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A Socio-CFD Approach to Reduce the Possibility of Airborne Bio-Contaminant Disease Infection in Indoor Spaces

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ABSTRACT

This paper introduces a novel socio-CFD method called Epidemic Hybrid Retrofitting (EHR) for enhancing natural ventilation in indoor public spaces to reduce the spread of airborne bio-contaminant diseases, such as COVID-19. The method aims to reduce the infection rate of diseases by improving Indoor Air Quality (IAQ) as a quantitative objective and maximizing user satisfaction as a qualitative objective. The EHR method consists of three phases, with another method called Computational Fluid Dynamics Parametric Optimization (CFDPO) to accelerate the CFD simulation process. The proposed methods were tested in a shared office in Cairo, Egypt, using a combination of observation, investigation, questionnaires, CFD analysis, linear regression analysis, mathematical calculations, and hybrid evaluation. The study observed a recurrence of COVID-19 infections in the case study office, which was attributed to insufficient natural ventilation and occupants' lack of adherence to WHO precautionary measures. Four retrofitting scenarios were suggested based on the application of the CFDPO method. An occupant survey and CFD analysis were conducted to evaluate retrofitting scenarios, and then the Cost Reduction factor (CRf) was introduced and considered. Considering quantitative and qualitative objectives has identified the optimal scenario as Single-centered Openable Windows (SOW) by increasing the window-to-wall ratio (WWR) on the outdoor (north-facing) façade to 14.96% while maintaining a balanced indoor opening design. The optimum solution effectively achieved the desired air change rates and occupant satisfaction. The results demonstrated the applicability of the EHR and CFDPO methods to attain the objectives. The proposed methods can be further adjusted to address additional objectives in future practices.

Index-words: *COVID-19; Retrofitting Façade; Health and Wellness; Indoor Air Quality (IAQ); Natural Ventilation; Occupant Satisfaction.*

I. INTRODUCTION

Various challenges face the architectural engineering sector. Among those challenges, the world is still becoming aware of the Coronavirus Disease 2019 (COVID-19) [1]. By October 2023, 231 countries have been affected by the COVID-19 epidemic, with over 697 million infected cases and over 6.9 million deaths [2]. During the outbreak of COVID-19, the World Health Organization (WHO) advised the public to some preventive procedures. These procedures are related to four main categories: dealing with others, providing a safe environment, maintaining good hygiene, and dealing with others when infected or suspected of COVID-19 [3]. As for dealing with others and providing a secure environment, some measures may affect the architectural design process. For example, it may direct the designers to new determents while designing public spaces in the early design stage. Even supposing that the vaccination will limit the infection of COVID-19, considering indoor air quality procedures from the early design stage will mitigate the chance of new airborne bio-contaminant pandemics.

Some existing public spaces may need executing retrofitting scenarios to mitigate infections. Supplying indoor spaces with sufficient fresh air could be one of the solutions [3]. The importance of providing indoor spaces with adequate fresh air is assuring the health and wellness of space users. In comparison, the American Society of Heating, Refrigerating, and Air-Conditioning (ASHRAE) mentioned that the users of indoor-closed spaces (which do not supply sufficient fresh air) might suffer from wellness troubles such as pneumonia and bronchial asthma. They may suffer from hypersensitivity, bio-contaminant diseases, respiration difficulties, and lung cancer caused by radon peril and poisoning by CO (carbon monoxide) [4] and [5]. The investigation found that increasing the natural ventilation per hour was effective in reducing the rate of COVID-19 infection [6]. Therefore, new creative retrofitting scenarios are needed to ensure a safe and healthy indoor environment.

Airborne bio-contaminant diseases (such as SARS-CoV-2 (COVID-19), SARS-CoV, and Middle East respiratory syndrome coronavirus (MERS-CoV)) spread initially among humans by direct communication transition, along with respiration drops with a diameter >5–10 μm [7]. Centers for Disease Control and Prevention (CDC) approved that COVID-19 is originally transmitted airborne and caused by sneezing, coughing, respiration, and chatting [8]. The main challenge of bio-contaminant airborne transmission is the particles < 5 μm. These particles stay in the air indefinitely unless the indoor space is well-ventilated [9]. If the space occupants breathe these particles, they precipitate in the lungs, causing dangerous health issues [10]. COVID-19 particles are transmitted in conditions like indoor spaces, insufficient natural ventilation or air handling, and prolonged exposure to the particles [11]. Nishiura et al. [12] proved that the transference of COVID-19 in indoor spaces was 18.7 times higher than in outdoor (open-air) spaces. The literature review approved the effectiveness of natural ventilation in decreasing the transmission of airborne contaminants inside spaces, for example, [13], [14]- [15]. Various publications investigated the aerosol behavior of bio-contaminant diseases (such as COVID-19), such as [16, p. 2], [17], and [18]. Furthermore, [16, p. 2] executed a laboratory experiment to compare the aerosol behavior of SARS-CoV-1 and SARS-CoV-2. Their investigation showed that the SARS-CoV-2 could maintain viable air for three hours (experiment duration). Additionally, Fears et al. [17] compared the aerosol behavior of SARS-CoV-2, SARS-CoV, and the Middle East respiratory syndrome coronavirus (MERS-CoV). Their laboratory experiment showed that SARS-CoV-2 infection can last an aerosol for up to sixteen hours. Moreover, Jiang et al. [18] detected the aerosol existence of SARS-CoV-2 in a solution hospital in China. As a result, they noticed the presence of aerosol SARS-CoV-2 in the air of the hospital solution section. Therefore, it is essential to ensure sufficient Air Change (ACH) in public indoor spaces to remove the viral aerosols.

Previous studies have investigated some factors that are related to energy efficiency and thermal comfort and their direct relation to the design process, leading to a shortage in investigating the indoor air quality effect on the design configurations [19]–[30] and [30]–[39]. The recently published journal papers for reducing the infection of airborne bio-contaminant diseases through natural ventilation are presented in Table I. The aim of analyzing those papers is to determine the scientific gaps within the scope of the application. Those publications are analyzed according to the classification of references, approach, building function or target participants, base-case model, dynamic parameters, objective functions, method, and criteria/conclusion. Several works of COVID-19 literature focused on the impact of applying precautionary procedures on minimizing COVID-19 infection rate, for example, [40], [41], [42], [43], [44] and [45]. The literature also includes review papers that analyzed and discussed COVID-19 indoor airborne transmission models and mitigation strategies [46], as well as modeling strategies for COVID-19 in three regions [47]. Additionally, the effect of natural and mechanical ventilation modes on the transmission of indoor airborne contaminants was investigated in [48].

The connection between COVID-19 transmission and HVAC systems was investigated in the literature in, for example, [49], [50] and [51]. Ren et al. [52] increased the airflow index and decreased the infliction rate inside a classroom using window retrofitting and natural ventilation-fans integrated scenarios. Xu et al. [53] validated the method of reducing the infection rate by increasing the natural airflow rate by applying different mediation strategies to schools in the U.S. Park et al. [54] minimized the infection rates for a classroom through natural ventilation by finding optimal WWR. Klompas et al. [55] recommended natural ventilation for enclosed shared spaces to avoid the accumulation of virus-laden airborne. Some other studies have developed new approaches for ventilation design to reduce the infection of airborne contaminants, such as in [56]–[58], or to enhance indoor air quality generally [59]. However, previous research has studied the mitigation of infection numerically, neglecting the social aspect represented by space users. This paper contributes to the knowledge by considering the social aspects of infection mitigation in addition to numerical analysis. The key contributions are: (1) a novel approach that combines quantitative and qualitative objectives to integrate numerical methods with spatial and social elements; (2) an investigation of the efficiency of natural ventilation on airborne contamination (COVID-19) transmission in enclosed public spaces, with a specific focus on the Egyptian context where the existing literature is limited; and (3) The CFDPO method aims to accelerate Computational Fluid Dynamics (CFD) time by merging the benefits of parametric optimization. The applicability of both EHR and CFDPO methods was tested by applying them to a real case study that suffers from a recurrence of infection of COVID-19. Actual infection rate calculations were gathered through a user questionnaire (investigation stage), and further calculations were executed to prove the problem mathematically. Involving the space users (through a user questionnaire – evaluation stage) while making the retrofitting decision is also considered an added contribution to the paper. The applicability of the proposed EHR and CFDPO methods was tested on a public shared office located in Cairo, Egypt.

This paper proposes two novel methods that target hybrid objectives aiming to reduce the infection of airborne bio-contaminant diseases by involving space users in the retrofitting scenario. First, the paper explains the methods through three sub-sections. Next, the paper presents the case study, including selection criteria, characterization, and CFD Model Validation and Configurations. Then, the results are illustrated in three sections. After that, the paper discusses the differences and similarities between its results and previous related study results through the discussion section. Additionally, it states the difficulties and limitations of this study. Finally, the conclusion gives an overview of the paper and its results and demonstrates the recommendations for future studies.

TABLE I
RECENT LITERATURE REVIEW FOR REDUCING THE INFECTION OF AIRBORNE BIO-CONTAMINANT DISEASES THROUGH NATURAL VENTILATION.

BF: Building Function, CS: Case Study, DP: Dynamic Parameters, DTM: Dynamic Thermal Modelling

Ref.	Approach	Location	BF/CS Type	Base-Case Model	DP.	Objective Functions (OF)	Method	Criteria / Conclusion
[60]	Assessment	-	Hypothetical	-	-	Smart Building Systems implementing CO_2 Sensors	Monitoring and CFD simulation	A new 'opportunity of infection' measure uses computational fluid dynamics and machine learning to measure indoor infection risk in office settings, highlighting the need for better ventilation techniques and improved modeling tools.
[61]	Assessment	London, UK	Office/ Authentic	open-space office	-	Hourly Airborne Infection rate (HAI)	DTM and CFD simulation	Understanding comprehensive interior airflow properties and associated concentration behaviors is critical for providing detailed design guidelines, such as supply air diffusers, occupancy, and furniture layouts, to limit the risk of airborne infection.
[62]	Assessment	Netherlands	Educational/ Authentic	Laboratory and two real classrooms	-	Natural ventilation	Monitoring	The researchers aimed to find a novel method to assess classroom ventilation performance. Additionally, they compared laboratory results with two real classroom measurements to find a guide for CO_2 measurements' best points.

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Ref.	Approach	Location	BF/CS Type	Base-Case Model	DP.	Objective Functions (OF)	Method	Criteria / Conclusion
[63]	Assessment	London, Italy	Home Workers/ Authentic	-	-	Indoor soundscapes, building services, window opening behaviour	Online Survey	The researchers assessed the home workers' behavior during COVID-19 pandemic using an online survey.
[64]	Assessment	London	Residential/ Hypothetical	One-bedroom flat (50.8 m^2) with one-sided ventilation	-	Temperature, relative humidity, CO_2, particle matter, occupancy, and opening patterns	Monitoring	The researchers used monitoring equipment to assess temperature, relative humidity, CO2, and particle matter in home working places. Additionally, they assist with occupancy and opening patterns.
[52]	Retrofitting	China	Educational/ Authentic	Classroom (14.0 m × 8.5 m × 5.0 m, V:595 m^3	Window openings position	Reduce infection risk through natural ventilation	CFD Simulation	The researchers tested various modes of window openings in a classroom to find the optimal for infection (with COVID-19) reduction.
[65]	Assessment	N/A	Commercial (cafe)/ Hypothetical	-	-	ACH, Infection risk	Numerical Simulation	According to infection risk (with COVID-19) measurements and calculations, the researchers recommended minimum ACH and the number of users on the dinner table.
[66]	Assessment	N/A	Public Space/ Hypothetical	-	-	Infection risk	Monitoring	The researcher developed a methodology to calculate the secondary expected infection risk (with COVID-19) in a public space when an original user is infected.
[67]	Assessment	Italy	Educational/ Authentic	Historical (252.2m^3), Standard (149.7m^3)	-	Infection risk	Monitoring	The researcher assessed the impact of occupancy, volume, CO2 monitoring, and natural ventilation on the infection risk of COVID-19.
[68]	Assessment	Mexico	Educational/ Hypothetical	Educational building), (0.1× 0.1×0.08) m	Window openings position	Standardization	CFD Simulation	The researchers aimed to assess four window positions that target finding new standards regarding natural ventilation. Their research recommended considering the renovation parameter and air renovation per hour while assessing natural ventilation.
[10]	Assessment	Turkey	Office/ Hypothetical	Single-zone room (16×16×4m)	Indoor temperature, opening-to-wall ratio, opening orientation	Infection risk	CFD Simulation	The researchers investigated the relationship between contaminant source position and various parameters (indoor temperature, opening-to-wall ratio OWR, and opening orientation). The results of their study show a direct relationship between reducing the infection of biocontainment diseases and maximizing indoor temperature and OWR. Additionally, they recommended considering reducing airborne bio-contaminant diseases in the building standards.

Ref.	Approach	Location	BF/CS Type	Base-Case Model	DP.	Objective Functions (OF)	Method	Criteria / Conclusion
[54]	Assessment	Korea	Educational/ Authentic	Three classrooms (64.62 m^2, 168.0 m^3)	Ventilation modes, W/ OWR	Infection risk	Field measurement	The researchers assessed the relationship between reducing COVID-19 infection and natural ventilation. This assessment happens through varying ventilation modes (single and cross ventilation) and W/OWR. Their study resulted in recommendations regarding the infection probability of COVID-19 coupling with natural ventilation and preventive procedures.
[69, p.2]	Analysis	N/A	-	-	-	Infection risk	Review	The researchers investigated the literature on the impact of natural ventilation on the infection risk of COVID-19. They concluded that the more ACH, the less infection risk of COVID-19.
[16, p. 2]	Experiment	USA	-	Laboratory experiment	-	COVID-19 aerosols behavior	Monitoring	The researchers executed a laboratory experiment the compare the aerosol behavior of SARS-CoV-1 and SARS-CoV-2. Their experiment showed that the SARS-CoV-2 could maintain viable air for three hours (experiment duration).
[17]	Experiment	USA	-	Laboratory experiment	-	COVID-19 aerosols behavior	Monitoring	The researchers compared the aerosol behavior of SARS-CoV-2, SARS-CoV, and the Middle East respiratory syndrome coronavirus (MERS-CoV). Their laboratory experiment showed that SARS-CoV-2 infection can last an aerosol for up to sixteen hours.
[18]	Assessment	China	Hospital/ Authentic	-	-	COVID-19 aerosols behavior	Field measurement	The researchers detected the aerosol existence of SARS-CoV-2 in a solution hospital in China. As a result, they detected the presence of aerosol SARS-CoV-2 in the air of the hospital solution section.

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II. METHODS

The research methodology presented in Figure 1 was conducted by finding the Epidemic Hybrid Retrofitting Method (EHR) (socio-CFD), which passes through three main phases and has gone through different procedures to fulfill the outcomes, as illustrated in Figure 2. As presented in Figure 2, the Computational Fluid Dynamics Parametric Optimization (CFDPO)[1] method was derived from the EHR method, which is presented in Figure 3.

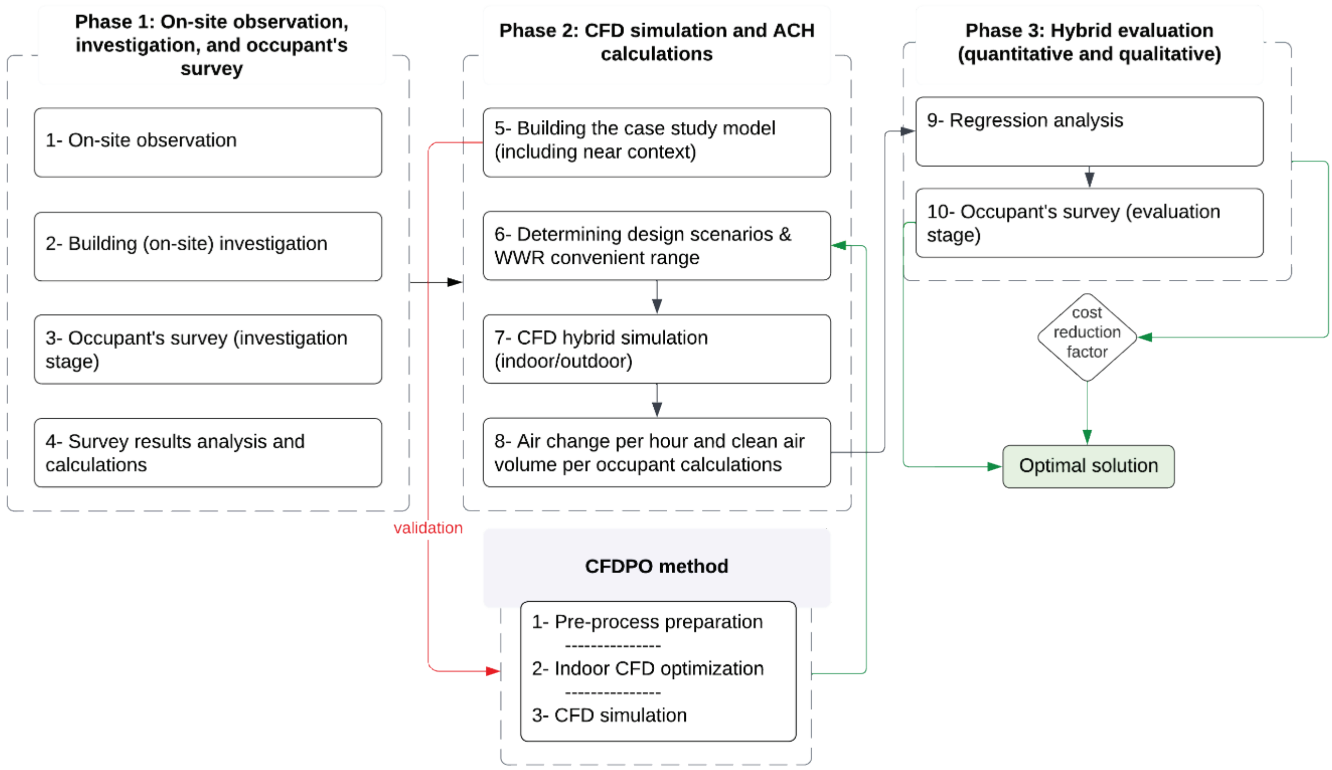

Fig. 1. Research methodology

[1]*The Computational fluid dynamics Parametric optimization CFDPO method aims to reduce computational time parallel with reaching accurate results regarding CFD assessments. The CFDPO method consists of three major phases, as presented in Figure 2. Hence proved that the CFD simulations consume plenty of computational time as in previous research such as [70], [71], [72], and [73]. Furthermore, through the empirical test to the case study, every option consumes around eight hours to get the CFD results (laptop processor specs: 12th Gen Intel® Core™ i3-1215U (10 MB cache, 6 cores, 8 threads, up to 4.40 GHz Turbo)). While the range of the retrofitting parameter varies, there is no reference to which options will fit. A need for fast CFD optimization has shown up to test the parameters and make a sensitivity analysis. Considering that metaheuristics algorithms consume less computational time compared to other algorithms, such as genetic algorithms, as proved in [74] and [75]. Therefore, swarm algorithm optimizers were selected in functioning the optimization process. Reference to the recently published literature review concerning the use of swarm algorithms in solving computational architecture problems [28], [76]. There are almost no published articles concerned the air change through CFD analysis using metaheuristics algorithms. Therefore, using swarm algorithms as a CFD optimizer to assess Air Change per Hour ACH is considered an additional contribution. Since the CFDPO method is derived from the EHR method, the CFDPO steps are included briefly in the EHR method structure. However, different cases may need to apply the CFDPO method solitary.*

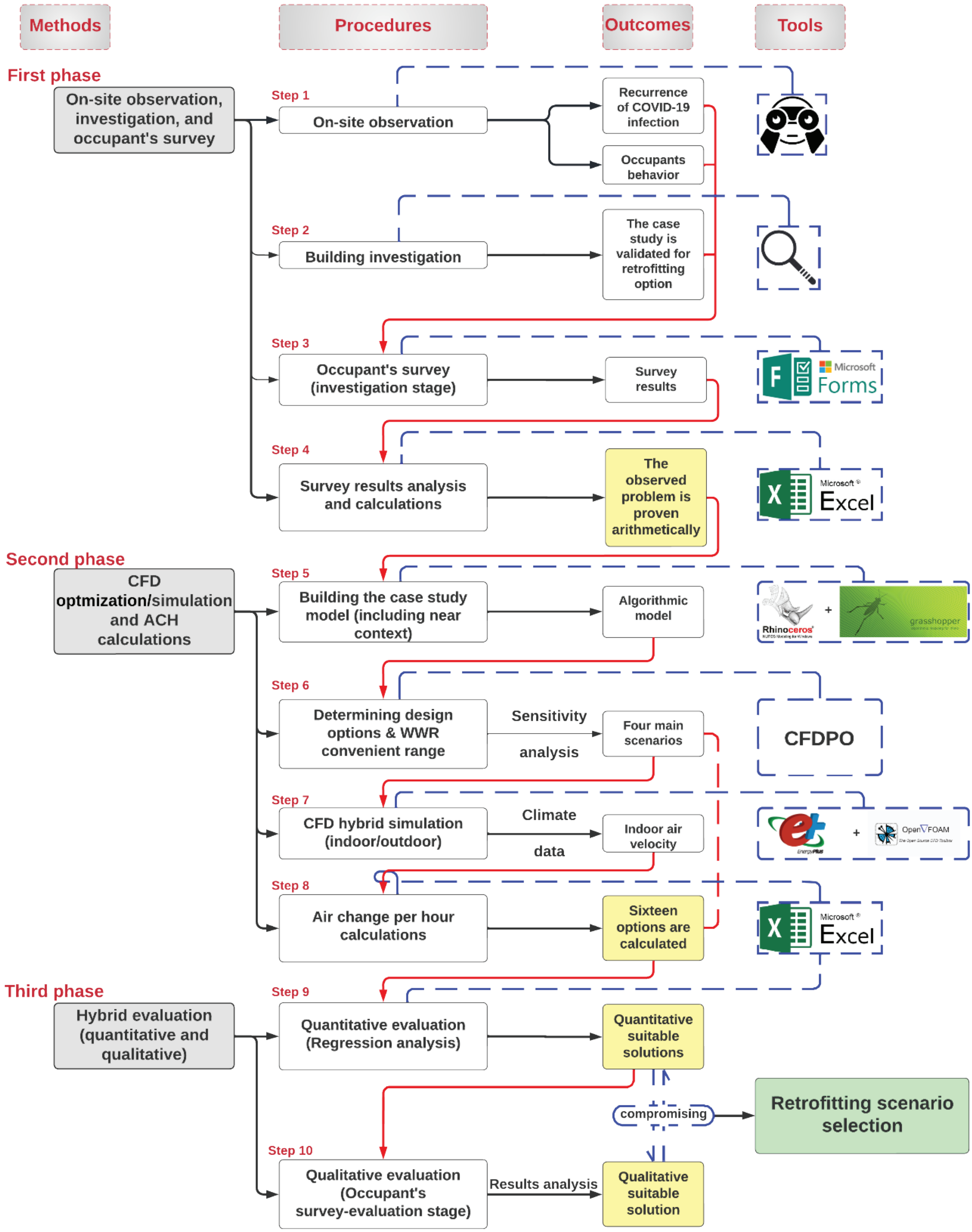

Fig. 2. Epidemic Hybrid Retrofitting (EHR)- (socio-CFD) method structure

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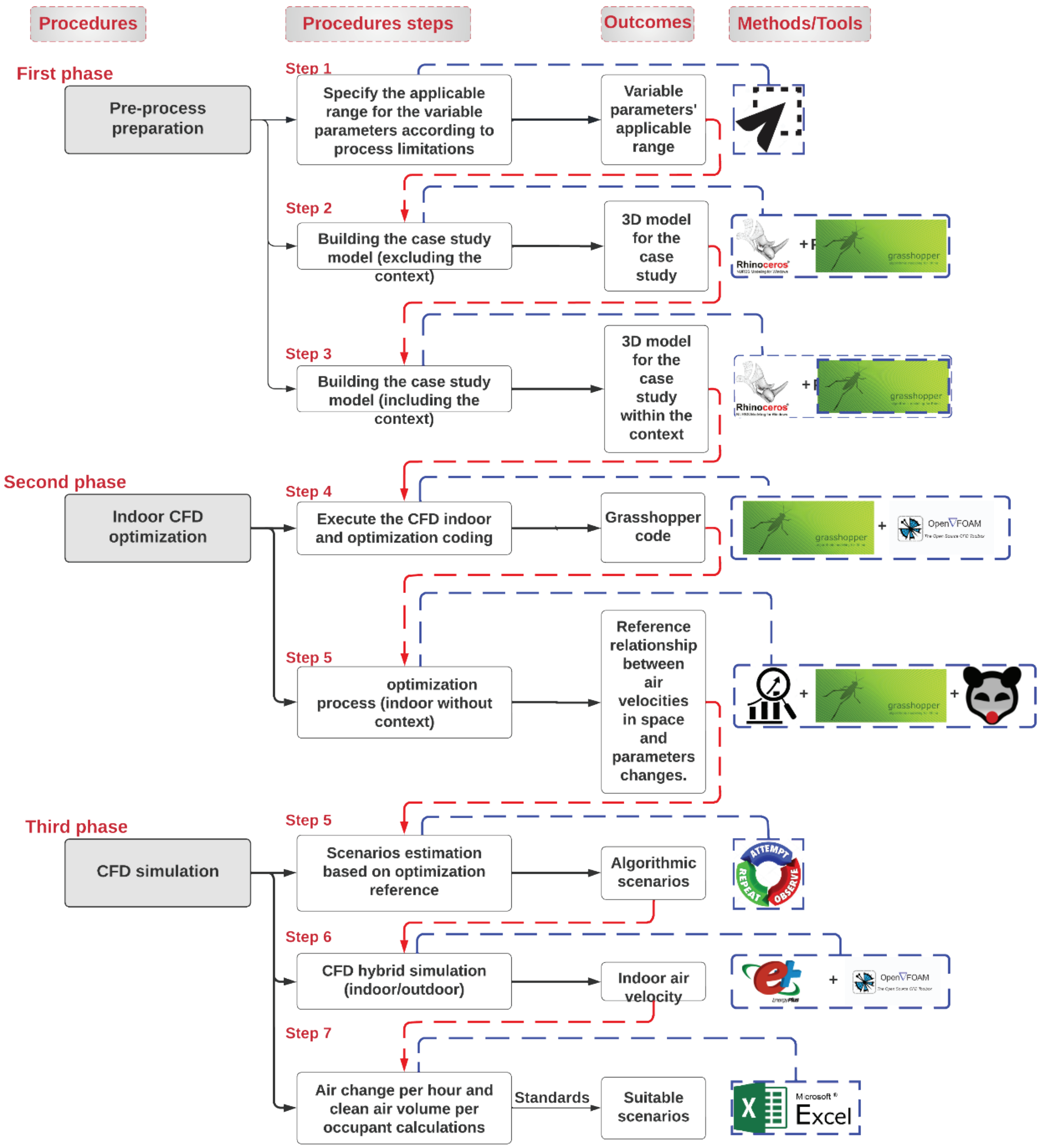

Fig. 3. Computational Fluid Dynamics Parametric Optimization (CFDPO) Method

A. First Stage: Onsite Observation, Investigation, and Occupant Survey

The first stage depends on four sequential steps. In the first step, the author observed the recurrence of COVID-19 infection among the occupants of the case study (shared office room). Additionally, the author observed some occupants' behavior regarding the use of indoor and outdoor openings. In the second step, the author executed a building investigation to ensure the need for a retrofitting option. In the third step, the author carried out an occupant survey to collect data concerning the COVID-19 infection rate and the reason behind some users' observed behavior (using Microsoft Forms [77]). The research considered those reasons to vary the options while developing the retrofitting scenarios. The primary purpose of the surveying is to calculate the actual infection rate for the case study. This survey was oriented to the case study occupants by email. The reactions were obtained by the beginning of 2022. The response was collected to include the period between December 2020 and March 2022 (one year and three months). The survey was composed of six sets of questions. The first seven questions were demographic and purposed to distinguish the occupants concerning age, gender, and educational degree, whether they resumed work physically or not when they continued, and how many their weekly working days. The subsequent question was to identify the occupant's position (workplace) based on an attached key plan presented in Figure 9. Then, the following four questions were organized to identify the infection rate among space users. Those four questions are designed to ask whether the occupant got infected with COVID-19 once or more and to identify the infection date/s.

Moreover, the questionnaire tests the commitment of the occupants to the precautionary procedures through the succeeding two questions. Those two questions were designed to get the average percentage of occupants' commitment to the WHO's three basic preventive measures. Those main preventive measures are to maintain a one-meter distance from others, wear a mask if you cannot guarantee this distance, cover a sneeze or cough with a tissue or bent elbow, and immediately dispose of the tissue in a closed-lid bin. In addition, avoid touching your eyes, nose, and mouth. Finally, wash your hands frequently with soap and water or hand sanitizer. Those two questions test self-commitment and colleagues' observed commitment. The average percentage of occupants' commitment (OC) to the WHO's preventive measures is calculated using equation (**1**. On the other hand, (SC) is the average self-commitment, and (COC) is the colleagues' observed commitment.

$$OC = \frac{SC+COC}{2} \quad (1)$$

The next question investigates the occupant's awareness of WHO's recommendations for utilizing natural ventilation in closed spaces. This question was designed to ensure occupants' awareness, especially when the researcher observed their behavior (usually do not open windows or doors). Therefore, the results of this question will either include or exclude the awareness issue in the research recommendations. The four questions were subsequently used to evaluate occupants' behavior regarding space openings (based on onsite observation) and to get some design guidelines for the retrofitting scenarios. Those questions were set to determine occupants' behavior regarding opening space windows and doors during the pandemic.

Additionally, they were set to identify the reasons behind occupants' behavior. This identification may lead to design guidelines regarding the retrofitting scenarios. Finally, in the fourth step, the author analyzed the surveying results. Furthermore, the author made the necessary calculations to prove the problem arithmetically. Regarding infection rates (IR), it can be calculated by f, where (Ni) is the number of infected users/occupants, (Nt) is the total number of space users, and (k) is a constant (100) [78]. According to the American National Standards Institute (ANSI) [79], the recurrence of infection is calculated for one million hours. Moreover, the Occupational Safety and Health Administration (OSHA) [80] calculates the recurrence of infection for two hundred thousand hours. The recurrence of infection reference (Rr) is calculated by using equation (3), where (N_{wo}) is the number of workers per case study (based on physical attendance ratio), (Hw) is the physical working hours per week, and (W) is the number of weeks.

Furthermore, the reassurance of infection rate (RIR) is calculated based on equation (4), where (WSL) is the total sick leave hours for workers, (Rr) is the recurrence of infection reference, and (k) is a constant (100). Finally, the peak of infection recurrence (RIR-Peak) is calculated using equation (5), where (WSL-Peak) is the total sick leave hours in the peak month (duration). (Rr-Peak) is the recurrence of infection reference calculated based on the peak duration, and (k) is a constant (100).

$$IR = \frac{N_i}{N_t} \times k \quad (2)$$

$$R_r = N_{Wo} \times H_w \times W \quad (3)$$

$$R_{IR} = \frac{W_{SL}}{R_r} \times k \quad (4)$$

$$R_{IR-peak} = \frac{W_{SL-peak}}{R_{r-peak}} \times k \quad (5)$$

B. Second Stage: CFD Optimization/ Simulation and ACH Calculations

The second stage consists of four steps. The fifth step (first in that stage) is about modeling the case study and near context using Rhinoceros 3D [81] and Grasshopper [82]. Moreover, the sixth step mainly revolves around determining design options & WWR convenience range using the CFDPO method presented in Figure 3. The seventh step is integrating two CFD analysis models: outdoor and indoor. This integration is accomplished to calculate the actual wind velocities in the indoor space, considering the location of wind data and the case study of the urban context. The CFD hybrid simulation is executed using EnergyPlus and OpenFOAM [83] [84]. Finally, the calculations of air change per hour and clean air volume per occupant using Microsoft Excel[85].

The infection risk (for airborne bio-contaminants in indoor spaces) is based on assessing the air change rate (ACH) and how ACH affects natural ventilation (NV) and indoor air quality (IAQ) [86] [87], [88]. Thus, air velocity and indoor space values (area, volume, and openings) are essential parameters in the calculation process. The calculations for natural ventilation are based on the air change rate inside the space. The calculations of air change rate (ACH) are based initially on case study dimensions (area and volume), opening direction, and air velocity as in Equations (6) and (7). Whereas (Qr) is the air flow rate in m3/s, (j) is the window/opening j of the case study, (i) is the cell number of the vertical plane throughout the window/opening, (v_i→) is the average velocity vector, (n_i→) is the ordinary direction to the window/ opening, and (Ai) is the corresponding window/ opening area of the cell. Finally, (ACH) is the air change per hour, and (V) is the volume of the space (case study).

$$Q_r = \frac{1}{2}\sum_{j}\sum_{i=1}^{n} |\, v_i\!\rightarrow \times\ n_i\!\rightarrow | \times A_i \qquad (6)$$

$$ACH = 3600\times\frac{Q_r}{V} \qquad (7)$$

Regarding the opening position, four scenarios were suggested, as presented in Figure 4. Those scenarios were proposed based on the results of the occupant's questionnaire (first stage). They aimed to solve the occupants' problems, which straggled them from opening windows/openings. The first scenario assessed air change for parallel-centered openings (PCO). Furthermore, the second scenario assessed Parallel side-shifted Opening (PSO).

Additionally, the third scenario assessed air change for Single-centered Openable windows (SOW). Finally, the fourth scenario is considered a centered-window-faced elevated opening. The four suggested scenarios are presented in Figure 4.

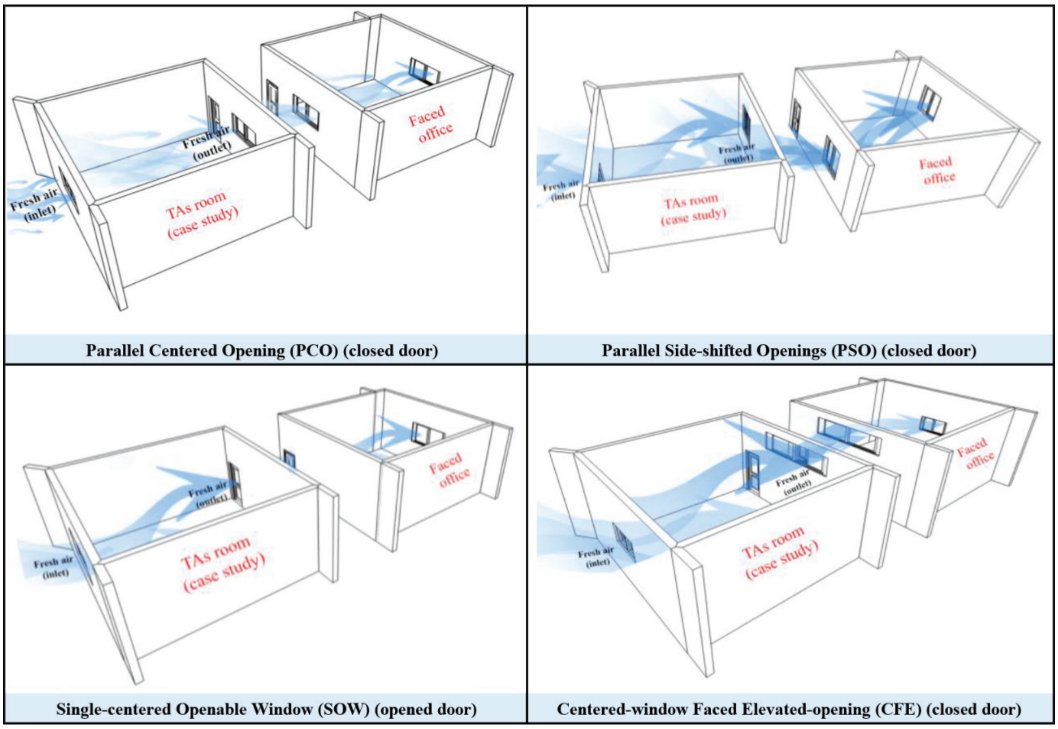

Fig. 4. The suggested scenarios for windows/openings positions

C. Third Stage: Hybrid Evaluation (Quantitative and Qualitative)

The third stage executes hybrid evaluation. This hybrid (socio-CFD) method depends on quantitative and qualitative guidelines. The quantitative guidelines are related to air change per hour standards. In addition, it introduces the Cost Reduction factor (CR_F), which refers to reducing the costs of retrofitting by selecting the best option that obtains minimum changes. The CRF can be defined as the ratio of the cost of the chosen retrofit option to the cost of the baseline retrofit option. The baseline retrofit option is typically the most extensive or expensive option that requires the maximum changes. The general equation (Equation ((8), for the CR_F can be expressed as:

$$CR_f = C_s \div C_b \tag{8}$$

Cs refers to the cost of the selected retrofit option, and C_b refers to the cost of the baseline retrofit option. The CR_F will have a value between 0 and 1, where a lower value indicates a more significant cost reduction compared to the baseline option.

The qualitative guidelines are associated with the analysis of the surveying results. First, the researchers did a quantitative evaluation regarding DIN 1946-part two standards [89]. DIN 1946-part two was updated to cope with the requirements of limiting the spread of COVID-19. For example, DIN 1946-part two defined a range of 10 to 14 ACH for computer offices (the same function as the case study). Then, the researchers analyzed the results using regression (for each retrofitting scenario), resulting in a functional equation (FE). The FE has the form Y= a + bX, where Y is the variable parameter, X is the objective function, b is the slope of the line, and a is the y-intercept [90]. While confounding variables were not included in the regression models, the focus remained on examining the direct relationship between W/OWR, air change values, and the corresponding outcomes for each retrofitting scenario. This targeted approach aimed to isolate the specific impact of these critical variables on the results, providing valuable insights into the effectiveness of the proposed retrofitting strategies.

While most of the literature review depends mainly on the quantitative evaluation methods, this hybrid stage contributes to merging the qualitative method into the evaluation process. The qualitative evaluation is done through the occupants' survey (evaluation stage). The survey results were collected in May 2022 using Microsoft Forms. The survey consists of three sets of questions. The first set is to select occupants' positions in the office. The second set is to choose and justify the suitable retrofitting scenario. The second set consists of three questions. Those questions aim to select the appropriate scenario and explain the reason. Finally, the third set determines the occupant's preferred ratio for window/opening.

Rigorous measures were implemented, including pre-testing of the survey instrument, ensuring clarity in question phrasing, and conducting data triangulation with complementary sources to corroborate findings. These measures assure the validity and reliability of the survey data collected using Microsoft Forms.

III. THE CASE STUDY

A. Selection Criteria

- **Functional:** The application targets shared public offices, specifically multiple users sharing a limited office area.
- **Spatial:** The application studies a specific climatic location (Cairo, Egypt).
- **Chronologically:** The study investigates the infection of COVID-19 in the period between December 2020 and March 2022.
- **Objectives:** This is a multi-objective study that targets environmental (IAQ-natural ventilation), health and wellness (reducing infections), and social (user satisfaction) objectives.
- **Retrofitting variables:** This study aims to change specific Façade variables: window/opening dimensions and window/opening to wall ratio (W/OWR).

B. Characterization

The suggested EHR (socio-CFD) method is applied to a free-running shareable multi-user office located in an educational building, specifically a teaching assistant's office inside a college building.

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The primary purpose of this implementation is to test the applicability of the EHR (socio-CFD) method. The case study is a shared office between 20 occupants occupied by 20 office units and 20 personal computers. Additionally, the office area is 49.7m2 and is in New Cairo, Cairo, Egypt. The office has one outdoor façade in the north, one indoor façade in the south, and two closed side faces in the east and west, as presented in Figures 5 and 6. The retrofitted Façades are north (outdoor) and south (indoor) Façades. The research suggests circulating the fresh air from the case study room (inlet) to the facing office room (outlet). Consequently, the retrofitting scenario/s means adding openable windows/openings to both sides of the case study (outdoor and indoor façade), as illustrated in Figure 5. The office's official working hours are between 9:00 a.m. to 5:00 p.m. The office is surrounded by campus buildings in the north and wide streets in the south, east, and west, as shown in Figure 6. The office is oriented in the north direction (N), as illustrated in Figure 4, and it is one of the domain wind directions presented in Cairo International Airport wind rose [83], as in Figure 7.

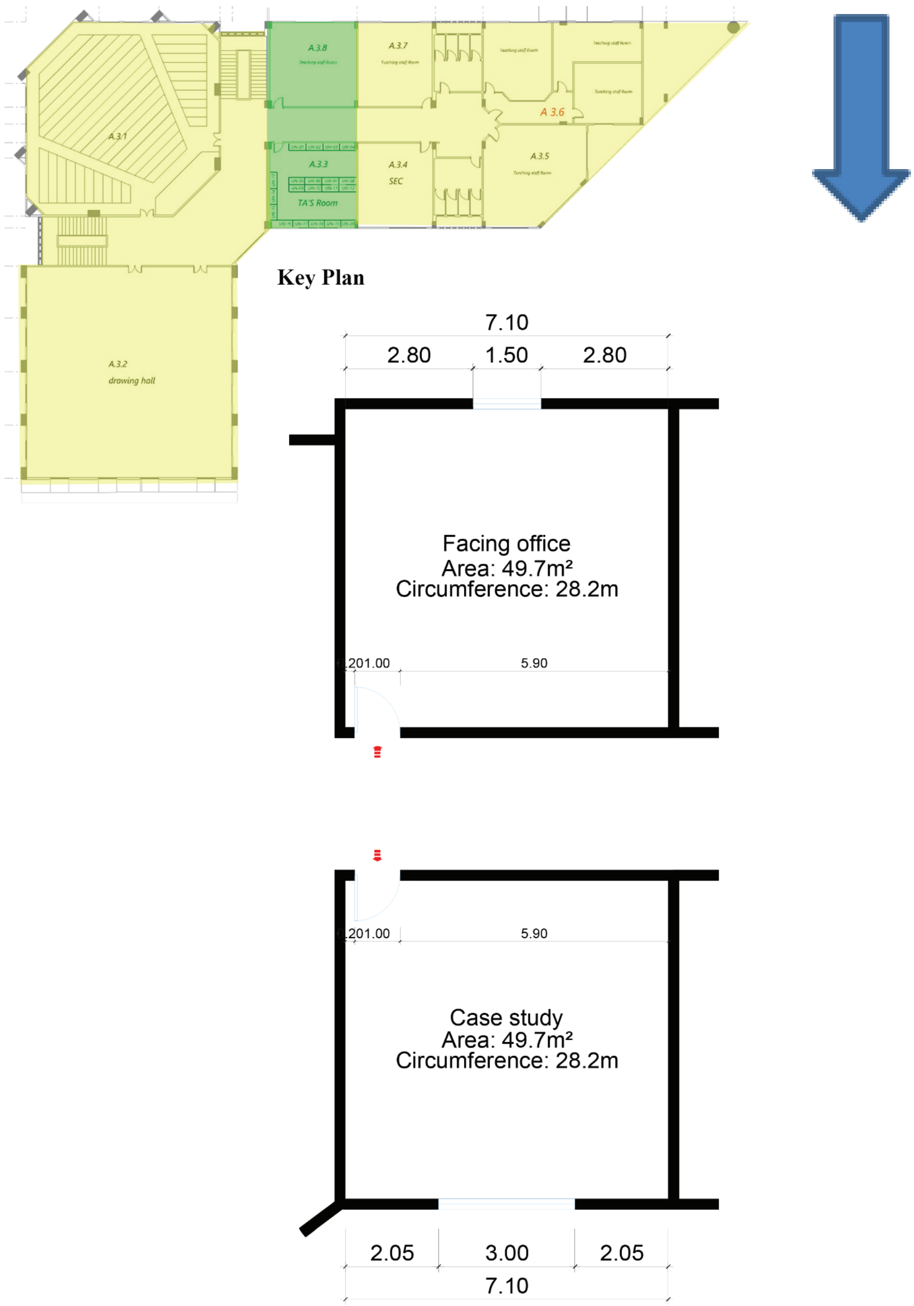

Fig. 5. Case study current plan
(The key plan is in the upper left, and the case study is highlighted in green. The north is on the upper right)

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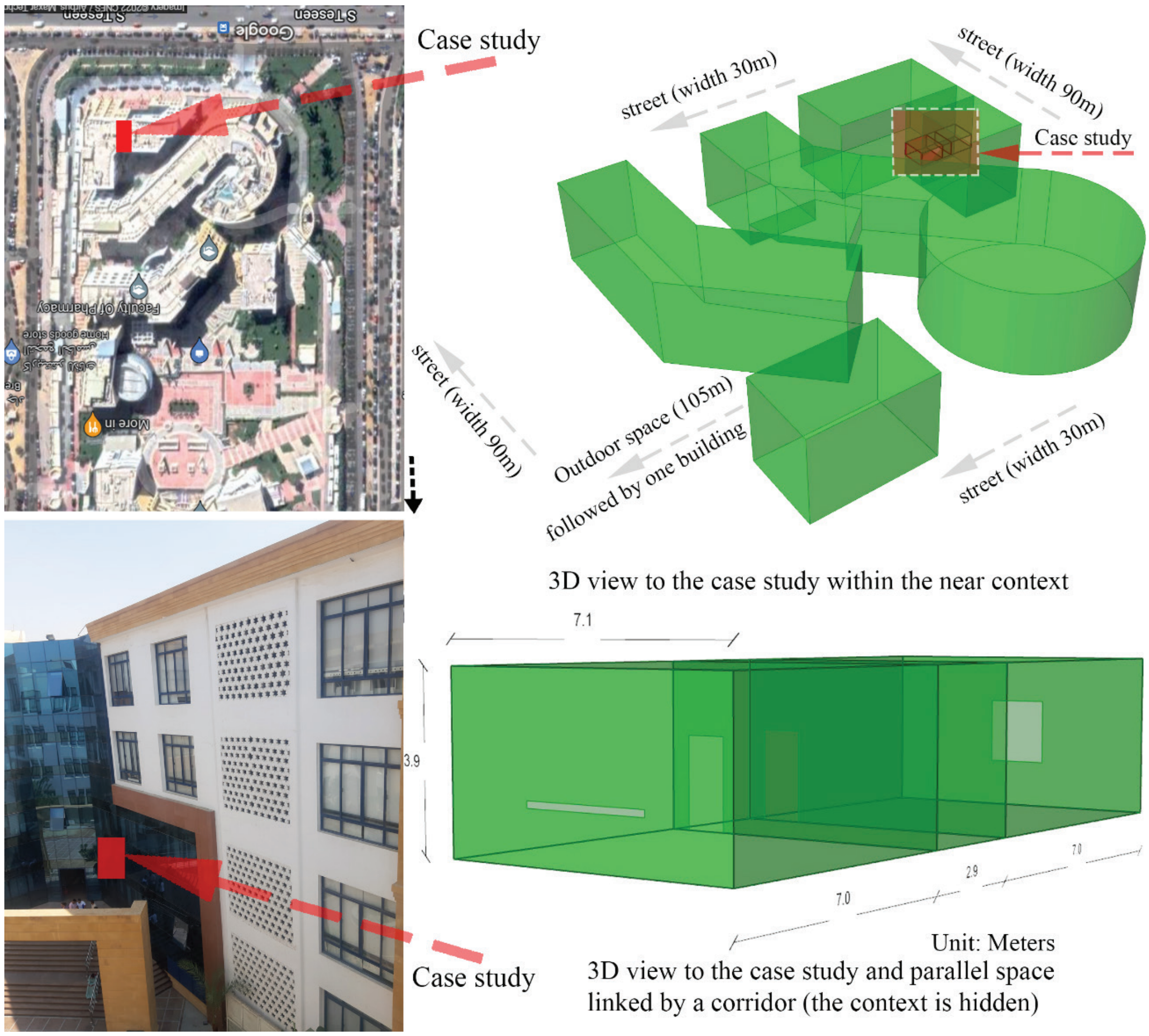

Fig. 6. The case study within the near context
(Upper left: a case study within the context in layout, upper right: the case study within context as a 3D model, down left: a case study in the actual photo, downright: a case study as a 3D model)

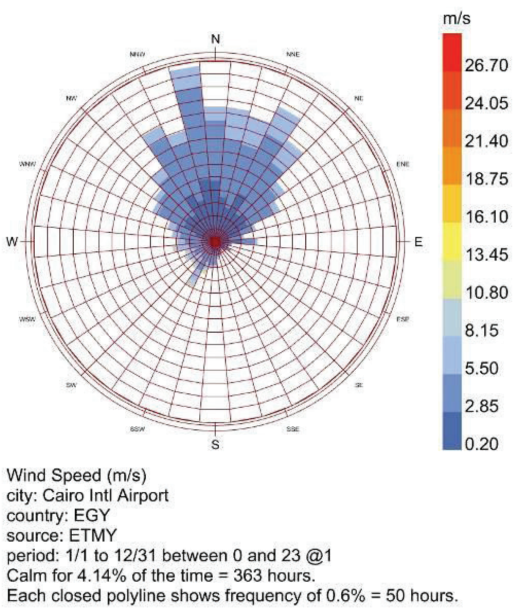

Fig. 7. Cairo International Airport Windrose, extracted from ladybug tools using energy plus weather file [83] and [91]

C. CFD Model Validation

Validation is the process of assessing the accuracy of a computational fluid dynamics (CFD) model in representing the real-world scenario it aims to simulate [92]. The validation process for this study sought to ensure the air velocity results inside the building matched actual measurements. Accurate air velocity is a critical parameter, as it underpins any subsequent calculations related to air changes within the building.

The CFD model was initially validated against detailed air velocity measurements collected from a heritage building in Alexandria, Egypt, as described in [93]. This validation process demonstrated that the model could accurately represent the real-world airflow conditions within the local climatic zone, with a discrepancy of less than 5% between the simulated and measured data - well within the acceptable range for model validation, as stated in the literature [94].

The research team thoroughly reviewed the available literature but could not identify any publicly available measured airflow data for buildings in the Cairo metropolitan area. As such, the Alexandria dataset represented the most relevant set of validation data that could be sourced for this study. For the research case study presented here, the same validated CFD code was then applied using wind speed data from the Cairo International Airport 623660 (ETMY) weather data file rather than the Alexandria dataset used in the initial validation. This decision was made because the case study building is in the Cairo metropolitan area, and the Cairo weather data were therefore considered more representative of the relevant climatic conditions. While some differences in the weather patterns between Alexandria and Cairo may exist, the validated performance of the CFD model provides confidence that it can still reliably simulate the airflow characteristics of the case study building using the Cairo weather inputs.

Additionally, the parametric approach used for the CFD analysis in this study has been validated by Sakiyama et al. [70], who compared the results to reference data from the French National Solar Energy Institute (INES, 2022). The parametric CFD approach was found to accurately capture the hourly distribution of wind speed and direction, which is a crucial factor in natural ventilation analysis [95]. The Butterfly plug-in requires wind velocity and direction data as inputs, which were obtained by processing weather data from the EnergyPlus website using the Ladybug plug-in [91] and [83].

D. The CFD Model Configuration

The CFD simulation was performed using the Butterfly plug-in, which is part of the Ladybug suite of tools for Grasshopper. This visual programming platform (Grasshopper) operates within the Rhinoceros 3D modeling environment [91] and [82]. Butterfly utilizes the blueCFD-Core 2017-2 framework, which incorporates OpenFOAM 5.x, MS-MPI 7.1, and ParaView 5.4.1 [96]. Since the study focused on wind-driven ventilation, the effects of thermal buoyancy were not considered. The CFD simulations were, therefore, conducted under isothermal conditions. OpenFOAM is a widely used computational fluid dynamics software with a comprehensive range of settings for solving complex fluid flow problems. The accuracy of OpenFOAM has been validated through wind tunnel experiments and onsite measurements [97] and [98].

The CFD analysis leveraged a reference script from the Ladybug Tools team [99], which was adapted to incorporate weather data for Cairo International Airport [83] and [91]. The dominant north wind direction, as well as the secondary northwest and east directions, identified in the airport wind rose, were used as inputs to the CFD model. The complete CFD script, including optimization steps, is provided in Appendix A.

1. Domain model

The domain model disintegrates the domain into real-world objects or concepts. It developed within the process of orientation and analysis of the objects. Moreover, it must determine the group of conceptual categories [100]. The case has run using realizable k-ϵ as a Reliability, Availability, and Serviceability (RAS) model to ensure accuracy [101]. The CFD simulation is set to stop when the value of the results (air velocity, pressure, epsilon, or K) reaches 0.001.

The CFD model setup encompasses both the indoor and outdoor environments, capturing the dynamic interactions between the external and internal spaces around openings [102]–[104]. Following the recommended best practices [105], the dimensions of the computational domain were determined. The domain windward, height, and lateral sides were set to five times the building height (H), while the leeward side was set to 15 times the building height to allow for flow redevelopment. The building height used in the analysis was 21.75 meters. The university buildings that were included in the wind tunnel testing had dimensions of 106 meters in length and 108 meters in width (while the case study had dimensions of 7.1 width × 16.9 length meters). As a result, the computational domain had the following dimensions: 540 meters in length, 326 meters in width, and 109 meters in height, leading to a blockage ratio of 0.43%. This blockage ratio meets the recommended values of less than 3% from previous studies to avoid the impacts of compressed flow [105] and [106].

2. Analyser settings

This study considered the turbulence of the wind; therefore, a turbulence RAS model, realizable k-ϵ, was implemented. Realizable k-ϵ is a model that deals with compressible and incompressible flows [107]. Moreover, the roughness (z0) is set to 1(m), and the landscape is set to skimming. Skimming refers to a landscape covered with similar building heights interspersed with open spaces with the same building height [108]. The evaluation plane is set in both vertical and horizontal directions. The horizontal plane (XP) is set on level +1.1m from room FFL (seating level). The CDF simulation and optimization were performed using 12th Gen Intel® Core™ i3-1215U (10 MB cache, six cores, eight threads, up to 4.40 GHz Turbo). The execution time for each simulation was around 33387.172 s, and clock time was around c s

3. Optimization

The optimization process was performed through MOpossum 2.2.4, which is a single/multi-objective optimization GH plug-in. The MOpossum contains different algorithms, such as RBFOPT, PSO, and ACO [109]. RBFOPT was used in this study for sensitivity analysis as a part of the CFDPO method.

4. Mesh manipulation and boundary settings

The mesh was generated using OpenFOAM's snappyHexMesh and blockMesh utilities. The background mesh from blockMesh was refined near the building by snappyHexMesh, with a minimum layer thickness of 0.01, a maximum of 0.7, and an expansion ratio of 1.1. Mesh quality was verified in ParaView [110] and statistically assessed with checkMesh. Each simulation runs around 1000 times. The simulation residuals that define the accuracy are presented in Table II.

Boundary conditions were defined from the weather data file with respect to air velocity values, atmospheric pressure profile, and wind direction. The reference height for wind velocity was set to 10m from ground level. Wall functions were used for ground and buildings, with y+ default values for the k-ε model. The outlet had a zero-static pressure condition.

TABLE II
CFD SIMULATION AVERAGE RESIDUALS

	Ux	Uy	Uz	P	k	epsilon
Residuals	6.1×10^{-5}	1.8×10^{-5}	2.9×10^{-4}	1.6×10^{-5}	2.2×10^{-4}	8.1×10^{-5}

IV. RESEARCH RESULTS

A. First-phase Results

The results of the application of the Epidemic Hybrid Retrofitting (EHR)- (socio-CFD) method are presented as follows:

The first stage started with an onsite observation and resulted in a recurrence of infection of COVID-19. Furthermore, the author observed some users' behaviors related to the lack of opening windows and doors despite the pandemic's peak. Those observed behaviors were against WHO precautionary procedures [7]. Then, the authors suggested starting with a retrofitting scenario and going through an investigation process to ensure that there is no option other than the retrofitting scenario. The investigation process assured the suggestion as the building is fully occupied, and there is no option to transfer some/all users to other well-ventilated spaces.

Afterward, an occupants' questionnaire was performed to validate the observation and get some design guidelines to suggest suitable retrofitting scenarios. Regarding the results of the occupants' demographic data, Figure 8 presents the demographic results. Graph A shows that 50% of the occupants are aged between 25 and 30. Furthermore, 40% are between 30 and 35 years old, and 10% are above 35 years old. Regarding occupants' gender, in graph B, 65% are females, and the remainder are males. Regarding their educational degree, in graph C, 65% hold Master of Science degrees, and the rest have bachelor's degrees. Finally, graph D presents the occupants' physical attendance in the peak month of infection (December 2020), which is 60% per day (12 users per day).

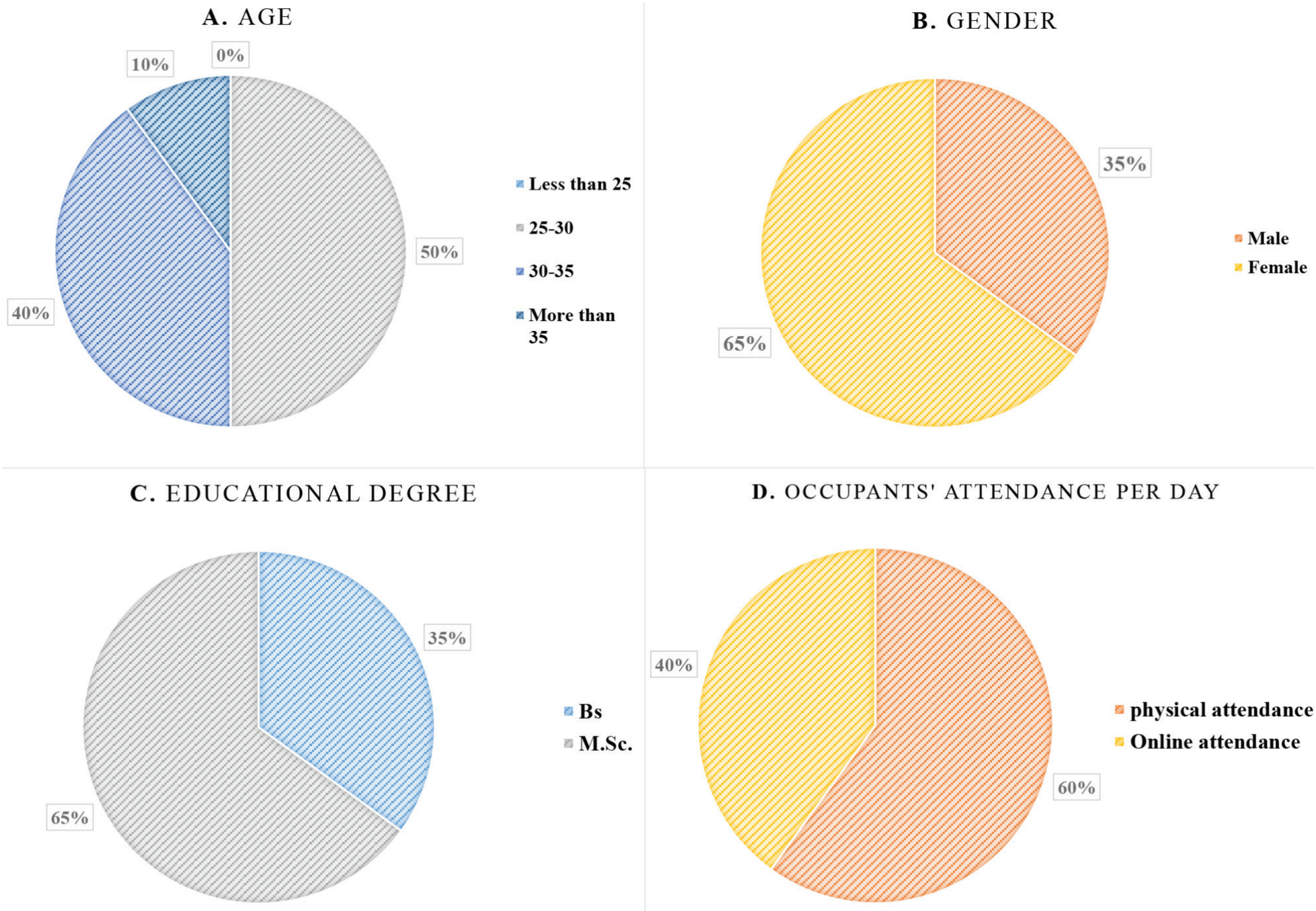

Fig. 8. Case study occupants' attributes: (A) Age, (B) Gender, (C) Educational degree, (D) Occupants' attendance per day (for the peak month of infection – December 2020)

Regarding the occupant's recurrence infection of COVID-19, Figure 9 represents infection dates and infection recurrence reference to the occupant's position. The user's infection with COVID-19 is verified by PCR test, blood analysis, and X-ray. As shown in Figure 9, the orange-shaded triangle represents the most frequent area of infection. Furthermore, the orange-shaded triangle represents the farthest area from natural ventilation (even if it is insufficient).

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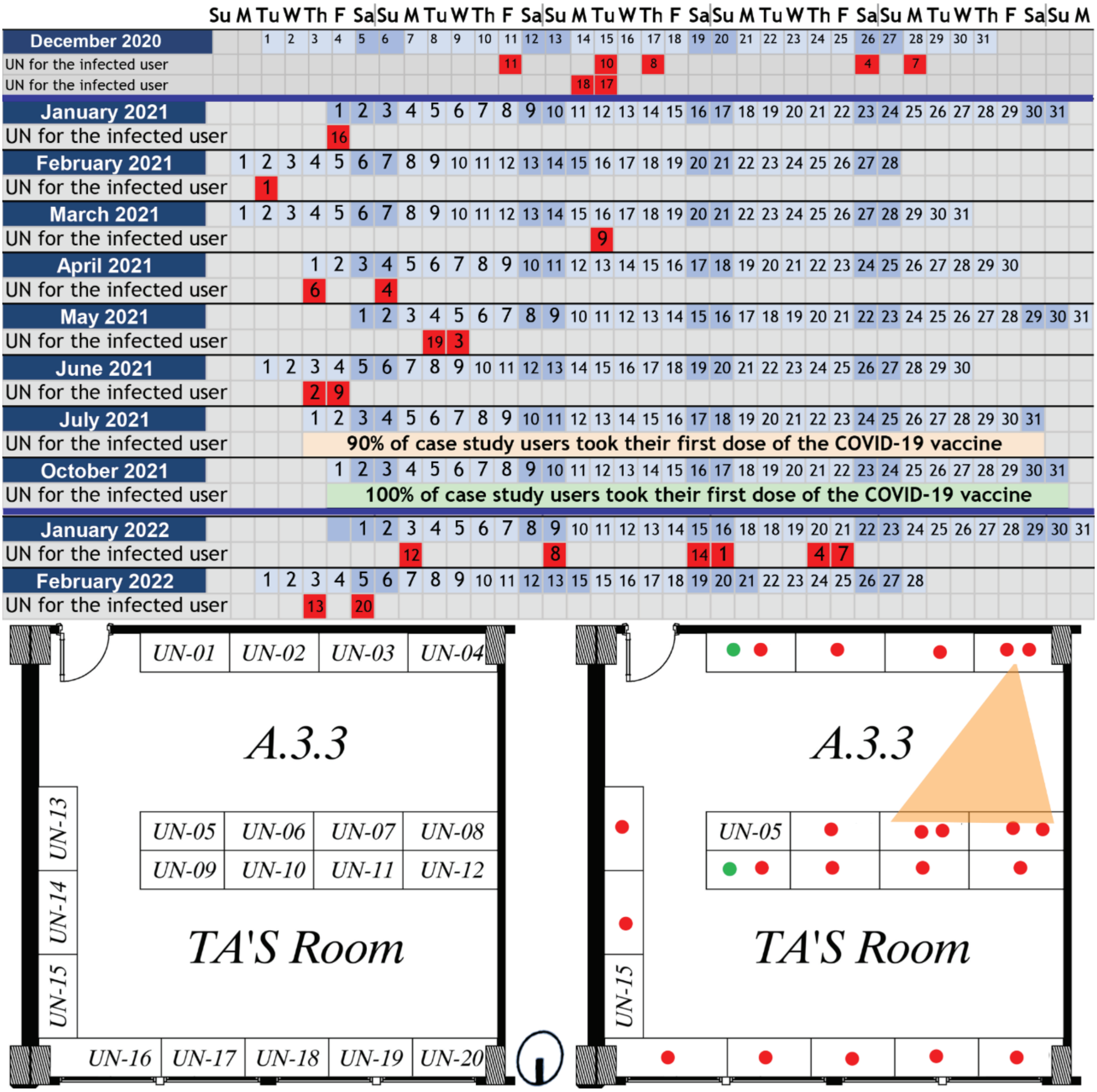

Fig. 9. Infection dates reference to occupants' position

Above is the calendar representing infection dates (August 2021, September 2021, November 2021, December 2021, and March 2022 are excluded from the calendar as there were no reported infections)- The red shaded number is the reference occupant's number refers to the infection date. The bottom left is the case study plan showing the occupant's reference number. The bottom right is the implementation of infections to the occupant's position (the red circle represents one infection through 15 days of a co-worker infection, the green circle refers to individual infection, and the orange triangle refers to the most infected area).

The infection rate for the selected case study was calculated using equation (2), and the result was 90%. Furthermore, the recurrence of infection is calculated and resulted in 22,176 hours (12 workers (reference to D in Figure 8), 16 months, 66 weeks, and 28 hours per week per worker) using equation (3). The average reassurance of infection rate (RIR) is calculated by equation (4) and resulted in 5.6% (1232 total sick leave hours in the sample duration). Whereas (WSL) is calculated based on giving each

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worker two weeks of sick leave from December 2020 to January 19, 2022, and one week of sick leave from January 20, 2022, till the end of March 2022 (based on the organization's internal regulations). Furthermore, the peak of infection recurrence (RIR-Peak) is calculated for December 2020 using equation (5), and the results are 19%.

The average percentage of occupants' commitment (OC) to the WHO's preventive measures is calculated using equation ((**1**, resulting in 71.6%. Regarding the occupant's awareness of WHO's recommendations for utilizing natural ventilation in closed spaces, 100% of the occupants assured their awareness. Regarding occupant behavior evaluation, 36.7% of space occupants used to open windows and doors during the pandemic. Consequently, 63.3% of space occupants did not consider opening space doors and windows despite the peak time of the pandemic. Comparing results, this happens despite their complete awareness of WHO's recommendations regarding using natural ventilation. Furthermore, 90% of the space occupants ensured that space windows and doors were closed most of the time.

Finally, the reasons behind not opening the windows and doors during the pandemic vary among the following chosen reasons. Half of the occupants (50%) referred to their behavior as the small size of the window, assuring that it will not affect the ventilation. In comparison, 30% of space occupants referred to their behavior as avoiding noise from outside. Finally, 20% of space occupants referred to their behavior as personal, social, and technical reasons. Those reasons are the refusal of some occupants (5%), facing the wall without an indoor opening (needs an indoor opening) (10%), and the difficulty of opening the window (it is unreachable) (5%).

B. *Second-phase Results*

The second stage results are categorized as follows:

CFD Optimization Results:

The indoor optimization acted as a sensitivity analysis. It mainly checks which design parameters primarily affect the objective function. The scatter charts of the optimization results are presented in Figures 10 and 11. The indoor absolute air velocity is mainly affected by the inlet area factor (outdoor WWR-North). Figure 10 represents a direct correlation between indoor absolute air velocity and inlet area factor.

In contrast, Figure 11 shows a random correlation between indoor absolute air velocity and outlet area factor. Therefore, the primary design factor is the WWR for the outdoor window (north-facing). Consequently, the proposed retrofitting scenarios aim to set a primary opening in the outdoor façade. At the same time, the secondary opening design for the indoor façade is varied between the window, door, and elevated opening.

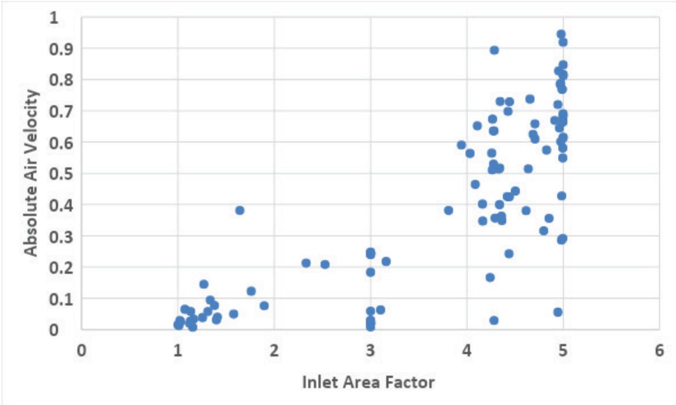

Fig. 10. Optimization results for the relation between inlet (north window) area factor and absolute average velocity

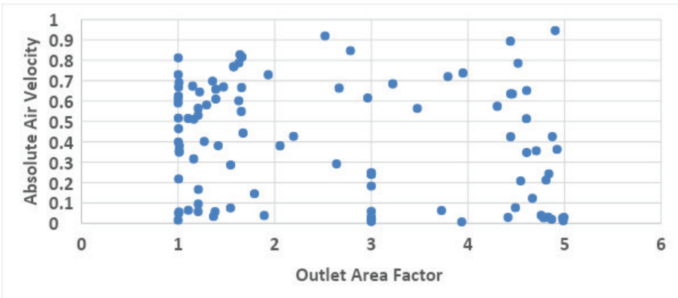

Fig. 11. Optimization results for the relation between outlet (south opening) area factor and absolute average velocity

CFD Hybrid Simulation Results:

The CFD hybrid simulation results included base case results and results for retrofitting scenarios. The base current case results are represented in Figure 12, whereas the ACH is below standards (ACH= 4.88, and the standard range is between 10 and 14) [6].

The CFD hybrid simulation results for the retrofitting scenarios are presented in Figures 13, 14, 15, and 16. At the same time, those figures show CFD simulation results for air velocity. Furthermore, it represents ACH for each option and the functional equation for each retrofitting scenario (which was conducted through the following step regression analysis).

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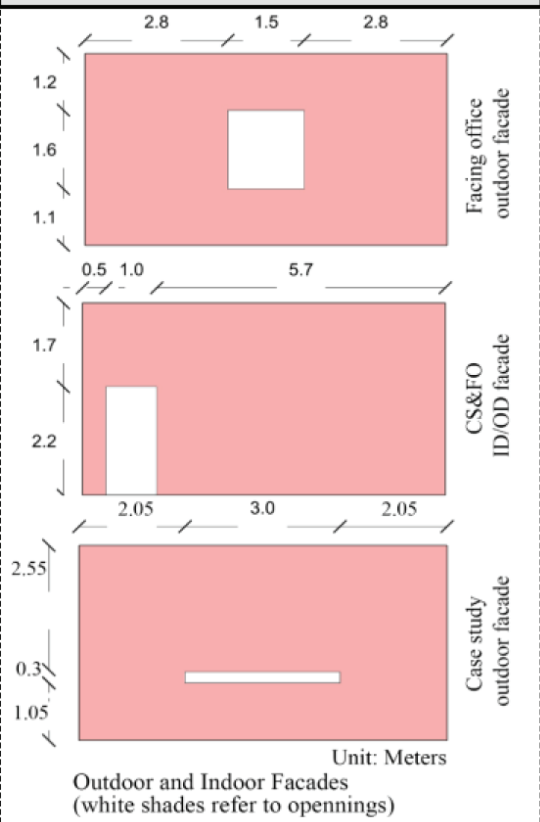
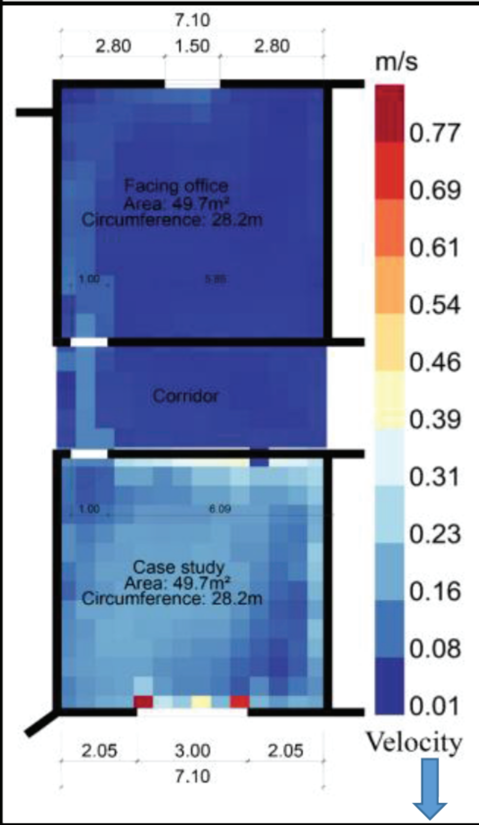
ST	SC	Model	Dynamic parameters OIFDP (m) W/OWR	SP	LP	W/OW	W/OH	Door condition	CFDS results (average air velocity)	Qr (m3/s)	ACH
Base Case	BC-01		FO:8.7%	FO:1.1 m	FO:1.2 m	FO:1.5 m	FO:1.6 m	Openend		Facing office: 0.05	Facing office: 0.93
			CS&FO:8%	CS&FO:0.0 m	CS&FO:1.7 m	CS&FO:1.0 m	CS&FO:2.2 m			Case study: 0.26	Case study: 4.88
			CS: 2.2%	CS: 1.1 m	CS: 2.6 m	CS: 3.0 m	CS: 0.2 m				

Fig. 12. Base case (current) model configurations, CFD simulation results, and ACH calculations

(ST: scenario title, SC: scenario code, OIFDP: openings information, dimension, and position, W/OWR: window/opening wall ratio, SP: sill position, LP: lintel position, W/OW: window/opening width, W/OH: window/opening height, CFDs: computational fluid dynamic scenarios, or: air flow rate, ACH: room air change per hour, BC-01 represents the minimum north opening value, and BC-02 represents the maximum north opening values (as the north opening ratio ranges between two opening options).

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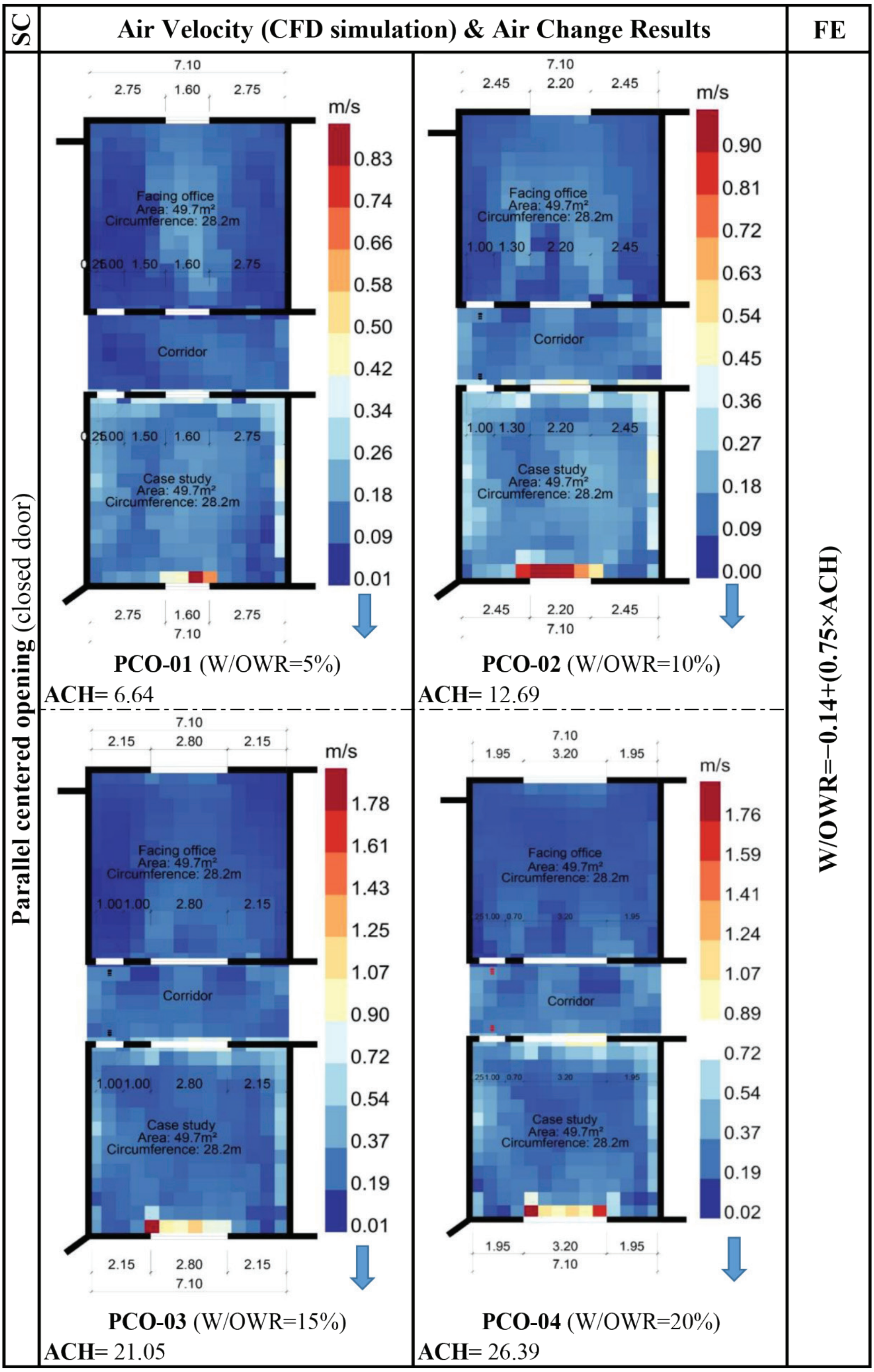

Fig. 13. PCO simulation results
(SC: Scenario, FE: Functional Equation)

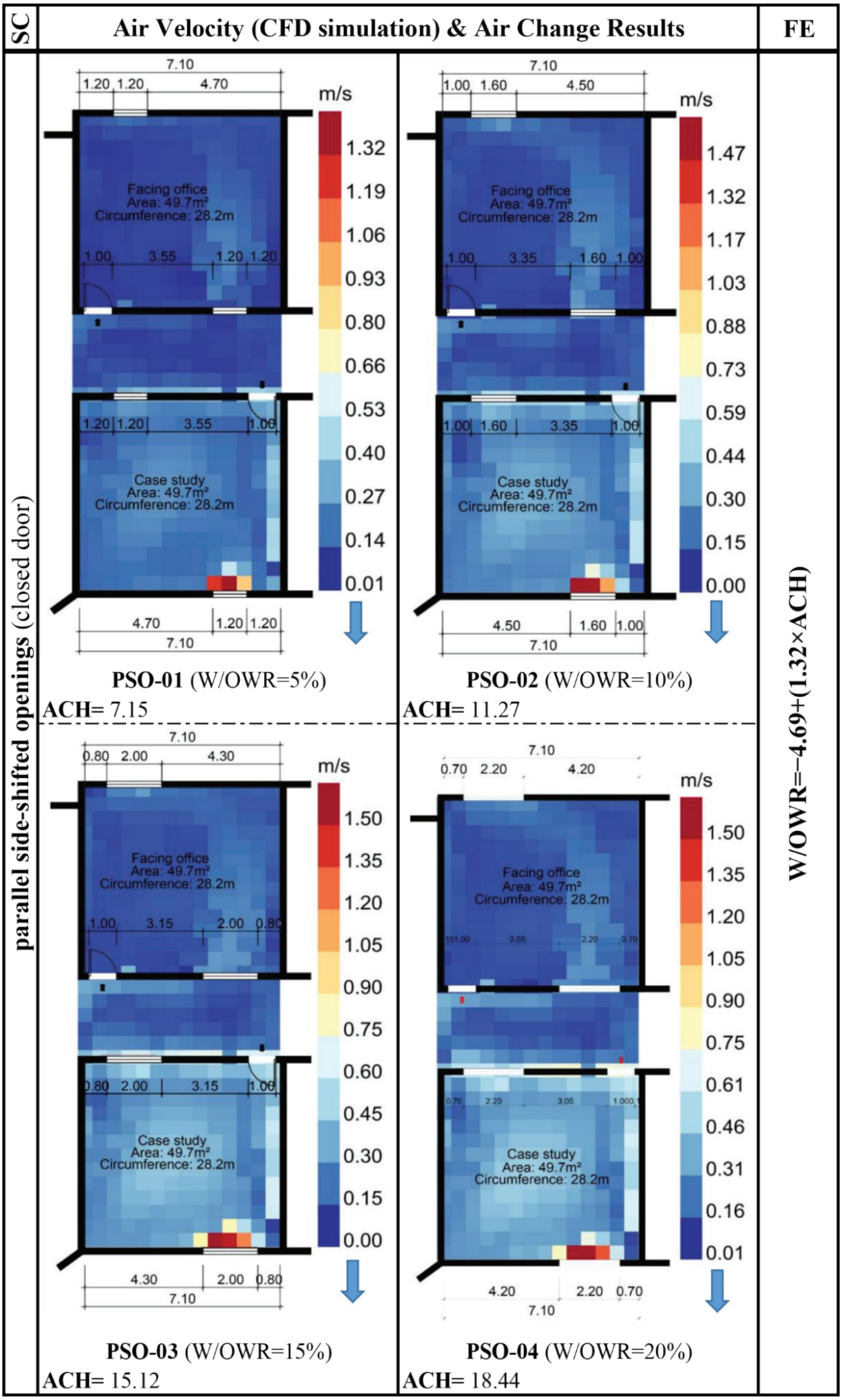

Fig. 14. PSO simulation results
SC: Scenario, FE: Functional Equation

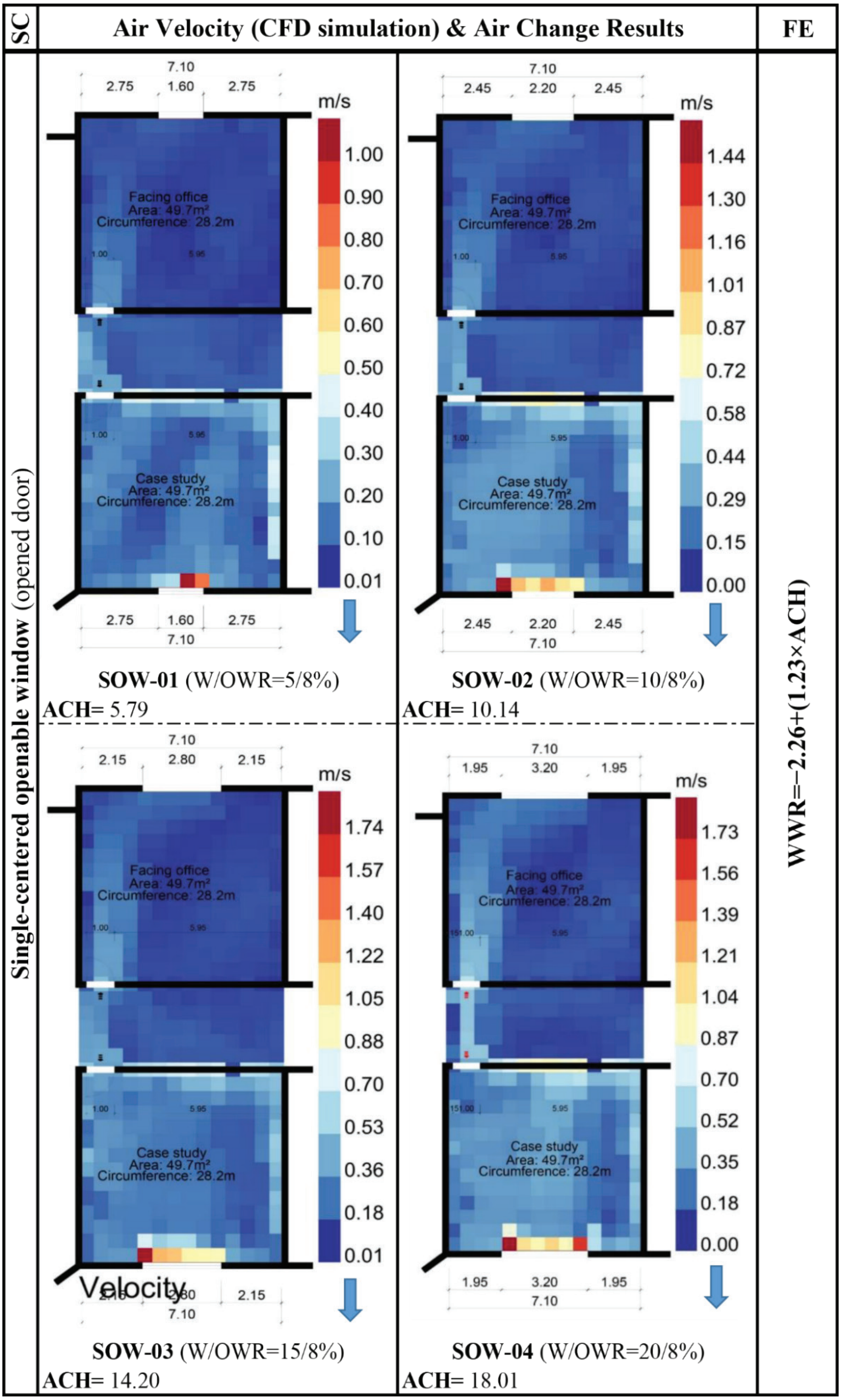

Fig. 15. SOW simulation results
SC: Scenario, FE: Functional Equation

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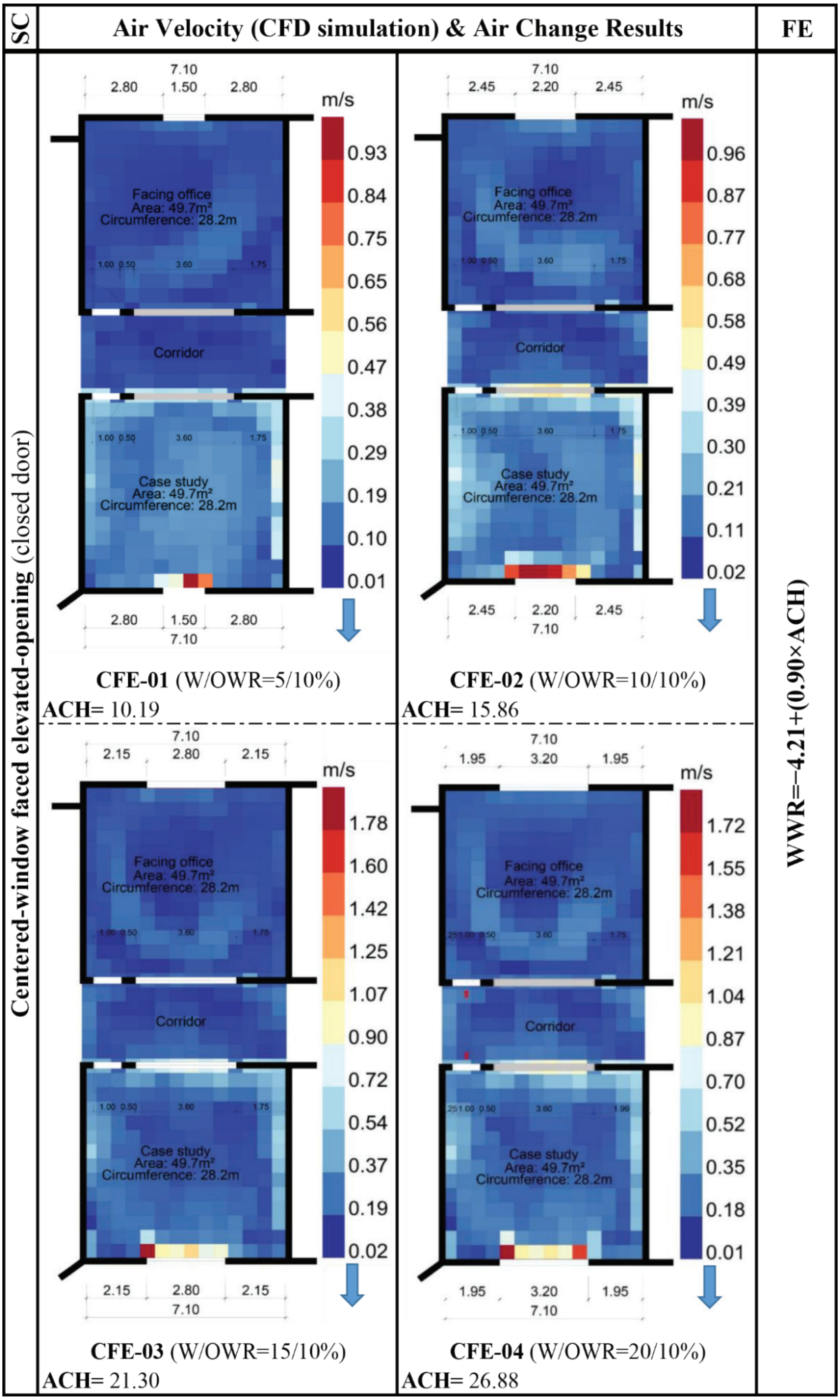

Fig. 16. CFE simulation results
SC: Scenario, FE: Functional Equation

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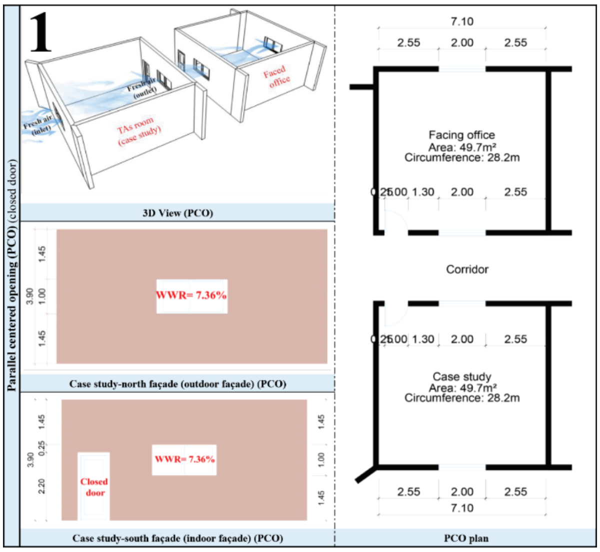
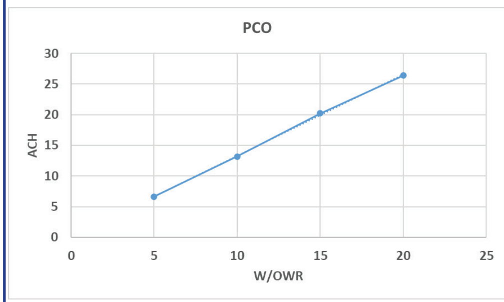
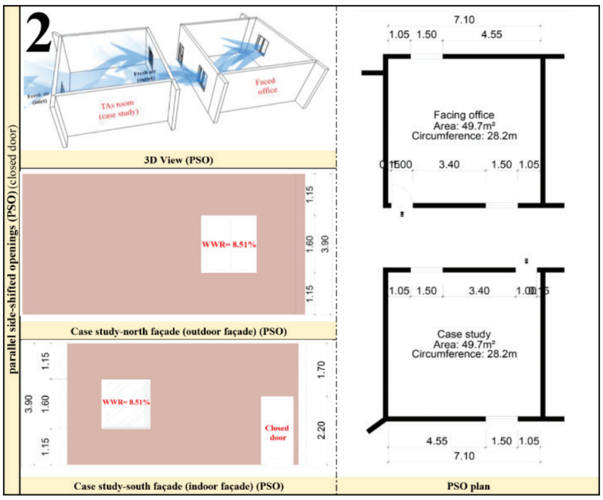
C. Third-phase Results

The evaluation of the simulation results is based on quantitative and qualitative methods. The quantitative evaluation results for the four scenarios are represented in Table III.

TABLE III
THE QUANTITATIVE EVALUATION RESULTS FOR THE FOUR SCENARIOS

RS	The minimum standard dimensional results	The relationship between ACH and W/OWR	FE	Cons & R.
PCO			$W/OWR =- 0.14 + (0.75 \times ACH)$	Cons.: $5 \leq W/OWR \leq 20.10 \leq ACH \leq 14$ R:W/OWR: $7.36 \leq W/OWR \leq 10.36$ (±0.21, *standared error*)%
PSO			$W/OWR =- 4.69 + (1.32 \times ACH)$	Cons.: $5 \leq W/OWR \leq 20$, $10 \leq ACH \leq 14$ R:W/OWR: W/OWR:$8.51 \leq W/OWR \leq 13.79$ (±0.38,standared error)

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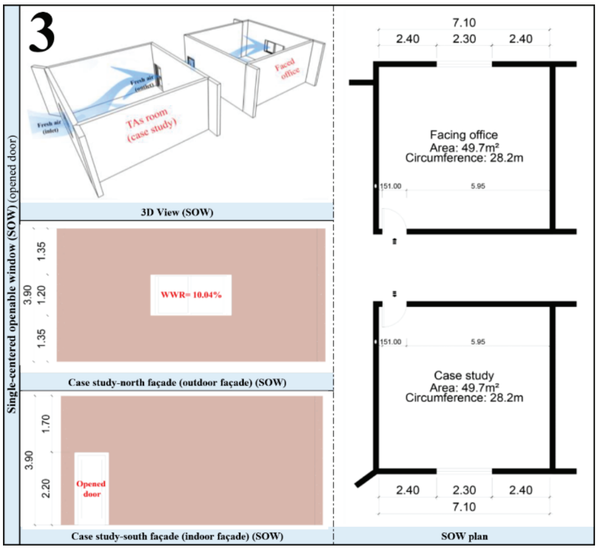
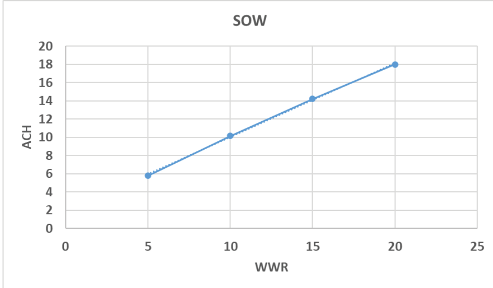
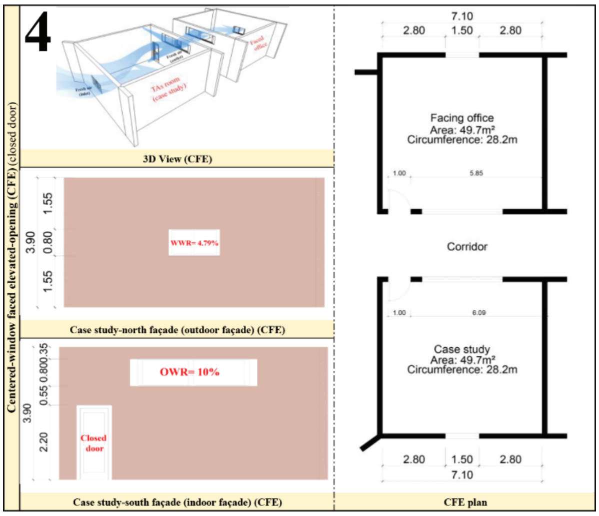
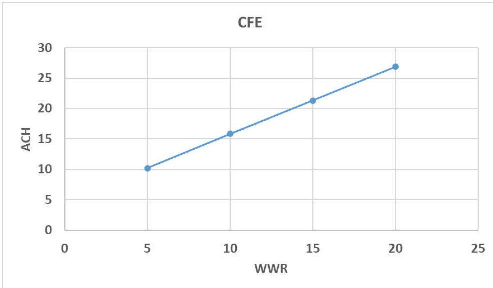
RS	The minimum standard dimensional results	The relationship between ACH and W/OWR	FE	Cons & R.
SOW			$WWR = -2.26 + (1.23 \times ACH)$	Cons.: $5 \leq WWR < 20$, $10 < ACH < 14$ R: WWR: $10.04 \leq W/OWR \leq 14.96$ (± 0.23, *standared error*)
CFE			$WWR = -4.21 + (0.90 \times ACH)$	Cons.: $5 \leq WWR \leq 20$, $10 \leq ACH \leq 14$ R: WWR: $4.79 \leq W/OWR \leq 8.39$ (± 0.06, *standared error*)

For the quantitative evaluation results, the linear equations resulted in a range of W/OWR and WWR. This range gives the dissection maker a variety to choose from according to the available windows/ openings of the national market. On the other hand, the results of the qualitative evaluation (occupants' survey (evaluation stage) represent the factors of user satisfaction. The occupant's surveying results for selecting the suitable retrofitting scenario are presented in Figure 17. Half of the occupants (50%) preferred the CFE scenario. Furthermore, equal interests went to both PSO and SOW scenarios with a percentage of (20%). Finally, the least chosen scenario was PCO. The occupants referred to avoiding distortion from the corridor while working as the main reason for selecting the CFE scenario. The last set of questions was designed to determine the occupant's preferable W/OWR (among the suitable range). Regarding the outdoor window (north faced), most occupants (70%) recommended the maximum allowed WWR. Regarding the indoor opening (south façade), occupants' recommendation was neutral.

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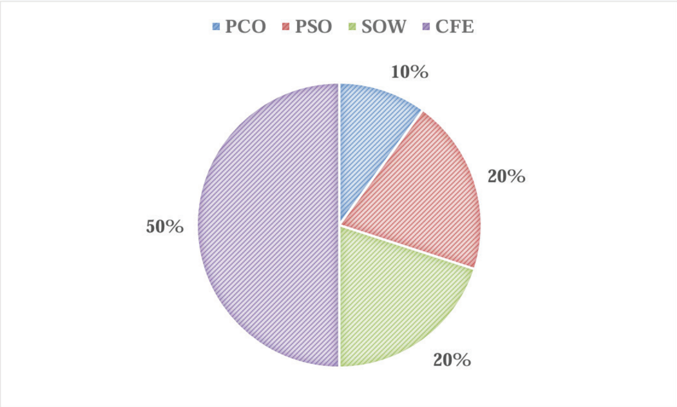

Fig. 17. Occupant's surveying results for selecting the suitable retrofitting scenario

This study considered decision-making based on a hybrid evaluation method combining quantitative and qualitative objectives. The evaluation objectives are Indoor Air Quality IAQ (natural ventilation), health and wellness (reducing infections), social aspects (concluded from users' survey), and reducing retrofitting costs.

Based on CFD analysis and ACH calculations, all four scenarios achieve the objective (with different W/OWR). By applying social aspects, the four scenarios are reduced into three scenarios (CFE, SOW, and PSO, respectively). Finally, after considering the CR_F, which targets the minimum significant changes, the retrofitting decision is SOW. The SOW scenario has a lower value of the CR_f, indicating a more considerable cost reduction compared to the baseline option (PSO). However, the WWR for the outdoor façade is 14.96% based on the occupant's recommendation for maximizing the WWR for the outdoor façade. The retrofitting decision is presented in Figure 18, whereas the plan, elevations, and 3D are illustrated.

The results reported above are for a free-running, shareable multi-user office positioned in an educational institution, especially a teaching assistant's office within a college building. The office is on the first level, opposite another office, separated by a corridor, and 20 people occupy it. The climate configuration is related to Cairo International Airport's weather. While the study focused on wind-driven ventilation, the effects of thermal buoyancy were not examined.

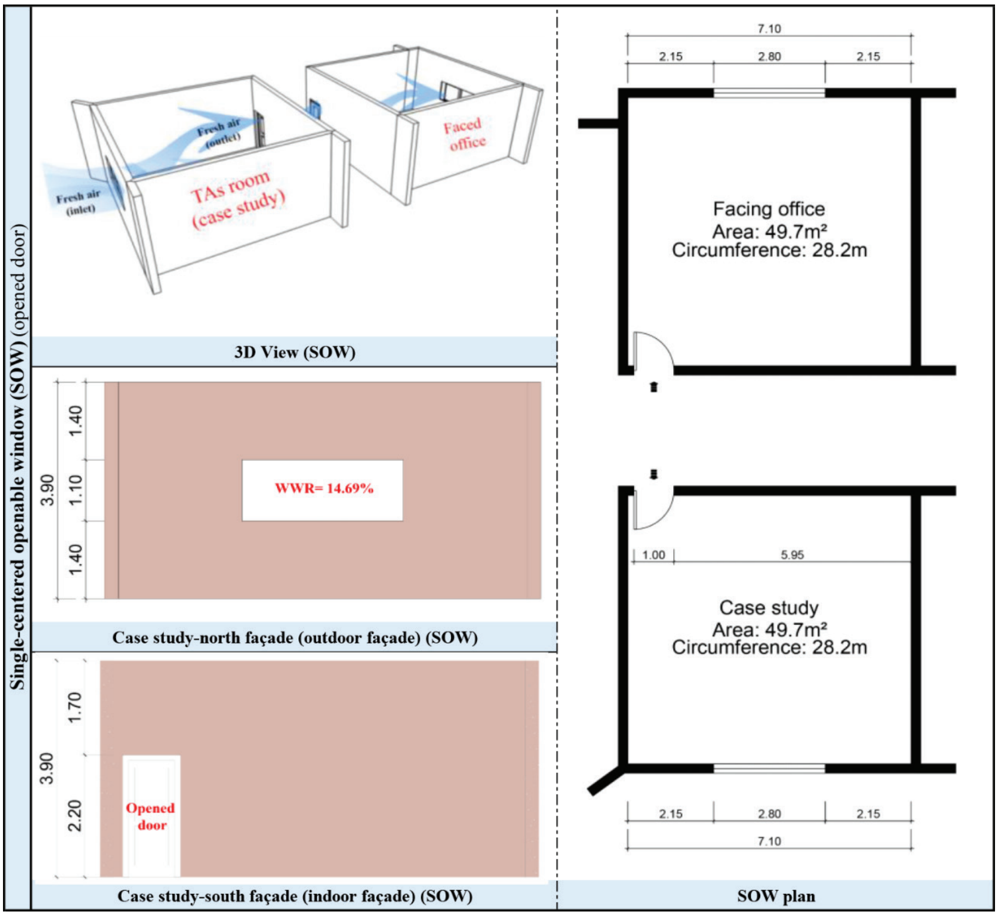

Fig. 18. The retrofitting decision based on hybrid evaluation

V. DISCUSSION

A. Previous Studies Feedback

This manuscript mainly proposes the EHR-(socio-CFD) method, which aims to reduce the infection of airborne bio-contaminant diseases using natural ventilation with space users involved in the retrofitting scenario. While the paper proposes a method and tests its applicability, some results that are related to infection and ACH rates can be discussed and compared to previous studies. The study calculated the infection rate for the case study, which was 90%; this is supported by several articles that studied the infection of COVID-19 in office buildings and stated that the infection rate may be high based on some parameters such as ventilation and occupancy rates [111], [112]. Moreover, the study revealed that most of the users 63.3% did not consider opening windows or doors despite knowing that it would reduce the possibility of infection; this is supported by a study that concluded that people tend to rely on mechanical ventilation systems even if there is a good possibility of having the same climate conditions using natural ventilation [113].

The CFD script/code was initially validated by comparing simulation results to measured data. When comparing the results of ACH to other previous studies [114] and [115], the infection rate of COVID-19 is most likely decreased to less than 1% in the case of the selected retrofitting scenario. This reduction can be achieved by taking into consideration the fact that the mask is worn inside the office.

B. Lessons Learned for Architectural Design

This study shapes two novel methods (EHR and CFDPO) that will help architectural designers solve problems related to users' health and wellness. The importance of this study lies in involving space users in the retrofitting scenario, which will enhance the retrofitting decision in terms of social interaction. The evaluation process yielded a range of W/OWR and WWR values from the linear regression models, which were developed based on the results of the CFD analysis. The accuracy of the CFD analysis was verified through comparison to field measurements, ensuring the reliability of the quantitative results used in the regression models. The qualitative evaluation through the occupant survey revealed that the CFE scenario was the most preferred, with 50% of occupants selecting it, likely due to their desire to avoid distortion from the corridor while working.

Additionally, the occupants recommended the maximum allowed WWR for the north-facing outdoor window, while their preferences for the indoor openings on the south facade were neutral. Overall, this study utilized a hybrid evaluation method that considered quantitative factors like indoor air quality and health, as well as qualitative social aspects from the user survey. After factoring in the goal of minimizing retrofitting costs, the SOW scenario was selected as the final retrofitting decision, with a WWR of 14.96% for the outdoor facade based on the occupants' recommendations.

C. Study Limitations

The study's limitations are described as follows: the measurement tools were not available, so the study used other studies' actual measured data to validate the CFD model. However, the availability of measured tools may lead to more reliable results. The proposed methods were tested on one shared office space. However, testing the same techniques on different case studies may lead to enhancements in the stages and steps of the methods. Including detailed cost analysis for the evaluation process may strengthen the practical application of the findings. These limitations may be considered in future studies.

VI. CONCLUSION

This research proposes the Epidemic Hybrid Retrofitting (EHR)- (socio-CFD) method, which aims to reduce the infection rate of airborne bio-contaminant diseases such as COVID-19 in shared public offices. It presents a hybrid framework that targets qualitative and quantitative objectives. Furthermore, The EHR-(socio-CFD) method replaces the optimization process with a multi-optional process that finds a suitable solution by compromising the hybrid objectives. On the other hand, while developing the EHR-(socio-CFD) method, a need for the (CFDPO) method has shown up to accelerate the simulation process. The CFDPO aims to use the benefits of the parametric optimization process (as a sensitivity analysis engine) to find suitable solution/s in a decent computational time. The applicability of the EHR and CFDPO methods was tested by applying them to a real case study. The case study is an indoor public space with the problem of recurrence of infections of COVID-19 among users. The application of the EHR-(socio-CFD) method has gone through different phases, which are presented in the manuscript. As a result of applying the EHR and CFDPO (within the EHR) methods in various phases and steps, the EHR and CFDPO methods have proved to be applicable and have led to suitable retrofitting decisions. The critical findings of the study are as follows:

- The onsite observation revealed COVID-19 infections, with occupant behaviors against WHO preventive procedures.
- An investigation was performed to conclude that there was no option to transfer occupants as the building was fully occupied.
- An occupant questionnaire validated observations and gathered design guidelines for retrofitting.
- Demographic data showed that 50% of occupants were 25-30, 65% were female, and 65% had master's degrees. 60% were physically present during the peak infection month.
- The infection rate was 90%, with a recurrence of 22,176 hours. The average reassurance of infection rate (RIR) was 5.6%, peaking at 19% in December 2020.
- Occupant commitment to WHO preventive measures was 71.6%, with 100% being aware, but only 36.7% actually opening windows and doors.
- Reasons for not opening windows included small size, noise, and personal, social, and technical factors.
- The CFD optimization results showed the inlet area factor (outdoor WWR-North) was the primary design parameter affecting indoor air velocity.
- The base-case model CFD simulation results showed the existing ACH was below the standard range (4.88 vs. 10-14).
- The CFD hybrid simulation results for retrofitting scenarios showed improvements in ACH and air velocity.
- The evaluation of retrofitting scenarios led to the selection of the SOW scenario based on the cost reduction factor, with a WWR of 14.96% for the outdoor façade based on occupant recommendations.

Future studies may investigate the possibilities of combining direct and indirect biomimetic architecture methods. The previously mentioned idea conceivably promotes solving complex architectural problems regarding the design process, retrofitting scenarios, and adaptation scenarios. Future studies may investigate the balance between air change, daylight, and thermal comfort. Furthermore, it may test new innovative strategies to obtain thermal comfort inside the space during the cooling season while considering the effect of natural ventilation on the process of air conditioning. Additionally, it is recommended that public-closed spaces be retrofitted to ensure sufficient clean air using both EHR and CFDPO methods. On the other hand, the research motivates young researchers to investigate more efficient methods that enhance the pond between biology and architecture. Finally, it is recommended that the minimum requirements for obtaining ACH in public spaces be added to the national regulations and recommendations.

Conversely, future studies may apply the same retrofitting method, considering more objective functions such as air temperature, thermal comfort, energy consumption, daylighting, etc. Furthermore, future studies may investigate the integration of natural ventilation and HVAC systems targeting reducing airborne bio-contaminant diseases along with thermal comfort and energy saving by simulating the cooling season. Furthermore, it may target more design variables and test new innovative strategies to obtain thermal comfort inside the space during the cooling season. Eventually, the proposed methods and frameworks may be applied to all kinds of typologies, either on the indoor space scale or on the building and urban scale. Statistical analysis of the results of the survey may be considered while applying to the urban scale to reach significant correlations between perception and physical variables.

Credit Author Statement

Randa Khalil: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review and editing, and Visualization;

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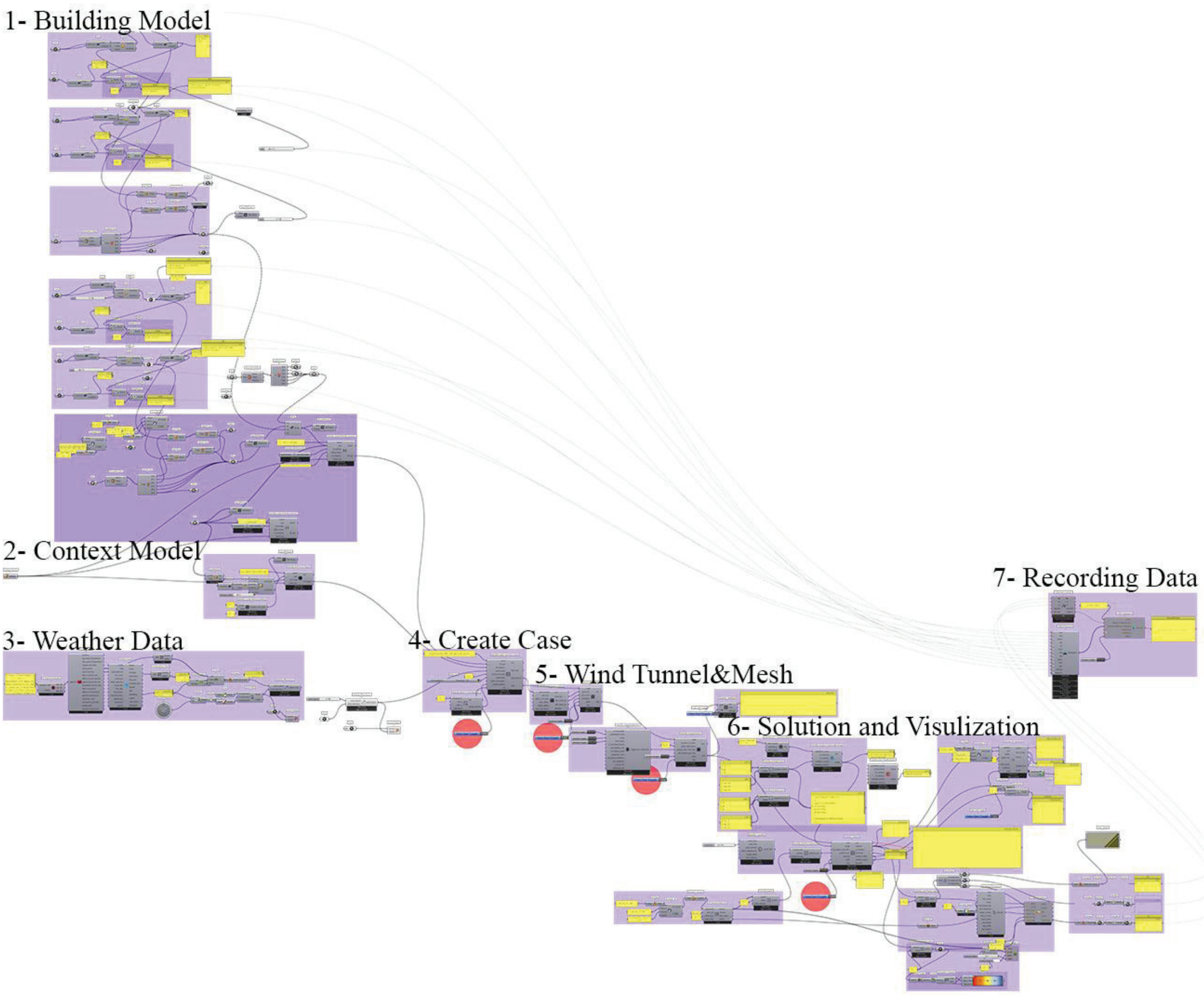
Data Availability Statement

The data that support the findings of this study are available from the corresponding author on randa.medhat@fue.edu.eg and randa.m.khalil@outlook.com upon request.

Appendix

The CFD-proposed workflow in Rhino Grasshopper. A sample of the scripts utilized in this research.



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