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OPTIMIZING CO2 SENSOR PLACEMENT IN 41 COOPER CLASSROOMS VIA CFD AND SENSOR DATA ANALYTICS

S Khan, P Sklavounos, E Taglia

ABSTRACT

Optimal indoor air quality is essential for maintaining the health and cognitive performance of students. 41 Cooper Square, Room 506, was selected to investigate the effectiveness of CO2 sensor placement for ventilation control since it has the highest student capacity of about 40 people at a given time. This study aims to optimize sensor positioning using Computational Fluid Dynamics (CFD) simulations, supported by empirical data from two HOBO MX sensors and a Particles Plus 8302 Particle Counter, whose specifications are in Appendix A. The results indicate that the most effective sensor location is centrally located, on the left side of the room when facing the same way as the students (shown in Figure 1). Additionally, the study acknowledges that although CO2 sensors are intended to transmit CO2 ppm readings to the building management system (BMS) for ventilation regulation, prevalent sensor malfunctions have necessitated reliance on temperature as an indicator for ventilation adequacy in the 41 cooper Square Building. .

INTRODUCTION

Health Effects due to High CO2 Levels

Elevated carbon dioxide (CO2) levels can adversely affect cognitive performance and health, making it essential to monitor and control these levels effectively. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) recommends maintaining indoor CO2 levels below 1,000 parts per million (PPM) to ensure a healthy and comfortable environment [1]. For reference, the average outdoor CO2 levels are typically around 400 PPM. When indoor CO2 concentrations exceed recommended levels, occupants can experience various symptoms such as drowsiness, headaches, and a decrease in cognitive functions.

More specifically, a study on indoor CO2 pollutant examined how different levels of CO2 affect human cognitive abilities and work performance. The authors exposed 22 participants to CO2 concentrations of 600, 1,000, and 2,500 ppm in a simulated office environment and assessed their decision-making skills using a computerized test. They found that compared to 600 ppm, at 1,000 ppm CO2, performance decreased by 11-23% on six out of nine scales, and at 2,500 ppm, performance decreased by 44-94% on seven out of nine scales. These results indicate that CO2 may have direct and negative impacts on human mental functions and productivity [2]. This finding of decreased performance due to higher Co2 levels is consistent with other studies of similar nature.

Therefore, there is a motivation to investigate whether the highest capacity room on average at 41 Cooper Square, being Room 506, has accurate readings of the volumetric bulk average CO2 concentration levels so as to best regulate the needed ventilation to mitigate these unwanted effects. To better visualize what Room 506's layout is like, refer to Figure 1.

CO2 Distribution Hypothesis

In order to optimize the placement of the CO2 sensor in room 506, our hypothesis is that the sensor will measure the most accurate volumetric bulk average CO2 levels if placed in the middle left of the room. This is based on our own thought experiment where the CO2 distribution in a room could be likened to the center of gravity in a physical object, such as a pencil.Just as the mass of a pencil is evenly distributed, resulting in a center of gravity at its midpoint, the CO2 in a room, when in a steady state, would similarly be evenly distributed and would have the most representative average for a sample to be taken. The diffusers and exhaust fans would be removed from the mass as there is air being extracted at these points, therefore causing the centre of mass to have moved to the centre left. The discrepancies with this theory are that steady-state is not achievable with fans and diffusers running, especially when variable in a non-idealized case. Also, there are many parameters that affect gas distribution physics, like capacity, where gas distribution in itself is more about diffu-

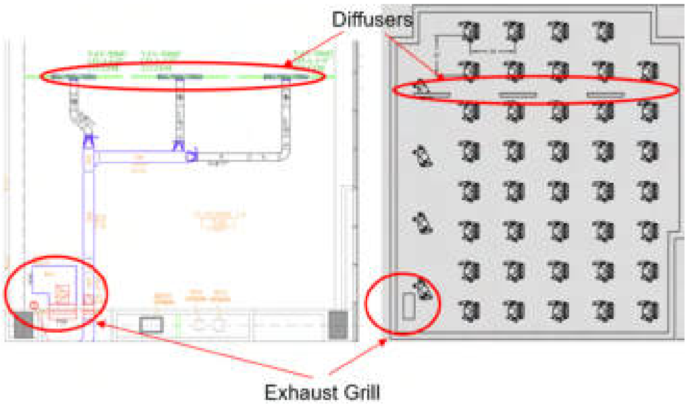

FIGURE 1. Room 506 Geometry

sion and flow dynamics rather than a 'static' center.

Objectives and Design Constraints

To properly frame the problem, we've delineated below are our objectives and design constraints:

In pursuit of accurate and relevant data, we will map the spatial relationship between CO2 sensor locations and the density of room occupants. Our data collection efforts will be strategically timed to coincide with regular occupancy patterns, with a focus on two-hour classroom sessions that will allow us to track CO2 levels as they fluctuate with occupancy. To ensure precision, we will record notes to our data with timestamps that correspond to shifts in occupancy or of the sensor, or any external factor.

To capture nuanced changes in CO2 levels that may inform sensor placement, we will engage in high-frequency data logging, allowing us to note subtle variances over shorter intervals.

Regarding design constraints, our attention will center on classrooms that not only experience substantial occupancy, but also share similar design characteristics. This approach ensures a homogeneous dataset conducive to comparison. Operation of CO2 sensors will be confined to periods of classroom activity, providing a true reflection of occupied states and eliminating data anomalies from times when the classrooms are empty. The consistency of our data will be further assured by employing the same model of CO2 sensors throughout the various environments, with the same settings.

The installation of sensors and the subsequent data collection will be executed with minimal intrusion, preserving the integrity of the classroom dynamics. We are committed to upholding privacy laws, guaranteeing that no personal data is captured during our research. Lastly, while we acknowledge the technical limitations of sensor sampling rates, adjustments will be made to optimize the frequency of data capture within the bounds of our equipment capabilities.

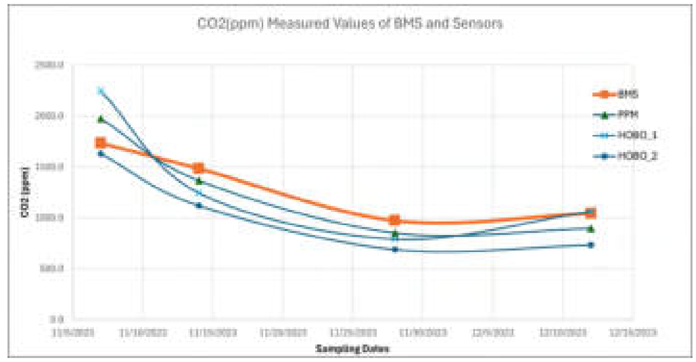

FIGURE 2. CO2 (PPM) Sensor Data

TABLE 1. Sensors Error To Most Average CO2 PPM Value

Date	BMS (ppm)	PPM (ppm)	Hobo1 (ppm)	Hobo2 (ppm)	Avg (avg. ppm)	Error (%)
11/7/23	1734.3	1975.1	2247.1	1629.4	1896.4	4.1
11/14/23	1484.6	1365.6	1244.9	1119.6	1303.7	4.5
11/28/23	972.0	850.6	791.8	689.0	825.8	3.0
12/12/23	1042.8	894.4	1062.7	733.2	933.3	4.2

METHODOLOGY

Experimental Methodology

Before each data recording session, all sensors are taken outdoors to be calibrated for at least ten minutes. Once calibrated, they were systematically placed around Room 506 for a three hour class that typically had a capacity of 40 individuals. Major changes in capacity were noted, as well as any external factors such as groupings around the sensors. This data was extracted once the sampling time expired, and this procedure was repeated with different locations throughout the room, giving a total of four different readings with the BMS sensor over a range of four dates as plotted in Figure 2.

The collected data from these four points were then averaged to determine a single, most representative CO2 concentration value for the entire classroom. This average serves as a benchmark against which the individual readings at each point are compared. To quantify the deviation of each point from the average, we calculated the percent error between the mean CO2 concentration and the readings from each location and tabulated in Table 1.

As is evident, the three percent error recorded on 11/28/23, which was the PPM CO2 sensor as it differed the least by around 25 ppm is found to be located in back left. This location is pinpointed in Figure 3.

Computational Simulation Methodology

The simulation of gas flow in Room 506 was conducted using Solidworks Fluid Flow Simulations.This was chosen as opposed to Ansys Fluent as a challenge given that we were not as

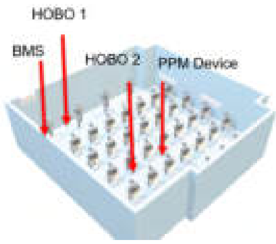

FIGURE 3. Location of Sensors in Room 506 the on 11/28/2023 case

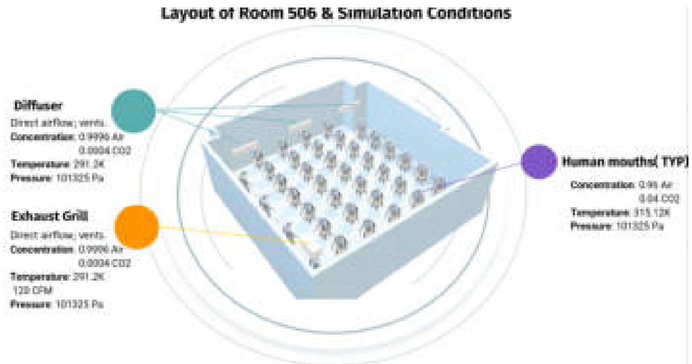

FIGURE 4. Simulation setup for inlet/outlet faces

familiar with it. The major difference between the two software is that for Solidworks, it automatically detects the computational domain, which you can then manually adjust, whereas for Ansys the fluid domain needs to be explicitly modelled and meshed, with the students and professors boolean-cut from it, thus making it a cavity. Meshing is also slightly different - unlike Ansys where each face that is to be a named selection for initial and boundary conditions is explicitly meshed, Solidworks assumes all but the fluid to be a face and so only diligently meshes the fluid by dissecting it into four quadrants. Depending on the choice of mesh fineness, these four quadrants are broken down into four more quadrants in our case in each direction. This mesh is shown in Figure 5.

Once this was done, the exhaust grill was setup as a fan with the average CFM for that day, being 120 CFM, while the diffusers and the mouth openings were set as environmental openings. This allowed for air to be recirculated both ways, thus best simulating breathing. Access to the Solidworks HVAC module would have meant easier initial and boundary conditions, but the temperatures, initial pressures, and concentrations of gases were set accordingly in Figure 4. The physical time for the simulation was set to the 7200 seconds, with a manual time step set to 1s to speed up computational time. To ensure convergence and mitigate any diverging errors, the time step factory of safety was set to 0.9 that reflects a conservative approach for the solver. For reference, the automatic time step that Solidworks would prescribe would be in the thousandths, meaning that the simulation time would be in the magnitude of days to solve.

The dimensions of the CAD models made in Onshape are shown in Figure 6 and Figure 7, which are the old and new CAD iterations, respectively. The original goal was to replace crude models of the humans and chairs with more realistic models, but this came at the detriment of almost three times the amount of meshing elements, meaning a greater solve time. Given that from earlier runs it was seen that these more realistic bodies had negligible impacts on gaseous flow, blocks with mouths were used instead. The size of the mouth was determined by averaging between studies done on the normal mouth opening in an adult Chinese and Indian population due to their large data sets [3] [4].

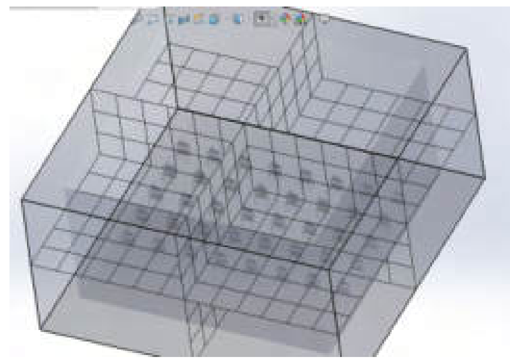

FIGURE 5. Solidwork's Quadrant Meshing Displayed

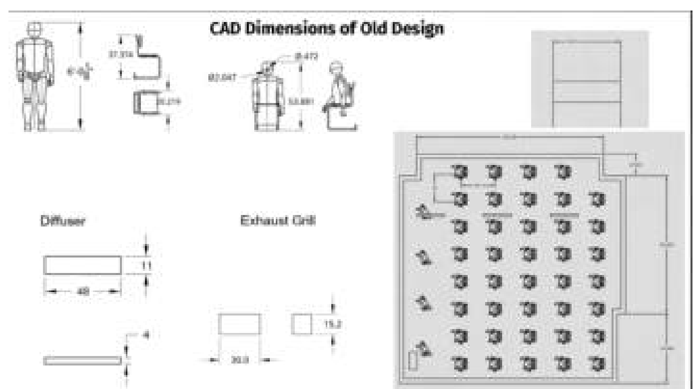

FIGURE 6. Older iteration, realistic humans with chairs CAD

These are some of the notable assumptions made in the preprocessing of the Fluid Flow Simulation:

- **Humidity is non-existent**, not parameter of interest. Bone Dry Air used.
- **Gravity** is 9.81 m/s^2
- **Steady State Conditions:**Flow field does not change with time, even though 7200 seconds is most probably not steady

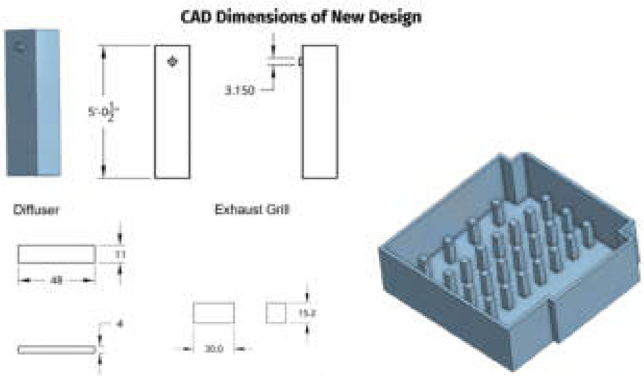

FIGURE 7. New, Simplified Human and Chair CAD

state.

- **Incompressible Flow:** Air density is assumed to be constant.
- **Homogenous Air Mixture:**No possibility for CO2 pockets when leaving prescribed air inlets.
- **Constant Physical Properties:** Viscosity and diffusivity are assumed constant throughout the simulation.
- **Constant Locations and Rates of Airflow into/out of people and into/out of room:** Voids variability that occurs in real life scenarios.
- **All doors were closed in reality**, so they were modelled as such.

Once the convergence criteria was set for each of the 'goals' being mainly the mass fraction of air and mass fraction of carbon dioxide, as well as the bulk average of these, the simulation was run. When trying to find the average CO2 concentration over time in a room using SolidWorks, the choice between 'average' and 'bulk average' depends on the specific objective. The average carbon dioxide concentration is the arithmetic mean , representing the the CO2 concentration averaged uniformly across the entire room, which is ideal for assessing mean concentration as if CO2 were evenly distributed. However, as this is not the case, the bulk average is more suited to the objective given that it accounts for CO2 density variations, giving more weight to areas with higher CO2 density and so it is useful for considering factors like airflow, CO2 sources, and the room geometry. Figure 8 outlines the residual plot of each of the global goals shown.A residual plot is a graph that shows the difference between the actual values and the predicted values of a model. It is used to assess the quality and accuracy of the model, as well as to identify any potential outliers or patterns. In this case, the residual plot shows the difference between the actual and predicted values of the mass fraction of air, mass fraction of carbon dioxide,the bulk average, etc. which are the global goals of the fluid flow simulation. The plot shows that the residuals are stabilizing over time, indicating that the model is converging to a solution. Without

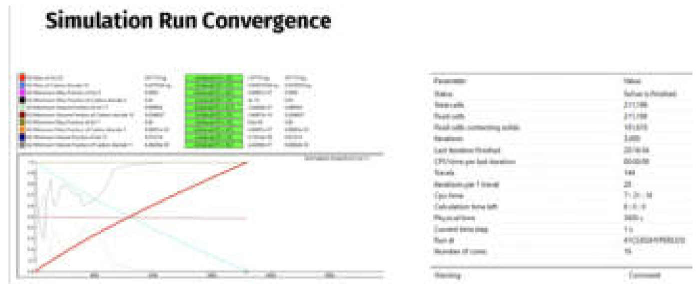

FIGURE 8. Convergence Criteria Being Met for the first 3600s

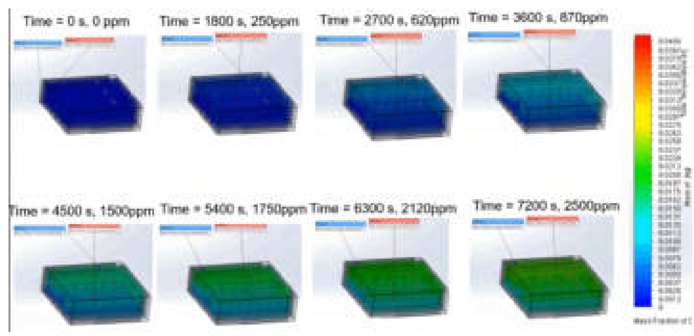

FIGURE 9. Carbon Dioxide Concentration Over Time in Room 506

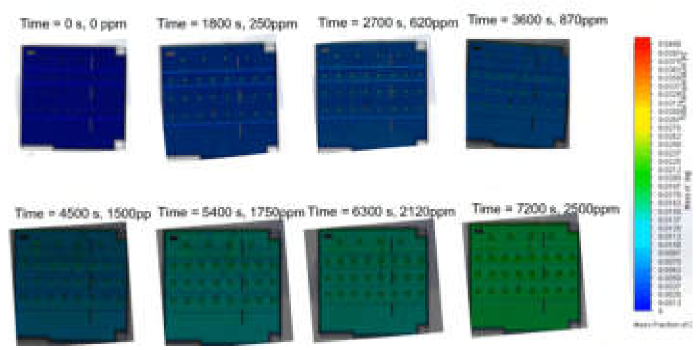

FIGURE 10. Top View of Room 506 Contour Plot

the use of residuals and a monitor plot, it is challenging to determine whether the solution yielded by the software is accurate and precise for use.

Cut plots for each plane help visualize the contour plots in a 3D space, and transient explorer was used to show the carbon dioxide concentration over the physical time of the simulation in Figure 9. Figure 10 is a top-down view of Room 506 to understand how carbon dioxide disperses across the room, while Figure 9 shows altitude as well.

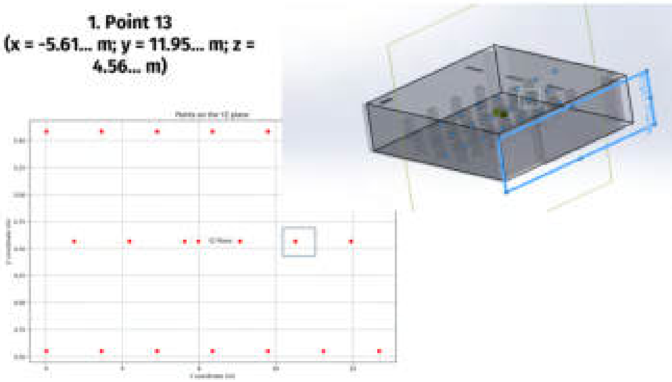

FIGURE 11. Location of Point 13 on the Plane Shown

Post-Processing Data Analysis

To determine which location is the most optimal, which is defined as being the closest representation of the room's volumetric bulk average carbon dioxide concentration, three planes with 20 probes each of varying vertical and horizontal height are placed depth-wise. These will report, over time, what the carbon dioxide concentrations are, which is then compared to the overall room's bulk average carbon dioxide concentration. Whichever probe is closest in value indicates the best position for a sensor to be, or for pre-existing HVAC systems, what type of offset the BMS needs to have for its measurements to account for its position. This was done by leveraging python and excel scripts and functions to reformat the data, use functions to locate the best value and the probe number, and then count how many times each probe was the closest across the 7200 seconds.

The figures below, namely Figure 11, Figure 12, and Figure 13, outline where on the plane the best three coordinates where in terms of being most accurate to Room 506's overall CO2 concentration (volumetric bulk average). As is seen , the middle plane is the top plane for the two best probes, particularly the middle plane and middle height. This is close to the hypothesis, but it has to be further tested for a conclusion to be drawn.

To understand the relationship between each plane and the probes themselves, as well as how significant tehy are by how much they deviate, standard deviations are used. If we refer to Figures 14 and 15, Figure 14 illustrates the standard deviations calculated from the 20 probes on each plane, whereas Figure 15 represents the standard deviations when all points from all planes are compared against each other over time. It is evident that over time, this difference is minimized as steady state is achieved. In reality, this would not converge in this way as air ventilation rates are not constant and vary. In this idealized case, it can be seen that the importance lies in the choice of the plane, rather than the altitude of the points.

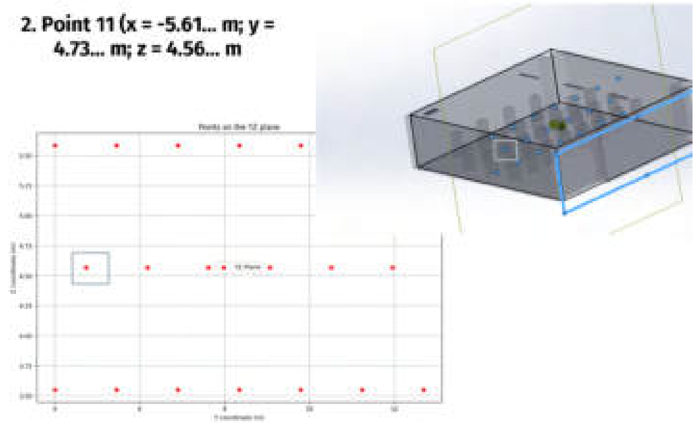

FIGURE 12. Location of Point 11 on the Plane Shown

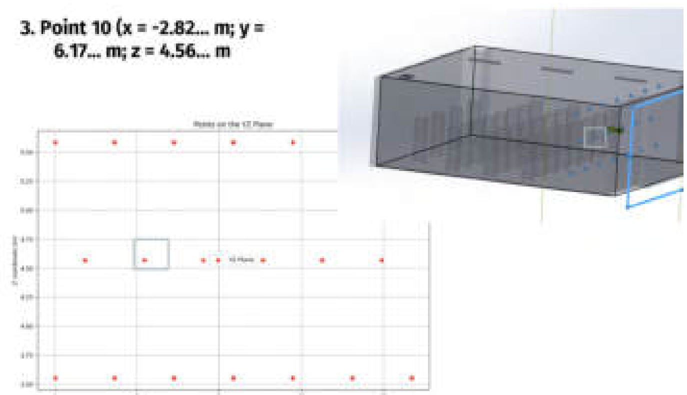

FIGURE 13. Location of Point 10 on the Plane Shown

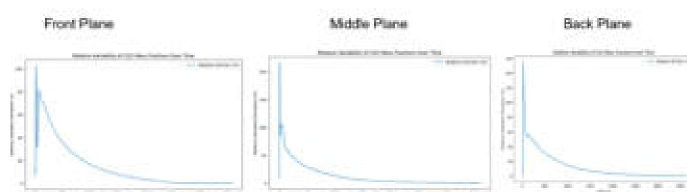

FIGURE 14. Relative Standard Deviation Percentage for each Plane's points over time

Nonetheless, when the plane is the middle one, and the points on that plane are chosen, it is best optimized. For the most optimized position, according to the computational simulations, the middle-right was the best point, as shown by Figure 11, followed by the middle left.

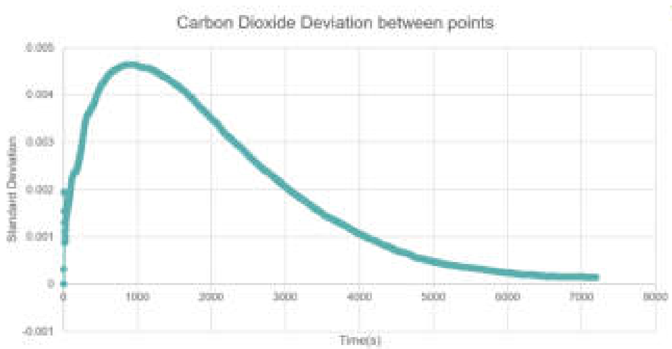

FIGURE 15. All Probes From All Planes Compared to Each Other

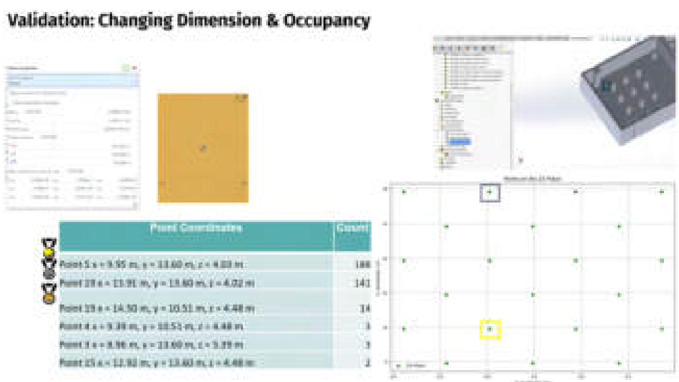

FIGURE 16. New Test Case with Different Room Geometry and Capacity of Room 427

Testing the Geometric Centre Hypothesis

These empirical and simulation results point to some truth for the hypothesis, but to truly confirm and accept this as fact, a different geometry will be simulated to see if the most precise sensor was near its centre of gravity. Room 406 was simulated, as shown in Figure 16, where the best probes were in the same plane, but in the back plane, as opposed to the centre of gravity shown. This indicates that geometry is not the only parameter that determines the coordinate closest to the volumetric bulk average point - it is also dependent on occupancy as well as other parameters that can be investigated as a separate study. Therefore, even though i the hypothesis was found out to be true for Room 506, its reasoning was disproved by testing out Room 427.

DISCUSSION AND RECOMMENDATIONS

As seen in the CO2 plots for the BMS, the CO2 measured in the room was consistently above the healthy air range as indicated by the red line. The CO2 averages were 1734.33, 1482.56, 972, and 1042.78 ppm for November 7, November 14, November 28, and December 12, outlined in Table 1.The Particle Plus Monitor and HOBO sensors also appeared to follow the same pattern. They were at levels above or near the maximum allowable limit for healthy air especially given the high occupancy in the room.

TABLE 2. STANDARDS FOR AIR QUALITY [5] [6]

	PM2.5 ($\mu g/m^3$)	TVOCs (ppb)	CO2 (ppm)
Healthy Range	< 14	< 400	400 - 1000

To study further why the CO2 levels were so high in room 506, the BMS CFM supply to the room was also studied. The average CFM supply to the room for each day of testing is listed below in Table 1. As seen from this table, the cfm reported was low for the first half of testing while for the other two half it was a reasonable supply given the occupancy. Since the BMS is temperature based it is possible that there was previous occupancy on November 28 and December 12 that caused the CFM to increase and continue supplying for the Senior Mechanical Engineering Capstone class. However, the CO2 levels were still not optimal for November 28 and December 12 even with the high cfm supply. This indicated that the BMS supply needed to be adjusted even further to accommodate the high occupancy. This was notified to facilities and changes are expected to be made to the minimum cfm supply.

In terms of placement, the average CO2 level of each device was compared to the BMS CO2 measured data for the according day. From these averages and these standard deviations, it can be revealed that the middle left portion of the room is most in line with the BMS CO2 measurement.

Additionally, CO2 levels were measured outside using the Particle Plus Monitor and two HOBO MX devices. Initially all three sensors measure high CO2 levels, but they reached steady state after a few minutes. The HOBO Logger 1 settled around 500ppm, the Particles Plus Monitor settled around 400 ppm, and the HOBO Logger 2 settled around 300 ppm as seen in Figure 17. The offset of the HOBO devices from the Particle Plus Monitor was adjusted to become Figure 18 by using equations and techniques discussed in Appendix A. The adjusted device equations were applied when the HOBO devices were in use for a more accurate comparison of data.

There are some limitations that must be noted about the data collection in terms of the sensors and the procedure for data collection. While multiple sensors were used to verify and cross check CO2 levels, all the sensors have not been factory calibrated in a few years so the data may be skewed.

With regards to the simulations, breathing patterns and simulating them, as well as flow-freezing time step techniques are worthwhile of discussion. To simulate breathing at first, a sinusoidal function was used as the profile for the inlet conditions from the mouths to the room as this would mean that there would be exhale, and then when the value was negative there would be inhale. However, when implemented, the residuals would spike and would not converge, given the constant and rapid polarisation of the values. To combat this, and to ensure there is some inhaling as well as exhaling, the mouths were modelled as environmental openings with body heat, and exhausted air concentrations. As for flow-freezing, it is a solver option that can be used to speed up the calculation of steady-state and transient problems. It works by freezing the values of all flow parameters, except for fluid and solid temperatures and fluid substance concentrations, at a certain point in the simulation. This allows the solver to focus on the parameters that usually converge more slowly and require more CPU time.However, flow-freezing also has some drawbacks and limitations. One of them is that it can affect the convergence and accuracy of the solution, especially for problems where convection is important. By freezing the flow parameters, the solver ignores the convective terms in the energy equation, which can result in unrealistic or unstable temperature distributions. This can also cause the solver to terminate abnormally, something that was common and so was avoided for this simulation.

CONCLUSIONS

This study aimed to optimize the placement of CO2 sensors in Room 506 at 41 Cooper Square by using CFD simulations and experimental sensor data to determine the optimal sensor location. Both methods identified the central left side of the room (from the students' perspective) as the most effective location. The empirical data confirmed this, and the CFD simulations ranked three points in the middle plane as the top locations, with two on the left and one on the right. The left side was deemed the best overall location due to its corroboration from the experimental data. With this finding, the BMS would retrieve carbon dioxide concentrations readings that were most precise in order to properly ventilate the classroom, as it is not currently doing so. It is important to bring these concentrations down as they negatively impact productivity and performance, as well as health.

Practical Applications

The study's findings have direct implications for enhancing building energy efficiency, particularly through the optimization of HVAC systems. By utilizing the insights gained on CO2 level monitoring and distribution, HVAC systems can be designed and operated more effectively, ensuring efficient air circulation, while maintaining healthy indoor air quality. This optimization is not only crucial for occupant comfort, but also plays a vital role in energy management. Buildings can achieve notable energy savings by adjusting ventilation in response to accurately monitored CO2 levels, thereby balancing occupant comfort with energy conservation.

Further, the integration of these findings with building automation systems can lead to more sophisticated and responsive air quality regulation. This is especially relevant for the optimization of Variable Air Volume (VAV) systems, where ventilation can be modulated based on real-time sensor data, enhancing both energy efficiency and indoor air quality. Additionally, adhering to and surpassing regulatory standards and guidelines set by bodies, like ASHRAE, becomes more feasible with the application of these insights. Such compliance not only ensures a healthier indoor environment but also positions the building as a model of energy-efficient and environmentally responsible design.

RECOMMENDATIONS

The next step involves integrating the average CO2 concentration and percent error calculations into the Building Management System (BMS). The BMS currently records CO2 levels at a fixed point in the room, which may not fully represent the overall air quality. To enhance the accuracy of the BMS readings, the development of an offset multiplier based on the calculated average and percent errors is needed. This multiplier will adjust the BMS's single-point reading to more accurately reflect the bulk average CO2 concentration in the room. By incorporating this offset, the BMS can make more informed decisions regarding airflow and ventilation adjustments, thereby optimizing the indoor air quality. This approach not only ensures a healthier environment for occupants but also enhances the efficiency of the building's HVAC system, leading to potential energy savings and improved environmental sustainability.This is more feasible than moving the sensor, which is pre-existing and wired in place.

As for recommendations with regard to this study, in an ideal scenario where time is not a constraint, extending the simulation duration beyond 7200 seconds would be preferable. Such an extension would allow for a comprehensive assessment of whether a steady state can be achieved within the simulated environment. Taking more sensor data for a clearer indication would also be advised and would bolster this study in credibility. Additionally, exploring simulations with varying cases of geometries and capacities beyond those explored is crucial to fully validate the hypothesis regarding the center of gravity and its impact on airflow dynamics.

To address the challenges posed by Solidworks when setting initial conditions, employing environmental openings has proven to be the most straightforward solution. This method circumvents common errors and streamlines the setup process. Moreover, the availability of a Solidworks HVAC module would significantly simplify the simulation of ventilation systems. Its plug-and-play capability could substantially reduce the learning curve for setting up the simulation.

Looking forward, it could be beneficial for future iterations of this work to include predictive models that estimate the outcomes of ventilation improvements. Such predictions could provide valuable insights for optimizing air quality and comfort within classroom settings.

Lastly, it should be anticipated that exporting data to Excel may be as time-consuming as the simulation itself. The process of preparing an Excel sheet with data for each plane and each volume parameter set aligns with the simulation's physical time—evidenced by the fact that it took 7200 seconds to export the data per plane. Therefore, adequate time should be allocated for data management to ensure a smooth and efficient workflow.

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A Appendix A: Sensor Specifications

TABLE 3. HOBO MX CO2 Logger Specifications

Specification	Value
Range	0 to 5,000 ppm
Accuracy	±50 ppm ±5% of reading at 25°C (77°F), less than 90% RH (non-condensing)
Warm-up Time	15 seconds
Calibration	Auto or manual to 400 ppm
Non-linearity	<1% of FS
Pressure Dependence	0.13% of reading per mm Hg (corrected via user input for elevation)
Operating Pressure Range	950 to 1,050 mbar (use Altitude Compensation for outside of this range)
Compensated Pressure Range	-305 to 5,486 m (-1,000 to 18,000 ft)
Sensing Method	Non-dispersive infrared (NDIR) absorption
Response Time (CO2)	1 minute to 90% in airflow of 1 m/s (2.2 mph)

TABLE 4. Particles Plus Monitor Handheld 8302-AQM Monitor Specifications

Specification	Value
Size Range	0.3 to 25.0 μm
Size Channels	Factory calibrated at 0.3, 0.5, 1.0, 2.5, 5.0, 10.0 μm variable binning
Flow Rates	2.83 LPM (0.1 CFM)
Concentration Limit	30,000,000 Particles/ft^3 @ 10% coincidence loss
Battery Run Time	10 hours
Light Source	Long life laser diode
Counting Efficiency	50% @ 0.5 μm; 100% for particles >0.75 μm per JIS
Zero Count	<1 count / 60 minutes (<1 particles / 6 ft^3). No fault count subtraction.

Appendix B: Calibration of Sensors

When calibrated to outside air, the HOBO sensors which overshoot or undershoot can be modelled and corrected to be closer to the more accurate Particles Plus Monitor Sensor. Figure 17 shows the raw sensors calibration curves, while Figure 18 is the adjustment of the HOBO sensors. To do this, a linear regression script in python was used, as well as interpolation to get in-between values as they all had different sampling frequencies. The equations for this adjustment that were yielded were:

- Adjusted $CO2_{HOBO1} = 0.868 \cdot CO2_{HOBO1} - 62.21$
- Adjusted $CO2_{HOBO2} = 1.196 \cdot CO2_{HOBO2} + 26.57$

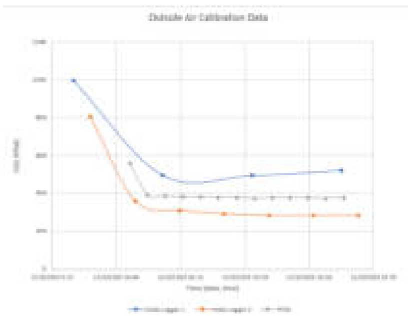

FIGURE 17. Outside Air Calibration Curves

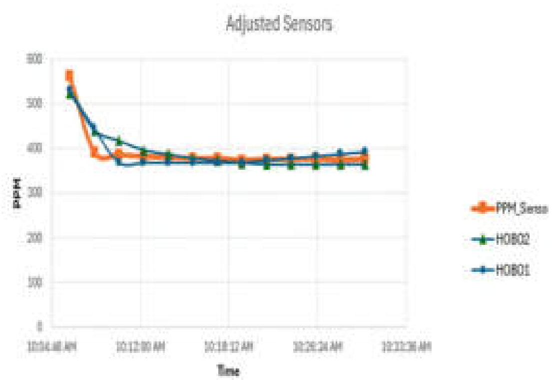

FIGURE 18. Adjusted HOBO Sensors using Equations

Appendix C: Sensor Data

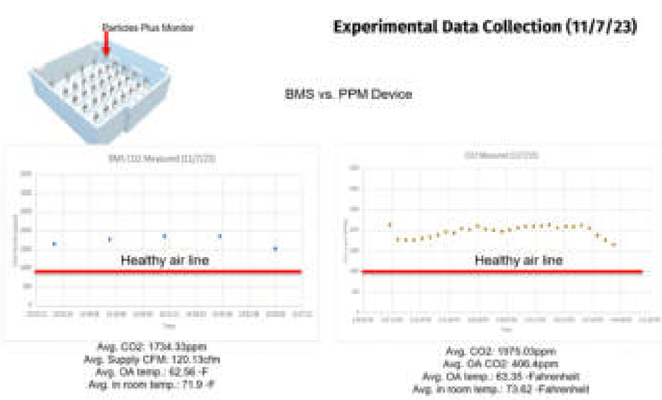

FIGURE 19. 11/7/23 Data

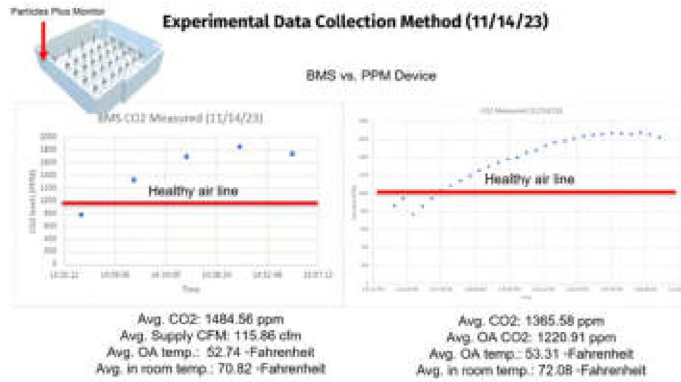

FIGURE 20. 11/14/23 Data

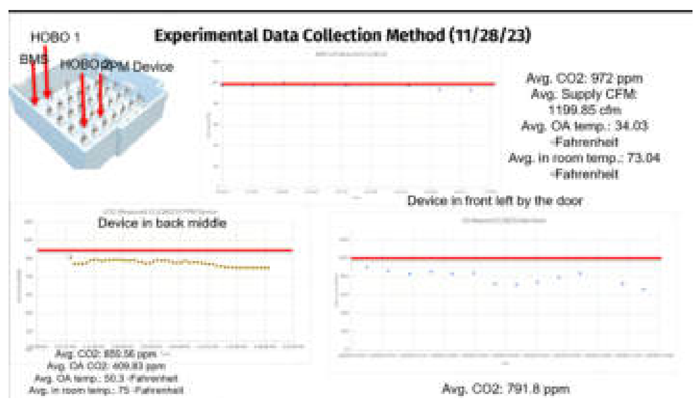

FIGURE 21. 11/28/23 Data

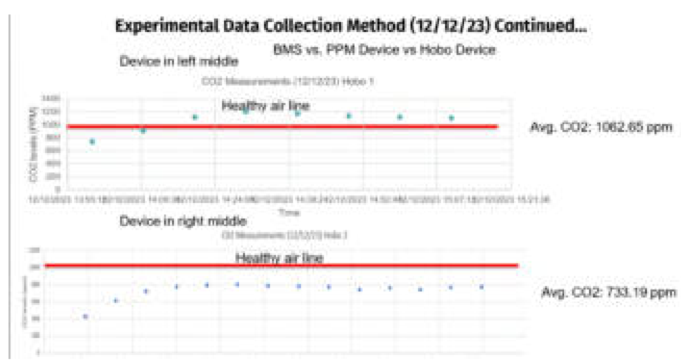

FIGURE 22. 12/12/23 BMS Data

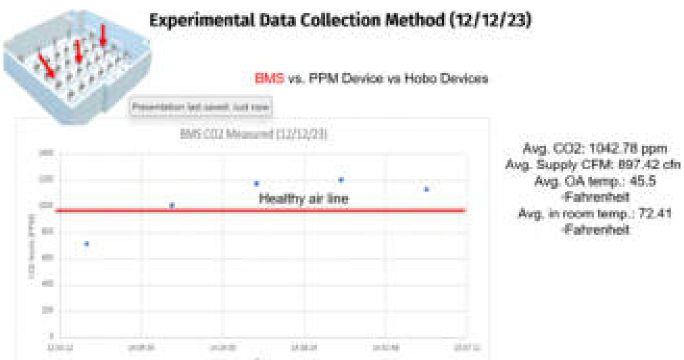

FIGURE 23. 12/12/23 HOBO Data

FIGURE 24. 12/12/23 PMM Data