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Computational Fluid Dynamics (CFD) Simulation of Indoor Air Quality Optimization

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Abstract: ***Indoor air quality (IAQ) in common vertical circulation spaces has become increasingly important due to rising urbanization and the growing trend of indoor living. Poor IAQ in these shared spaces, where residents frequently move in and out of their apartments, can have a significant impact on occupant well - being, especially during events like the COVID - 19 pandemic. To address this issue, this paper investigates the influence of design parameters on IAQ variables using a simulation - based approach with computational fluid dynamics (CFD). The results show a strong correlation between space design and key IAQ factors, including air changes per hour (ACH), humidity, and CO2 concentration, revealing potential challenges such as inadequate ventilation and increased risk of infection transmission. In response to these findings, the study recommends a re - examination of the design of common vertical circulation spaces in future housing developments and proposes strategies to improve natural ventilation and overall IAQ. The proposed solutions aim to enhance indoor environmental quality and occupant health. This research provides valuable insights into the relationship between space design and IAQ, offering actionable recommendations for improving building design practices in response to modern health and comfort needs.***

Keywords: Indoor Air Quality, Stair Design, Natural Ventilation, Relative Humidity, CO_2 Concentration, Airborne Infection, Jordan

1. Introduction

Airborne diseases have historically posed significant threats to global health, claiming millions of lives [1]. The COVID - 19 pandemic has further highlighted the profound impact of such diseases on both healthcare systems and economies [2], [3]. Given that individuals spend a large portion of time indoors, indoor environmental quality (IEQ) plays a critical role in the transmission of airborne viruses [4]. Factors such as air pollutants, humidity, and CO2 concentration can enhance the survival and spread of pathogens [5], [6]. Health authorities, including the World Health Organization (WHO), emphasize the importance of adequate ventilation in mitigating the spread of airborne diseases [7].

The COVID - 19 pandemic revealed the vulnerabilities of densely populated apartment buildings, where quarantine measures highlighted flaws in building design [8]. Infection control measures, particularly optimized ventilation systems, are essential in such settings [9], [10]. Using Jordan as a case study, this research examines the transmission risks of airborne viruses in high - density residential buildings, specifically focusing on shared stairwells that serve as common pathways for residents. These areas represent high - risk zones for virus transmission, making airflow dynamics and ventilation strategies crucial [11]– [13].

Addressing the lack of research on shared circulation spaces and airborne contamination, this study investigates airflow dynamics in vertical circulation spaces of apartment buildings. The findings provide evidence - based recommendations for designing healthier indoor environments in multi - story residential structures.

Figure 1 represents a chart - flow of the phases of this research. Initially, it involved identifying a base case building by examining the fundamental architectural forms and typologies commonly found in Amman's apartment buildings, as well as the design features of the vertical circulation space. The Jordanian National Building Code provided the needed Data on the layout of the common circulation spaces, however specific indoor air quality standards, such as openings were not available. Due to this regulatory gap method involving systematic sample collection of 138 cases of apartment buildings was used to determine prevalent openings design within the space. The following equation streamlines the process and enables the efficient calculation of the required sample size.

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

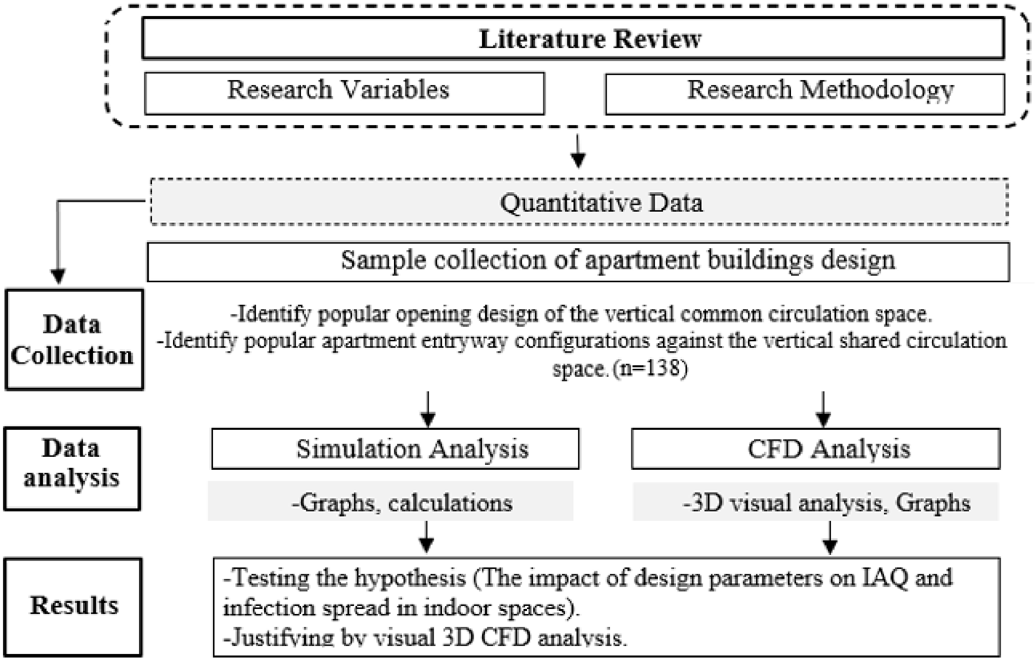

Figure 1: Research Framework

Following this, a simulation was conducted, involving numerical assessments of the design attributes specific to the common vertical circulation zone within the most popular apartment building typology. Examining popular architecture forms and typologies of the common space found in Amman focusing on key parameters including Air Changes per Hour (ACH), Relative Humidity (RH), and CO_2 levels. In addition, the research examines the patterns in which air flows throughout the common vertical circulation space and in and out of apartment unit. Lastly, the research proposed design strategies to enhance natural ventilation, ensuring alignment with prescribed indoor air quality standards. The performance of these strategies was then evaluated. Figure 2 illustrates the framework in which the CFD analysis was performed for testing and optimizing purposes.

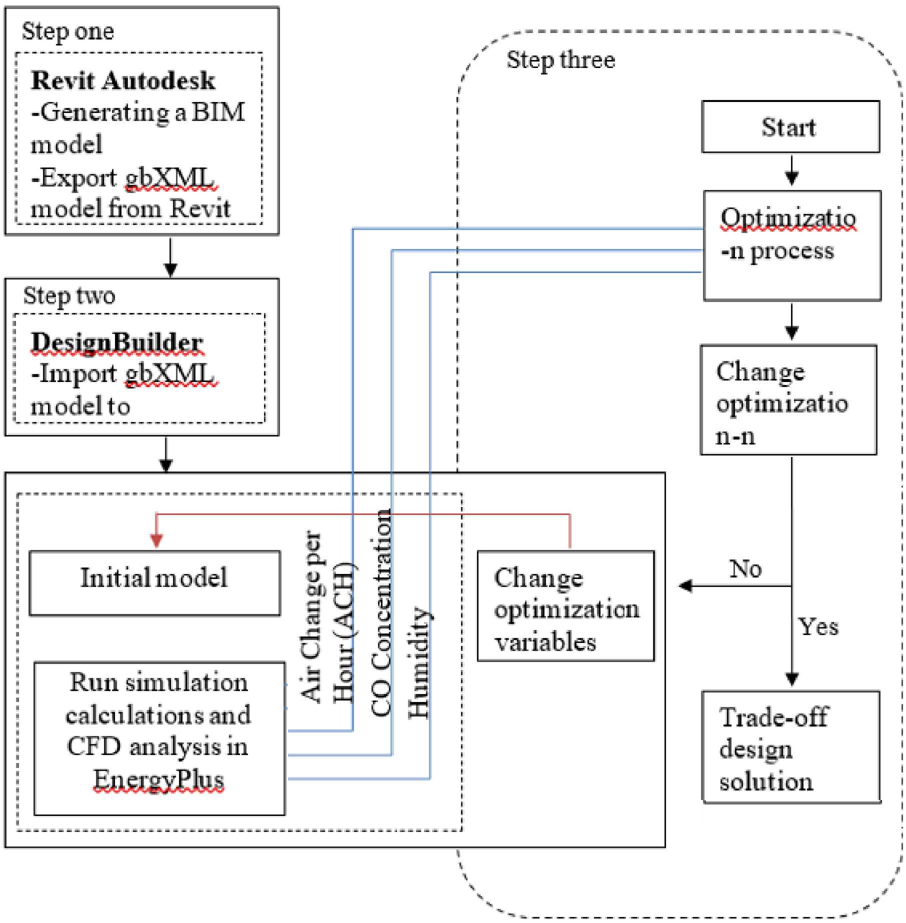

Figure 2: Research Framework

This study employed Computational Fluid Dynamics (CFD) to model airflow and temperature distribution in a building using DesignBuilder v6 as the simulation platform. DesignBuilder's integrated CFD module, validated by various studies, has proven reliable when compared to measured data and other CFD software [14]– [16]. It facilitates the creation of detailed 3D models to analyze air movement, flow patterns, and contaminant dispersion, helping to identify ventilation challenges and evaluate design modifications. This approach supports energy - efficient design while enhancing indoor air quality and comfort [17].

For turbulence modeling, the study utilized the k - ϵ model from the Reynolds - Averaged Navier - Stokes (RANS) family, which is effective for simulating indoor airflow [55]. Convergence was achieved with a maximum of 3000 iterations, ensuring the Root Mean Square Error (RMSE) dropped below 1E−5 and airflow and temperature values stabilized in the building model. A grid sensitivity analysis assessed grid sizes from 0.1 m (very fine) to 0.5 m (very coarse) under typical winter ventilation conditions. The optimal grid size was 0.3 m, balancing computational efficiency and accuracy. Finer grids (0.1 m) increased computational cost with little gain in accuracy, while coarser grids (0.4 m and 0.5 m) resulted in velocity prediction errors of 3% and 8%, respectively. A 3D Cartesian grid with 403, 848 cells was ultimately employed. The study used both external and internal boundary conditions. External conditions involved constant wind velocity and direction, while internal conditions were derived from EnergyPlus simulations, which computed surface temperatures during naturally ventilated occupied periods. Natural ventilation rates were calculated based on factors such as window opening sizes and buoyancy effects, accounting for stack and wind pressure differentials. The ventilation rates (q) through cracks and openings were computed as per the following equation:

$$q = C - (\Delta P)^n$$

Validation tests:

This section presents the validation test of the Quantitative analysis approach, along with the corresponding results. The test is performed using the simulation software, DesignBuilder, the study tests the impact of design parameters of a space on its IAQ. In the first test numerical Data for ACH (Air Change per Hour) and RH (Relative humidity) parameters were provided through simulation calculations. Further calculations were performed using Omni Calculator for CO_2 concentration, incorporating the ACH and RH outputs alongside additional information. Daily values of ACH and RH were calculated during the selected run period in the common vertical circulation space (Figure 3 and 4). Maximum and minimum values were recorded. The data indicates that the maximum ACH was 1.9604 on February 18 and the minimum was 0.810524 on March 19. The RH peaked at 76.19479% on January 22 and was at its lowest on March 4 with 31.43041%. Based on specified room settings CO2 concentration was calculated, ranging from 3777 ppm –3827 ppm.

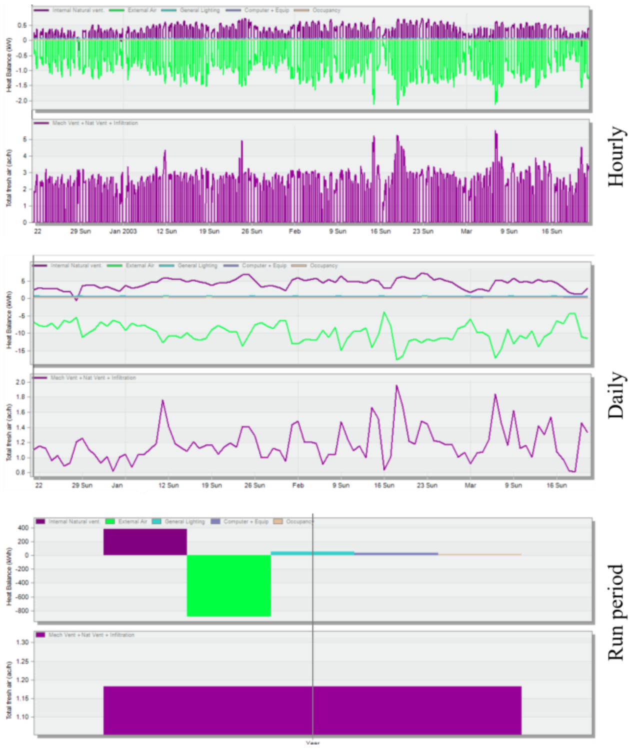

Figure 3: Air Change Per Hour (ACH) Calculations of the Base Case

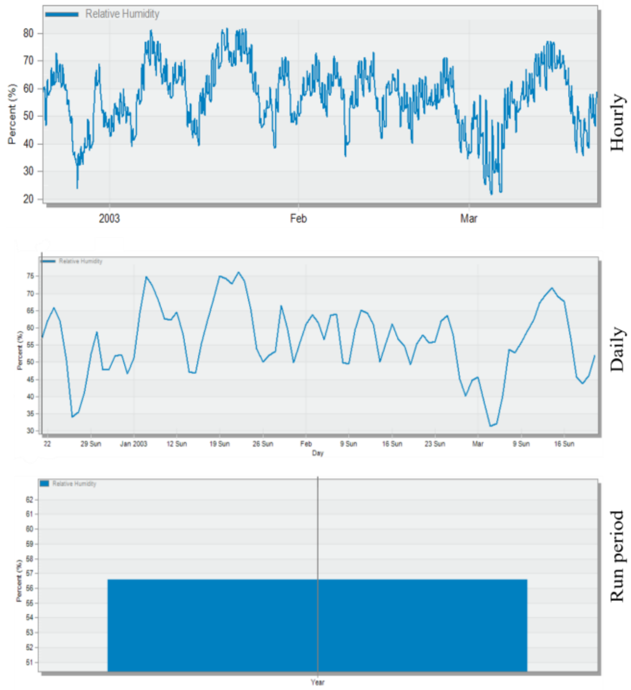

Figure 4: Relative Humidity Calculations of the Base Case

In the second test airflow between the common vertical circulation space and apartment units. When an apartment entryway door is operated a continuous airflow exchange occurs between the common vertical circulation space and adjacent units. Presented in Figure 5, A CFD analysis of an apartment building including3D contours and a section displaying pressure values throughout the building. Due to the pressure difference once an apartment entryway door is operated, an airflow exchange occurs between the circulation space and the apartment unit. As a result, Airflow exchange facilitates the transmission of contaminants from apartment units into the common space as illustrated in figure 6 and promotes the spread of contaminants among apartment units within the building.

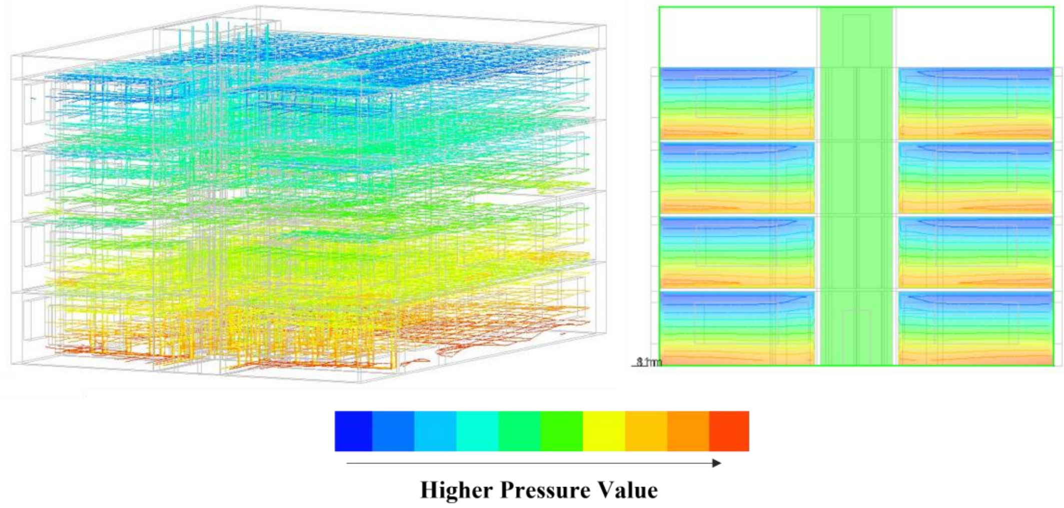

Figure 5: Pressure 3D - Contours and Pressure Section of the Popular Design of Apartment Buildings in Amman – Jordan

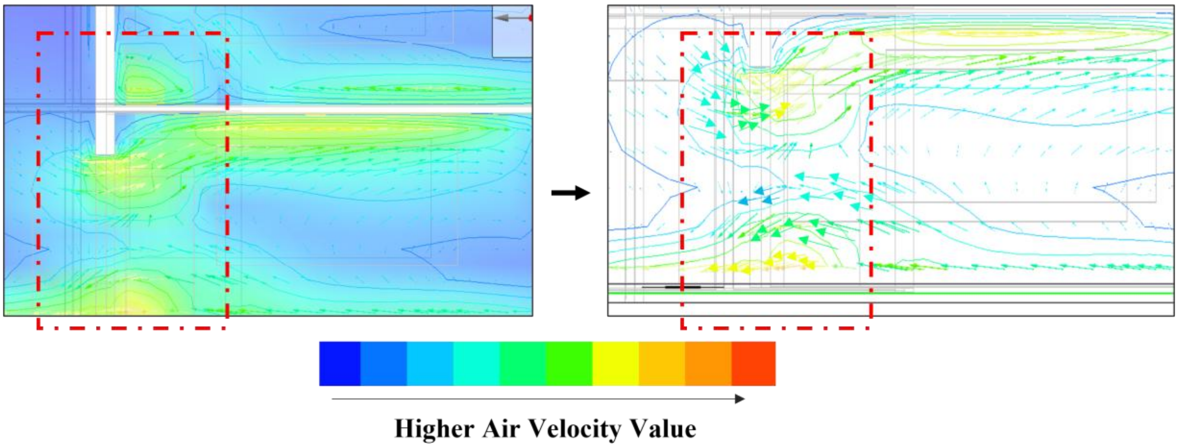

Figure 6: Airflow Exchange CFD analysis Between an Apartment unit and the Common Vertical Circulation Space

Measurements of indoor air quality (IAQ) in the common vertical circulation space of existing apartment designs revealed inadequate natural ventilation, with rates significantly below the recommended 12 air changes per hour (ACH). The recorded natural ventilation rate was only 1.1826 ACH, accompanied by high CO_2 concentrations (3777–3827 ppm), indicating poor air quality despite safe relative humidity levels.

To address this, a strategy focused on enhancing natural ventilation through the design of openings (windows, vents, and louvers) was proposed. Simulations tested the effectiveness of these strategies. Table1

Table 1: Comparison of Different Opening Types for Natural Ventilation in the Common Vertical Circulation Space

Type			Simulation Calculations for run period		Estimates
			Average Air Change per Hour (ACH)	Average Relative Humidity (RH) (%)	Carbon Dioxide (CO2) (ppm)
Operable Window	Window - to - wall ratios	15%	2.18567	56.35674	3, 535 – 3, 584
		20%	2.18655	56.31277	3, 535 – 3, 584
		25%	2.18834	56.30376	3, 535 – 3, 583
		30%	2.18839	56.29379	3, 535 – 3, 583
Vents	Vent - to - wall ratio	15%	3.54746	51.26499	3, 232 – 3, 278
		20%	4.14844	51.41116	3, 099 – 3, 145
		25%	4.83556	51.49707	2, 970 – 3, 014
		30%	5.48719	51.56995	2, 845 – 2, 889
Louvers	Type	Vertical	12.5516	62.38641	1, 090 – 1, 125
		Horizontal	12.6527	62.38732	1, 078 – 1, 113

The type of opening significantly impacts natural ventilation performance. Vents and louvers were particularly effective in improving ACH rates and IAQ, suggesting that these should be prioritized in design considerations to optimize natural ventilation and create healthier indoor environments.

2. Conclusion

This paper has highlighted the critical importance of indoor air quality (IAQ) in common vertical circulation spaces, which is often overlooked in building design. Through simulations and computational fluid dynamics (CFD) analysis, the study evaluated IAQ factors in current designs and identified poor air quality in these spaces, stressing the need for IAQ to be a key consideration in design decisions. The research showed that IAQ is heavily influenced by spatial and ventilation design. To address this, the study offers recommendations that architects can apply to inform future housing policies. By understanding the relationship between IAQ factors and design parameters, architects can optimize ventilation strategies and spatial composition in built environments. With the growing recognition of infection control and the impact of air quality on user comfort and well - being, IAQ and designing for infection control should be a continuous focus. The findings present an opportunity to improve IAQ in common vertical circulation spaces, enhancing occupant well - being. In summary, this analysis has demonstrated the crucial connection between IAQ, design parameters, and infection control, providing valuable insights for architects and professionals aiming to create healthier indoor environments. Future work could focus on developing advanced design strategies that integrate IAQ considerations more effectively.

Declaration

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 article.

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