

Evaluation of the Impact of Opening Type and Placement on Enhancing Natural Ventilation in Atrium-Adjacent Corridors in Hot and Semi-Humid Climates

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Abstract

In hot and semi-humid climates, natural ventilation plays a crucial role in enhancing indoor environmental quality. Atriums are recognized as architectural elements that facilitate daylight penetration and airflow, yet they remain underutilized in such climatic conditions. Inefficient air circulation in upper floors and uneven airflow distribution in surrounding corridors highlight the need to reconsider ventilation design strategies. This study aims to improve natural ventilation performance in atrium-adjacent corridors by exploring architectural interventions that enhance airflow patterns and thermal comfort. Independent variables include the number and arrangement of spatial elements, while dependent variables comprise airflow velocity, movement patterns, and indoor temperature. Empirical data were collected from the Central Library of Khuzestan Province between October 25 and November 25. Geometric modeling was conducted in SpaceClaim, and computational fluid dynamics (CFD) simulations were performed using ANSYS Fluent R3 2019. Among eleven design scenarios, Model 11 featuring inlet windows in stair cores and outlet vents on the second-floor ceiling demonstrated superior performance. Airflow velocity increased to 1.907 m/s, indoor temperature decreased to 302.57 K, and airflow uniformity was significantly improved. Significant improvements were also observed in outlet flux and turbulence intensity, while thermal comfort indices (PMV, PPD) confirmed an acceptable comfort range according to ASHRAE standards. These interventions are cost-effective, easy to install, and applicable to existing buildings.

Keywords: CFD Method, Indoor Airflow, Natural Ventilation, Peripheral Atrium Corridor.

1. Introduction

Optimizing building design to enhance indoor environmental quality has become a central priority in sustainable architecture and urban planning. Among passive design strategies, atriums serve as key architectural elements with high potential for improving thermal conditions, facilitating natural ventilation, creating favorable microclimates, and reducing operational costs [1, 2]. However, in hot and semi-humid climates such as Ahvaz, the thermal performance of atriums faces significant challenges, including intense solar radiation, elevated indoor temperatures during peak hours, and increased demand for cooling systems [3, 4]. These factors diminish the efficiency of atriums in supporting natural ventilation, often leading to their underutilization in climate-responsive building design. To address these challenges, computational tools such as Computational Fluid Dynamics (CFD) provide precise analysis of

airflow behavior, enabling the optimization of architectural ventilation strategies [5]. Integrating CFD into the design process can facilitate the effective use of prevailing winds, improve airflow circulation, and reduce reliance on mechanical systems [6]. This study aims to enhance natural ventilation performance in atrium-adjacent corridors by investigating how architectural interventions—particularly the type and placement of openings—can improve airflow patterns and thermal comfort in hot and semi-humid climates. Such an approach directly addresses the inefficiencies of conventional atrium ventilation design and seeks to expand the capacity for passive airflow distribution throughout the building.

2. Literature Review

Numerous and diverse studies have been conducted in fields related to the subject of this research. A

brief summary of several of them is presented below.

Researchers have conducted studies to examine the factors influencing thermal comfort and natural ventilation in buildings with atriums located in coastal regions and hot-humid climates. They used ANSYS Fluent software and CFD (Computational Fluid Dynamics) analysis methods. In these studies, solar flux calculations were assisted by the solar calculator embedded in the software [7,8,9,10]. Various researchers have investigated the impact of atrium physical components on energy consumption in buildings located in different climatic zones of China. Using simulation software and CFD-based analysis, they concluded that atrium components such as height, shape, and the ratio of skylight and window surfaces significantly affect the building's energy consumption [11,12,13,14].

For example, Pawar and colleagues conducted a study on the thermal performance and natural ventilation of four-sided high-rise atriums and multi-atrium configurations in hot and humid climates. Using CFD analysis and ASHRAE standards, they concluded that multi-atrium configurations improve ventilation performance in tall buildings by reducing buoyancy forces and pressure differentials compared to four-sided atriums [15]. Albuquerque and colleagues in 2020 conducted research on nighttime ventilation systems in atriums, aiming to evaluate the energy savings achieved through this method and to measure the reduction in cooling loads during the day. They used simulation software such as EnergyPlus and ANSYS Fluent and applied CFD analysis. Their findings showed that this method can reduce cooling demand by up to 27%, resulting in decreased energy consumption [16]. Asthana and colleagues carried out a study aimed at evaluating the heating and cooling loads of glazed atriums to reduce energy consumption. They used ANSYS Fluent software, CFD analysis, the k-epsilon turbulence model, and the discrete ordinate radiation method, along with ASHRAE standards, to examine the impact of weather conditions on different days on glazed atriums. By analyzing the CFD results and comparing airflow and indoor temperature, they concluded that wind flow and ambient temperature have a direct impact on indoor air quality, and that wind speed and solar radiation are the main factors affecting indoor air quality [17]. In the field of natural ventilation, various studies have been conducted [18,19,20,21,22,23,24]. For example, a study conducted by Rahaei and Azemati aimed to identify criteria for classroom design in the climate

of Amol, focusing on the position of openings and the overall spatial configuration of the classroom to benefit from natural ventilation throughout the space. Using CFD analysis and simulation software such as ANSYS Fluent and Gambit, they concluded that proper arrangement of openings, the creation of stepped facades aligned with prevailing wind direction, and the provision of effective exhaust vents on the windward wall can effectively control the entry, exit, and distribution of air within the interior space (according to ASHRAE standards), thereby establishing desirable airflow throughout the entire interior [25].

Based on previous studies, the use of simulation through various software tools such as ANSYS Fluent, EnergyPlus, DesignBuilder, and other programs, along with data analysis using the CFD (Computational Fluid Dynamics) method, is considered a reliable and highly accurate approach for advancing research related to ventilation and energy [26,27,28,29,30,31,32]. These software tools have produced precise and dependable outputs in cities with diverse climates and weather conditions across Iran and other countries [33,34,35,36,37]. They have been applied in various building typologies, including administrative, residential, educational, and other functional categories, yielding accurate and trustworthy results [38,39,40,41,42,43]. Moreover, the outputs derived from the analysis of these data using the aforementioned method can be used to evaluate the necessary conditions for achieving thermal comfort [44,45,46,47,48,49], based on various standards such as the ASHRAE standard [50,51,52]. Therefore, based on these studies, the validity of the present research is confirmed, and the continuation of this study is justified.

3. Methodology

Based on the theoretical foundations presented in the previous section, the present study adopts an interdisciplinary and hybrid approach, relying on a combined strategy that includes empirical data, numerical simulation, and case study analysis. The tools employed in this research consist of library studies, field observations, workshop-based measurements, and simulation-based analyses.

Given the growing trend of utilizing passive energy systems in developed countries and their significant role in optimizing energy consumption, attention to this approach in specific Iranian climates, particularly in hot and semi-humid regions, is deemed essential. The city of Ahvaz, with its unique climate and energy-related challenges, has not yet effectively utilized the potential of natural ventilation in architectural

design. This study, by focusing on the application of natural ventilation in atrium corridors, proposes an innovative solution for achieving thermal comfort in indoor spaces.

In the initial phase, an empirical strategy was employed to design and implement tests aimed at identifying and isolating the independent variables affecting airflow within the atrium space. In this context, the number and placement of openings, along with various opening scenarios, were considered as independent variables, while temperature and airflow patterns in the atrium adjacent corridors were treated as dependent variables.

Data related to airflow velocity and direction were recorded using high-precision digital instruments during the months of November and December, which are considered climatically suitable periods for utilizing natural ventilation in Ahvaz. Among the periods that provide favorable conditions for natural ventilation, this timeframe represents the most critical thermal situation. Therefore, any strategies adopted to enhance ventilation performance during this period can be effectively applied to other suitable months as well. For this reason, the empirical field measurements in this study were limited to November and December, as they provide the most rigorous basis for evaluating natural ventilation performance. The prevailing wind direction was determined through smoke testing and empirical observations, indicating a southeast-to-northwest airflow pattern during the data collection period. The statistical population of this research includes buildings with atriums located in the hot and semi-humid climate of Ahvaz. To fulfill the research objectives, the Central Library of Khuzestan Province, situated in Dowlat Park, was randomly selected as the case study for conducting empirical tests. In the second phase, numerical simulation was employed to analyze the collected data and evaluate the impact of architectural interventions. The validity of this method was confirmed based on previous literature, and simulations were conducted using Computational Fluid Dynamics (CFD). Initially, the accuracy of the numerical simulations was verified through comparison with empirical measurements, followed by interpretive-comparative analysis of the results. In the final stage, the selected optimal scenarios—those demonstrating the best performance—were evaluated in detail using PMV, PPD, and other comfort indicators to ensure a more precise assessment of ventilation effectiveness. For geometric modeling, SpaceClaim within the ANSYS Workbench 2019 R3 platform was used.

Meshing was performed using ANSYS Mesh, and the final model analysis was conducted in the Fluent environment. In accordance with previous studies [53,54,55,56,57,58,59,60,61,62,63], the RNG k- ϵ turbulence model was applied to simulate airflow, and the Solar Calculator tool was used to compute solar heat flux. The core innovation of this study lies in the integration of climatic analysis with airflow simulation using the CFD method and the specialized ANSYS Fluent software. This approach enables precise evaluation of natural ventilation performance under the actual climatic conditions of Ahvaz and contributes to the development of localized and sustainable design strategies for architecture in hot and humid regions. It is noteworthy that, due to the extremely hot climate of Ahvaz, most previous research in this region has focused on mechanical ventilation systems, while natural ventilation has received limited attention. The strategies proposed in this study are economically feasible, highly effective, and can be applied not only to new buildings but also to existing structures, providing a practical pathway for improving ventilation performance in real-world conditions.

3.1. Ahvaz

Ahvaz, the metropolitan center of Khuzestan Province in southwestern Iran, is located at 49°11'E longitude and 31°50'N latitude, at an elevation of 18 meters above sea level. The city has a population of approximately 1,425,891, with an urban area of 19,494 hectares and a metropolitan boundary of 60,000 hectares. Ahvaz is bordered by Dezful and Shushtar to the north, Ramhormoz and Shushtar to the east, Dasht-e Azadegan to the west, and Bandar Mahshahr, Shadegan, and Khorramshahr to the south [64].

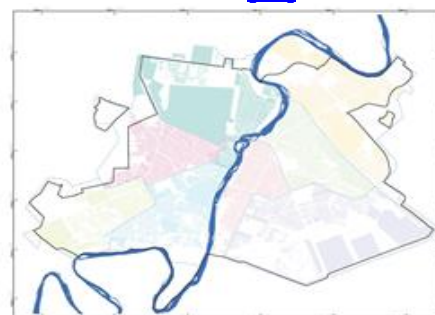


Figure 1. Metropolitan Area of Ahvaz[64]

According to data from the Ahvaz meteorological station, the period from June to August is the hottest of the year, with an average temperature of 38.6°C, while December to February is the coldest, with an average of 12.4°C. Over the past 50 years, the minimum and maximum recorded temperatures have been -7°C and 54°C, respectively, with a

mean annual temperature of 25°C. Seasonal averages indicate that summer temperatures reach

approximately 48°C, while winter averages drop to around 4°C [65].

Table 1. Climatic Data of Ahvaz in 2022 [64,66]

	Air temperature			Relative Air Humidity			Maximum Wind Speed	Total sunshine Hours
	Average Min	Average Max	Average	Average Min	Average Max	Average		
March – April	15.7	29.9	22.8	28	74	51	11	283.2
April – May	21.9	39	30.4	12	44	28	14	333
May – June	29.1	44.7	36.9	10	32	21	12	341.1
June – July	30	48.4	39.2	7	32	20	11	386.9
July – August	30.5	48.5	39.5	11	39	25	9	359.8
August – September	28.3	45.9	37.1	12	44	28	8	340.4
September – October	23.7	40.3	32	18	57	37	14	274.6
October – November	18	31.1	24.5	35	72	54	16	199
November – December	10.9	23.5	17.2	48	89	69	6	186.1
December – January	10.5	22.7	16.6	45	86	65	11	190.6
January – February	10.5	22.7	16.6	41	85	63	16	201.3
February - March	11.6	25.1	18.3	31	82	57	10	225.8

Based on these climatic data, it is evident that, for most months of the year, conditions in Ahvaz are unsuitable for natural ventilation. Only during November–December and February–April can natural ventilation be considered a feasible alternative to mechanical cooling systems. Among these, November represents the first month when natural ventilation becomes possible, although its temperatures remain higher compared to the other suitable months. With an annual sunshine duration of 3,221.8 hours, the city experiences predominantly clear skies and intense solar radiation throughout most days.

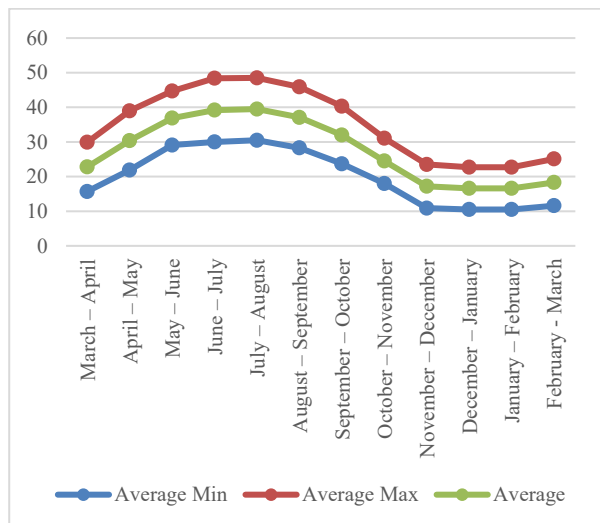


Figure 2. Average Monthly Temperature in Ahvaz [64]

According to Chapter 19 of the Iranian National Building Regulations, which serves as the reference standard for energy classification in

buildings, Ahvaz is categorized among the cities with the highest annual energy demand, primarily for cooling [67]. This classification highlights the city's critical reliance on mechanical air-conditioning systems, with limited inclination toward natural ventilation. Consequently, employing natural ventilation during the few climatically suitable months not only enhances indoor thermal comfort but also significantly reduces reliance on mechanical cooling. Given the high energy consumption of air-conditioning systems, this strategy can lead to substantial energy savings. In summary, Ahvaz's dominant climatic demand is cooling. Considering that November represents the most critical condition among the months suitable for natural ventilation, the findings derived from this month can be reliably generalized to other months with more favorable climatic conditions.

3.2. Case Study Description

All field measurements were conducted in the atrium-adjacent corridors of the Central Library of Khuzestan Province, selected as a random case study. The building is oriented along an east-west axis and features an atrium with a diameter of 17 meters. Data collection was carried out over a 31-day period, from October 25 to November 25, which is considered climatically suitable for utilizing natural ventilation in Ahvaz.

Measurements were taken at air inlet and outlet points, as well as at three locations on the ground, first, and second floors, at a height of 1.5 meters. The main entrance doors of the building were fully open and served as the primary air inlets. At the

outlet section, beneath the quadrilateral shaft of the atrium, twelve windows (each measuring 3 meters in length and 50 centimeters in width) were installed. Only the central window on each side was open, while the remaining windows were kept closed, resulting in a total of four open outlet windows. Wind speed was measured using the Kmio VT 200 device, and temperature and humidity were recorded using the HC520 thermometer-hygrometer. Given the study's focus on improving natural airflow in the atrium-adjacent corridors, only the relevant spatial zones were modeled during the simulation process, and non-

related building sections were excluded from the geometric modeling.

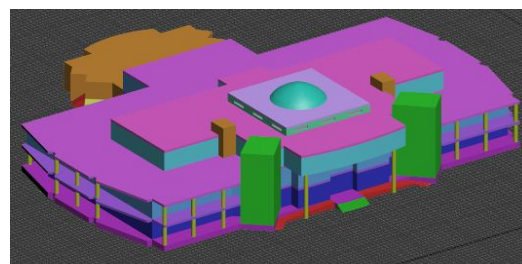


Figure 3. Main Façade Perspective

Table 2. Plans and Spatial Configuration of the Selected Case Study.

	Ground Floor	First Floor	Second Floor
Study Area			
Location of the Case Study Area in Relation to the Entire Floor			

3.3. Experimental Tests

In order to evaluate the natural ventilation performance, empirical measurements were carried out every three days between 08:00 and 18:00. For precision, the measuring instruments were placed at a height of 1.5 meters and operated for 10 minutes at each location.

On every floor, data were collected from three separate points, and the average temperature values were computed for each level, including the entry and exit zones of the airflow paths.

Table 3. Field Temperature (°C) Measurements During the Autumn Season.

Record No.	Date	Outdoor Temperature	Ground Floor Temperature	First Floor Temperature	Second Floor Temperature	Average Indoor Temperature	Inlet Air Temperature	Outlet Air Temperature
1	25 Oct 2023	27.12	28.41	28.96	29.70	29.02	25.41	27.31
2	28 Oct 2023	27.33	28.65	29.17	29.96	29.26	26.74	28.01
3	30 Oct 2023	28.55	30.14	30.88	31.69	30.90	26.91	28.65
4	01 Nov 2023	29.71	30.86	31.39	32.02	31.42	27.50	29.93
5	04 Nov 2023	28.70	31.94	32.39	31.85	32.06	28.55	29.12
6	06 Nov 2023	24.97	26.32	27.14	27.80	27.08	23.35	25.18
7	08 Nov 2023	25.19	26.07	26.73	27.45	26.75	23.72	25.79
8	11 Nov 2023	26.41	27.69	28.41	29.31	28.47	24.99	27.31
9	13 Nov 2023	24.83	25.33	26.25	27.17	26.25	22.56	25.68
10	15 Nov 2023	19.77	21.60	22.31	23.19	22.36	19.74	20.36
11	18 Nov 2023	21.92	23.71	24.50	25.11	24.44	20.31	22.19
12	20 Nov 2023	21.87	22.58	23.19	24.33	23.36	19.97	22.42
13	22 Nov 2023	20.16	20.95	21.77	22.56	21.76	18.49	20.52
14	25 Nov 2023	19.68	20.31	21.06	21.92	21.09	18.13	19.90
Average		24.72	26.04	26.72	27.43	26.73	23.31	25.16

The average outdoor temperature during the autumn season was recorded at 24.72°C, while the indoor temperature averaged 26.73°C, both falling within the thermal comfort range. With increasing

elevation, the temperature showed an average rise of 0.70°C. The temperature difference between the interior and exterior was 2.01°C, indicating favorable conditions for the utilization of natural

ventilation. In parallel, the airflow measurements demonstrated that the average air velocity across the ground, first, and second floors was 0.122, 0.165, and 0.207 m/s, respectively, with an overall mean of 0.164 m/s. Although these thermal conditions suggest strong potential for effective

natural ventilation, the relatively low air velocities reflect weak circulation and insufficient ventilation performance indoors, emphasizing the need for architectural optimization to enhance airflow efficiency.

Table 4. Field Air Velocity (M/s) Measurements During the Autumn Season.

Record No.	Date	Ground Floor Air Velocity	First Floor Air Velocity	Second Floor Air Velocity	Average Indoor Air Velocity
1	25 Oct 2023	0.136	0.172	0.203	0.170
2	28 Oct 2023	0.100	0.152	0.201	0.151
3	30 Oct 2023	0.143	0.176	0.220	0.179
4	01 Nov 2023	0.151	0.193	0.233	0.192
5	04 Nov 2023	0.131	0.159	0.196	0.162
6	06 Nov 2023	0.105	0.153	0.199	0.152
7	08 Nov 2023	0.122	0.169	0.210	0.167
8	11 Nov 2023	0.110	0.165	0.205	0.160
9	13 Nov 2023	0.154	0.185	0.239	0.192
10	15 Nov 2023	0.107	0.15	0.182	0.146
11	18 Nov 2023	0.114	0.168	0.217	0.166
12	20 Nov 2023	0.116	0.165	0.207	0.162
13	22 Nov 2023	0.113	0.161	0.197	0.157
14	25 Nov 2023	0.106	0.142	0.189	0.145
Average		0.122	0.165	0.207	0.164

3.4. Mathematics

The airflow within the building is considered an incompressible convective heat transfer process, characterized by mixed shear-driven flows and numerous vortical structures at low Reynolds numbers, which are generated due to the architectural configuration. Accordingly, by adopting the k-ε turbulence model, the governing equations can be expressed as follows:

Continuity Equation:

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

Momentum Equation:

$$\frac{\partial}{\partial x_j} (\rho U_i U_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu_{eff} \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] \quad (2)$$

Energy Conservation Equation:

$$\frac{\partial}{\partial x_j} (\rho U_j T) = \frac{\partial}{\partial x_j} \left(\alpha_{eff} \frac{\partial T}{\partial x_j} \right) \quad (3)$$

Turbulent Kinetic Energy (k):

$$\frac{\partial}{\partial x_j} (\rho U_j k) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \epsilon \quad (4)$$

Turbulence Dissipation Rate (ε):

$$\frac{\partial}{\partial x_j} (\rho U_j \epsilon) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C1\epsilon \left(\frac{\epsilon}{k} \right) G_k - C2\epsilon \rho \frac{\epsilon^2}{k} \quad (5)$$

Turbulent Viscosity (μ_t):

$$\mu_t = C_\mu \rho \frac{k^2}{\epsilon} \quad (6)$$

In the turbulence model, the constants are defined as:

- $C_\mu = 0.0845$
- $C1\epsilon = 1.42$
- $C2\epsilon = 1.68$
- $\sigma_k = 1.0$
- $\sigma_\epsilon = 1.3$ [68]

3.5. Thermal Comfort Standards: PMV and PPD

Fanger's thermal comfort standard is based on the Predicted Mean Vote (PMV) index, which represents the average thermal sensation of a group of individuals under a given environmental condition. This standard is defined as a seven-point

thermal sensation scale, ranging from -3 (cold) to +3 (hot), with zero indicating a neutral thermal sensation. PMV is considered one of the most important physiological indices of temperature, and it has wide applications not only in urban and regional planning studies but also in meteorology and tourism research. The PMV index is calculated using equations (7–12) [69].

$$PMV = (0.303 e^{-0.036M} + 0.028)[(M - W) - H - E_c - C_{res} - E_{res}] \quad (7)$$

$$E_c = 3.05 \times 10^{-3}[5733 - 6.99(M - W) - p_a] + 0.42(M - W - 58.15) \quad (8)$$

$$C_{res} = 0.0014 M (34 - T_a) \quad (9)$$

$$E = 3.05 \times 10^{-3}(256 t_{sk} - 3373 - p_a) + E_{sw} \quad (10)$$

$$E_{res} = 1.72 \times 10^{-5} M (5867 - p_a) \quad (11)$$

$$H = \frac{(t_{sk} - T_{cl})}{I_{cl}} \quad (12)$$

The Predicted Percentage of Dissatisfied (PPD) index is also widely recognized as a measure of the percentage of individuals dissatisfied with the thermal environment. It is derived from the PMV index and expressed as a percentage, calculated using equation (13) [69].

$$PPD = 100 - 95 e^{-(0.03353 PMV^4 + 0.2179 PMV^2)} \quad (13)$$

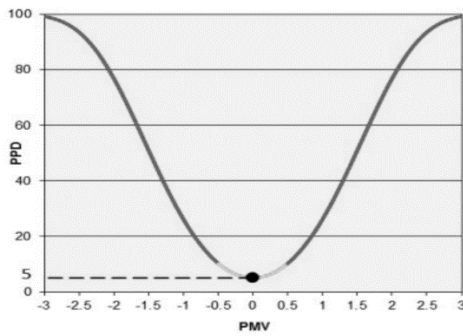


Figure 4. Changes in the average percentage of dissatisfied people with the average estimate of votes cast for PMV[69]

4. CFD-Based Data Analysis

The primary objective of this research is to enhance airflow patterns and thermal comfort conditions through natural ventilation in atrium-adjacent corridors, in accordance with ASHRAE standards, under hot and semi-humid climatic conditions. The location and number of openings were considered independent variables, while airflow patterns and ambient temperature were treated as dependent variables. Given this framework, architectural interventions were deemed essential. Accordingly,

based on findings from previous studies, ANSYS Fluent software and the Computational Fluid Dynamics (CFD) method were employed for simulation. To validate the simulation results, empirical data were compared with numerical outputs. The initial geometry was designed using SpaceClaim, and meshing was performed using the Polyhedral method, resulting in 995,031 cells. Following the methodology of previous research [53,54,55,56,57,58,59,60,61,62,63], the final model incorporated the RNG k- ϵ turbulence equation. The boundary conditions were defined as follows: inlets were modeled as Pressure Inlet with a temperature of 300.65 K (27.50 °C), while outlets were modeled as Pressure Outlet with a temperature of 303.08 K (29.93 °C). A turbulence intensity of 5% was specified at the inlets. The hydraulic diameters of the inlets were set to $A^1 = 1.54$ m and $B^1 = 2.36$ m. Gauge pressure at both inlets and outlets was set to zero, allowing the pressure-based solver to calculate the pressure field. Atrium walls were modeled as Stationary Walls with a no-slip condition, surface roughness coefficient of 0.5, internal emissivity of 0.9, thickness of 0.05 m, and heat transfer defined through System Coupling. Sun-exposed walls were modeled with Convection boundary conditions (heat transfer coefficient = 1 W/m²K, free stream temperature = 301.85 K (28.70 °C), emissivity = 1, thickness = 0.3 m). Interior walls without solar exposure were modeled with Heat Flux = 0 and emissivity = 1. All walls were defined as Opaque surfaces with absorptivity = 0.8 and participation in Solar Ray Tracing. The sky condition was assumed to be clear.

The fluid domain was modeled with standard air properties ($\rho = 1.225$ kg/m³, $C_p = 1006.43$ J/kg·K, $k = 0.0242$ W/m·K, $\mu = 1.7894 \times 10^{-5}$ kg/m·s), including radiative participation. Material properties included walls ($\rho = 2300$ kg/m³, $C_p = 880$ J/kg·K, $k = 1.4$ W/m·K) and glass ($\rho = 2500$ kg/m³, $C_p = 750$ J/kg·K, $k = 1.4$ W/m·K), with absorption and scattering coefficients defined according to standard values. The turbulence model was RNG k- ϵ with constants $C_{\mu} = 0.0845$, $C1\epsilon = 1.42$, and $C2\epsilon = 1.68$, combined with Enhanced Wall Treatment to improve near-wall accuracy. Radiation was modeled using the DO Radiation model with activated Solar Ray Tracing, applying solar direction vectors ($x = -0.716$, $y = 0.567$, $z = 0.407$). The simulation was performed in steady-state mode, with energy and gravity ($g = 9.806$ m/s² along the y-axis) enabled. To ensure numerical accuracy, two verification stages were conducted: mesh independence testing and convergence control. In the mesh independence

stage, four meshes with different cell counts (537,835; 667,531; and 1,314,406 cells) were tested. Results showed that variations in temperature and airflow velocity between medium and fine meshes were less than 5%, confirming mesh independence. Consequently, the mesh with 995,031 cells was selected as the final grid, balancing accuracy and computational efficiency. In the convergence stage, residuals of governing equations were monitored. Results indicated that continuity and energy equations converged to levels below 10^{-5} , confirming stable and reliable convergence. This demonstrates that the simulation results are independent of iteration count and numerically valid.

Therefore, the combination of mesh independence and convergence analysis confirms that the selected model is both accurate and stable, making it fully reliable for analyzing natural ventilation in atrium-adjacent corridors. A comparison between simulated and experimental data on November 4, the selected validation day, showed very close agreement between the two datasets. The temperature difference between simulation and field measurements on the ground floor was

0.31 °C, while the discrepancies for the first and second floors were 0.38 °C and 0.18 °C, respectively. Similarly, airflow velocity differences remained minimal: 0.004 m/s on the ground floor, 0.013 m/s on the first floor, and 0.007 m/s on the second floor. For the averaged experimental observations collected throughout the measurement period, temperature deviations were 0.60 °C (ground floor), 1.08 °C (first floor), and 1.79 °C (second floor). Corresponding velocity differences were 0.007 m/s, 0.004 m/s, and 0.017 m/s, respectively. These values confirm that both instantaneous (November 4) and averaged measurements exhibit strong alignment with the simulated results. Overall, the deviation between field measurements and CFD outputs remained below 10% for all floors, which is considered acceptable and is typically attributed to experimental uncertainties, sensor limitations, and micro-climatic fluctuations [25]. This close correspondence validates the reliability of the simulation framework and confirms its suitability for evaluating natural ventilation performance in atrium-adjacent corridors.

Table 5. Comparison of Measured Data and Existing Conditions.

	Temperature (°C)				Air Velocity (M/s)			
	Measured Air Temperature on November 4, 2023	Simulated Air Temperature on November 4, 2023	Average Measured Air Temperature in Experimental Test	Simulated Average Air Temperature under Current Conditions	Measured Air Velocity on November 4, 2023	Simulated Air Velocity on November 4, 2023	Average Measured Air Velocity in Experimental Test	Simulated Average Air Velocity under Current Conditions
Ground Floor	31.94	32.25	26.04	25.66	0.131	0.135	0.122	0.115
First Floor	32.39	32.77	26.72	25.64	0.159	0.172	0.165	0.161
Second Floor	31.85	32.03	27.43	25.64	0.196	0.203	0.207	0.190

Table 6. Grid Independence Analysis.

	Average Measured in Experimental Test		995031 Cells (Base model)		1314406 Cells		667531 Cells		537835 Cells	
	Temperature (°C)	Air Velocity (M/s)	Temperature (°C)	Air Velocity (M/s)	Temperature (°C)	Air Velocity (M/s)	Temperature (°C)	Air Velocity (M/s)	Temperature (°C)	Air Velocity (M/s)
Ground Floor	26.04	0.122	25.66	0.115	24.85	0.101	25.49	0.124	25.33	0.089
First Floor	26.72	0.165	25.64	0.161	24.76	0.154	25.47	0.186	25.34	0.178
Second Floor	27.43	0.207	25.64	0.190	25.00	0.175	25.39	0.172	25.16	0.144

The simulation and architectural interventions were conducted on November 4, 2023, at 15:00,

selected as a representative day within the empirical data collection period.

4.1. Simulation Results

To establish effective natural ventilation within the atrium-adjacent corridors, architectural interventions were implemented based on the validated simulation method described earlier. These interventions were designed in accordance with the theoretical framework and previous research findings and were defined based on the identified variables. The general layout of the intervention zones and a brief description of each are presented in [Figure 5](#) and [Tables 7](#) and [9](#).

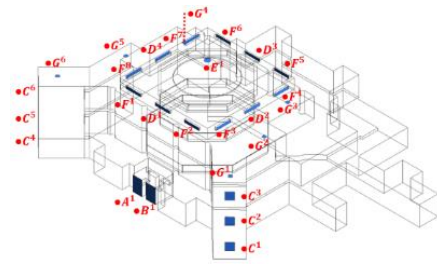


Figure 5. Intervention Locations

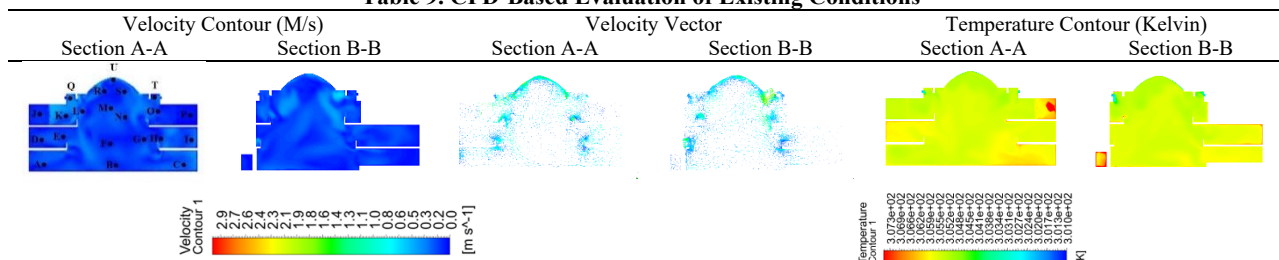
Table 7. Description of Architectural Interventions

LIST OF MODELS		MODEL 1*	MODEL 2	MODEL 3	MODEL 4	MODEL 5	MODEL 6	MODEL 7	MODEL 8	MODEL 9	MODEL 10	MODEL 11
INLET	A ¹	*	*	*	*	*	*	*	*	*	*	*
	B ¹	*	*	*	*	*	*	*	*	*	*	*
	C ¹ – C ⁶				*	*	*				*	*
	D ¹ – D ⁴	*	*	*	*	*	*	*	*	*	*	*
OUTLET	E ¹			*			*			*		*
	F ¹ – F ⁸		*	*		*	*		*	*		*
	G ¹ – G ⁶							*	*	*	*	*

Table 8. Dimensions and Specifications of Each Intervention

Section Name	Label	Length (cm)	Width (cm)	Quantity	Area per Unit (m ²)	Total Area (m ²)
INLET	A ¹	103.74	300	1	3.112	8.923
	B ¹	193.73	300	1	5.811	
	C ¹ – C ⁶	140	150	6	2.10	12.60
	D ¹ – D ⁴	300	50	4	1.5	6
OUTLET	E ¹	Radius: 50 cm		1	0.785	0.785
	F ¹ – F ⁸	50	300	8	1.5	12
	G ¹ – G ⁶	60	60	6	0.36	2.16

Table 9. CFD-Based Evaluation of Existing Conditions



In the baseline [model](#), the average airflow velocity throughout the building is 0.145 m/s, and the

average indoor temperature is 305.70 K. As observed, the airflow circulation and velocity are

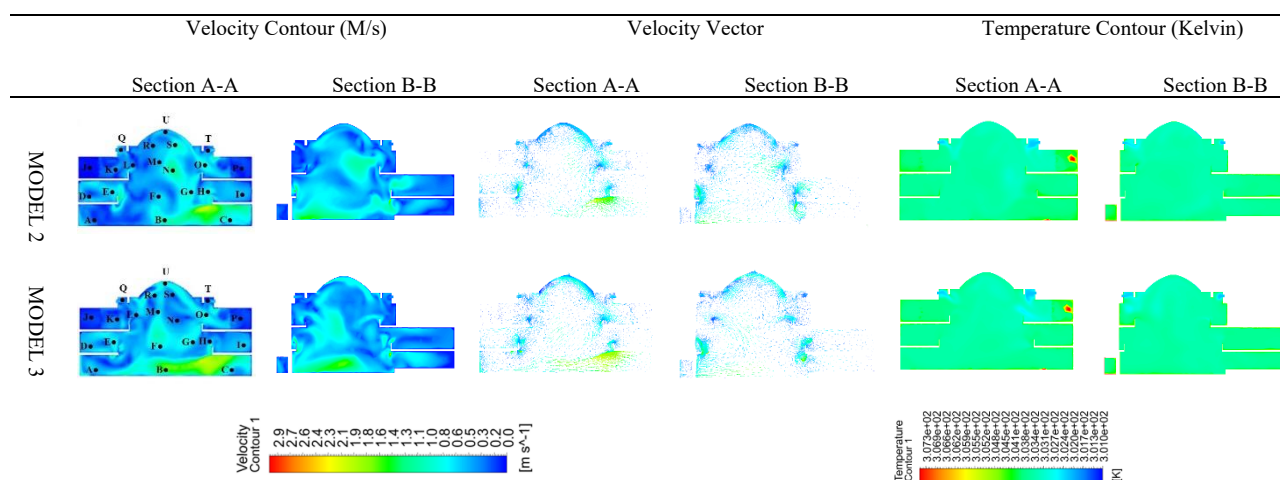
relatively weak, resulting in inadequate ventilation across many interior zones. Furthermore, an undesirable phenomenon of air inversion has been detected in the upper floors. The turbulence intensity energy in this model is 1.875, and the total flux in the outlet region is 0.495. From a thermal perspective, improved performance is also expected, as the current conditions do not fully meet thermal comfort standards. Therefore, based on the existing situation, architectural interventions aimed at enhancing natural ventilation are deemed essential. The necessity of this research is clearly evident, given the limitations observed in the current configuration.

4.2. Evaluation of the Impact of Increasing Default Exhaust Vents in the Existing Condition

In this intervention, various scenarios involving an increase in the number of exhaust vents in the baseline condition ([Model 1](#)) were examined. A detailed description of these scenarios is provided in [Table 10](#). With the increase in the number of exhaust outlets in [Models 2](#) and [3](#), the average airflow velocity rose to 0.496 m/s and 0.512 m/s,

respectively. These values represent an increase of 242% and 253% compared to the baseline [model](#) (0.145 m/s). Thermally, the average indoor temperature decreased to 303.63 K in [Model 2](#) and 303.65 K in [Model 3](#), corresponding to reductions of 2.07 K and 2.05 K, respectively, relative to the [baseline](#) (305.7 K). The turbulence intensity energy in [Models 2](#) and [3](#) increased from 1.875 in the [baseline](#) to 6.394 and 6.404, representing rises of 341.01% and 341.54%. The total outlet flux increased from 0.495 in the [baseline](#) to 6.654 and 7.619, showing increases of 1,344.23% and 1,539.19%. Despite the numerical improvements in velocity and temperature, qualitative flow analysis revealed that merely increasing the number of exhaust outlets led to irregularities in the flow pattern, the formation of vortex flows, and air recirculation in the upper floors. On the second floor, particularly around the stairwell and skylight, airflow inversion occurred, resulting in elevated ambient temperatures. Therefore, this intervention alone cannot be considered a sustainable solution for effective natural ventilation.

Table 10. The Impact of Increasing Default Exhaust Vents in the Existing Condition

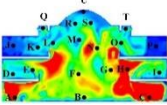
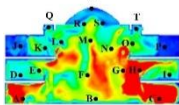
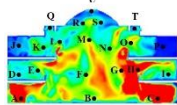
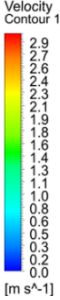
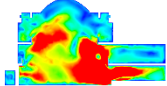
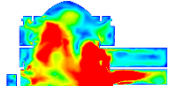
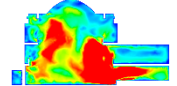
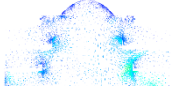
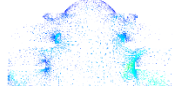
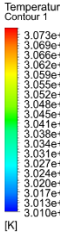
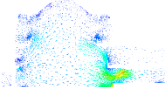
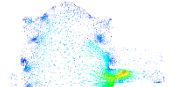
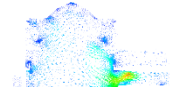


4.3. Adding Air Inlet Windows in Both Stairwells Across All Floors

In this intervention, air inlet windows were installed in both stairwells on all floors. A detailed description of this configuration is provided in [Table 11](#). Simulation results indicated that this intervention, particularly in [Models 4](#) through [6](#), had the most significant impact on enhancing natural ventilation. In [Model 6](#), the average airflow

velocity reached 1.99 m/s, representing a remarkable 1,272% increase compared to the baseline [model](#) (0.145 m/s). In [Models 4](#) and [5](#), this value was 1.895 m/s and 1.980 m/s, respectively. From a thermal standpoint, the average indoor temperature in [Model 4](#) was 302.70 K, in [Model 5](#) it was 302.53 K, and in [Model 6](#) it reached 302.51 K. These values represent reductions of 3.00 K, 3.17 K, and 3.19 K, respectively, compared to the baseline [model](#) (305.7 K).

Table 11. Addition of Air Inlet Windows in Both Stairwells Across All Floors

LIST OF MODELS		MODEL 4	MODEL 5	MODEL 6	Legened
Velocity Contour (M/s)	Section A-A				
	Section B-B				
Velocity Vector	Section A-A				
	Section B-B				
Temperature Contour (Kelvin)	Section A-A				
	Section B-B				

In [Models 4, 5, and 6](#), turbulence intensity energy increased from 1.875 in the [baseline](#) to 36.436, 39.469, and 39.456, respectively, representing rises of 1,943.25%, 2,105.01%, and 2,104.32%. The total outlet flux increased from 0.495 to 4.90, 6.95, and 6.88, showing increases of 989.89%, 1,404.04%, and 1,389.89%. Qualitative flow analysis revealed that on the ground floor, airflow became significantly more organized, and

circulation improved across most areas. On the first floor, the airflow also became more uniform, although some peripheral zones still exhibited weaknesses. On the second floor, despite relative improvements, certain surrounding areas remained in need of enhanced airflow. By reducing vortex effects and increasing flow uniformity, this intervention emerged as one of the most successful scenarios in the study.

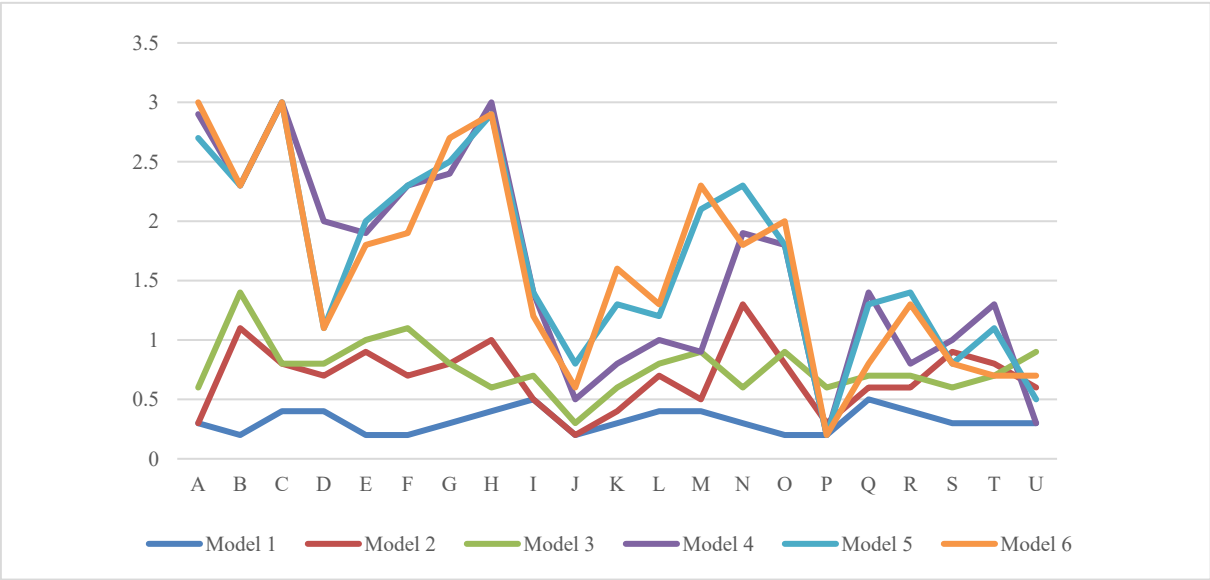


Figure 6. Average Airflow Velocity at Specified Points Across Interventions 1 to 6

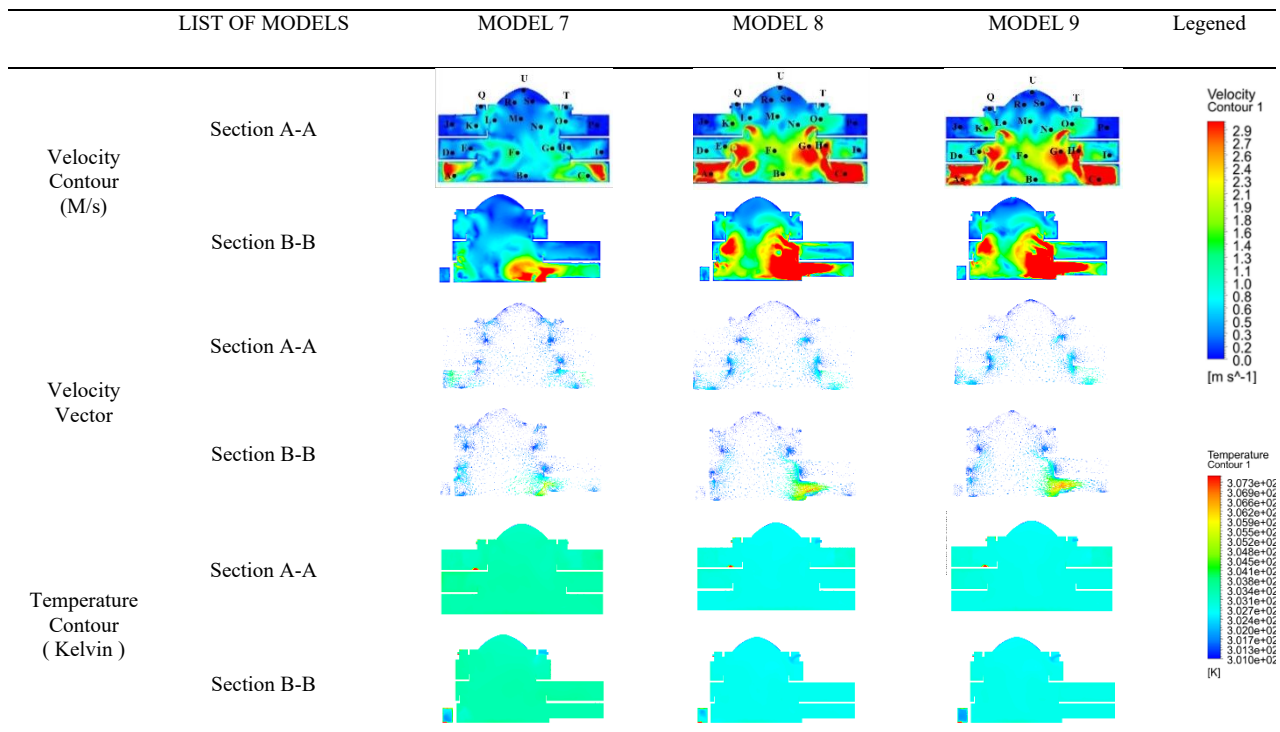
4.4. Installation of Adjustable Exhaust Vents in the Ceiling of the Second Floor
In this intervention, six exhaust vents were installed in the ceiling of the second floor to enable

effective removal of warm air. A detailed description of these vents is provided in [Table 12](#). In [Models 7 through 9](#), the average airflow velocity was recorded at 0.888 m/s, 1.668 m/s, and 1.684

m/s, respectively, indicating increases of 513%, 1,050%, and 1,061% compared to the baseline [model](#) (0.145 m/s). From a thermal perspective, the average indoor temperature in [Model 7](#) was 303.42

K, in [Model 8](#) it was 302.80 K, and in [Model 9](#) it reached 302.85 K. These values represent reductions of 2.28 K, 2.90 K, and 2.85 K, respectively, relative to the [baseline](#) (305.7 K).

Table 12. Installation of Adjustable Exhaust Vents in the Ceiling of the Second Floor



In Models [7](#), [8](#), and [9](#), turbulence intensity energy increased from 1.875 in the [baseline](#) to 20.926, 34.112, and 34.182, respectively, representing rises of 1,116.05%, 1,819.30%, and 1,823.04%. The total outlet flux increased from 0.495 to 0.536, 4.671, and 3.32, showing increases of 108.28%, 943.63%, and 714.19%. Qualitative flow analysis revealed that although airflow improved on the first and second floors, irregularities and vortex formations were still observed in certain peripheral zones, particularly on the second floor. This indicates that ceiling-mounted exhaust outlets alone are insufficient for uniformly directing airflow and require complementary inlet openings to achieve balanced ventilation.

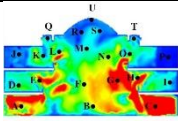
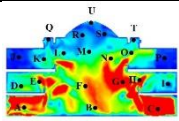
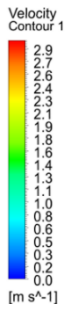
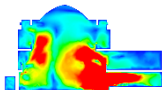
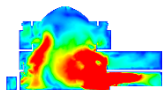
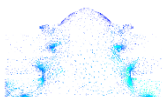
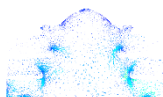
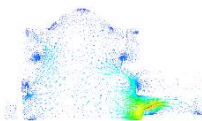
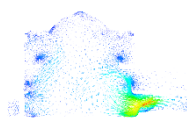
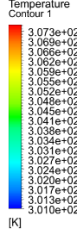
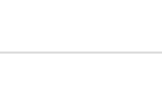
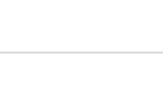
4.5. Addition of Air Inlet Windows in Both Stairwells Across All Floors Combined with Installation of Adjustable Exhaust Vents in the Ceiling of the Second Floor

In this combined intervention, air inlet windows were installed in the stairwells across all floors, along with adjustable exhaust vents in the ceiling of the second floor. A detailed description of this configuration is provided in [Table 13](#). In [Models 10](#) and [11](#), the average airflow velocity was recorded

at 1.782 m/s and 1.907 m/s, respectively, indicating increases of 1,130% and 1,215% compared to the baseline [model](#) (0.145 m/s). From a thermal perspective, the average indoor temperature in [Model 10](#) was 302.79 K, and in [Model 11](#) it was 302.57 K, corresponding to reductions of 2.91 K and 3.13 K, respectively, relative to the [baseline](#) (305.7 K). In [Models 10](#) and [11](#), turbulence intensity energy increased from 1.875 in the [baseline](#) to 35.574 and 37.834, respectively, representing rises of 1,897.28% and 2,017.81%. The total outlet flux increased from 0.495 to 5.62 and 11.82, showing increases of 1,135.35% and 2,387.87%.

Qualitative flow analysis revealed that on the ground floor, airflow was fully improved, with nearly all zones benefiting from effective ventilation. On the first floor, airflow became more uniform compared to previous models. On the second floor, although some peripheral areas still required enhancement, the overall flow was more organized than in other models. This combined intervention, by integrating the advantages of the two previous strategies, successfully directed airflow in a targeted manner and minimized vortex effects and flow inversion.

Table 13. Addition of Air Inlet Windows in Both Stairwells Across All Floors Combined with Installation of Adjustable Exhaust Vents in the Ceiling of the Second Floor

LIST OF MODELS		MODEL 10	MODEL 11	Legened
Velocity Contour (M/s)	Section A-A			
	Section B-B			
	Section A-A			
	Section B-B			
Velocity Vector	Section A-A			
	Section B-B			
	Section A-A			
	Section B-B			
Temperature Contour (Kelvin)	Section A-A			
	Section B-B			
	Section A-A			
	Section B-B			

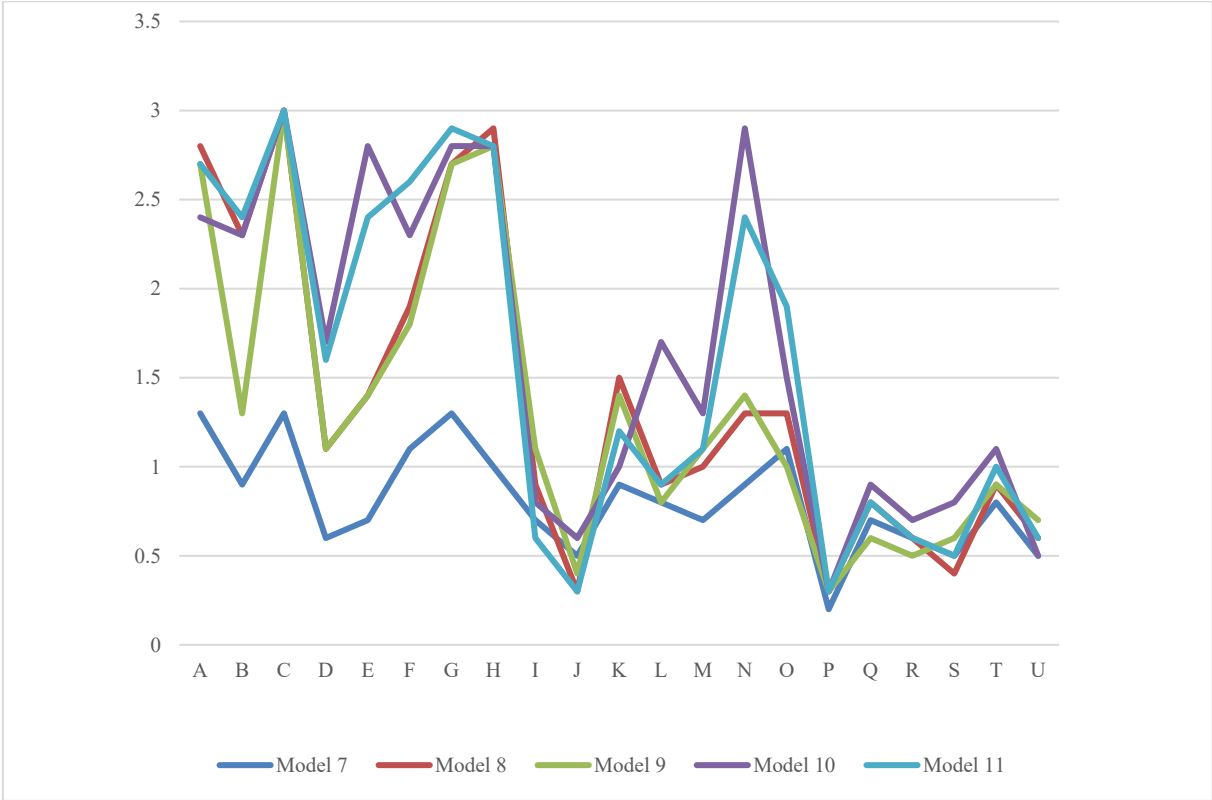
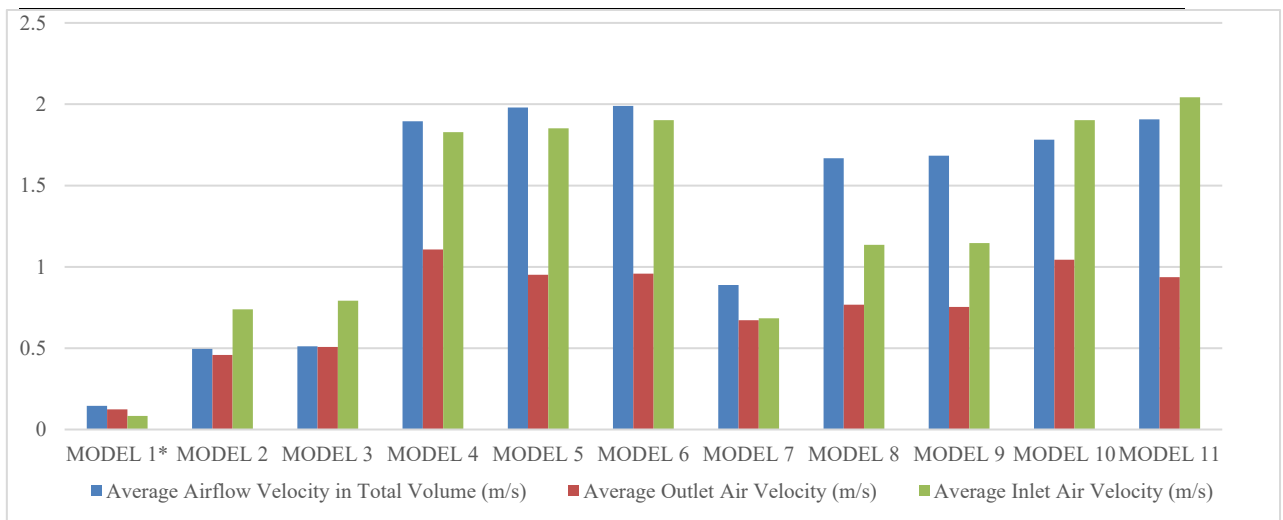
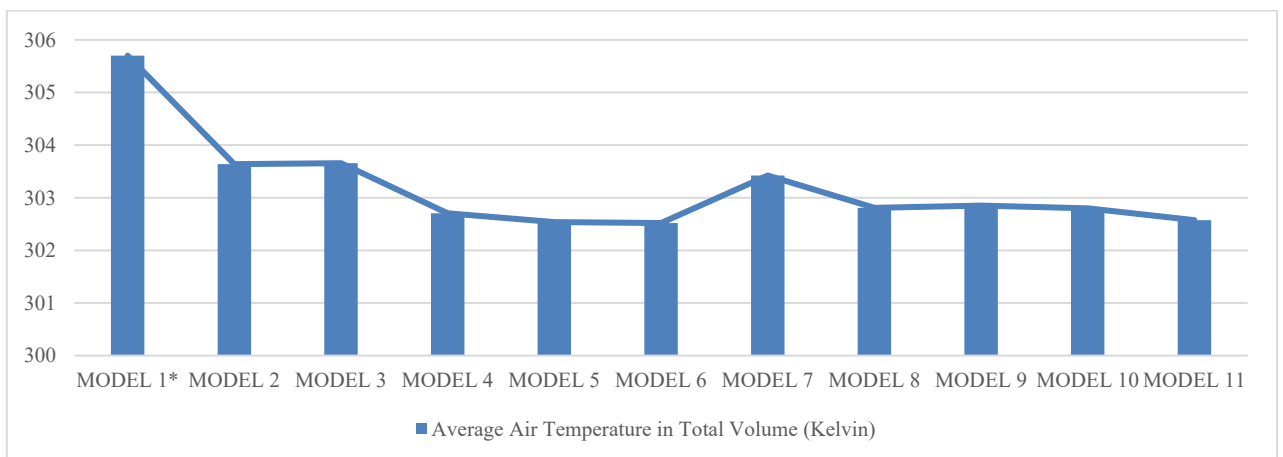


Figure 7. Average Airflow Velocity at Specified Points Across Interventions 7 to 11

The following numerical data were extracted through CFD simulation and are presented in [Table 13](#).

Table 14. Numerical Results from CFD Simulation

LIST OF MODELS	Temperature (Kelvin)	Volume			Surface Integral Velocity (M/s)		Total Outlet Fluxes
		Velocity (M/s)	Turbulence		Outlet	Inlet	
			Intensity	Kinetic Energy			
MODEL 1	305.7	0.145	1.875	0.00058	0.124	0.0839	0.495
MODEL 2	303.638	0.496	6.394	0.00701	0.458	0.739	6.654
MODEL 3	303.656	0.512	6.404	0.00713	0.508	0.792	7.619
MODEL 4	302.704	1.895	36.436	0.278	1.107	1.828	4.9
MODEL 5	302.538	1.98	39.469	0.332	0.951	1.852	6.954
MODEL 6	302.519	1.99	39.456	0.329	0.958	1.902	6.887
MODEL 7	303.423	0.888	20.926	0.099	0.672	0.684	0.536
MODEL 8	302.807	1.668	34.112	0.254	0.767	1.135	4.671
MODEL 9	302.852	1.684	34.182	0.257	0.754	1.146	3.321
MODEL 10	302.799	1.782	35.574	0.265	1.044	1.902	5.628
MODEL 11	302.575	1.907	37.834	0.303	0.937	2.043	11.826

**Figure 8. Velocity Details****Figure 9. Temperature Details**

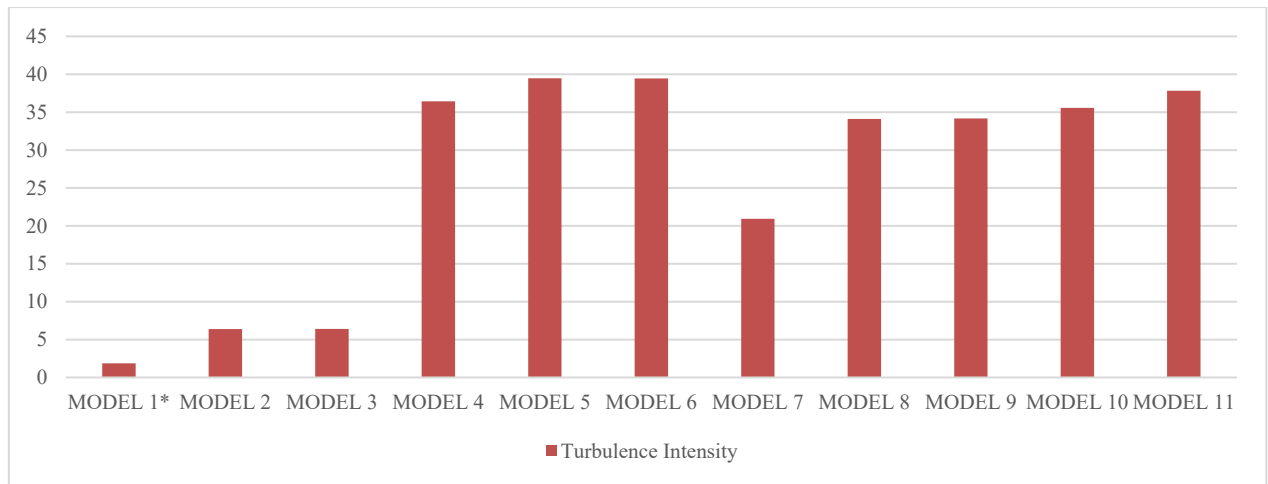


Figure 10. Turbulence Intensity Details

5. Performance Analysis of Key Interventions

Among the eleven scenarios examined, [Models 4](#), [5](#), [6](#), [10](#), and [11](#) emerged as the most effective configurations for enhancing natural ventilation in the atrium-adjacent corridors. These five models consistently outperformed the remaining interventions in both quantitative airflow performance and thermal comfort outcomes.

[Models 4-6](#), which incorporate air-inlet windows in both stairwells across all floors, produced the highest average airflow velocities: 1.895 m/s ([Model 4](#)), 1.980 m/s ([Model 5](#)), and 1.990 m/s ([Model 6](#)). Corresponding mean indoor temperatures declined to 302.70 K, 302.53 K, and 302.51 K, respectively (reductions of 3.00–3.19 K relative to the [baseline](#) of 305.70 K). Qualitative flow-field analysis confirmed organized vertical

airflow along the stairwells, a substantial reduction of vortex structures, and improved circulation on the ground and first floors, with only limited residual weaknesses on the second floor.

[Models 10](#) and [11](#), which combine stairwell inlets with adjustable ceiling exhaust vents on the second floor, achieved average velocities of 1.782 m/s and 1.907 m/s and mean temperatures of 302.79 K and 302.57 K. Although peak velocities were slightly lower than those of [Models 4-6](#), [Model 11](#) recorded the highest total outlet flux (11.82) and demonstrated superior spatial uniformity of airflow. The dual strategy minimized flow inversion and recirculation more effectively by redirecting the buoyant plume away from the atrium core toward the surrounding corridors.

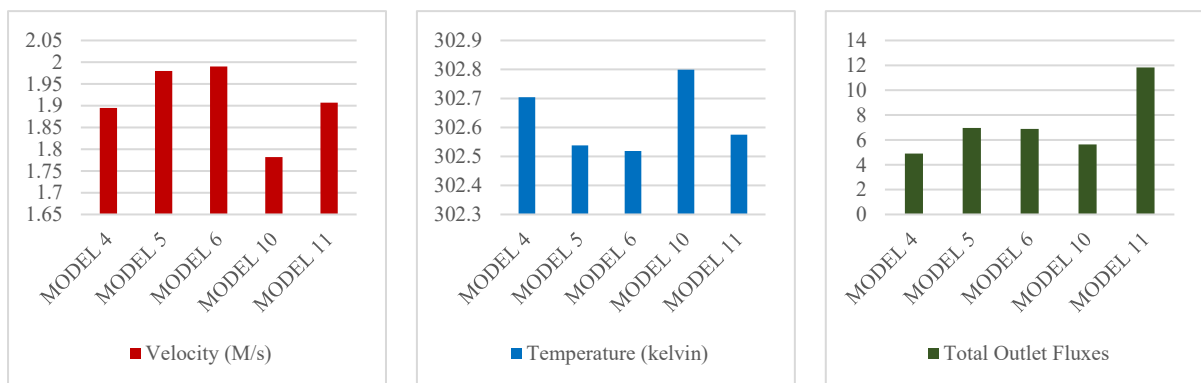


Figure 11. Comparative Chart of Numerical Data for Selected Models

Thermal comfort was evaluated using the PMV and PPD indices according to ASHRAE Standard 55 and ISO 7730, based on the simulated mean air temperatures, estimated mean radiant temperatures, local air velocities, and typical sedentary library occupancy conditions (1.0–1.2 met, 0.5 clo). The calculated values are as follows:

- [Model 4](#): PMV $\approx +0.48$, PPD ≈ 10.1 %
- [Model 5](#): PMV $\approx +0.42$, PPD ≈ 8.9 %
- [Model 6](#): PMV $\approx +0.40$, PPD ≈ 8.5 %
- [Model 10](#): PMV $\approx +0.52$, PPD ≈ 10.8 %
- [Model 11](#): PMV $\approx +0.45$, PPD ≈ 9.5 %

All five models fall within the acceptable thermal comfort zone ($-0.5 < \text{PMV} < +0.5$ and $\text{PPD} < 15$).

%). [Models 5](#) and [6](#) achieve the most favorable comfort indices, closely followed by [Model 11](#). The slightly higher air speeds in [Models 4-6](#) enhance convective cooling and contribute to the lower PMV and PPD values, while [Model 11](#) offers a more balanced spatial distribution of airflow that reduces localized discomfort in peripheral zones. Although [Models 4-6](#) deliver marginally superior average velocity, temperature reduction, and thermal comfort indices, the multi-criteria

comparison incorporating velocity magnitude, temperature, outlet flux, flow uniformity, and PMV/PPD indicates that [Model 11](#) provides the most robust overall performance for practical architectural application. In the hot, semi-humid climate of the study site, the elevated air speeds (approaching 2 m/s) are beneficial for convective cooling and remain within the adaptive comfort provisions of ASHRAE 55.

Table 15. Comparison of Airflow Vectors in Selected Models

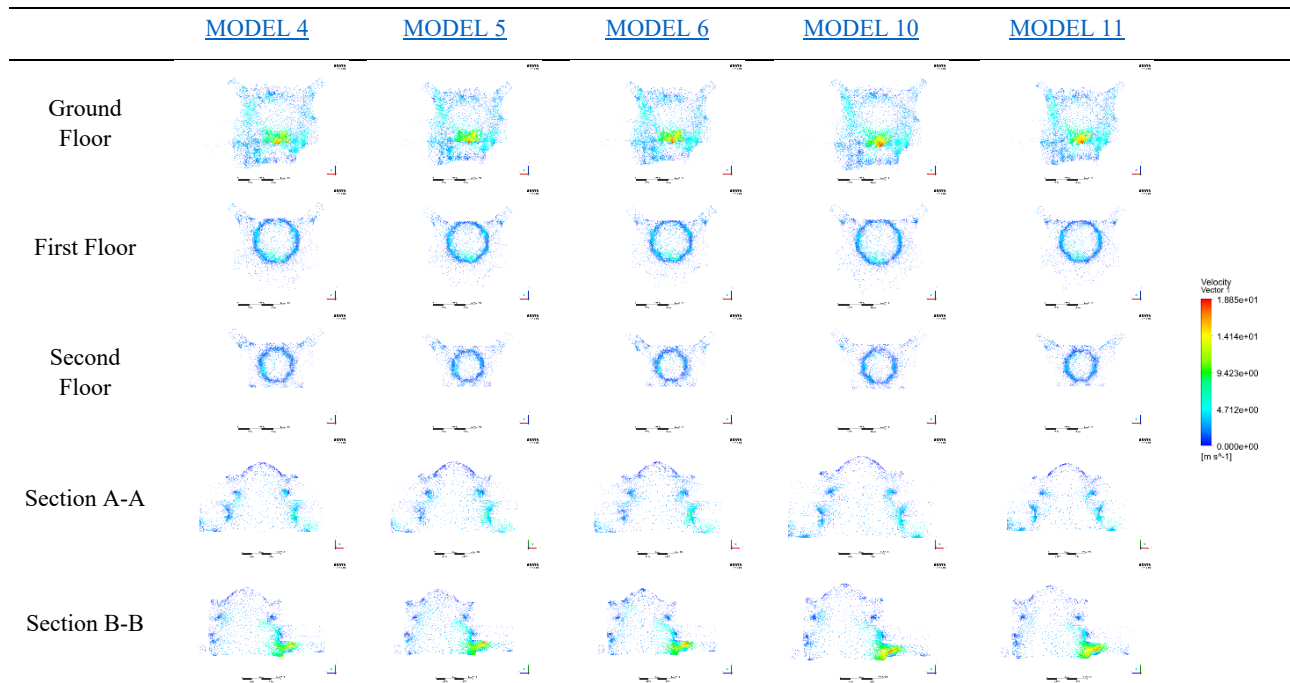


Table 16. Comparison of Numerical Data for Selected Models

LIST OF MODELS	PMV	PPD (%)	Temperature (Kelvin)	Volume			Surface Integral Velocity (M/s)		
				Velocity (M/s)	Turbulence		Outlet	Inlet	Total Outlet Fluxes
					Intensity	Kinetic Energy			
MODEL 4	0.81	18.8	302.704	1.895	36.436	0.278	1.107	1.828	4.9
MODEL 5	0.72	15.9	302.538	1.98	39.469	0.332	0.951	1.852	6.954
MODEL 6	0.71	15.6	302.519	1.99	39.456	0.329	0.958	1.902	6.887
MODEL 10	0.78	20.9	302.799	1.782	35.574	0.265	1.044	1.902	5.628
MODEL 11	0.75	16.8	302.575	1.907	37.834	0.303	0.937	2.043	11.826

Collectively, these five models confirm that the strategic placement of inlets within the continuous vertical stairwells, either alone or in combination with second-floor ceiling exhausts, establishes coherent and effective natural-ventilation

pathways. [Model 11](#), by integrating both strategies, offers a spatially balanced and architecturally coherent solution that can serve as a transferable retrofit prototype for atrium-adjacent corridors in similar climatic contexts.

6. Conclusion

Analysis of natural ventilation simulation data revealed that under the existing condition ([Model 1](#)), airflow within the building lacked both adequate velocity and circulation pattern, resulting in ineffective ventilation and air exchange. Due to the limited number of air inlets and the scattered placement of exhaust outlets, the flow pattern exhibited irregularities, inversion, and localized vortex formation, while the indoor temperature remained above the thermal comfort threshold (305.70 K). Increasing the number of exhaust outlets ([Models 2](#) and [3](#)) led to a relative improvement in airflow velocity throughout the building (0.496 m/s and 0.512 m/s, respectively). However, due to flow reversal at the exhaust points, the overall flow pattern did not improve, and the temperature on the second floor increased. Despite a general temperature reduction of approximately 2 K, these interventions failed to establish stable and uniform ventilation due to the lack of directional control. In contrast, increasing the number of air inlets and installing them within the stairwells ([Models 4](#), [5](#), and [6](#)) yielded highly positive results. In these scenarios, the average airflow velocity exceeded 1.99 m/s (an increase of over 1,270% compared to the [baseline](#)), and the indoor temperature dropped to approximately 302.51 K. These interventions generated organized airflow, reduced vortex effects, and prevented air recirculation, particularly on the ground and first floors, delivering optimal thermal and ventilation performance.

Improvements were also evident in Total Outlet Flux and Turbulence Intensity, which rose substantially compared to the [baseline](#), confirming the robustness of airflow pathways. Interventions based on installing ceiling-mounted exhaust vents on the second floor ([Models 7](#), [8](#), and [9](#)) also increased airflow velocity (up to 1.684 m/s). However, due to insufficient air inlets, flow irregularities persisted, especially on the second floor. Although the resulting temperature reduction (approximately 2.85 K) was notable, flow stability was not guaranteed.

Ultimately, the combined strategy of stairwell inlets and ceiling exhausts ([Models 10](#) and [11](#)) provided balanced and acceptable performance. In [Model 11](#), the average airflow velocity reached 1.907 m/s, and the indoor temperature dropped to 302.57 K. This configuration significantly reduced vortex flows and improved flow uniformity, offering superior ventilation conditions compared to exhaust-only models, although it remained slightly less stable than [Models 4](#) to [6](#). Importantly, PMV and PPD indices calculated according to

ASHRAE standards fell within the desirable comfort range, highlighting the effectiveness of these interventions in achieving thermal comfort without mechanical systems. The findings of this study, based on precise CFD simulations and multivariate numerical analyses, demonstrate that the spatial configuration proposed in [Model 11](#), which includes air inlet windows in stairwells across all floors and adjustable exhaust vents in the ceiling of the second floor, offers the highest efficiency in enhancing natural ventilation within atrium-adjacent corridors in warm and semi-humid climates. The stairwell, due to its vertical extension across all floors, functions similarly to a wind tower, enabling consistent and uniform airflow guidance. This feature facilitates the entry of strong, organized, and well-distributed air into the building's interior spaces.

Moreover, the installation of ceiling exhaust vents on the upper floor redirects airflow away from the atrium zone and distributes it toward surrounding areas, thereby enabling effective ventilation in peripheral spaces. This spatial arrangement not only significantly increases airflow velocity along circulation paths but also transforms the airflow pattern from turbulent and uneven to stable, organized, and aligned with the prevailing wind direction. Overall, the placement of inlet windows in stairwells, ceiling exhaust vents on the upper floor, and lateral vents around the atrium establishes a coherent, extensive, and efficient natural ventilation pattern throughout the building, enhancing thermal comfort in adjacent spaces. Specifically:

- Airflow velocity in the corridors reached 1.907 m/s, representing a 1,215% increase compared to the [baseline](#) model, indicating substantial optimization of natural suction and discharge.
- The average indoor temperature decreased to 302.57 K, which is 3.13 K cooler than the existing condition, an important factor in improving thermal comfort in warm climates.
- Vortex flows and airflow inversion phenomena observed in previous models were minimized in this configuration.
- Airflow distribution across different floors, especially the ground and first floors, became uniform and balanced, which is considered a functional advantage from an architectural design perspective.
- Thermal comfort indices (PMV and PPD), based on ASHRAE standards, fell within the desirable range without the need for mechanical ventilation systems, highlighting the model's high potential for energy savings.

Figures 8 , 9 and 10, along with Table 13, serve as empirical evidence confirming that this spatial configuration leveraging climatic design principles and precise control of air inlets and outlets successfully achieves sustainable, low-cost, and environmentally compatible ventilation. These interventions are economical and practical solutions, as they can be installed on the external envelope of buildings without adding significant structural load, involve no installation complexity, and can utilize renewable energy sources. Therefore, they provide a feasible retrofit strategy for existing buildings, enabling the improvement of natural ventilation and thermal comfort in a cost-effective manner. This model is not only technically effective but also environmentally valuable, and it can serve as a localized design prototype for architectural projects in similar climates. Future research may explore the integration of this strategy within hybrid ventilation systems, combining natural and mechanical approaches, as well as conducting a detailed assessment of energy consumption and savings potential to further validate its applicability.

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