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Evaluating heating, ventilation, and air-conditioning systems toward minimizing the airborne transmission risk of Mucormycosis and COVID-19 infections in built environment

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ABSTRACT

This ongoing global pandemic of the COVID-19 has generated a significant international concern for our respiratory health. For instance, the breakout of the COVID-19 pandemic was directly linked to the spread of infectious particles in indoor environments between humans, underlining the significance of rigorous and effective actions to limit the transmission of diseases. Recently, Mucormycosis infections in COVID-19 patients have been identified. This investigation aims to investigate potential infection control HVAC solutions for indoor environments, as well as their core mechanisms for reducing infectious disease risk through simulation models of a valid building in a hot climatic region. Considering recent international recommendations, the investigation relies on a methodology of testing a validated building energy model to several systems in the light of infectious diseases prevention. All proposed models are exposed to cost analysis in line with carbon emissions, and indoor thermal conditions. The analysis outlined through parametric simulations, the effectiveness of the proposed DOAS in supplying 100% fresh ventilation air and enhancing the control of the indoor relative humidity simultaneously. Finally, through an enviro-economic assessment, the study concluded that the DOAS model reduced the CO_2 emissions to 691 tons, with a potential of reducing HVAC and whole-building energy use by 37% and 16%, respectively in the hot arid climate, with a return on investment of about 6%.

1. Introduction

With infections of the COVID-19 virus being recorded all across the world, health authorities are concentrating their efforts on limiting the virus's transmission. Filter masks do not provide complete protection against coronaviruses, and protection should be based on the employment of many measures simultaneously [1,2]. Therefore, understanding how coronavirus transmits allows us to take the essential precautions to avoid infections. The virus that causes COVID-19, according to specialists, transmits primarily through person-to-person contact. Respiratory diseases could be spread by aerosols of varying sizes: respiratory droplets are greater than 5–10

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BES	Building Energy Simulations
CAV	Constant Air Volume
CO_2	Carbon Dioxide
CVRMSE	Coefficient of Variation of the Root Mean Square Error
DBT	Dry Bulb Temperature
DOAS	Dedicated Outdoor Air System
FCU	Fan Coil Units
GWh	Gigawatt Hours
HVAC	Heating, Ventilation, and Air Conditioning
LPD	Lighting Power Densities
NACA	National Asthma Council Australia
NMBE	Normalized Mean Bias Error
PBP	Payback Period
ROI	Return on Investment
VAV	Variable Air Volume
WBT	Wet Bulb Temperature

μm in diameter, while droplet nuclei are less than 5 μm in diameter [3]. According to existing information, the COVID-19 virus is largely spread between humans via respiratory droplets and interactions [4–8]. When a human comes in physical contact (within 1 m) with a patient who has respiratory symptoms (e.g., coughing or sneezing), his or her mucosae (mouth and nose) or conjunctiva (eyes) are at risk of exposure to possibly infectious respiratory aerosols. Fomites in the immediate area of the infected person can potentially transmit the disease [9]. Therefore, COVID-19 viral infection can emerge through direct touch with infected people as well as indirect contact with surfaces in the nearby area or items touched by the infected individual. Airborne spread differs from droplet transmission in that it relates to the occurrence of microorganisms within droplet nuclei. They are commonly regarded to be less than 5 μm in diameter particles that can exist in the air for extended durations, around 3 h, and be transferred to someone else across distances wider than the traditional 1–2 m [10]. The generation of aerosols, as well as the wide range of virus loads in patients, necessitates tailoring the HVAC systems' safety to the unique control requirements. Indoor transmission of SARS-Cov-1 and MERS-CoV was thought to be aided by HVAC systems that were not intended to accommodate infectious people [11].

Along with the COVID-19 pandemic, regions in India have begun announcing a "black fungus" epidemic as incidences of the deadly rare infection increase among COVID-19 patients. Mucormycosis is a fungal infection that has a 50% death rate. It affects patients leading to the nose, blurry vision, pain in the chest, blood coughing and breathing difficulties [12]. The fungus can eventually travel to the brain necessitating significant surgical operations to remove the eye or a portion of the skull and jaws. COVID-19 could have played a role in vulnerability to Mucormycosis [13]. Mucormycosis is transmitted by coming in touch with fungus particles in the environment. After the fungus reaches the skin through a scratch, burn, or other sorts of skin damage, a skin infection can develop [14]. Mucormycosis has no vaccination till now but there may be some treatments to reduce the odds of acquiring mucormycosis for patients with weak immunological systems [14]. Additionally, inhaling spores from the air could cause the infection to spread to the lungs or sinuses. Daily, the average human breaths in around 16 kg of air [15]. Inhaling contaminated air may include especially aggressive compounds, is a major cause of sickness leading to the common cold and flu, bronchitis, headache, eye inflammation cough, dizziness, and the development of toxins in the blood [15]. Since the fungi that cause mucormycosis are so abundant in the surroundings and atmosphere, it is impossible to escape inhaling fungal spores. Fungi are common in indoor spaces and cause a variety of medical conditions, from local non-invasive pathologies to aggressive and widespread infections [16]. According to Ref. [16], there are currently no techniques or equipment available to totally eradicate the fungus from indoor facilities. Mold contamination is unavoidable; however, the use of air filtration systems, isolation, and environmental protection measures can help to reduce occupants' exposure [16]. Whether it is a chilly, rainy season or a hot, humid summertime, indoor activities could cause moisture and the growth of molds. Mold can spread on a variety of surfaces, including walls, clothing, books, toys, and even CDs. It has the ability to convert beloved treasures into musty antiques.

In general, for black mold to expand and thrive, it requires a source of moisture. Molds form spores that are transmitted through the air. These spores can be found indoors in any environment. They cannot be avoided, and they can survive in environments where mold cannot thrive. Mold spores grow in moist conditions. It is necessary to enhance the methods now available for studying indoor fungus in clean surroundings, as well as to identify markers of indoor air quality indoors [16]. Airborne mycological examinations should provide information regarding indoor environmental quality and thus should be performed regularly in indoor facilities [16]. Numerous studies have suggested increasing the amount of outdoor air considering outside air can be used to decrease any indoor airborne contamination. In some regions, a huge quantity of outdoor air might cause moisture control issues. A case report provided by Russo et al. [17] advocates employing a multidiscipline strategy to drive stakeholder responsibility of the environment and enhance Infection Prevention (IP) procedures. They added that the upcoming difficulties, include maintaining a constant focus on recognized risks and handling practices transition when new objectives and issues emerge. In hot climatic regions, William et al. [18,19]

investigated the effectiveness of the dedicated outdoor air system (DOAS) on a healthcare facility's energy consumption. On the other hand, and with the global concerns about mucormycosis, it is brought to our attention that HVAC systems can effectively enhance the control of moisture indoors, eliminating the growth of mold.

With the increasing concern about health issues and airborne transmission, several references limited the humidity levels to certain conditions [20,21]. Dietz et al. [20] recommended, according to ASHRAE, 40–60% indoor relative humidity to assist in minimizing the virus spread and survival. However, the virus survival in aerosols was determined at a relative humidity of 65% [20]. Furthermore, according to NACA, relative humidity of 30%–60% is quite suitable for most occupants [22]. Low humidity leads to very dry air, which enhances the probability of airborne diseases such as flu, probably as they survive longer in cool dry environments and also because of irritable nasal passages that facilitate their capture. Eczema could be inflamed, and dry skin could also be painful [22]. Dust mites and mold, which are two of the most prevalent, irritating asthma and allergy triggers, thrive in higher humidity environments [22,23]. Fig. 1 introduces the ideal humidity levels viruses, respiratory irritations, and mold growth.

Bearing this in mind, the study in hand proposes and highlights the effectiveness of implementing an energy-efficient temperature and humidity independent control system, DOAS, in buildings for today and future pandemic preventions through various simulations on a valid building.

2. Methodology

A dynamic simulation model is employed to analyze the thermal performance of a facility in Cairo, Egypt. In this investigation, the modeling tool DesignBuilder, featuring the EnergyPlus user interface, has been used. Designers can assess the retrofitting behavior using simulations, examining the influence of the action on the building's thermal loads. The baseline model is validated based on actual metered consumption confirmed by ASHRAE validation techniques, considering the weather conditions of Cairo, Egypt, as well as the existing facility's construction and operating records. Following the validation, different HVAC systems are investigated for enhanced indoor environmental quality with the aim to reduce indoor contamination and mold prevention (Fig. 2).

3. Model development and validation

To ensure comfort conditions, a particular quantity of energy must be supplied or extracted (heating/cooling) from the building space. This energy is heavily influenced by exterior climatic conditions including outdoor air temperature, humidity levels, and wind characteristics, as well as internal occupancy, heat and moist flow through the envelope and interiors, etc. [25]. This energy serves as a load on the HVAC system installed to control the building's heat and moisture. Cairo is classified as a hot climate region with annual design conditions of DBT and WBT given by 38.1 °C and 21.2 °C respectively [26]. The HVAC system serving the baseline model is terminal FCU. The recommended ventilation rates and occupant densities are based on the room type as per ASHRAE standard 62.1 [27]. Internal loads, including LPD and plug loads, are according to ASHRAE [26,28].

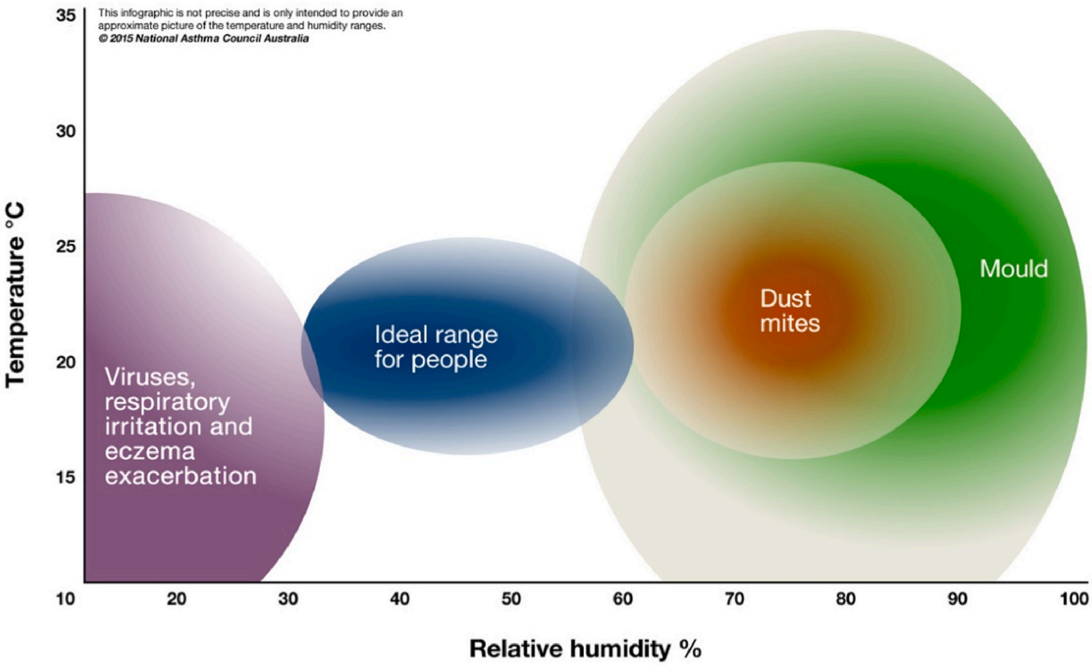

Fig. 1. Ideal temperature and humidity levels for respiratory problems patients [24].

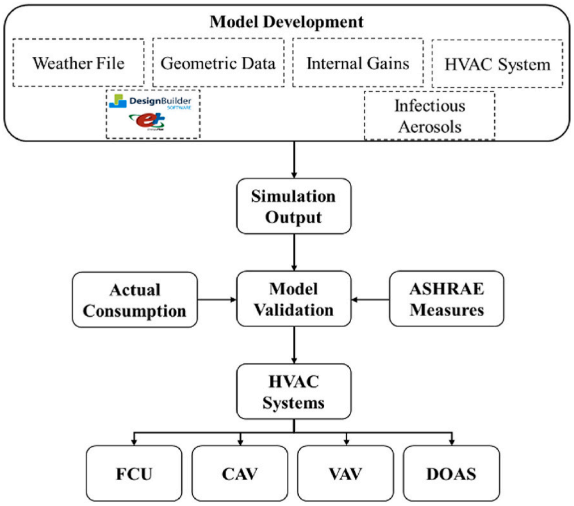

Fig. 2. Modeling flowchart.

Fig. 3 shows the model layout and Table 1 summarizes the building description.

Table 2 tabulates the occupied building zones percentage.

The forward approach in developing a BES model is predicting the outcome variables using the model's precise structure and parameters in response to a specified set of inputs variables [25]. White-Box models are those that have been generated using this approach. Since most of the energy transfer mechanisms are integrated into the formation of the BES modeling structure, those simulations are quite reliable [25]. The building model is validated compared to the on-site metered energy data. As shown in Fig. 4, the model tends to be realistic and comparable to the existing building with a CVRMSE of about 3% and an NMBE of 6%.

Following the validation, a sensitivity analysis is undertaken to reveal that around 45% of the building energy use goes to the HVAC systems aligned with the values provided by Refs. [18,19,25,29,30].

4. HVAC systems

The prime purpose of the HVAC system is to keep the temperature and humidity level of the building space within the appropriate limit levels while taking into consideration air velocity, quality, and noises. HVAC systems are classified into various classifications according to the conditioned air delivery method. This manuscript classified the HVAC systems under investigation into terminal units as FCU, All-Air systems as CAV, VAV, and hybrid system DOAS.

FCU is equipment that draws airflow from a room into the unit and then blows it across a cooling or heating coil. They typically only circulate indoor air, requiring a secondary ventilation system and being inefficient compared to typical solutions as variable air volumes.

In high-occupancy buildings, recirculating ventilation systems through one or more typical air handling units, CAV and VAV, condition a mixture of outside and recirculated air (supply air) to more than one ventilation zone [26]. These zones could have different outside air fractions, as specified by ASHRAE, but every air handling unit just provides one fraction [26]. Therefore, the air handler's outdoor airflow rate is determined by the zone requiring the highest outdoor air fraction [26]. Consequently, all other zones obtain extra outside air than required, known as over ventilation.

In many HVAC applications, the cooling and dehumidification system is unable to properly meet the imposed load requirements of the building when the dehumidification load is high, either due to large internal moisture generation or high ventilation flow rate [31]. Consequently, the improper design and operation of the HVAC equipment to address humidity control issues can lead to poor indoor air quality, and excess energy use [31].

The DOAS system is a conceivable alternative HVAC solution supplying the exact amount of recommended outside ventilation air required by each zone [19]. The air is introduced at lower dew-point temperatures, allowing it to absorb the space latent load as well as a portion of the sensible load, effectively decoupling the latent and sensible loads [18,19,32].

The four HVAC systems under investigation line diagrams are illustrated in Fig. 5.

5. Results and discussion

Proper ventilation and indoor air quality have been proven, in previous studies, to reduce the indoor contaminants and virus spread through airborne transmission. The study in hand has some limitations. This analysis is based on testing the systems on institutional buildings, assuming proper ASHRAE ventilation requirements are set, the building operates during working hours in the hot climate. Future work should include the investigation of these systems on different building types, e.g., healthcare facilities, commercial, and

Fig. 3. Model isometric.

Table 1
Building summary.

Location	Cairo, Egypt
Climate	Hot-Arid
Use	Institutional
Stories	6
Built-up Area (m^2)	11,350
Conditioned Area (m^2)	8728
Walls U-Value (W/m^2. K)	1.924
Roof U-Value (W/m^2. K)	2.27
Window-Wall Ratio	30%
Glazing U-Value (W/m^2. K)	3.094
Glazing SHGC	0.503

Table 2
Building zones percentage.

Zone	Area (m^2)	Area %
Call Center	43	0.5
Classrooms	693	7.9
Corridors	2253	25.8
Dry Lab	407	4.7
GYM	150	1.7
Lecture Halls	707	8.1
Libraries	466	5.3
Lobby	827	9.5
Lounges	453	5.2
Meeting Rooms	276	3.2
Offices	1584	18.2
Receptions	634	7.3
Restaurants	237	2.7
Total	8728	100

worship buildings.

Similar to the idea of Chirico and Rulli [33] in examining the problem of thermal conditions indoors, and to effectively introduce an efficient design for hot climatic regions, the HVAC systems for a validated building is tested and the annual overall building response is addressed through a reliable dynamic building simulation tool.

Temperature and humidity are known to enhance viral transmission if not well controlled [33]. Most HVAC system operates on controlling the indoor environment based on indoor temperature control. The simulations show that all systems are approximately resulting in the same indoor temperature control as graphically illustrated in Fig. 6a. However, according to several studies mentioned earlier, the influential factor for virus survival is moisture and relative humidity. With this in mind, the simulated models are tested against humidity levels control. According to the simulations, the FCUs are the poorest in controlling indoor relative humidity. The CAV and VAV systems have almost the same indoor environmental quality as they just differ in the operating conditions. The CAV changes the supply temperature with a constant airflow to handle the indoor loads, while the VAV systems supply a constant temperature with a variable air flow rate which affects the energy positively. According to the DOAS operating principle, the simulations

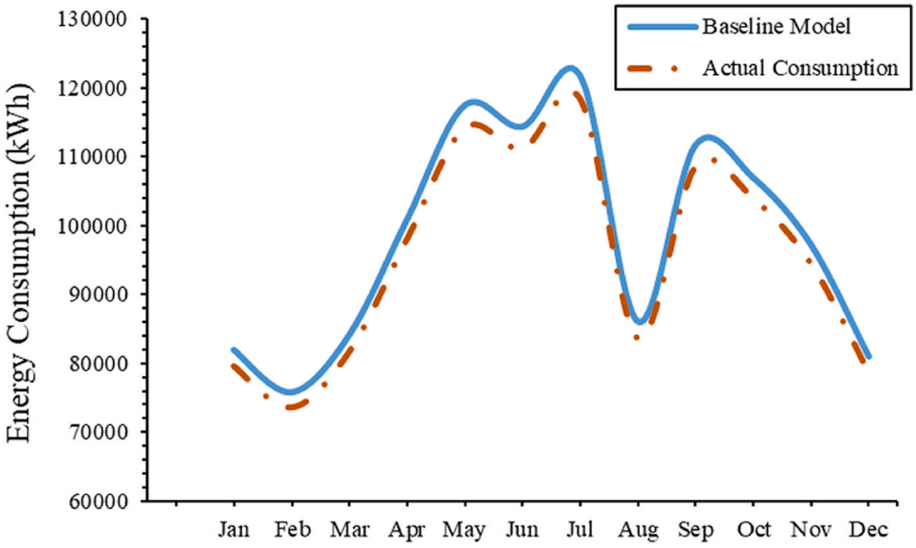

Fig. 4. Model validation.

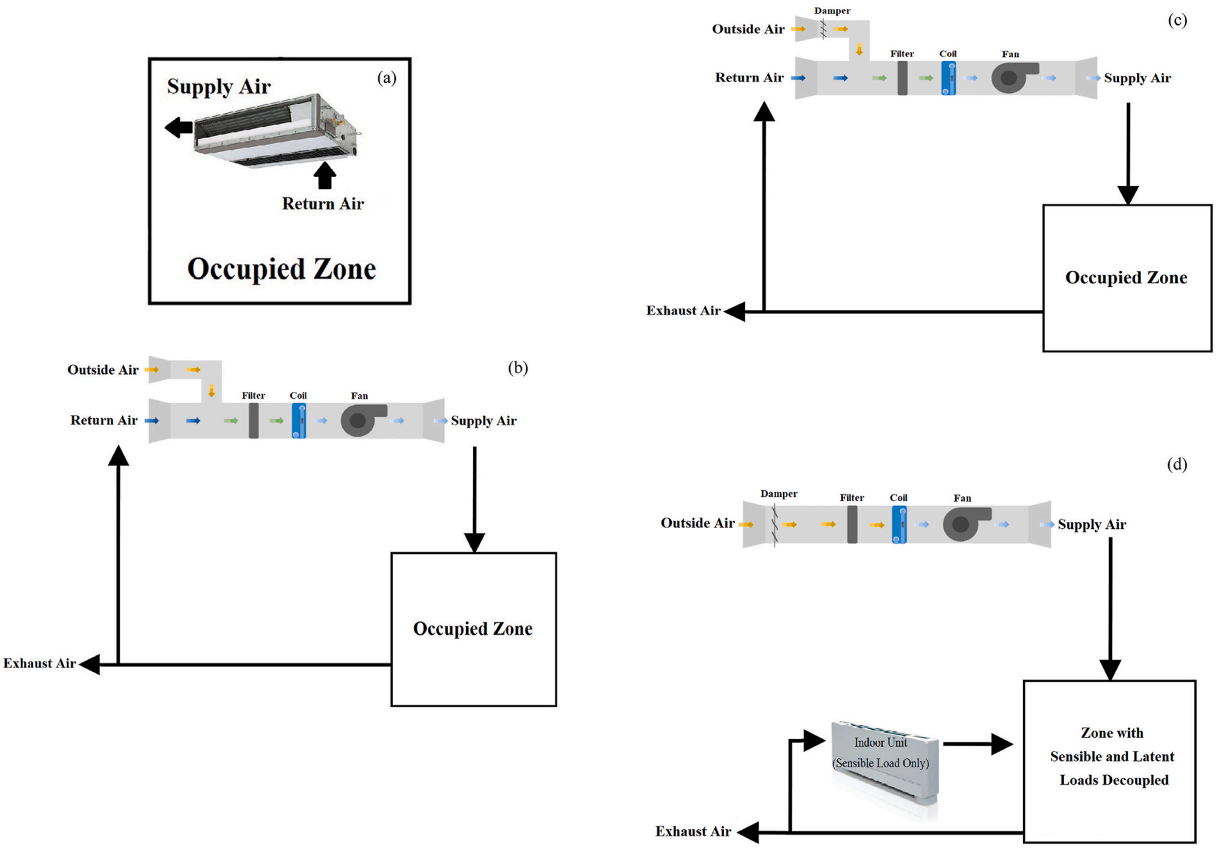

Fig. 5. Tested HVAC Systems, a) FCU, b) CAV, c) VAV, d) DOAS.

revealed the effective temperature and humidity independent control of the proposed DOAS. Fig. 6 illustrates a) temperature and b) relative humidity for the tested models investigated.

The models are also tested for the resulting whole-building energy use, HVAC energy utilization, and CO_2 emissions. The outcomes are graphically illustrated in Fig. 7.

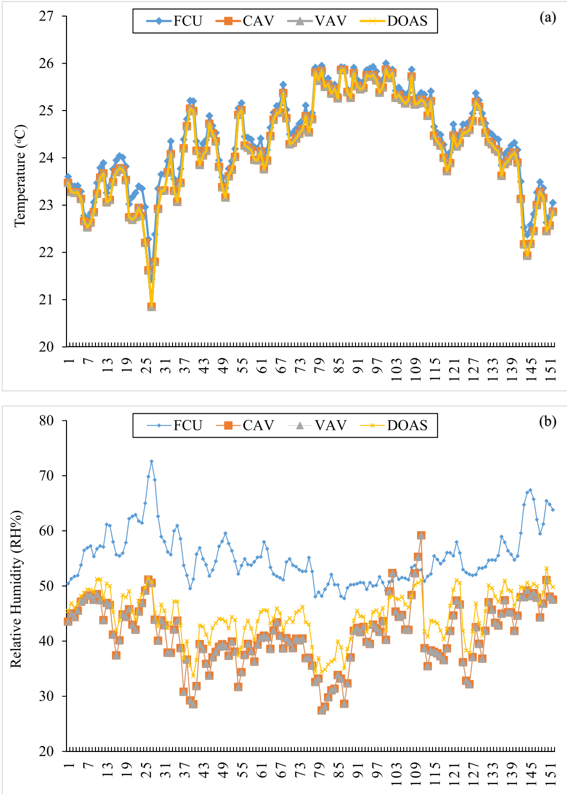

Fig. 6. Models Comparison: a) Temperature and b) Relative Humidity.

As Fig. 7 shows, DOAS is significantly reducing the HVAC energy consumption, as well as the whole building energy use. As with any engineering project, the proposed models are to undergo a cost analysis before implementation. Following the cost assessment procedures by Ref. [34], Table 3 shows the cost analysis results of each implementation according to the surveyed prices in Egypt[1] and compared to the baseline model. The investment in this study is the cost difference between the proposed system and the baseline FCU model. The running cost and savings are calculated based on 1.6 EGP per kWh, the latest tariff [35,36].

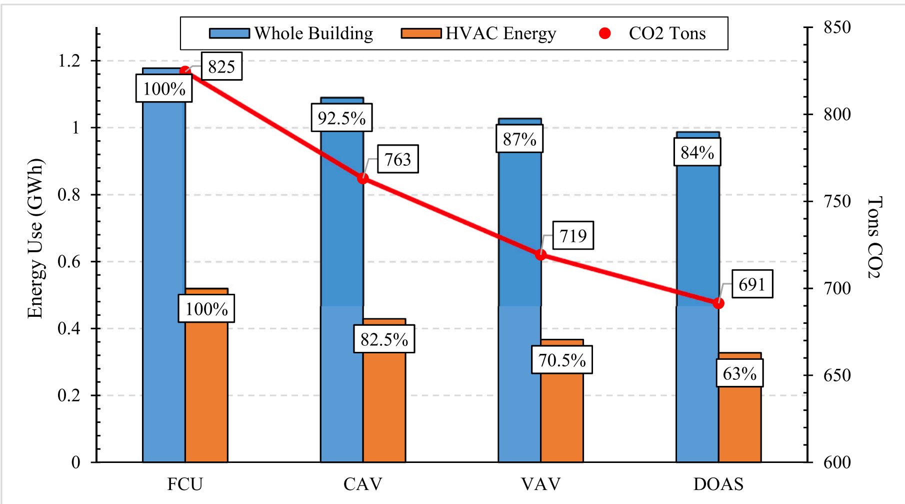

Fig. 7. Models energy responses and CO_2 reductions.

[1] Based on Egyptian market prices, 2021.

Table 3
Proposed models cost analysis.

Model	Whole Building Energy Use (GWh)	HVAC Energy Use (GWh)	HVAC Initial Cost (USD)	Building Running Cost (USD)	Total Savings	ROI
FCU	1.17	0.52	483,674	119,724	–	–
CAV	1.09	0.43	845,578	110,823	8,900	1.62%
VAV	1.03	0.37	1,011,017	104,444	15,279	1.91%
DOAS	0.99	0.33	703,517	100,402	19,321	5.80%

Despite the cost-effective potential of the DOAS shown in Table 3, the current situation of the global epidemic necessitates prioritizing systems that provide higher levels of outdoor air. The proposed DOAS has proven its ability to energy-efficiently support the building with the recommended ventilation rates. It additionally shows a great potential toward indoor humidity control with noticeable enviro-economic potential compared to other HVAC systems.

Authorship contributions

Conception and design of study: Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.

Acquisition of data: Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.

Analysis and/or interpretation of data: Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.

Drafting the manuscript: Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.

Revising the manuscript critically for important intellectual content: Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.

Approval of the version of the manuscript to be published (the names of all authors must be listed):

Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.

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.

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