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Original Research

Integrated Analysis for Evaluating Efficiency and Cost-Benefit of Indoor CO_2 Improvement: an Innovative Approach

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Abstract

This study contributes by emphasizing the effectiveness of indoor air quality improvement technologies. Initially, it quantifies the outdoor air demand and proposes various combinations of ventilation equipment and improvement strategies. Through flow field simulations, it anticipates optimal ventilation configurations to ensure better mixing and dilution of introduced fresh air indoors. Furthermore, it evaluates the costs associated with effective improvement technologies by assessing different improvement schemes comprehensively, considering installation costs as well as long-term expenditures, including operational and maintenance costs. The study reveals that Scheme 3 (Two ERV units) has the highest installation cost but achieves the greatest improvement effectiveness. However, when evaluating across other cost dimensions such as operational costs, maintenance costs, and improvement benefits, Scheme 2 (One ERV with one exhaust fan) emerges as the optimal choice. Scheme 2 demonstrates the best unit cost improvement benefit at 0.77 ppm/US$, whereas Scheme 3 exhibits the lowest at 0.59 ppm/US$. These findings underscore the importance of considering not only initial setup costs but also ongoing expenses when assessing the benefits of indoor air quality improvement technologies, as these factors can significantly influence decision-making regarding improvement measures.

Keywords: computational fluid dynamics, indoor air quality (IAQ), carbon dioxide, energy recovery ventilation system, efficiency

Introduction

Poor indoor air quality in environments like homes, offices, and school classrooms, where students spend significant time [1–3], negatively impacts cognitive function, comfort, concentration, fatigue, sleepiness, and academic performance [4–7].

Human exhalation releases carbon dioxide (CO_2), a primary metabolite, typically at levels of 3.8% to 5% (38,000 to 50,000 ppm) [8]. In crowded indoor spaces with poor air exchange, CO_2 can accumulate, potentially increasing other indoor pollutant concentrations. Assuming good outdoor air quality and minimal indoor sources, CO_2 serves as an indicator of human metabolic

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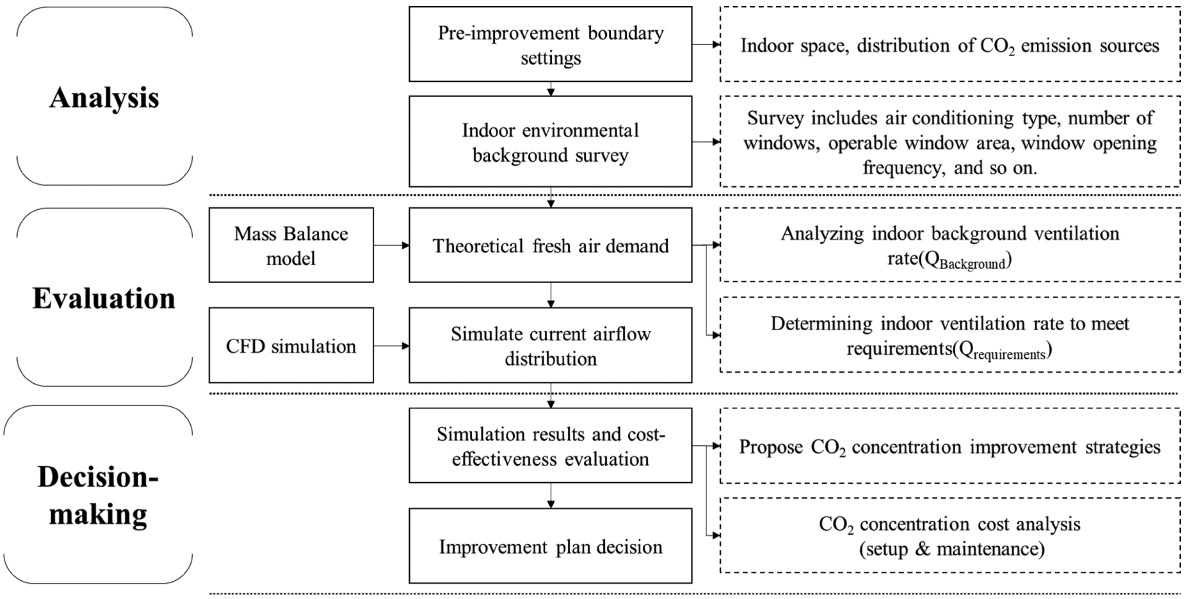

Fig. 1. The implementation process for the proposed method.

activity [6,9–14]. Given the inevitability of CO_2 emissions, effective ventilation is crucial for maintaining indoor air quality [6,8–9,15]. Consequently, monitoring CO_2 concentration has become a standard approach to controlling indoor air quality.

According to ANSI/ASHRAE Standard 62.1-2010, normal outdoor background CO_2 concentrations typically range between 300 and 500 ppm. Due to global warming, CO_2 levels are increasing annually, with an average concentration of approximately 455 ppm (±28 ppm) [6,8,16]. Therefore, maintaining a stable indoor CO_2 concentration is considered appropriate, not exceeding outdoor levels of around 650 to 700 ppm [16]. For good indoor air quality, CO_2 concentrations should ideally range from about 400 ppm (close to outdoor averages) to 1500 ppm, which is the average level for health conditions [6].

Indoor air quality is categorized as follows: 'excellent' when indoor CO_2 concentrations from human respiratory metabolism remain below 1,000 ppm, 'good' between 1,000 and 1,400 ppm, 'satisfactory' between 1,400 and 2,000 ppm, and 'unacceptable' above 2,000 ppm [9]. Standards such as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Ventilation Code, the Hong Kong Indoor Air Quality Management Group, and the Taiwan Indoor Air Quality Standard recommend that indoor CO_2 concentrations do not exceed 1,000 ppm [18,19].

Studies emphasize the critical impact of classroom air quality on students' physical health, mental well-being, and academic performance, prompting global attention to this issue. Becerra et al. [6] found that during teaching hours, CO_2 concentrations averaged 1,530 ppm, varying from -24% to +31%. They recommended enhanced ventilation strategies, such as opening windows between classes or during breaks, to lower CO_2 levels. Ramalho et al. [21] examined indoor air quality in 567 homes and 310 educational facilities in France, noting health risks associated with elevated CO_2 levels exceeding standards. Johnson et al. [8], studying third-grade classrooms in twelve primary schools, linked poor indoor air quality to discomfort, health issues, increased absenteeism, and reduced cognitive function, despite adequate HVAC systems managing temperature and humidity but insufficient fresh air supply.

This study's significance lies in its exploration of strategies to improve indoor air quality in university classrooms using existing air conditioning and energy recovery ventilation (ERV) systems, coupled with computational fluid dynamics (CFD) software to simulate indoor CO_2 concentration distributions. This approach is not limited to university settings but can be extrapolated to other educational institutions and high-capacity buildings. In many regions, especially those with hot and humid climates, relying solely on natural ventilation often fails to meet students' comfort needs, directly impacting their health and academic performance.

Furthermore, amidst the current COVID-19 pandemic, the combination of adequate ventilation practices and classroom mask-wearing can significantly reduce the transmission of SARS-CoV-2 aerosols. This underscores the relevance of addressing immediate health concerns while enhancing long-term indoor environments through improved CO_2 concentration management and monitoring strategies.

Materials and methods

Concept and Structure of the Research

This study particularly emphasizes that its method allows users to select the most cost-effective improvement option before making investments. The study assesses the current ventilation status of the improved space, simulates the current flow field, and estimates the theoretical fresh air requirement using a mass balance model. Various improvement plans are then evaluated to anticipate their effects. Fig. 1 illustrates the implementation process of the proposed method in this study.

Research hypothesis

1. Use average indoor occupancy and CO_2 concentration for consistent improvement assessment conditions.
2. Outdoor CO_2 concentrations exhibit minimal variation; therefore, the background outdoor CO_2 concentration is taken as the average value.
3. Assume regular window ventilation conditions.
4. Ignore short-term CO_2 concentration changes from door openings.
5. Exclude maintenance costs adjusted for inflation.
6. Exclude interest rates adjusted over time.
7. Calculate the depreciation period and operational costs over 8 years.

Methods for Analyzing Indoor Ventilation Rates

This study aims to demonstrate the feasibility of the proposed analytical method by improving indoor air quality in a professional and shared-use classroom at the College of General Education in New Taipei City, northern Taiwan. This includes monitoring indoor air quality and simulating indoor airflow patterns within the classroom. The selection of this classroom for study is primarily due to its regular indoor activities (for educational purposes) and minimal variation in occupancy.

The study selects a single classroom as the research space, with interior dimensions of 14.228 meters in length, 7.162 meters in width, and 2.94 meters in height, resulting in a floor area of 101.90 square meters and a volume of 299.59 cubic meters. It hosts seven classes weekly, each divided into two 50-minute lessons, with class sizes varying from 45 to 60 students based on attendance. Three non-dispersive infrared (NDIR) CO_2 sensors were installed to monitor CO_2 concentrations, providing accurate readings (±3% up to 2,000 ppm) with a response time of less than 10 seconds at a flow rate of 30 cc/min.

This study demonstrates the application of analytical methods in a school environment, emphasizing that the proposed analytical methods are applicable not only to schools but also to various indoor spaces.

Analysis Methods for Indoor Ventilation Rates

To analyze the indoor environmental ventilation conditions, this study referenced Kang et al. [22]. Utilizing a mass balance model, the study estimated indoor ventilation based on indoor CO_2 concentration, occupancy, space volume, and outdoor CO_2 concentration. Considering typical classroom usage characteristics with an average session duration of 50 minutes, the study calculated the average indoor ventilation (background ventilation before improvement).

For individual indoor CO_2 generation rates, please refer to Persily and de Jonge [23]. The indoor CO_2 generation rate accounts for passive activities such as discussions, activities, and light walking during class, estimated at 0.0004 m^3/min per person. The mass balance model is:

$$V\frac{dC}{dt} = (B \times P) + (Q \times C_{out}) - (Q \times C_{(t)}). \tag{1}$$

The mass balance model is solved as follows:

$$\frac{dC}{dt} = \frac{B \times P}{V} + \frac{QC_{out}}{V} - \frac{QC_{(t)}}{V} \tag{2}$$

and

$$C_{(t)} = k'e^{-\frac{Q}{V}t} + \frac{B \times P}{Q} + C_{(out)}. \tag{3}$$

Assuming that the indoor CO_2 concentration is equal to the outdoor concentration when the room is empty, the final solution is given by:

$$C_{(t)} = \frac{BP \times 10^6}{Q}\left(1 - e^{\frac{Q}{V}t}\right) + C_{out} \tag{4}$$

where $C_{(t)}$ is the indoor CO_2 concentration at time t (ppm), B is the indoor individual CO_2 production rate (0.0004 m^3/min-p), P is the number of people in the room (p), Q is the room ventilation capacity (m^3/min), V is the volume of the space (m^3), and C_{out} is the outdoor CO_2 concentration (ppm).

Tools and Methods for Simulating and Analyzing Indoor Airflow

In this study, Computational Fluid Dynamics (CFD), specifically ANSYS CFD Premium, was utilized to analyze natural ventilation scenarios using the k-turbulence model. This model is known for providing reasonable and accurate indoor airflow distribution results [24].

The accuracy of CFD simulations relies on several critical factors, including the comprehensiveness of the database, which must handle nonlinear ventilation systems integrating airflow and pollutant concentrations, as well as random variations in indoor environmental conditions and precise prediction of turbulence effects. Additionally, the computational capabilities of the hardware used for large database storage significantly impact simulation accuracy [25].

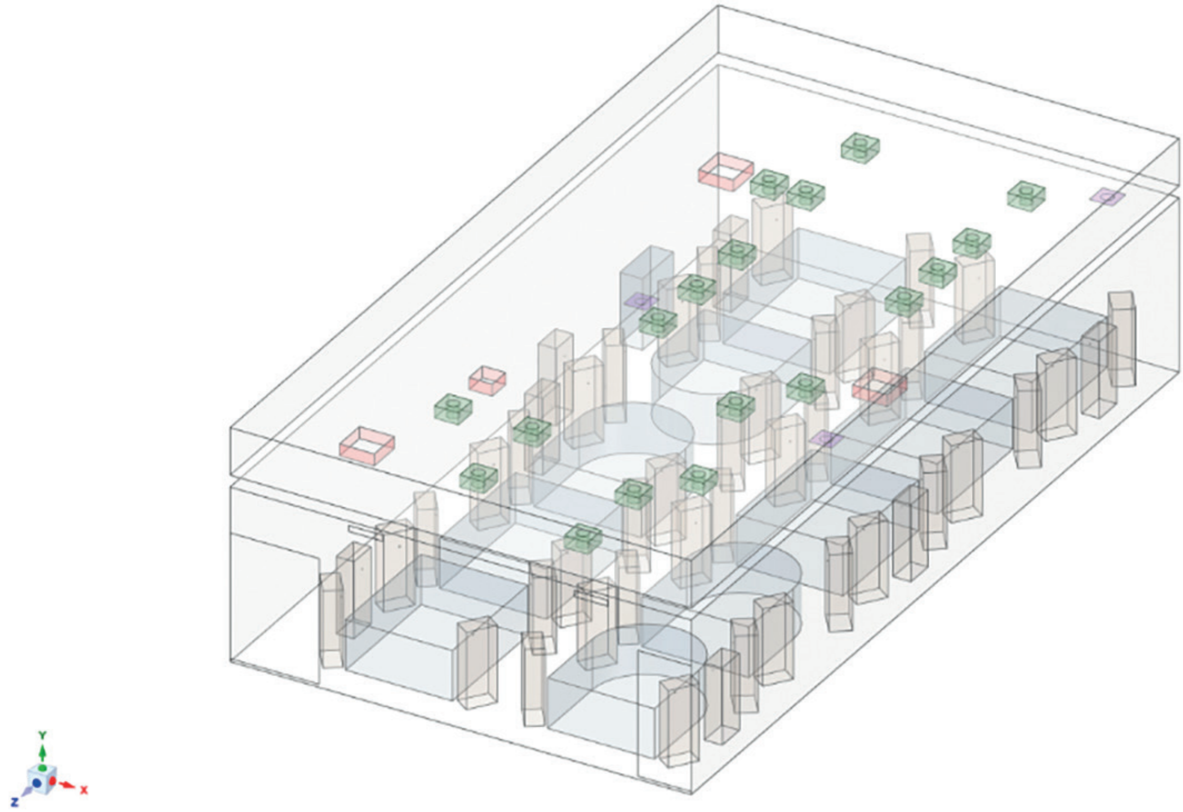

Fig. 2. Modelling of the space.

Z. Feng et al. [26] emphasize the pivotal role of mesh quality in CFD simulations. While reducing the number of mesh elements can shorten simulation times, it may compromise the fidelity of representing uneven velocity gradients and turbulence diffusion. Therefore, validation against measured data is essential to scrutinize simulation results [27].

Now, considering the specific setup of this study, the space measures 14.228 meters in length and 7.162 meters in width, with a total floor area of 102.33 square meters. It accommodates 50 individuals, seated at desks arranged for 5 people each. The airflow analysis incorporates a uniform mouth opening size of 1 cm × 1 cm and a breathing height of 1.2 meters, depicted in Fig. 2. To ensure precise simulation of the flow field, the mesh used in this research consists of 838,060 elements, meeting ANSYS' recommended mesh quality standards. Specifically, the minimum orthogonal quality of the mesh is 0.156 (within the acceptable range of 0.15-0.20), and the maximum skewness is 0.844 (within the acceptable range of 0.80-0.94).

The exhaled CO_2 concentration per person is estimated at 40,552 ppm based on ANSI/ASHRAE Standard 55-2010, considering a relaxed standing metabolic rate of 1.2 met [28]. Fig. 2 illustrates the space space model used for simulating CO_2 concentration distribution in ANSYS CFD Premium.

Application Cases of Analytical Methods

Evaluation of Ways to Improve Indoor CO_2 Concentration

Computational Fluid Dynamics (CFD) is an effective design tool for assessing indoor air quality and ventilation systems. Combining it with the advantages of Building Simulation (BS) or other technologies can enhance its analytical capabilities [29]. The analysis method proposed in this study integrates mass balance with CFD simulation analysis.

First, the mass balance method is used to estimate the background ventilation rate of the indoor environment. Then, using ASHRAE Standard 62.1-2019, the theoretical outdoor air requirement is evaluated based on the current environment (number of occupants and space size). If the theoretical outdoor air requirement is less than the actual ventilation rate, ventilation improvement is needed. Conversely, if the theoretical outdoor air requirement is greater than the actual ventilation rate, the current ventilation rate meets the needs of the occupants.

According to ASHRAE Standard 62.1-2019, the recommended demand for outside air per person in a space is 5 L/s-p, and the demand for outside air in a zone is 0.6 L/s-m². Based on the area of 102.33 m² in this

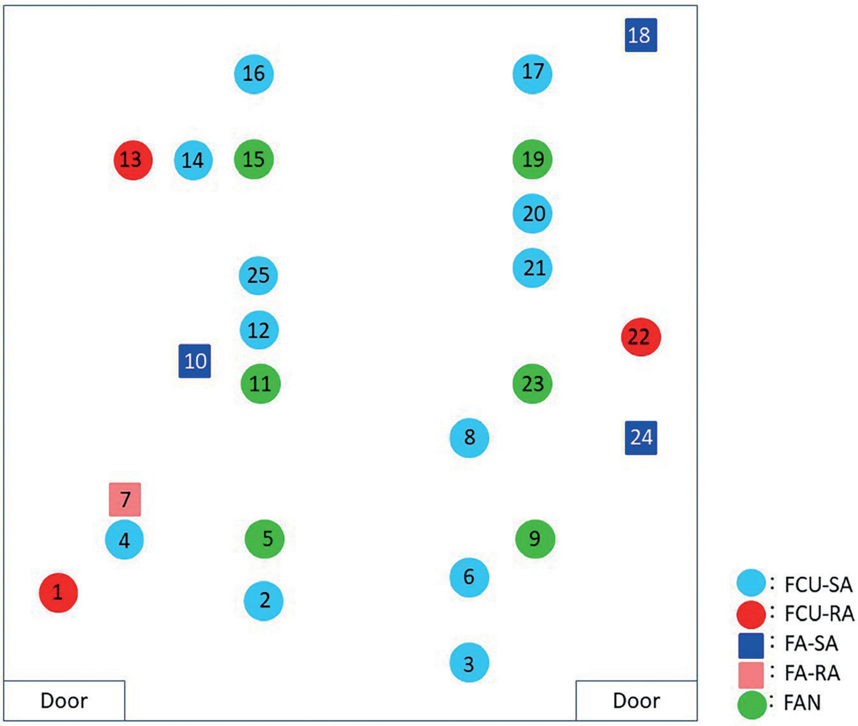

Fig. 3. Overhead view of the space.

study, the estimated demand for outside air in the space is 6.02 L/s-p. Considering the maximum occupancy of 60 people in the space, the total external air demand is estimated to be 1,339 CMH or 4.5 air changes per hour.

According to previous mass balance estimations, the background average ventilation rate before improvement was 15.2 m^3/min (912 m^3/hr), and the lowest ventilation rate was 4.3 m^3/min (258 m^3/hr). Considering the worst-case ventilation scenario (more stringent improvement conditions) (airtight and low leakage rate), the lowest ventilation rate of 4.3 m^3/min (258 m^3/hr) was used as the baseline for pre-improvement assessment.

Commercially available fresh air units range from 250 CMH to 1,500 CMH. Since the height of the 1,500 CMH unit is considered an issue in the existing space, adding an additional 500 CMH is unnecessary as it is neither cost-effective nor does it improve efficiency. Therefore, 1,000 CMH was initially adopted as the new airflow capacity for this study. The design of the relevant air conditioning configuration and the location of the fresh air outlet in the space are shown in Fig. 3.

The boundary condition for the CFD simulation was measured on-site. The indoor CO_2 concentration was monitored over a period of 12 weeks, with data collected weekly for each of the six weeks before and after the space improvement. The analysis of CO_2 concentration improvement during indoor classes is presented in Table 1.

Results and Discussion

Current Indoor Environmental Survey

Each class comprised two sessions, each lasting approximately 50 minutes, with participant numbers varying across classes. Frequent movement of individuals in and out of the space during the first session potentially disrupted background ventilation, leading to a possible overestimation of ventilation rates. Consequently, this study focused on analyzing the average hourly CO_2 concentrations measured by the three CO_2 sensors during the second session of each class. In this study, to verify the changes in the number of people indoors before and after the improvement, we recorded the number of people indoors from the first week to the sixth week. This was done to illustrate that the variation in the number of people indoors was minimal and did not affect the research results. As shown in Table 2.

The results of indoor CO_2 concentration monitoring over a six-week period, both before and after the improvements, are presented in Table 3. The weekly indoor CO_2 concentrations from the first to the sixth week before the improvement were as follows: 1,627±337 ppm in the first week, 2,285±862 ppm in the second week, 2,034±727 ppm in the third week, 1,682±731 ppm in the fourth week, 2,033±613 ppm in the fifth week, and 1,504±590 ppm in the sixth week. The average indoor CO_2 concentrations over the six-week period ranged from 1,504 to 2,547 ppm.

Table 1. Parameters for air conditioning in the space.

No.	Code name	Area (m^2)	Air velocity (m/s)	No.	Code name	Area (m^2)	Air velocity (m/s)
1	FCU-RA	0.342	0.03	15	FAN	0.105	3.80
2	FCU-SA	0.096	3.08	16	FCU-SA	0.096	2.56
3	FCU-SA	0.096	2.27	17	FCU-SA	0.096	3.25
4	FCU-SA	0.096	0.35	18	FA-SA	0.148	1.34
5	FAN	0.105	3.25	19	FAN	0.105	3.40
6	FCU-SA	0.096	0.76	20	FCU-SA	0.096	4.20
7	FA-RA	0.342	0.18	21	FCU-SA	0.096	0.96
8	FCU-SA	0.096	1.65	22	FCU-RA	0.342	0.26
9	FAN	0.105	1.76	23	FAN	0.105	1.78
10	FA-SA	0.096	1.85	24	FA-SA	0.148	1.59
11	FAN	0.105	3.09	25	FCU-SA	0.096	1.95
12	FCU-SA	0.096	0.38	26	SENSOR-1	-	-
13	FCU-RA	0.342	0.23	27	SENSOR-2	-	-
14	FCU-SA	0.096	2.87	28	SENSOR-3	-	-

Note: FCU-RA for mini fan return, FCU-SA for mini fan outlet, FAN for recirculating fan, FA-RA for fresh air return, FA-SA for fresh air outlet.

Table 2. Changes in the number of people indoors from the 1st week to the 6th week.

No. of week	Changes in the number of people	Before improvement	After Improvement (Scheme 1)	Variation from pre- to post-improvement
1st week	P ± SD(Range)	47±7(40–59)	50±5(45–56)	+6.4%
2nd week		54±5(50–59)	52±6(46–59)	−3.7%
3rd week		53±4(45–55)	52±7(42–59)	−1.9%
4th week		51±2(50–53)	51±3(47–56)	0%
5th week		55±1(54–56)	55±3(52–59)	0%
6th week		54±4(50–57)	51±2(49–52)	−5.6%

CO_2 concentrations exceeding 1,000 ppm were recorded in the space during school hours [11,40,41]. In spaces lacking a mechanical extract ventilation (MEV) system, the maximum CO_2 concentration reached 2,547 ppm, aligning with the findings of Haddad et al. [30].

The space was equipped with a split-type air-conditioning system that lacked an air exchange function. Changes in CO_2 concentration during the morning class period (10:20–11:00) were observed (Fig. 4), indicating an initial background CO_2 concentration of approximately 500 ppm before the class commenced. The class duration was 40 minutes. CO_2 concentration steadily increased from the initial level of 500 ppm to 1,600–2,000 ppm, demonstrating a progressive accumulation over the course of the lesson.

Poor indoor air quality in educational facilities not only contributes to chronic health issues among children but also manifests in non-specific discomfort symptoms such as sick building syndrome (SBS). Among various indicators of ventilation quality, CO_2 concentration serves as a critical measure of indoor air quality [29].

According to Vassella et al. [9], natural ventilation is commonly utilized in European schools, resulting in elevated CO_2 concentrations during cold winters due to closed windows. Their study highlighted that over 67% of spaces exceeded the Swiss standard of 2,000 ppm for CO_2 concentrations, contrasting with conditions in Taiwan. Taiwan, characterized by a subtropical climate with high temperatures and humidity, experiences outdoor temperatures exceeding 30°C during the summer months.

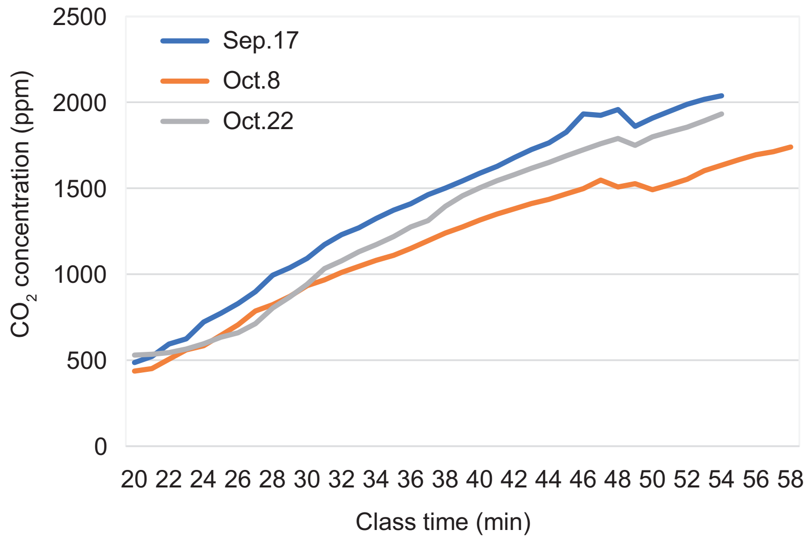

Fig. 4. Trend of CO_2 Concentration in the space prior to improvement.

Table 3. Indoor CO_2 concentrations and ventilation rates observed during the six-week period before the improvement.

Week number	CO_2 concentration	Ventilation rate
	ppm ± SD (Range)	m^3/min ± SD (Range)
1^{st} week	1,627±337 (1,279–2,130)	14.4±3.9 (9.0–20.3)
2^{nd} week	2,285±862 (1,289–2,792)	9.4±11.4 (<1–24.0)
3^{rd} week	2,034±727 (1,267–2,937)	13.3±7.9 (4.8–23.2)
4^{th} week	1,682±731 (1,066–2,491)	18.1±11.5 (7.0–30.3)
5^{th} week	2,033±613 (1,457–2,676)	13.5±7.2 (6.5–20.6)
6^{th} week	1,504±590 (1,156–2,185)	21.9±10.5 (10.0–29.5)

Consequently, air-conditioning systems are typically sealed to prevent heat infiltration and maintain indoor comfort.

In this study, the average indoor ventilation rate was estimated based on hourly monitored indoor CO_2 concentrations, occupancy levels, room volume, and a constant outdoor CO_2 concentration of 404 ppm, as referenced in Table 2 following Kang et al. (2016) [22]. Weekly ventilation rates during space use were as follows: 14.4±3.9 m^3/min in week 1, 9.4±11.4 m^3/min in week 2, 13.3±7.9 m^3/min in week 3, 18.1±11.5 m^3/min in week 4, 13.5±7.2 m^3/min in week 5, and 21.9±10.5 m^3/min in week 6. The overall average indoor ventilation rate ranged from 9.4 to 21.9 m^3/min, corresponding to 1.9–4.4 air changes per hour.

Under conditions of inadequate ventilation, natural ventilation led to CO_2 concentrations exceeding 1,000 ppm in 50% of cases, 1,500 ppm in 10% of cases, and 2,000 ppm in 3% of cases. However, the implementation of indoor occupant density control and mechanical ventilation reduced instances of CO_2 concentrations above 1,000 ppm to 28% of spaces during school hours [31].

Assessing Indoor CO_2 Reduction in Scheme 1

The primary method to enhance indoor CO_2 concentrations is through effective ventilation. To mitigate the impact of external corridors or adjacent space noise on indoor environments, this study implemented dedicated fresh air equipment to enhance indoor air quality. Following the design guidelines of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE Standard 62.1-2013), a theoretical fresh air supply of 6.7 L/s.p. per person is recommended. Given a maximum occupancy of 60 individuals, this translates to an estimated requirement of 1,447 cubic meters per hour (CMH). However, the initial background indoor

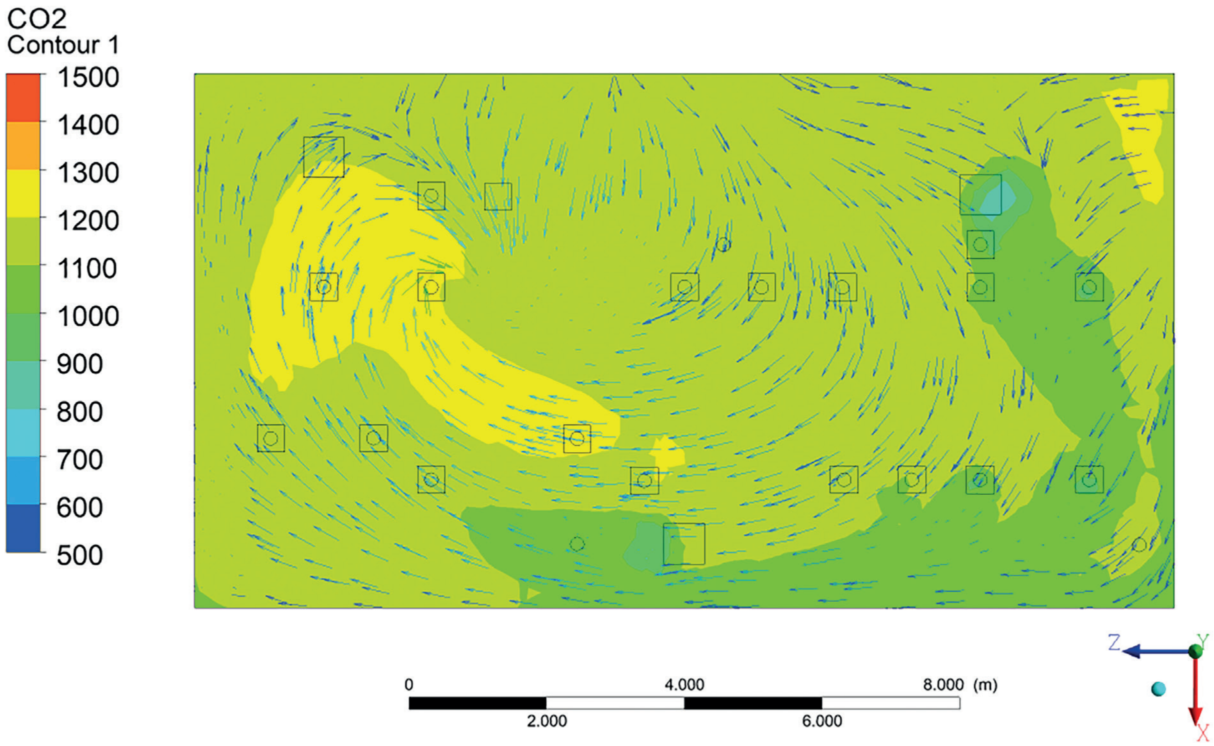

Fig. 5. Indoor CO_2 Concentration Before Improvement.

ventilation rate prior to improvement was only 4.3 m³/min (equivalent to 258 CMH), which fell short of the required 1,189 CMH.

Balancing per capita improvement and equipment cost-effectiveness, a conservative design approach was adopted, targeting an airflow rate of 1,000 CMH to enhance the effectiveness of the ventilation equipment. To ensure uniform distribution of fresh air provided by the Energy Recovery Ventilation (ERV) system within the space, this study utilized indoor flow field simulation and CO_2 concentration distribution analysis to strategically plan the placement of fresh air outlets and return air vents. The Lee and Lee (2022) study conceptually resembles this study by analyzing the economic feasibility of Energy Recovery Ventilation (ERV) systems to determine suitable ventilation rates for office space characteristics. It provides decision-making tools and evaluates tenant benefits and costs [32]. However, the primary methodological difference between this study and theirs lies in this study's initial quantitative assessment of outdoor air demand. Subsequently, it proposes different ventilation equipment and improvement strategies, complemented by flow field simulations to optimize duct configurations. This ensures effective mixing and dilution of introduced fresh air indoors.

After confirming the required ventilation rate for the space, a simulation was conducted at 9 am on October 31st with 50 occupants present to assess the distribution of CO_2 concentration before improvement. The simulation results indicated that the indoor CO_2 concentrations ranged from 850 to 1,250 ppm (as depicted in Fig. 5). The indoor flow field analysis coupled with CO_2 concentration mapping (Fig. 5) revealed weaker airflow in the left area of the space, suggesting potential air stagnation zones.

To mitigate the airflow stagnation in the left area of the space, this study enhanced the Energy Recovery Ventilation (ERV) system and strategically positioned three fresh air inlets along with one return air outlet. The fresh air inlets were strategically placed at the front, middle, and rear of the space. Post-improvement simulations indicated reduced indoor CO_2 concentrations ranging from 750 to 950 ppm (results shown in Fig. 6).

The predominant regional CO_2 concentration averaged around 1,150 ppm, consistent with on-site monitoring where the average concentration was 1,156 ppm, with an error range of 9.2% between simulated and actual values. The simulation outcomes illustrated in Fig. 6 demonstrated improved airflow dynamics in the previously identified stagnation area, effectively lowering indoor CO_2 levels. The overall regional CO_2 concentration averaged approximately 850 ppm, with an average indoor CO_2 concentration of 788 ppm. Compared with on-site monitoring, the error between modeled and actual values was 7.9%. To show the average values from the simulation and the actual monitoring, with a difference of less than 10%, all simulated results fall within an acceptable error range. The calculated results are shown in Table 4.

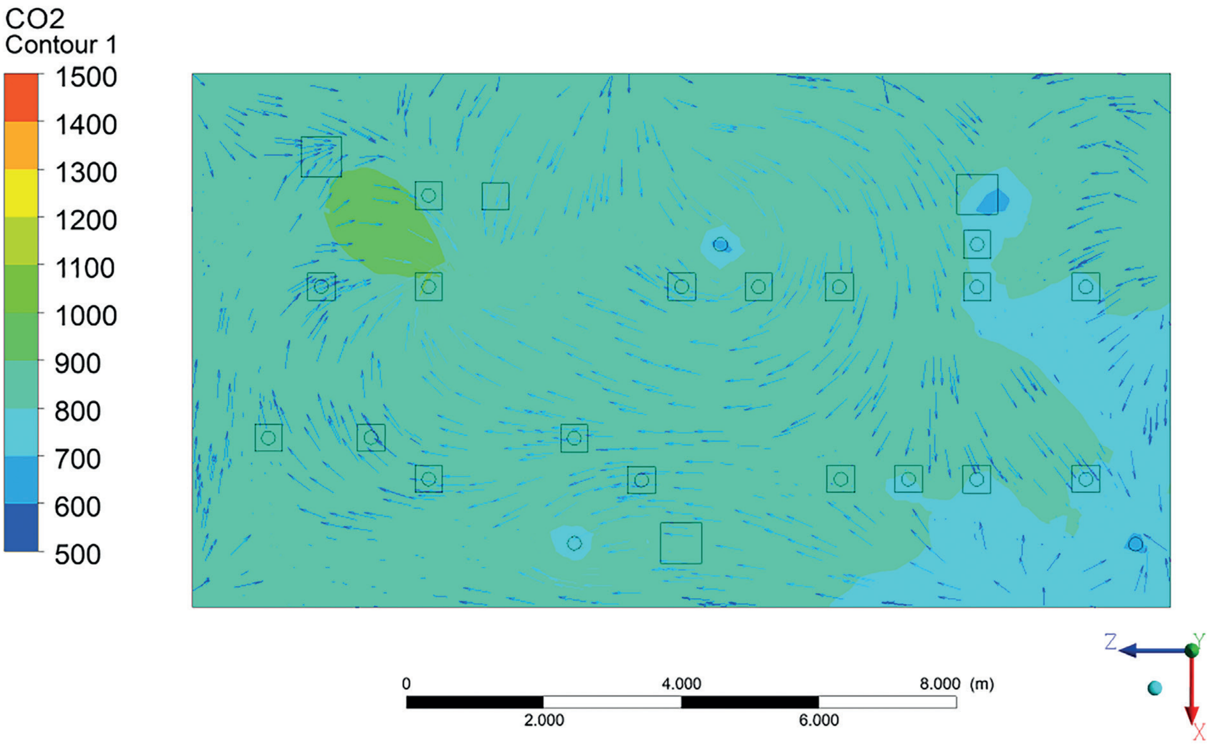

Fig. 6. Indoor CO_2 Concentration After Improvement by Scheme 1.

Table 4. Scheme 1: CO_2 simulated and actual average error analysis.

Item	Simulated average	Actual average	Error (%)
Before improvement (ppm)	1,050	1,156	9.2
After improvement (ppm)	850	788	7.9

The outcomes of utilizing the Energy Recovery Ventilation (ERV) system to enhance indoor CO_2 levels are summarized in Table 2. Post-improvement, weekly CO_2 concentrations in the space ranged from 1,173±235 ppm with a ventilation rate of 27.6±10.3 m^3/min in week 1 to 1,234±258 ppm with a ventilation rate of 25.6±8.2 m^3/min in week 6. Compliance with guidelines from the Swiss Federal Office of Public Health (FOPH) suggests maintaining CO_2 levels below 1,400 ppm throughout the school day [19].

Comparative analysis pre- and post-improvement indicates changes in indoor occupancy ranging from -5.6% to +6.4%. Indoor ventilation increased by 16.9%, achieving 219.1% of the original level, while indoor CO_2 concentration decreased by 18.0%, lowering to 56.1% of the original level. Studies indicate that in the absence of Mechanical Exhaust Ventilation (MEV), maximum CO_2 concentrations can reach 2,786 ppm, highlighting the effectiveness of MEV systems in reducing indoor CO_2 concentrations [6, 42].

Analyzing Optimal Improvement and Cost-Effectiveness Schemes

This study implements Scheme 1, utilizing a single ERV system, and introduces two additional enhancement proposals: Scheme 2 (ERV with an exhaust fan) and Scheme 3 (two ERV systems). Evaluating their effectiveness and cost-efficiency involves employing an analytical framework tailored for indoor air quality enhancement and cost-benefit analysis, detailed in Table 5.

To ensure methodological consistency, Scheme 2 and Scheme 3 are evaluated under identical baseline conditions derived from the initial environmental survey of Scheme 1. Key metrics include a weekly occupancy of 262 individuals, a background ventilation rate of 258 CMH, and initial CO_2 concentrations simulated at a peak of 2786 ppm, reflecting poor indoor air quality pre-improvement.

The study adheres to stringent conditions outlined by ASHRAE Standard 62.1-2019, focusing on minimal background ventilation and calculating necessary airflow adjustments. Both pre- and post-improvement scenarios involve an average occupancy of 50 individuals, with Scheme 1 implementing a 1,000 CMH ERV system, while Scheme 2 includes a simulated addition of a 1,000 CMH exhaust fan, and Scheme 3 integrates two ERV systems rated at 1,000 CMH and 500 CMH, respectively.

This study compared three ventilation schemes using CFD simulations: Scheme 2 achieved the highest CO_2 reduction (1,738 ppm), followed by Scheme 3 (1,705 ppm), and Scheme 1 (1,458 ppm). Initial setup costs varied: Scheme 3 was the highest (US$20,857), followed by Scheme 2 (US$16,129), and Scheme 1 was the lowest (US$15,877). Daily operating costs, based on assumed electricity consumption, ranked highest for Scheme 3 (US$209.5), followed by Scheme 2 (US$148.5), and Scheme 1 the lowest (US$142.9). Maintenance costs, primarily annual filter replacements, were US$57 for Schemes 1 and 2, and US$114 for Scheme 3.

Annual operational expenses, including setup amortization over 8 years, showed Scheme 3 with the highest annual equipment costs (US$2,607.1), followed by Scheme 2 (US$2,016.1), and Scheme 1 the lowest (US$1,984.6). Operational and maintenance costs per year were highest for Scheme 3 (US$323.5), followed by Scheme 2 (US$205.5), and Scheme 1 the lowest (US$199.9). Overall annual operational expenses ranked highest for Scheme 3 (US$2,930.6), followed by Scheme 2 (US$2,221.6), and Scheme 1 the lowest (US$2,184.5). In terms of cost efficiency per unit concentration improvement, Scheme 2 demonstrated the lowest cost per ppm (US$1.3), followed by Scheme 1 (US$1.5), and Scheme 3 the highest (US$1.7). Scheme 2 (Simulation) also showed the highest efficiency at 0.77 ppm/US$, whereas Scheme 3 (Simulation) was the least efficient at 0.59 ppm/US$. These findings align with previous research findings (Zong et al., 2020) [36].

The authors utilized various evaluation methods, including energy consumption, building maintenance, HVAC technology, and others, to demonstrate the economic advantages of enhancing indoor air quality [33, 34]. Djukanovic et al. employed DOE-2 software to simulate energy usage and costs linked to increasing outdoor air supply rates in buildings. Their findings highlight substantial economic benefits, where annual productivity gains exceed tenfold the yearly increases in energy and maintenance expenses. Additionally, achieving an 'excellent' air quality level could lead to a payback period of less than four months for initial HVAC system costs [34].

Seppanen and Fisk extensively assessed the benefits of improving indoor environments, highlighting reductions in healthcare costs, absenteeism, and turnover rates, along with enhanced work performance [35]. This study introduces a novel analytical approach and cost evaluation framework distinct from previous works [33–35]. It emphasizes the effectiveness of indoor air quality improvement technologies and evaluates the costs associated with various enhancement schemes, including installation, operation, and maintenance expenses. Our research prioritizes these economic aspects over other potential benefits like improved productivity and reduced medical costs. Comparing natural, mechanical, and hybrid ventilation options, hybrid solutions are found to optimize average air exchange rates. This underscores the critical role of considering construction costs, ongoing maintenance, and equipment investments in enhancing indoor air quality, with careful management of occupancy density to maximize cost-effectiveness.

When evaluating indoor ventilation improvement plans, it's essential to weigh both the benefits and comprehensive costs, including future maintenance. Based on the findings in Table 6 regarding indoor CO_2 concentration improvement, Scheme 2 (One ERV with one exhaust fan) emerges as the most effective and cost-efficient among the studied schemes. It achieves significant CO_2 reduction with moderate enhancement costs. Exhaust and ceiling fans enhance thermal comfort and airflow within the space [37, 46]. In contrast, Scheme 3 (Two ERV systems) shows lower improvement and cost-effectiveness. Despite some CO_2 reduction benefits, higher initial investment costs make it less viable overall. This highlights the importance of considering not only equipment costs but also substantial expenses such as construction and ongoing maintenance. Adjusting occupancy density can further optimize the cost-benefit ratio.

However, all evaluations of indoor air quality improvements mentioned above include a focus on energy efficiency, highlighting its critical role in assessing improvement costs. Recent professional research underscores that indoor environmental conditions significantly impact occupants' health and comfort. Poor indoor conditions, characterized by higher pollution levels, are estimated to cost the U.S. economy billions annually due to increased incidence of diseases like asthma and allergies, which reduce productivity. Moreover, as climate change progresses, buildings face heightened challenges from external environmental conditions [38]. For example, rising outdoor temperatures increase the demand for indoor cooling, leading to higher annual energy consumption. This underscores the ongoing tension between indoor air quality improvements and energy efficiency amidst escalating greenhouse gas emissions.

Conclusions

This study significantly contributes to understanding the intricate relationship between indoor air quality improvements and energy efficiency considerations. It conducts a comprehensive economic analysis that not only quantifies the costs associated with enhancing indoor environments but also evaluates the economic benefits through reduced health-related productivity losses. By highlighting the effectiveness of technologies aimed at improving indoor air quality, the study systematically assesses outdoor air demand and recommends optimal ventilation equipment and methods. Utilizing computational

Table 5. Indoor air quality enhancement and cost-benefit analysis across sub-schemes.

ASHRAE Standard 62.1-2019: Theoretical fresh air volume required			1,447 CMH		
Scheme Actual measurement Simulation			Scheme 1	Scheme 2	Scheme 3
			Simulation		
Strategies for Enhancement			One ERV	One ERV with one exhaust fan	Two ERV
Improvement method	Improvement equipment	ERV system (CMH)	1,000	1,000	1,000+500
		Exhaust fan (CMH)	-	500	-
	Natural ventilation	Minimum background ventilation (CMH)	258	258	258
Concentration before improvement (ppm)			2,786	2,786	2,786
CFD simulation of average concentration improvement post-enhancement (ppm)			1,328	1,048	1,081
Difference in concentration before and after improvement (ppm)			1,458	1,738	1,705
Set-up cost	Equipment cost (US$)[1]		1,983	2,127	3,136
	Air purification box (US$)		267	267	490
	Construction costs (US$)		12,618	12,726	16,222
	Monitoring and control system costs (US$)		1,009	1,009	1,009
	Sub-total		15,877	16,129	20,857
Operating costs	Power (W)		580	580+23	580+270
	Operating hour		1,848	1,848	1,848
	Power consumption (kWh)		1,072	1,114	1,571
	Electricity[2](US$)		142.9	148.5	209.5
Maintenance costs	Primary filter (annual replacement frequency) (US$)		25	25	50
	Secondary filter (annual replacement frequency) (activated carbon and PM2.5 filter) (US$)		32	32	64
	Sub-total		57	57	114
Annual amortized improvement equipment installation cost (based on eight years of equipment amortization) (US$/yr)			1984.6	2016.1	2607.1
Annual operational and maintenance costs (US$/yr)			199.9	205.5	323.5
Annual total cost (US$/yr)			2184.5	2221.6	2930.6
Unit concentration improvement cost (US$/ppm)			1.5	1.3	1.7
Unit cost improvement benefit (ppm /US$)			0.67	0.77	0.59

NOTE: [1], The exchange rate is 1 USD to 30 TWD for the fee calculation. [2], The electricity rate used in this study is 4 TWD per kilowatt-hour.

Table 6. Indoor CO_2 concentration improvement schemes decision-making.

Item		Scheme 1 (Actual measurement)	Scheme 2 (Simulation)	Scheme 3 (Simulation)
Strategies for Enhancement		One ERV	One ERV with one exhaust fan	Two ERV
CO_2 concentration improves efficiency		★	★★★	★★
Improve costs	Overall improvement costs encompass a spectrum of expenditures, comprising setup costs, operating costs, and maintenance costs associated with the implemented enhancements.	★★★	★★	★
	Annualized cost of space improvement (Based on an estimated 8-year lifecycle)	★★★	★★	★
	Cost per unit improvement in concentration per year.	★★★	★★	★
Total analysis	Improve efficiency	Low	High	Moderate
	Improve costs	Low	Moderate	High
Prioritize scheme		2	1	3

Remarks: ★★★The benefits of CO_2 concentration improvement are significantly pronounced, while the associated improvement costs are the most economical.

fluid dynamics simulations, it pre-evaluates duct configurations to ensure efficient mixing and distribution of fresh air indoors.

The improvements implemented in the Energy Recovery Ventilation (ERV) system led to substantial increases in indoor ventilation rates and significant reductions in CO_2 concentrations. However, even with a conservative new airflow rate of 1,000 cubic meters per hour, current measures were deemed insufficient, underscoring the ongoing challenge of maintaining indoor CO_2 levels below 1,000 ppm, particularly during periods of minimal outdoor wind activity.

During outbreaks of infectious diseases, enhancing ventilation efficiency emerged as crucial in reducing transmission risks among occupants. Among the evaluated schemes, Scheme 2 (one ERV and one exhaust fan) demonstrated notable improvements in CO_2 concentration at reasonable costs, emphasizing the necessity of considering both initial installation expenses and long-term operational and maintenance costs.

To mitigate potential increases in air conditioning energy consumption resulting from enhanced ventilation strategies or higher outdoor air ventilation rates, the study recommends integrating management strategies such as controlling indoor personnel density to prevent overcrowding. This approach ensures effective control of indoor air quality while optimizing operational efficiency. Looking ahead, the study advocates for the development of effective indoor CO_2 monitoring methods integrated with ventilation systems. This integration aims to optimize energy use while maintaining optimal indoor air quality, thereby contributing to the reduction of greenhouse gas emissions associated with energy consumption.

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Conflict of Interest

The authors declare no conflict of interest.

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