Indoor air quality (IAQ) evaluation of higher education learning environments

Lama, Supreet, Fu, Charlie ORCID: https://orcid.org/0000-0002-2019-5445 and Lee, Angela (2022) Indoor air quality (IAQ) evaluation of higher education learning environments. Journal of Smart Buildings and Construction Technology, 4 (1). ISSN 2810-9511

10.30564/jsbct.v4i1.4042

Journal of Smart Buildings and Construction Technology
https://ojs.bilpublishing.com/index.php/jsbct

ARTICLE

Indoor Air Quality (IAQ) Evaluation of Higher Education Learning Environments

Supreet Lama[1] **Changfeng Fu**[1*] **Angela Lee**[2]

1. University of West London, London, UK
2. University of Salford, Manchester, UK

ARTICLE INFO

Article history
Received: 2 November 2021
Accepted: 29 November 2021
Published Online: 5 January 2022

Keywords:
Indoor air quality
Temperature
Carbon dioxide (CO_2)
Humidity
Human comfort
Educational building

ABSTRACT

Indoor Air Quality (IAQ), particularly in educational facilities, is gaining considerable interest and is a synonymous indicator towards evaluating human comfort. Factors such as CO_2 concentration, temperature, and humidity play crucial parts in determining an acceptable level of IAQ. Many studies have also demonstrated that the indoor air quality of classrooms affects students' concentration and performance. Today with the threat of a global pandemic, the demand of clean & fresh indoor air quality in education buildings is extremely intensive. This study focuses on investigating IAQ situations and changes in different typical functional spaces of a higher education building in the UK. CO_2, temperature, and humidity data in various learning environment were monitored via data loggers during the winter. Associated with data monitoring, a set of questionnaires surveys were carried out to evaluate the user's experience. The results of this study show that temperature and CO_2 concentration in the classrooms was constantly higher than the government guidance on a daily basis. The analysis also shows that temperature and humidity increased with CO_2 levels, but at a much lower rate. This study has revealed poor and concerning IAQ in higher education buildings in the UK, particularly in larger rooms with high occupancy. Along with the findings, this paper also identifies possible impact or factors and proposes solutions to overcome these issues.

1. Introduction

Indoor air quality (IAQ) plays a pivotal role in maintaining occupants' comfort, performance and wellbeing and is a major contributor to human health [36]. Indoor air pollution may cause or aggravate illnesses [28], increase mortality [36], and have a major economic and social impact [9]. Furthermore, it has been proven that a number of respiration related diseases are directly caused or developed by poor IAQ by means of pollutants such as radon, carbon monoxide, formaldehyde and various biological contaminants [1,28,23]. Maintaining good IAQ is important in today's digital age, where people spend around 90% of their time indoors [21,26]; and of which for

**Corresponding Author:*
Changfeng Fu,
University of West London, London, UK;
Email: Charlie.fu@uwl.ac.uk

DOI: https://doi.org/10.30564/jsbct.v4i1.4042

a typical student, around 30% of their time is spent in classrooms [5]. Therefore, it is pertinent to understand how various factors affect IAQ, and how this impacts the perception of comfort for its users. There are numerous factors that influence the overall indoor environment which includes indoor air quality (IAQ), humidity, ventilation, thermal comfort, lighting etc [26]. The lack of maintenance of any of these factors to appropriate levels can cause discomfort to some or all occupants.

Specifically, within educational buildings, poor IAQ in can cause various health implications such as headaches, eye irritation, coughing and nausea – and more importantly, it can impede on student performance as well as their learning ability. This can particularly cause negative effects for those suffering with allergies and pulmonary diseases [2]. Polluted indoor air can sometimes also contain carcinogens, which if exposed for a long period of time, can promote the formation of cancer [16].

Sources of pollutants in a higher education setting range from outdoor air and traffic to materials used for construction and furnishing, cleaning products, electrical equipment, and various lab appliances. In addition, buildings and HVAC (heating, ventilation and air conditioning) systems have deteriorated as a result of ageing and inadequate maintenance or have become obsolete as a result of technological advances. Added to this, the amount of fresh air being brought into buildings has decreased in order to reduce the amount of energy needed to heat or cool it. Thus, there is less fresh air available to dilute indoor air contaminants/ pollutants. Indoor air concertrations are largely uncharacterised, but they have likely increased over time as a wider mix of chemicals are used and air exchange rates in the buildings decrease to improve energy efficiency [35]. Chemical concentrations are often highest indoors because many of the pollutant sources are found inside buildings, and because of limited degradation indoors compared with outdoors. In addition, people who may be exposed to indoor air pollutants for the longest periods of time are often those most susceptible to the effects of indoor air pollution, and are namely the young, the elderly, and the chronically ill. Hence, maintaining a high level of IAQ can also be classed as a measure of prevention of various illnesses and diseases, and as such, can be evaluated by temperature, CO_2 levels and humidity. This study furthers existing research by providing by evaluation of IAQ of monitored levels and regulatory guidance, against user's satisfaction in practice, to determine true perceived and actual IAQ comfort levels.

1.1 Room Temperature and Regulations

The internal room temperature is one of the most important parameters that determines occupier's comfort. There are various thermal comfort criteria recommended by various organisations and bodies. The Chartered Institute of Building Services Engineers (CIBSE) [6] recommends indoor temperatures ranging between 19-21°C during the winter within a learning environment. Whereas the Health and Safety Executive [18] suggests maintaining a minimum temperature of 16°C in an indoor working environment, such as an office or a classroom; noting, a maximum temperature was not provided. However, Building Bulletin (BB) 101 [7] recommends temperatures between 17°C - 25°C during winter for school environment, where the recommended temperature for a classroom is around 20°C.

However, studies conducted in various educational establishments around the world have shown a significant difference in temperature preference by the occupants. A study conducted [13] in East Australia (Sydney) shows that students were comfortable at a temperature of 23.4°C, but preferred cooler temperatures of 22.6°C. In another study [32] during autumn in Nepal concluded that the mean comfort temperature was 26.9°C. Whereas in a study conducted in a university building in China [38] identified that temperatures between the range of 16°C – 22.4°C were acceptable in classrooms. Wargocki and Wyon [34] conducted similar studies in a school environment during the summer in Denmark and concluded that by providing sufficient cooling (from 25°C to 20°C), the student's speed of completing numeric and two language-based tasks significantly improved. The study also concluded that. By increasing the rate of air circulation from 5.2 L/s to 9.6 L/s, the students were able to significantly improve their performance on four numerical exercises.

Based on the Köppen−Geiger Climate Classification [22], the North part of China has arid climate, whereas Eastern Australia, mid-mountain region of Nepal and Denmark have temperate climate, similar to that of the UK where this study has been conducted. Hence, a comparison can be made between the results of this study and the results of previous studies.

1.2 Carbon Dioxide Levels & Regulations

As previously discussed, there are various types of pollutants present in indoor air, but due to its natural occurrence and substantial effect on human beings, carbon dioxide (CO_2) concentration is used as an indicator for IAQ [7,25]. Whilst CO_2 is not directly dangerous to humans, some studies [21,31] have shown that high levels of concentration can affect a person's physical and mental performance, such as their ability to make decisions. CO_2 levels are often higher indoors due to exhalation of CO_2 by occupants. This level can rise exponentially if the area has full/crowded occupancy, such as in a classroom or small meeting rooms that often lack adequate ventilation.

The atmosphere consists of 0.04% CO_2 (and 21% O_2), where the average concentration level in an outdoor environment is between 400-500 ppm; and within an indoor environment with good ventilation can range between 400-1,000 ppm [24,35]. In order to maintain a constant CO_2 concentration level below 1,000 ppm, an air circulation of 15 cubic feet per minute (cfm) per occupant is recommended [8]. In teaching and learning spaces, guidance document BB 101 [7,14] recommends an average concentration of 1,000 ppm or less where mechanical ventilation is used and 1500 ppm or less where natural ventilation is used. In both mechanically and naturally ventilated spaces, the maximum concentration of CO_2 should not exceed 1500 ppm and 2000 ppm, respectively, for more than 20 consecutive minutes.

However, within a fully occupied lecture hall, CO_2 can reach levels of 5,000 ppm, which can impact concentration and reduce high-level cognitive abilities [19,29]. The HSE [18] recommends staying within an area with CO_2 concentration of 5,000 ppm for a maximum of 8 hours and 15,000 ppm for 15 minutes or less. CO_2 concentration above 5,000 ppm can begin to cause health issues such as headache, nausea and sleepiness. Furthermore, a significant study in this area was carried out at the Lawrence Berkeley National Laboratory and SUNY Upstate Medical University [31]. It demonstrated that when the CO_2 level is between 1000 ppm and 2000 ppm, occupants may feel that the air is unfresh and often start to feel drowsy; when the CO_2 level is raised to between 2000 ppm to 4000 ppm, occupants in this environment may feel difficulty breathing, their faces often turn red and they may start to feel a convulsion; when CO_2 levels reach between 4000 ppm and 6000 ppm, occupants may experience permanent brain damage, and often lose consciousness, and more seriously, may die if they stay in such an environment for a long period of time.

In a study conducted by [14] in primary schools in the UK identified that sensation of air is more correlated to CO_2 levels than temperature during non-heating season and more correlated to temperature than CO_2 during heating season. They also concluded that air quality perception improved by around 43% when CO_2 levels were below 1000 ppm and temperature were within occupant's thermal comfort range. Hence, to improve occupant comfort, balance between various factors affecting indoor comfort needs to be maintained individually.

1.3 Humidity Levels and Effect on Performance

Humidity is the concentration of moisture present in the air. A relative humidity between 40-70 percent is required for a comfortable environment [20,26]. Studies [32,37] have shown that low and high levels of humidity can impact the concentration and performance of occupants. There are health risks associated with levels of humidity which includes increased risk of asthma and viral infections, dry eyes, flaky skin, sore throat etc.

Overall, IAQ plays a crucial role in achieving and sustaining human comfort, which is a condition of the mind that expresses satisfaction within the environment. Comfort is achieved upon fulfilment of several conditions including thermal, visual, noise, air quality and personal factors [15,26]. This research aims to investigate changes of indoor environment quality in various types of learning environments within Higher Education (University) learning spaces against user' satisfaction, in short, to evaluate IAQ in practice (users' satisfaction) against monitored levels and regulatory guidance.

2. Research Method

This research utilises both objective measurements and subjective surveys. Air temperature, CO_2 levels and humidity were measured and analysed as an indicator for IAQ. These objective datasets were collected using three different types of data loggers, namely: an internal Tinytag temperature and humidity data logger, an internal Tinytag CO_2 data logger, and an external temperature and humidity data logger. In order to capture and distinguish changes of indoor environment, the data collection of this study was carried out during winter of 2019 in the UK over a two-week period, whereby natural ventilation was limited (namely, the windows of the building were shut most of the time). The data loggers were connected to power outlets and placed at 1.2m above the floor (average human sitting height) and were in operation for the entire two-week duration. Other possible impact factors, such as the area of the monitored learning environment, the number of occupants, and the facilities within the rooms (such as computers) were also recorded (the room volume and the activities being carried out can also affect the levels of CO_2 and humidity, which ultimately affects human comfort [21].

The university building investigated for this study is located in the Greater London area; and represented a typical Higher Educational building across the UK – steel frame construction with solid and curtain wall cladding system. The part of the building used for this study was originally constructed in the late 1800s and has since been refurbished with the notable addition of external insulation to the solid walls and double-glazed windows. Different types of learning spaces were selected within the Higher Education building, 5 in total, namely: classroom, lecture hall, computer rooms and a specialist learning space [textile room]. This also helped diversify the data, identify level of comfort in various rooms and also provided an opportunity to identify the effect of equipment in a room on user comfort. Table 1 provides background of the learning environments surveyed.

Table 1. Rooms surveyed

ROOM ID	*ROOM TYPE*	*FLOOR*	*AREA (m^2)*	*Height (m)*	*CLASS DURATION (hrs)*
R01	Computer room	Third	65	2.8	3
R02	Classroom	Third	52	2.8	2
R03	Lecture Hall	First	78	2.8	3
R04	Computer room	First	45	2.8	3
R05	Textiles room	Ground	69	2.8	4

The building has mechanical ventilation installed; however, it was not in operation in majority of the rooms surveyed. The only room that had mechanical ventilation in operation was the textiles room (R05), where various paints and other chemicals were in use and therefore mechanical means were used in support of health and safety guidelines. The remaining rooms are all naturally ventilated.

The objective measurements were to be compared to a subjective survey, which would be used to corroborate against user's perceived satisfaction. A survey was conducted in the form of a questionnaire with Likert-type questions to analyse comfort levels throughout the class, and against differing objective measurements gathered with the Tinytag devices. The survey was conducted at the beginning and at the end of the class to analyse changes in IAQ perception over the duration of the class. All users of each survey room (students and staff) were invited to partake in the study.

The analysis of Likert questionnaire was carried out by converting the overall responses from each room into percentages. This was administered by assigning a value from 0 to 4: where 0 equated to very uncomfortable, and 4 equated to very comfortable. Next, the maximum possible value for each survey was calculated by adding the number of responses and multiplying the result with the maximum assigned value, which was 4. Subsequently, the actual combined value of every survey was calculated by multiplying the number of times an answer was selected by its value and adding them together. Finally, the average percentage of satisfaction was calculated using the following formulae

$$\left(\frac{\text{Actual combined value}}{\text{Maximum possible value}}\right) \times 100$$

The average percentage of satisfaction was then used to conduct a simple and multiple regression analysis between the objective and subjective measures.

3. Data Collection

3.1 Temperature Measurement

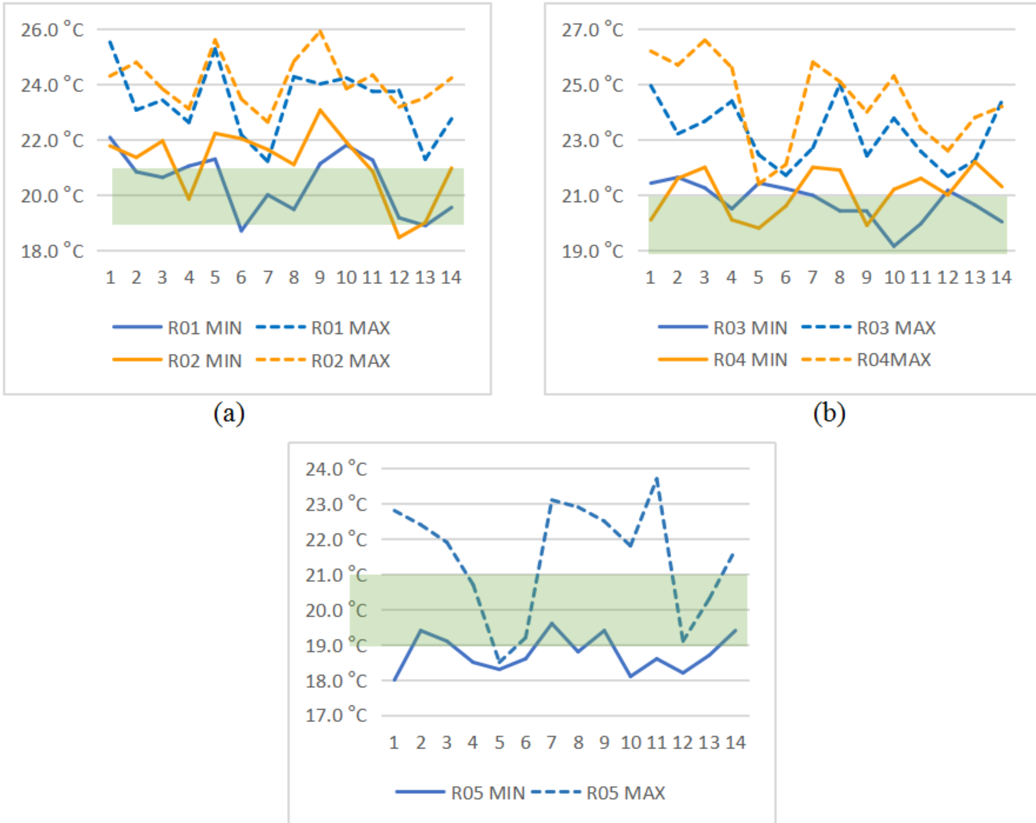
Objective measurements were conducted over a two-week period which included, temperature, CO_2, and humidity levels. Figure 1 (a, b & c) shows changes in minimum and maximum temperature over 14 continuous days for each learning environment. The maximum recorded temperature was 26.6°C in room R04. The green shaded area within each graph denotes the range of comfortable temperature based on the guideline provided by CIBSE (2015), which is between 19°C - 21°C. The minimum temperature occurred mostly occurred during the night when no one was present in the building. It can be seen in the graphs that the temperature in all the classes exceeded the recommended range on a daily basis which can be deemed to be theoretically uncomfortable. The dip in maximum temperature seen in days 6 & 7 and 13 & 14 occurred during the weekend.

3.2 Carbon Dioxide Measurement

Figure 2 (a, b & c) shows the minimum and maximum recorded CO_2 levels across the 5 rooms over 14 continuous days. An observation of the graph shows that rooms R02 and R03 are the worst performing rooms in terms of CO_2 levels. All minimum CO_2 levels were recorded overnight when there were no occupants. The considerable fall in the level of CO_2 was recorded during the weekend. The green shaded area denotes the concentration level of CO_2 required in educational buildings i.e., 1500 ppm in naturally ventilated and 1000 ppm in mechanically ventilated. Room R03 had alarming levels of CO_2, which constantly surpassed the 2000 ppm (for a max of 20 mins) limit on a daily basis, and even exceeded 4000 ppm at one point.

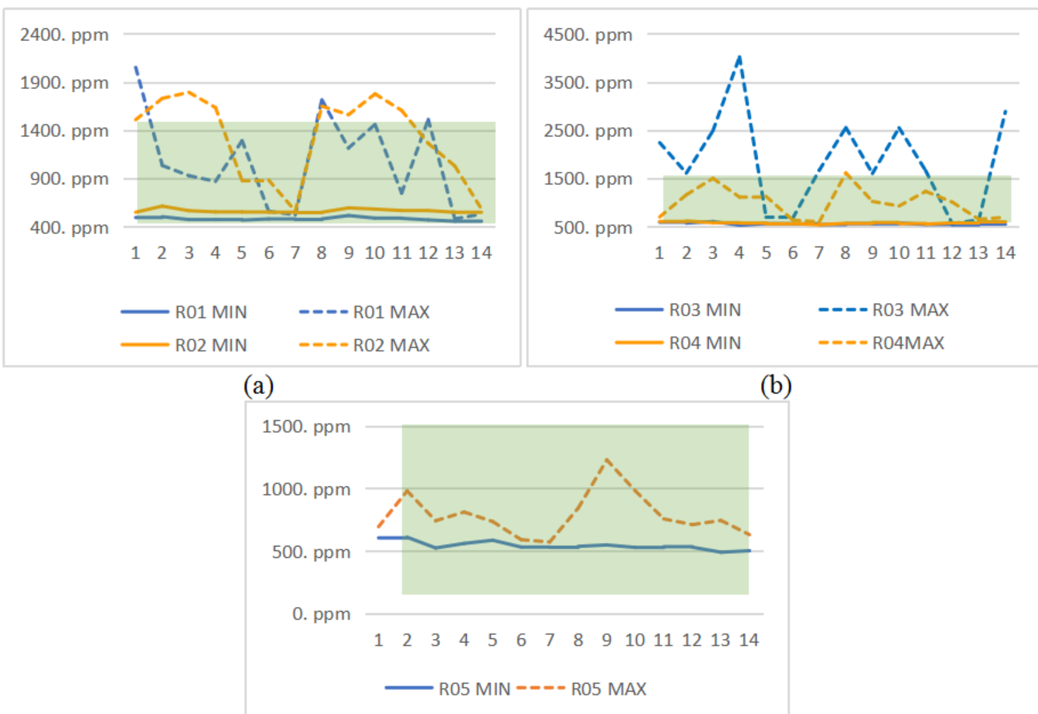
3.3 Humidity Measurement

Figure 3 (a, b &c) shows the relative humidity percentages recorded within the 5 surveyed rooms over



(c)

Figure 1. Minimum and maximum temperature recorded over 2 weeks.



(c)

Figure 2. Minimum and maximum CO_2 reading over 2 weeks

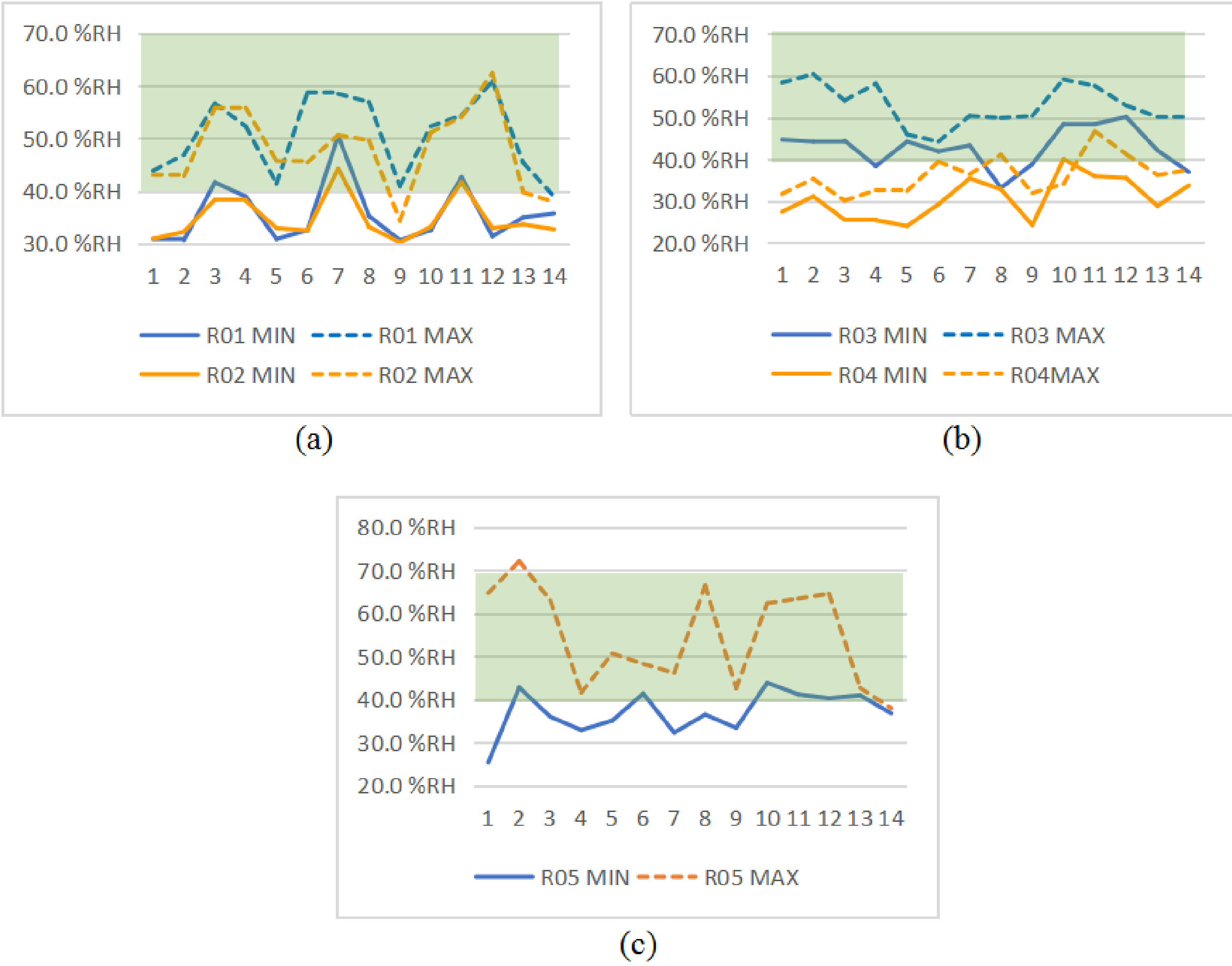


Figure 3. Minimum and maximum humidity levels over 2 weeks.

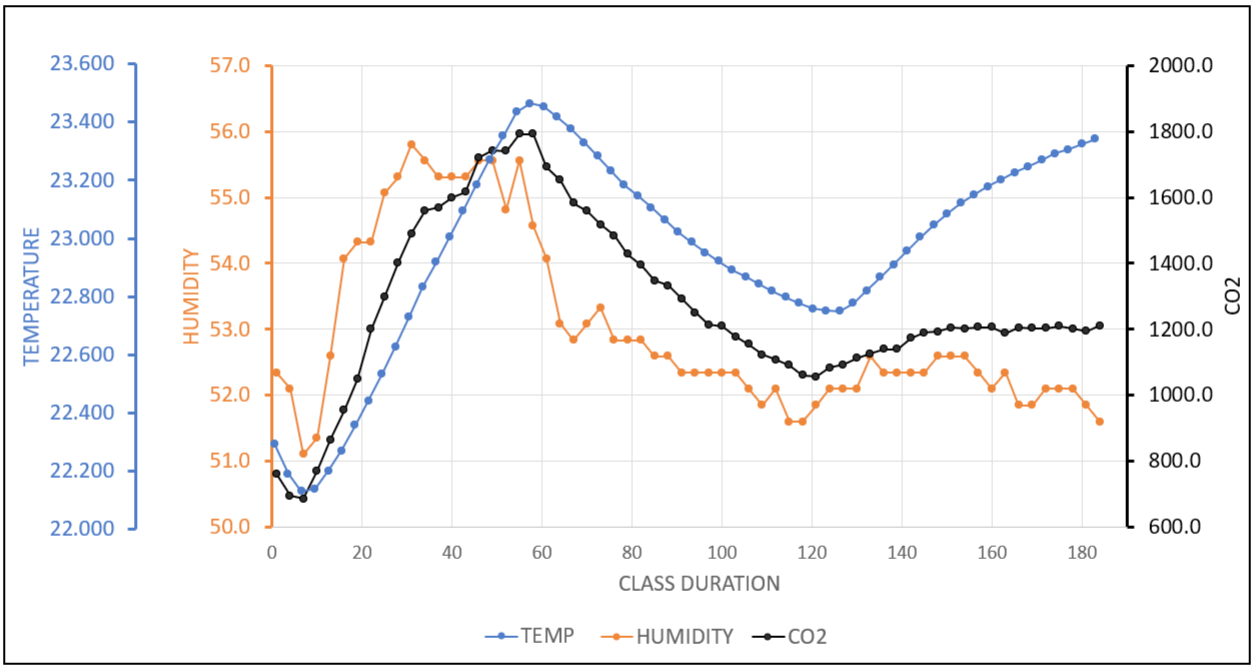
14 days. The graphs show that the relative humidity of the majority of the rooms fall within the recommended 40 – 70% level, denoted by the green shaded area. The minimum levels were mostly recorded during the night or weekends when no users were present in the building. Only room R04 shows humidity levels dropping below 40% during the 14 days of survey.

3.4 Overall Indoor Air Quality

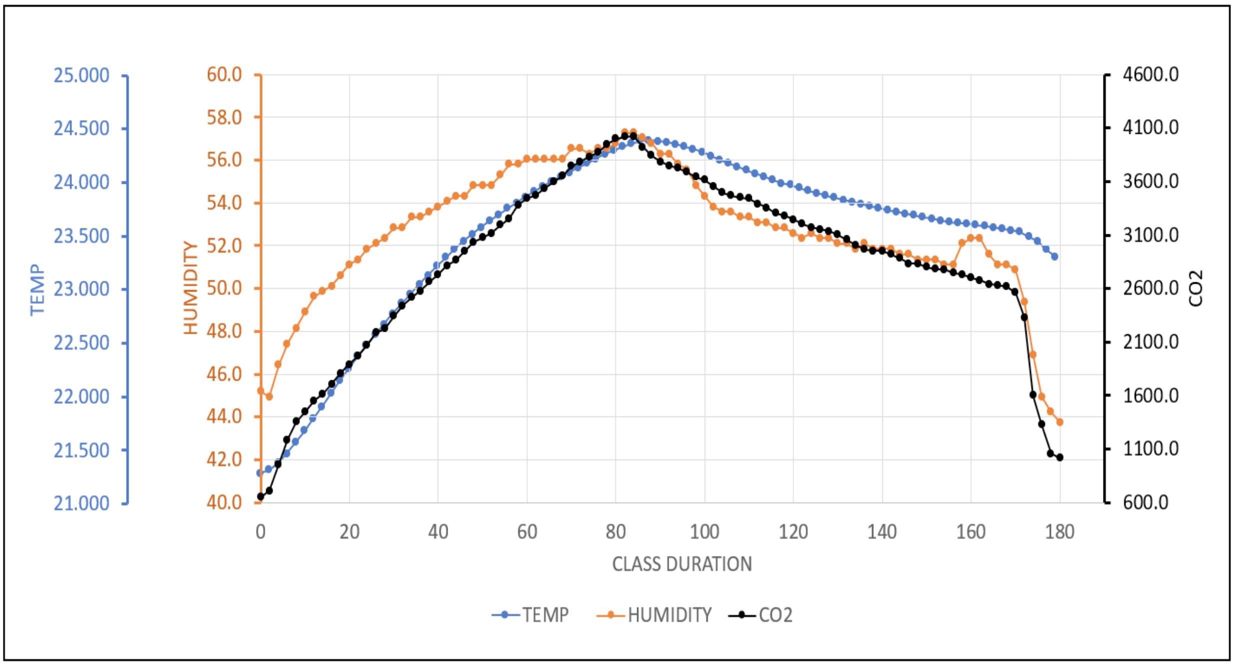
Considering all the factors measure during this study, room R02 and R03 were identified as the worst performing out of the 5 rooms. In order to further identify the rate of decline in indoor air quality, the day with the highest levels of temperature, CO_2 and humidity in R02 and R03 were selected. Figure 4 a & b shows the increase and subsequent decrease in level of the 3 factors over the duration of a 3-hour class. It can be seen that all 3 factors follow a similar upward and downward trend reaching their respective maximum levels at similar times.

3.5 Questionnaire Survey

A survey was also conducted in the form of a questionnaire with dichotomous questions at the beginning and end of class, shown in Table 2 & 3. A total of 61 completed forms were collected from the 5 rooms surveyed and included staff and students. The results of the survey showed lecture hall R03 had the greatest decrease of 14% and 12% in comfort related to air quality and temperature, respectively. The objective data collected over the 3-hour class also shows that CO_2 levels peaked at over 2500 ppm and temperature exceeded 24 °C, which is relatively higher than the their rooms. The room's overall human comfort also decreased by 8% throughout the duration of the class. Over 54% of the users desired the room to be cooler. However, air quality comfort in room R01 and R04 increased over the duration of the class by 6% and 4% respectively. This can be attributed to the opening of windows halfway through the class, as some of the students commented that the room 'felt stuffy'.



(a) 3-hour reading of Room R02



(b) 3-hour reading of Room R03

Figure 4. Fluctuation in temperature, CO_2 & humidity.

Table 2. Beginning of class survey

Survey questionnaire: Start of class

How comfortable are you with the current temperature of the room?	• Very comfortable • Comfortable • Neutral • Uncomfortable • Very uncomfortable	• 4 • 20 • 22 • 12 • 3
Would you like the current temperature of the room to change?	• Cooler • No change • Warmer	• 25 • 34 • 2
How comfortable are you with the current air quality of the room?	• Very comfortable • Comfortable • Neutral • Uncomfortable • Very uncomfortable	• 6 • 14 • 22 • 17 • 2
Do you feel that a mechanical ventilation would be beneficial in this room?	• Yes • No	• 48 • 5
How would you rate your overall comfort in this room?	• Very comfortable • Comfortable • Neutral • Uncomfortable • Very uncomfortable	• 4 • 23 • 22 • 10 • 2

Table 3. End of class survey

Survey questionnaire: End of class

Do you feel that your level of concentration reduced towards the end of class?	• Yes • No	• 49 • 12
Did the level of temperature affect your concentration?	• Yes • No	• 27 • 34
Did the quality of air affect your concentration?	• Yes • No	• 37 • 24
How comfortable are you with the current temperature of the room?	• Very comfortable • Comfortable • Neutral • Uncomfortable • Very uncomfortable	• 1 • 21 • 22 • 15 • 2
Would you like the current temperature of the room to change?	• Cooler • No change • Warmer	• 33 • 27 • 1
How comfortable are you with the current air quality of the room?	• Very comfortable • Comfortable • Neutral • Uncomfortable • Very uncomfortable	• 1 • 15 • 27 • 15 • 3
How would you rate your overall comfort in this room?	• Very comfortable • Comfortable • Neutral • Uncomfortable • Very uncomfortable	• 2 • 18 • 21 • 18 • 2

4. Results and Analysis

4.1 Temperature Change

Figure 5. Change in temperature.

As highlighted earlier, a comfortable working temperature during the winter period ranges between 19-21°C. However, the analysis of temperature data collected over the 2-week period shows that all of the classes exceed this range on a daily basis. Figure 5 shows readings from room R02 and R03 were the highest amongst the 5 rooms surveyed. In both cases, the temperature exceeded 21°C from the early morning till the end of day. In case of room R02, the temperature remained above 24°C for the entire day (9:00-17:00). The slight dip in temperatures seen in Figure 1 correspond to lunch hours for majority of the classes in the university, where occupancy significantly lowered.

Delving further into the rooms with the highest temperatures i.e., R02 a classroom and R03 a lecture hall, it was identified that by the time students enter the room the temperature was already over the higher level (21°C) of the recommended range and remained over this level for the entire duration of the class. On average the temperature rose at a rate of 3.75% and 3.81% per hour in R02 and R03, respectively. This means that if the temperature of R02 is 20°C at the beginning of the class, within an hour the temperature will reach around 20.75°C, and around 22.25°C, over a 3-hour duration, given that no windows or doors are opened.

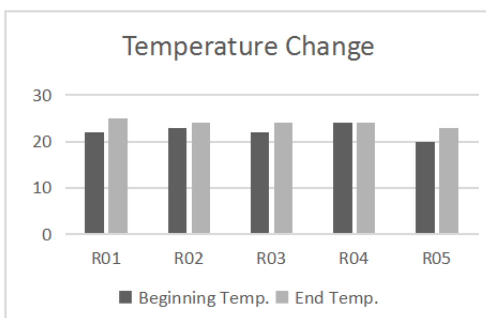


Figure 6. Change in temperature in the surveyed rooms.

Figure 6 shows the temperature of each of the five classrooms at the beginning and end of the class on the day survey questionnaire was completed. It can be seen that classrooms temperatures rose on four instances and remained the same on one occasion, which can be associated with increased capacity/use of the learning environment when heat is emitted by human bodies as well as equipment used in the room. It should be noted that every room, apart from room R05, began with a temperature of over 22°C. The greatest rise in temperature was 3°C in R01 and R05, reaching 25°C and 23°C respectively, which is above the recommended comfort level of 21°C. The mean temperature of the 5 rooms surveyed was 22.3°C, with a standard deviation of 2.06.

The temperature and satisfaction data obtained at the beginning and end of the class were combined together. A simple regression analysis was conducted in Excel to work out the relationship between classroom temperature and student comfort satisfaction. The results of the regression analysis in Figure 7 show that the variance (R^2) is 78%, F value is 29.06, p value (Significance F) = 0.0006. Based on the regression analysis principles, R^2 over 60% indicates that temperature strongly influences satisfaction. And p value less than 0.05 indicates that the results of the analysis are statistically significant. The analysis also demonstrates a negative relationship between temperature and satisfaction. According to temperature readings, all the classes were already above 20°C at the start of class where the mean satisfaction percentage was 57.8%. By the end of class, the satisfaction percentage had fallen to 52.2%, in short, satisfaction fell as temperature increased.

Table 4. Regression analysis - results

Regression Statistics	
Multiple R	0.8855
R Square	0.7842
Adjusted R Square	0.7572
Standard Error	4.1811
Observations	10

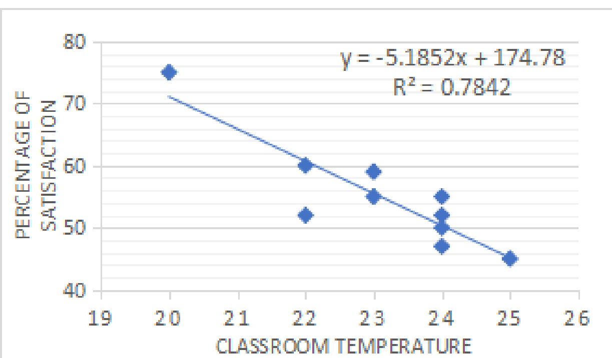


Figure 7. Regression analysis of temperature & satisfaction.

Table 5. Regression analysis –Analysis of variation

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	508.1481481	508.1481481	29.06779661	0.00065264
Residual	8	139.8518519	17.48148148		
Total	9	648			

4.2 Air Quality and Human Comfort

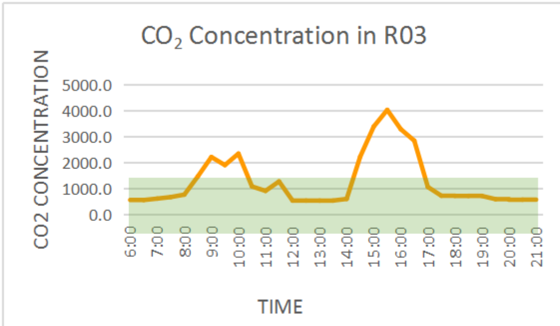


Figure 8. Carbon dioxide levels in Lecture Hall

The analysis of the data collected showed that CO_2 levels in 4 of the 5 rooms surveyed surpassed the required limit (green shaded area) of 1500 ppm during a 2- or 3-hour class as required by the Department of Education [7]. The maximum concentration level recorded was 4,020 ppm in R03, a 98-seat lecture hall, during a 3-hour lesson, as seen in Figure 8. During these 3 hours, the level of CO_2 was over 1500 ppm 90.11% of the time, i.e., around 2 hours and 40 minutes. It only took 12 minutes and 25 minutes from the start of class for CO_2 levels to exceed 1500 ppm and 2000 ppm, respectively. The level remained over 2000 ppm for around 2 and half hours, greatly exceeding the recommended 20 minutes limit. Over the course of 14 days, 42% of CO_2 levels in room R03 exceeded the required 2000 ppm limit. This limit increased to 60% if weekend readings are excluded.

Table 6 below shows the duration of time it took for CO_2 levels to reach 1500 ppm as well as the maximum recorded level in all of the 5 rooms over the 14 days period. The only exception in this study was room R05, a textiles room, which uses mechanical ventilation (MV). During the entire 2 weeks of recording in this room, CO_2 levels peaked at 1228 ppm and dropped to a low of 558 ppm during the night and weekend. This room does not consist of any windows; hence this relatively low level of CO_2 can only be attributed to the efficient use of MV.

In order to determine the rate of increase of CO_2 levels, the data from R02 and R03 were taken, which were read at 3-minute intervals by the logger. The analysis of this data showed that CO_2 in R02 rose at an average rate of

67.66% per hour, whereas in R03 CO_2 rose at 61.11% per hour. These data were taken from the beginning of a class till CO_2 reached the maximum level before falling significantly which would indicate that a window or door had been opened. It was also identified that in R02 levels of CO_2 exceeded the required level of 1500 ppm 12.38% of the time. However, in R03 CO_2 levels exceeded this level 70.26% of the time.

Table 6. Duration for CO_2 to reach required maximum limit.

Rom ID	Start CO_2	Max CO_2	Time to reach 1500 ppm	Time to reach Max
R01	959 ppm	1708.4 ppm	210 mins	270 mins
R02	686 ppm	1792.3 ppm	27 mins	48 mins
R03	596 ppm	4020.5 ppm	15 mins	90 mins
R04	796 ppm	1609.9 ppm	90 mins	96 mins
R05	558 ppm	1228.5 ppm	111 mins (to reach 1000 ppm)	231 mins

Furthermore, analysis of CO_2 data from R02 showed that during the day when levels reached its maximum of 1,792 ppm the rate of increase from the start of the class, 55 minutes earlier, was 116.79% per hour, whereas the rate of decrease, till the end of class, was much lower at -47.32% per hour. Similarly, in R03 the rate of increase from the start of the class, 90 minutes earlier, was 92.03% per hour to reach its daily maximum of 4020.5 ppm, whilst the rate of decrease was -52.64% per hour.

A regression analysis was carried out in order to determine the relationship between indoor air quality and user's comfort. The result of the analysis however, indicated that the model only explained 14% of the variance and was not statistically significant, $F (1,8) = 1.26, p = 0.30$. The overall satisfaction with IAQ was only 47%, which stands at odds with the result of the regression analysis.

A regression analysis carried out to test the relationship between user comfort and indoor humidity indicated that only 3% of the variance could be explained by the model. The overall result was statistically insignificant, $F (1,8) = 0.29, p = 0.60$.

4.3 Multiple Regression Analysis

After obtaining one significant and two insignificant models, a multiple regression analysis was performed with three independent variables (i.e., temperature, CO_2 & humidity) and one dependant variable i.e., student comfort. The result of this analysis indicated that the model explained over 70% (adj. R^2) of the variance and was a significant predictor of student comfort, $F (3,6) = 7.8, p= 0.017$. However, indoor temperature was the most significant contributor to this model, B = -5.07, p = 0.0053. Indoor CO_2 (B = -0.002, p = 0.9) and humidity (B = 0.15, p = 0.56) did not contribute significantly to this model.

5. Discussions

5.1 Temperature and CO_2 Interpretation

The aim of this study was to investigate whether changes in IAQ within a university building [during winter] corroborates user's perception towards IAQ over the duration of a class. The results of the study indicate that the IAQ of the 5 rooms surveyed decrease after around 30 minutes from the start of each class, either due to changes (an increase) in temperature or CO_2 or both. In general, classes were 3-4 hours in duration, and typically had one or two short breaks. 4 out of the 5 rooms surveyed were naturally ventilated, however the windows were mostly closed during the survey period [Winter] hence, the rate of air exchange was low. The doors in every room were fire resistant, which are required to remain closed at all times, and possibly aggravated the IAQ.

The temperature in the rooms surveyed remained constantly high in majority of instances, with the 98-seater lecture hall (R03) constantly exceeding the recommended temperature of 21°C. The windows in all rooms are aluminium framed, with double glazed awning windows. However, these windows could only open up to an angle of 20°, and roller blinds are used to keep light out during classes/presentations [via a projector], restricting the amount of air circulation. Both simple and multiple regressions have also shown a strong negative correlation between temperature and satisfaction.

The correlation between the change in CO_2 as well as humidity and student comfort was insignificant. This result has been observed in other studies including Griffiths & Eftekhari [12], who concluded that temperature, rather than air quality, affects comfort among staff and students. The findings of this study has also shown that classroom temperature plays a bigger role in determining student comfort. This, however, does not suggest that CO_2 and humidity did not play any part in determining student comfort. The analysis of the survey showed that over 53% of the occupants were not satisfied with the quality of air, and over 60% believed that the quality of air affected their concentration by the end of the class. This can simply mean that the occupants may have found it difficult to isolate their sensory experiences or base their comfort on a single factor [10]. This result also concurs with findings by Frontczak & Wargocki [11], which concluded that thermal comfort was the greatest parameter that influenced overall satisfaction with IAQ.

A simple observation of minimum and maximum temperature and CO_2 figures also show that the average internal temperature has been constantly higher than the maximum limit in a room. However, average maximum CO_2 and humidity have remained below the maximum limit in 3 of the 5 rooms surveyed, which might explain the lack of correlation between these variables and temperature.

On the other hand, CO_2 data gathered over the 2-week survey period have shown that at some point in the day, concentration exceeds the required 1500 ppm level in every room. Overall, around 39% of the CO_2 recorded exceeded the 1500 ppm limit over the 14 days, or 55% if weekends (no occupancy) are excluded. In worst situations, such as where a room is full, levels of CO_2 have exceeded 4000 ppm within 90 minutes. This can cause issues with occupants' concentration, performance and even create health issues.

This is particularly worrying due to the on-going SARS-CoV-2 virus, which can remain active in the air for at least 3 hours and is capable of airborne transmission [4]. Should the rate of ventilation in these rooms remain the same, then there might be a high probability of transmission of the virus, possibly though an asymptomatic carrier.

5.2 Proposed Changes to Maintain Comfortable IAQ

5.2.1 Installation of Temperature and CO_2 Sensors inside Classrooms

It was observed during this study that the University uses temperature sensors to control the heating in the survey building, which is typical of many Higher Education facilities across the UK. However, these sensors, in this instance, were placed in the corridor, which are generally cooler than the learning spaces due to the lack of stationary occupants. This may be a contributing factor as to why the temperature in the learning rooms were regularly above 20°C, even during the night when there was no occupancy. There were no CO_2 sensors present in the building. Installation of CO_2 sensors in each room is advocated, or at least in larger lecture halls and classrooms is proposed in order to accurately monitor and control temperature and CO_2 levels.

5.2.2 Mechanical Ventilation System

As seen in room R05 which was served by a MV system, the temperature, CO_2 and humidity levels were mostly within the required limits, without the presence of any windows. The level of comfort in that room was also the highest at 75% at the start of class.

Installation of a MV system is proposed to maintain a comfortable IAQ. However, due to the vast time and cost involved with MV systems, a sensor controlled mechanical window could be installed instead. Along with individual sensors in each room, these mechanical windows could be installed and automatically open when the temperature and CO_2 levels rise, and close once the levels drop back within the desired range.

CO_2 concentration levels can be used as an indicator of IAQ [7] in a room which may contain various pollutants including Volatile Organic Compounds (VOCs) as well as the SARS-CoV-2 virus. Natural and mechanical ventilation (HVACs) are both considered good measures to remove respiratory particles [3]. However, in the interest of minimising risk of transmission of the SARS-CoV-2 virus, building management should look into filtering recirculated air or even stop the recirculation of air in mechanically ventilated rooms altogether [27].

5.2.3 Changes in Timetable

It was observed during the data collection of this study, that the temperature and CO_2 levels were already high in the learning space when a new group of students entered the class. This was particularly true in case of afternoon classes when a class had already taken place in that room earlier. To tackle this issue, a more robust timetable needs to be arranged. Buildings service teams could arrange for personnel to manually open windows between classes to ensure adequate circulation of air. The length of classes may also be an issue as temperature and CO_2 levels considerably rise over the duration of a 3-to-4-hour class. At least 2 to 3 breaks between classes are recommended as a measure to lower these levels. The data have also shown that CO_2 levels can reach levels of 1500 ppm within 15-30 minutes in a full class, hence a break every 40-50 min, along with opening of windows, may help maintain the room at a comfortable level.

6. Conclusions

This study analysed temperature, CO_2 and humidity data from 5 [learning/study] rooms in a higher education building in London across a 2-week period during the winter, the data of which was evaluated against perception survey data regarding users' level of comfort. The temperature data have shown that in all of the rooms surveyed, exceeded the recommended comfortable temperature range of 18°C - 21°C on a daily basis. The mean temperature was 22.3°C, and over 54% of the occupants expressed discomfort and a desire for a cooler temperature. The result of a simple and multiple regression analysis was significant and explained around 78% and 70% of the variance in user comfort, respectively. It also showed a negative correlation between the two variables. It was concluded that the heat emitted by the radiators in the learning rooms contributed to the high temperatures. This occurred because the sensors that control the radiators in classrooms are located in the corridors, which are always relatively cooler, hence causing the radiators in the classrooms to run continuously. On average, the rate of increase in temperature was around 3.75% per hour.

Monitoring and controlling the temperatures of classrooms can also lead to considerable savings in energy usage. Nicol, Humphreys & Roaf [30] argue that reduction in temperature by 1°C can reduce energy usage by around 10%. Based in this calculation the university building in this study can save between 13% – 43% of energy being used. The university building used in this study has an area of over 20,000m^2, which means that the savings in energy usage can be very significant.

The CO_2 data was found to be a good an indicator of air quality overall; the CO_2 levels regularly exceed the required limits within the 5 surveyed rooms, and this often occurred within the first 30 minutes of a class commencing. The highest recorded levels of CO_2 exceeded 4000 ppm in a [large occupancy] lecture hall. This study has also shown that during the afternoon, CO_2 levels are already close to the required maximum limit when the students and staff enter the room for a 3/4-hour class, which further aggravated the IAQ. The average rate of increase of CO_2 levels in R02 and R03 were 67.66% and 61.12% per hour, respectively. Amongst the three factors used in this study, levels of CO_2 rose at the highest rate of over 60% per hour, followed by humidity at over 9% per hour and then temperature at 3.75% per hour.

The regression analysis between CO_2, humidity and student comfort were insignificant. However, this does not mean that these factors did not affect the student's comfort, as over 53% of them were not happy with the air quality. This study has also shown that over 55% of the CO_2 levels exceeded the required 1500 ppm limit if weekends are excluded. During class time in R03, CO_2 levels were over 1500 ppm 70.26% of the time on average.

These issues need to be addressed by the University and building management as a matter of urgency, particularly during the on-going COVID-19 pandemic to reduce the transmission of the SARS-CoV-2 virus, which can remain active in the air for hours. A change in priorities might also be necessary in favour of keeping the pollutants and virus at bay. A couple of windows can be opened for around 30 minutes before or at the start of each class (depending on the timetable) to circulate the air, even if it means that the room temperature might drop by a few degrees.

The results of this study reflect low human comfort levels and have shown that the IAQ in this building is concerning and may have a negative effect on the wellbeing of its students and staff. Alarmingly, this is likely to be typical across the Higher Education sector in the UK. A number of changes are proposed in this paper, such as adjusting timetables, use of mechanical ventilation and installation of sensors in every room to monitor and control the IAQ individually, that will improve the prevailing IAQ – both physically and in perception.

Abbreviations

°C: Degree Celsius
CO_2: Carbon dioxide
HSE: Health & Safety Executive.
CFM: Cubic Feet per Minute
IAQ: Indoor Air Quality
MV: Mechanical ventilation
NV: Natural ventilation
O_2: Oxygen
PPM: Parts Per Million
WHO: World Health Organisation

References

[1] Allen, J., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., Spengler, J., 2016. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of Green and conventional office environments, Environmental Health Perspective. 124(6), 805-812.

[2] Annesi-Maesano, I., Baiz, N., Banerjee, S., Rudnai, P., Rive, S., 2013. Indoor Air Quality and Sources in Schools and Related Health Effects, Journal of Toxicology and Environmental Health, Part B, (16)8, 491-550.

[3] Asanti, K., Voden, L. & Majeed, A., 2021. Healthier schools during the COVID-19 pandemic:ventilation , testing and vaccination. Journal of the Royal Society of Medicine, 0(0), 1-4.

[4] Azuma, K., Yanagi, U., Kagi, N., Kim, H., Ogata,

M & Hayashi, M., 2020. Environmental factors involved in SARS-CoV-2 transmission: effect and role of indoor environmental quality in the strategy for COVID-19 infection control. Environmental Health and Preventative Medicine. 25(1), 1-16.

[5] Bakó-Biró, Z., Clements-Croome, D.J., Kochhar, N., Awbi, H.B. & Williams, M.J., 2012. Ventilation rates in schools and pupils' performance. Building and Environment, 48, 215- 223.

[6] CIBSE, 2015. CIBSE Guide A: Environmental Design. 8th ed. CIBSE: London.

[7] Department for Education, 2016. Guidelines in ventilation, thermal comfort and indoor air quality in schools: Building Bulletin 101.

[8] Downing, C. C. & Bayer, C. W., 1993. Classroom indoor air quality versus ventilation rate, ASHARE Trans, 99(2), 1099-1103.

[9] Fisk, W. J., Lei-Gomez, Q. & Mendell, M. J., 2007. Meta-analyses of the associations of respiratory health effects with dampness and mold in homes. Indoor Air, 17, 284-296.

[10] Fransson, N., Västfjäll, D. & Skoog, J., 2007. In search of the comfortable indoor environment: A comparison of the utility of objective and subjective indicators of indoor comfort. Building and Environment, 42(5), 1886-1890.

[11] Frontczak, M. & Wargocki, P., 2011. Literature survey on how different factors influence human comfort in indoor environments. Building and Environment, 46 (4), 922-937.

[12] Griffiths, M. & Eftekhari, M., 2008. Control of CO2 in a naturally ventilated classroom. Energy and Buildings, 40(4), 556-560.

[13] Haddad, S., Synnefa, A., Marcos, M. A. P., Paolini, R., Delrue, S., Prasad, D. & Santamouris, M. On the potential of demand-controlled ventilation system to enhance indoor air quality and thermal condition in Australian school classrooms. Energy and Buildings, 238.

[14] Korsavi, S; Montazami, A; Mumovic, D, 2020. Indoor air quality (IAQ) in naturally-ventilated primary schools in the UK: Occupant-related factors. Building and Environment, Volume 180.

[15] Hens, H., 2011. Applied Building Physics: Boundary conditions, building performance and material properties. 1st ed, Berlin: Ernst & Sohn.

[16] Hoskins, J. A., 2003. Health effects due to indoor air pollution, Indoor and Built Environment, 12(6), 427-433.

[17] HSE, 1999. Health and safety law: What you should know. Leaflet, ISBN 0 7176 1702 5.

[18] HSE, 2013. Workplace health, safety and welfare regulation 1992. 2nd ed, London: HSE Books.

[19] Jacobson, T.A., Kler, J.S., Hernke, M.T., Braun, R.K., Meyer, K.C., Funk W.E., 2019. Direct human health risks of increased atmospheric carbon dioxide. Nature Sustainability. 2(8), 691-701.

[20] Jiang, J., Wang, D., Liu, Y., Di, Y., Liu, J., 2021. A holistic approach to the evaluation of the indoor temperature based on thermal comfort and learning performance. Building and Environment. 196.

[21] Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C., Engelmann, W.H., 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. Journal of Exposure Analysis and Environmental Epidemiology. 11, 231-252.

[22] Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen−Geiger climate classification updated. Meteorologische Zeitschrift. 15(3), 259-263.

[23] Kukadia, V., Upton, S., 2019. Ensuring good indoor air quality in buildings. BRE Trust: Watford.

[24] Kulshreshtha, P., Khare, M., Seetharaman, P., 2008. Indoor air quality assessment in and around urban slums of Delhi city, India. Indoor Air. 18(6), 488-498.

[25] Marques, G., Ferreira, C.R., Pitarma, R., 2019. Indoor air quality assessment using a CO2 monitoring system based on internet of things. Journal of Medical Systems. 43(3), 1-10.

[26] McMullan, R., 2018. Environmental science in building. 8Th ed, Palgrave Macmillan: Basingstoke.

[27] Megahed, N.A., Ghoneim, E.M., 2021. Indoor air quality: Rethinking rules of building design strategies in post-pandemic architecture. Environmental Research. 193, 1-9.

[28] MENDELL, M.J., 2007. Indoor residential chemical emissions as risk factors for respiratory and allergic effects in children: a review. Indoor Air. 17, 259-277.

[29] Moore, P., 2016. The positive impact of human CO2 emissions on the survival of life on earth. 1st ed, FCPP: Winnipeg.

[30] Nicol, F., Humphreys, M., Roaf, S., 2012. Adaptive thermal comfort: Principles and practice. 1st ed. Routledge: Oxon.

[31] Satish U., Mendell M.J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., Fisk, W.J., 2012. Is CO2 an Indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance, Environmental Health Perspectives. 120(12), 1671-1677.

[32] Shrestha, M., Rijal, H.B., Kayo G., Shukuya M.,

March 2021. A field investigation on adaptive thermal comfort in school buildings in the temperate climatic region of Nepal, Building and Environment. Volume 190.

[33] Wang, Z., Ning, H., Zang, X., Ji, Y., 2016. Human thermal adaptation based on university students in China's severe cold area. Science and Technology for the Built Environment. 23(3), 413-420.

[34] Wargocki, P., Wyon, D., 2007. The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children. HVAC&R Research. 13(2), 193 -220.

[35] Weschler, C., 2009. Changes in indoor pollutants since the 1950s. Atmospheric Environment. 43, 153-169.

[36] WHO, 2010. The right to healthy indoor air. Bilthoven, The Netherlands, WHO regional Office for Europe.

[37] Wolkoff, P., 2018. Indoor air humidity, air quality, and health – An overview. International Journal of Hygiene and Environmental Health. 221(3), 376-390.