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ScienceDirect
Energy Reports 8 (2022) 137–152
www.elsevier.com/locate/egyr

TMREES22-Fr, EURACA, 09 to 11 May 2022, Metz-Grand Est, France

Multi-objective integrated BES-CFD co-simulation approach towards pandemic proof buildings

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Received 10 June 2022; accepted 25 June 2022
Available online xxxx

Abstract

COVID-19 has posed an extraordinary burden to those professionals responsible for properly operating and safely maintaining facilities throughout this disaster. Considering this global pandemic, the common spaces in buildings must be reconsidered to accommodate a future in-presence existence. Governments address human health and safety as the most vital considerations worldwide; thus, Heating, Ventilation, and Air Conditioning (HVAC) designs, airflow patterns, and temperature distribution must all be reconsidered to achieve such healthy circumstances. Based on this, a Building Energy Simulation-Computational Fluid Dynamics (BES-CFD) validated model has been analysed in terms of various HVAC designs. The simulations assessed the proposed solutions in terms of energy-saving, operational CO_2 emissions, thermal comfort enhancement, and infection control. The results were closely examined and showed that the Underfloor Air Distribution (UFAD) system generates approximately laminar vertical airflow, reducing the likelihood of indoor infections and viral transmission. Supply air is delivered to the inhabitants' zone without sacrificing mixing efficiency, ensuring long-term indoor environmental quality. Moreover, the UFAD model proved to be more cost-efficient compared to the Conventional Overhead Distribution (COHD) and has a lower carbon footprint and energy consumption. In terms of thermal comfort, the dynamic simulations showed a noticeable enhancement in PMV. Additionally, the UFAD provides a vertical temperature gradient profile that is sufficiently uniform. Moreover, the integrated DOAS-UFAD systems' effectiveness was proved through a techno-economic analysis with a Return on Investment of 8.25% and a Payback period of 7.3 years.

Peer-review under responsibility of the scientific committee of the TMREES22-Fr, EURACA, 2022.

Keywords: BES; CFD; COVID-19; DOAS; Environment; IEQ; Thermal comfort; UFAD

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https://doi.org/10.1016/j.egyr.2022.06.091

Peer-review under responsibility of the scientific committee of the TMREES22-Fr, EURACA, 2022.

Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BES	Building Energy Simulation
BPS	Building Performance Simulation
CDC	Centres for Disease Control and Prevention
CFD	Computational Fluid Dynamics
COHD	Conventional Overhead Distribution
CVRMSE	Coefficient of Variation of the Root Mean Square Error
DBT	Dry Bulb Temperature
DOAS	Dedicated Outdoor Air System
GW	Gigawatts
GWh	Gigawatt-hours
HVAC	Heating, Ventilation, and Air Conditioning
IEQ	Indoor Environmental Quality
LPD	Lighting Power Density
MERS	Middle East Respiratory Syndrome
NMBE	Normalized Mean Bias Error
PMV	Predicted Mean Vote
PPL	Plug and Process Load
SARS	Severe Acute Respiratory Syndrome
SHGC	Solar Heat Gain Coefficient
U	Overall Heat Transfer Coefficient
UFAD	Underfloor Air Distribution System
WBT	Wet Bulb Temperature
WHO	World Health Organization
WMDV	Wall-mounted Displacement Ventilation
WWR	Window-Wall Ratio

1. Introduction

Few events in human history have created an emergency event as the global pandemic did, especially in terms of governmental responses all over the world. The post-pandemic effect on the world will shape and change the world differently from the one that came before [1]. In December 2019, China announced an epidemic of the new coronavirus SARS-CoV2. Corona viral infections are a broad family of respiratory pathogens that are capable of causing minor respiratory disorders in human beings, such as the common cold and flu. Two different coronavirus outbreaks, severe acute respiratory syndrome (SARS) and the Middle East respiratory syndrome (MERS), however, resulted in catastrophic endemics. These disorders can result in deadly infections of the lower respiratory tract [2].

The coronavirus had an exceptional diffusion worldwide, with 469,822,676 total cases around the world and 6,075,249 total death cases (COVID-19 Dashboard by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU, March 20, 2022) [3]). To limit the transmission of the virus, health authorities invested time and effort in understanding how coronavirus transmits. Since the early weeks of the COVID-19 epidemics, the World Health Organization (WHO) and numerous public health organizations have noted that aerosol or airborne spread is possible only during certain medical treatments. Therefore, N95 masks were advised for healthcare staff performing these procedures. But in March 2020, the US CDC stated that SARS-CoV-2 transmits mostly 'via respiratory secretions generated whenever an infected individual sneezes, coughs or speaks that might fly in the mouths or nostrils of individuals who are close or perhaps be breathed. The CDC began describing the coronavirus transmission by 'airborne' or 'aerosol' by October 2020. To limit viral dissemination, certain public health bodies have begun providing recommendations aimed at airborne transmissions, such as the necessity of face masks. However, there was resistance to the role of the airborne route of transmission for COVID-19 among some public health organizations. Particle size defines the difference between the droplet and aerosol transmission. Droplets are discharged with a diameter wider than 5 or 10 μm [4,5]. These particles are believed to obey a semi-ballistic path and settle within about 1–2 meters of the person who discharged them.

In contrast, those smaller than 5 μm are termed 'aerosols' [5]. Apart from direct contact and aerosol diffusion, it was reported that airborne transmission is the major transmission mode of SARS-CoV-2, especially in enclosed spaces, as shown in Fig. 1. Poor ventilation can aggravate aerosol transmission. For example, Guo et al. [6] discovered several positive samples when analysing the air in various areas around Huoshenshan Hospital. Other studies by Chen et al. [7] and Liu et al. [8] verified the existence of positive air samples. The wide range of viral loads in patients necessitates the modification of the safety of the HVAC systems to match the control requirements. It is thought that HVAC systems aid in the transmission of SARS-Cov-1 and MERS-CoV [9]. To mitigate the risks associated with infection in enclosed environments, various institutions proposed significant transformations in HVAC requirements in terms of operational guidelines issued to control the airborne transmission.

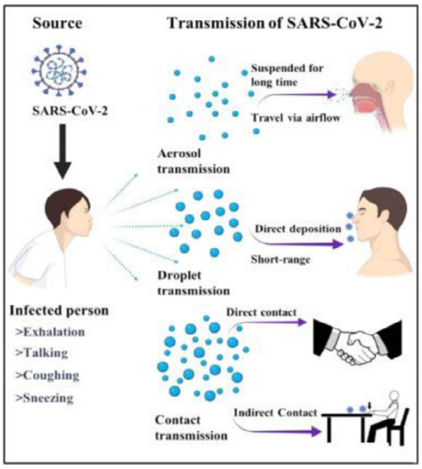

Fig. 1. Modes of coronavirus transmission [8].

The major purpose of the ventilation system is to dilute contaminated indoor air by introducing fresh air, hence preserving safe, acceptable indoor environmental quality. The effectiveness with which indoor air pollutants are removed is dependent on the ventilation rates and airflow patterns. The primary issue associated with controlling indoor biological pollution through ventilation systems is related to seeking an approach that helps in quickly eradicating and destroying the internal biological contamination when a certain combination of ventilation rates, airflow patterns, and maybe ultraviolet germicidal irradiation (UVGI) from the perspective of ventilation design is used [10]. Wei et al. [11] argue that due to the considerable amount of building energy usage, retrofitting existing facilities to increase energy performance is in high demand. The energy consumption and indoor air quality of an office building with a renovated HVAC system were analysed. Prior to and after the renovation, energy data was collected. They concluded that the updated HVAC system could reduce energy usage by fifty percent while mostly keeping acceptable interior thermal conditions. Pan et al. [12] investigate the appropriate HVAC operational processes in organizations from an engineering perspective in order to preserve a safe and hygienic indoor environment, as well as to tackle the reduction of COVID-19 diffusion throughout the building. According to research, increasing the amount of outside air can aid reduce internal contamination levels and limit the spread of infectious pathogens, including viruses and bacteria. They stressed the need for adaptive design to address the needs of unanticipated emergencies, such as epidemics and the considerations of increased outdoor air in HVAC design. However, the main contributor to higher energy consumption in hot climatic regions is the introduction of high volumes of fresh air [9]. William et al. [9,13] proposed an energy-efficient dedicated outdoor air system (DOAS) as a solution to introduce the recommended amount of fresh air. But the airflow pattern has a significant impact on risks of airborne transmission too. To the authors' knowledge, the analyses of integrated DOAS and underfloor air distribution (UFAD) systems have not been addressed yet, especially in Egyptian buildings with hot climate conditions. Thus, this paper analyses indoor airborne transmission risks through integrated validated BES-CFD models and propose an energy-efficient infection control solution towards pandemic-proof buildings.

2. Methods and tools

This article implies a combined methodology of two integrative computational analyses of Building Energy Simulation (BES) and a Computational Fluid Dynamics (CFD) space dependent. Through integrating a BES with CFD simulations, extensive insight into the facility's indoor air conditions is generated, which increases the reliability of the energy findings [14,15]. A BES enables the investigation of the building's performance for a given time frame and possibly the entire year. Since the air is presumed to be under ideal mixing conditions, such a computing node will accurately reflect a whole zone, and an examination of HVAC systems and interior ambient conditions may be performed [15]. Alternatively, by incorporating the actual dimensions of the space, CFD modelling can predict the distribution of interior temperatures, air movement, and thermal comfort, often to a single moment. Accordingly, using a combined BES-CFD model to analyse the indoor environmental conditions in conjunction with the facility's energy utilization is the optimum technique [16].

In this investigation, the EnergyPlus simulation engine is utilized within DesignBuilder. DesignBuilder is considered as it effectively enables the designer to reuse the BES prototype for CFD analysis [17]. Researchers contrasted the DesignBuilder CFD module to a professional commercialized CFD software suite. The investigation observed that the CFD package within DesignBuilder is similar to professional CFD software due to its apparent low Root Mean Square (RMS) variations among outcomes [18].

The computational framework of the building dynamic energy modelling is specified by creating a 3D representation and defining the building location and climatic conditions, orientation, building envelope characterization, internal gains, and occupants' densities and activities. These data were fed into the DesignBuilder simulation model. The built-up model is then calibrated and validated, contrasted to in-situ energy measurements, followed by a verification employing ASHRAE validation measures [19].

Considering the global COVID-19 pandemic, this study assesses the HVAC systems and the positions of air supply and extraction systems via fully integrated BES-CFD models. As illustrated in Fig. 2, the analysis methodology aims to decrease the possibility of respiratory transmitted aerosols in the built environment while enhancing indoor thermal conditions and reducing Carbon footprint. The boundary conditions for the CFD computations are extracted precisely from the prior BES model. Meanwhile, the turbulence model, discretization, convergence iterative error, and mesh are configured and implemented in the CFD model [20].

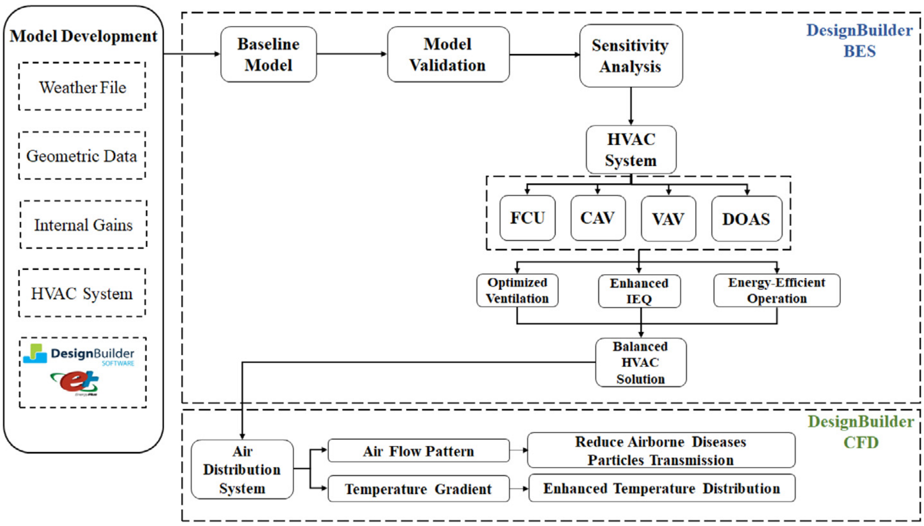

Fig. 2. Graphical Methodology.

3. Building description

A data-accessible educational institution in Cairo, Egypt, is identified for analysis. Cairo is classified as a hot-arid climate, identified as BWh according to the Köppen Geiger climate classification [21–23]. For global applicability, Cairo is considered a Zone 2B climatic region by ASHRAE with a Dry Bulb Temperature (DBT) of 38.2 °C and Wet Bulb Temperature (WBT) of 21.2 °C [24].

The case study six-story building with an area of 11,350 m^2 and a typical operating schedule between 08:30 AM to 4:00 PM, five days a week, is depicted in Fig. 3. As with most university facilities globally, the facility runs at around half capacity throughout August, owing to annual vacations.

Fig. 3. Actual Building and Built-up Model Axonometric.

3.1. Envelope characterization

Construction records from Egypt's construction and development industries have been used to form the baseline model. The overall heat transfer coefficient of the walls and roof are 1.924 and 2.27 $W/m^2 \cdot K$, respectively [13]. With a Window-Wall Ratio (WWR) of approximately 30%, the windows' overall heat transfer coefficient and Solar Heat Gain Coefficient (SHGC) values for the 6mm Blue Double Glass with a 6mm air gap are given by 3.094 and 0.503, respectively [25].

3.2. Internal heat gains

Internal gains are basically the heat loads generated within a structure, such as occupants, lights, and equipment. The occupant densities, together with the suggested lighting power density (LPD) and plug and process load (PPL) adopting the space-by-space technique, are tabulated in Table 1.

3.3. Ventilation requirements

Ventilation is the operation of removing stale interior air from a facility, room, or enclosed area and substituting it with fresh outdoor air. Proper ventilation is necessary for respiration since the oxygen concentration steadily decreases in a dense zone; thus, it is necessary to remove or dilute air contaminants, smoke, and odours, as well as to manage the indoor temperature and relative humidity levels within the zone being utilized. The suggested ventilation rates are summarized in Table 2.

3.4. Model validity

Various techniques abound for verifying energy models of buildings. These techniques are generally categorized as analytic, laboratory, and realistic practices, with the last category being precise (comparison of simulation findings to existing actual data) [30]. The practical validation implies tying together statistics from building measured data and simulation results. The built-up model is validated in this study by comparing it to the facility's real energy data, as presented in Fig. 4. Any measurement must be subjected to error analysis to conduct an investigation properly. According to ASHRAE validation indices, the built-up model resulted in acceptable values of 6% NMBE and 3% CVRMSE [19].

Table 1. Standardized occupant densities, LPD, and PPL of Institutional buildings [26–29].

Zone	Occupant density (#/100 m^2)	LPD (W/m^2)	PPL (W/m^2)
Classroom	65	13.4	4.7
Coffee Stations	20	7	18.54
Conference/Meeting	50	13.3	9.38
Corridors	–	9.9	2
Labs	25	15.5	10.95
Lecture hall	150	13.4	2
Libraries	10	11.5	13.3
Lounges	50	7.9	2.12
Main entry lobbies	10	9.7	2.5
Office Spaces	5	12	11.95
PC lab	25	18.4	21.5
Reception Areas	30	5.9	5.59
Restaurants	70	11.6	66.74

Table 2. Recommended institutional buildings ventilation rates [26,29].

Zone	Ventilation rate (L/s-person)	Ventilation rate (L/s-m^2)
Classroom	3.8	0.3
Coffee Stations	2.5	0.3
Conference/Meeting	2.5	0.3
Corridors	–	0.3
Labs	5	0.9
Lecture hall	3.8	0.3
Libraries	2.5	0.6
Lounges	2.5	0.6
Main entry lobbies	2.5	0.3
Office Spaces	2.5	0.3
PC lab	5	0.6
Reception Areas	2.5	0.3
Restaurants	3.8	0.9

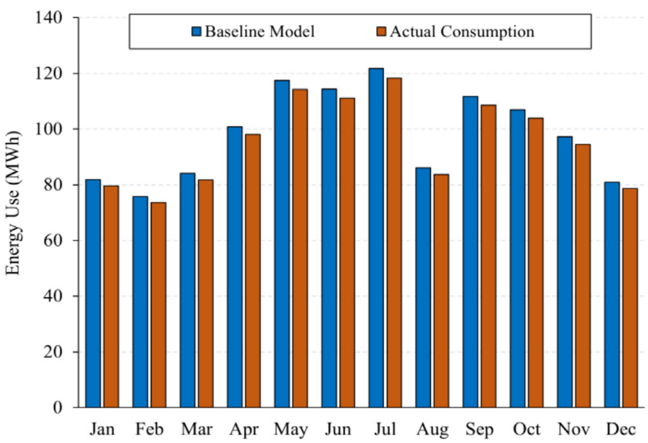

Fig. 4. Building Energy Model Validation.

The base model's energy consumption is determined by calculating the proportion of each constituent to total energy consumption. The monthly energy utilization per constituent is portrayed in Fig. 5. As it can be seen, HVAC systems are the highest energy consumers except during the winter months, a period in which lighting consumption predominates with monthly energy use.

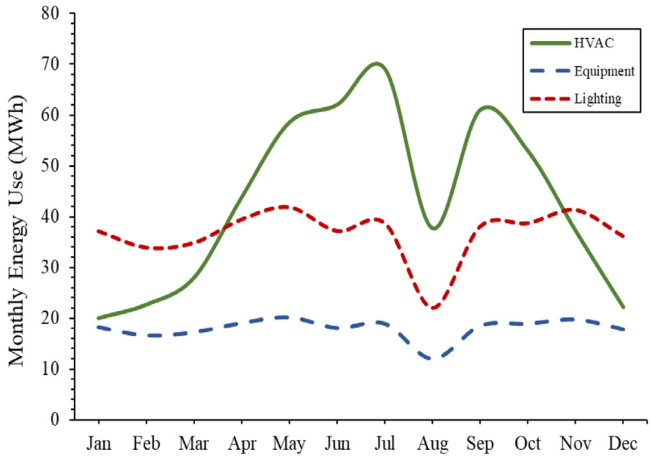

Fig. 5. Monthly Baseline Model Energy Analysis.

Upon confirming the base case, a local sensitivity analysis found that HVAC records approximately half of gross building energy demand, primarily commensurate with HVAC energy use in matching climates [13,31–34].

3.5. HVAC and Indoor Environmental Quality (IEQ)

The HVAC system is essential for maintaining a safe and pleasant IEQ for its residents. Considering electrical energy generation and distribution are typically around 33% efficient, it requires around 3 kWh of total energy to produce and transport 1 kWh to the end-users [35]. Accordingly, several initiatives aim to develop novel HVAC system topologies, optimize HVAC designs, and improve functioning. All these initiatives are intended to enhance the building's efficiency. Therefore, energy use for air conditioning buildings decreases and byproducts carbon emissions. But, with the global COVID-19 and Mucormycosis pandemic, several researchers recommended introducing higher fresh air rates to reduce indoor respirable contaminants.

As a function of these considerations, the HVAC solutions for examination are divided into three categories: terminal units (FCU), all-air systems (CAV, VAV), and hybrid systems (DOAS). Air is drawn through the FCU and afterwards blown onto the heating/cooling coil as it moves through the unit. A supplementary ventilation mechanism is usually necessary and, therefore, ineffective compared to other solutions. In multi-occupancy facilities, re-circulating ventilation solutions equipped with one or multiple typical air handling units, CAV and VAV, conditions a mix of outdoor and re-circulated air (supply air) for multiple ventilation zones [24]. Different zones may contain different percentages of outdoor air, but each air handling unit offers only one percent. Hence, the air handling units outside airflow rate is decided by the zone that necessitates the greatest amount of the outside airflow. Therefore, excessive ventilation occurs in various other zones when a zone receives extra outdoor air. In several HVAC systems, the cooling and dehumidification system is inadequate to satisfy the facility's required loads when the moisture levels are elevated, either owing to excessive indoor moisture creation or high outdoor ventilation airflow. As a byproduct, erroneous design and execution of HVAC systems that manage humidity control challenges may result in inferior IEQ and excessive energy usage [36]. Alternate HVAC systems such as DOAS could deliver each zone with the precise quantity of outdoor ventilation air needed.

Additionally, there are established relationships between infection risks and many indoor factors, such as relative humidity, airflow pattern, frequent maintenance of ventilation units, type of employed air filters, and ventilation rates [37–39]. The performance of DOAS is proven by delivering the exact amount of fresh air necessary, controlling indoor relative humidity, and mitigating the risk of airborne diseases indoors [9,13].

In this study, various HVAC systems are contrasted to the integrated DOAS-UFAD system, aiming to reduce the infection risks in the built environment. The UFAD system's fundamental concept is to deliver air via a raised floor. The air is supplied at a suitable velocity and pattern that achieve conditions of almost laminar flow [40]. Due to improved ventilation efficiency, UFAD allows the air supply temperature to be 17 °C, compared to 13 °C in overhead systems, increasing the HVAC system's COP and reducing energy utilization [20,40–43]. Bearing this in mind, a classroom has been selected for the CFD model. Once the model has converged, the airflow patterns (velocity vectors) and the temperature profiles have been compared. The as-built Conventional Overhead Distribution (COHD) systems and design alternatives deliver the same air supply as the Wall-mounted Displacement Ventilation system (WMDV) and UFAD system in terms of enhanced IEQ.

4. Results and findings

The validated baseline model utilizing FCU has been contrasted with a variety of HVAC solutions: FCU, CAV, VAV, DOAS and DOAS+UFAD. The outcomes of the various solutions are categorized: Building Performance Simulation (BPS), Thermal Comfort Assessment, CFD model outcomes, and cost-effectiveness analysis.

4.1. Building performance simulation

The performance of these various HVAC systems is compared to determine their influence on energy efficiency and environmental impact. Each system was evaluated individually to ascertain its influence. The outcomes are graphically illustrated in Fig. 6.

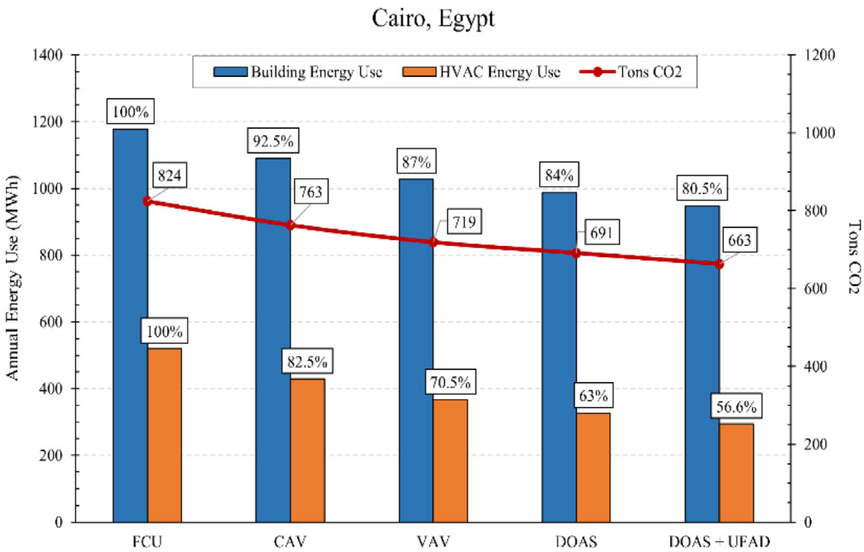

Fig. 6. Tested models energy reduction and Carbon footprint.

The responsiveness of the building reaction to various HVAC systems is tabulated in Table 3.

The outcomes reveal the effectiveness of the proposed integrated DOAS-UFAD. The HVAC energy use was reduced by about 43%, and byproducts reduced the building's operational costs and CO_2 emissions by approximately 20% with respect to the FCU system.

The model is then tested for indoor airflow patterns and temperature profiles using the integrated BES-CFD module.

4.2. Thermal comfort assessment

Residents' comfort considerations are the foremost major operational difficulty faced by facilities operators on a daily basis. Numerous investigations have shown that thermal comfort helps improve human health, productivity,

Table 3. Building energy use, HVAC energy use and CO_2 emissions.

Model	Building energy use (MWh)	HVAC energy use (MWh)	CO_2 emissions reduction
FCU	1178	520	-
CAV	1090	429	7%
VAV	1027	367	13%
DOAS	988	327	16%
DOAS + UFAD	948	294	20%

and wellbeing [35,44]. Building residents experience stress as a result of a deficiency of thermal comfort. Thermal comfort is a state of mindset characterized by satisfaction with a human's thermal surroundings [45]. Consequently, efficient approaches are rarely applied in practice in developing nations, possibly because the knowledge is not widely understood or recognized. Comfort and energy usage are also linked to numerous design decisions made at diverse phases of the design process [25]. Because of this, designers should be developed to act as a bridge among the regions of healthy designs so that inhabitants and facilities can be adequately conditioned.

While comfort is a very subjective feeling for individuals, several guidelines indicate the ideal values for sustaining indoor settings. Fanger constructed a 7-point gauge to measure thermal comfort, which was eventually adopted by ISO 7730 and ASHRAE 55, standardized as "(+3 hot, +2 warm, +1 slightly warm, 0 neutral, −1 slightly cool, −2 cool, and −3 cold)" [45,46]. The models under investigation ran numerous simulations to predict the PMV response. The outcomes are visualized in Fig. 7.

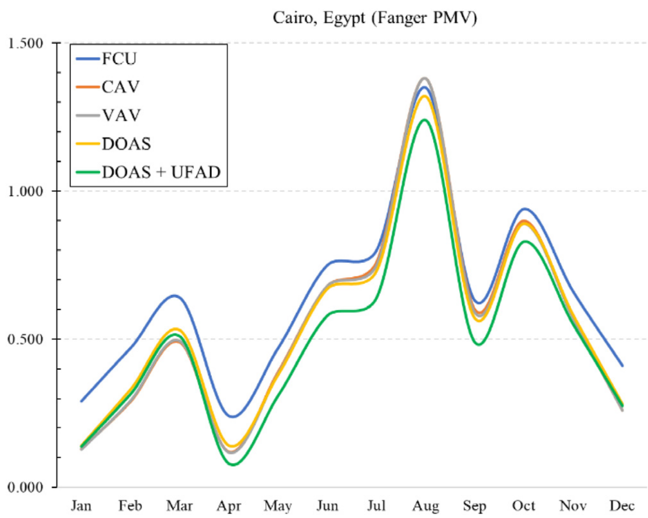

Fig. 7. Resulting PMV among tested HVAC systems.

The greatest PMV values are witnessed in the baseline FCU model. The DOAS+UFAD model's average PMV index was reduced by 22% compared to the baseline model. As per the findings of the dynamic models, an enhancement in interior comfort is directly noticeable.

4.3. CFD modelling outcomes

Air movement and flow pattern are also crucial. Different supply and extraction arrangements have been put through the tests to evaluate better the temperature gradient and airflow patterns in the classroom's occupied and breathing zones. With this in perspective, three setups, the ceiling linear slot conventional overhead distribution system (COHD), wall-mounted displacement ventilation linear slot system (WMDV), and the underfloor air distribution system (UFAD) linear slot. The supply and extract overhead linear bar grills have been identified within the computational domain according to the as-built model. The boundary conditions generated earlier in BES observations were employed to develop and simulate the air supply. By analysing the internal homogeneity and flow vectors, CFD simulations are conducted, promoting vertical indoor airflow patterns so that exhaled air by residents with probable infections does not affect others but is predominantly driven into the extraction vents. Thus, the airborne infection risks are reduced through enhanced, nearly laminar airflow patterns.

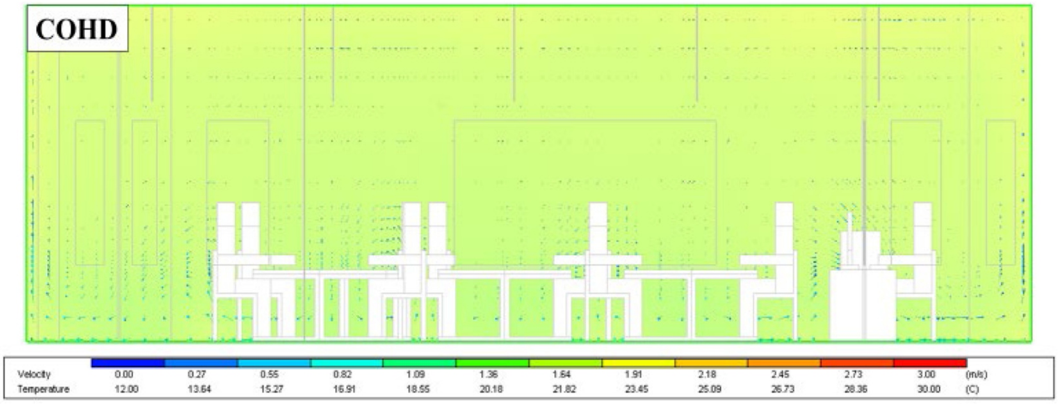

Fig. 8. CFD side view air velocity and temperature section, COHD.

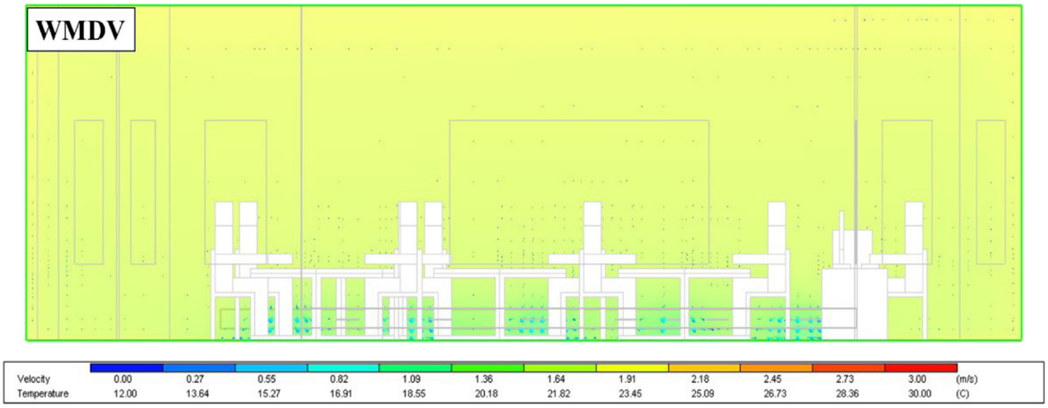

Fig. 9. CFD side view air velocity and temperature section, WMDV.

A recent study conducted in hot climatic locations indicated a warmer indoor environment increases comfortability and enhances health over time, highlighting that the mean comfort temperature observed is between 24 and 24.8 °C [44]. Figs. 8 and 9 depict an approach for developing an advantageous indoor temperature profile that balances energy efficiency with the needs of occupants' comfort. As demonstrated in Figs. 8, 9, and 10, the vertical temperature gradient profile produced by the WMDV and UFAD system is relatively uniform, attaining nearly 24 °C compared to 22 °C in COHD, minimizing localized discomfort and unpleasant vertical variances.

CFD models are undertaken by examining the internal homogeneity and flow vectors, supporting vertical interior airflow patterns such that exhaled air from inhabitants with likely infections does not influence others but is mainly guided towards the extracting vents. As a result, airborne infections are mitigated due to the improved, nearly laminar airflow patterns.

As detected in Figs. 8, 11, and 14 the COHD systems result in a turbulence swirling air motion that transfers aerosols between individuals in the breathing zone. The WMDV systems show less turbulence than COHD systems, as per Figs. 9, 12, and 15. On the contrary, the UFAD system's airflow is nearly laminar vertical, such that the

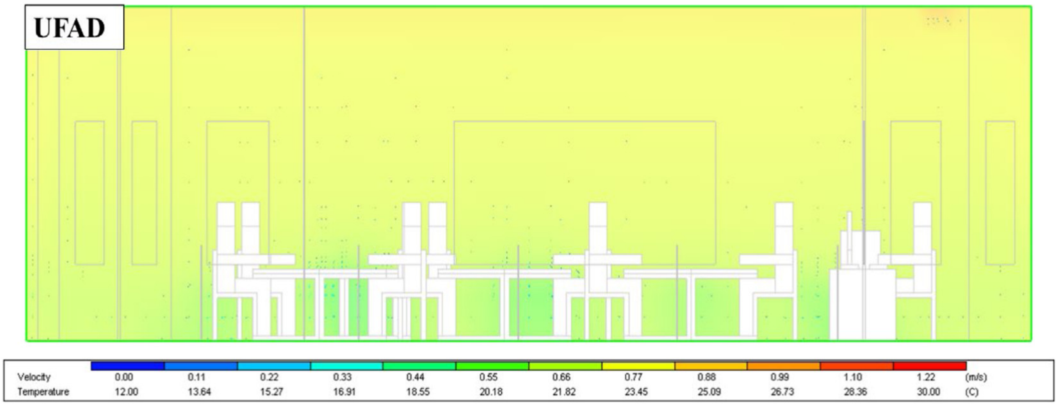

Fig. 10. CFD side view air velocity and temperature section, UFAD.

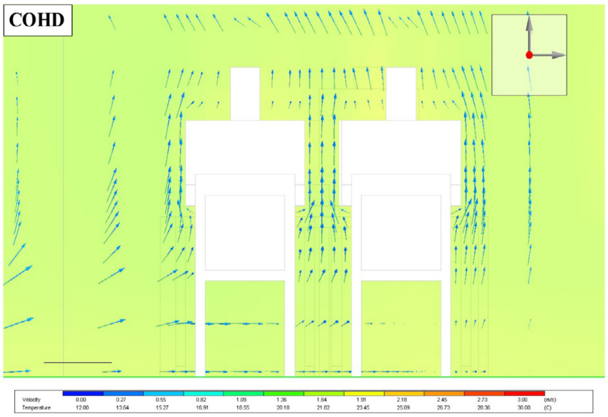

Fig. 11. CFD back view air velocity and temperature section, COHD.

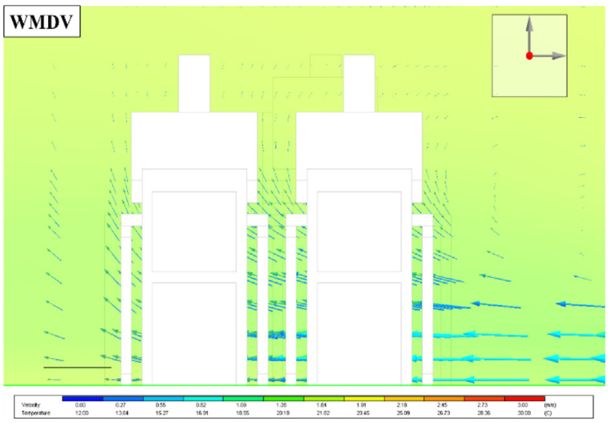

Fig. 12. CFD back view air velocity and temperature section, WMDV.

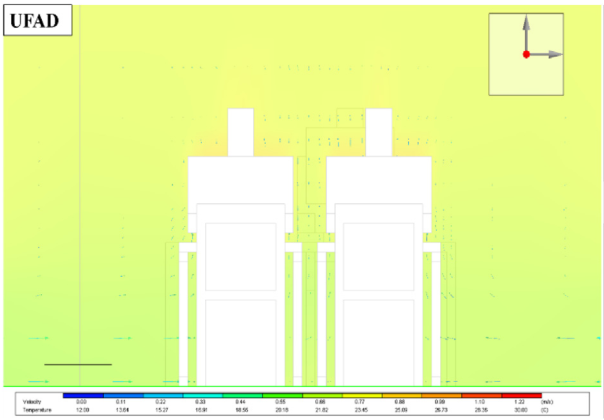

Fig. 13. CFD back view air velocity and temperature section, UFAD.

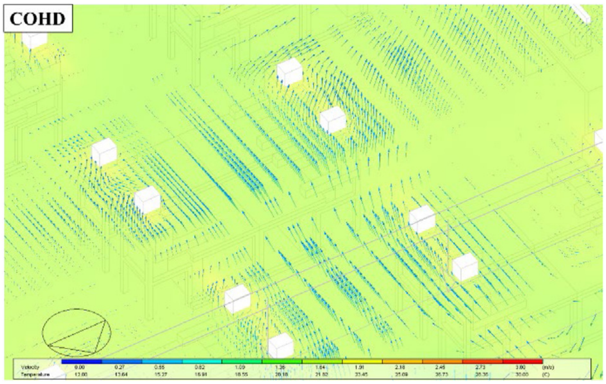

Fig. 14. CFD occupant level air velocity and temperature section, COHD.

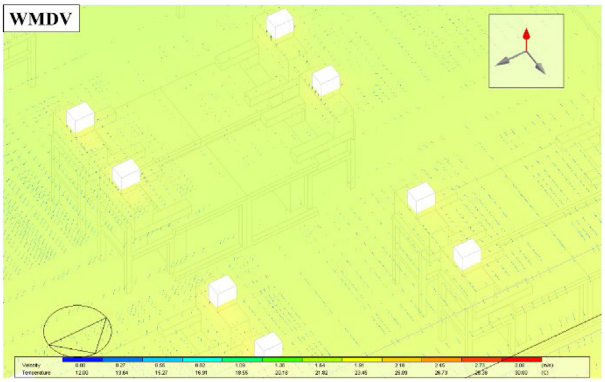

Fig. 15. CFD occupant level air velocity and temperature section, WMDV.

ceiling-mounted grilles instantly absorb the breathed air, as shown in Figs. 10, 13, and 16. Thus, the UFAD solution may be the most suitable practical approach for reducing aerosol transmission indoors.

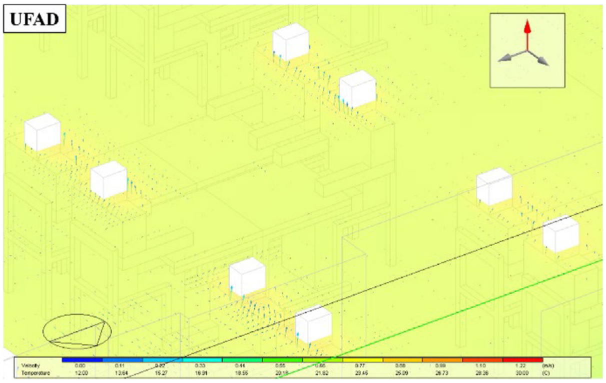

Fig. 16. CFD occupant level air velocity and temperature section, UFAD.

4.4. Cost-effectiveness analysis

An economic assessment known as cost-effectiveness analysis evaluates the costs and benefits of various solutions. Decision-makers that intend to attain a specific target may benefit from these findings. Following [9,47], the HVAC systems pricing considers the market costs, including the differential costs of UFAD, as demonstrated in Table 4.

Table 4. Cost-effectiveness of the alternative solutions.

Model	HVAC system Initial cost (USD)	HVAC system Increased cost %	Building running cost (USD)	Total savings (USD)	Return on investment (ROI)	Payback period (Years)
FCU	483,674	–	119,724	–	–	-
CAV	845,578	75%	110,823	8,900	1.62%	37.3
VAV	1,011,017	110%	104,444	15,279	1.91%	31.7
DOAS	703,517	45%	100,402	19,321	5.80%	10.4
DOAS + UFAD	770,626	60%	96,347	23,376	8.25%	7.3

Despite the increased initial cost of the proposed DOAS-UFAD solution, the resulting operational cost savings has demonstrated its potential towards energy efficiency. The techno-economic assessment revealed the effectiveness of integrated DOAS-UFAD systems with a Return on Investment of 8.25% and a Payback period of 7.3 years.

Alongside the DOAS's cost-effectiveness, as demonstrated in Table 4, the universal epidemic's current state mandates prioritizing solutions that deliver larger volumes of outside air. But providing these amounts of fresh air through COHD systems may lead to airborne particles turbulence, requiring in-depth analysis of airflow pattern. The air distribution systems have been analysed in terms of turbulence, highlighting the effectiveness of the integrated DOAS-UFAD systems in supplying the required fresh air amount while creating a nearly laminar airflow pattern, reducing the risk of airborne transmission.

5. Discussion

Experts believe that introducing fresh outdoor air into the built environment can maintain a safe and healthy environment and reduce the spread of COVID-19 and Mucormycosis. But, the supply of large quantities of fresh air is conversely the primary cause of increased energy use in hot climates. Consequently, many initiatives strive to establish innovative HVAC system configurations, optimize HVAC designs, and enhance system performance. In this analysis, diverse HVAC designs are contrasted, aspiring to decrease the infection threats in the built environment.

The key recommendations to reduce airborne infections in enclosed spaces in the current investigation are: (1) implementing a DOAS as a practicable solution that proves its ability to maintain indoor humidity levels within recommended healthy range, (2) widening the use of UFAD systems that demonstrated its ability to supply almost laminar airflow that reduces the turbulence of infected particles, (3) executing the integrated DOAS-UFAD enhanced the indoor thermal comfort conditions, (4) the applicability of the proposed solution has been verified through extensive techno-economic analysis.

6. Conclusion

The prevailing global pandemic of COVID-19 has been closely associated with the dissemination of pathogenic aerosols via human-to-human contact indoors, highlighting the critical need for intense and comprehensive efforts to prevent infection spread. The primary objective of this investigation was to determine the major factors that lead to energy savings while emphasizing healthy indoor conditions. Numerous HVAC solutions have been analysed for their capability to disseminate indoor airborne contaminants using an integrated BES-CFD simulation platform. For analysing indoor conditions, the combined BES-CFD co-simulation gives precise records. This proposed solution integrates multiple approaches for designing and renovating buildings, focusing on health and safety requirements. The energy-efficient proposed solution simultaneously combines both DOAS and UFAD systems' advantages.

The conclusions are summarized as follows:

- UFAD configuration shows lower operational costs compared to COHD and WMDV.
- The proposed formation decreases the use of HVAC energy by 43%, building energy, and carbon footprint byproducts by about 20%.
- The economic efficiency of the integrated DOAS-UFAD configuration is favourable, with an ROI of 8.25% and a payback period of 7.3 years.
- Delivering supply air precisely to the inhabitants' zone without compromising mixing efficiency ensures sustainable indoor environmental quality.
- The UFAD system preserves a relatively uniform vertical temperature gradient profile, improving indoor thermal comfort.
- Compared to COHD systems, the UFAD system's air is approximately laminar vertical, facilitating the ceiling-mounted grilles to capture the airborne aerosols more effectively.
- The integrated DOAS-UFAD systems enhanced indoor thermal comfort (PMV).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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