# Should current indoor environment and air quality standards be doing more to protect young people in educational buildings?

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## Abstract
Indoor environmental quality (IEQ) and indoor air quality (IAQ) were assessed in a recently refurbished educational building at Loughborough University, through a monitoring campaign in accordance with Building Bulletin (BB) 101. A particular focus of this work was on emissions from building materials. Volatile organic compounds (VOCs) were measured using diffusive (passive) methods involving Thermal Desorption (TD), Gas Chromatography (GC) and Mass Spectrometry (MS) techniques. The results show that although the building performs satisfactorily with respect to guidelines for overheating and ventilation performance according to BB101 (2018) the current guidelines only assess Total Volatile Organic Compound (TVOC) limits which fail to identify the source of IAQ problems. The presence of numerous VOCs indicates that quantification of individual compounds is necessary to assess long-term health risks.
**Keywords** Indoor Air Quality, Volatile Organic Compounds, Gas Chromatography, Mass Spectrometry, Building Bulletin 101.

## 1.0 Introduction
According to the European Environment Agency (1) indoor and outdoor air pollution has the greatest single impact on human health in Europe and are together responsible for the majority of environment-related diseases. It is estimated that about 2 million life years are lost every year from exposure to poor air quality in Europe (2). The quality of the indoor environment is a particular concern since in developed countries humans spend on average 90% of their time indoors (3) and indoor air is often more contaminated than outdoor air, since it contains additional pollutants emitted from building materials and consumer products (4)

The main focus of this research is on indoor air quality (IAQ), a term which encompasses the ‘physical, chemical and biological characteristics of air in the indoor environment and its relation to the occupant’s physical and psychological heath, comfort and productivity’ (5). IAQ within school classrooms is of great importance because students are particularly susceptible to poor air quality (6) as they breathe higher volumes of air relative to their body weights and their tissues and organs are still developing (7). Indoor air pollution has the potential to cause both long and short-term health problems, particularly for students and staff with allergies, asthma or airway hyper-reactivity (8); but also impacting their productivity and degrading the learning environment, comfort, and academic attainment of students (9,10,11,12,13).

Although carbon dioxide ($CO_2$) concentration has been widely used as a proxy indicator of IAQ (14,15,16,17) the hypothesis proposed here is that $CO_2$ concentrations can be well below threshold limits, without revealing the risks posed by diverse indoor pollutants and that these cannot be ignored in a school environment. This research therefore aims to assess whether the current guidance in BB101 is adequate in relation to assessing IAQ risks in the context of educational buildings. By using a case study building (section 3.1) the implementation of BB101 is explored whilst the risks of volatile organic compounds (VOCs) in the indoor air were contiguously monitored and identified by means of diffusive (passive) air sampling. The results were then collated, and the findings evaluated in relation to BB101, the UK Building Regulations and international standards on indoor air quality.

## 2.0 Background

### *2.1 Principal findings from the literature*

The health, comfort, well-being and productivity of occupants can be directly related to the quality of air inhaled indoors. Indoor air can become stale and polluted due to the presence of indoor airborne pollutants originating from numerous sources within and around a building (Figure 1).

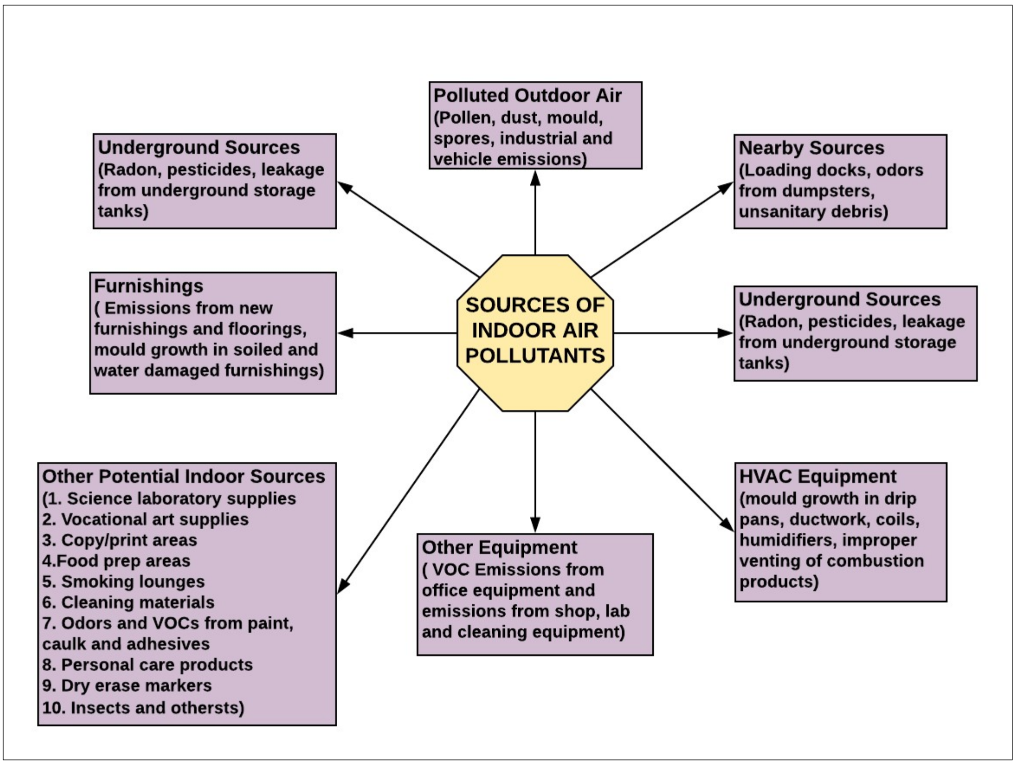



**Figure 1 - Sources of indoor pollutants (14,15)**

Children spend more time in educational institutions than in any other indoor environment except their home. They spend about 30% of their life in school and about 70% of their time inside a classroom during school days (18). Despite these statistics relatively little has been published regarding indoor air contaminants arising from within educational buildings and particularly on the impact of refurbishment measures on IAQ. The concern over human exposure to indoor pollutants and their harmful effects on health, productivity, comfort and well-being has led to the formulation of a number of indoor environment and ventilation design guidance documents as well as national and international standards.

## *2.2 Ventilation control and IAQ standards*

A timeline of the evolution of standards applicable to UK schools between 2003-2018 can be seen in Figure 2.

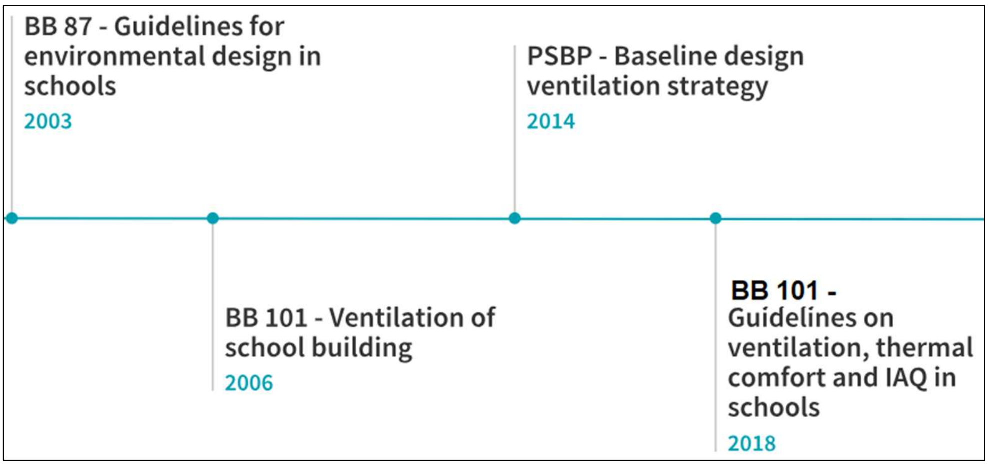



**Figure 2 – Evolution of ventilation design standards in UK schools**

It should be noted that all of the above standards (Figure 2) use $CO_2$ as a determinant for good IAQ. As a result, modern IAQ control strategies have relied largely on demand control ventilation (DCV) which operates based on the $CO_2$ concentration within a space. The WELL (2018) building standard formulated by the International WELL Building Institute also uses $CO_2$ concentration as one of the measures to define ventilation effectiveness. Although relatively high levels of $CO_2$ exposure pose no danger to health, they can lead to reduced concentration and a decrease in the academic performance of students (19,20,21).

## *2.3 Conflicting arguments in relation to IAQ control*

The current standards for IAQ control such as Building Bulletin (BB)101 (14,15), CIBSE Guide B2 (22), CIBSE Guide A (23) and Approved Document F – Ventilation(16) specify outdoor air flow rates (ventilation rates) that are adequate to dilute gaseous contaminants and to achieve the maximum permissible threshold limit values (TLVs) for $CO_2$ (24,25,26) but they ignore the contamination generated by other sources such as building materials and consumer products located within the building (27,28). The indoor environment consists of various pollutants whose concentration indoors depends upon the following factors (29):

- Volume of air contained in the indoor space
- Rate of production of each pollutant
- Rate of release of each pollutant
- Rate of removal of the pollutant from the air via reaction or settling
- Rate of air exchange with the outside air
- Quality of the outside air

From this perspective, the precise ventilation rate needed (using contaminant dilution) to maintain acceptable levels of pollutants in a building is difficult to predict. This is further compounded by the fact that the combined effect of two (or more) pollutants can be synergistic (C>A+B), additive (C=A+B), antagonistic (C<A+B) or independent (23,30).

## *2.4 Effect of energy efficiency and design measures on IAQ*

The evolution of teaching pedagogy towards active learning and learner-centred teaching processes (31) has led to changes in the internal layouts and design of school buildings (32). Alongside this, tightening of Part L of the UK building regulations and the introduction of the Energy Performance Building Directive (2010/31/EU) has driven improvements in the energy performance of buildings across the EU, through cost-effective measures. These changes have collectively led to a reduction in school ventilation rates by an estimated factor of five which has in turn increased the concentration of indoor air pollutants by the same factor (33). Thus, measures to conserve energy by sealing buildings as tightly as possible and minimising air changes can inadvertently lead to increased indoor air pollution with serious health consequences (33). According to Yu and Crump (34) the use of (new) building materials when performing energy-efficient building refurbishment/renovations, and the changes that this induces on building ventilation, insulation and air tightness, can considerably impact on the indoor environment. Thus, the focus of attention must be shifted towards the main contributor to indoor pollution in modern airtight buildings, which numerous authors have documented as being attributable to the emission of volatile organic compounds (VOC) emanating from building materials and consumer products (28,33-39).

## *2.5 Volatile organic compounds*

VOCs are carbon-based chemicals, so named because they have melting points below room temperature and boiling points in the range from 50-100°C to 240-260°C. Their concentration is higher indoors as compared to outdoors due to numerous indoor sources, limited dilution volumes and relatively low ventilation rates (40,41,42). Some of the most common indoor sources of VOC can be seen in Figure 3.


**Figure 3 - Common sources of VOCs in the indoor environment (42,43)**

The occurrence and temporal profile of VOCs is highly dynamic in nature. Building materials can act as emission sinks before subsequently becoming secondary sources as they reemit adsorbed chemicals (43). Whilst adsorption may lead to lower peak concentrations, the subsequent desorption process prolongs the presence of indoor air pollutants (43). The type of material and compounds present affects the rate of adsorption and desorption, which can be visualised in time dependency profiles (Figure 4).

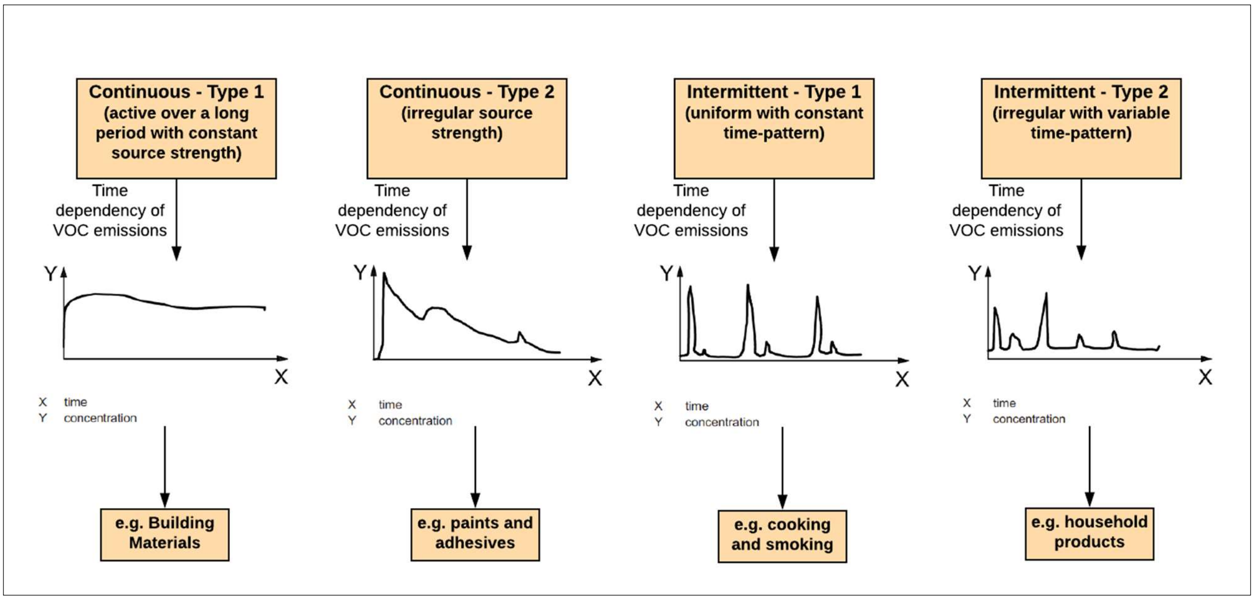



**Figure 4 - Emission characteristics and time dependency of VOC sources (44,45)**

## *2.6 Building standards – current response to VOCs*

Individual VOC concentrations depends upon the presence or absence of an extremely wide range of potential emission sources. Identification and quantification of all individual VOCs occurring in the indoor air is difficult as the knowledge base is still sparse. Hence many guidelines and researchers have adopted the simplified method of assessing total volatile organic compounds (TVOC) rather than individual values. Using this approach, the summation of concentrations of the identified and non-identified volatile organic compounds in the measured air sample provides the total volatile compound (TVOC) value (46). A major drawback of this approach however is that it is of little help in determining the toxicological properties of specific substances (47) or the source or extent of the problem (28).

Due to the paucity of guidance pertaining to the estimation of individual VOCs and their contribution to IAQ, TVOC concentrations above 300 $\mu g/m^3$ (averaged over an 8-hour period) have been widely adopted as an indicator of poor IAQ (14,15,16,25). However, there is an inadequate scientific basis from which to establish limiting values/ guidelines for TVOCs and considering it in this way presents an unquantifiable risk for the health and wellbeing effects occurring within buildings (48).

## 3.0 Methodology

In order to assess the implications of BB101 and legislative guidance in the context of a refurbished educational building a broad IEQ monitoring strategy was developed which involved repeated measurements of dry bulb temperature, operative temperature, relative humidity, ventilation flow rates as well as IAQ parameters. The IAQ monitoring campaign consisted of measuring $CO_2$ concentrations continuously and conducting discrete diffusive (passive) air sampling regimes to identify all the possible VOCs in the space. This approach provided the potential to detect VOCs originating from various sources rather than limiting the findings to isolating specific known compounds. The influence of outdoor air brought in via the ventilation system was not directly studied however as this would have required repeated long-term sampling around the vicinity of the buildings to establish repeatability of the compounds identified (typically over an extended period spanning two seasons to capture the cold and warm periods of the year). Thus, a working methodology was devised to understand, within a relatively short time frame, the extent of exposure to VOCs for the building occupants and whether this could engender any serious health risks.

### *3.1 Case study building*

The recently refurbished School of Architecture - Keith Green Building located within the Loughborough University campus (Figure 5) was chosen for the study. The open studio space located on the first-floor space (Figure 6) was identified for the IAQ monitoring campaign after strong odours were noted to persist several months after completion of refurbishment works on 02-August-2017. This led to occupants resorting to opening windows for extended periods, to let in fresh outside air, as the mechanical ventilation system was unable to reduce the presence of strong odours. The IAQ monitoring campaign was designed in such a way as to determine whether the suspected contaminant sources originated from the building materials or were being introduced from occupant activities.


**Figure 5 - School of Architecture - Keith Green Building, Loughborough University**

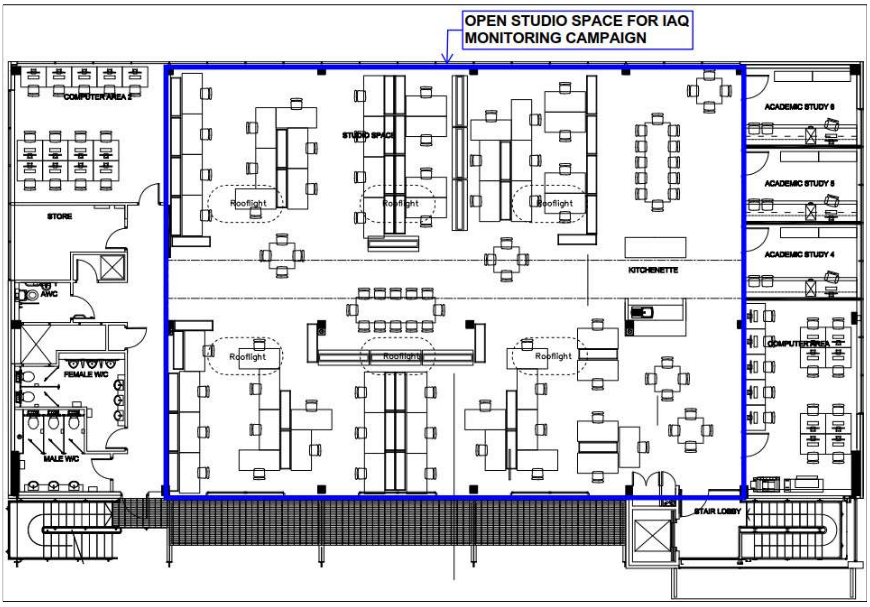



**Figure 6 - Architectural floor plan of the open-studio space on the first floor of the Keith Green Building**

Heating to the open studio space is provided via a low temperature hot water (LTHW) trench heating system. The open studio space is mechanically ventilated using ducted VAV supply and extract ventilation which operates based on the $CO_2$ setpoint in space.

## *3.2 Measuring devices location plan*

The location of the measuring devices in the monitored open studio space can be seen in Figure 7. A description of various indoor environmental variables that were measured with these devices is given in Table 1.

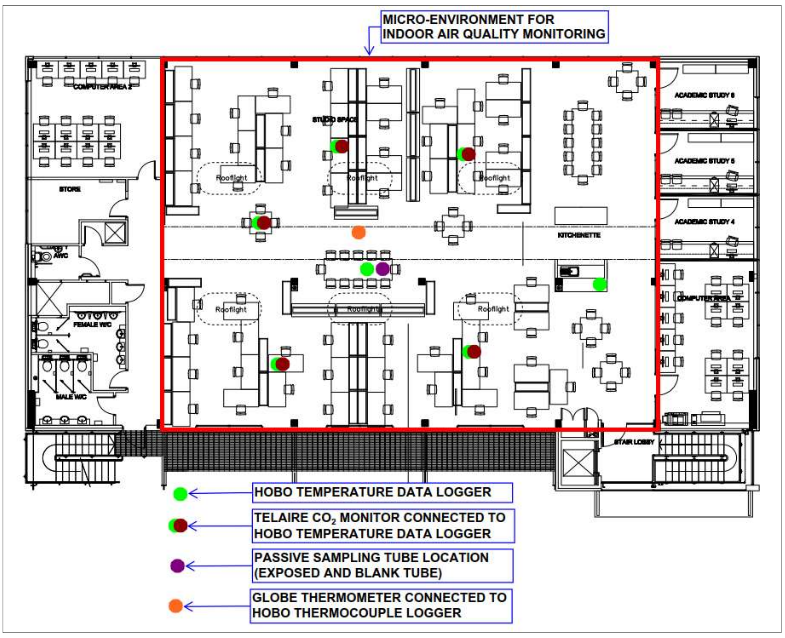



**Figure 7 - Location plan of measuring devices in the monitored environment**

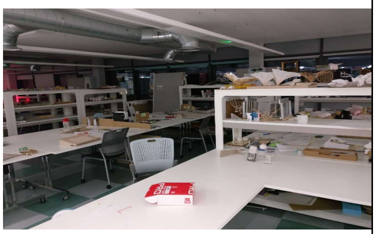
| Measuring device | Indoor environmental variable | No. of sensors | Location | Interval |
|---|---|---|---|---|
| Temperature and Humidity Data Logger | Dry bulb and Operative temperature | 7 | At table height | Every 15 minutes |
| | Relative humidity | | | |
| $CO_2$ monitor connected to data logger | Carbon Dioxide concentration (ppm) | 5 | At table height | Every 15 minutes |
| Passive Sampling Tube | Volatile Organic Compounds (boiling point range from 50°C-100°C to 240°C-260°C) | 2 | At table height | 8-hour exposure |
| Building Management System (BMS | Dry bulb temperature (°C) | 2 | At ceiling level | Every 15 minutes |
| | Relative Humidity (%) | 2 | | |
| | Carbon Dioxide concentration (ppm) | 2 | | |

**Table 1 - Location plan of measuring devices in the monitored environment**

## *3.3 Description of the monitoring scenarios and their hypothesis*

The IAQ monitoring campaign was divided into different measurement scenarios with the intention of capturing the exposure of occupants to indoor pollutants under different operational conditions. The VOC sampling measurements for all three IAQ monitoring scenarios are described in Table 2. During this process paired sampling tubes, (namely an exposed tube and a blank tube) were deployed side-by-side (Figure 8). The exposed tube was kept open to the indoor environment to capture the VOCs present in the indoor air whilst the blank tube remained closed (thereby acting as a control, to account for the background weight of the compounds and instrument variations present during the preparation of the two tubes). The tubes were placed at the centre of the open studio space at table height, as this is considered a representative height for the breathing zone position (51). For each scenario, three independent sampling measurements were taken to establish repeatability between the VOCs detected. All the air sampling measurements were conducted during unoccupied periods to eliminate the effects of off-gassing from humans as the aim of the study was to identify only the contribution of VOCs originating within the indoor environment due to materials that had gone into the refurbishment as well as any models and materials stored in the space.


**Figure 8 - Exposed tube and blank tube used for air sampling**

| Sr No. | Measurement Scenario | Hypothesis of scenario | Condition of space |
|---|---|---|---|
| 1 | <u>Scenario 1 (Unoccupied, night-time, ventilation system OFF)</u><br>In this scenario, the air sampling was carried out during the night from 22:00-06:00 (i.e. 8 hours) on the 25th, 26th and 27th May 2018 when there was no occupancy.<br><br>While conducting the air sampling measurements for this scenario, the open studio space consisted of mini-architecture models prepared by the students | To simulate the combined effect of the following:<br>• Off-Gassing from architectural models<br>• Off-Gassing from materials (wall coverings, furniture, paints etc) that have gone into the refurbishment.<br>• VOCs brought in via outside air | <br><br> |

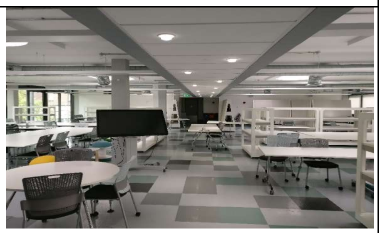
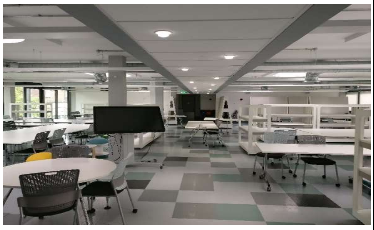
| | | | |
|---|---|---|---|
| 2 | Scenario 2 (Unoccupied, daytime, ventilation system OFF)<br>In this scenario, the air sampling was carried during the daytime from 09:00-17:00 (i.e. 8 hours) on the 4th, 5th and 6th July 2018 when there was no occupancy.<br><br>While conducting the air sampling measurements for this scenario, the open studio space was cleared of the architecture-models to isolate the off-gassing from them | The aim of this scenario was to simulate the effect of the empty building and capture the following:<br>• Off-Gassing from materials (wall coverings, furniture, paints etc) that have gone into the refurbishment.<br>• VOCs brought in via outside air | <br><br> |
| 3 | Scenario 3 (Unoccupied, daytime, ventilation system ON)<br>In this scenario, the air sampling was carried out during the daytime from 09:00-17:00 (i.e. 8 hours) on the 17th, 18th and 19th July 2018 when there was no occupancy. | While conducting the air sampling measurements for this scenario, the ventilation system in the open studio classroom was switched ON, it is expected to have led to dilution of the VOCs | <br> |

**Table 2 – Measurement scenarios and hypothesis**

## *3.4 Description of various measurement scenarios and their hypothesis*

Gas Chromatography Mass Spectrometry (GCMS) is an instrumental technique comprising of a gas chromatograph (GC) coupled to a mass spectrometer (MS) which through a step-wise process leads to the sequential separation, identification and quantification of the VOCs present in a sample. The final step of this procedure results in the identification of individual compounds within the GCMS (as shown in Figure 9).

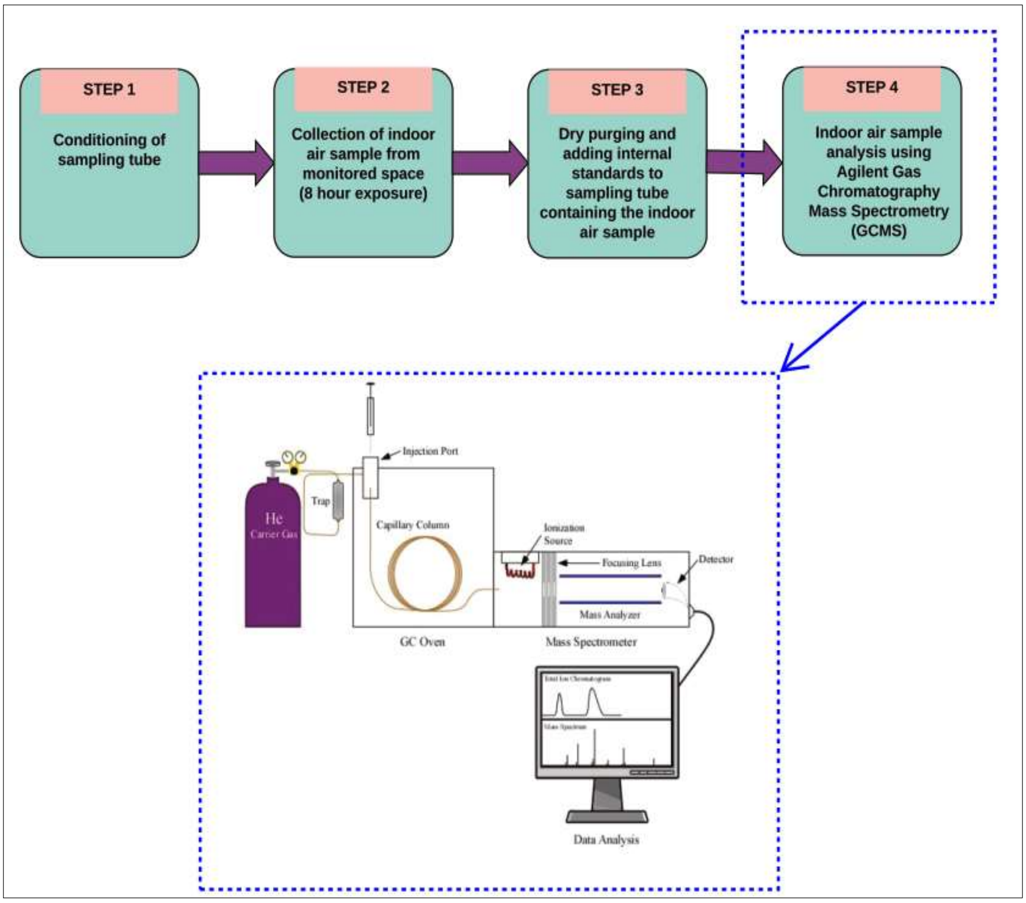



**Figure 9 - Schematic of GCMS showing the steps involved in VOC detection (52)**

## *3.5 Procedure for establishing repeatability for compounds detected in the chromatogram and elimination of background weight of compounds*

The output of the indoor air sample analysis using GCMS and Mass hunter software is given in the form of a graph known as a chromatogram which represents the different VOCs present in the indoor environment based on the retention time (tr) of each VOC. The chromatograms display the retention time (tr/min) represented on the X-axis and the Peak area value (I) counts on the Y-axis (see Figures 11-13). The analysis of each air sample was undertaken with 60mins as the total retention time.

The following procedure was used for the analysis of data, in order to establish repeatability between compounds and elimination of the background effect of VOCs for each measurement scenario as follows:

- Step 1 – Normalising the peak area value

The peak area values of the compounds detected in the exposed and blank tube are normalised to the internal standard Toluene-$d_8$ which was used for conditioning of tubes. Toluene-$d_8$ is classified as a deuterated solvent, which means that one or more of its hydrogen atoms have been substituted with deuterium atoms ($^2H$). Deuterated solvents are widely used in GCMS because the resonance frequency of a deuteron ($^2H$) is very different from that of proton ($^1H$), which avoids peaks from the solvent occurring in the proton spectrum (i.e. causing background noise to overlap with the signal). The unit of the peak area value is counts. For the exposed tube, the normalised peak area value is calculated by dividing the peak area of the compound in the exposed tube by the peak area value of Toluene-$d_8$ in the exposed tube. For the blank tube, the normalised peak area value is calculated by dividing the peak area of the compound in the blank tube by the peak area value of Toluene-$d_8$ in the blank tube.

- Step 2 – Elimination of background effect

As described in section 3.3, there are two tubes (i.e. one exposed and one blank) which are kept in the indoor environment during each sampling period. The compounds present in the exposed tube for a particular sampling period (e.g. sampling conducted on 25$^{th}$ May 2018) are then cross-checked against those present in the blank tube for the same sampling period (i.e. sampling conducted on 25$^{th}$ May 2018). If a compound is found to be present in both the exposed and the blank tube, then the normalised peak area value calculated in Step 1 for that particular compound in the exposed tube is reduced by the normalised peak area value calculated in Step 1 for the same compound in the blank tube. If the result of this subtraction is positive, it indicates that a quantity of the compound present in the blank tube has been eliminated thus leaving only the contribution arising from the exposed tube (i.e. the indoor environment sample). If the result of this subtraction is negative, it indicates that compound was present in the blank tube and not in indoor environment and should be discarded. If the compound is not present in the blank tube, then Step 3.

- Step 3 – Accounting for the injection rate of the internal standard Toluene-$d_8$

The injection rate of Toluene-$d_8$ is 0.069 nanograms (ng). The normalised peak area values calculated in Step 1 & 2 are divided by this injection rate to gives the quantity of a particular compound in counts/nanograms (ng) equivalent of internal standard Toluene-$d_8$.

- Step 4 – Establishing repeatability of identified compounds

As described in Table 2, three air sampling measurements (each with one exposed and one blank tube) were conducted for each measurement scenario as a form of quality control to establish repeatability between the compounds identified. Each compound identified in an air sampling measurement was checked for its availability in other air sampling measurements of the same measurement scenario. Compounds found to be repeated in all three air sampling measurements of a measurement scenario indicate their undistinguished presence. Once the compounds repeatedly present in all three air sampling measurements for each measurement scenario were established, these compounds were then checked for their presence across the three distinct measurement scenarios.

Only the compounds repeatedly present in each measurement scenario and across measurement scenarios are reported.

It is to be noted that identification of the compounds isolated by this study was limited to those compounds listed by the national institute for standards and technology (NIST) library and to the ones that possess a chemical compound name and chemical abstract service (CAS) number. Unknown compounds (i.e. those without a chemical compound name or CAS number) were discarded since their relevance could not be established in the literature.

# 4.0 Results

Results derived from the methodology in section 3.0 are presented in this section. The first stage of the results examine the overall IAQ in the space, which was assessed by means of measuring the $CO_2$ concentration in the monitored space (see section 3.2), according to ventilation performance standards, namely BB101 (2018). The indoor air was also assessed for the presence of the VOCs originating from the materials that have gone into the refurbishment and arising from occupant activities such as model making. A diffusive (passive) sampling method was used with an 8-hour exposure period (see section 3.3). The results are presented in the form of chromatograms (see section 4.2) depicting the various VOCs identified in the indoor environment.

## *4.1 Assessment for carbon dioxide ($CO_2$) concentration*

The $CO_2$ concentration in ppm was monitored by the BMS at 15-minute intervals and was used as a marker for determining the adequacy of ventilation (i.e. whether sufficient fresh air is supplied for dilution of $CO_2$ and RH arising during teaching hours). $CO_2$ was monitored at two locations in the open studio space. An average between the two readings was used to assess the ventilation performance of the space. Data recorded during the occupied period of 09:00-17:00, Monday to Friday from 1$^{st}$ April 2018 until 31st August 2018 were used for this analysis. The results can be seen in Figure 10.

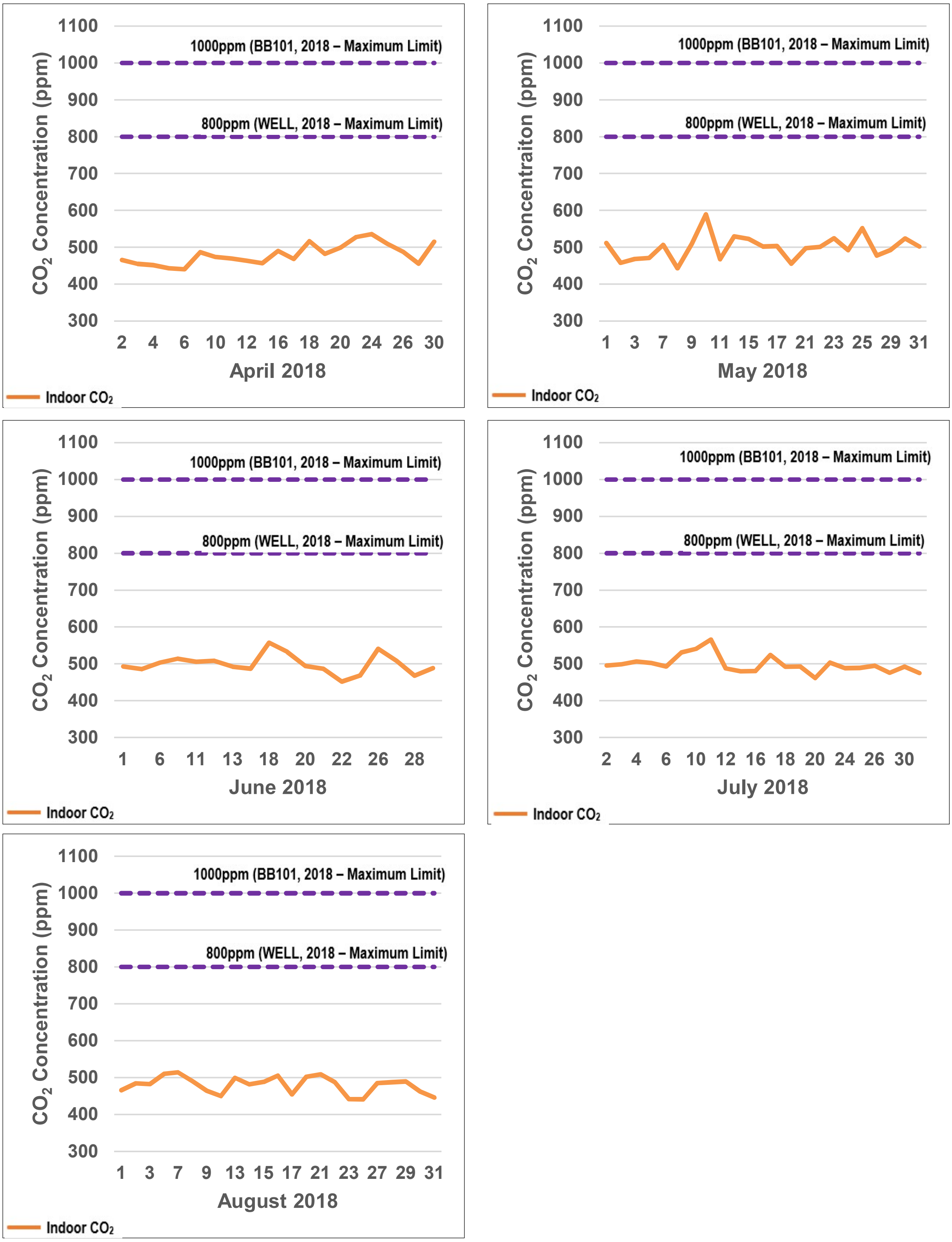



**Figure 10 – Results for $CO_2$ concentration observed in the open studio space from April – August 2018**

It is seen that the $CO_2$ concentration across the monitored period remains well below the current threshold limits specified by BB101 (2018) and the WELL (2018) standard.

### *4.2 Results of diffusive (passive) sampling for detection of VOCs in indoor air*

Diffusive (passive) sampling was conducted in the open studio space at the first-floor level of the Keith Green building. After collection of each indoor air sample, it was analysed by thermal desorption gas chromatography and mass spectrometry (as described in section 3.4). This analysis produced a series of graphs known as chromatograms which represent the number of identified and unidentified compounds for each measurement scenario. The nomenclature used for identification of the chromatograms is shown in Figure 11.

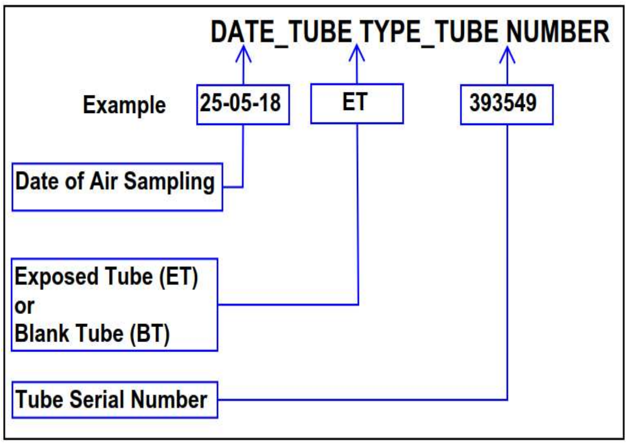



**Figure 11 – Nomenclature used for chromatograms**

The chromatograms produced as a result of the different measurement scenarios can be found in Figures 12-14. From the chromatograms, it is seen that several compounds are present in the indoor air sample. Thus, indicating a very rich reaction vessel in the monitored environment with a lot of unidentified chemistry in the indoor air of the open-studio space.

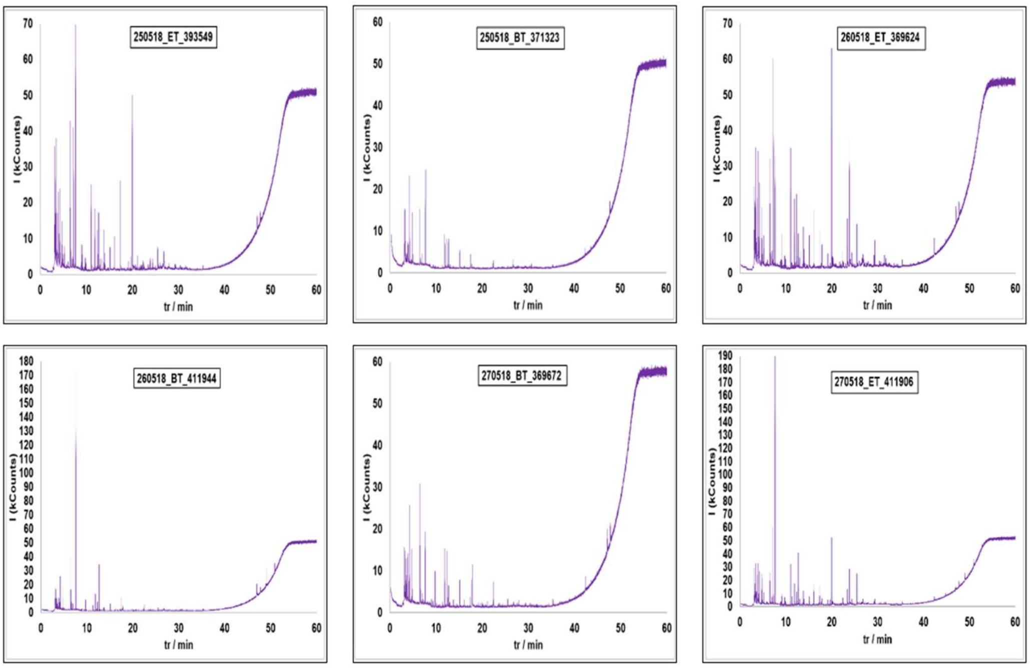



**Figure 12 – Chromatograms for measurement scenario 1 (unoccupied, night-time, ventilation system OFF)**

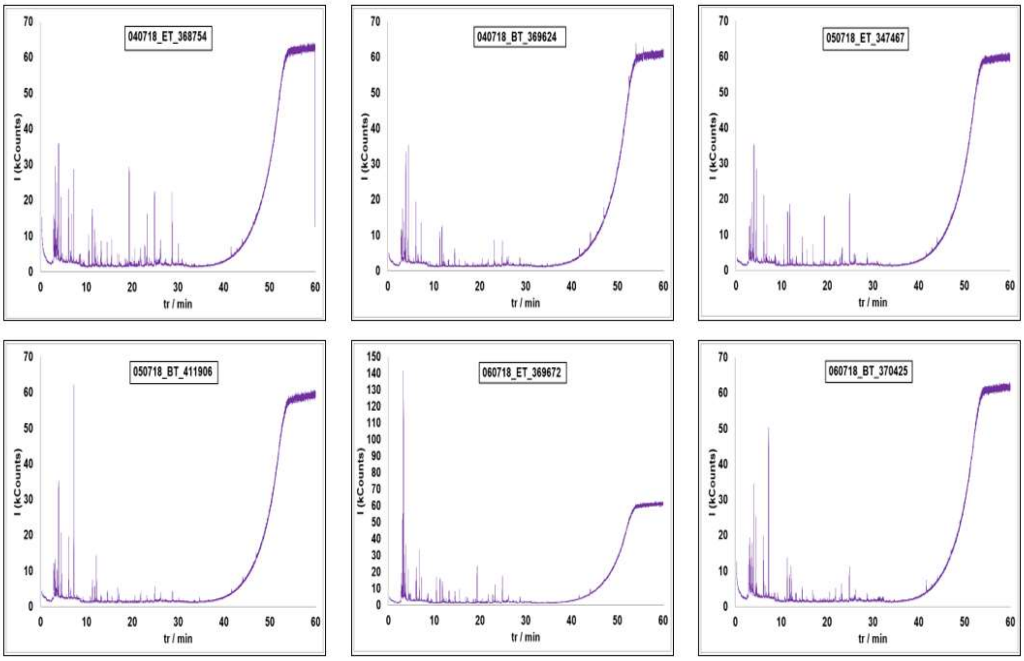



**Figure 13 – Chromatograms for measurement scenario 2 (unoccupied, daytime, ventilation system OFF)**

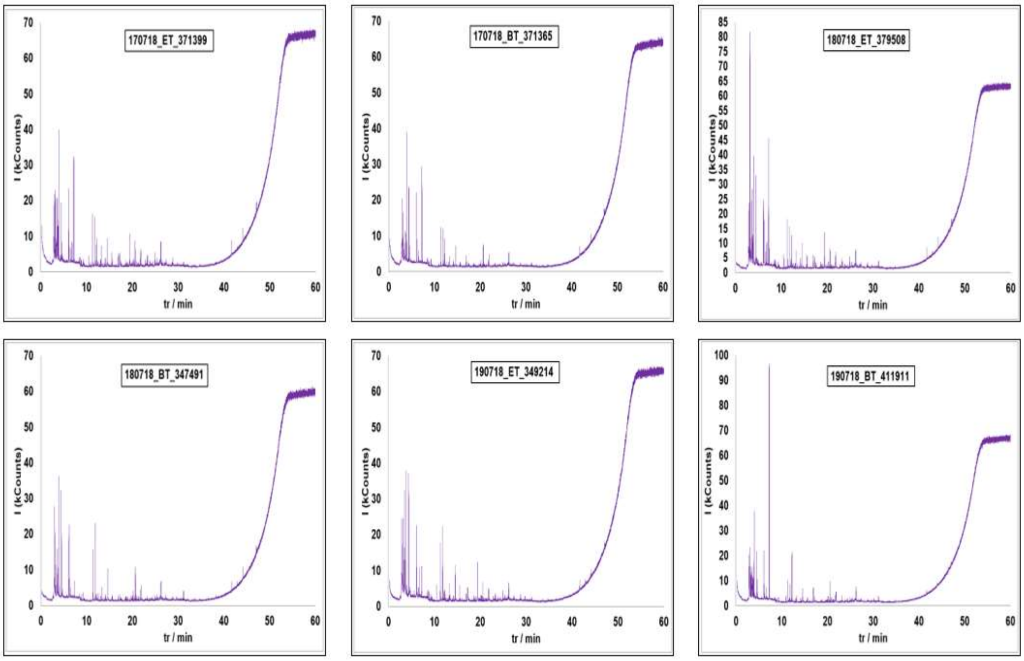



**Figure 14 – Chromatograms for measurement scenario 3 (unoccupied, daytime, ventilation system ON)**

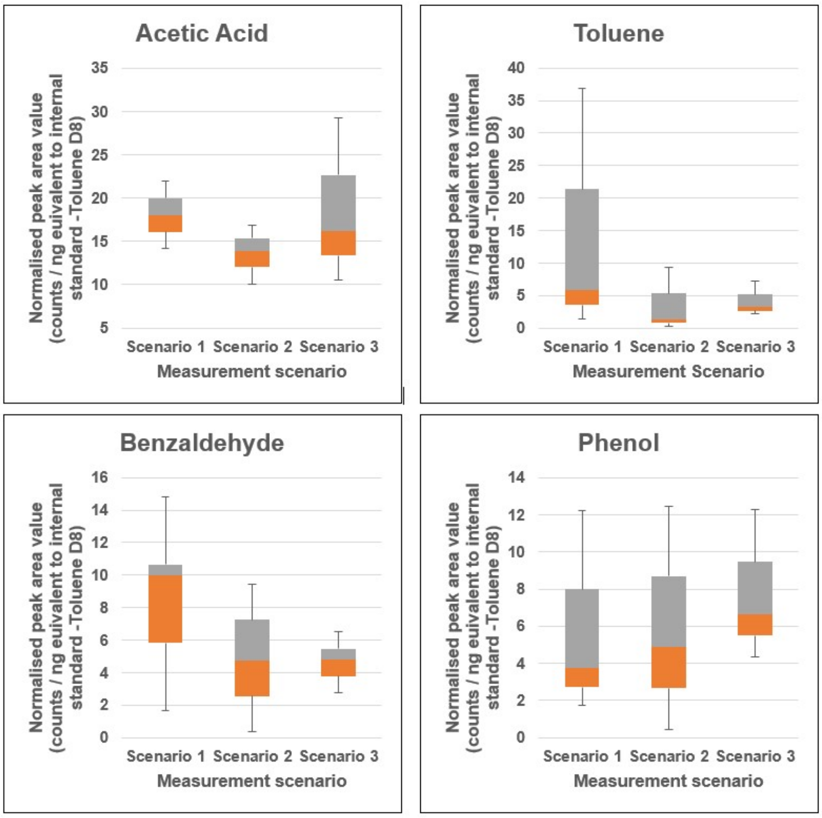



**Figure 15 – The variation in the normalised peak area value for acetic acid, toluene, benzaldehyde and phenol across the three measurement scenarios**

Based on the analysis of the chromatograms in Figures 12-14, it is seen that the compounds repeatedly found in all measurement scenarios were: acetic acid, toluene, benzaldehyde and phenol. Thus, indicating their undistinguished presence in the indoor environment. The variation in the normalised peak values for these compounds are shown in Figure 15. It is also seen that the presence of toluene and benzaldehyde has subsequently reduced due to the introduction of ventilation (in Scenario 3). However, the presence of acetic acid and phenol is not reduced by the ventilation system state and this requires further investigation.

## 5.0 Discussion

$CO_2$ readings (measured at 15 minutely intervals) were used to check whether sufficient outside (fresh) air was supplied by the mechanical ventilation system for the dilution of $CO_2$, RH and odours generated indoors. It is seen from the results (Figure 10) that at no time did the average $CO_2$ concentration exceeded 1000ppm during the teaching hours and nor did the maximum concentration measured during any teaching day exceed 5000ppm, as set out by BB101 (2018). The measured $CO_2$ concentration also compared favourably to other relevant standards (including CIBSE, WELL and ESFA) Table 3.

| Sr No | Ventilation Standards | Criteria for $CO_2$ concentration thresholds (ppm) | Compliance check for monitored environment |
|---|---|---|---|
| 1 | Guidelines on ventilation, thermal comfort and indoor air quality in schools. (BB101, 2018) | ‘daily average concentration of carbon dioxide during the occupied period of less than 1000 ppm and so that the maximum concentration does not exceed 1500 ppm for more than 20 consecutive minutes each day, when the number of room occupants is equal to, or less than the design occupancy' (BB101, 2018). | ✓ |
| 2 | Chartered Institute of Building Service Engineers (CIBSE) Guide B2 (CIBSE, 2016) | 800-1000 ppm recommended range | ✓ |
| 3 | WELL Building standard (IWBI, 2018b) | Carbon dioxide levels of below 800 ppm needs to be maintained in the space | ✓ |
| 4 | Education and Skills Funding Agency (ESFA), Annex 2F, 2017 | same as BB 101 (2018) | ✓ |

**Table 3 - Comparison of different ventilation standards and their criteria for compliance with $CO_2$ concentration to be maintained in a space against the measured $CO_2$ concentration of the monitored environment.**

Indoor $CO_2$ concentrations varied in the range of 433 – 589 ppm. This finding can be attributed to one or more of the following factors specific to the operation of this building:

- The fresh air supply rate exceeded the specified 8 litres/second (l/s) per person for classrooms according to BB101 (2006) and BB101 (2018).
- The $CO_2$ measurement was taken at only two locations in the open studio space. This could have led to an underestimation of localised $CO_2$ concentrations for a space with an area of $377m^2$. Whilst BB101 (2006) and BB101 (2018) indicate that the $CO_2$ levels should be measured at seated head height no information regarding the number of sensors or their recommended location is provided.
- During the summer period low to moderate occupancy was observed after June 2018
- The demand control ventilation (DCV) system employed in the building is responding promptly to the changes in the $CO_2$ concentration
- The location of the circular supply diffusers and return air grille is facilitating good air mixing, which is leading to sufficient dilution of $CO_2$ with outside (fresh) air

The open studio space can be considered to have good IAQ on the basis that it meets the criteria specified by CIBSE (2016), BB101 (2018), WELL (2018) and ESFA (2017) for maintenance of $CO_2$ concentration thresholds. However, this consideration does not account for other indoor air pollutants stemming from a combination of indoor and outdoor sources (via ventilation system or leaks or cracks). An indication of the VOC compounds present in the indoor air of the monitored environment can be seen in section 4.2. With no requirement to test for them in any of the current standards affecting schools and educational buildings the presence of these compounds would have gone unnoticed until the occurrence of any health symptoms associated with these compounds which may have then triggered an investigation and subsequent detection.

The diffusive (passive) sampling method adopted for this study was a non-targeted approach aimed at detecting all of the VOC compounds present in the indoor environment of the open-studio space. From the results it was found that acetic acid, toluene, benzaldehyde and phenol were repeatedly present in all three measurement scenarios (Figure 15). This confirms their presence in the indoor environment and suggests that they are originating from the building materials or being introduced via the ventilation system (as opposed to being introduced by occupants or short duration activities).

The presence of toluene is concerning as repeated exposure can lead to cognitive impairment and vision and hearing loss according to agency of toxic substances and disease registry (53). However, the source of this contaminant might originate from vehicular traffic using the car park adjacent to the building and further tests would be needed to confirm this. The other identified compounds such as acetic acid, benzaldehyde and phenol are commonly associated with indoor sources (e.g. floor polish, cleaning products, photocopiers, air fresheners etc). Further studies would be required to isolate the precise indoor and outdoor source responsible for the emission of these compounds. This would involve testing samples of the indoor materials present under controlled conditions (i.e. emission chamber tests) to obtain the emission characteristics of the specific compounds. Having identified the source of these compounds a detailed sampling plan would be required in order to capture these compounds in the indoor environment and understand their time dependent concentrations.

Whilst it is possible to associate some VOCs with a localised indoor emission episode other can be formed as a result of reactions with other VOCs or due to photolysis, hydrolysis or oxidation taking place in the indoor environment. VOCs can also be formed via interactions between individual VOCs. Due to the presence of numerous potential sources (Figure 2) and the various chemical constituents that have gone into the manufacture of these products, associating the presence of specific compounds to these sources can be complex and time consuming This complexity has meant that to date guidelines applicable to educational buildings in the UK (BB101, 2006; BB101, 2018) have specified Total VOC (TVOC) limits, where levels above 300 μg/m3 indicate poor IAQ. The generic nature of TVOC as a metric can however mask the hazardous properties of individual VOCs. Furthermore, the time dependency of VOC emissions is not constant, and this coupled with the diverse sources of possible contaminants suggests that more comprehensive VOC screening protocols are needed in these standards.

The IAQ campaign was conducted on the 9th Month (i.e. May 2018) and 11th Month (i.e. July 2018) after completion of the refurbishment on August 2017. Hence, the number of compounds present, and their concentration measured during this study might be less compared to if the study was carried out closer to the refurbishment. An ideal method would have been to conduct the IAQ campaign before the refurbishment and on a monthly basis subsequent to the refurbishment to see the effect of time on the trend in the overall concentration of VOCs.

It should also be noted that the IAQ campaign was carried out during the spring and summer period which could have influenced the actual concentration of VOCs due to increases in background ventilation rates during summer (through the increased frequency of opening of windows) as opposed to the winter. An ideal approach would have been to carry out the same IAQ campaign during the winter period and to compare the results obtained to capture the seasonal effect of VOCs. Outdoor air can also be a source of VOCs which are subsequently transferred into the indoor environment via the ventilation system. However, measurements were carried out only for the indoor environment (i.e. indoor air) and not for the outdoor air and further tests would be required to isolate the air supply as a potential source of contaminants.

Chromatograms were used to identify each compound present in the space during the 8-hour sampling period for different measurement scenario. But the chromatogram can give information only about the peak area value (area under the curve) for each compound corresponding to its retention time in the gas chromatography column and not its absolute concentration in the space. To derive the actual concentrations of the identified compounds, a calibration curve is created which involves comparing a pure form of the compound identified against the one found in the indoor air. This process provides the concentration of each compound in ppm or $\mu$g/m3 which can then be compared with recommended guideline values in the literature.

The number of samples collected in this study (n=18) would be considered relatively small for reliable quantification or assessing the significance of compounds. However, this study was intended to serve as a pilot study to highlight the strengths and limitations of current guidelines used in assessing educational buildings. In so doing this research has led to the identification of candidate target compounds (acetic acid, toluene, benzaldehyde and phenol) for follow-up studies and further research. A more in-depth investigation is required to identify the indoor environmental conditions and construction materials that have led to the formation of the target compounds.

Of the detected VOCs, only some could be positively identified due to the limitations in national institute of standards and technology (NIST) database and the complexity of the compounds present. There is a need to conduct more studies to document the properties of a significant number of unnamed compounds and determine their implication on human health. The VOCs identified across the measurement scenarios here included: ethanol, acetic acid, 1-butanol, pentanal, toluene, hexanal, styrene, benzaldehyde and phenol. Of those, acetic acid, toluene, benzaldehyde and phenol were found to be repeatedly present in all measurement scenarios, which strongly suggests their presence in the indoor environment. However, the actual concentrations of these compounds were not measured at this stage for comparison with indoor permissible limits, since this could imply a liability issue if published. The compounds were expressed in the form of normalised peak area values here which indicates their quantity in counts / nanograms equivalent to internal standard.

Another point worth noting is that there is no guidance in the ventilation standard BB101 (2018) regarding the number or location of the sensors needed to obtain realistic measurements of the dry bulb temperature or $CO_2$ concentration in a space based on its area. For this study, 2 sensors each (for the dry bulb temperature and $CO_2$ concentration) were used in an area of 377$m^2$. Further research would be required to establish whether these are sufficient to be considered representative of the monitored space.

## 6.0 Conclusions

The main aim of the study was to investigate the indoor air quality of a recently refurbished educational building by assessing the $CO_2$ concentration and identifying the VOCs that are contributing to the indoor air pollution load as a result of the refurbishment.

$CO_2$ concentration, which is widely used as a key indicator for ventilation performance for the control of IAQ, was found to be well below thresholds specified by all of the relevant standards. This could be because the occupancy of the space was below the designed occupancy during the period of this study or that the ventilation flow rates were set to high in the BMS system.

The $CO_2$ concentration maximum threshold specified in BB101 (2006) was reduced from 1500ppm to 1000ppm in the recently released BB101 (2018) highlighting the importance of relatively low $CO_2$ thresholds in maintaining a comfortable and effective learning environment. However, $CO_2$ concentration should not be conflated with IAQ and the VOCs originating from a variety sources both indoor and outdoor cannot be ignored due their potential to cause serious short and long-term health effects. Currently the ventilation standard BB101 attempts to address this problem by specifying a TVOC limit (where TVOC >300 $\mu g/m^3$ indicates bad IAQ). However, BB101 (2018) falls short of indicating specific VOC screening protocols or the targeted sampling of known carcinogens or other hazardous compounds.

In this study a non-targeted approach was adopted to assess the IAQ of the space. The diffusive (passive) sampling technique used led to the detection of numerous harmful VOCs that could not have been detected by simply referring to the $CO_2$ concentration or the concept of TVOC limits. The term 'good indoor air quality' in schools depends upon 'minimising the impact of indoor sources of pollutants and the reduction of outdoor pollutant ingress' (14,15) however the first step in achieving this goal is to define adequate measurement protocols. A more robust perspective implies a need to go beyond $CO_2$ and TVOC limits, where the quantification of individual VOCs and their health impacts are factored in whenever the IAQ of a space is being classified. This issue is of paramount importance in the context of educational buildings in which young people spend a high proportion of their developing lives.

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