Arc Re-Entry:

Guide to Measuring $PM_{2.5}$

By Kristina Koh, Chris Pyke, and Dagny Carlsson

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Introduction

As students spend an increasing amount of time in classrooms, the indoor air quality (IAQ) of classrooms plays a larger role in students' health. Perhaps one of the most notable measures of IAQ, particulate matter (PM) is a mixture of aerosols and solids that vary in composition and size. Particles are categorized by size such that PM_{10} is a particle that has a diameter of 10 microns or less and $PM_{2.5}$ is that of 2.5 microns or less; it is important to note that, due to this categorization, particles of $PM_{2.5}$ would be included when discussing PM_{10}. It is helpful to categorize them in this way to better identify possible emission sources.

The majority of the $PM_{2.5}$ sources originate from gasoline and diesel-powered vehicles (**Maloney and Sicherer 2005**). Indoor sources often include fibers from clothing or calcium-rich particles from chalk or building deterioration (**Amato et al. 2014**).

Due to their small size, these particles can have drastic effects on human health. Children can be exposed to heavy metals and products of combustion through inhalation of PM, increasing carcinogenic risks and asthma symptoms (**Sah et al. 2019**). In a study surveying 6,590 children attending French schools where students were exposed to varying levels of $PM_{2.5}$ it was found that the higher the exposure, the greater the likelihood of the child experiencing asthma-related symptoms, having rhinitis, or developing asthma (**Annesi-Maesano et al. 2012** and **Yang et al. 2018**). Correspondingly, high concentrations of $PM_{2.5}$ have shown to cause respiratory and cardiovascular damage and chronic obstructive pulmonary disease (**Hu et al. 2018**). In an eight-year study examining 1,759 children exposed to $PM_{2.5}$ in Southern California schools, lung development was reduced in those who were exposed to higher levels of air pollution (**Gauderman et al. 2004**). There exists a wide range of possible PM concentration and composition due to variation between school location, building materials, and other variables in academic environments.

Along with the negative health effects and multiple sources of PM, another reason to measure is its unpredictability. When investigating mitigation measures for other indoor air quality factors such as carbon dioxide, ventilation management is often a solution. However, with regard to PM2.5, naturally ventilated schools in Palestine were studied, and there was no significant correlation between ventilation rate and $PM_{2.5}$ nor wind speed and $PM_{2.5}$ (**Elbayoumi et al. 2013**). In another study measuring IAQ in schools in Portugal, it was concluded that floor area variation such as outdoor location and cleaning practices impacted IAQ measurements more than any classroom factor, emphasizing the need to measure more schools (**Madureira et al. 2015**).

With the risk associated with high amounts of particulate matter in the air, particularly for children, and the lack of correlation between PM and building or location characteristics, PM 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. However, due to possible financial and time constraints, this may not be achievable. This guide provides instructions and thresholds to help gauge a school's air quality without requiring air monitoring in every room so as to reduce equipment costs and time, ensuring that schools of various means can still monitor air quality for their students. It also includes our approach to defining whether a school has "good", "better", or "best" occupied time coverage, floor area coverage, and measured $PM_{2.5}$ levels.

Instructions

Schools have varying HVAC systems, classrooms, and schedules that force each school to measure its air quality in different ways. To better streamline this process, the following are suggestions for where in a school and where within a classroom to place PM sensors.

Placement of $PM_{2.5}$ Sensors in a School

With a finite number of monitors, schools have limited options for monitor placements. Below are some potential goals a school may want to achieve and suggestions for sensor placement to achieve these goals based on their ventilation mode.

1. **Mechanical Ventilation**

Mechanically ventilated schools measuring $PM_{2.5}$ often have goals of determining air handler filter efficiency, human contribution or internal generation of $PM_{2.5}$ within a room, or source contribution of $PM_{2.5}$ usually from an outside combustion source.

To determine air handler filter efficiency and test how well the ventilation system protects the school from its ambient surroundings, a sensor can be deployed outside 5 meters away from the inlet of the air handler (**RESET Standard**). The next sensor should be placed in a room with low traffic and occupancy like a library such that the $PM_{2.5}$ levels can be attributed to the filtered air as closely as possible. This room is ideally far away from potential $PM_{2.5}$ sources like kitchen stoves or vehicular traffic. If a third monitor is allowed, two monitors should be placed in this low occupancy/traffic room to ensure precision. The difference between the monitor deployed outside near the inlet and the monitor(s) placed inside can help determine HVAC filter efficiency.

If the goal is to determine occupant contribution or international generation of $PM_{2.5}$ within a classroom or space, monitors should first be placed in the same manner as the air handler filter efficiency strategy above to determine a baseline for what $PM_{2.5}$ levels are in low traffic and low occupancy rooms away from sources. Subsequent monitors can be deployed in a classroom far away from $PM_{2.5}$ sources and in a high occupancy room such that the difference in $PM_{2.5}$ levels between the baseline classroom and high occupancy classroom can be attributed to human contribution and internal $PM_{2.5}$ generation.

Schools may also want to find the source contribution of $PM_{2.5}$ such as the PM concentration due to increased traffic in the mornings. Exploring how much ambient sources breach the classroom can be beneficial in determining the level of exposure students are exposed to when near vehicular traffic. To achieve this, the baseline air handler efficiency setup is needed before comparing $PM_{2.5}$ levels to classrooms near sources of $PM_{2.5}$. After air handler efficiency is established, monitors can be placed in low occupant rooms nearest to the $PM_{2.5}$ source. This may be an outward facing perimeter classroom right next to the drop-off zone. The low occupancy will allow the PM levels to be mostly attributed to the source.

2. **Natural Ventilation**

Schools that operate solely on natural ventilation may have some similar goals such as determining source contribution, internal PM generation, or building efficiency. Below is a chart of where schools could measure based on their goal of testing envelope and window infiltration factor against ambient sources or internal PM generation which can be from indoor combustion or human generation.

	Far from $PM_{2.5}$ Source	Near $PM_{2.5}$ Source
Low Occupant Density	Envelope and Windows	Envelope and Windows
High Occupant Density	Internal PM Generation	Internal PM Generation

Sensor Placement–Best Practices

The sensor placement strategies above are considered best practices for those with enough monitors to place multiple in one classroom. However, measurement of any space and at least one monitor within a school is enough to gain recognition for monitoring $PM_{2.5}$.

Some of these strategies suggest placing a monitor 5 meters away from the inlet of an air handler unit. If there are not enough monitors to achieve this, one can also use online resources such as **BreezeoMeter** or **PurpleAir** to find the school's general ambient $PM_{2.5}$ levels.

Placement of $PM_{2.5}$ Sensors within a Classroom

For measurements that have the goal of finding internal generation or human contribution, sensors should be deployed in the breathing zone (ie. the height of a sitting student) of around 1 meter (3.3 feet) as illustrated in **Razali et al. 2015**, **Jan et al. 2017**, and **Faria et al. 2020**. Because classroom activities and student tampering can compromise a sensor's accuracy, there is less agreement on where within a classroom sensors should be placed. Some options have been beside a teacher's desk (**Deng and Lau 2019**), the middle of the classroom (**Dorizas et al. 2015**), and in the back wall away from the door (**Fromme et al. 2007**). In general, it is best that the sensor is in a position where it can be protected from tampering.

Measuring $PM_{2.5}$

$PM_{2.5}$ will be assessed based on the area measured (square feet), occupied time measured (hours), and concentration level (ug/m3). In turn, these data are interpreted to estimate the fraction of occupied hours when conditions are in the good, better, or best ranges.

$PM_{2.5}$ Comprehensiveness Score

Arc will generate a $PM_{2.5}$ Comprehensiveness Score ("PM2.5 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", "better", or "best" range). Because the maximum value for each subscore is 100, the maximum possible Comprehensiveness Score is 300.

A few details about how each subscore is computed:

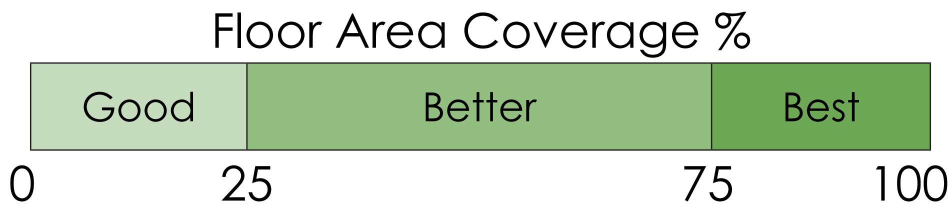
Floor area coverage indicates the fraction of the project covered by each type of sensor. Depending on the school's measuring goal, users can divide their school into zones in accordance with the PNNL education building prototypes' occupied zones such that each floor area coverage can be calculated as 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 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 $PM_{2.5}$ measurements during the last 90 days. For Arc, a time period is "covered" if at least one measurement is taken during the occupied period in a project.

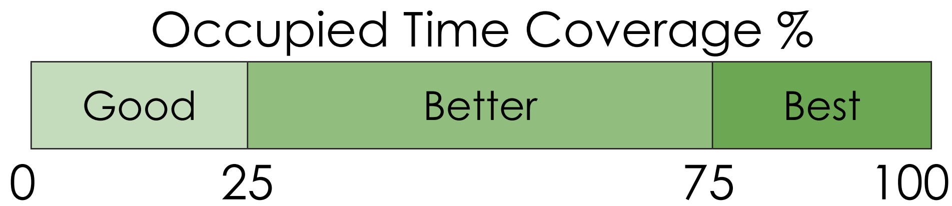
For the purpose of measuring schools, we are assuming 8 occupied hours a day of operations and 1 hour as a fundamental unit of occupied time coverage (a.k.a., freshness period for measurements). Consequently, occupied time coverage is defined as the percentage of hours within a period that have one or 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 $PM_{2.5}$ 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.

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



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).

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

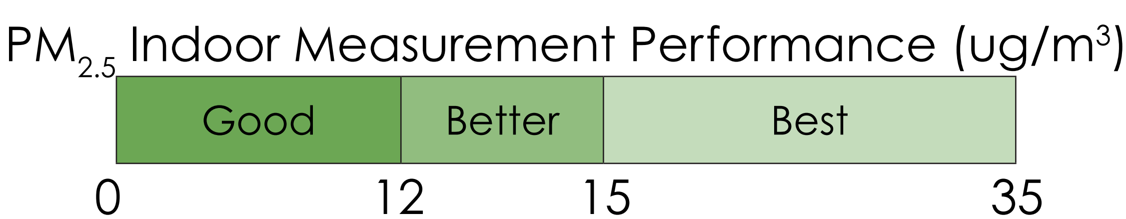
- **Low Coverage:** <25% of occupied hours are associated with measurements
  - *Enter 25% for the applicable date range.*
- **Medium Coverage:** 25%-75% of occupied hours are associated with measurements
  - *Enter 50% for the applicable date range.*
- **High Coverage:** >75% of occupied hours are associated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

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.

Figure 3. Draft thresholds used to assign time in each condition: good, better, best. These thresholds are subject to further review and adjustment based on sensor uncertainty. The upper limit of 35 ug/m3 is defined by the EPA as their standard 24-hour mean limit. Source: Parag Rastogi, arbnco.



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 $PM_{2.5}$ Comprehensiveness Comp Score.

The PM2.5 Comprehensive Score combines the three equal elements:

- Floor Area Coverage
- Occupied time Coverage
- Performance (as the fraction of time in the "good", "better", or "best" condition)

Note on Data Quality

Objective measures of data quality are not currently part of the $PM_{2.5}$ Comp Score. However, the quality of $PM_{2.5}$ 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**). An extensive peer-review 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.

$PM_{2.5}$ Comp Score Example

Floor area coverage

- PM2.5 is measured in 2 out of 20 classrooms or enclosed spaces.
- The floor area coverage is estimated at 10%

Occupied time coverage

- PM2.5 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

Measurement Performance

- $PM_{2.5}$ measurements ranged from 2 ug/m^3 to 52 ug/m^3 in an equal distribution of hours.
- The performance value is 20% "best" (≤12 ug/m^3), 6% in "better" (≤15 ug/m^3), and 40% in "good" (≤35 ug/m^3).
- The total percentage of measurements in "good", "better", or "best" are summed (ie. 20+6+40=66)

Total PM2.5 Comp Score = 10/100 + 25/100 + 66/100 = 101/300

Performance Reports

Projects can input their floor area coverage, temporal coverage, and $PM_{2.5}$ 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

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