Arc Re-Entry:
Guide to Measuring CO2

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Introduction

To improve the well-being of students or be recognized for their healthy environments, schools can measure indoor air quality (IAQ). Examples of factors that make up IAQ include particulate matter (PM), thermal comfort, and carbon dioxide (CO2). High levels of CO2 have proven to play a negative role in student performance. From a study of 60 schools in Scotland, CO2 demonstrated an inverse relationship with school attendance. An incremental increase of 100 ppm of CO2 over 1000 ppm was associated with half a day of absence per school year (**Gaihre et al. 2014**). High concentrations can have an impact on grades too. A study of a Latvian school used student surveys and tests to examine CO2 and academic performance. There was a moderately negative correlation between CO2 concentration and test performance as students performed worse when exposed to higher concentrations of CO2. However, simple measures such as opening doors and windows for at least 15 minutes were enough to maintain low CO2 levels (**Bogdanovica et al. 2020**). The decrease in students' attention intensity in classrooms with an average of 2909 ppm CO2 has been found to be of similar magnitude to that of students skipping breakfast (**Coley et al. 2016**).

Much of the exceedances of CO2 derive from issues with HVAC systems or low ventilation rates. Thus, CO2 can be a great indicator for HVAC performance (**Johnson et al. 2018**). Given the numerous types of HVAC system types, HVAC operating conditions, and seasonal variation, measuring CO2 is essential in ensuring well-maintained ventilation equipment. HVAC systems both new and old are susceptible to improper ventilation of schools. In 104 classrooms in California that were retrofitted with new HVAC equipment, there were maintenance issues in 51% of the studied classrooms. Some were improperly installed or lacked commissioning, but all of them were associated with under-ventilated classrooms (**Chan et al. 2020** and **Fisk et al. 2012**). CO2 measurement, therefore, is necessary to ensure HVAC systems are delivering sufficient ventilation.

With the risk associated with high concentrations of CO2, particularly for children, and the lack of guarantee of HVAC function, CO2 levels need to be measured in schools accurately and efficiently to support the health, comfort, and productivity of students and faculty. Ideally, every classroom, office, gym, and library would be measured across all hours to best illustrate a school's IAQ. Due to financial and time constraints, this may not be achievable. This guide provides directions and thresholds to help gauge a school's air quality without requiring air monitoring in every room all the time as to reduce equipment costs and time and to ensure that schools of various abilities can still maintain good air quality for their students. It also includes our approach to defining whether a school has "good", "better", or "best" occupied time or floor area measurement and "good" or "acceptable" CO2 performance levels.

Instructions

Schools have varying HVAC systems, classrooms, and schedules that result in each school measuring their air quality in different ways. In order to streamline this process better, suggestions are given for where in a school and where within a classroom to measure.

Placement of CO2 Sensors in a School

With a finite quantity of monitors, schools have limited options for which locations to place their monitors. Below are some potential goals a school may want to achieve and suggestions for sensor placement to achieve these goals.

1. Finding the school's average CO2

As the primary source for CO2 indoors is occupant respiration, sensors should be placed in rooms where occupants spend the majority of their time. For those who want to focus on classroom monitoring specifically, a random sampling of classrooms' CO2 levels can provide the school's average CO2. For those who want to investigate non-classroom settings such as offices or libraries that have high occupancy times, monitors can be placed both in random classrooms and in those non-classrooms.

If users want to sample based on occupancy, they can also weight classrooms based on their occupancy such that higher occupied classrooms are more likely to be sampled than lower occupied classrooms. After classrooms are weighted, monitors can be randomly deployed where classrooms with greater occupancy are more likely to be measured.

2. Finding the school's maximum CO2

Best practices would be to sample spaces with high occupancy and/or low ventilation rates. Maximum CO2 levels are found in occupied classrooms with low ventilation or poorly operating HVAC systems. If a space has peak occupancy and low ventilation simultaneously, high CO2 should be expected. For example, if a cafeteria had no running ventilation system and closed windows during lunch hours, the school's maximum CO2 could be found there.

3. Determining HVAC operating conditions

To determine HVAC operating conditions, measurements in air ducts under the same HVAC zone need to be compared to determine whether they are operating as intended. Areas with unusually high levels should have their HVAC installation checked.

Placement of CO2 Sensors within a Classroom

In general, sensors should be placed in the breathing zone (ie. the height of a sitting student) of around 1 meter (3.3 feet) as illustrated in **Stazi et al. 2017**, **Razali et al. 2015**, and **Jan et al. 2017**. Because classroom activities and student tampering can compromise the accuracy of a sensor, there is less agreement on where exactlya classroom sensor should be placed. Some suggest placing sensors beside a teacher's desk (**Deng and Lau 2019**), away from windows in the middle of the classroom (**Branco et al. 2015**), and in the back wall away from the door (**Fromme et al. 2007**). Sensors placed in lower areas of movement and wind in the breathing zone are ideal for more accurate measurements.

Measuring CO2

CO2 will be assessed by determining the fraction of occupied space and time covered by measurements. In turn, these data are interpreted to estimate the fraction of occupied hours when conditions are in the good, better, or best ranges.

CO2 Comprehensiveness Score

Arc will generate a CO2 Comprehensiveness Score ("CO2 Comp Score") by adding together 1-100 scores for floor area coverage (floor area, rooms, or HVAC zones), occupied time coverage (operating hours), and performance (time in "good" or "acceptable" range).

A few details about how this is computed:

Floor area coverage indicates the fraction of the project covered by each type of sensor. There are two ways to achieve this.

1. Users can assume that an individual sensor covers approximately 500 square meters (5,280 square feet) (**RESET Air Standard for Commercial Interiors**) or following guidance from their vendor or product manufacturer (e.g., **arbnco Best Practice Guide**). While sensor coverage will differ based on building layouts and installation practicalities, projects should aim for the smallest effective coverage area of a sensor, and the coverage area of a single sensor should not exceed 500 m2. For example, at least one sensor in each HVAC zone or enclosed room could suffice for adequate coverage, provided those zones or enclosed rooms are smaller than 500 m2 each.

As examples:

- Measurements from one sensor covering 500 m2 in a 5,000 square meter open space would be presumed and documented to provide a coverage of 10% (500 m2 / 5000 m2).

- Estimate an effective radius around each sensor and derive the covered area based on manufacturer or vendor guidance (e.g., arbnco Best Practice Guide).
- Follow and reference guidance from a third-party standard, such the RESET Air Standard 2.0 for the design and operation of monitoring networks.

2. Depending on the school's measuring goal, users can divide their school into zones in accordance with the PNNL education building prototypes' occupied zones such that each floor area coverage can be calculated as a fraction of the number of zones measured compared to the total number of zones. They can also determine floor area coverage as a fraction of classrooms measured, HVAC zones, or other functional units.

PNNL Building Prototypes considers the following as an occupied zone:

- Classroom
- Computer Lab
- Office space
- Gym, stadium (play area)
- Kitchen
- Cafeteria, dining
- Library

Arc assumes that coverage continues from the last reported value through the present unless this value is changed due to reorganisation of space or sensor layouts. Arc combines values as an average of daily values to provide an estimate for a given time period.

Figure 2. Draft thresholds used to categorize floor area coverage: good, better, best. These thresholds are subject to further review and adjustment based on sensor uncertainty.

Tips for Entering Floor Area Data Coverage

Some users may not be able to provide a quantitative estimate of floor area data coverage. We know that there are many potentially confounding factors and unknowns (e.g., the area covered by any given sensor). It is important to remember that the purpose is to provide a rough estimate of the fraction occupied space associated with each measurement (i.e., are you covering a small fraction of the area, most of the space, or all of the space).

If a quantitative estimate is not possible, users may estimate coverage and enter the following values:

- **Low Coverage:** <25% of occupied space is associated with measurements
  - *Enter 25% for the applicable date range*
- **Medium Coverage:** 25%-75% of occupied space is associated with measurements
  - *Enter 50% for the applicable date range*
- **High Coverage:** >75% of occupied space is associated with measurements
  - *Enter 100% for the applicable date range*

Describe your estimate with a piece of document. This can be a simple note explaining your rationale.

Occupied time coverage indicates the fraction of time covered by IAQ measurements during the last 90 days. For Arc, a time period is "covered" if at least one measurement is taken during the period in a project.

For the purpose of measuring schools, we are assuming 8 occupied hours a day of operations and 1 hour as a fundamental unit of occupied time coverage (a.k.a., freshness period for measurements). Consequently, occupied time coverage is defined as the percentage of hours within a period that have one or more readings for a given parameter. Additional measurements during a given period do not increase coverage (i.e., occupied time coverage has a maximum value of 100% which is satisfied by at least one reading each hour). This means that 1 day has a maximum of 8 readings that will count towards occupied time coverage.

A high measurement rate, e.g., those recommended by standards such as WELL and RESET, are better for a richer, more representative characterisation of CO2 measurement. To keep this metric simple, Arc requires a report only every hour (i.e., the reporting interval).

Arc assumes that coverage continues from the last reported value through the present unless this value is changed with new value. Arc combines values as an average of daily values to provide an estimate for a given time period.

Figure 2. Draft thresholds used to categorize occupied time measured: good, better, best. These thresholds are subject to further review and adjustment based on sensor uncertainty.

Tips for Entering Occupied Time Data Coverage

Some users may not be able to provide a quantitative estimate of occupied time data coverage. We know that there are many potentially confounding factors and unknowns. It is important to remember that the purpose is to provide a rough estimate of the fraction occupied hours associated with each measurement (i.e., are you covering a small fraction, most hours, or all of them).

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    - *Enter 50% for the applicable date range.*
- **High Coverage:** >75% of occupied hours are associated with a measurement
    - *Enter 100% for the applicable date range.*

Describe your estimate with a piece of document. This can be a simple note explaining your rationale.

Performance is divided by thresholds into three categories: good, better, and best. Each period is assigned to one of the three categories.

Performance is typically integrated over some period of time, most often hours or days. These periods may contain any number of sensor readings. The intent is to communicate the percentage of **occupied** time in each category. For example:

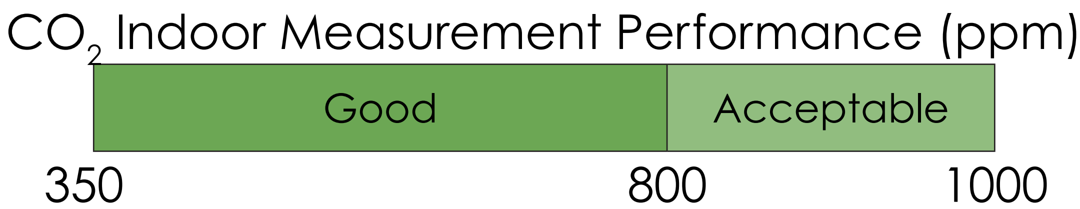
- If hourly (for sub-hourly) occupied data are available, Performance would be calculated as the average of hourly values. Missing values would be excluded from Performance, because they are already accounted for in the preceding metrics.
- If daily data during occupied hours are available, Performance would be calculated as the average of daily values. Again, missing values would be excluded.

The result would be the average fraction of periods in each of the three categories over the last 90 days. Data older than 90 days do not contribute to the CO2 Comprehensiveness Comp Score.

The CO2 Comprehensive Score combines the three equal elements:

- Floor Area Coverage
- Occupied Time Coverage
- Performance (as the fraction of time in the "good" or "acceptable" condition)

Figure 3. Draft thresholds used to assign time in each condition: good and acceptable. 0-800 ppm is deemed good as the **CDC**, **ASHRAE**, and CIBSE 2018 all recommend ventilation rates that result in 800 ppm CO2. The upper limit is 1000 ppm as effects on cognitive performance begin for short term exposure exceeding 1000 ppm (**Azuma et al. 2018**). These thresholds are subject to further review and adjustment based on sensor uncertainty.



Note on Data Quality

Objective measures of data quality are not currently part of the CO2 Comp Score. However, the quality of CO2 measurements is a significant management issue, and it varies significantly based on a variety of factors, including sampling design, sensor placement, sensor capabilities, sensor maintenance, data processing, and more (**RESET Standard**). Extensive peer-reviewed literature is emerging in this area with publications such as **Sun et al. 2019** and **Chojer et al. 2020**, and the **U.S. Environmental Protection Agency Air Sensor Toolbox**. Arc Re-Entry users may consider the benefits of third-party accredited hardware as one element of a comprehensive strategy to promote data quality.

CO2 Comp Score Example

Floor Area Coverage

- CO2 is measured in 2 out of 20 classrooms and occupied spaces.
- The floor area coverage is estimated at 10%

Occupied Time coverage

- CO2 measurements occurred over 2 hours per school day for 90 days
- The school operates 40 hours a week
- The occupied time coverage is estimated at 25% for the week

Performance

- CO2 measurements ranged from 500 ppm to 1500 ppm in an equal number of hours.
- The performance value is 30% "good" (≤800 ppm), 20% in "acceptable" (≤1000 ppm)

Total CO2 Comp Score = 10/100 + 25/100 + 50/100 = 85/300

Performance Reports

Projects can input their floor area coverage, temporal coverage, and CO2 performance data into Arc Re-Entry. Arc Re-Entry provides tools to help facility managers use indoor air quality measurements to inform operations. Every Arc user can collect, manage, and score data through the Re-Entry section under Meters & Surveys. Arc Essentials users can create, download, and share customized reports for projects and portfolios.

Contact

Contact Chris Pyke (cpyke@arcskoru.com) to provide feedback or get more information.

About Arc

Arc™ is a global technology platform that allows teams overseeing the sustainability of buildings and places to collect data, manage and benchmark progress, measure impact and improve performance. Created and operated by Green Business Certification Inc. (GBCI), Arc empowers its users to understand and enhance their sustainability performance, promote human health and wellbeing and contribute to a higher quality of life.

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