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HNEI Indoor Air Quality Study: Analytical Summary

Subtask 4.3

Prepared for
Hawai‘i Natural Energy Institute

Prepared by
MKThink and RoundhouseOne

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Preface

In the 2021 subaward (FY 2021 |Subaward #MA1565 | Project #6107633) with the Hawaii Natural Energy Institute, MKThink, (a registered dba for Miller Kelley Architects), studied the movement of carbon dioxide (CO_2) in a sample set of classrooms through on-site sensors and computer modeling. CO_2 was selected as a critical variable for this study because high concentrations of this gas reflect poor ventilation conditions, a condition which can potentially accelerate the transmission of viral infections, such as COVID-19, a deadly virus that has plagued the globe since 2020.

The previous study leveraged field testing through both “Air Angel” Indoor Air Quality sensors and computational fluid dynamics (CFD) modeling. The results included data driven insights into the performative mechanics of the actual and modeled ventilation systems and the impact of the mechanics on indoor air quality (IAQ). The focus of this study are two (2) key variables:

1. Volume of air input
2. Exhaust vent location relative to supply vent location.

The core findings from subaward MA1565 have been outlined in a report detailing the data analysis and summary findings.

A supplemental award (FY2023 Project #6107828) has been provided in 2023 to further distill the data with the objective to enhance the clarity of spatial distribution of carbon dioxide in a classroom environment in a concise visually compelling format. The emphasis on visualization is aimed at understanding the impact of Air Changes per Hour (ACH) and supply-exhaust vent locations on CO_2 distribution.

Also, the subaward will review and attempt to increase validation of these findings.

Combined the subaward intends to further support accessible and actionable insights and next steps research.

The 2023 Award deliverables include a series of tables and graphic exhibits and interpretations, accompanied by an interpretive analysis to address the following key four (4) questions:

Task 1: CFD Result Summary

MKThink will summarize the data analyses with visualizations of carbon-dioxide concentration and location within the spaces. The report may include the following information, but not limited to,

1. Divide the volume of space into a three-dimensional matrix to understand where the concentration of CO_2 is elevated.
2. Identify what fraction of the room is above the Key Performance Index (KPI) index for acceptable CO_2 levels.
3. Visually understand the ramifications of each of the design conditions on CO2 concentration.

Task 2: Comparison of CFD data against measured data.

MKThink will compare the CFD results against sensor-based field measurements to validate the models. The results of this comparison will be summarized in a technical report.

Task 3: Benchmarking against Key Performance Index

MKThink will relate the findings from CFD models to publicly available Key Performance Indices (KPIs) (example, ASHRAE).

1. Identify publicly available sources for standards/ codes/ policies.
2. Relate the findings from this research to data from other comparable classroom environments under reasonably similar external environments.

Task 4: Qualitative recommendations

MKThink will provide HNEI with observations and recommendations for strategic mitigation and/or maintenance of healthy IAQ environment. MKThink will use best practices, codes, and policies as a basis to identify qualitative strategies to help mitigate & maintain healthy indoor AQ while optimizing energy consumption. Additional recommendations will identify areas of research that may be explored in the future to further the understanding of the relationship of energy with IAQ mitigation.

Introduction

In wake of the COVID-19 pandemic since 2021, maintaining known and healthy indoor air quality (IAQ) has become of critical importance for safeguarding public health, particularly in shared higher density indoor spaces such as classrooms. Also, interest and requirements for energy conservation, especially in challenged "edge" conditions such as island and remote locations, provides a need for additional knowledge relating to the spatial distribution of indoor air and energy consumption.

The research within the sub-awards (Project #6107633 and FY2023 Project #6107828) investigates the relationships between indoor air, specifically carbon dioxide, and location of exhaust vent relative to the supply vent in representative conditions. The methods include using:

1. Air Changes per Hour (ACH) and
2. Carbon dioxide (CO_2) concentration as an indicator for potential SARS-CoV-2 presence, as suggested by Peng Z. and Jose J., 2021.

> *(Peng Z. and Jose J., 2021): "CO2 is co-exhaled with aerosols containing SARS-CoV-2 by COVID-19-infected people and can be used as a proxy of SARS-CoV-2 concentrations indoors. Indoor CO2 measurements by low-cost sensors hold promise for mass monitoring of indoor aerosol transmission risk for COVID-19 and other respiratory diseases."*

The sub-award references building operation industry standards set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Per the ASHRAE standards, it is critical to maintain occupied rooms with CO_2 levels below 1,000 ppm to prevent health issues such as decreased concentration, dizziness, and nausea. This ensures optimal operational conditions and promotes a healthier environment.

The goal of this research is to inform impacts, through quantifiable measures, that affect IAQ - and, specifically carbon dioxide (CO_2) buildup - through efficient use of ventilation systems to ensure both safety and sustainability. To accomplish this, we scrutinize how variations in ventilation techniques impact CO_2 levels, drawing on findings from the 2021 subaward study. The insights may increase the ability to inform and guide the creation and operation of safer, healthier, and more energy efficient human performance environments such as those for learning, but also by extension other indoor environments with similar conditions and performance needs.

Methodology

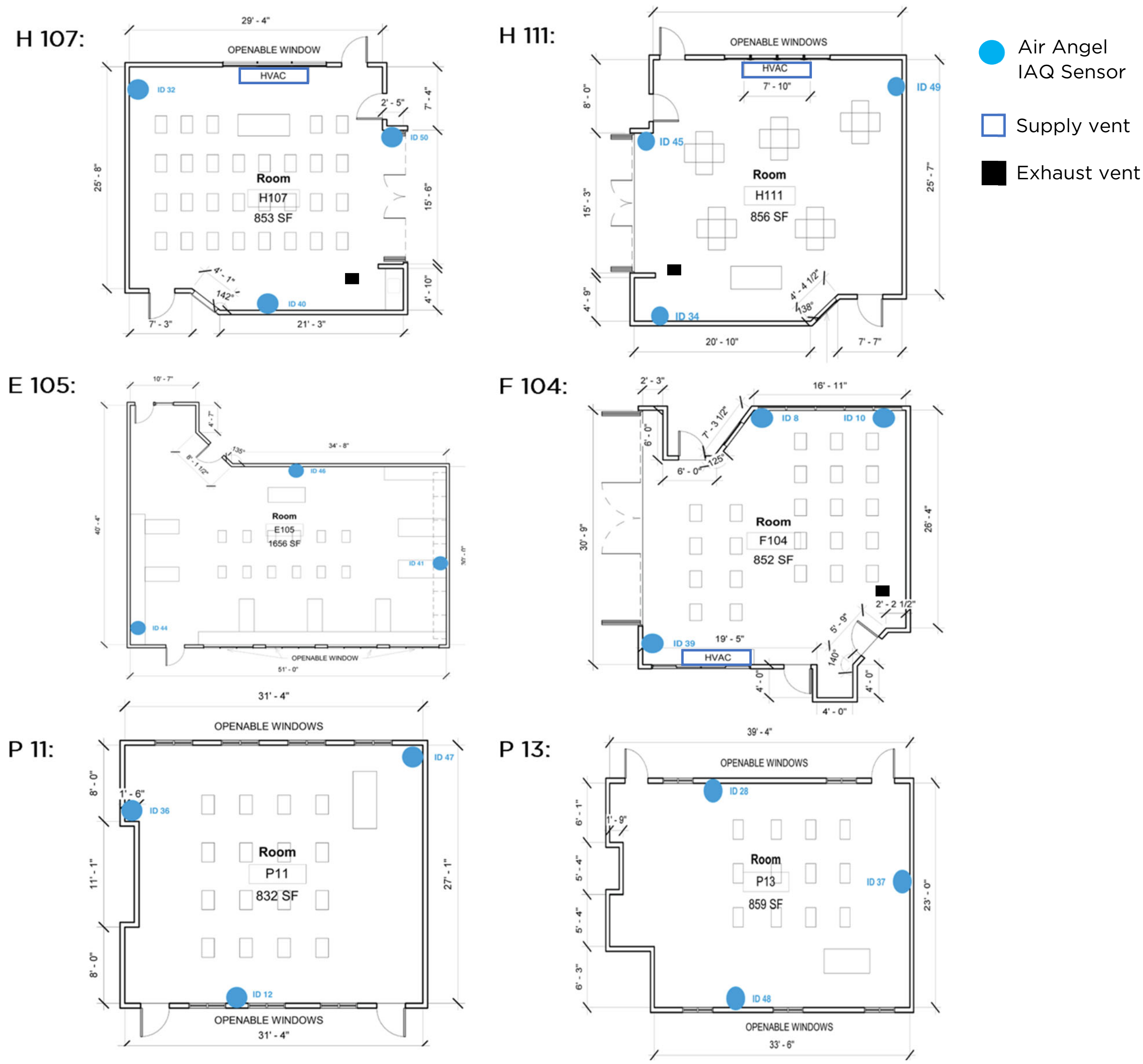
Seven indoor atmospheric attributes were measured by Air Angel Integrated Environmental Sensors (IES) in classrooms of typical size, ie, 800-1300 ft^2 as illustrated in *Figure 1*.

1. Temperature (F)
2. Relative Humidity (%)
3. Carbon Dioxide (ppm)
4. Particulate matter 2.5, 10 (ppm)
5. Total Volatile Organic Compound (Index)
6. Light (Lux)
7. Noise (dB)

Additional "spot sensors" - measuring one (1) function each and linked to the other data inputs through the shared data management system (DMS) - were deployed to enable a better understanding of how occupant behavior, HVAC operations, and air exchange with outside environments could affect indoor air quality. These spot sensors included the following types and brands:

1. Airthings: a third-party CO_2 sensor to validate the data measured by the Air Angel IES sensors.
2. Efento: door/window sensors to capture the opening/ closing of doors and windows.
3. Efento Temperature Sensors: to use air temperature as a proxy for HVAC operational status.
4. Purple Air: outdoor air quality sensor, used to compare indoor and outdoor CO_2 levels.
5. Ambient Weather station: outdoor humidity, temperature, wind speed, and direction.

Figure 1. Methodology – Six classroom configurations and sensor locations



Data was collected over four months in 2022. This data was analyzed and stored for future reference. To address unpredictable variations caused by human behavior and HVAC system operation, this study focused on a single, controlled room without operable windows. Computational Fluid Dynamics (CFD) modeling was introduced to provide a detailed analysis of the situation.

Classroom H111 was selected from the initial six profiles and served as the basis for the CFD model. This model included room dimensions (856 sqft for H111), door and window placements and sizes, as well as HVAC vent and exhaust locations. The simulation assumed a steady state, with individuals represented as 1.3m tall cylinders. Their exhalations emitted CO_2 at a constant rate of 40,000 ppm, equivalent to 3.29E-4 m^3/s. Twelve scenarios with thirty-one individuals each were modeled with sealed doors.

The HVAC system's efficacy was evaluated by varying the air changes per hour (ACH) at 3, 5, and 7 ACH. These ACH values were simulated at different mass injection velocities: low (0.9 m/s), medium (1.5 m/s), and high (2.0 m/s). CO_2, as part of the air exhaust, was simulated to exit the room through specific ventilation points. Different seating arrangements were used to mimic CO_2 emission patterns by individuals in each scenario run.

The 2021 sub award (Project #6107633) employed eight equations to compute boundary conditions for CFD, considering variables like fluid density (rho), vector velocities in three dimensions (u, v, and w), total energy (Etot), turbulent kinetic energy (k), turbulent dissipation rate (esp), and a conserved scalar (f). Notably, not all variables were solvable due to the nature of the equations. To improve accuracy, zero-order interpolation was used instead of linear interpolation, providing more precise results for CO_2 flow in low ACH scenarios.

In the CFD modeling, CO_2 levels were assessed across cross-sections along three-dimensional X, Y, and Z planes within the room. Five cross-sections were analyzed for each of the three planes. Figure 2 illustrates the strategy for selecting the locations of these cross-sections where CO_2 concentrations were examined.

Figure 2. A model simulation of a typical classroom with approximate planar cut locations. Five planer cuts were studied in each plane (X, Y, Z).

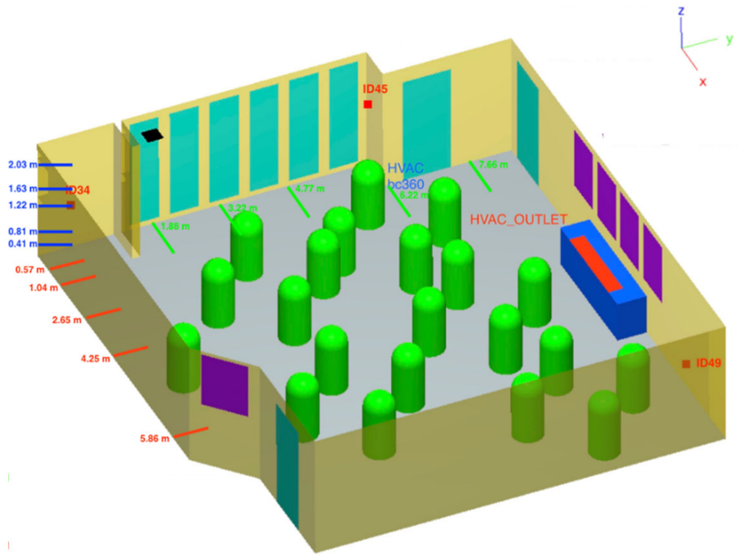
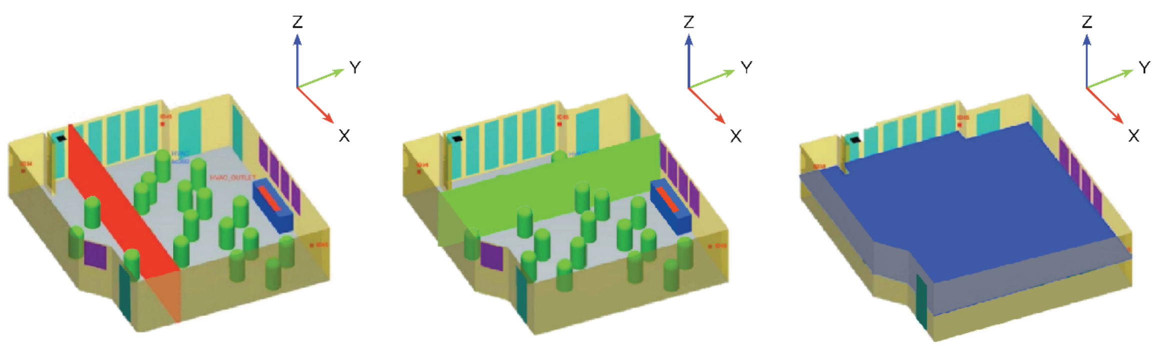


Figure 3. Modeled X, Y, Z cross-section planes of the classroom

X Cut	Y Cut	Z Cut
refers to a 2-D slice taken of the room along the X-axis	refers to a 2-D slice taken of the room along the Y-axis	refers to a 2-D slice taken of the room along the Z-axis



Twelve scenarios (S1 - S12) were created to investigate the impact of various factors on carbon dioxide levels across different sections of the classroom. Each scenario was specifically designed to address four key research questions:

1. The placement of the HVAC exhaust vent in relation to the supply vent.
2. The number of Air Changes per Hour (ACH).

Figure 4 provides an illustration of the vent locations concerning exhaust for each of these twelve scenarios.

Figure 4. Modeled vent location with respect to fixed exhaust location

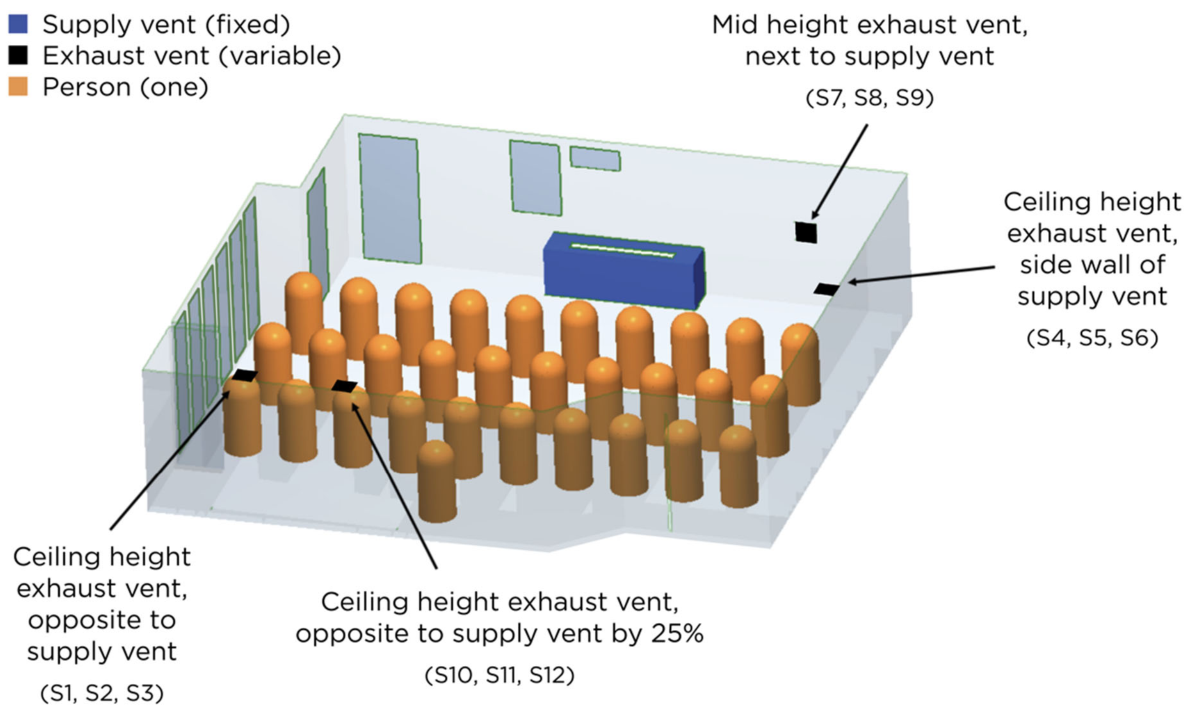


Table 1 summarizes the variables in each scenario (S).

Table 1. Variable setting for each scenario (S)

Scenario (S) No.	HVAC Exhaust Location	HVAC Exhaust Position	Air Changes per Hour (ACH)
1	Opposite to vent	At ceiling	3
2			5
3			7
4	On side wall	At ceiling	3
5			5
6			7
7	Next to vent	At mid-height	3
8			5
9			7
10	Opposite vent	25% over from center of ceiling	3
11			5
12			7

Note: The total number of occupants in all twelve scenarios was fixed at 31 occupants.

Data Analysis

Analysis of CFD model data revealed significant CO_2 concentration differences across the twelve scenarios, with a variation of approximately 99% (~ 3X), as shown in Figure 6.

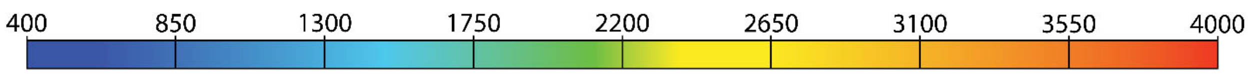
Difference in Avg. CO_2 in S1-12

$$\frac{|V_1 - V_2|}{\left[\frac{(V_1 + V_2)}{2}\right]} \times 100 = \frac{|842 - 2490|}{\left[\frac{(842 + 2490)}{2}\right]} \times 100 = \frac{|-1648|}{\left[\frac{3332}{2}\right]} \times 100 = \frac{1648}{1666} \times 100 = 0.989196$$

ASHRAE suggests indoor CO_2 levels in schools should be ≤1,000 ppm, but only two scenarios met this standard (16%). Most scenarios (83%) had CO_2 concentrations between 1,000-3,000 ppm, exceeding ASHRAE's threshold. Within this group, 20% had average CO_2 levels 200ppm above 1,000 ppm.

Note: The color scale representing the CO_2 concentration in the CFD models generated in subaward 2021 (Project #6107633) ranges from blue (400 ppm) to red (4,000 ppm).

Figure 5.1. Color scale used to represent CO_2 concentrations in CFD models.



For a more intuitive interpretation of the data and alignment with the ASHRAE CO_2 concentration standards, this report will use a different color spectrum ranging from green (<800 ppm) to red (>2,000 ppm) to purple (> 3500 ppm).

Figure *5.2*. Revised color scale used to represent CO_2 concentrations in this report.

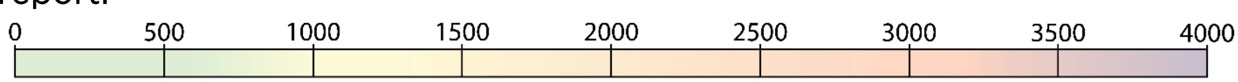
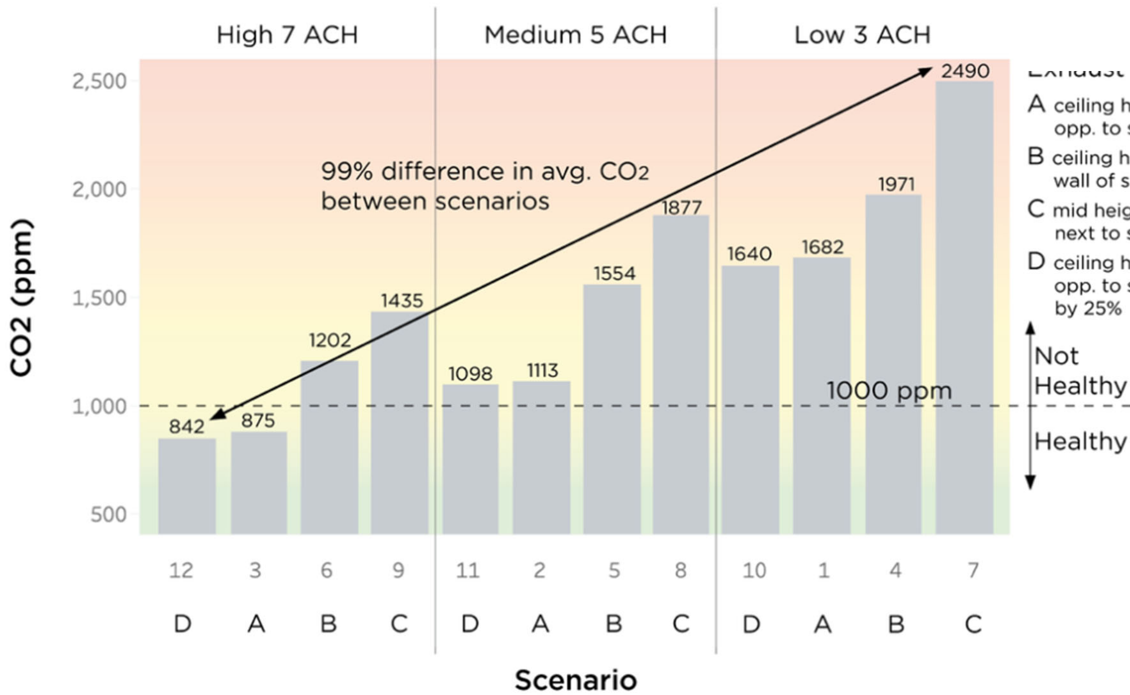


Figure 6. Variation in average Carbon Dioxide (CO_2) concentrations across 12 scenarios (S)



Deliverables

1. Task 1: Spatial Variability of Carbon Dioxide

Figure 7 demonstrates the spatial distribution of CO_2. In scenarios 2 and 11, where exhaust vents are positioned opposite to supply vents, the spatial variance of CO_2 levels remains within a narrower range, primarily staying below 2,000 ppm. Conversely, in scenarios 5 and 8, where exhaust vents are adjacent to supply vents, there is greater spatial variance, with CO_2 levels exceeding 2,000 ppm in some areas. Among these scenarios, scenario 8 exhibits the most significant spatial CO_2 variance, with the highest CO_2 levels, extending up to 5,500 ppm.

The variability of carbon dioxide dispersion is notably lower in scenarios 2 and 11, with a standard deviation below 400, while in scenario 5, it reaches 620, and in scenario 8, it peaks at 1108. In scenarios 2 and 11, the lower standard deviations indicate that CO_2 levels are relatively consistent across the space, which may suggest more effective ventilation and air distribution. In contrast, scenarios 5 and 8 exhibit higher variability, which can be associated with less effective ventilation.

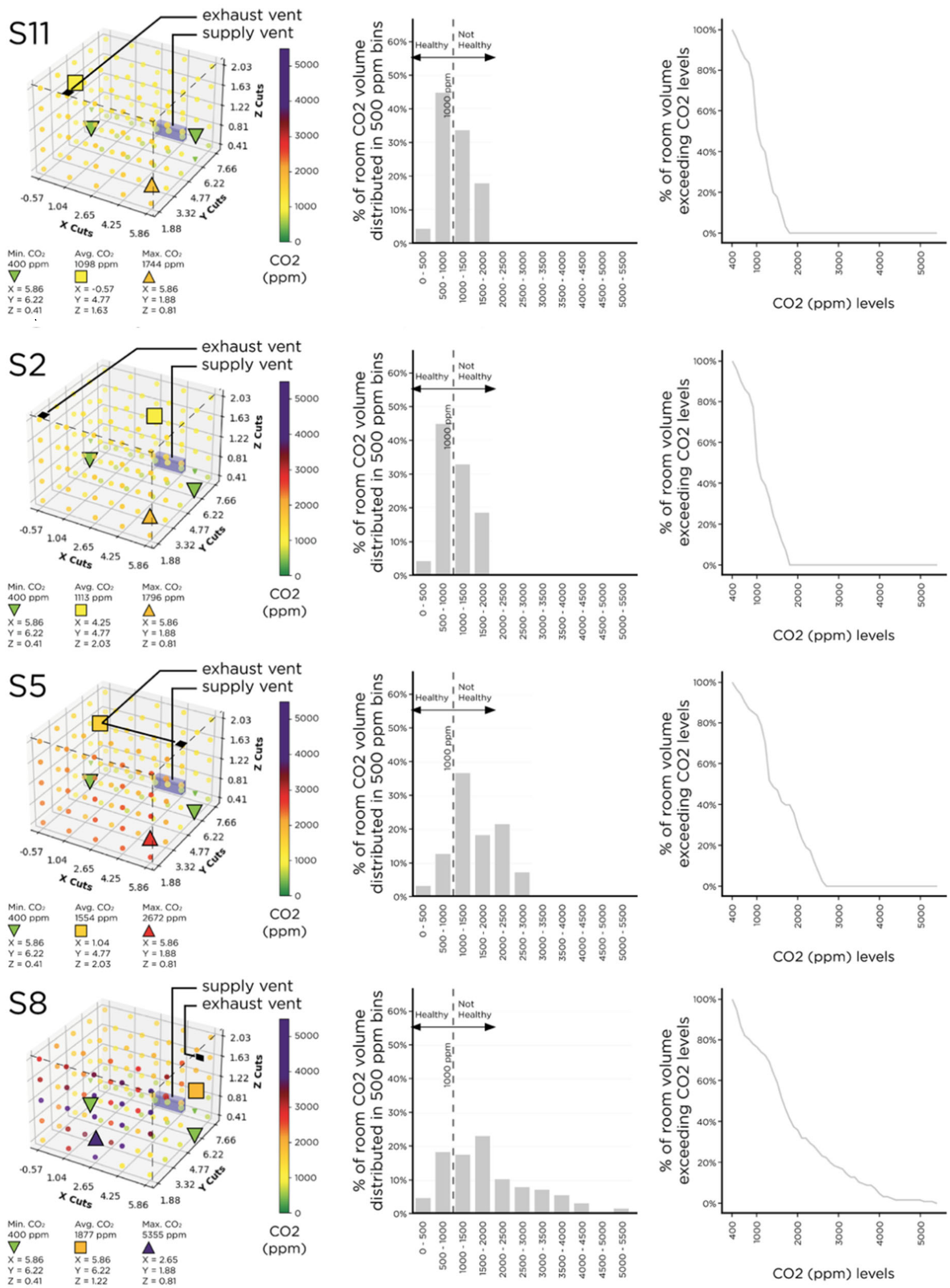
Additionally, the avg CO_2 in S 2 and 11 are closer to the field measured values with a difference under 84%. S 5 differs from field measurements by over 93% and S8 by over 107%. Since the CFD is modeled around classroom H111 where the exhaust vent is positioned on the opposite wall to the supply vent, similar to the conditions in S2 and 11, the minimal difference in average CO_2 between the field and models is validated.

Table 2 summarizes the statistics of scenarios 2, 5, 8 and 11.

Table 2 Statistics Summary of scenarios 2, 5, 8 and 11.

Scenario	Statistical Variance in the Scenario	Standard Deviation in the Scenario	Percent Difference between Scenario avg. and H107 avg.	Percent Difference between Scenario avg. and H111 avg.
S11	118838	345	82%	63%
S2	128119	358	83%	65%
S5	384681	620	108%	93%
S8	1227927	1108	121%	107%

Figure 7. Spatial Variance of CO_2 (ACH 5)



Task 2: Comparison of CFD data against measured data.

Figures 8.1 and 8.2 provide a comparison between sensor-measured data from classrooms H107 and H111 and the CFD-modeled carbon dioxide data. The scenarios are ordered in the increasing order of averages from S12 to S7 in Figure 8.1 and 8.2. The classrooms H107 and H111, were chosen for focus in this report because their supply and exhaust vent configurations are similar to each other, with the supply and exhaust vents located opposite to each other.

Scenarios 12, 11, 10, 1, 2, 3 were modeled with exhaust vents located opposite to the supply vents, making them more akin to the vent configuration of classrooms H111 and H107. This allows for a more direct comparison of CO_2 levels between the CFD models and actual classroom settings. The field-measured data averages for classrooms H107 and H111 closely match the data from scenarios 12 and 3, particularly when considering an Air Changes per Hour (ACH) rate of 7. This similarity suggests that scenarios 12 and 3 in the CFD models are more representative of the real-world ventilation conditions observed in the classrooms H107 and H111.

Table 3 summarizes the statistics of scenarios 12, 3, 11 and 2.

Table 3. Statistical and Comparative summary S1-12 and Field Measurements at H111 and H107.

Scenario	Statistical Variance in the Scenario	Standard Deviation in the Scenario	Percent Difference between Scenario avg. and H107 avg.	Percent Difference between Scenario avg. and H111 avg.
S12	72582	269	58%	39%
S3	79278	281	62%	42%
S11	118838	345	82%	63%
S2	128119	358	83%	65%
S6	394140	628	89%	71%
S9	461665	680	102%	86%
S5	384681	620	108%	93%
S10	213779	462	112%	97%
S1	248925	499	114%	99%
S8	1227927	1108	121%	107%
S4	593388	770	124%	110%
S7	601554	776	137%	125%

In the CFD-modeled scenarios, the levels of carbon dioxide (CO_2) are significantly higher than those observed and measured in real-world field conditions. The disparity between the field measurements and CFD simulated CO_2 may be due to various factors, including simplifications or assumptions made in the CFD modeling process that might not fully represent the complexity of the real environment. It is important to recognize and address these discrepancies to improve the accuracy and reliability of CFD models for predicting indoor CO_2 concentrations and air quality. This information underscores the need for further refinement and validation of CFD models to better align with real-world measurements and ensure that they can effectively guide decisions related to indoor air quality and ventilation systems.

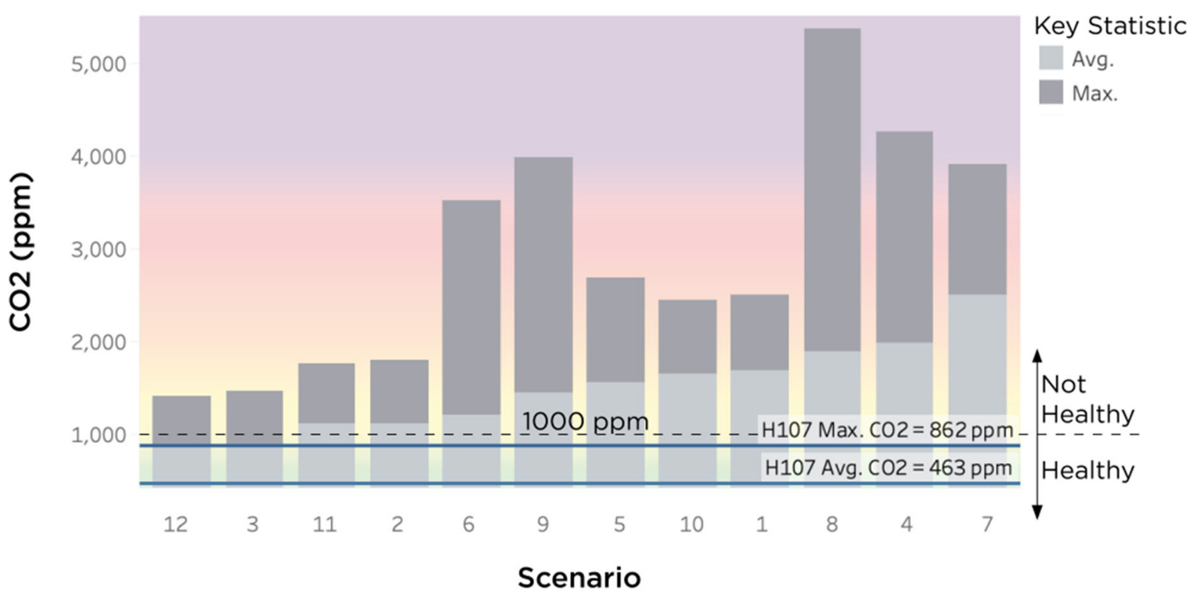
Figure 8.1. Spatial Variance of CO_2 – H107

1. How does modeled CO_2 compare against field measured CO_2?
2. Are there any scenarios with CO_2 concentrations close to field measured CO_2?

Data measured in H107 compared against modeled CO_2

Findings

Most realistic* scenario is **S12, 3, 11, 2**	Diff. btwn. H107 avg. and S12 avg. = **379 ppm**	Diff. btwn. H107 max and S12 max = **546 ppm**	Diff. btwn. H107 avg. and S8 avg. = **1414 ppm**	Diff. btwn. H107 max and S8 max = **4493 ppm**



Results

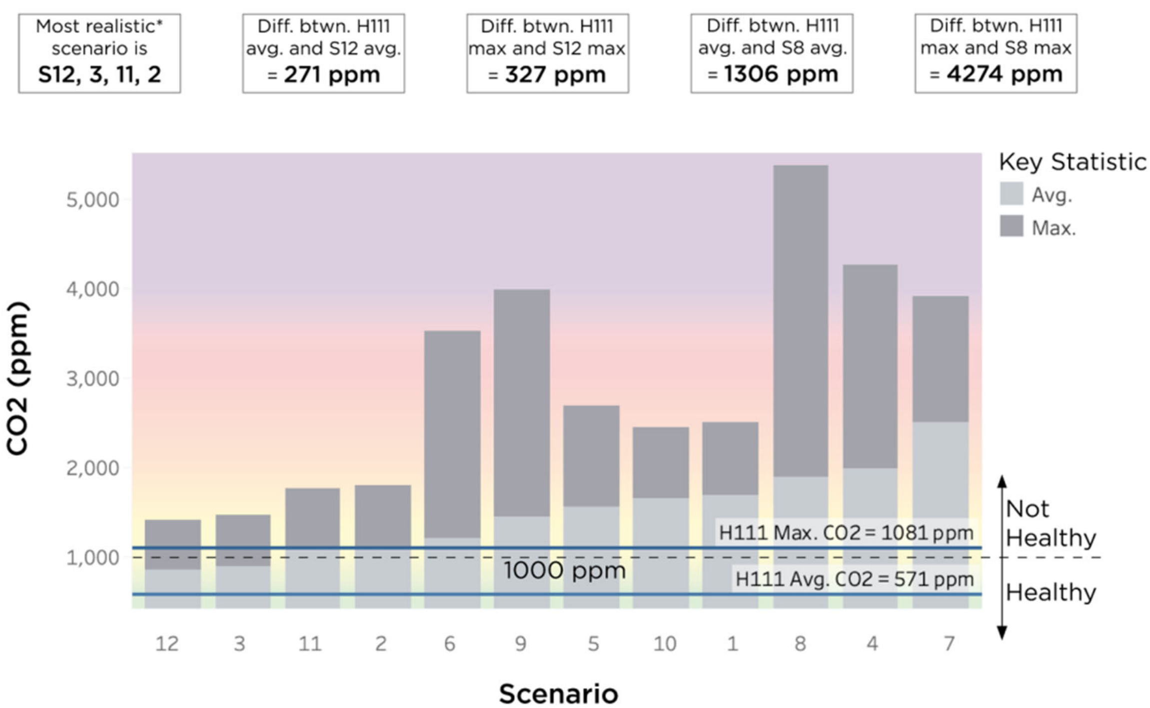
- CO_2 is higher in modeled scenarios compared to field measured CO_2, indicating that the variables that have been used to model the scenarios need to be verified

Figure 8.2. Spatial Variance of CO_2 – H111

1. How does modeled CO_2 compare against field measured CO_2?
2. Are there any scenarios with CO_2 concentrations close to field measured CO_2?

Data measured in H111 compared against modeled CO_2

Findings



Results

- CO_2 is higher in modeled scenarios compared to field measured CO_2, indicating that the variables that have been used to model the scenarios need to be verified

Task 3: Benchmarking against Key Performance Index

This report references building operation industry standards set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). This standard recommends maintaining CO_2 levels around 1,000 ppm as a general guideline for acceptable indoor air quality.

Task 4: Qualitative recommendations

Building upon the findings of this study, there are several avenues for future research that could further enhance our understanding of indoor air quality management and energy efficiency. The following areas warrant exploration:

1. Enhancing the realism of Computational Fluid Dynamics (CFD) models for more accurate indoor air quality assessments.
2. In-depth analysis of the relationship between supply vent – exhaust vent positioning to optimize indoor air quality while conserving energy.
3. Development of energy consumption prediction models to minimize operational costs and environmental impact.
4. Investigation of the integration of multiple variables, including additional air quality factors, occupancy levels, outdoor air quality, and building characteristics, for improved indoor air quality management strategies.

By addressing these research areas, we can advance our knowledge in indoor air quality management, energy efficiency, and sustainable architecture. This will contribute to creating healthier and more environmentally friendly built environments for the benefit of individuals and institutions.

References

1. ASHRAE Standards for healthy air quality in classrooms

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