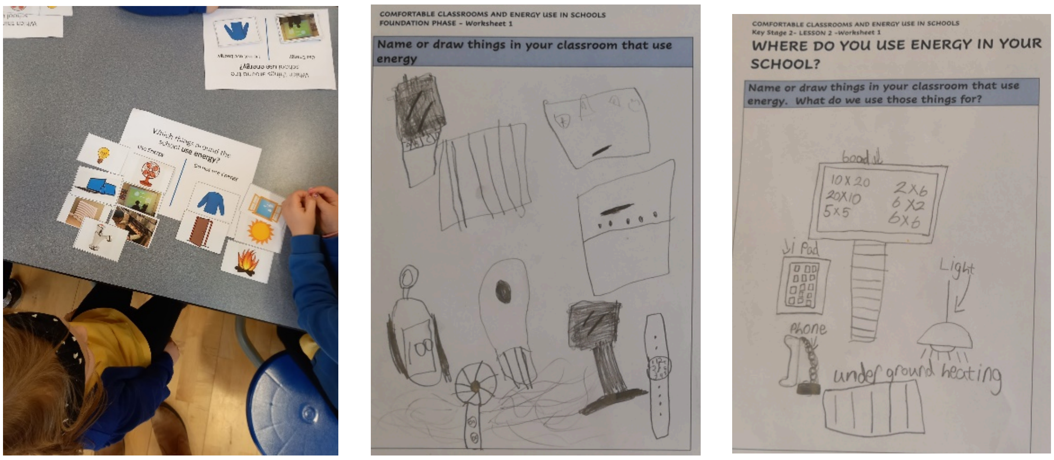
Example of monitoring data used by pupils in Workshop 2

Practical exercises included:

Cart sorting exercises

Templates for drawings

Templates for pupils to collect monitoring data related to concepts discussed (temperature, air quality, lighting levels)



Example of resources used during workshop 2 -left to right- (1) Card sorting (2) Foundation phase (3) Key stage 2

Photos of workshops with pupils. Source: Teachers in School A

7 Summary and recommendations

The study monitored six classrooms to identify the indoor environmental conditions, with a focus on temperature and CO_2; considering seasonal variations in autumn and winter. Other parameters such as relative humidity, ppm, regime of opening/closing windows were also monitored.

In terms of thermal comfort, the monitoring data suggest that the temperature of monitored classrooms are generally within acceptable levels during occupied hours in autumn and winter as compared to CIBSE Guide A benchmarks and Building Bulletin 101. Classrooms that have experienced colder than recommended benchmarks are still within acceptable temperature levels if considering than pupils tend to prefer cooler environments given the typical activity levels and clothing levels of pupils engaged in learning in classrooms.

The monitoring data suggest that averaged CO_2 concentration levels of the classrooms were maintained within Welsh Government green and amber light zone during occupied hours. The predominant strategy was based on simple but effective behavioural actions and adaptations (windows, doors, flexible use of classrooms). It should be noticed that it is very challenging to characterise the indoor air quality. While CO_2 concentration levels are a widely accepted proxy for indoor air quality further analysis is necessary to understand better the connection between CO_2 measurements, occupant actions and building design and management conditions.

Qualitative user studies to identify the thermal experience and the perception of air freshness in classrooms were conducted to contextualise the monitoring data. Pupils from School A where monitoring data in winter shows that classrooms are between 16-18^{o}C show a good satisfaction levels with the temperature of their classrooms (67% of pupils reporting to feel comfortable) while 26% of pupils in this school reported to feel cold. In School B where the monitoring data suggest winter temperatures between 17-19^{o}C there were mix responses both in terms of temperature and air freshness in the classroom without a clear majority of pupils reporting any predominant perception trend.

The data suggests that the participating schools have been implementing guidance to promote fresh air and ventilation by keeping windows and doors open during occupied hours. This strategy has been adapted in relation to the needs to maintain thermal comfort in different seasons. During winter season, when outdoor temperature drops, window opening times have been scheduled, whenever possibly, to times when pupils are not in the classroom to avoid discomfort due to cold temperature in the classroom. For example, windows and external doors in classrooms are open before the start of the school day, during lunch breaks and outdoor play times and after the end of the school day. The patterns of CO_2 concentration suggest trends around opening/closing of windows and doors to promote ventilation. The monitored classrooms show that CO_2 concentration levels tend to be within green and amber light zone as per Welsh Government guideline in autumn and in winter. The data suggest that the balance between CO_2 and temperature requirements is achievable in autumn but is likely to be more challenging in winter.

In terms of engagement and learning activities with pupils, the Cardiff University team designed and delivered two Workshops: 'Building Doctors' and 'Healthy Comfortable classrooms in energy efficient ways'. The workshops were tailored to Foundation and Key stage 2 and included hands-on activities led by pupils. Feedback was received from teachers for the planning and delivery of the workshops. The workshops were designed to involved hands-on activities led by pupils to discuss concepts related to thermal experience, air freshness, building performance of their schools and more broadly (building) sustainability.

Pupils practiced numeracy skills and discussed building performance concepts. Pupils measured and discussed monitoring data from own classrooms, suggesting ideas to improve classrooms' comfort and ventilation. Pupils in all year groups were able to engage with monitoring data (both data collected by Cardiff University team as well as data collected by themselves) and reflect about building performance concepts of different complexity in relation to what they do in their classrooms and in relation to sustainability implications. These hands-on activities led by pupils using monitoring data of their schools offer the opportunity for experiential and practical learning about sustainability to integrate the six areas of learning and experience as per New Welsh Curriculum. The activities of this project directly focused on (1) Maths and numeracy and (2) science and technology; and had indirect links to (3) literacy and communication. There is potential for resources to include arts, and health and wellbeing in relation to sustainability and citizenship aspirations. The use of monitoring data by pupils from their own schools could support schools to deliver the aspirations of the UK Policy Paper 'Sustainability and climate change:

a strategy for the education and children's services systems'[2] in relation to Action area 3: Education estate and digital infrastructure and Action area 4: Operations and supply chains; which aims to prepare 'children and young people to face climate change challenges and opportunities with appropriate knowledge, skills and pastoral care.

Recommendations based on lessons learned from this project are as follows:

- It is important to record indoor environmental conditions and associate the results to energy performance data whenever possible to have a better understanding of the performance of the building stock. This may enable to identify strategies to promote healthy classrooms while moving towards Zero carbon aspirations.
- In the context of COVID-19, it is important to promote long-term monitoring of CO_2 concentration levels as proxy of indoor air quality; temperature to indicate thermal comfort conditions, and relative humidity to indicate risk of mould and condensation and to explore the balance between promoting ventilation, thermal comfort and energy conservation.
- The use of benchmark data to analyse profiles and patterns of monitoring data is important to understand the performance of schools. Examples of industry guidance and standards include Welsh Government Guidance for CO_2 concentrations, thermal comfort guidance by CIBSE Guide A Building Bulletin 101, and BS EN 16798-1:2019 'Energy performance of buildings - ventilation for buildings. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, to consider the indoor environmental conditions and energy use holistically.
- Different types of studies and levels of granularity are likely to be required to understand the existing conditions of classrooms: long-term monitoring studies; inspection of buildings to determine their condition and opportunities afforded by mechanical systems and architecture features to enhance indoor air quality, and user studies to identify occupancy patterns and adaptations. Follow-up in-depth

[2] UK Policy Paper 'Sustainability and climate change: a strategy for the education and children's services systems' published in April 2022 available at https://www.gov.uk/government/publications/sustainability-and-climate-change-strategy/sustainability-and-climate-change-a-strategy-for-the-education-and-childrens-services-systems

monitoring studies and observational user studies could be combined with long-term analysis to identify good practice and implement remedial action at building level or behavioural adaptation when long-term data flags out issues with existing conditions.

- Current challenges related to the COVID-19 pandemic combined with imperatives to move towards Zero Carbon and respond to the Climate Change agenda are likely to lead to the establishment of different categories of indoor environmental quality that may reflect the diversity of the educational building stock
- There are clear opportunities to include monitoring data as part of the learning experience of pupils, particularly in Primary Schools. Such opportunities could contribute to aspirations by UK Policy Paper 'Sustainability and climate change: a strategy for the education and children's services systems' and could be aligned with the New Welsh Curriculum if designed carefully. Sustainability is a cross-cutting area where different skills and disciplines converged and that can equip pupils with agency to take positive action to respond to challenges and opportunities faced in the context of climate change.

Future work is suggested to analyse different school building types related to building condition, year of construction, DEC/EPC and architectural designs or configurations. This could enable a better understanding of diversity of opportunities and challenges in achieving a range of indoor environmental targets related to CO_2, thermal comfort and energy use. Such studies should consider the occupant dimension of building performance and operation: pupils and teachers have adapted very quickly into new ways of using and operating their classrooms; occupants' actions are likely to yield positive results if feedback, support and education is provided to enable them to make the most of existing features and building potential.

8 References

[1] CIBSE, 2015. Environmental design: CIBSE Guide A. London: The Chartered Institution of Building Services Engineers.

[2] Building Bulletin 101, 2018: Guidelines on ventilation, thermal comfort and indoor air quality in schools, Education and Skills Funding Agency.

Appendix 1: Monitoring instrumentation- Technical information

Wireless Temperature and Humidity Sensor - Coin Cell Powered

- These sensors are perfect for monitoring ambient temperatures around the sensors physical location.
- Scientific grade sensor
- +/- 2% humidity accuracy (between 0% – 100% RH)
- +/- 0.5°C temperature accuracy (between 0°C–100°C)

Wireless Carbon Dioxide (CO_2) Sensors - AA Battery Powered

The ALTA Wireless Carbon Dioxide Sensor uses an ultra low-power, high-performance CO_2 sensor to measure the amount of carbon dioxide in ambient air.

Monnit wireless CO_2 sensors allow monitoring the level of carbon dioxide (CO_2) gas in the surrounding air.

The ALTA Wireless Carbon Dioxide Sensor measures the amount of CO_2 in the ambient air surrounding the element. It is programmed to take readings at a set interval to accurately calculate CO_2 levels, then send the time-stamped data to the iMonnit Online Sensor Monitoring and Notification System at user-specified time intervals.

- Measures 0 to 10,000 ppm CO_2
- Accurate to +/- 45 ppm + 3% of reading
- Sensor produces instantaneous CO_2 readings and 8-hour time weighted average reading
- Operating temperature ranges: 0°C to 50°C
- Operating humidity range: 0% to 95%
- Commercial grade sensors are designed for applications in ordinary environments (normal room temperature, humidity and atmospheric pressure).

ALTA Wireless Open-Closed Sensors - Coin Cell Powered

Monnit wireless open/closed sensors provide information on the status of doors, windows, cabinets, etc.

- Sense immediate door or window access.
- Sense if a door, window, drawer is opened or has been left open
- Monitor access to specific areas of buildings.
- Sensor Magnet with Mounting Flange

ALTA Monnit Wireless Air Particulate Meter AA

The ALTA wireless PM2.5 sensor measures PM1, PM2.5 and PM10 concentrations in the air and transmits the measurement to iMonnit.

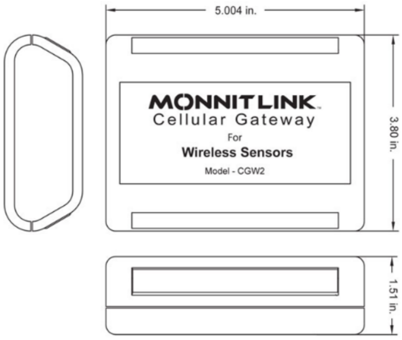
The PM2.5 sensor works by turning on a small fan at the beginning of a measurement cycle to bring in a volume of ambient air and measuring the particulate matter (PM) content of that sample volume.

The sensor measures PM content using a laser that scatters based on the number and size of particles suspended in the air. It is important to keep the inlet ports of the sensor clear to ensure proper readings.

ALTA Ethernet Gateway

The MonnitLink™ Ethernet gateway allows your Monnit Wireless Sensors to communicate with the iMonnit™ Online Wireless Sensor Monitoring and Notification System without the need for a PC.

AC power supply, Existing Internet connection required,
No PC required for operation, Real time TCP interface,
SNMP poll and trap interface, MODBUS TCP interface,
FCC, IC and CE certified.



Enclosure Material ABS

Storage Temperature: -20 to +60°C

Operating Temperature: +5 to +45°C

Operating Frequency: 868 MHz Operating Frequency

Certifications: CE Certified. Tested and found to comply with: EN 300 220-2 V3.1.1 (2017-02), EN 300 220-2 V3.1.1 (2017-02) and EN 60950.

Integrated on-board data storage allows ALTA sensors to store data messages if communication to a wireless gateway is disrupted (power outage, Internet outage, or out of range).

<u>Tinytag TGU-4500</u>

Indoor temperature and relative humidity data logger with built-in sensors (Brand: Gemini).

The TGU-4500 monitors temperatures ranging from -25 to +85°C, and relative humidity from 0 to 95% using built-in sensors. It is primarily suited to indoor monitoring.

- Built-in temp/RH sensor
- 32,000 reading capacity
- Delayed start option
- Low battery monitor
- User-replaceable battery
- Splash-proof case (IP53)
- High reading resolution
- Fast data offload
- User-programmable alarms

Tinytag Plus 2 – TGP-4500.

Rugged, waterproof outdoor temperature and relative humidity logger with built-in sensors.

The TGP-4500 monitors temperatures from -25 to +85 °C, and relative humidity from 0 to 100% using built-in sensors. The coated RH sensor offers good resistance to moisture and condensation, and like the rest of the Plus 2 range, this accurate and reliable unit is ideal for monitoring in outdoor and industrial applications.

Certifications: IP68 rated, CE certified

Telaire 7001 CO_2 Sensor and Hobo Datalogger

The Telaire 7001 handheld carbon dioxide sensor features patented absorption infrared technology. Each sensor measures CO_2 and temperature and can calculate and display real-time ventilation rates. When combined with the HOBO MX1104, MX1105, or UX120-006M, it can record CO_2. When connected to analog inputs on a HOBO H22, RX3000, or U30 series logger, it can record temperature and CO_2. The Telaire comes with a power adapter, but also operates up to 70 hours on 4 AA batteries.

The Telaire T7000 series CO_2 Monitor is an use-to-use temperature and carbon dioxide monitor designed for use in residential or commercial applications. With the ability to display CO_2 readings in less than 30 seconds, it is ideal for identifying energy saving opportunities in over-ventilated spaces, determining if air quality complaints are due to insufficient ventilation, or locating the presence of combustion fumes generated from vehicles and appliances.

The data logging kit option combines the easy-to-use T7001 with a pocket-sized Hobo logger from Onset Computer Corporation. The T7001D kit has the ability to calculate and display the cfm/person ventilation rate as well as record CO_2, temperature, and RH data over time making it useful for indoor air quality (IAQ) applications. The kit includes software and cables.

Applications for the Telaire T7000 Series CO_2 Monitors:

- Identify areas with low or substandard ventilation

- Identify hidden energy savings in over-ventilated spaces
- Determine if ventilation is a factor in air quality complaints
- Locate the presence of combustion fumes from vehicles and appliances
- Use as a reference to calibrate wall mounted CO_2 sensors

<u>EnviSense CO_2 Monitor and data logger</u>

•	Measuring range CO_2	0 - 5000 ppm
•	Measuring range humidity	5 - 95% RH
•	Measuring range temperature	0 - 50 °C
•	Sensor	NDIR
•	Width	120 Millimeter
•	Depth	35 Millimeter
•	Height	90 Millimeter
•	Suitable for	Rooms < 100 m^2

The CO_2 meter should be placed at table height in a place where it is not directly breathed into, at least 1.5 metres from an open window or door, or hanged it on the wall.

Appendix 2: Monitoring sensor location

Monitoring devices have been installed since July 2021 to provide a baseline of data regarding empty classes before the beginning of the school year. Following the Monitoring Plan, the following equipment has been installed:

In each one of the three classrooms under study per school:

- 1 CO_2 concentration sensor (remote monitoring).
- 1 Temperature and Relative Humidity sensor (remote monitoring).
- 1 sensor to record whether the window is open/closed (remote monitoring).
- 2 Temperature and Relative Humidity sensors/data loggers

In chosen communal areas of the schools:

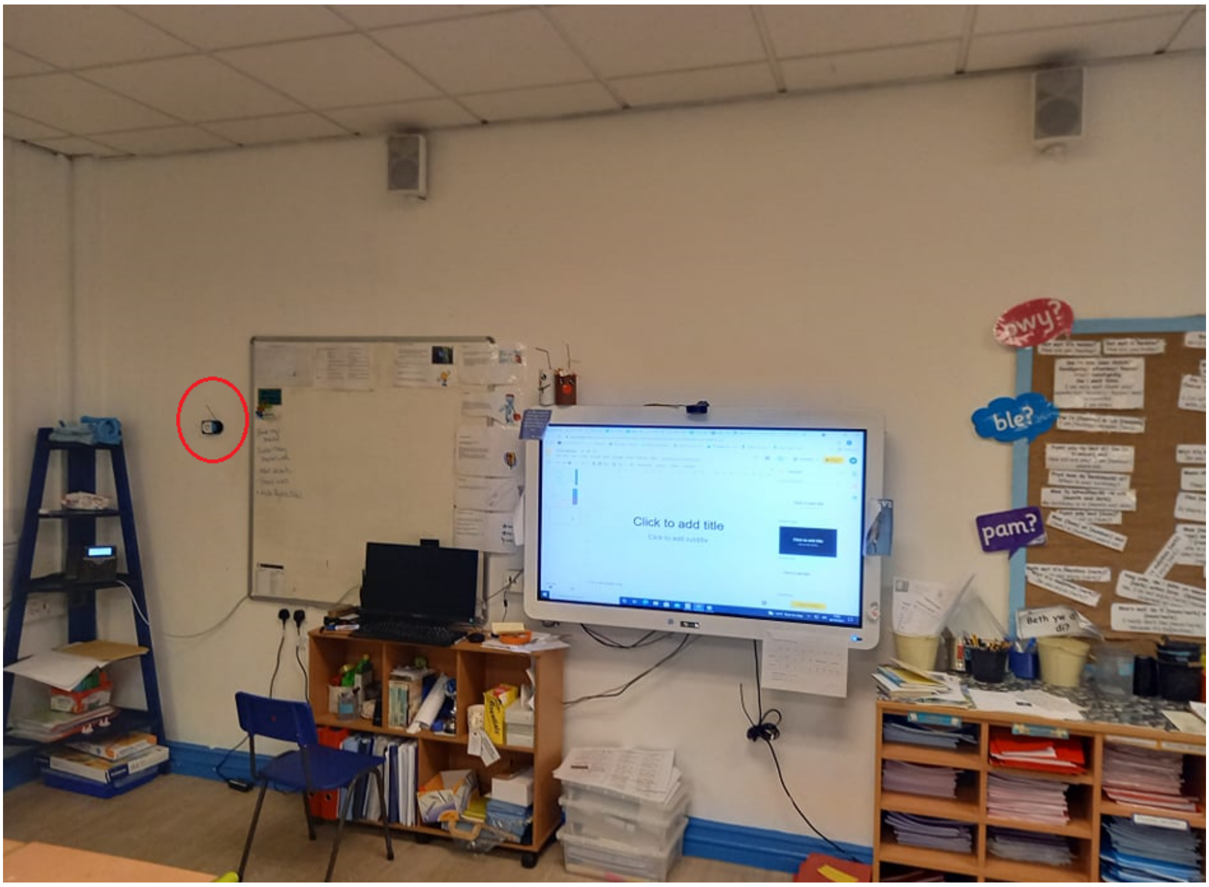
- Temperature and Relative Humidity sensors at the entrance, dinning and gym.
- PM2.5 concentration sensor at the entrance.

Below are presented some indicative photos of the installed sensors.

T/RH sensor in School A , classroom A

T/RH and CO_2 sensors in School A - classroom B

T/RH and CO_2 sensors in school A, classroom C



CO$_2$ sensor in School B, classroom C

T/RH sensors in School A, classroom C

Outdoor T/RH sensors in School A (left) and School B (right)

Window open/closed status installed sensor in School B

The gateway for receiving and transmitting the monitoring data

Particulate Matter sensors at the entrance of the School B

Appendix 3: Monitoring instruments used by pupils during Workshop 1 'Building doctors and Feverish Buildings'

EnviSense CO_2 Monitor and data logger

- Width 120 mm
- Height 90 mm
- Depth 35 mm
- Connection Mini-USB to USB with 230V adapter
- Cable length 1 meter
- Startup time   30 seconds countdown
- Operating humidity Between 0% – 95% (not-condensed)
- Suitable for CO_2 measurement Yes
- Suitable for humidity measurement Yes
- Suitable for temperature measurements Yes
- Measuring range CO_2 0 – 5.000 ppm
- Measuring range humidity 5% – 95% RH
- Measuring range temperature 0°C – 50°C
- Operating temperature 0°C – 50°C
- Storage temperature -20°C – 60°C

- Power supply 5 V DC via USB-port
- Weight 170 grams
- Warranty 3 years

Indoor/Outdoor RH/T

- Max/Min Temperature Memory
- 2 sensors for Indoor/outdoor (or 2 different temperature environments)
- Indoor Temp Range: 14 to 122 degF (-10 to 50 degC)
- Outdoor Temp Range: -58 to 158 degF (-50 to 70 degC)

DIGITAL THERMO-HYGROMETER W/TEMP AND RH (Pen Style Hygrometer)

- Temperature in °F or °C (14 - 122°F / -10 to 50°)
- 5 to 95% Relative Humidity (RH)
- Fast, accurate electronic sensor
- Displays relative humidity and temperature at the same time
- MIN/MAX record
- Data hold
- Auto power-off

Surface T sensor

The infrared laser thermometer is very robust and is well suited to applications where contact measurement is not possible or desirable.

The HL-550 is very easy to use: simply point and measure. The measurement is read within 1 second and the laser pointer helps to precisely identify your measurement point.

The units are best suited to the measurement of matt, non-reflective surfaces. The temperature readouts are backlit making them easy to read, even in the dark.

- Laser targetting
- 0.95 emissivity (fixed)
- °C/°F selectable
- Automatic data hold
- Auto power off
- Low battery indication
- Backlit LCD display
- Over range indication
- Supplied with 9V battery and soft case
- 160mm x 82mm x 42mm