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METHODS TO IMPROVE INDOOR ENVIRONMENTAL QUALITY (IEQ) IN CLASSROOMS IN HOT CLIMATES

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Abstract. As classrooms become increasingly crowded, there is a clear need to establish defined criteria for designing educational spaces. Overcrowding in classrooms can significantly increase the concentration of CO_2, which may negatively impact the students' health and their ability to learn. This research study aimed to understand the situation in an average classroom at King Abdulaziz University by measuring CO_2 levels over a full school day using monitoring equipment. The results showed that CO_2 concentrations exceeded the limits of acceptable values set by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). A proposed solution where a digital model of the classroom was developed and simulative tools were applied to create virtual classrooms was implemented. Several strategies, including architectural changes, modifications to schedule-driven ventilation systems, redesign of indoor climate control elements, and change point analysis techniques, were incorporated into simulations. This allowed for the assessment of existing parameters against proposed alternatives, yielding safer designs regarding critical CO_2 concentration values while supporting appropriate learning conditions. Soundly based recommendations are provided in the conclusion section for informed decision-making, aimed at designing efficient future classrooms and developing practical criteria for actively improving educational spaces.
Keywords: Education, Indoor Environmental Quality, Students Performance, Indoor Air Quality, Classroom

1. Introduction

Indoor Environmental Quality (IEQ) refers to the condition of a building's internal environment as it relates to the health and welfare of the occupants. "Indoor environmental quality (IEQ) refers to the quality of a building's environment in relation to the health and wellbeing of those who occupy space within it" [1].

In modern societies, achieving optimal learning standards, cultural development, and education have increasingly become primary objectives. Competition in this area has necessitated constant evaluation and advancement of educational systems and facilities. One of the most significant challenges for these societies is population density, which fosters a greater demand for access to education on a regional basis [2].

The increase in student enrolment has resulted in larger class sizes, which have revealed increasing deficiencies relative to acceptable indoor air quality standards. Previous studies have established that poor Indoor Air Quality (IAQ), especially excess carbon dioxide concentration, also known as CO_2, has been proven in many studies on school-aged students to be detrimental to their health and academic achievement [3].

To solve these problems correctly, strategies for ventilation systems are also crucial. Natural ventilation is one of the most cost-effective techniques applicable; however, its usefulness is limited by local weather conditions. In mechanically cooled regions, hot areas provide an alternative, though they can be quite energy-greedy [4].

2. Materials and Methods

2.1 Research Sample

The research sample was a classroom located on the second floor of King Abdulaziz University, building number 535. The floor area of the classroom is 7.5 × 9.14 meters, with a total of 40 occupants. The classroom depends on a central air conditioning system and contains three fixed windows.

2.2 Data Collection

This research was conducted using quantitative analysis. After selecting the research sample, an appointment was scheduled to take measurements on 07/10/2019. The measurements were conducted over the course of a full working day. During this period, the classroom windows remained closed, relying solely on mechanical ventilation. Only between sessions was the door open. Other than that, the door was always kept closed, especially during lectures.

The main goal of the design system was to identify methods to improve indoor air quality in existing classrooms. The research evaluated natural, mechanical, and hybrid ventilation systems through simulation techniques. Multiple trials were conducted and compared through IDA ICE simulation software to detect the most effective outcomes in each scenario. This iterative process allows for further development of the design criteria, helping to improve the existing architectural guidelines for educational buildings. Furthermore, the simulation presents a clear picture of the maximum number of students per classroom, enhances ventilation schedules, and proposes spatial optimization [5]

2.3 Measurement and Environmental Inputs

HOBO MX1102 CO_2 logger was used inside the classroom for the CO_2 concentration measurement. Throughout a working day, the device recorded CO_2 levels, temperature, and relative humidity every 10 minutes. At the center of the classroom, the CO_2 logger was placed at a height of 1.1 meters above the floor. Figure 1 shows an illustration of the device location [6].

Under normal indoor conditions, the reading accuracy for the **HOBO MX1102** can reach up to ±50 ppm ±5% with a CO_2 measurement range of 0 to 5,000 ppm. The measurement range of the temperature is 0°C to 50°C with an accuracy of ±0.21°C; meanwhile, the accuracy of the relative humidity is ±2% and recorded from 1% to 90% [6](Onset Computer Corporation, 2023).

The device follows standardized protocols for indoor environmental monitoring, and it is factory-calibrated.

Moreover, **IDA ICE** simulation software provided an integrated weather database for external climate conditions. The software collects the meteorological data using the nearest official weather station. In this case, the weather station is located at **King Abdulaziz International Airport in Jeddah, Saudi Arabia**. These data were essential for accurately simulating natural ventilation performance and validating energy and air quality models under real climate conditions [5].

2.4 Simulation Modeling

Following the identification of elevated indoor CO_2 levels above acceptable limits, a building simulation model was developed using **IDA ICE 4.8** to test various ventilation strategies. The model achieved a simulation error rate of 5.46% when compared to real-world measured data, ensuring acceptable accuracy for scenario testing. Through multiple simulation runs, various mechanical, natural, and hybrid ventilation systems were evaluated to identify the most effective solution for improving indoor air quality and energy performance within the constraints of the existing classroom design [5].

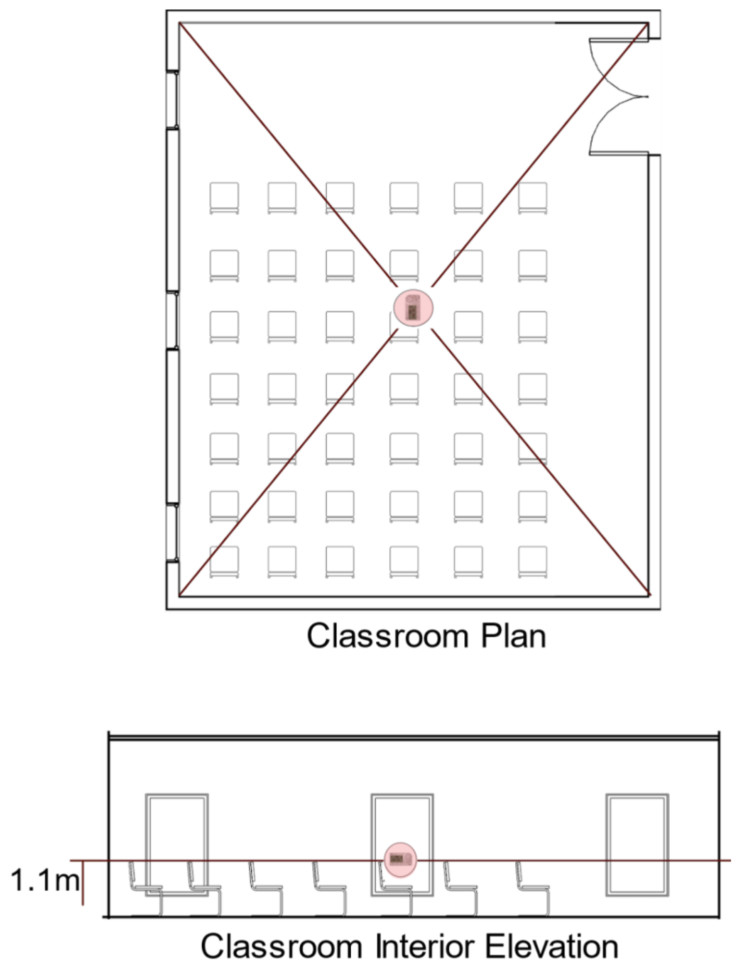


Figure 1. An image showing the placement of the measuring device (HOBO MX CO_2 logger) inside the classroom.

3. Results

3.1 Analysis of Measurement Results

CO_2 levels began to rise as soon as students were present in the classroom, and the longer they remained, the higher the concentration became. After just one hour of occupancy, the CO_2 concentration exceeded **1,000 ppm**, surpassing the recommended indoor air quality threshold defined by **ASHRAE Standard 62.1**, which indicates the need for immediate improvements in ventilation and fresh air intake.

Figure 2 illustrates the CO_2 concentration profile over a full working day (5:00 AM to 5:00 PM). Notably, CO_2 levels remained above **1,000 ppm** between **10:00 AM and 2:00 PM**, coinciding with peak student occupancy. This highlights the direct relationship between occupancy density and indoor air degradation.

In terms of thermal conditions, **Figure 3** presents the air temperature data collected over the same period. Temperature readings remained consistently between **22°C and 23°C**, which reflects the stability provided by the central air-conditioning system. No natural ventilation was used during this period, and the classroom remained closed, relying solely on mechanical ventilation, with doors open only between lectures.

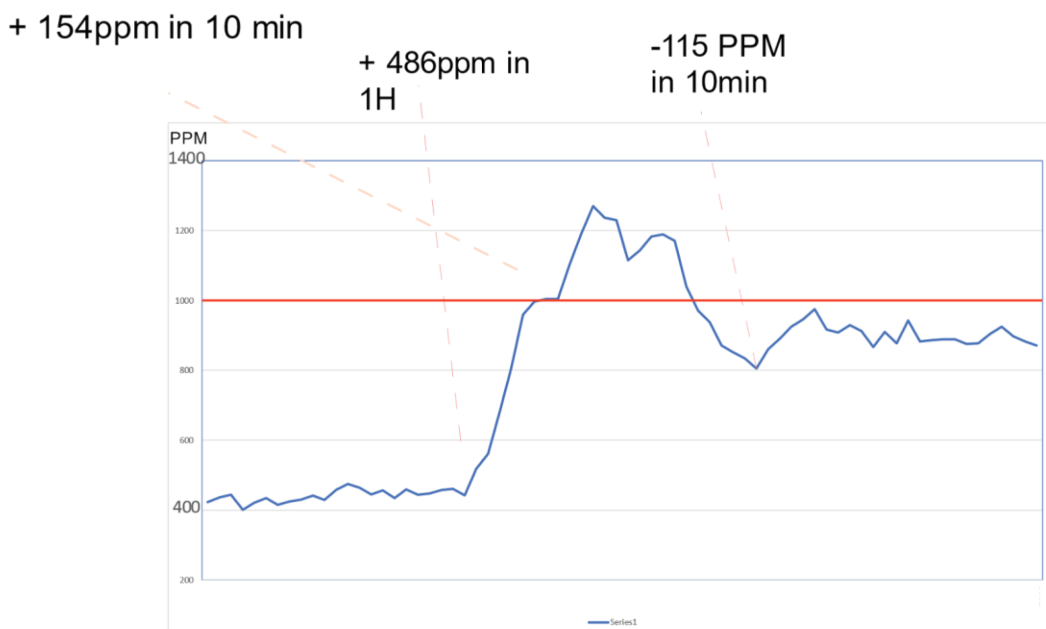


Figure 2. A graph showing the results recorded by the HOBO MX1102 carbon dioxide logger for measuring CO_2 levels during a school day.

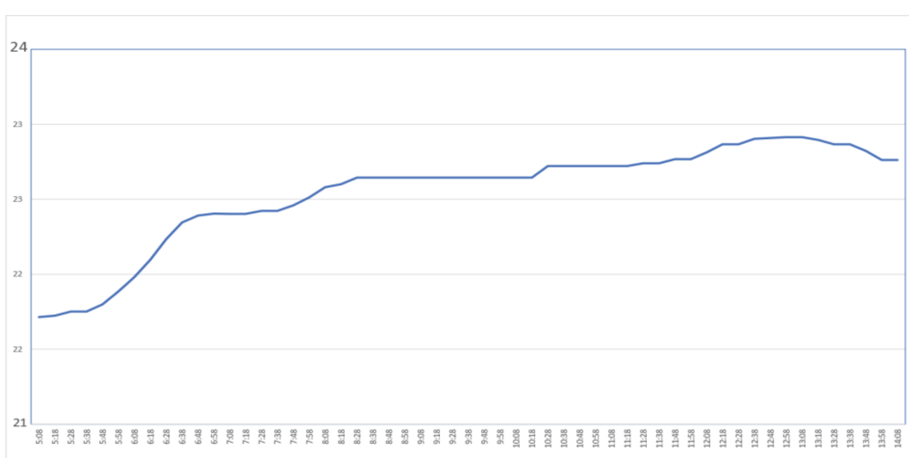


Figure ٣. A graph showing the results recorded by the HOBO MX1102 carbon dioxide logger To measure temperatures over a

3.2 Building Simulation Model

Following the field measurements, which confirmed that indoor carbon dioxide concentrations exceeded international health-based standards, a **digital simulation model** of the classroom was developed using **IDA ICE** software. The main purpose of the simulation is to evaluate the outcome of various ventilation strategies, like natural, mechanical, and hybrid, on the indoor air quality, energy efficiency, and thermal comfort. The model accurately reflected the architectural dimensions of the classroom, HVAC configuration, window placements, and actual occupancy schedules. It was calibrated using the real-world CO_2 data collected on-site. The **error margin** between the measured and simulated values was calculated at **5.46%**, confirming the reliability of the model for further scenario testing.

- **Figure 4** presents the 3D digital model used in the simulation, showing spatial geometry, HVAC placements, and boundary conditions.
- **Figure 5** displays a comparative graph showing the close alignment between **measured CO_2 levels** and **simulated data**, reinforcing the accuracy of the calibration.

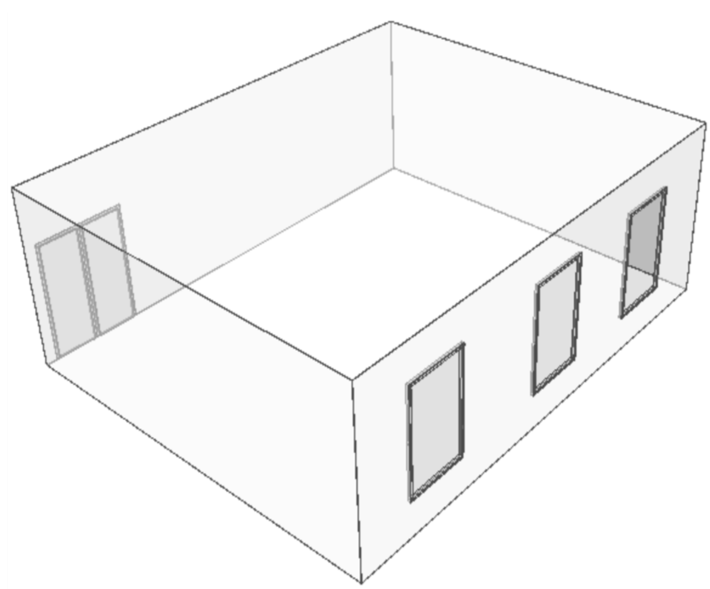


Figure 4. An illustration of the classroom's geometrical shape. Curated in IDA ICE software for simulation of the classroom indoor environmental parameters.

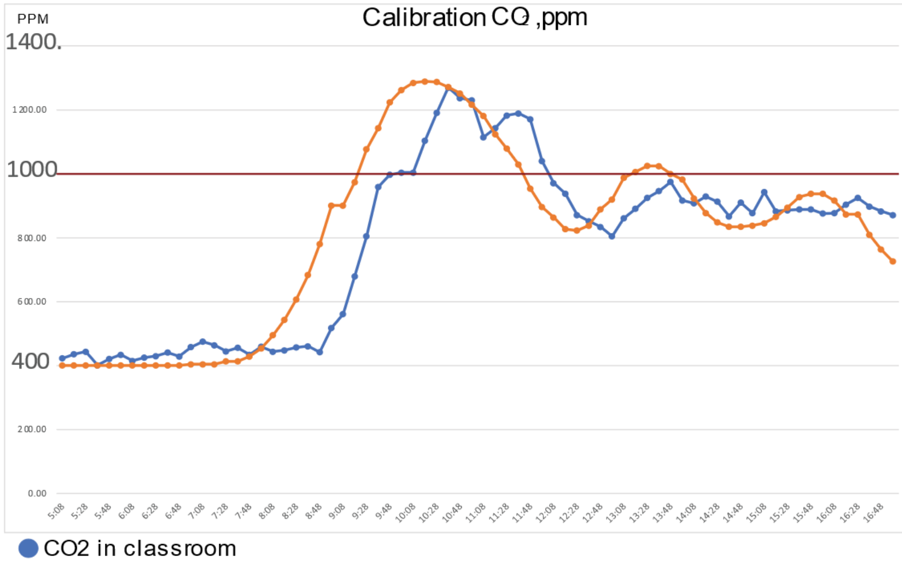


Figure 5. The graph illustrates the correlation between real-time CO_2 measurements and simulation results, showing a high degree of accuracy with a margin of error of 5.46%.

3.3 Scenario Planning

3.3 Scenario 1: Adaptive Window Operation

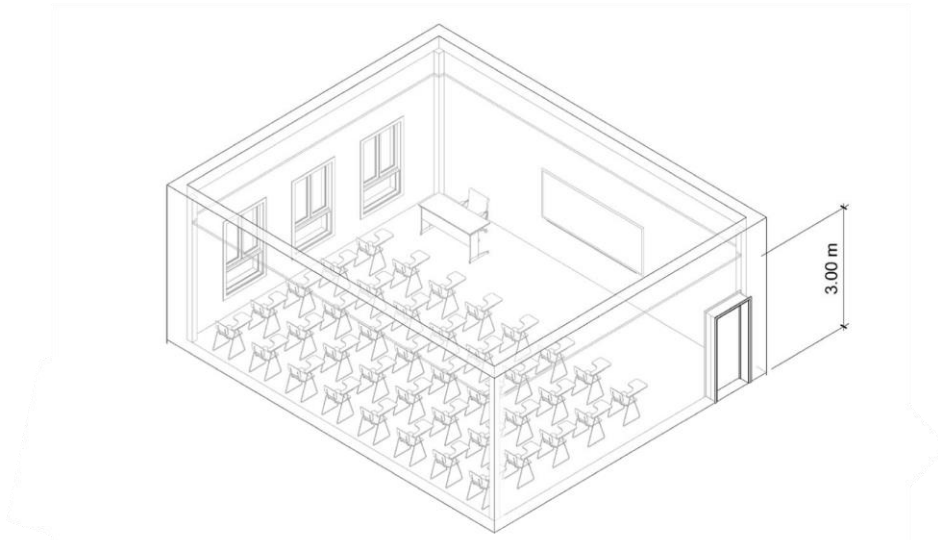
This scenario examined the potential of mitigating indoor CO_2 buildup by adjusting window opening schedules during critical hours. Although larger openings (50%–75%) did contribute to lowering CO_2 levels, they also introduced higher indoor temperatures (up to 33°C) and significantly increased energy consumption, due to thermal gain from the hot outdoor environment. These trade-offs suggest that window operation alone, without design modifications, may be inadequate in hot climates.

3.4 Scenario 2: Window Design Optimization

A second scenario, focused on modifying the geometry and configuration of the windows, was developed to enhance the effectiveness of natural ventilation without compromising thermal comfort or energy efficiency.

Figures **6** and **7** provide context for the base classroom configuration :

- **Figure 6** illustrates a longitudinal classroom section, including the full ceiling height (3.6 m), suspended ceiling.



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- **Figure 7** shows the standard window dimensions (1.8 m width × 1.2 m height, sill height at 0.9 m).

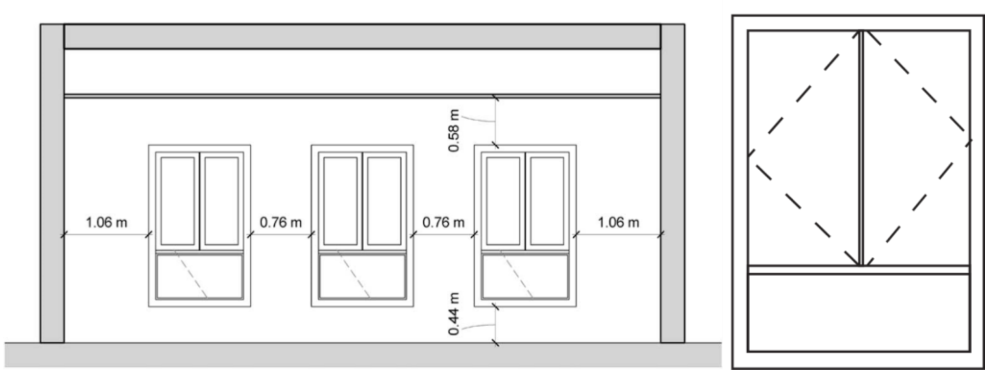
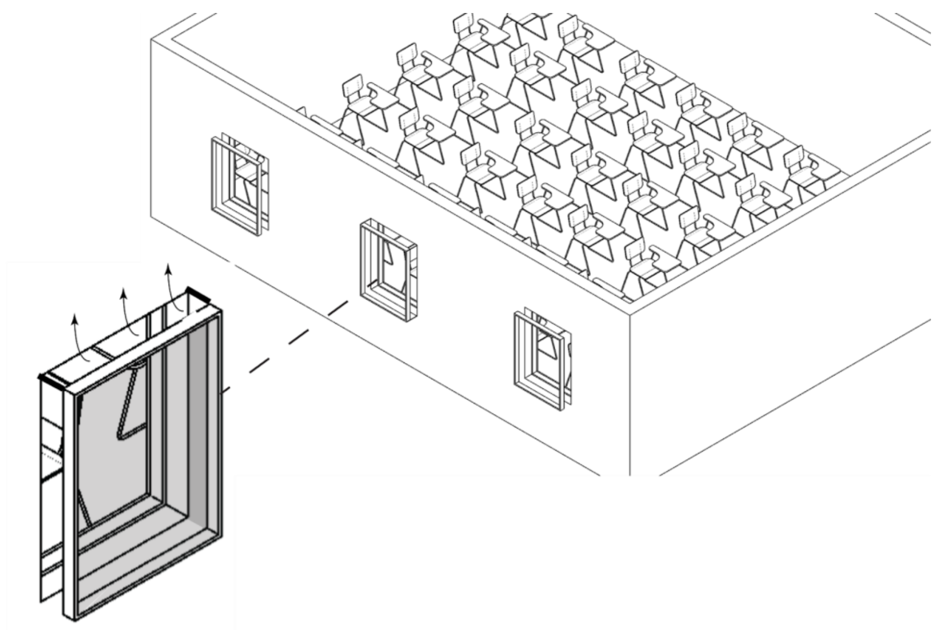


Figure 7 An elevation view illustrating the traditional classroom windows on the north-facing façade, with each window measuring 1.2 meters in height and 1.8 meters in width, and a sill height of 0.9 meters above the floor pollutants..

In this scenario, a **glass slide** was introduced outside the window at a 0.3-meter offset to redirect airflow and reduce direct thermal gain. The depth of the window recess was also adjusted (ranging from 0.1 m to 0.4 m), and the opening ratio was varied (25%, 50%, 75%, and 100%).

Figures **8**, **9**, and **10** illustrate the proposed window configuration :

- **Figure 8** presents an isometric view illustrating the placement of the redesigned window within the classroom wall, accompanied by a close-up detail that highlights its design
- **Figure 9** presents both the front and side views of the proposed window system, illustrating various simulation scenarios. The diagram details the window opening ratios and the spatial offset between the window and the external glass slide. These configurations formed the basis for the parametric simulations conducted in Scenario 2



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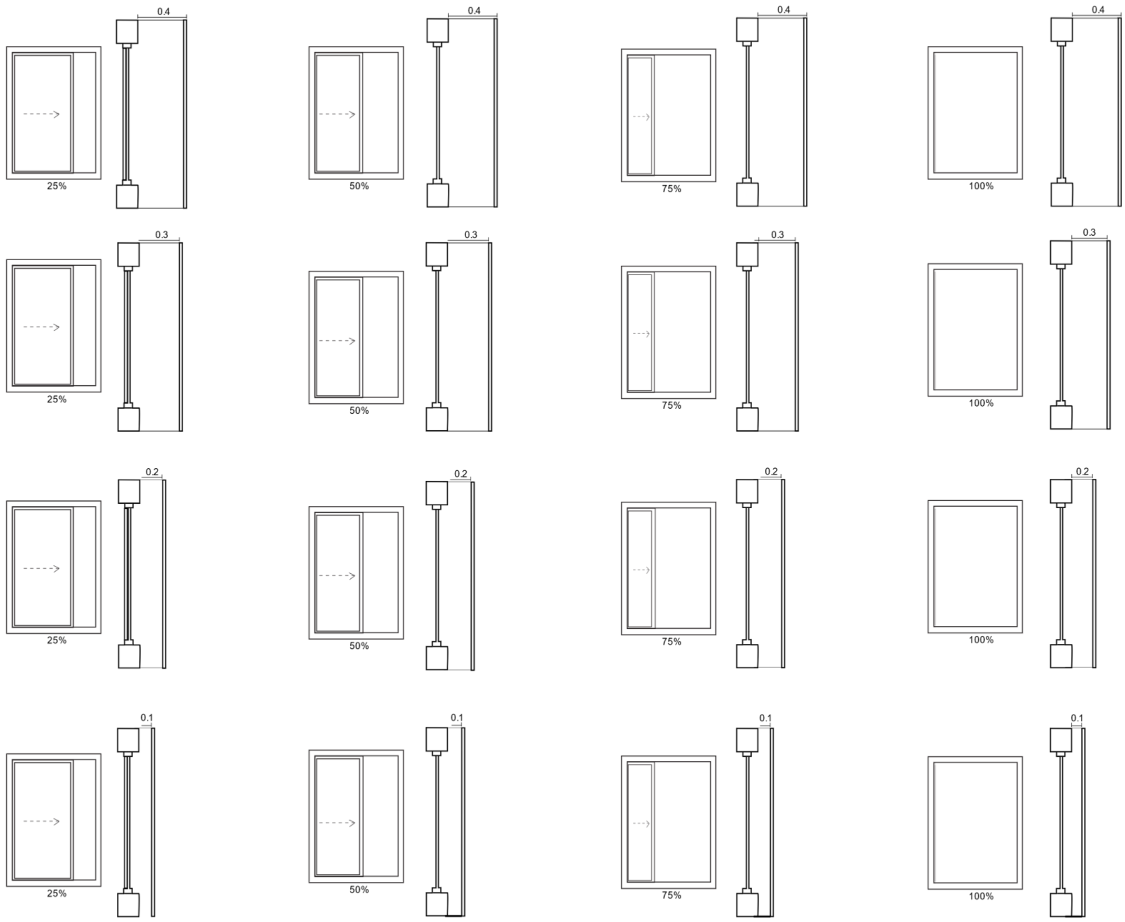


Figure 9 presents both the front and side views of the proposed window system, illustrating various simulation scenarios. The diagram details the window opening ratios and the spatial offset between the window and the external glass slide. These configurations formed the basis for the parametric simulations conducted in Scenario 2

3.5 Performance Results of Modified Designs

Simulation outcomes demonstrated that the most effective configuration was a **75% opening with a 0.4 m depth and an external glass slide**. This setup achieved:

- The **lowest CO_2 concentration**, consistently under 1000 ppm.
- **Moderate indoor temperatures** (23.5–24°C).
- **Acceptable energy consumption** (~220–230 kWh/day).

- **Improved airflow uniformity**, minimizing pollutant accumulation.

Figures **1٠** and **1١** summarize these results :

- **Figure 1٠** shows the relationship between CO_2 concentration and mean indoor temperature across all configurations.

- **Figure 1١** presents a comparison of CO_2 levels and energy consumption, highlighting the

- **Figure 1٠** shows the relationship between CO_2 concentration and mean indoor temperature across all configurations

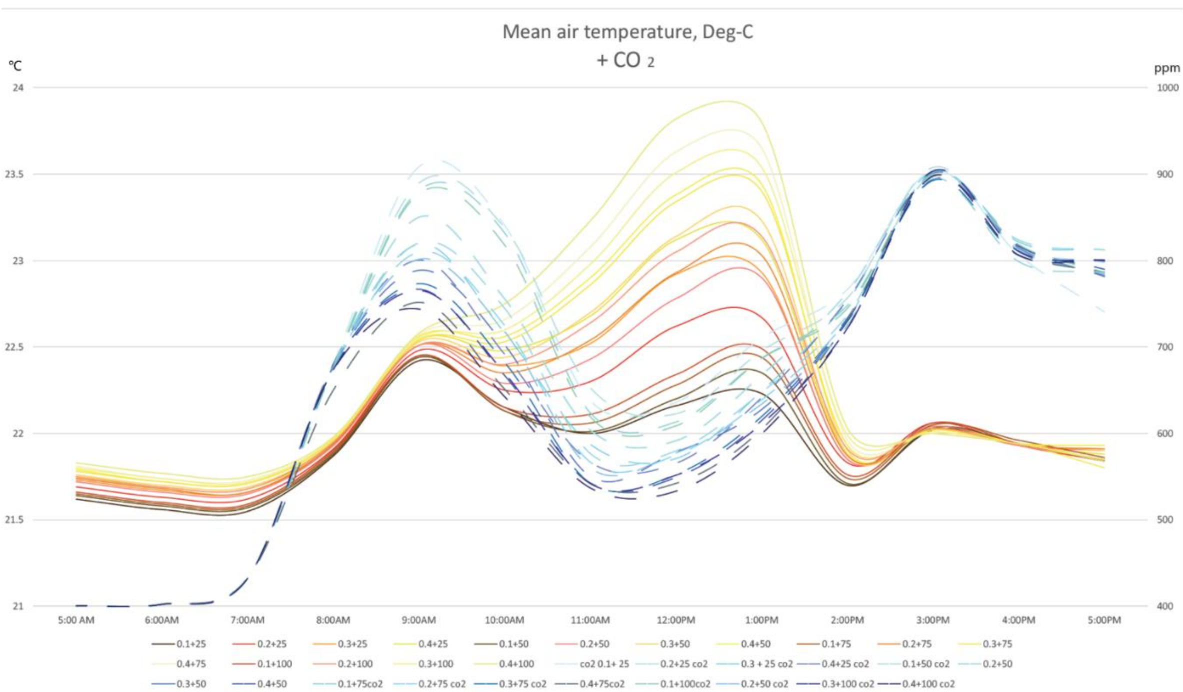
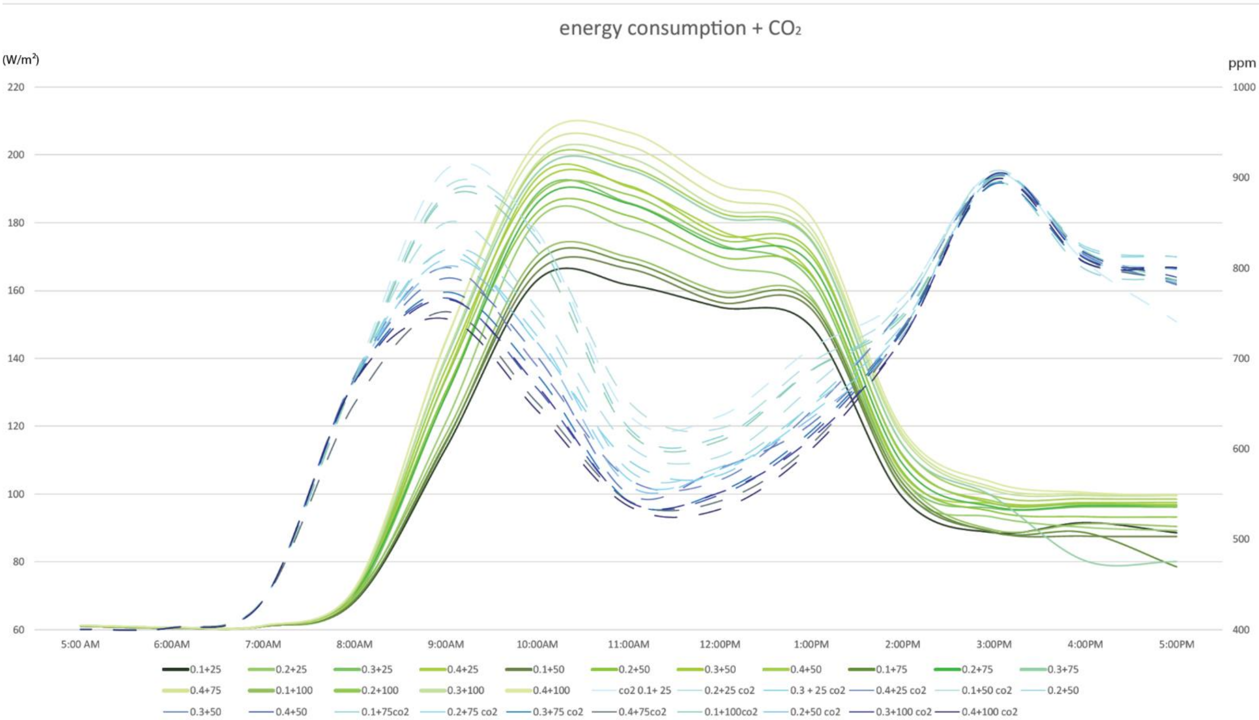


Figure 10 shows the relationship between CO_2 concentration and mean indoor temperature across all configurations



4. Discussion

Figure 11 presents a comparison of CO_2 levels and energy consumption, highlighting the balance achieved in the optimal scenario

The findings underscore the complexity of achieving optimal indoor environmental quality in educational buildings located in hot climates. A hybrid strategy—integrating architectural design with mechanical systems—emerges as essential for balancing air quality, comfort, and energy efficiency.

Reflection on Scenario 1

The first scenario confirmed that while operable windows can partially mitigate CO_2 buildup, their effectiveness is limited without strategic design enhancements. Larger openings during peak periods reduced CO_2 but led to significant increases in indoor temperatures and energy usage, reinforcing the observations of Pereira et al. (2017) that unregulated natural ventilation in hot climates may be counterproductive.

Impact of Window Geometry and Glass Slide (Scenario 2)

Scenario 2 demonstrated that thoughtful window modifications—specifically increasing depth and adding a deflective glass slide—can significantly enhance ventilation performance. These modifications:

- Directed airflow efficiently.
- Reduced thermal hotspots.
- Minimized energy penalties.

This aligns with studies by Pantelic et al. (2018) and Colinart et al. (2019), which emphasize the importance of façade geometry in optimizing passive ventilation.

Figures **6–٩** provided spatial understanding of the design, while Figures **١٠–1١** quantified the environmental improvements. Together, they confirm that **passive design strategies**, when implemented with precision, can reduce reliance on mechanical systems and support healthier, more energy-resilient learning environments.

Future research is encouraged to explore:

- Seasonal variability in ventilation effectiveness.
- Integration of real-time environmental sensors.
- Behavioral adaptations and user-driven control strategies.

By embedding such insights into early-stage architectural planning, designers can meaningfully improve student well-being and academic performance in dense, hot-climate educational environments.

6. Patents

Not applicable.

Author Contributions: Y.K. carried out the site survey, analyses, and data collection; M.B. provided supervision for all the work.
Methodology, Y.K.;
Software, Y.K.;
Validation, Y.K. and M.B.;
Formal Analysis, Y.K.;
Investigation, Y.K.;
Resources, Y.K.;
Data Curation, Y.K.;
Writing—Original Draft Preparation, Y.K.;
Writing—Review and Editing, Y.K. and M.B.;
Visualization, Y.K.;
Supervision, M.B.;
Project Administration, Y.K.;
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Informed Consent Statement:
Not applicable.

Data Availability Statement:

The data available for this study from the first author. It can be provided if needed upon request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

Not included

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