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Research article

Evaluating airflow dynamics in common vertical circulation spaces of a multi-floor apartment building for mitigating airborne infection risks: A CFD modeling study

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A R T I C L E I N F O

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A B S T R A C T

As more people increasingly inhabit indoor spaces, the importance of interior environment design has grown significantly. The focus of this research is to assess the air flow and air change per hour (ACH) within common service vertical circulation spaces in apartment buildings, emphasizing the potential role of these spaces in mitigating airborne infections. The intricate relationships between the design parameters of these spaces and variables related to air circulation are examined. To achieve this goal, the investigation employed a simulation-based approach, utilizing computational fluid dynamics (CFD) analysis to scrutinize the prevalent design of common vertical circulation spaces. The simulation outcomes unequivocally reveal that the design of these spaces has a direct impact on air circulation patterns, often influencing suboptimal conditions. Armed with these insights, this research advocates for a reevaluation of design considerations of common service vertical circulation in forthcoming housing projects. Furthermore, this research proposes innovative design solutions and strategies aimed at enhancing natural ventilation and overall air flow within common service vertical circulation spaces while evaluating their performance.

1. Introduction

Throughout history, airborne diseases have been responsible for some of the deadliest pandemics, resulting in the loss of millions of lives [1]. The recent COVID-19 pandemic, caused by an airborne virus, has emerged as one of the deadliest and most severe pandemics in recorded history, and is characterized by its unpredictable behavior [2,3]. Additionally, the impact of these airborne diseases extends beyond the immediate health crisis, affecting economies, healthcare systems, and daily life on a global scale. The lessons learned from managing such pandemics are shaping future strategies for disease prevention and mitigation. In light of these challenges, a noteworthy paradigm shift is unfolding in the domain of built environment design. Architects and designers are meticulously reassessing the spatial configurations and operational dynamics of interior spaces with the overarching objective of mitigating the risk of disease transmission [4].

The indoor environment plays a pivotal role in quality of life, as people spend approximately 65–90% of their time at home [5,6]. Evidential inquiry emphasizes the ease of transmission of airborne viruses, primarily in the form of respiratory droplets or aerosols, which can traverse through the air, posing infection risks to those in proximity [7,8]. Notably, viruses may exploit air pollutant particulates as efficacious vectors, and in the presence of pollutants, viruses can survive longer and potentially become more virulent

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[7,9]. Understanding air flow dynamics within ventilated spaces is crucial for mitigating the indoor transmission of airborne diseases [10].

Airborne virus transmission poses a considerable challenge, particularly in closed, poorly ventilated, and compact spaces [8,11]. Emphasizing this concern, the World Health Organization (WHO) and Centers for Disease Control and Prevention (CDC) underscore the critical importance of maintaining good indoor air quality (IAQ) to mitigate the risk of airborne virus spread, highlighting the need to avoid enclosed, confined spaces [7,12,13]. Nonetheless, implementing such measures to maintain optimal IAQ can be particularly challenging, especially in cases where multiple individuals cohabit within relatively confined living spaces or in instances where the number of occupants significantly exceeds the spatial capacity of the residence [13,14]. A study conducted in three different cities in Canada aimed to highlight the relationship between the type of residential dwelling and mortality rates associated with airborne infections. The findings revealed a compelling association, indicating that individuals residing in apartments, whether situated in low-rise or high-rise buildings, experienced significantly greater mortality rates during episodes of airborne outbreaks than did those residing in single detached houses [15].

Since the 1990 s, Jordan's architectural landscape has undergone a dramatic shift, with apartment buildings becoming the prevailing form of housing [16]. This trend is evident in construction permits: between 2020 and 2023, a staggering 83% (13.6 million square meters) of the 16.4 million square meters allocated to residential buildings were dedicated to apartments, encompassing both new constructions and additions to existing structures [17]. This preference for multi-unit dwellings has not only reshaped the Jordanian skyline but also revealed unique challenges, as highlighted during the COVID-19 pandemic.

In Jordan, the prevalent architectural design of apartment buildings involves all residents sharing a common vertical circulation area as their primary route in and out of their homes. Consequently, this shared vertical circulation space assumes a pivotal role in facilitating the exchange of air between individual apartments, thus exerting a substantial influence on the IAQ within these dwelling spaces [18]. It means that if any airborne virus is found in a building all residents are at a high risk of becoming infected.

Despite the strict social distancing measures implemented in public spaces [19,20], the pandemic has exposed the vulnerability inherent in the high density of apartment living. The sheer number of apartment buildings – a staggering 7242 – placed under individual quarantine upon detection of a single COVID-19 case within their walls stands as a stark reminder of the interconnectedness within these structures. This phenomenon was particularly evident between March and September 2020, when the virus's spread necessitated stricter isolation measures [21]. The headline titled "My building gave me the coronavirus" gained international attention during that period of time, shedding light on the unique challenges posed by the design and management of apartment buildings in the context of a highly contagious airborne virus [22].

Several studies have emphasized the significance of proper ventilation design within indoor environments to mitigate the transmission of airborne viruses. This approach applies to various settings, including healthcare facilities, public buildings, educational institutions, office complexes, and both single detached houses and apartments [10,13,23–25]. Research in this domain delves into the intricacies of ventilation systems, exploring the effectiveness of air exchange rates, filtration technologies, and airflow patterns in minimizing the concentration and spread of airborne pathogens [26–28]. Studies have investigated the role of natural ventilation, mechanical ventilation systems, and hybrid approaches, considering factors such as occupancy density, building layout, and climatic conditions [27,29]. Simultaneously, a parallel body of research has focused on the architectural design of interior spaces to maximize natural ventilation [30]. Researchers have also delved into the intricacies of airflow patterns by strategically placing windows, wind catchers, vents, and other architectural elements to optimize ventilation and minimize the concentration and spread of airborne pathogens [31–34].

One of the primary considerations in ventilation design is the establishment of adequate air exchange rates [35]. The WHO recommends a minimum natural ventilation rate of 60 L per second per person, coupled with at least six air changes per hour (ACH) to minimize the risk of airborne virus transmission [36,37]. The significance of these ventilation standards has been further underscored during pandemics, with CDC doubling the recommended air changes per hour to 12 (12 ACH) in critical areas to enhance IAQ [38].

Humidity and carbon dioxide (CO_2) play pivotal roles in the design of infection control methods within indoor environments [39]. Maintaining an optimal relative humidity (RH) is crucial, as studies have shown a significant correlation between humidity levels and infection rates [40–42]. The role of humidity in reducing infection rates involves a complex interplay of biological and physical factors. At optimal levels, moisture in the air can hinder the transmission of airborne pathogens such as viruses and bacteria. This occurs through several mechanisms: first, by trapping and preventing their evaporation into smaller, more easily suspended droplets; second, by promoting the aggregation of these droplets into larger, heavier particles that readily settle out of the air; and last, by influencing the viability of certain pathogens, potentially reducing their infectivity [39,40,43]. Recommendations from leading organizations, including the Environmental Protection Agency (US EPA) and American Society of Heating, Ventilation, Refrigeration, and Air-Conditioning Engineers (ASHRAE) advocate for indoor RH levels between 30% and 60% to prevent microbial growth and infection transmission [39].

On the other hand, the CO_2 concentration is a critical indicator of IAQ and infection risk [23,44]. The measurement of CO_2 levels in indoor environments provides valuable insights into the adequacy of ventilation and the potential for airborne disease transmission [45]. Outdoor CO_2 concentrations typically range from 250 to 400 parts per million (ppm), but indoor levels are influenced by factors such as occupancy, duration of occupancy, and the amount of outdoor air entering the space [4,44]. In spaces with limited ventilation and prolonged occupancy, indoor CO_2 levels can exceed 1000 ppm, indicating the need for improved ventilation [11,24]. Monitoring CO_2 levels has been recognized as an effective tool for mitigating the risk of airborne infection, with recent studies demonstrating success in controlling the probability of infection through airborne transmission in naturally ventilated environments [45,46].

In densely populated residential structures, where individuals share common staircases, the risk of transmission becomes more pronounced. Stairwells can function as quasi-isolation areas, necessitating specific attention to their design parameters. Understanding the dynamics of airflow within staircases, including factors such as ventilation rates, airflow patterns, and the potential for pathogen-laden droplets to disperse, is essential. The architectural design of staircases encompasses a range of variables crucial for effective airflow and ventilation, and minimizing the risk of virus transmission. Key considerations include the width, length, volume, height, location, openings, and relationship to airflow patterns within the building [47]. The length, width, and volume of a staircase impact its overall capacity and may influence airflow dynamics. Additionally, the height of the staircase plays a crucial role in facilitating effective vertical circulation and supporting natural ventilation throughout the building. The design of openings, including doors and windows, significantly shapes airflow dynamics in staircases. Considerations such as location, size, and design, including factors such as the window-to-wall ratio (WWR), play a crucial role in influencing ventilation efficiency and airflow patterns. Locating staircases in areas with significant foot traffic, close proximity to main entrances, and easy access to apartment entry halls may contribute to the overall ventilation strategy of buildings. Choosing materials in constructing staircases with antimicrobial properties or those that are easy to clean can help mitigate the potential for surface transmission of pathogens, further supporting infection control measures.

Within the Jordanian context, some studies have explored interior design responses to the COVID-19 pandemic [48,49], shedding light on present and future modifications in house design to combat the spread of airborne infections in apartment buildings during pandemics. Regrettably, there is a dearth of research focused on the shared vertical circulation space among apartment residents, an area that has been notably overlooked. Consequently, a pressing need exists to address this gap, potentially yielding essential design

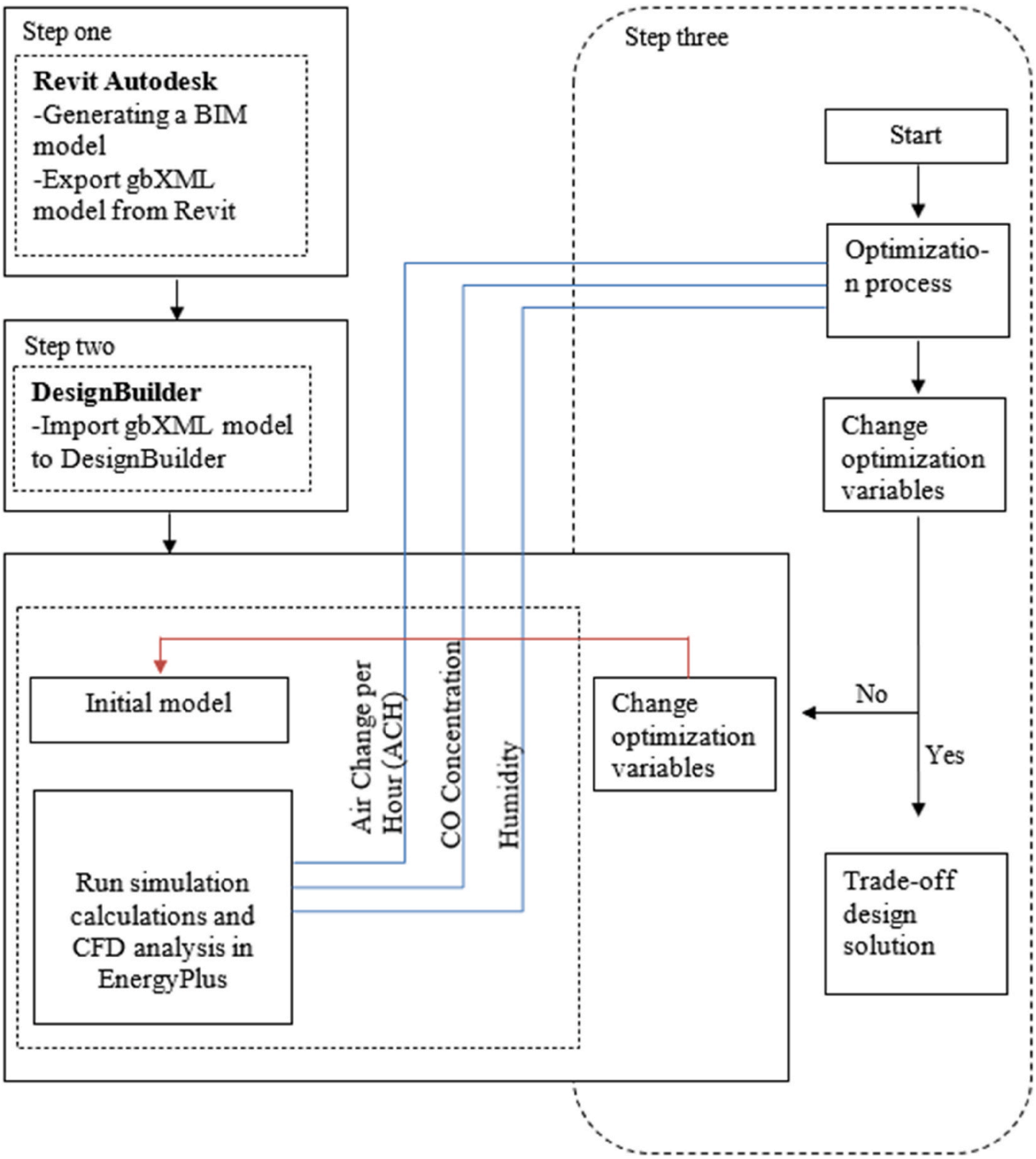

Fig. 1. Simulation and CFD analysis framework.

guidelines, codes, and standards for architects and designers working on future apartment building projects in Jordan, particularly concerning infection control measures.

This study focused on evaluating airflow dynamics in the vertical circulation space within an apartment building. This research contributes evidence-based insights that inform the design of multi-floor buildings to foster a healthier indoor environment.

2. Methodology

This study aimed to investigate air flow patterns within apartment buildings, focusing on common circulation spaces. This study initiated with the identification of a base case building, involving the typical apartment building floor layout and common vertical circulation space characteristics. Utilizing government resources and a sample study, we gathered data to construct a detailed 3D model for subsequent computational fluid dynamics (CFD) simulations using DesignBuilder software. The CFD simulation setup encompassed geographic location specifications and the configuration of the turbulence models, boundary conditions, and solver settings.

The initial phase of the simulation centered on the base case to evaluate the existing conditions of the common circulation space. Key parameters such as ACH, RH, and CO_2 levels were measured. Subsequent simulations involved the exploration of various scenarios to understand airflow patterns. Proposed solutions to increase ACH were then simulated, considering architectural modifications and ventilation system upgrades. The results from each simulation were analyzed to identify effective strategies for improving natural ventilation, aligning with prescribed IAQ standards, and minimizing virus transmission risks.

Fig. 1 delineates the procedural steps employed in utilizing DesignBuilder throughout the research process.

This investigation is primarily centered on Amman, the capital of Jordan, which was selected for its status as the demographic focal point and for the nexus of the nation's highest density of apartment buildings. This strategic focus is instrumental in garnering precise and representative data regarding the prevalent design attributes of apartment buildings across Jordan. Additionally, the city of Amman has experienced the highest incidence of apartment building lockdowns during the recent pandemic, providing a rich dataset that encapsulates the multifaceted challenges associated with airborne infection within such structures. The culmination of these factors positions Amman as an ideal locus for a nuanced exploration of apartment building design issues in the context of infectious disease transmission, thereby affording valuable insights into user responses vis-à-vis the extant architectural configurations.

2.1. Study area description

The simulated building is situated in Amman, the capital of Jordan, positioned within the arid subtropical steppe climate zone (Latitude 31°96′N and Longitude 35°93′E). Amman experiences a climatic duality influenced by a Mediterranean climate to the west

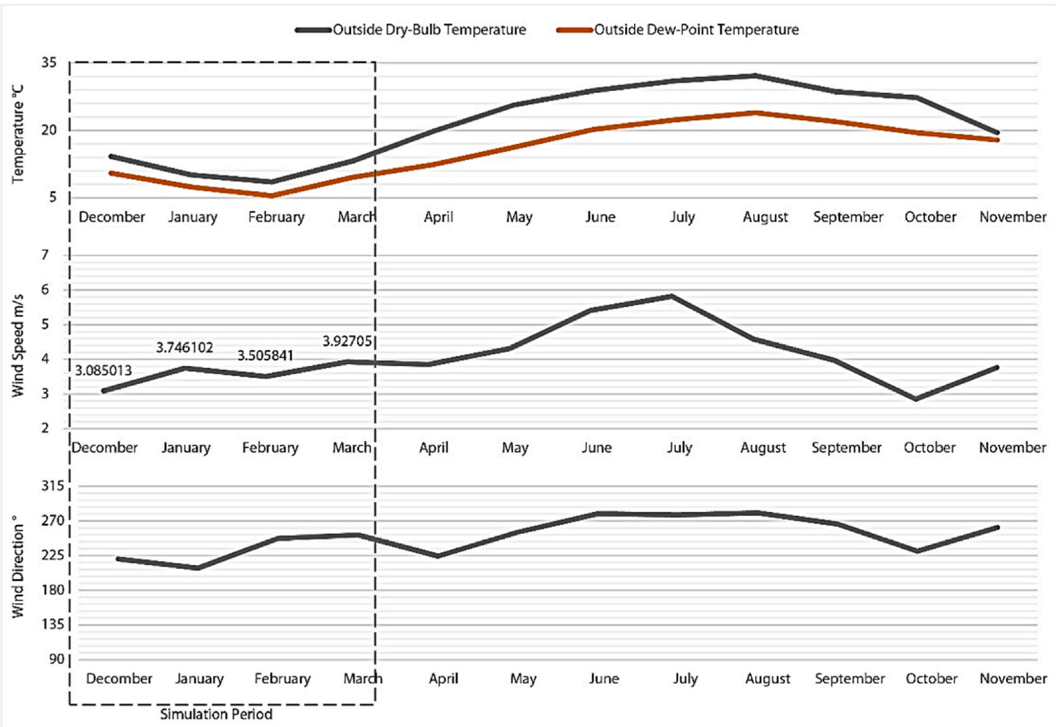

Fig. 2. Weather data for amman: temperature, wind speed, and wind direction during the simulation year.

and expansive deserts to the east, resulting in a pronounced annual temperature range characterized by distinct seasonal variations—sweltering summers and chilly, rainy winters. The summer months, spanning June to September, exhibit warm to hot conditions, with average daytime temperatures fluctuating between 30 and 35 °C (86–95 °F). Notably, the average maximum temperature reaches approximately 32 °C, occasionally exceeding 36 °C during peak summer periods. These months are characterized by low humidity levels and predominantly clear skies. On the other hand, winters, spanning December to February, are cooler and relatively wetter, with daytime temperatures ranging from 10 to 15 °C (50–59 °F), averaging approximately 13 °C (Fig. 2). Winds exhibit variability in direction, with prevailing westerly winds occurring during the winter months, maintaining an average annual speed of approximately 3.4 m/s. The study's operational timeframe was deliberately set during the winter season, spanning from December 21st to March 21st. This selection was guided by the heightened significance of this period in facilitating airborne infection transmission. Various environmental factors prevalent during winter contribute to an elevated risk of airborne infection transmission.

2.2. Identification of the base case layout

2.2.1. Apartment building floor layout

The delineation of the base case architectural layout was initiated with an examination of intrinsic architectural configurations prevalent in Amman's apartment buildings. A data collection process was undertaken, leveraging reports from the Jordan Department of Statistics (DoS), with the latest iteration disseminated in 2017, serving as a primary reference source [50]. Amman, as the study's focal point, showcases a diversity of multi-floor apartment buildings, each exhibiting a distinct number of units per floor. According to the statistical information procured from the Jordanian DoS [50], these multi-unit apartment structures in Amman consistently manifest configurations featuring 1, 2, 3, or 4 apartments per floor, as visually elucidated in Fig. 3. Intriguingly, the statistical insights derived from DoS underscore the preeminence of 4-floor apartment structures, characterized by a layout of two apartments per floor and unit dimensions ranging from 120 to 150 square meters. Notably, this specific architectural typology emerges as the predominant and highly sought-after choice among real estate clientele in the urban landscape of Amman, Jordan.

2.2.2. The configuration of the common vertical circulation

Subsequent to the identification of base case architectural layouts, the configuration of the common vertical circulation space was meticulously elucidated, guided by the stipulations delineated in the Jordanian National Building Code [51]. Notably, particular emphasis was placed on staircase design specifications, encompassing dimensions designed to optimize user comfort and usability. It is imperative to highlight, however, the notable absence of explicit standards within the code pertaining to IAQ considerations within this spatial context. Additionally, a conspicuous gap exists in design requirements relating to openings in the common vertical circulation space of apartment buildings and apartment unit entryway designs.

In response to this regulatory void, a method involving systematic sample collection and analysis was employed. A purposive sampling strategy was used to draw samples from diverse locations within Amman city. The essential attributes of each sampled building, including the number, locations, and areas of openings, as well as the apartment units' entryway design, were meticulously documented. Appendix 1 provides a comprehensive catalog of the sampled apartment buildings across Amman city.

Notably, a comprehensive field survey approach was utilized for data and sample acquisition, encompassing on-site imagery and information solicited from building proprietors, contracting entities, and publicly accessible websites for apartment unit rentals or purchases. Stringent selection criteria govern this sampling process, focusing on parameters such as the following:

- Apartment buildings with four stories.
- Buildings featuring two apartments per floor.
- Buildings constructed after 2015.

With the uncertainty regarding the total number of apartment buildings in the city of Amman, the sample size was calculated based on an unknown value of the population. The following equation simplifies the process and facilitates the calculation of the required sample size.

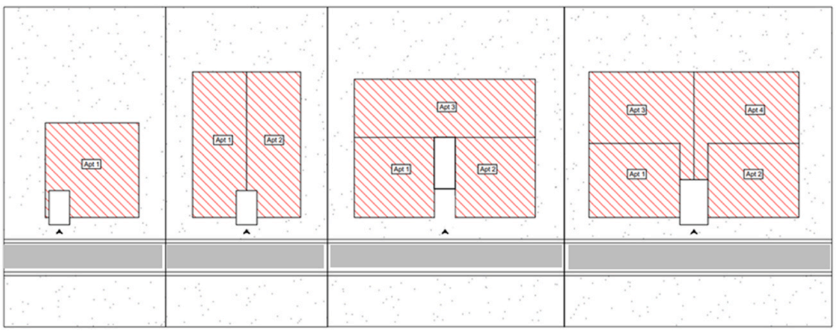

Fig. 3. Floor-plan existing designs (authors, 2022).

$$Sample\ Size = (Z\ Score)2 * StdDev * \frac{(1 - StdDev)}{(margin\ of\ error)2}$$

were Z score the confidence level (constant value), and Std. Dev. is the Standard Deviation.

The confidence level chosen for this study is 90%, with a margin of error set at 10%. However, determining the standard deviation is based on the expected variance. Since sample collection has not yet been conducted, a conservative estimate of 0.5 was employed. A total of 138 samples were subsequently collected.

Following an analysis of each case, the findings unequivocally establish that the common design for openings in the vertical circulation space of Amman's apartment buildings predominantly features a configuration devoid of operable windows characterized by

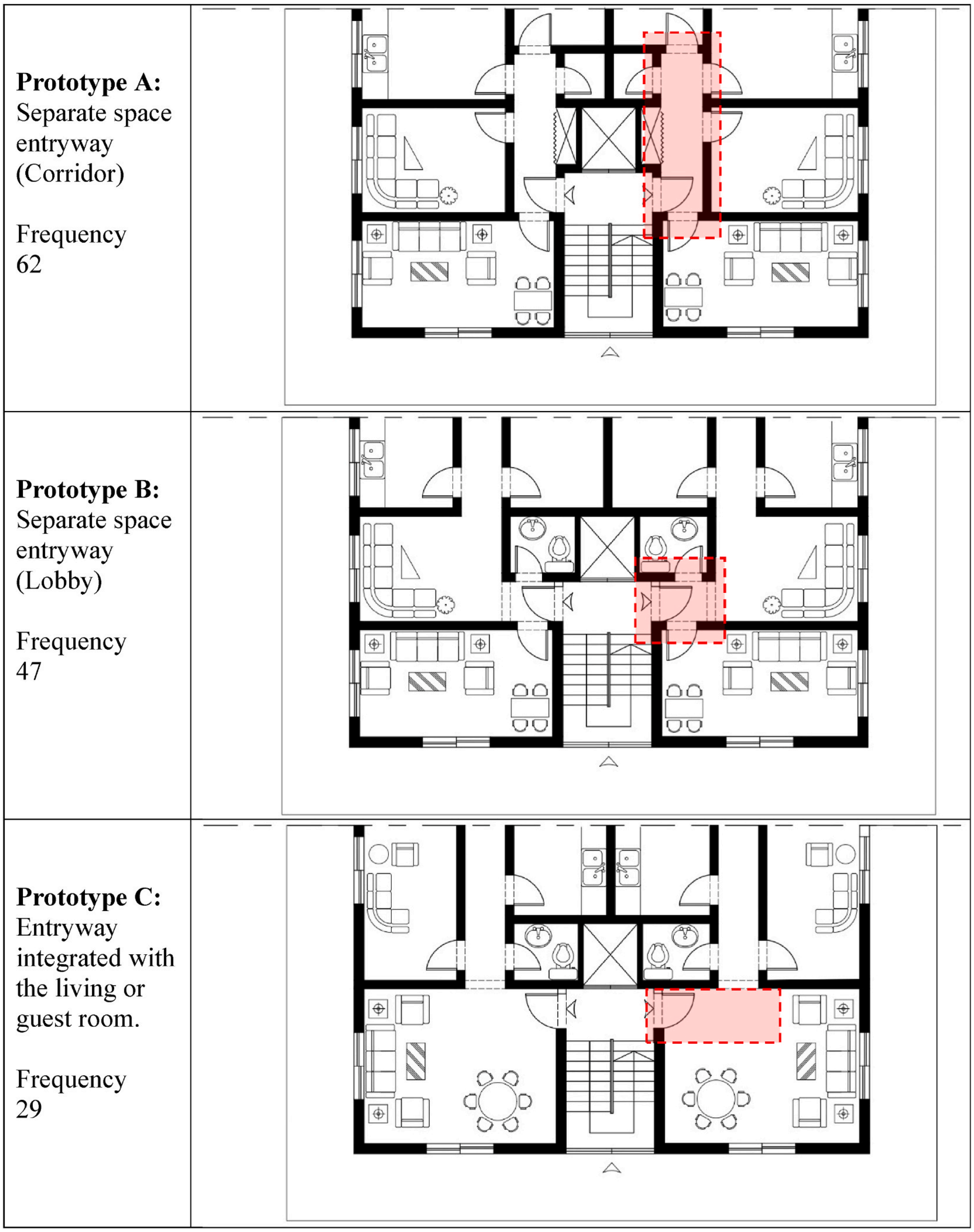

Fig. 4. Apartments entryway design prototypes (authors, 2022).

a glazed façade. This architectural choice marks a departure from traditional reliance on operable windows for active ventilation. Instead, the design strategically relies on the building's main entrance to the stairwell, assuming a pivotal role as the primary source of ventilation. This illuminates the newfound significance of the stairwell, emerging as a central hub orchestrating the seamless distribution of air not only within the common circulation space but also within adjoining spaces on the same floor and across different levels.

2.2.3. Apartment unit entryway design

The analysis of the 138 cases revealed three main design prototypes that were most commonly repeated in apartment unit designs, as depicted in Fig. 4, along with the frequency of each prototype.

Prototypes A and B feature a separate, defined, enclosed, or semi-enclosed entryway space. In Prototype A, this space is a corridor, while in Prototype B, it is a lobby. In contrast, Prototype C integrates the entryway with another space, typically either the living room or the guest room. The spaces adjacent to the common vertical stairwell, mainly the entryways of apartment units, were used to analyze and measure airflow exchange among apartment units in apartment buildings.

2.2.4. Simulated building layout

The study building is a multi-floor structure comprising four levels, featuring two apartments on each floor, with each apartment having a floor area of 148 m^2 (refer to Fig. 5). A stairwell vertically and horizontally connects the apartments, measuring 2.85 × 4.96 × 13 m. The main entrance, situated on the ground floor's main façade, serves as the primary inlet for external air. The main entry of each apartment unit functions as the outlet, allowing the airflow circulating within the stairwell to enter the apartment. The door's approximate opening area is 100% of the total door area, with the entry door for each apartment configured based on specific scenarios, either to examine airflow between the staircase and apartment on the same level (door set to be operable) or to assess flow between floors. The air temperature is set at 20 °C. The building's stairwell faces the north, representing the worst-case scenario for minimal airflow. The simulation considers the minimal prevailing airflow based on weather data specific to the location, where the

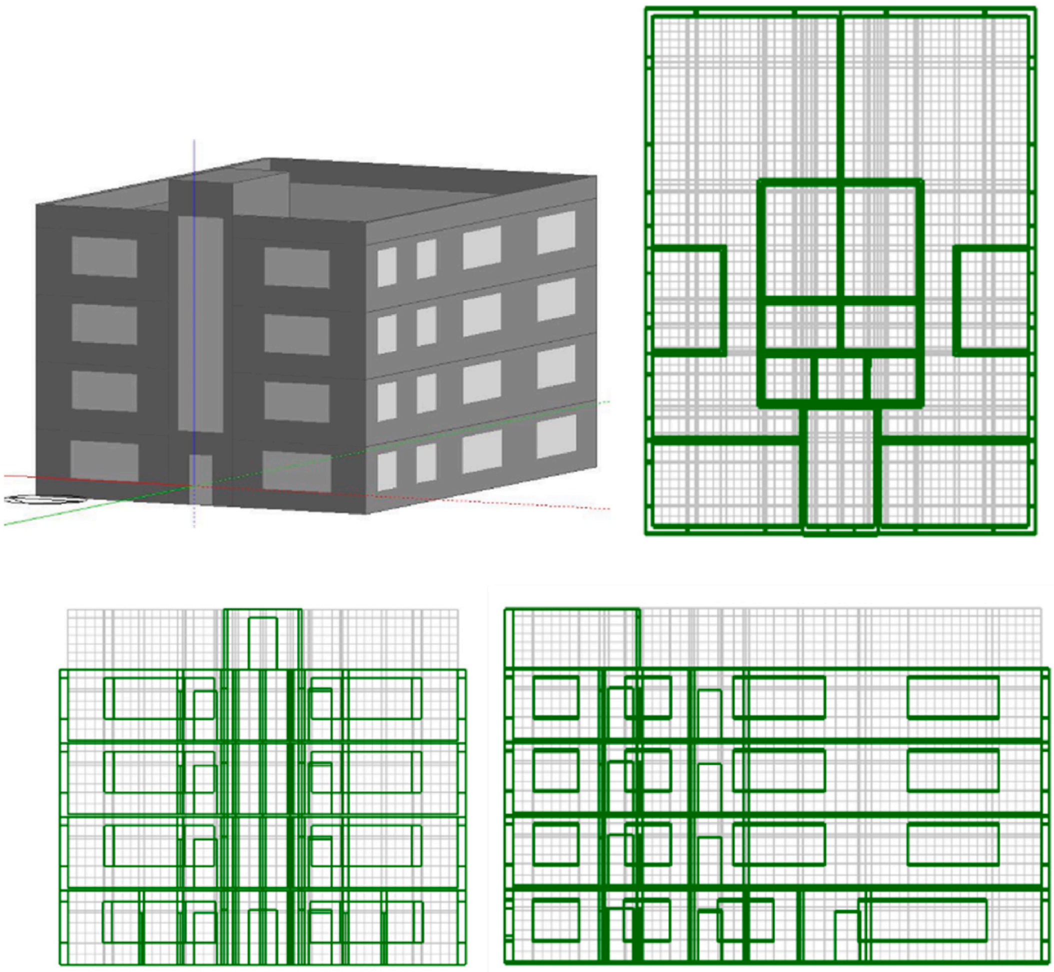

Fig. 5. 2D and 3D representations of the building layout.

least airflow originates from the north.

Table 1 lists the model settings and construction specifications utilized to initiate the simulation and CFD analysis. Additionally, Table 2 outlines the building settings concerning the typical activities of the population in Amman. The activity tab serves as the input data repository for building occupancy, metabolic rate set points, and equipment usage.

2.3. Computational fluid dynamics simulation

This study utilized CFD to simulate airflow and temperature distribution within the building, utilizing DesignBuilder v6 as the simulation software. DesignBuilder's integrated CFD code has undergone validation through numerous studies, including comparisons with measured data from field measurements of existing buildings and other CFD packages [34,52–55]. The DesignBuilder CFD tool enables the creation of detailed 3D building models to analyze air movement, flow patterns, and contaminant dispersion in buildings. This approach facilitates the identification of ventilation issues and the assessment of the impact of design changes. This tool supports the evaluation of design strategies, optimizing energy efficiency, and improving indoor comfort and air quality for healthier environments [56].

2.3.1. Turbulence model and convergence

The k-ϵ turbulence model, a well-established member of the RANS family, was chosen due to its extensive testing and suitability for indoor airflow simulations [55]. Convergence of the simulation was achieved by setting the maximum outer iterations to 3000 and monitoring two criteria:

- Residual Root Mean Square Error (RMSE): This value should fall below $1E^{-5}$, indicating minimal discrepancies between successive iterations.
- Stabilization of dependent variables: Key airflow and temperature values within the building model should reach a steady state.

2.3.2. Grid sensitivity analysis

The accuracy of CFD simulations hinges on the chosen grid size. A grid sensitivity analysis was conducted for the mid-level floor of the building, testing various grid spacing from 0.1 m (very fine) to 0.5 m (extremely coarse). Air velocities were monitored for different ventilation scenarios during a typical winter condition.

The analysis revealed the following:

- A fine grid size (0.2 m) offered nearly identical results to a medium grid size (0.3 m).
- Using a very fine grid (0.1 m) became computationally expensive for the building's size.
- Both coarse (0.4 m) and very coarse (0.5 m) grids introduced significant errors in velocity predictions (3% and 8%, respectively).

Therefore, a medium grid size of 0.3 m was chosen as the optimal balance between accuracy and computational efficiency. This process resulted in a 3D Cartesian grid with 403,848 cells encompassing the computational domain.

Table 1
Construction specifications.

Element	Material	Thickness (cm)	U value (W/m^2 K)
Exterior floor	Stone	5	0.79
	Concrete	18	
	Insulation	3	
	Block	10	
	Plaster	2	
Internal partition	Plaster	2	1.90
	Block	10	
	Plaster	2	
Internal ceiling/floor	Tiles	3	1.20
	Mortar	3	
	Sand	7	
	Insulation	0.5	
	Reinforcement	25	
	Plaster	2	
Roof	Gravel	10	1.80
	Concrete	5	
	Insulation	0.5	
	Reinforcement	20	
	Plaster	2	
Windows	Aluminum frame	0.6	5.70
	Single glazing		

Table 2
Model settings and input data.

Input Data	Value
Family size	6 members
Metabolic rate	0.8 met
Occupancy density	80 W/P
Lighting	5 W/m^2
Clothing	1.00
Appliances	0
Infiltration	Neglected value

2.3.3. Boundary conditions

This study implemented both external and internal boundary conditions. The external conditions included constant wind velocity and direction. Internally, EnergyPlus simulation was employed to compute the internal surface temperature, incorporating a calculated natural ventilation option. Natural ventilation was exclusively activated during occupied periods throughout the day and night. The calculation of natural ventilation considered factors such as opening and crack sizes, buoyancy, and wind pressures.

On the basis of stack and wind pressure differences, the ventilations rates (q) through the cracks and window openings are calculated as follows:

$$q = C - (DP)^n \tag{1}$$

The methodology employed DesignBuilder's CFD code to simulate the base case, calculating parameters such as ACH and RH. ACH represents the rate at which the air within a space is exchanged with fresh outdoor air, while RH indicates the moisture content in the air. The equations used for ACH and RH in DesignBuilder are defined as follows:

$$ACH = \frac{AirflowRate\ (in\ cubic\ feet\ per\ miutes)}{Room\ Volume}\ x\ 60 \tag{2}$$

$$RH = \frac{ActualWaterVaporPressure}{Saturation\ Water\ Vapor\ Pressure}\ X\ 100\% \tag{3}$$

The omni calculator was subsequently utilized to estimate the concentration of CO_2 using the ACH and RH values. The equation for calculating CO_2 involves complex relationships with ACH and RH. The Omni Calculator [57] is an online platform offering a diverse array of free calculators spanning mathematics, physics, finance, health, engineering, etc.

Subsequently, the calculated ACH, RH, and CO_2 values were systematically compared to established standards or benchmarks.

In the realm of air quality regulations, specific codes pertaining to staircase air quality are notably absent. However, the ASHRAE offers valuable guidance. ASHRAE's Standard 62.2–2016, titled "Ventilation and Acceptable Indoor Air Quality in Residential Buildings", recommends a minimum of 0.35 ACH and no less than 15 cubic feet of air per minute (cfm) per person for homes [58]. These ventilation rates aim to ensure that the IAQ meets the human occupants' standards and minimizes adverse health effects. ASHRAE also advises intermittent exhaust capacities for kitchens and bathroom exhaust systems to regulate pollutant levels and moisture in these spaces. On a broader scale, the WHO recommends a natural ventilation rate of at least 60 L/second per person and a minimum of six ACHs for indoor spaces [36,37]. In response to the efficiency of ventilation systems and the need for prompt airborne contaminant removal, the CDC doubled the recommended ACH to 12 after the SARS outbreak [38]. Recognizing the potential transmission of microorganisms through airborne droplets, particularly through smaller aerosols (<5 μm), emphasizes the importance of adequate ventilation [26,45]. Higher ventilation airflow rates, specifically targeting concentrations in stationary pollution sources, prove effective [26]. Stairwells, with their distinct characteristics, demand special attention as potential infection pathways, underscoring the critical role of proper ventilation values in minimizing the risk of infection transmission within these spaces.

Studies conducted on relative humidity to control flu and other viruses have recommended an RH ranging from 40% to 60% [43]. Moreover, leading industry organizations' recommendations for appropriate indoor RHs were approximately the same:

- The U.S. EPA has an indoor RH between 30 and 60%.
- ASHRAE recommends an indoor RH of 65% to prevent microbial growth and infection transmission [58].

Table 3 provides an overview of the CO_2 concentration limits established by public health guidance and other relevant documents,

Table 3
CO_2 level limit for Infection Control.

Source	CO_2 level limit
ASHRAE	1000–1200 ppm
Minnesota Department of Health	<800 ppm
Federation of European Heating Ventilation and Air Conditioning Associations (REHVA)	<800 ppm
US Centers for Disease Control and Prevention	<800 ppm

facilitating the assessment and mitigation of the risk of disease transmission [11]. It is recommended that CO2 concentrations not exceed 1000 ppm.

Additionally, an airflow chart depicting the direction and rate of airflow was generated to comprehend the airflow patterns for the base case. The software was subsequently used to explore various scenarios, including the examination of apartment doors in operation. This aimed to understand airflow exchange from the stairwell to the apartment units on the same floor and different floors. Furthermore, CFD analysis was conducted to scrutinize airflow into apartment units with different entryway design configurations. This comprehensive methodology enabled a thorough investigation into the dynamics of airflow and ventilation within a multi-floor apartment building.

DesignBuilder was utilized to perform simulations encompassing diverse scenarios, each scrutinizing the influence of distinct design features on airflow dynamics and ventilation within the investigated environment. The simulations incorporated variations in opening sizes or WWRs, vents, and vertical and horizontal louvers. Reflecting these variables, various modifications were implemented on the digital model. Within the simulation, windows were designated as inlets and subsequently redefined as vents, maintaining the

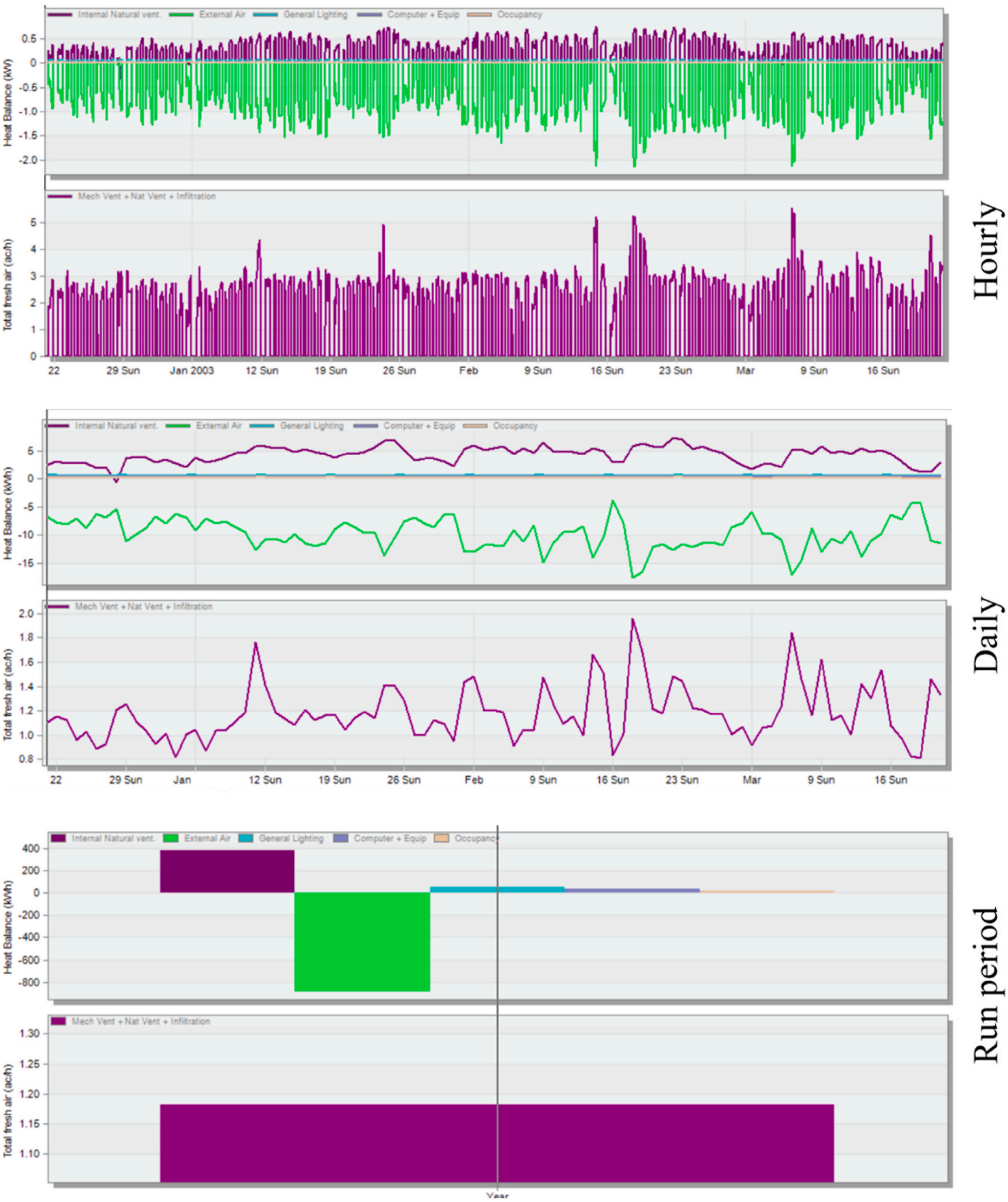

Fig. 6. Air change per hour calculations of the base case.

condition that all apartment doors remained closed. The CFD code was applied to calculate ACH and RH values.

3. Results

3.1. Simulation calculations and CFD analysis

3.1.1. Base case simulation analysis

The CFD simulation calculations yielded numerical data for the ACH and RH parameters. To determine the concentration of CO_2 in space using the omni calculator, additional calculations were necessary. These calculations involved utilizing the ACH and RH output data, along with supplementary information.

Daily calculations of ACH and RH were performed for the entire run period of the common vertical circulation area (see Figs. 6 and 7). The figures show the maximum and minimum values recorded during this period. On February 18, the space exhibited a maximum ACH of 1.9604, indicating a higher air exchange rate, whereas on March 19, a minimum ACH of 0.810524 was registered. The RH data revealed that the space reached a maximum of 76.19479% on January 22, reflecting elevated humidity levels, while the minimum RH of 31.43041% was observed on March 4.

The CO_2 concentration in the space was determined using the Omni Calculator, as illustrated in Fig. 8. The CO_2 concentration ranged from approximately 0.38%–0.38% (equivalent to 3777–3827 ppm) based on the specified room settings.

3.1.2. Airflow exchange between the common space and an apartment unit

Continuous airflow exchange occurs between the common vertical circulation space and the adjacent units whenever the entryway

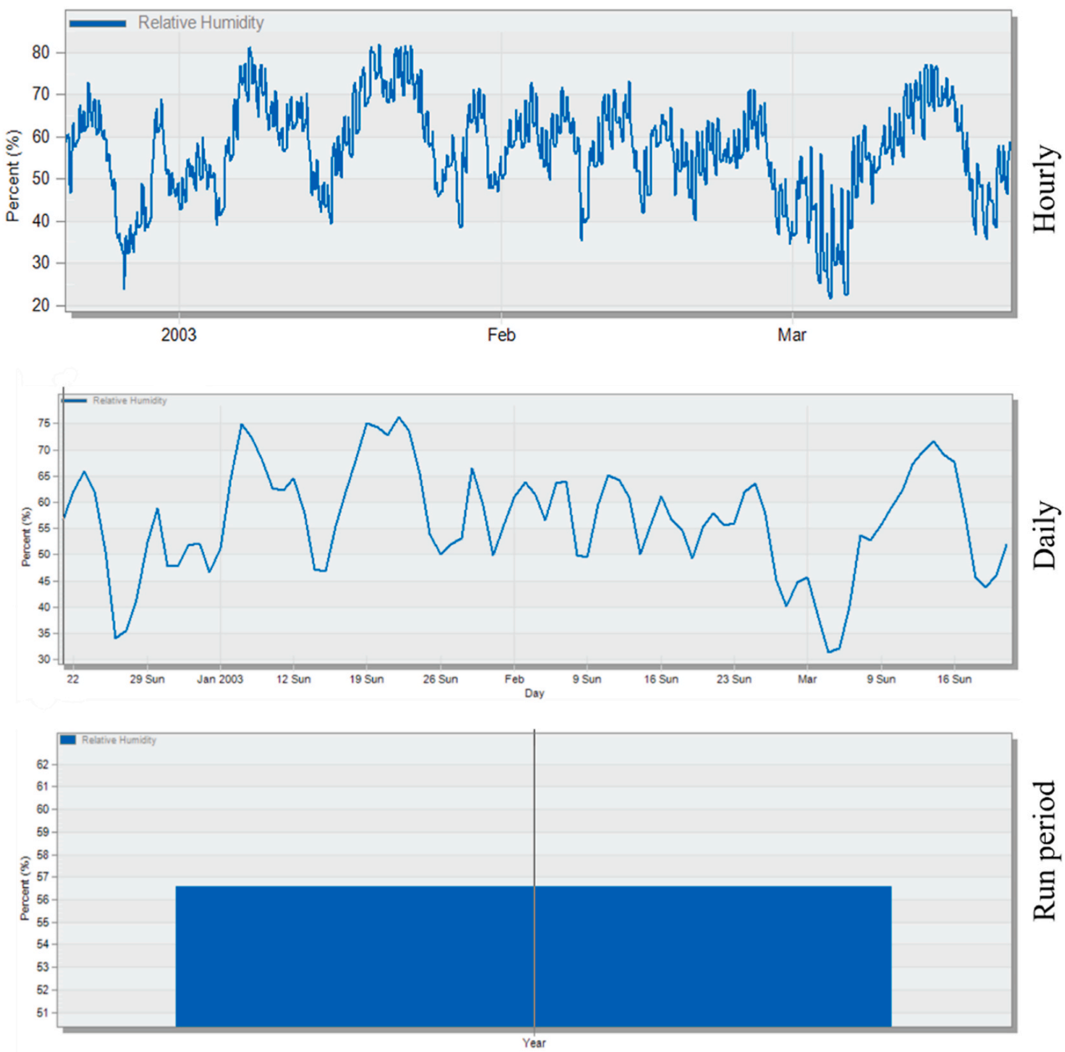

Fig. 7. Relative humidity calculations of the base case.

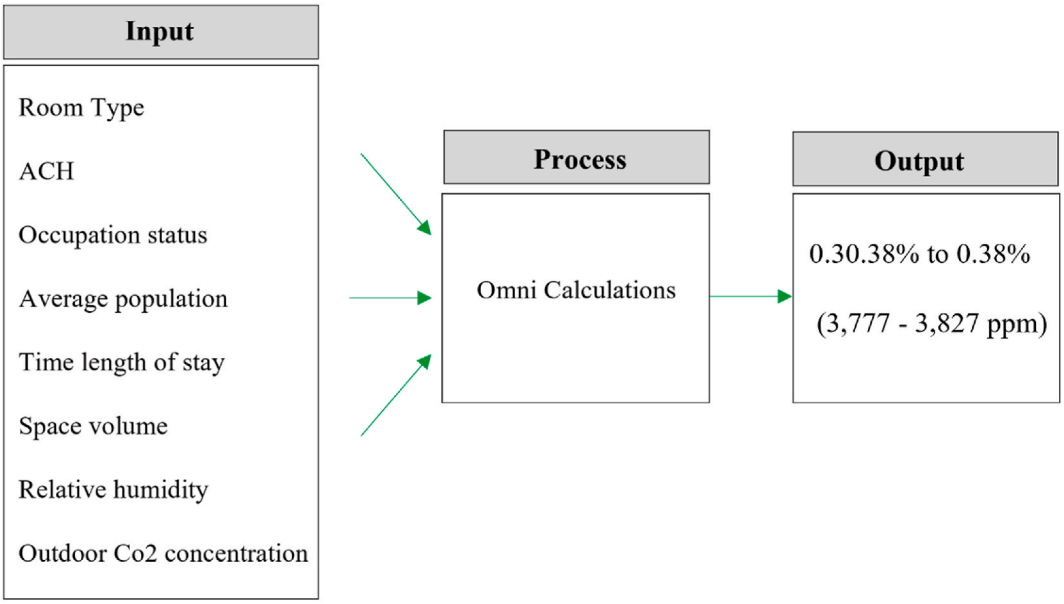

Fig. 8. CO_2 concentration.

door is opened. CFD analysis, presented in Fig. 9, provides valuable insights into the airflow dynamics within the apartment building. This analysis included 3D contours and a section displaying pressure values throughout the building. Significantly, the analysis reveals notable pressure differences between the common vertical circulation space and the adjacent areas. These pressure differences create a gradient that promotes airflow whenever an opening, such as the entryway door in operation. Fig. 10 depicts the airflow dynamics between the common vertical circulation space and adjacent apartment units. On one side of the entry, lower pressure directs airflow from the common space into the apartment unit, while on the other side, higher pressure guides airflow from the apartment unit into the common space.

This airflow exchange has dual issues. First, it enables the transmission of contaminants from apartment units into the common space, potentially introducing pollutants or airborne particles. Second, airflow exchange facilitates the dissemination of contaminants among various apartment units within the building, meaning that if one unit harbors contaminated air, airflow exchange can disperse these contaminants to neighboring units.

3.1.3. *Airflow exchange among apartment units*

Airflow exchange between different apartment units manifests in two distinct manners through the common vertical circulation space. First, when air is exchanged between the common space and an apartment unit, any contaminated air from the apartment unit lingers in the common area and flows into the next apartment unit when its door is in operation. Second, the simultaneous opening of two apartment unit doors results in immediate airflow exchange between the two units. Fig. 11 presents the results of the CFD analysis,

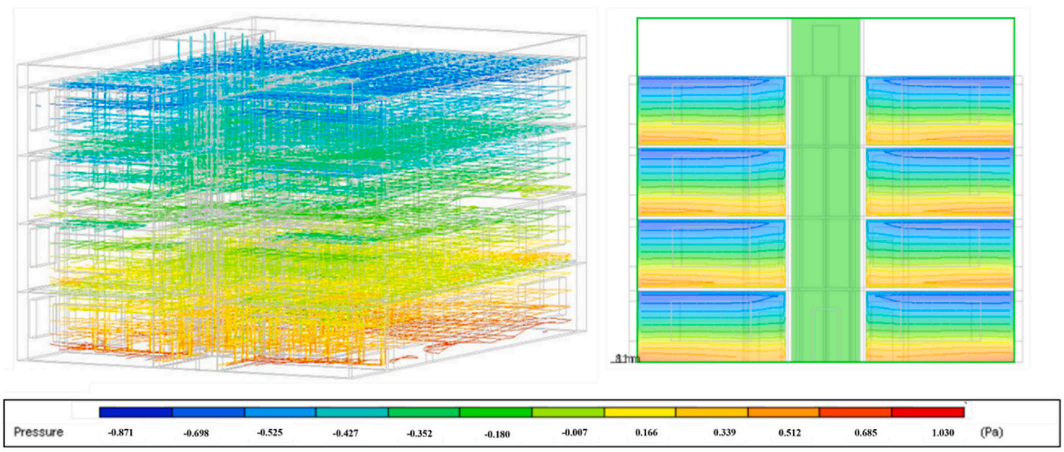

Fig. 9. Pressure 3D-contours and pressure section.

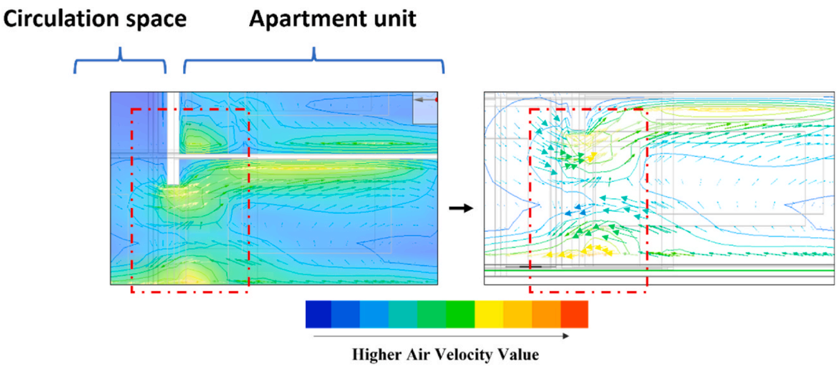

Fig. 10. Airflow exchange CFD analysis between an apartment unit and the common vertical circulation space.

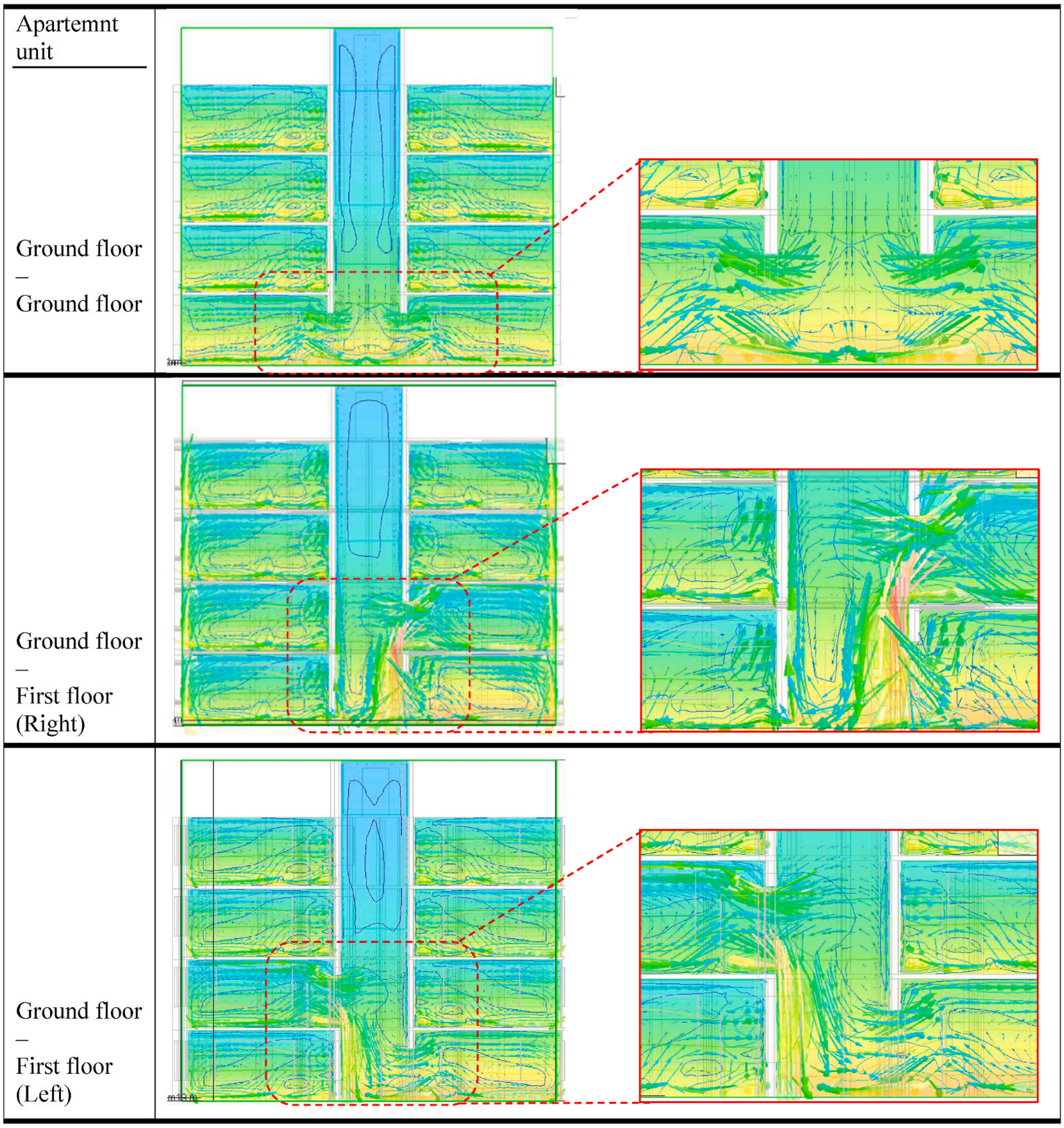

Fig. 11. CFD analysis of airflow exchange between different apartment units.

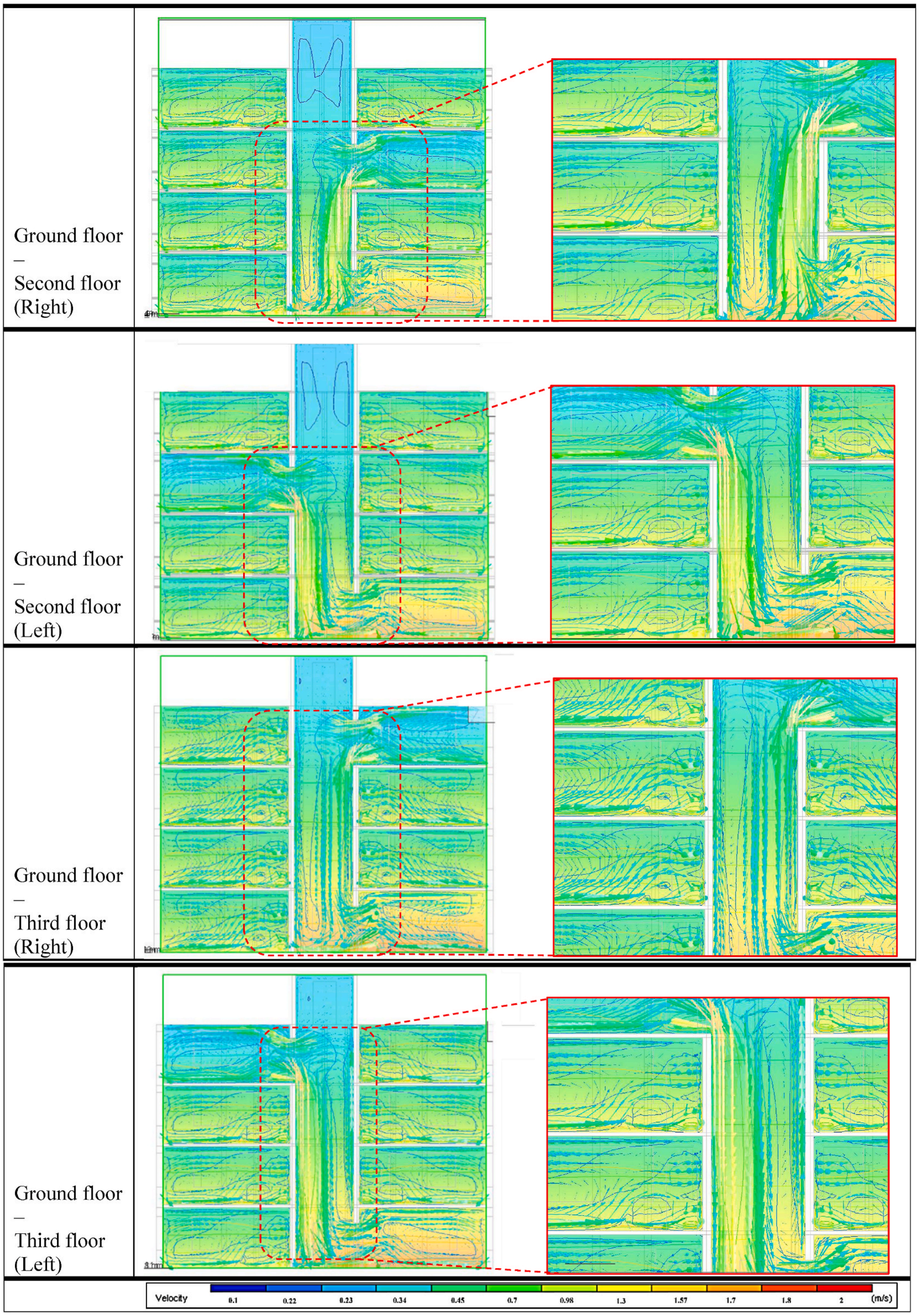

Fig. 11. (*continued*).

depicting the airflow exchange and patterns within the common vertical circulation space when two apartment unit doors are simultaneously opened.

Several scenarios were explored and analyzed to discern the behavior and intensity of airflow exchange between the two apartment units. The analysis involved sequentially opening the doors of apartment units one at a time, following the initial opening of the door of the ground floor apartment unit. Each scenario was examined separately to track variations in airflow exchange and intensity.

The CFD findings demonstrated that the pressure disparity between the apartment unit and the vertical circulation space fostered airflow exchange between them. Additionally, owing to the stacking effect within the vertical space, air exchanged from one apartment unit traverses the circulation shaft and enters the other apartment unit, as outlined in Fig. 11. The analysis further revealed that airflow exchange between two apartment units is more likely to occur with a greater volume of air and higher velocity when the two apartments are located on different floors, attributed to the larger pressure difference across the vertical space separating the two

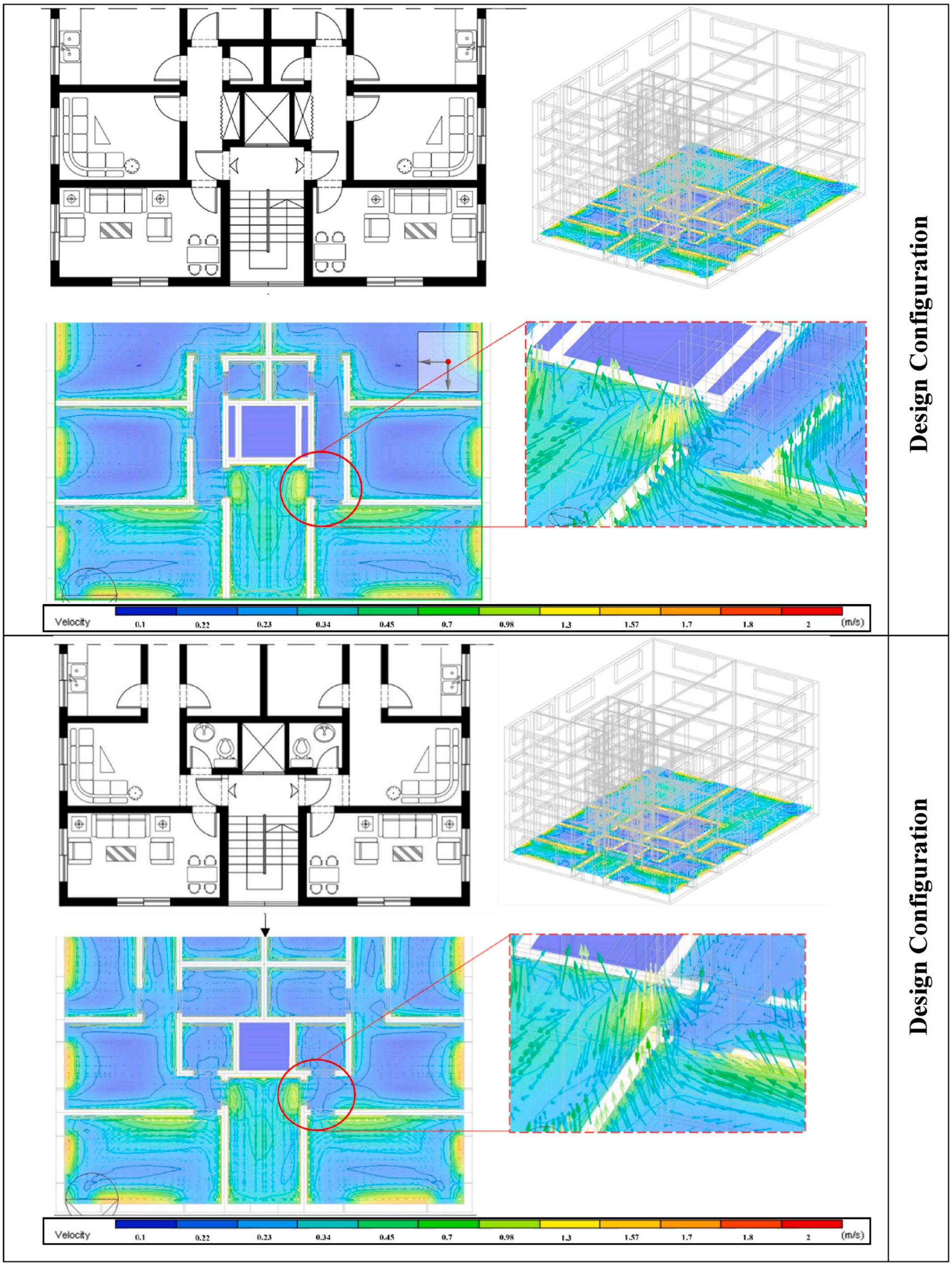

Fig. 12. Airflow into apartment units with different entryway design configurations.

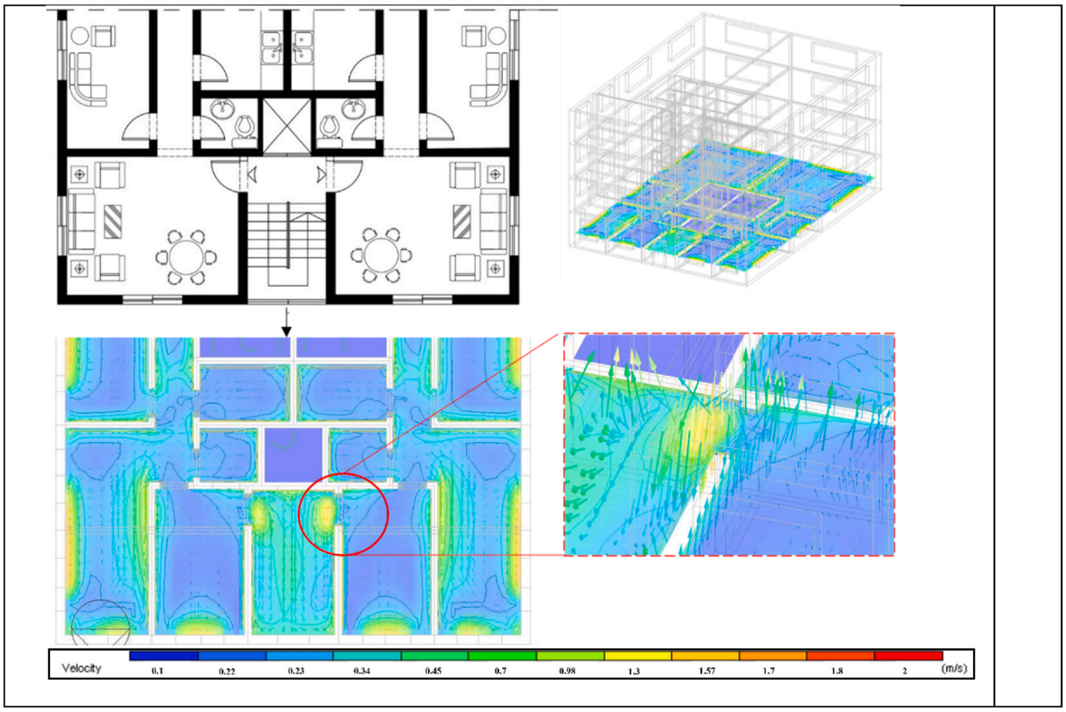

Fig. 12. (*continued*).

floors.

3.1.4. Airflow exchange among apartment units based on the entryway type

Fig. 12 presents the results of CFD analysis for the three entryway designs, labeled A, B, and C. The analysis reveals distinct variations in the behavior of airflow exchange between the common space and the entryway area, primarily due to the different design configurations of the entryway.

In apartment units of type, A and B, the entryway is a small transitional area, serving as a corridor in type A and a lobby in type B. On the other hand, in apartment units of type C, the entryway is an integral part of a larger room, such as the living room or guest room, and is not a defined space on its own. The different design configurations of the entryway area have an impact on the airflow dynamics, as confirmed by CFD analysis.

The CFD analysis results indicate that the entryways of design types A and B exhibit a noticeably lower amount of airflow entering the space, and the airflow occurs at a slower velocity than that of design type C. This can be attributed to the relatively smaller area of the entryway in designs A and B compared to the common vertical circulation space. As a result, the entryways in designs A and B experience higher pressure, which restricts the airflow into the space, resulting in lower airflow values and velocities.

In contrast, the entryway design in type C has a larger area than the common vertical circulation space. This larger area leads to a relatively lower pressure in the entryway, creating favorable conditions for faster and higher-volume airflow into the space. The findings highlight the significance of entryway design configurations in influencing the airflow patterns and exchanges between the common vertical circulation space and the apartment units.

3.2. Natural ventilation enhancement strategies

The IAQ measurements conducted on the popular existing design of the common vertical circulation space in apartment buildings revealed inadequate natural ventilation rates, falling significantly below the recommended rates for a safe and contamination-free environment. The recorded natural ventilation rate for the space was 1.1826 ACH, while the recommended rate was 12 ACH. This indicates poor natural ventilation performance, which can lead to stagnant air and compromised IAQ.

Furthermore, the low ventilation rate resulted in high CO_2 concentrations in the space, ranging from 3777 to 3827 ppm. Elevated CO_2 levels are indicative of inadequate fresh air supply and can contribute to discomfort, reduced cognitive function, and potential health risks for occupants.

On the positive side, the common vertical circulation space exhibited a safe RH level, suggesting that moisture control was maintained adequately within the space.

To improve the IAQ and achieve acceptable ACH and CO_2 concentrations, a natural ventilation enhancement strategy was proposed. The focus of the strategy centered on the design element of openings, as they play a crucial role in facilitating natural ventilation and can significantly impact its effectiveness and behavior within indoor spaces. The following simulations aimed to test the influence of WWRs and opening types, including basic windows, vents, and vertical and horizontal louvers. The aim was to assess the effectiveness of these strategies in improving airflow and ventilation in the common vertical circulation space.

3.2.1. *Testing the application of windows with different WWRs*

Table 4 presents the simulation calculations for traditional operable windows with different WWRs applied to the popular existing design of the common vertical circulation space. Despite testing various WWRs ranging from the minimum to maximum recommended values (15%–30%), the tested parameter measurements did not exhibit a significant difference and did not approach the targeted values for achieving a healthier indoor environment.

The change in the air change rate was barely noticeable, primarily due to the poor operation schedule of manually operable windows, particularly in common service spaces such as the common service stairwell in apartment buildings, as specified by the UK's National Calculation Method for Non-Domestic Buildings (NCM). The highest recorded ACH value was 2.189 ACH, which was observed when the WWR was set to the maximum allowed value of 30%. This limited improvement in the ACH rate suggested that the manual operation of windows may not be sufficient to achieve optimal ventilation and airflow in the common vertical circulation space.

Additionally, the CO_2 concentration remained at an unacceptable level, ranging from 3535 to 3583 ppm, regardless of the tested WWRs. This indicates that the applied changes in the opening sizes did not effectively mitigate the buildup of CO_2 or improve the IAQ.

These findings suggest that relying solely on varying the WWR without addressing other factors such as window operation mechanisms and ventilation strategies may not yield significant improvements in IAQ within the common vertical circulation space.

3.2.2. *Testing the application of vents and louvers*

When vents were utilized as an alternative opening type, a noticeable improvement in the ACH value was observed. A vent with a minimum open area of 15% of the wall per floor resulted in an ACH value of 3.547464, with a corresponding CO_2 concentration ranging from 3232 to 3278 ppm. Increasing the vent area to 30% of the wall per floor further improved the ACH value to 5.487196, with a reduced CO_2 concentration of 2845 to 2889 ppm. Despite these improvements, the application of vents alone was insufficient to achieve the recommended values for infection control in the common vertical circulation space.

On the other hand, vertical and horizontal louvers demonstrated the most significant improvement in the ACH rate. When using louvers with a 15% open area relative to the total wall area were used, the ACH rate reached approximately 12 for both the vertical and horizontal configurations. This indicates that louvers were highly effective at facilitating airflow and ventilation in the common vertical circulation space.

Overall, the analysis suggested that the choice of opening type can significantly impact the natural ventilation performance in the common vertical circulation space. Vents and louvers in particular showed promise in enhancing the ACH rate and improving IAQ. Combining these opening types with appropriate design considerations and airflow management strategies can further optimize natural ventilation and create a healthier indoor environment for apartment building residents.

4. Discussion

This study highlighted the relationship between the design of staircases and IAQ factors for infection spread, which was investigated in the context of apartment buildings in Amman, Jordan. This research focused on ACH, RH, and CO_2 factors by discussing the following:

4.1. *The significance of design parameters on mitigating airborne infection*

The first objective of this study was to assess how staircase design could contribute to the spread of airborne infections. This study aimed to develop a better understanding of this phenomenon by examining the previous literature and structuring research variables

Table 4
Comparison of different opening types for natural ventilation in the common vertical circulation space.

1.1.1.1 Strategy			Simulation calculation for the run period		Estimates
			Average Air Change Per Hour (ACH)	Average Relative Humidity (RH)	Carbon Dioxide (CO_2)
Traditional Operable Window	Window-to-Wall ratio (WWR)	15%	2.18567	56.35674	3535–3584 ppm
		20%	2.18655	56.31277	3535–3584 ppm
		25%	2.18834	56.30376	3535–3583 ppm
		30%	2.18889	56.29379	3535–3583 ppm
Vents	Opening to Wall ratio	15%	3.54746	51.26499%	3232–3278 ppm
		20%	4.18484	51.41116%	3099–3145 ppm
		25%	4.83556	51.49707%	2970–3014 ppm
		30%	5.48719	51.56995%	2845–2889 ppm
Louvers	Type	Vertical	12.5516	62.38641%	1090–1125 ppm
		Horizontal	12.6527	62.38732%	1078–1113 ppm

accordingly. The significance of indoor design parameters for airborne infection was emphasized, based on evidence from various scholars who have demonstrated the positive impact of indoor design on IAQ and their influence on user experience in the space and their reactions to the space [59–61]. IAQ factors such as ventilation rate, humidity, and CO_2 concentration are affected by design parameters and play a crucial role in the spread of airborne diseases [45].

Following a literature review, the research identified three main design parameters: space volume, opening area, and opening type, which were considered independent variables that affect ventilation rates and patterns [44,62–65]. The literature highlights that the COVID-19 pandemic has underscored deficiencies in the design of shared spaces, leading to suboptimal IAQ and consequently higher infection rates. The results obtained from the simulation and CFD analysis highlighted the significant impact of staircase design on the natural ventilation rate, RH, and CO_2 concentration. The CFD analysis results of the existing design of the common vertical circulation space in apartment buildings clearly demonstrated how the poor design of the space negatively affects IAQ. The natural ventilation rate in the popular existing design was significantly lower than the recommended rate, the RH was less than the recommended value, and the CO_2 concentration exceeded the recommended range. The popular existing design registered a natural ventilation rate of 1.1826 ACH compared to the 12 ACH recommended rate, an RH of 56.60342% compared to the 65% recommended value, and a CO_2 concentration of 3777 ppm compared to the 1000–1200 ppm recommended value.

Prior investigations have explored the impact of common circulation corridors on the propagation of pathogens within interconnected spaces [24,66]. This study redirects attention to investigate the influence of entry characteristics, with the aim of mitigating the potential ingress of pathogen-laden air into interior living areas from shared vertical circulation spaces. The CFD analysis revealed that a smaller designed entryway (lobby/corridor) yielded reduced airflow into the living spaces of the apartment unit when compared to an entry open directly to adjacent living spaces (living room/guest room), and the airflow in the former occurred at a slower velocity. These findings accentuate the paramount importance of integrating transitional spaces between vertical circulation areas and living spaces within the apartment, thereby advocating for the incorporation of small lobbies or entry halls as effective transitional zones.

4.2. Techniques for enhancing natural ventilation rate

The second objective of this study was to evaluate various techniques for enhancing the natural ventilation rate in the shared vertical circulation space of apartment buildings, catering to a diverse range of users. This study focused on two influential design parameters, namely the WWR and opening type. These parameters were analyzed and tested through simulation analysis, leading to the following conclusions:

a) The opening size is a crucial factor when designing for natural ventilation. In contrast, the study findings indicate that the application of different WWRs, ranging from the minimum to maximum recommended values, has a limited impact on improving the indoor environmental quality in the shared vertical circulation space. This limitation arises from the limited frequency of window operation in such common areas, as indicated by the National Calculation Methodology for the Energy Performance of Buildings Directive (UK NCM). Therefore, solely relying on variations in the WWR may not significantly enhance the IAQ in these spaces.
b) Determining the suitable opening type, according to the building, is a critical design decision for ensuring an adequate ventilation rate within the space [66,67]. The study demonstrated that the implementation of different opening types, including vents, vertical louvers, and horizontal louvers, led to a significant improvement in the targeted IAQ variables. However, it is noteworthy that only the application of vertical and horizontal louvers successfully meets the minimum recommended values for airborne infection control in indoor shared spaces. This suggests that the strategic incorporation of vertical and horizontal louvers can effectively enhance the IAQ and mitigate the risk of airborne infection transmission within the shared vertical circulation space of apartment buildings.

4.3. Proposing guidelines and strategies

The third objective of the study is to influence decision-making in future projects and propose recommendations to develop existing housing policies and codes to assist in the design of a contamination-free shared zone. This can be achieved through the following points:

- Entryway design configuration: It is crucial to consider the design of the entryway space adjacent to the common vertical circulation area. Instead of integrating the entryway as part of a room, it is recommended that the entryway be designed as a separate or a transitional space such as a corridor or lobby. This separation helps to minimize the direct airflow between the entryway and the shared circulation space, reducing the potential for airborne contamination transfer.
- Openings design: Traditional operable windows have shown limited effectiveness in enhancing IAQ variables in shared spaces. Therefore, it is advisable to avoid their use in these areas. Instead, the application of louvers is recommended as a more efficient and sustainable solution for natural ventilation. Louvers allow for significantly more ventilation compared to traditional windows and have a smaller carbon footprint. Incorporating louvers in the design of shared spaces can contribute to improved IAQ and reduce the risk of airborne infection transmission.

5. Conclusions

The study concludes by emphasizing the overlooked significance of IAQ in common spaces, particularly the shared service vertical circulation space in apartment buildings. The literature review highlighted the lack of attention given to the role of these spaces in spreading airborne diseases and the limited empirical studies on the link between IAQ and infection spread.

The investigation employed CFD analysis and online calculations to evaluate ACH, RH, and CO_2 concentrations within the existing design of the common stairwell. The results revealed poor IAQ in the space. This study highlights the role of staircase design and its spatial relationships in influencing ventilation rates and patterns. Architects can use the recommendations from this study to inform future housing policies, design decisions, and projects. Understanding the design parameters helps architects determine the composition and ventilation design of spaces.

Infection control and IAQ should be considered ongoing processes, with professionals recognizing the direct impact of space quality on user comfort and well-being. The current situation of common vertical circulation spaces in apartment buildings presents an opportunity for further design developments that prioritize IAQ and the well-being of occupants.

Overall, this research contributes to the understanding of the relationships among IAQ, design parameters, and infection control, emphasizing the importance of IAQ in common spaces and providing insights for architects and professionals to create healthier and more comfortable living environments.

This study has made significant contributions to the field of residential building design. However, it is essential to acknowledge and discuss the various limitations inherent in the study. These limitations serve as crucial points to consider when interpreting the findings and may guide future research endeavors in this domain.

- Exclusion of Particulate Matter (PM): This study focused on key parameters such as CO_2 concentration, RH, and ACH to assess IAQ and ventilation dynamics. However, the absence of PM data is a limitation. Integrating the PM into the model would have provided a more comprehensive evaluation of IAQ, especially concerning the effects of varying opening sizes and types.
- Simplified Ventilation Scenarios: This study simulated a range of ventilation scenarios to understand airflow patterns. However, the simulations were based on simplified scenarios, and real-world complexities, such as occupant behavior, seasonal variations, and external environmental factors, were not fully considered. Future studies could benefit from incorporating more nuanced and realistic parameters.
- Assumptions in the Simulation: The CFD simulations made certain assumptions about the building's geometry, material properties, and boundary conditions. Efforts were made to align these with real-world conditions, but variations may exist. Further model refinement and validation against empirical data could enhance the accuracy of the model. Additionally, while recognized as valuable in certain modeling studies, an in-depth uncertainty and sensitivity analysis were not performed in this study. This research prioritized assessing ventilation dynamics under diverse scenarios, and a detailed exploration of uncertainty aspects was beyond the immediate scope.
- Limited Temporal Scope: The temporal analysis in this study focused on specific dates, capturing variations in airflow during winter months. The duration of the study provides insights into seasonal changes but may not fully capture long-term trends or transient conditions. A more extended monitoring period could offer a more comprehensive understanding of dynamic environmental influences
- Codal References: Stairwells, which are unique in design and function, lack specific codal references for ventilation standards. The study attempted to align with guidelines from organizations such as WHO, ASHRAE, and CDC, drawing parallels with codes related to spaces with similar characteristics. However, the absence of dedicated stairwell codes may introduce variability in interpretations. Recognizing this limitation, future research could undertake a more in-depth exploration of relevant building codes and standards to enhance the study's alignment with established practices.

Ethics declarations

Ethical approval is not applicable to this research, as it does not involve the use of animals or humans as subjects.

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Data and material availability statement

The data or models that support the findings of this study are available from the corresponding author, B.O, upon request.

Additional information

No additional information is available for this paper.

The use and declaration of AI and AI-assisted technologies in scientific writing

Only these technologies are used to improve readability and language, not to replace key researcher tasks such as interpreting data or drawing scientific conclusions.

CRediT authorship contribution statement

Bushra Obeidat: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Mai Hathal Al-Zuriqat:** Writing – original draft, Visualization, Formal analysis.

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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Abbreviations and Nomenclature

WHO	World Health Organization
CDC	Centers for Disease Control and Prevention
IAQ	Indoor Air Quality
ACH	Air Changes Per Hour
CO_2	Carbon Dioxide
RH	Relative Humidity
CFD	Computational Fluid Dynamics
ASHRAE	American Society of Heating, Ventilation, Refrigeration, and Air-Conditioning Engineers
The US EPA	The United States Environmental Protection Agency
WWR	Window-to-Wall Ratio
PM	Particulate Matter
q	Volume flow rate through the opening or crack
DP	Pressure difference across the opening
n	Exponent varying between 0.5 for fully turbulent flow and 1.0 for fully laminar flow
C	Flow coefficient depending on size and shape of opening/crack

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e26596.

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