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Optimizing School Classroom Facades to Control Airborne Diseases Transmission through Human Centric-CFD Framework

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Abstract The COVID-19 pandemic highlights the need for school designs that prioritize health, well-being, and sufficient natural ventilation rates, alongside engaging learning environments. In conventional double-loaded school layouts, only one classroom typically aligns with the optimal wind direction, achieving standard ACH rates. This study addresses research gaps by introducing two frameworks: the EDS for early design and the RO for retrofitting existing educational structures. The EDS framework optimizes the façade design variables for a hypothetical classroom to maximize the average air velocity (AAV), while the RO framework investigates façade design variables within a real case study to identify optimal configurations that meet the standard ACH. Key design parameters analyzed for the EDS include the Window-to-Wall Ratio (WWR), Opening-to-Wall Ratio (OWR), and Façade height (FH) correlated with AAV. The RO framework considered window/opening position, WWR, and OWR associated with achieving needed ACH and improving the learning environment. The EDS included a CFD-parametric optimization approach engaged with developed GHPython codes and linear regression analysis. CFD simulations for specific design scenarios were performed in the RO framework to assess ACH while improving the learning environment. The EDS framework analysis demonstrates that key design variables (OWR, WWR, and FH) explain 33.1% of the variance in AAV, with optimal configurations achieving an AAV of 0.65 m/s. Regression analysis highlights the substantial positive impact of OWR on AAV and underscores the negative influence of facade height, aiding in formulating design strategies that enhance indoor air quality in classrooms. The RO framework, applied to classrooms in Cairo, Egypt, demonstrates versatility in enhancing IAQ through optimal configurations of WWR and OWR. Simulations identified optimal opening ratios: 20% W/OWR in foundation-stage classrooms (ACH of 6.94) and 30% WWR with 10% OWR in primary-stage classrooms (ACH of 7.33). These configurations reduced infection risks below 1%, supporting findings from related studies on ventilation and infection risk, and affirming the RO framework's efficacy in designing healthier educational environments. The EDS and RO frameworks offer valuable tools for improving IAQ and learning conditions in classrooms; future studies may investigate frameworks across diverse settings and user feedback may be included to refine their real-world effectiveness.

Keywords Health and Wellness, COVID-19, Airborne Diseases, Natural Ventilation, Classroom, Optimization, Positive Learning Environment

1. Introduction

During the COVID-19 pandemic, which reached 231 countries and led to over 698 million infections and 6.94 million deaths [1], schools worldwide suspended in-person attendance to limit virus transmission, causing significant effects on students' learning outcomes [2]–[4]. As schools reopened, strategies to prevent future respiratory outbreaks became essential due to their impact on education. Architectural designers are urged to follow World Health Organization (WHO) guidelines, particularly those promoting sufficient natural ventilation in public spaces [5], [6].

Previous research has often prioritized facade elements aimed at energy efficiency and thermal comfort, with less focus on the important factor of indoor air quality (IAQ) [7]–[14]. The commonly used double-loaded classroom design, where two classrooms face each other across a central corridor, is efficient in land use but can make achieving adequate air changes per hour (ACH) challenging. Typically, one classroom faces the prevailing wind, benefiting from improved ventilation, while the other often receives less airflow. Special conditions, such as respiratory health concerns, require increased ACH for safe learning environments, though many classrooms face difficulty in meeting these standards due to design limitations. Several studies have explored the relationship between precautionary procedures and COVID-19 infection rates [15]–[18], while others have concentrated on improving IAQ in educational settings. Nevertheless, further investigation into the interplay between IAQ and qualitative design aspects is warranted [16], [17]. Additionally, research has addressed the importance of natural ventilation in indoor spaces [19]–[21]. Current guidelines largely emphasize perceived air quality, yet many schools fail to meet these standards, resulting in suboptimal IAQ. It is imperative to develop innovative ventilation strategies that transit from comfort-based to health-focused designs. Personalized ventilation systems have shown promise in enhancing local IAQ by protecting occupants from nearby pollutants, but more research is necessary to validate their efficacy in school environments [22].

This paper aims to bridge the gaps in existing research by (A) proposing an optimization framework for classrooms that enhances natural ventilation, (B) addressing the challenges of providing adequate natural ventilation in double-loaded classroom layouts, particularly for classrooms oriented away from the wind, and (C) incorporating human-centric parameters in the retrofitting of indoor spaces to improve the learning environment. The study presents novel frameworks designed to optimize or retrofit school classroom facades, enhancing natural ventilation and ensuring sufficient ACH, while considering human-centric aspects. The first framework targets the early design stage (EDS) through a CFD-parametric optimization process, while the second framework focuses on retrofitting (RO) existing educational structure. These frameworks prioritize health considerations from the outset of the design and retrofitting processes, ensuring that both new and existing educational facilities promote student wellness.

Accordingly, Section 1 introduces the research background and identifies research gaps. Section 2 presents a literature review, divided into two subsections: 2.1 covers the literature on reducing airborne disease transmission through natural ventilation, while 2.2 discusses the provision of a productive learning environment (PLE) in school classrooms. Section 3 details the methodology, including research frameworks, case studies, data, variables, thresholds, and CFD model validation. Section 4 addresses the results and discussion, and Section 5 concludes the paper.

2. Literature Review

2.1. Reducing the Infection of Airborne Diseases through Natural Ventilation in School Environments

The literature review on reducing the infection of airborne diseases through natural ventilation in school environments highlights several crucial findings regarding the effectiveness of various ventilation strategies. However, it also reveals significant gaps that warrant further investigation. While some studies have established correlations between ventilation rates and infection risk, critical gaps that this paper aims to address remain [19]–[21], [23]. A foundational aspect of effective natural ventilation is the necessity for adequate air changes per hour (ACH). Research indicates that achieving a minimum of 5 ACH can drastically reduce the risk of airborne diseases to below 1% during regular class durations [16]. However, most existing studies primarily focus on quantifying the effectiveness of current ventilation standards without exploring innovative optimization frameworks tailored specifically to classroom environments.

This oversight reveals a need for a structured approach that combines computational fluid dynamics (CFD) with parametric optimization to improve natural ventilation in schools. Current studies often overlook challenges presented by double-loaded classroom layouts, where classrooms face each other along a central corridor, making adequate airflow difficult, particularly for rooms facing away from prevailing winds [17]. Although some research acknowledges the limitations of these layouts [24], specific strategies to enhance ventilation in these setups are limited. This paper proposes solutions to improve natural airflow in such challenging designs, enhancing indoor air quality and reducing infection risks.

Additionally, much of the research emphasizes technical ventilation improvements but tends to ignore human-centered aspects, like comfort, health, and the psychological effects of design on students. While studies recognize ventilation's role in limiting airborne pathogen spread, they often overlook how elements like window placement influence students' productivity [25]. This paper argues that including these human-focused factors in retrofitting classrooms is essential for creating healthier, more supportive learning spaces. Moreover, limited research addresses ventilation upgrades in older buildings, focusing instead on new construction. This gap is concerning as many older school facilities may not meet current health standards. The proposed Retrofitting (RO) framework applies ventilation strategies to existing buildings, aiming to improve student health in schools that otherwise lack updated infrastructure.

The frameworks in this study—the Early Design Stage (EDS) framework and the Retrofitting (RO) framework—target these gaps. The EDS framework uses CFD-parametric optimization to guide design choices, centering health from the start, while the RO framework brings these strategies to older buildings, enabling effective ventilation retrofits. By addressing both new and existing school buildings, these frameworks have the potential to improve student well-being. Though some studies apply CFD to optimize ventilation, there is a need for real-world validation that includes human-centered factors.

For instance, while references [26], [27], demonstrate the theoretical effectiveness of specific design configurations, practical assessments in actual school environments remain limited. This gap highlights the need for studies that bridge the gap between theoretical models and real-world applications considering qualitative aspects.

Table 1 illustrates the most related literature review on reducing the infection of airborne diseases through natural ventilation in educational environments.

In conclusion, while existing literature emphasizes the importance of natural ventilation in enhancing IAQ and reducing the transmission of airborne diseases, significant gaps remain. By addressing the challenges of double-loaded classroom layouts, incorporating human-centric parameters, and developing frameworks for both new designs and retrofitting existing structures, this study aims to advance the discourse on effective educational space design. Ultimately, this research is poised to contribute to the promotion of healthier, more adaptable learning environments in schools, ensuring that both students and educators can thrive.

2.2. Providing a Positive Learning Environment (PLE) in School Classroom

Providing a Positive Learning Environment (PLE) in school classrooms is essential, as it significantly impacts pupils' social skills, health and wellness, and learning outcomes. The Environment Rating System (ERS) has established a scale rating system to evaluate group-care programs for children aged five to twelve during their after-school hours. This scale comprises 47 elements, divided into seven subscales: program structure, staff development, activities, interactions, space and furnishing, and health and safety [34]. While the ERS scale specifically addresses after-school activities, the principles underlying these subscales can also be applied to in-school activities, highlighting the need for consistent evaluation across different learning contexts. Despite the established framework provided by the ERS, significant gaps exist in its application to the school day. For instance, while the literature acknowledges the importance of spatial design, such as optimal window positions and natural ventilation, there is insufficient empirical research linking these design choices directly to improved health outcomes and reduced airborne disease transmission in real classroom settings [35]. This study aims to fill this gap by investigating how specific design elements can enhance PLE while simultaneously mitigating health risks.

Additionally, the literature often categorizes students by age groups, with the foundation stage group (ages three to five) and the primary group (ages five to eleven) receiving distinct attention [36], [37]. However, the existing research tends to generalize the needs of these groups rather than exploring the nuanced differences in their environmental requirements. For example, while the foundation stage group benefits from play-based learning in open environments, the transition to more structured learning in the primary stage raises questions about how these environments should adapt to support evolving educational strategies [38]. This study explores how spatial design can be tailored to meet the developmental needs of different age groups in school settings.

Although research shows that classroom environments play a vital role in student engagement and motivation [39], few studies examine how these environmental factors work together with specific teaching methods and curriculum goals. The existing literature often neglects the link between environmental quality and teaching effectiveness, an important factor for creating supportive learning spaces. This study will examine this connection, particularly how natural ventilation and facade design impact both health and educational outcomes. Research has documented the effects of classroom design on emotional well-being and academic performance, emphasizing elements like acoustics, lighting, and air quality [40]. However, gaps persist around how to implement these factors practically in real-world classrooms. For example, while studies suggest that natural light can improve focus and reduce fatigue, few address how to integrate these features cost-effectively in resource-limited school environments [41]. This study will aim to close this gap by providing practical recommendations for budget-friendly design strategies.

Table 1. The literature review on reducing the infection of airborne diseases through natural ventilation in school environments

Ref.	**Case Study**	**Location**	**Objective**	**Method**	**Results**
[16]	Ten classrooms	Dublin	School ventilation rates and the COVID-19 indoor Airborne disease transmission potential are linked.	Mentoring and sensing	When ACH is 5: Presents Less than 1% infection risk during regular class durations and 5% throughout an 8-hour school day. Depending on classroom-specific factors, the lowest attainable ventilation rate reflects an infection risk of 7-12% (per class) and 75-100% (per school day). The wearing of masks within the indoor school setting provides protection. In situations with suboptimal ventilation rates, the likelihood of infection can be lowered from 7-12% to 1-5% for defined class durations. Over an eight-hour school day, the possibility of infection can be reduced from 75-100% to 18-43%. These reductions are available depending on the mask used.
[17]	Classroom	Italy	Monte Carlo approach combined with building performance modeling.	Mentoring and simulation	Emphasizing integrating diverse methods (for example, mixed-mode ventilation and face masks) can reduce risk for learners and educators.
[24]	Thirty-six classrooms in four schools	UK	Evaluating the indoor temperature and CO_2 concentration.	Mentoring and data pipeline	Significant differences were found when data from different schools and classes within the same school were compared.
[25]	Two classrooms	Slovenia	The effect of various urban contexts and classroom' windows on the CO_2 concentrations.	Mentoring	The urban context of the schools has a significant impact on IAQ (IAQ).
[20]	Classroom	-	The effect of natural ventilation on the airborne transmission of COVID-19 when a couple of infected students sneezed.	Mentoring, CFD, and Eulerian-Lagrange	Around 57% and 60.2% of the virus droplets (150 m d 1000 m) fell on the infected pupil's desk, whereas tiny droplets traveled in the airborne field. The effect of natural ventilation within the classroom on the travel of virus droplets was insignificant in the scenario of Redh 8.04.
[26]	Typical Polish classroom	Poland	Enhance IEQ while lowering the risk of infection with COVID.	Simulation and programming	The optimized controller with IE capabilities enhanced classroom ventilation and significantly lowered CO_2 concentrations. The users' thermal comfort was improved. The energy consumption increased. The controller had no significant effect on transmission.
[21]	Nine classrooms in a rural primary school	Spain	Evaluating natural ventilation techniques to reduce the possibility of infection with COVID-19.	Monitoring	The chance of infection was less than 14%. As a result, this study delivers a robust reaction against infectious diseases such as Covid 19 in school buildings where economic budgets for investment and maintenance are minimal.
[28]	Two secondary classrooms Laboratory	Netherlands	Find the finest sites for CO_2 measurement points	Monitoring	The position on the wall opposite the windows and the location on the front wall (near the instructor) were recommended as the best measurement points for naturally ventilated classrooms. One measurement point was sufficient because CO_2 was well-mixed in mechanically ventilated classrooms.

[27]	Classroom	China	Minimize the infection risk of COVID-19	CFD simulation	Altering window openings can raise the Airflow Distribution Performance Index (ADPI) by 17% while decreasing the chance of infection by 27%. The window-integrated fan improves ventilation performance and prevents disease transmission, resulting in an ADPI of 99%, and students sitting near the windows have an 11% chance of contracting an illness.
[19]	Exceeding 1000 classrooms	Italy	Investigating the correlation between increasing ventilation and decreasing the infection risk	Statistical analysis (regression models)	Compared to mechanical ventilation systems, the probability of infection for students dropped by at least 74% compared to natural ventilation. According to the regression study, each additional unit of ventilation rate per person results in a relative risk decrease of 12 to 15%.
[18]	Typical Classroom	Italy	Studies the feasibility of containing COVID-19 infection in interior spaces by boosting ventilation rates attained by high energy efficiency systems	Monitoring	Highly infectious circumstances with reproducing number Ro values are above 13. Robust mechanical ventilation would significantly reduce indoor virus concentrations and, as a result, infection risk. Facemasks are helpful even at minimal usage levels (from 50%) due to high ventilation rates. R0 is reduced by one in this manner. It is possible to reduce energy use by 60% to 72%.
[29]	Highschool classroom	Italy	Reducing the risk of aerosol infection	Monitoring	A dynamic evaluation of the complicated risk function across the whole exposure duration (rather than merely tracking the immediate CO_2 level) is required to regulate the infection risk from aerosolization appropriately.
[30]	111,485 schools	The US.	Evaluating the impacts of diverse intervention options, such as air filtration, improved ventilation, and hybrid education.	Modeling	Air filtration is the most efficient when using filters of MERV 13. To keep infection risk below 1% in most schools, coordinated intervention techniques will cause an infection risk of less than 1%.
[31]	Education classroom	Mexico	Evaluating the natural ventilation using air age	CFD simulation	Evaluating natural ventilation using ACH criteria might lead to incorrect judgments. It is recommended that natural ventilation standards be improved with the age of air-related characteristics.
[32]	11 classrooms	Italy	Limit the possibility of Sars-CoV-2 transfer by air.	Monitoring and data treatment	Real-time visualization of CO_2 concentrations is superior to just following regular ventilation techniques.
[15]	Three classrooms	Korea	Analyze the performance of natural ventilation in a school building based on window opening rates, locations, and weather conditions.	Measurement (field), tracer gas decay, and Wells-Riley equation	The mean ventilation rates under cross-ventilation circumstances were 6.51 h1 for a 15% window opening and 11.20 h1 for a 30% window opening. The ventilation rates for single-sided ventilation were lowered to around 30% of the averages from the cross-ventilation situations. When a mask is put on, and over 15% of the room windows are open for cross-ventilation, the infection chance is below one percent in all circumstances. With single-sided ventilation and a mask, the infection risk can be kept to 1% if the exposure period is shorter than 1 hour. However, despite how often a face mask is used, the infection rate surpasses 1% in all situations when exposure time exceeds 2 hours. Furthermore, when the air conditioning was turned on with WWR 15%, the power usage increased by 10.2%.
[33]	nonmedical functions such as classrooms	-	Building ventilation can reduce the risk of transmission of SARS-CoV-2 in nonmedical settings.	Analytical	Various recommended methods for its correct usage, such as maintaining and cleaning air conditioning systems for companies, schools, and residences, have been developed.

Additionally, most existing research examines the physical classroom environment separately from social dynamics, missing how these aspects together shape the overall Positive Learning Environment (PLE). Creating a sense of belonging is essential for enhancing social interaction [42], yet there is little research on how design can support or hinder these social connections. This study will investigate how purposeful design choices can foster community and collaboration among students, promoting a more well-rounded PLE. In conclusion, while current studies lay the groundwork for understanding PLE in classrooms, significant gaps remain. This study seeks to address these by focusing on the age-specific needs of students, the interaction between environmental quality and teaching goals, practical design solutions, and the social elements that contribute to a positive learning environment.

3. Methodology

3.1. Research Framework

This research proposes two frameworks that deal with the problem of the recurrence of infection of airborne bio-contaminant diseases (such as COVID-19). These frameworks consider the human-centric parameter and the pupils' stage learning environment requirements. The first framework (EDS) represented in Figure 1 considers the early design stage, and the second one (RO) deals with retrofitting scenarios. EDS involves a systematic approach to integrating health metrics into the design of educational facilities. This methodology includes steps such as modeling the indoor classroom, setting up the CFD model, and CFD simulation and optimization, distinguishing it from RO represented in Figure 2, which focuses on existing structures. In this study, the underlying hypothesis posits that integrating health-centric parameters into the design and retrofitting of educational facilities can significantly improve IAQ and student well-being. This hypothesis is grounded in existing literature that highlights the correlation between environmental conditions and health outcomes in educational settings [21].

The early design stage is addressed by the EDS framework illustrated in Figure 1. It incorporates five main phases featuring a developed GHPython script that involves the calculations of average air velocity (AAV) as a main objective in the optimization process. This aims to maximize the average air velocity inside the classroom targeting enhancing the IAQ. The design variables for the EDS are constrained by façade design parameters of WWR, OWR, and façade/classroom height. First, the classroom model is developed using Rhinoceros 3D and Grasshopper [43], [44]. Then the CFD model was configured by developing a GHpython code that calculates the average air velocity for the classroom at the breathing level of students (average between standing and seating positions). Afterward, the CFD simulation and optimization were run aiming to maximize the objective function within the effective range of design variables. When optimal result is achieved, the scatterplots are developed to represent the relationship between the objective function and design variables. Ultimately, a linear regression analysis was conducted to determine the coefficients of the design variables for predicting average air velocity.

Targeting retrofitting existing educational facilities, the RO framework aims to reduce airborne bio-contaminant disease infections while considering building a positive learning environment. As illustrated in Figure 2, the RO framework consists of four steps. (A) Modeling and validation of the CFD model. (B) CFD simulation for the Base Case (BC). (C) The involvement of human-centric parameters while considering performative computation parameters [45]–[47] (dynamic parameters and objective function). (D) Optimization and CFD simulation for suggested scenarios.

The first step consists of 4 levels: (A) Coding the CFD simulation model and modeling a measured reference building using Rhinoceroses (CAD software) [43], Grasshopper (visual programming software) [44], and Butterfly (CFD plugin that utilizes OpenStudio software) [48]. (B) Validating the CFD model by comparing the simulation results to the measured ones for the reference building. (C) Modeling the two classrooms within their context. (D) Create a CFD case from the school model.

The second step consists of two levels: (A) running the CFD simulation for the base case. (B) Calculating the ACH and compare it to the standards.

The third step involves human-centric parameters through (A) suggesting retrofitting scenarios suitable for the foundation stage class in terms of providing PLE. The suggested scenario supports an open learning environment ideal for classrooms as multi-activity places for children to use in the foundation stage (B), the same as the primary stage class. The proposed scenario supports a closed learning environment suitable to their stage that focuses on learning requirements for the primary stage. Open and closed learning environments refer to the relationship between the classroom and the faced one. Open means that the classroom-centered opening in the corridor-faced wall will enhance the interaction between pupils in the two-faced classrooms. This matches the nature of learning for the foundation stage, as they mostly learn through playing. Additionally, it improves the quality of the learning environment by engaging the pupils with others [38]. The closed scenario refers to elevating the opening in the corridor-faced wall to focus on the study for classroom pupils. Because the pupils at the primary stage mainly focus on studying the curriculum during classroom time, and they interact with other pupils in other shared spaces [38].

The fourth step utilizes dynamic parameters and objective functions in the CFD optimization process through 4 levels, (A) the manual optimization process (by testing three scenarios for each case. (B) CFD simulation for each suggested scenario. (C) ACH calculations using air velocity. (D) Comparing ACH to the standards, if met stop the process, if not try another option.

The fifth step concerns developing scatterplots for each design variable against the objective function (AAV) using TTtoolBox.

Eventually, the last step performs regression analysis to conclude the equation that presents regression coefficients for predicting average air velocity (AAV) using IBM SPSS Statistics software.

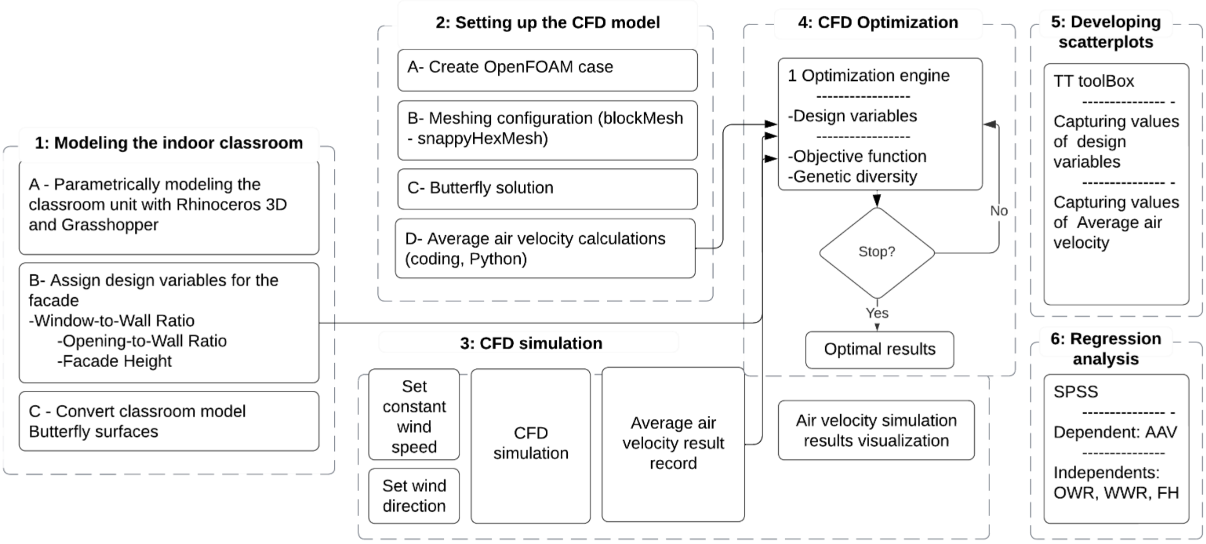


Figure 1. The first proposed framework (EDS) (single column)

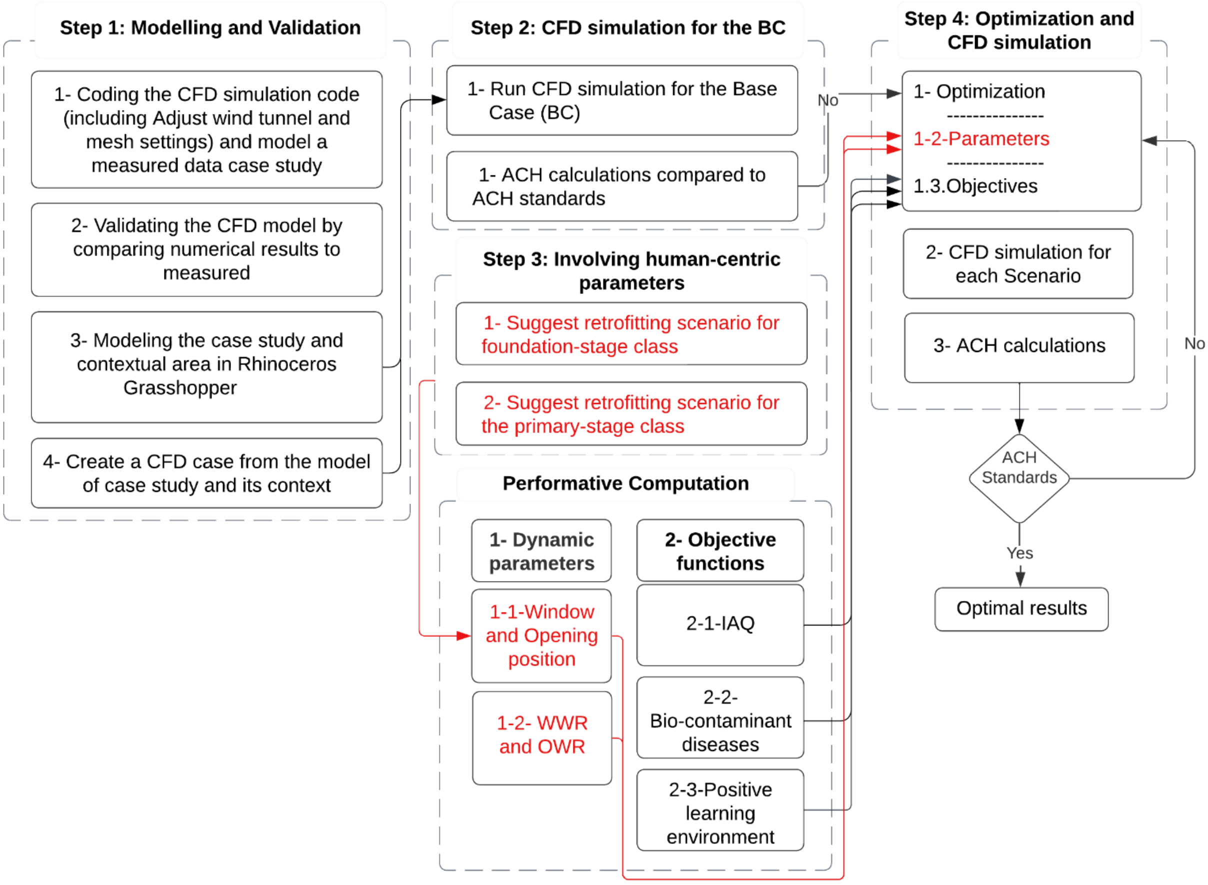


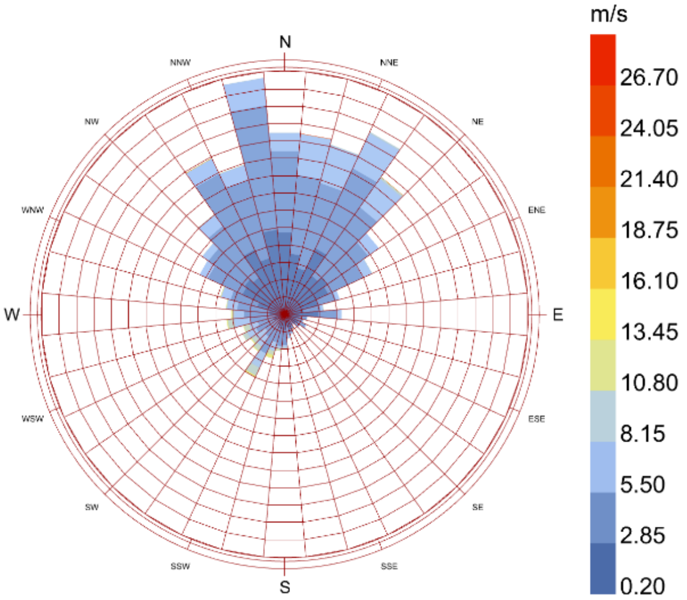
Figure 2. The second proposed framework (RO) (colored- single column)

3.2. Case Study

This section examines the application of both the EDS and the RO frameworks through specific case studies. While the RO framework is particularly suited for enhancing existing educational facilities, the EDS framework is illustrated using hypothetical design scenarios. These scenarios demonstrate the potential impact on future educational projects, emphasizing how innovative design approaches can significantly improve indoor air quality and student well-being. For the EDS framework evaluation, a hypothetical classroom measuring 7.10 meters in width, 6.8 meters in depth, and 3 meters in height is utilized. The design focuses on understanding how various design variables influence internal air velocity, which is critical for achieving optimal ventilation. To isolate the effects of these design parameters, a constant wind speed is maintained throughout the simulation. This controlled approach allows for a thorough examination of how changes in design impact airflow dynamics within the classroom environment.

In contrast, the RO framework is applied to an actual school classroom located in Cairo, Egypt. This site was selected due to its representative double-loaded classroom layout, which is common in many educational institutions. The layout consists of two classrooms positioned opposite each other, with one classroom oriented to face the prevailing wind direction while the other does not. This arrangement creates a unique scenario for studying cross-ventilation, as airflow can pass from one classroom to the other through openings in the indoor façade. Each classroom measures 7.10 meters in width, 6.8 meters in depth, and 3.9 meters in height separated by a corridor of 2.7 meters in width. Figure 3 illustrates the wind rose for the location of the case study, specifically at Cairo International Airport [49], [50]. This visual representation indicates the prevailing wind patterns in the area, which play a crucial role in the effectiveness of natural ventilation strategies. Understanding these patterns is essential for assessing how well the classrooms can utilize cross-ventilation to enhance air quality.

The study of the double-loaded classroom layout reveals important insights into how wind direction affects ventilation. The classroom facing the wind is expected to experience higher air velocity, promoting better air exchange compared to its counterpart. This cross-ventilation mechanism is facilitated by strategically placed openings in the façade, ensuring that fresh air can flow between the two spaces. This setup not only helps to improve indoor air quality but also provides a more comfortable learning environment for students. Overall, this case study serves as a practical example of how the RO framework can be effectively implemented in existing educational facilities, while simultaneously showcasing the potential of the EDS framework through hypothetical scenarios. By analyzing both frameworks in this context, the research aims to identify best practices and highlight the significance of thoughtful design in enhancing educational spaces.



Wind Speed (m/s)
city: Cairo Intl Airport
country: EGY
time-zone: 2.0
source: ETMY
period: 1/1 to 12/31 between 0 and 23 @1
Calm for 4.14% of the time = 363 hours.
Each closed polyline shows frequency of 0.6% = 50 hours.

Figure 3. Wind rose of Cairo, Egypt for the RO case study. [49], [50] (colored- single column)

3.3. Data, Variables, and ACH Threshold

To examine the influence of design variables on average air velocity within the EDS framework, a linear regression analysis was conducted using IBM SPSS Statistics software. Independent variables included the OWR, WWR, and FH. This analysis aimed to determine the predictive value of these design features on ventilation performance in a classroom setting. The SPSS regression model generated coefficients for each predictor variable, assessing their individual contributions and statistical significance in predicting average air velocity.

Descriptive statistics for the continuous design variables in the hypothetical case study, as detailed in Table **2**, summarize data characteristics for each key variable under the EDS framework. This table includes the Opening-to-Wall Ratio (OWR), Window-to-Wall Ratio (WWR), Façade Height (FH), and Average Air Velocity (AAV), based on 950 samples. OWR and WWR values ranged from 0.05 to 0.40, with means of 0.0965 and 0.1041, respectively, and standard deviations of 0.08902 and 0.09408, indicating moderate variability. Façade Height (FH) showed minimal variation with a mean of 3.205 meters and a standard deviation of 0.1418. Average Air Velocity (AAV) had a broader range, spanning from 0.000552 to 0.653734, with a mean of 0.16607920 and a standard deviation of 0.143425075, suggesting considerable variability across different configurations.

The RO framework was evaluated in the real case study, presented in Table 3, where WWR and OWR values were adjusted to 10, 20, 30, 10/10, 20/10, and 30/10, following literature guidance [15]. Window and opening positions were chosen to optimize the PLE as indicated by the literature [38]. Objective functions included enhancing Indoor Air Quality (IAQ), which correlates directly with the Air Changes per Hour (ACH) inside the classroom [16], and reducing the risk of airborne infections, which inversely correlates with ACH [27]. Enhancing the PLE was also targeted through strategically positioning windows and openings.

DIN 1946-Part 2 establishes a threshold for the required air changes per hour (ACH) in indoor spaces, classified by their functional use, to help mitigate COVID-19 transmission. For school classrooms, the standard recommends an ACH range of 6 to 20 [51]. The literature indicates that achieving 5 ACH can reduce infection probability to less than 1% in classroom settings [16]. Based on a comparison of standards and literature recommendations, this research will adopt a minimum threshold of 6 ACH for classrooms facing the wind direction. This ensures that the ACH in both classrooms remains within the recommended range.

Table 2. The descriptive statistics of the hypothetical case study (continuous) design variables (EDS framework)

Variable	N	Minimum	Maximum	Mean	Std. Deviation
OWR	950	0.05	0.40	0.0965	0.08902
WWR	950	0.05	0.40	0.1041	0.09408
FH	950	3.0	3.4	3.205	0.1418
AAV	950	0.000552	0.653734	0.16607920	0.143425075

Table 3. The quantification methods of real case study design variables (RO framework)

Parameters		Scenario	Units	Method	Values
Window and opening position	Foundation-stage classroom	A central opening in each façade (indoor and outdoor facades)	-	A scenario that enhances the PLE for the foundation stage (the proposed window/opening position prioritizes play-based learning in open environments)	-
	Primary-stage classroom	A central opening in the outdoor façade and an elevated opening in the indoor facade	-	A scenario that enhances the PLE for the primary stage (transition to a more structured learning environment)	-
WWR or OWR	Foundation-stage classroom	-	%	Window or opening ratio to the area of the wall	10%
		-	%		20%
		-	%		30%
	Primary-stage classroom	-	%		WWR 10% OWR 10%
		-	%		WWR 20% OWR 10%
		-	%		WWR 30% OWR 10%

3.4. The CFD Model Validation and Configuration

Validation is the procedure of evaluating the accuracy of a computational fluid dynamics (CFD) model in representing real-world conditions. In this study, the validation approach involved confirming that air velocity values within the building aligned with actual observations. Accurate air velocity measurements are crucial as they underpin all future calculations regarding air changes within the building. The CFD model was initially validated using comprehensive air velocity measurements from a heritage building in Alexandria, Egypt, which showed a discrepancy of less than 5% between simulated and measured data, within acceptable limits for model validation [52]. Due to the absence of publicly available airflow data for buildings in the Cairo metropolitan area, the Alexandria dataset was the most relevant for this investigation. Consequently, the same validated CFD algorithm was applied using wind speed data from the Cairo International Airport meteorological data file in the real case study, ensuring that the data reflected local climatic conditions. The study utilized a parametric methodology corroborated by Nayara Sakiyama et al. [53], which effectively represented hourly variations in wind speed and direction, essential for assessing natural ventilation.

The CFD model for the hypothetical case study was developed by creating a GHpython code that computes the average air velocity at the breathing level of pupils in the classroom, considering both standing and seated postures. The CFD optimization comprised 4784 iterations, with erroneous average air velocity values excluded, resulting in 950 valid results. The duration of each iteration in the optimization process was around 164 seconds. The optimization procedure was conducted using Octopus 0.4, a plugin in Grasshopper. The CDF optimization and simulation were conducted with the 11th Gen Intel(R) Core(TM) i7-11800H @ 2.30GHz 2.30 GHz processor.

CFD simulations for the real case study were conducted with the Butterfly plug-in, part of the Ladybug toolset for Grasshopper, utilizing the blueCFD-Core 2017-2 framework. The focus was on wind-driven ventilation, excluding thermal buoyancy effects, under isothermal conditions. The CFD model configuration for the real case study included both interior and outdoor environments, illustrating interactions around apertures. The computational domain was defined according to best practices, with dimensions set at five times the building height on the windward, height, and lateral sides, and fifteen times the height on the leeward side [54]. The research utilized an RNGkϵpsilon turbulence model, appropriate for both compressible and incompressible flows, with a roughness (Z_0) established at 1 meter. The simulation utilized meteorological data, with wind velocity reference height established at 10 meters above ground level.

The assessment horizontal plane for the real and hypothetical case study is established at a height of +1.1/1.2m above the finished floor level (FFL) of the classroom to represent the average level of standing and seating [55]. The simulation time for the real case study was approximately 25,200 seconds. The mesh was created using OpenFOAM's snappyHexMesh and blockMesh functions and refined near the building to ensure accuracy. Boundary conditions were defined based on the meteorological data file, with wall functions applying default y+ values for the RNGkϵpsilon, and the exit exhibiting a zero static pressure condition. This comprehensive validation and modeling approach not only enhance the reliability of the CFD simulations but also provide a solid foundation for future studies aimed at optimizing natural ventilation in buildings.

4. Results and Discussion

The results indicate that the suggested frameworks for EDS and RO effectively improve IAQ and the learning environment in educational facilities. The results are elaborated upon in detail below.

4.1. Results of the EDS Framework

The implementation of the EDS framework demonstrates a marked improvement in indoor air quality (IAQ), as indicated by the regression analysis and the visual data representations. The analysis reveals that the model explains 33.1% of the variance in average air velocity (AAV), suggesting a notable influence of the design variables considered. Figure 4 illustrates the Pareto front solutions, highlighting the nondominated solutions within the EDS framework. These solutions represent optimal trade-offs among design variables that maximize AAV while maintaining balance across other performance metrics. The CFD simulation results for the design variables that achieve the best solution for AAV (0.65 m/s) are presented in Figure 5, with optimal values of 40%, 35%, and 3.1 meters for OWR (inlet), WWR (outlet), and FH, respectively. The presence of these nondominated solutions indicates that strategic design decisions can lead to enhanced airflow characteristics in classroom environments, aligning with the overarching goals of the EDS framework.

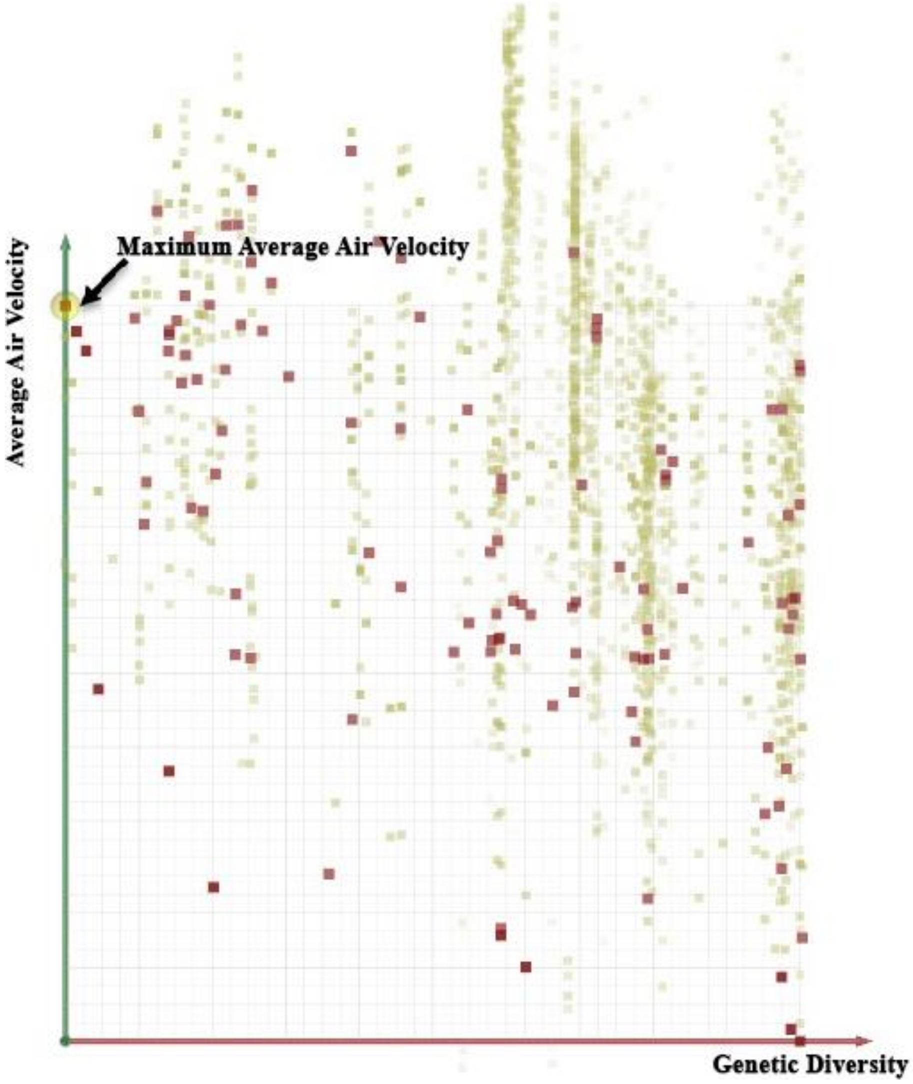


Figure 4. Optimization results for EDS framework, with each cube symbolizing one iteration. (colored- single column)

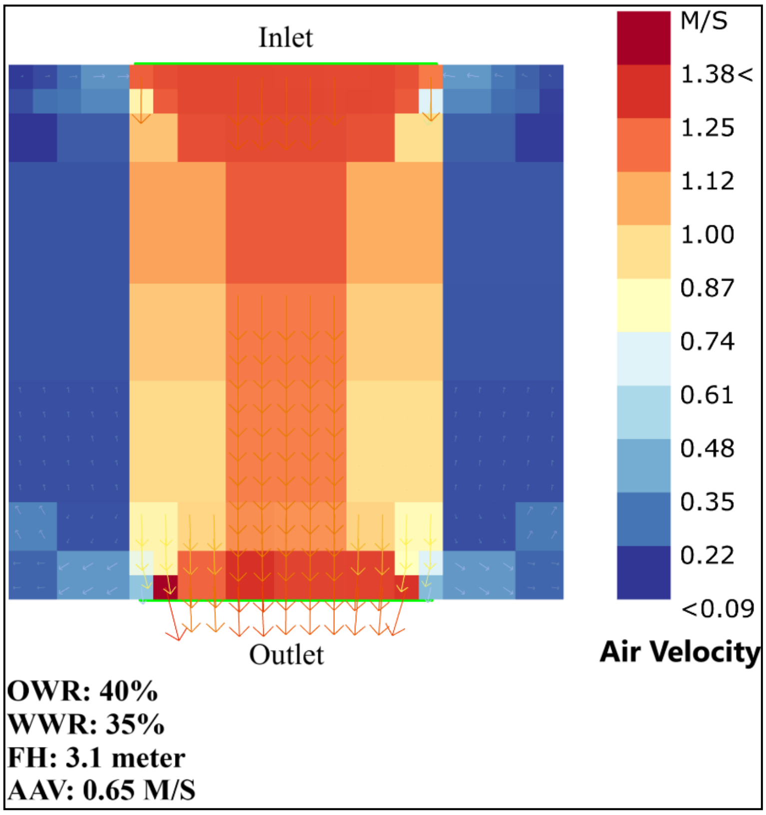


Figure 5. Best solution CFD simulation results for the hypothetical case study EDS (the window and openings are drawn in green) (colored- single column)

In Figure 6, scatterplots depicting the relationship between the hypothetical case study design variable values and AAV reinforce the insights gleaned from the regression analysis. The scatterplots provide a visual representation of how variations in the OWR, WWR, and FH impact average air velocity. The observed trends further support the hypothesis that proactive design measures can effectively enhance IAQ in educational settings. The regression equation derived from the analysis is expressed as:

$$\boldsymbol{AAV = 0.889 + 0.733OWR + 0.147WWR - 0.253FH} \quad (1)$$

Equation 1 emphasizes the relative contributions of each independent variable to AAV. The constant term (0.889) signifies the baseline average air velocity when all independent variables are at zero. The positive coefficient for OWR (0.733) indicates a strong positive relationship, where increases in OWR are associated with significant improvements in AAV. Conversely, the negative coefficient for FH (-0.253) suggests that greater facade heights may detrimentally affect air velocity, highlighting the need for careful consideration of vertical space in the design.

Table 4 outlines the regression coefficients, detailing the unstandardized (B) and standardized (β) coefficients, along with their respective p-values. Significant predictors, including OWR ($p < 0.001$) and FH ($p < 0.001$), affirm the robustness of these variables in predicting AAV. The WWR is marginally significant ($p = 0.007$). The statistical validity of the model is further reinforced by the ANOVA F-test, which yielded a p-value of < 0.001, indicating a strong predictive relationship between the independent variables and the outcome.

Overall, the EDS framework not only underscores the importance of design in enhancing IAQ but also establishes a foundation for comparing these results with those from the RO framework, ultimately aiming to advance the effectiveness of proactive design strategies and student engagement in educational environments.

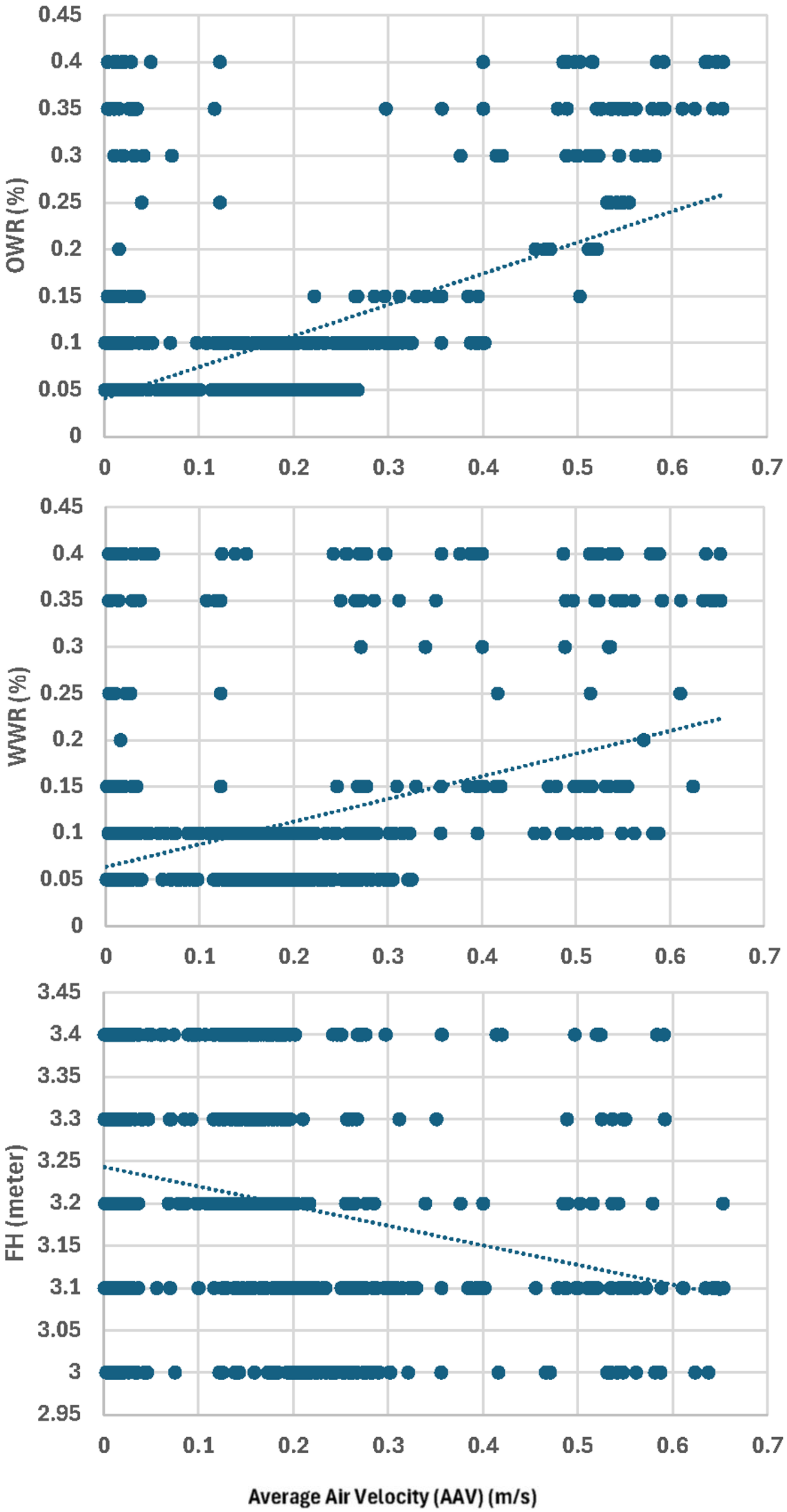


Figure 6. Scatterplots of the EDS hypothetical case study design variables values against average air velocity value (single column)

Table 4. Regression coefficients for predicting average air velocity (AAV)

Independent Variable	B	β	P
(Constant)	0.889		<0.001
Opening-to-Wall Ratio (OWR)	0.733	0.455	<0.001
Window-to-Wall Ratio (WWR)	0.147	0.097	0.007
Classroom/Façade Height (FH)	-0.253	-0.214	<0.001
R^2		0.331	
ANOVA - F Test P		<0.001	

4.2. Results of the RO Framework

Comparing outcomes from the EDS framework with those from the RO framework offers valuable insights into the effectiveness of proactive design strategies and their impact on student engagement. The RO framework is particularly versatile, applicable to various case studies, and capable of addressing a range of design challenges. For this study, the RO framework was applied to a classroom in a private school located in New Cairo, Cairo, Egypt, with results illustrated in Figure 7, Figure 8, and Figure 9. The stages and results of the RO framework are summarized in Figure 7. Key findings at each step include:

Step 1: Validation of the CFD model by comparing numerical results to measured data, confirming model accuracy.

Step 2: The ACH (Air Changes per Hour) was found to be insufficient for classrooms oriented against the wind direction.

Step 3: The authors proposed two scenarios optimizing window and opening positions to enhance the PLE. The following are the findings of Step 4:

- For the foundation stage classroom, the optimal W/OWR for a central opening on each façade is 20%, achieving an ACH of 6.94. The CFD simulation for this optimum solution is shown in Figure 8.
- For the primary stage classroom, which includes a central outdoor opening with an elevated indoor opening, the optimal results are 30% WWR for the outdoor façade and 10% OWR for the indoor façade, achieving an ACH of 7.33. The corresponding CFD simulation is presented in Figure 9.

The probability of infection with airborne diseases in foundation and primary stage classrooms decreased to below 1% for against-wind direction orientations, as referenced in [16]. In a similar study [15], researchers concluded that a 15% WWR for cross-ventilation significantly reduces infection rates to below 1%, aligning with this study's findings where infection rates dropped to less than 1% with more than 15% W/OWR in the foundation classroom. However, while that study also examined hybrid (mechanical/natural) ventilation scenarios, our study focused solely on natural ventilation. Another study [16] found that an ACH rate of 5 or higher correlates with infection risks below 1%, consistent with our findings. While the WWR and OWR optimal values vary, our findings suggest an optimal WWR of around 20-30% for central openings and 10% for elevated openings, whereas other studies, such as [15], found variations like a 15% WWR optimal value.

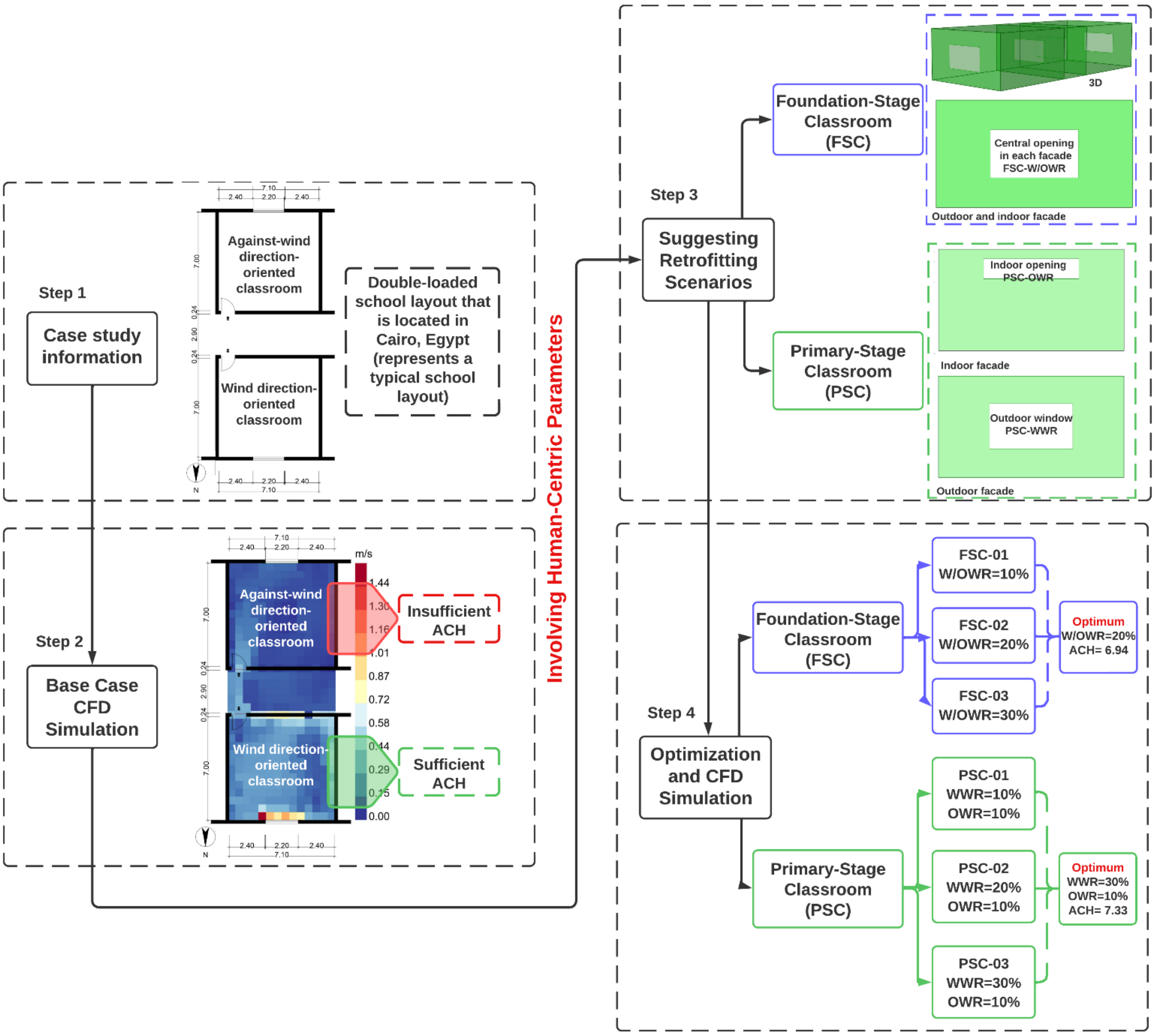


Figure 7. Execution stages and results for applying the RO framework to the case study. (colored- single column)

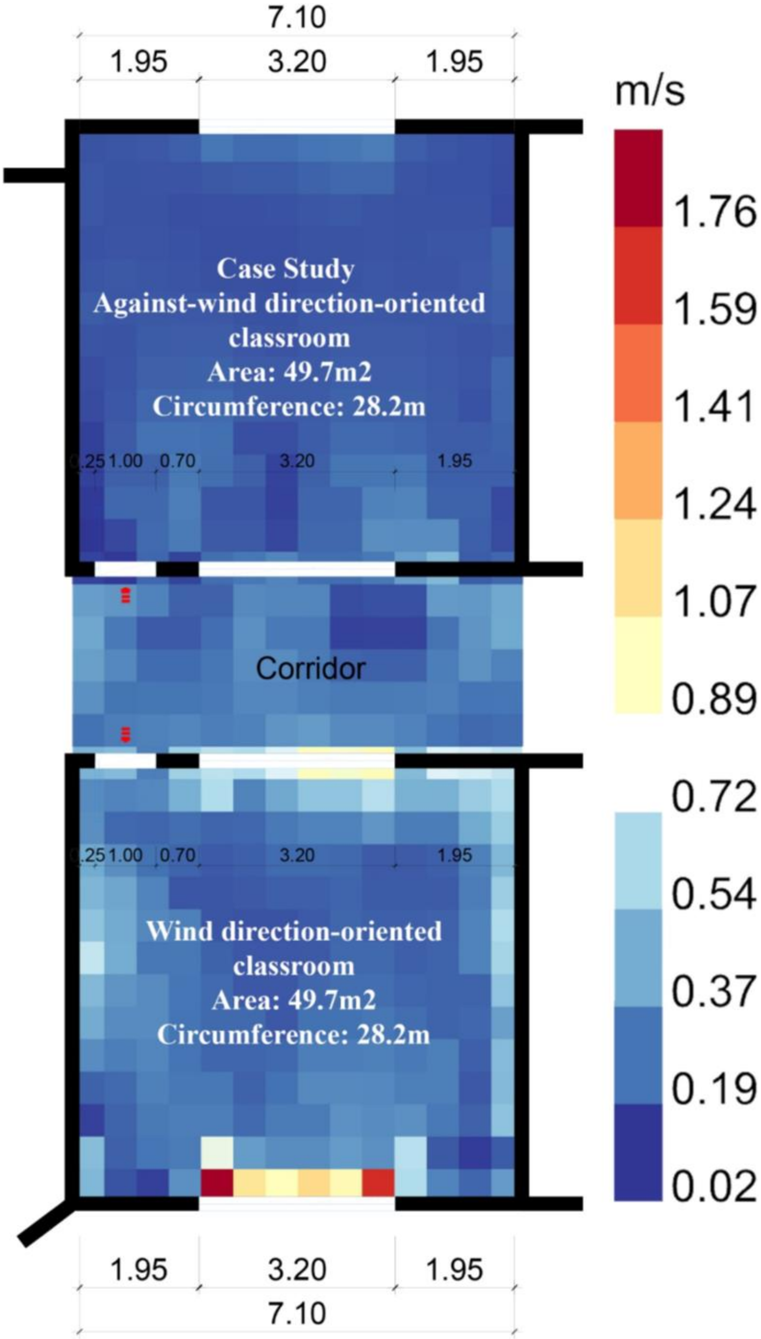


Figure 8. The CFD simulation result for the optimum solution of FSC. (colored- single column)

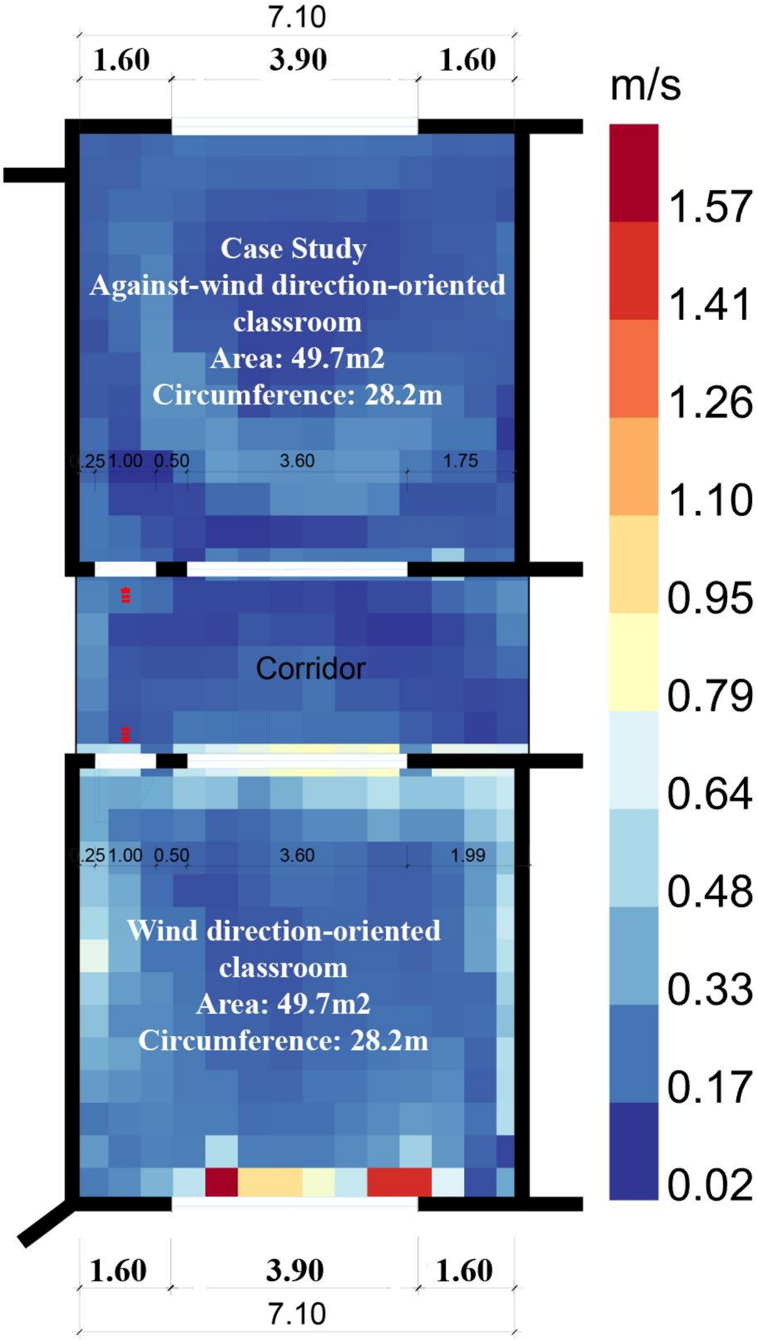


Figure 9. The CFD simulation result for the optimum solution of PSC. (colored- single column)

The proposed EDS and RO frameworks offer structured approaches to designing classrooms that support improved IAQ, reduced airborne disease transmission, and enhanced learning environments. However, several limitations remain within both frameworks.

The EDS framework, while effective in identifying variables that influence average air velocity (AAV) and IAQ improvements, similarly faced limitations. The statistical model used in EDS explains only 33.1% of the variance in AAV, suggesting that additional environmental or behavioral factors, not accounted for in this study, may also significantly influence airflow. Additionally, because this framework was only tested in hypothetical scenarios rather than real classroom settings, the findings may not fully represent the complexity of live environments.

For the RO framework, the reliance on validated CFD simulations in the absence of specialized measurement tools limits the capacity to confirm results under real-world conditions fully. The analysis was conducted on a single case study, constraining the broader applicability of findings across diverse building types and climates. Furthermore, time constraints prevented the inclusion of direct feedback from school building occupants. Collecting qualitative data from teachers, students, and other users—through questionnaires or focus groups—could provide valuable insights into comfort and usability, essential in understanding the activity-space relationship and informing occupant-centered design decisions. Furthermore considering the effectiveness of isolation, and social distancing factors on the infection rates is a limitation of this study. Finally, both frameworks were developed with numerical modeling tools, which, while validated, may not capture all dynamic interactions in occupied spaces.

Future research should address these limitations by expanding the frameworks' application across multiple schools and climate zones and integrating feedback from occupants to ensure designs align with actual user needs while considering other relevant factors such as social distancing. This could strengthen the evidence base for these frameworks and support their use as robust tools in architectural design for educational environments.

5. Conclusions

This paper presents novel frameworks for designing or retrofitting classrooms to improve IAQ, reduce airborne disease transmission, and create more supportive learning environments. By reviewing the literature on how natural ventilation reduces airborne infection risks and how design variables can promote PLE in school settings, the study identifies existing research gaps. To address these, it introduces two frameworks, one is broad and the other is specifically designed for different stages of school building design, aimed at enhancing IAQ and reducing health risks in classrooms. The EDS framework is developed to optimize façade design variables, including WWR, OWR, and FH, in hypothetical classroom scenarios, aiming to maximize AAV through a CFD-parametric optimization approach using custom GHPython code and linear regression analysis. The EDS framework begins by creating a classroom model in Rhinoceros 3D with Grasshopper. A GHpython code is then used to configure the CFD model, calculating average air velocity at the student's breathing level. Next, CFD simulation and optimization are conducted to maximize air velocity within the design variable range. Scatterplots illustrate the relationship between air velocity and design variables. Finally, a linear regression analysis was performed to find the coefficients of design variables for predicting average air velocity. Results from the EDS framework reveal that these key design parameters explain 33.1% of the variance in AAV, with optimal configurations achieving 0.65 m/s AAV. Findings highlight OWR's positive impact on airflow and the negative effect of increased façade height, providing a basis for early-stage strategies that can significantly improve IAQ in educational spaces.

The Retrofitting Optimization (RO) framework, focused on improving existing educational facilities, assesses and adjusts window/opening position, WWR, and OWR to meet the recommended ACH standards. The framework consists of four steps: modeling and validating the CFD model, running the CFD simulation for the Base Case, considering human-centric parameters, and optimizing and simulation for suggested scenarios. The first step involves coding the CFD simulation model, validating it, and creating a CFD case from the school model. The second step involves running the simulation and calculating the ACH for the base case. The third step involves human-centric parameters, suggesting retrofitting scenarios suitable for the foundation stage class, such as an open learning environment for multi-activity classrooms and a closed learning environment for primary-stage students (open and closed describe the relationship between the two opposite classrooms). The fourth step uses dynamic parameters and objective functions in the CFD optimization process, including manual optimization, simulation, ACH calculations, comparison to standards, scatterplots, and regression analysis. Applied to classrooms in Cairo, Egypt, the RO framework's CFD simulations confirmed optimal configurations: a 20% W/OWR for foundation-stage classrooms achieving an ACH of 6.94 and a 30% WWR with 10% OWR for primary-stage classrooms reaching an ACH of 7.33. Both configurations lowered airborne infection risk to below 1%, aligning with other studies linking increased ventilation with reduced infection rates.

Together, the EDS and RO frameworks provide robust tools for enhancing IAQ and creating healthier learning environments. They fill critical gaps in the literature by addressing both early-stage design considerations and the retrofitting of existing structures. They represent a novel integration of health and environmental design principles, emphasizing the need for a holistic approach to educational environments. This research underscores the importance of prioritizing health in both new constructions and renovations, paving the way for further studies that can expand upon these findings and contribute to improved health outcomes in learning environments. In conclusion, both EDS and RO contribute valuable insights to the field of educational design. Future research should broaden the frameworks' applicability by testing them in diverse climatic regions and school types, while also incorporating direct feedback from occupants, such as students and teachers, to refine design strategies that support both health and learning in educational spaces.

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