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Computational fluid dynamics based assessment of passive vertical ventilation shaft configurations for improving indoor air quality in multi-story residential buildings

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ABSTRACT

Shared vertical ventilation shafts are commonly used to ventilate bathrooms in multi-story residential buildings, yet weak pressure gradients and unseparated airflow paths can reduce exhaust effectiveness and allow air exchange between connected bathrooms. This study used computational fluid dynamics to evaluate passive bathroom ventilation shaft configurations in a multi-story residential building in Irbid, Jordan. A conventional shared-shaft baseline was compared with alternative duct configurations, including a bottom opening, an increased duct size, roof extensions combined with bottom openings, a roof extension with dual bathroom windows, and a proposed ventilation pathway incorporating a basement extension. The simulations were performed using a building model developed in Autodesk Revit and analyzed in Autodesk CFD under a 3 m/s wind inlet condition and a zero pressure outlet. The baseline shared shaft produced weak airflow, with a readable velocity magnitude of 0.076127 m/s over a measured region of 53,718.3 cm². The proposed three-channel configuration increased velocity magnitude to 0.147702 m/s over a comparable region of 52,890.2 cm², representing an approximately 94.0% improvement. Vector-field interpretation showed that the proposed configuration produced a clearer directional pathway from lower fresh-air entry through side supply channels and bathroom openings toward the central exhaust shaft and outdoor discharge. The findings indicate that separating supply and exhaust paths is more effective than relying only on shaft enlargement or roof extension. The proposed configuration can support low-energy ventilation design by reducing stagnation and lowering the likelihood of inter-bathroom air exchange in dense residential buildings.

Keywords: computational fluid dynamics, passive ventilation, indoor air quality, vertical ventilation shaft, residential buildings, airflow direction, Irbid.

INTRODUCTION

Indoor environmental quality is a major determinant of comfort, health, and well-being in residential buildings, and ventilation is one of its most influential physical components because it governs the dilution, removal, and directional movement of indoor pollutants, moisture, odors, and airborne particles (Al Horr et al., 2016; Mannan and Al-Ghamdi, 2021). Inadequate residential ventilation can increase the accumulation of indoor contaminants and reduce perceived air freshness, particularly in enclosed or semi-enclosed spaces where pollutant generation is frequent and exhaust pathways are weak or unstable (Mannan and Al-Ghamdi, 2021; Guyot et al., 2018). Residential ventilation also has direct implications for health-related indoor air quality and energy demand because ventilation systems must balance pollutant removal with low-energy operation (Belias and Licina, 2024). These concerns are especially relevant in multi-story residential buildings, where airflow is influenced by wind pressure, buoyancy forces, envelope leakage, internal openings, vertical shafts, and pressure differences between connected spaces (Lai et al., 2020; Hajdukiewicz et al., 2024).

Bathrooms are critical spaces in residential ventilation design because they generate moisture, odors, and short-term airborne contaminants that require effective exhaust pathways (Mannan and Al-Ghamdi, 2021; Kumar et al., 2022). In many multi-story apartment buildings, bathroom ventilation depends on vertical shafts that connect several bathrooms through windows or wall openings. When pressure differentials are weak or poorly controlled, these shared air pathways can create unintended airflow interactions between connected spaces (Lai et al., 2020; Miller et al., 2026). Under low-velocity or unstable pressure conditions, shared vertical ducts may experience stagnant airflow, recirculation, or reverse-flow behavior, reducing passive exhaust effectiveness and increasing the possibility of odor and pollutant transfer between bathrooms (Hajdukiewicz et al., 2024; Miller et al., 2026). Evidence from a residential outbreak investigation also showed that bathroom vertical ventilation ducts can act as plausible pathways for aerosol movement between vertically connected apartments when airflow direction and pressure balance are unfavorable (Miller et al., 2026). Although the present study does not measure infection transmission or pathogen survival, this evidence supports the need to evaluate airflow direction, pressure behavior, and inter-bathroom air exchange in shared residential ventilation shafts (Miller et al., 2026; Hajdukiewicz et al., 2024).

Passive ventilation is an important environmental engineering strategy because it can improve indoor air quality while reducing dependence on energy-intensive mechanical ventilation systems (Belias & Licina, 2024; Plazas & de Tejada, 2024). Natural ventilation is driven mainly by wind pressure and buoyancy forces, but its performance depends strongly on opening position, shaft geometry, wind direction, surrounding obstruction, and the pressure relationship between inlet and outlet zones (Jiang et al., 2023; Hajdukiewicz et al., 2024). In residential buildings, natural ventilation can support pollutant dilution and thermal regulation, but its effectiveness is highly context-dependent because local weather, building geometry, and occupant-controlled openings influence airflow rates and direction (Lai et al., 2020; Plazas & de Tejada, 2024). Therefore, passive bathroom ventilation shafts should be evaluated as airflow systems in which duct dimensions, inlet and outlet locations, roof extension, basement connection, and pressure differentials jointly determine ventilation performance (Hajdukiewicz et al., 2024; Zhang et al., 2020).

Computational fluid dynamics is widely used to analyze natural ventilation and indoor airflow because it can visualize velocity fields, pressure distribution, recirculation zones, and flow paths within complex building geometries (Hajdukiewicz et al., 2024; Zhang et al., 2020). CFD is particularly useful for comparing ventilation design alternatives before physical implementation, especially when the research question involves three-dimensional flow behavior, wind-driven pressure effects, and local recirculation patterns that are difficult to capture using simplified airflow models (Hajdukiewicz et al., 2024). However, credible CFD-based ventilation research requires transparent reporting of model geometry, computational domain, mesh settings, turbulence model, boundary conditions, convergence criteria, and sensitivity or verification procedures (Hajdukiewicz et al., 2024; Zhang et al., 2020).

The case of Irbid, Jordan, provides a relevant context for examining passive ventilation in residential buildings because Greater Irbid Municipality has experienced substantial urban expansion and increasing built-up development in recent decades (Awawdeh et al., 2024). Urban expansion in Greater Irbid Municipality increased approximately ninefold between 1967 and 2020, indicating major transformation in the spatial structure of the city and its residential environment (Awawdeh et al., 2024). Irbid has also been studied as a hot-summer Mediterranean urban context in which building form, urban block configuration, and environmental performance are important design concerns (Khraiwesh and Genovese, 2023). These conditions make Irbid a suitable setting for investigating passive, low-energy ventilation strategies in multi-story residential buildings.

Despite the growing use of simulation to evaluate building environmental performance, limited research has specifically examined shared bathroom ventilation shafts in multi-story residential buildings in Irbid. The present study addresses this gap by evaluating airflow behavior in a typical multi-story residential building where bathrooms are connected to a shared vertical ventilation duct. The study compares a conventional baseline shaft with a sequence of alternative configurations and a proposed separated three-channel duct system. The aim is to identify a passive ventilation configuration that improves airflow direction, reduces stagnation, and lowers the likelihood of inter-bathroom air exchange.

Figure 1 presents the conceptual framework of the study. The framework links the residential context of multi-story buildings in Irbid with the baseline problem of shared bathroom ventilation ducts, the pressure-driven airflow mechanisms investigated through CFD, and the expected indoor environmental risk of stagnation and inter-bathroom transfer. It then organizes the tested design scenarios and the proposed three-channel configuration, which separates side fresh-air supply channels from a central exhaust channel. The framework also identifies the CFD performance indicators used in the comparative assessment, including velocity, pressure, reverse flow, recirculation, and stagnant zones, and connects these indicators to the study's expected contribution: passive, low-energy ventilation recommendations for improving bathroom air exchange and indoor air quality in Irbid residential buildings.

MATERIALS AND METHODOLOGY

Study design

This study adopted a simulation-based environmental engineering approach to evaluate the airflow performance of passive vertical bathroom ventilation shafts in multi-story residential buildings in Irbid, Jordan. The methodological framework is shown in Figure 2. The workflow began with defining the residential shaft problem, modeling the building and duct geometry, exporting the model to Autodesk CFD, defining the computational air domain and boundary conditions, running comparative simulation cases, and interpreting velocity fields and flow direction.

The study was structured around three stages. First, a baseline residential ventilation shaft was modeled to represent a common arrangement in which four bathrooms are connected to a shared vertical duct through window openings. Second, alternative shaft configurations were simulated to examine the effect of duct size, roof extension, bottom opening, and basement extension on airflow behavior. Third, a proposed separated duct system was assessed. This system divided the shaft into three vertical channels, with two side channels functioning as fresh-air supply paths and one central channel functioning as the exhaust path.

Study context and model configuration

The study was conducted in the context of multi-story residential buildings in Irbid, Jordan. The selected configuration represents a residential condition in which bathrooms are positioned around a shared vertical service duct. Figure 3 presents the field and geometric references used to frame the model, including existing shaft conditions, the vertical section, and the plan relationship between the four bathrooms and the central duct.

The baseline condition was defined as a shared vertical bathroom shaft serving four bathrooms. Each bathroom was connected to the duct through a window opening, and the bathroom doors were assumed closed to isolate the performance of the shaft and bathroom openings. Under this conservative condition, airflow depends

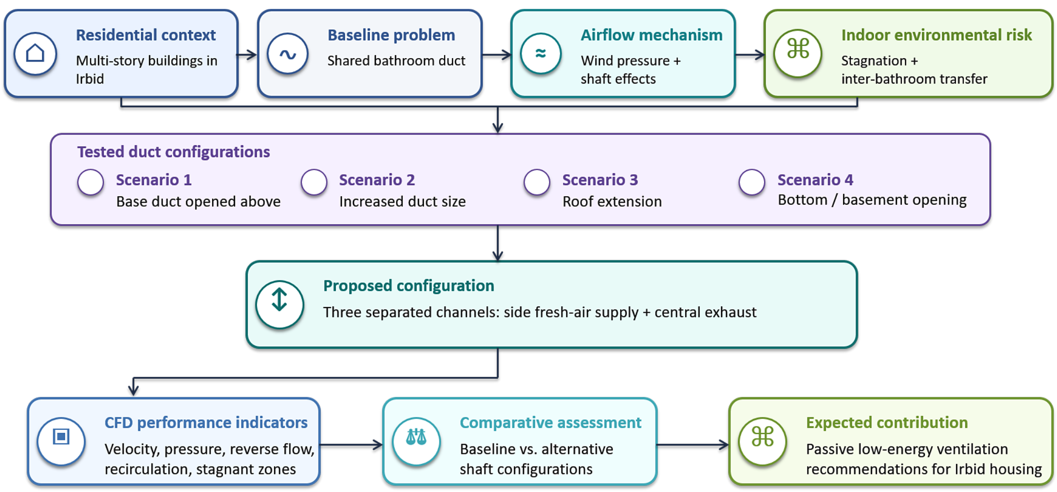

Figure 1. Conceptual framework linking residential shaft configuration, pressure-driven airflow, CFD assessment, and indoor air-quality improvement

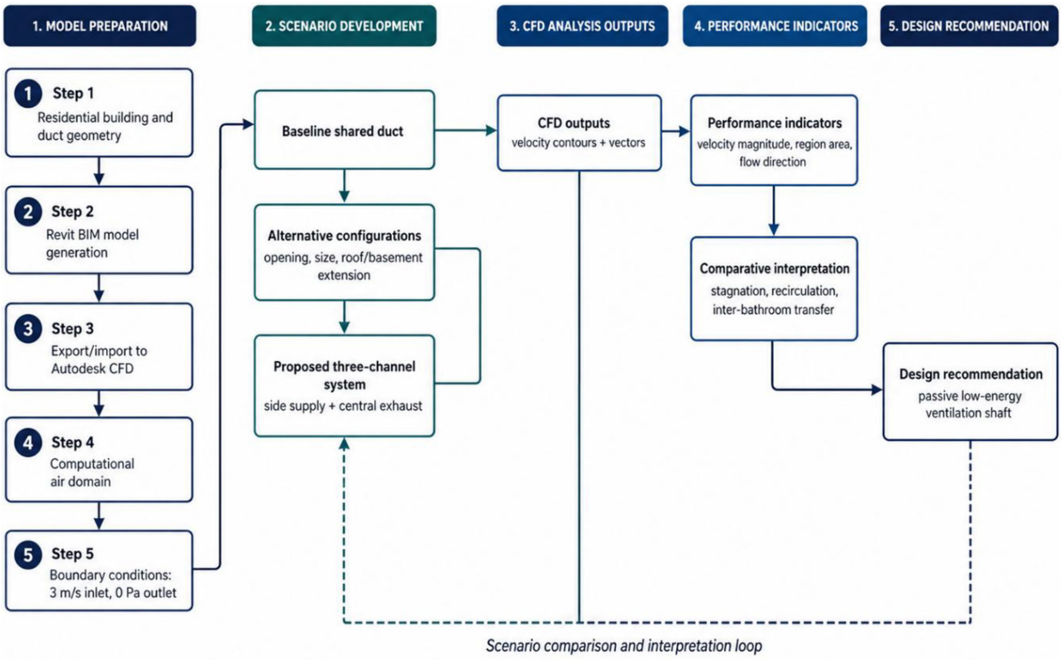

Figure 2. Simulation and CFD analysis framework for the passive bathroom ventilation-shaft study

mainly on pressure-driven movement through the shaft rather than additional exchange through doors or internal leakage paths.

Simulation cases

The CFD study compared five main duct-configuration scenarios and a proposed separated-channel solution. The cases were developed to isolate the influence of shaft opening condition, duct size, roof extension, bottom connection, basement extension, and channel separation on ventilation performance. Figure 4 presents the CFD scenario images extracted from the simulation file, while Table 1 summarizes the purpose of each case.

Model development and boundary conditions

The residential building and vertical ventilation-shaft configurations were first modeled in

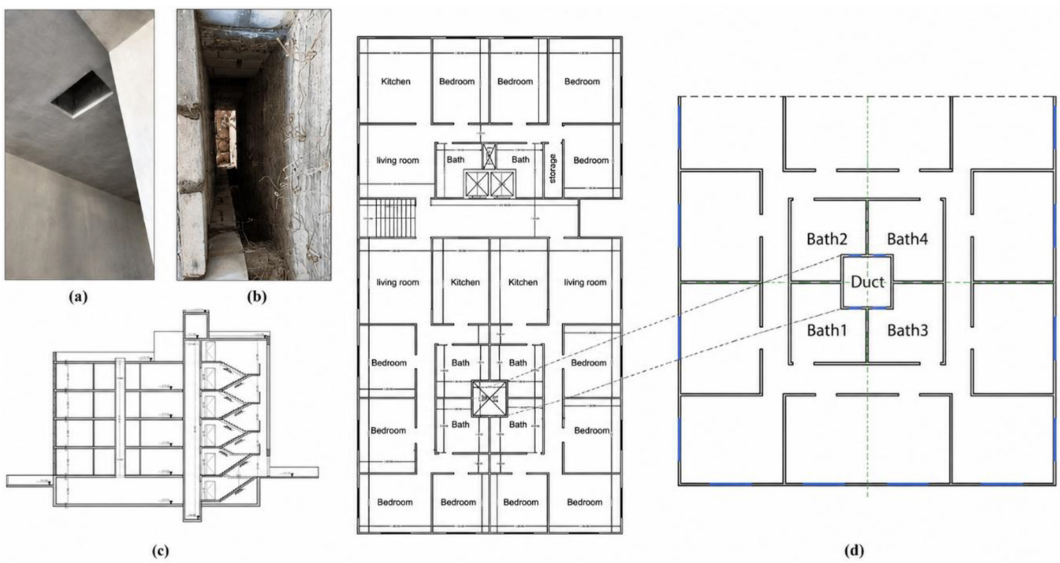

Figure 3. Field and geometric references for the studied ventilation shaft: (a) existing duct opening, (b) shaft view, (c) building section with vertical duct, and (d) plan of four bathrooms connected to a shared duct

Table 1. Simulated ventilation-shaft configurations

Case	Configuration	Design purpose
a	Baseline shared duct	Reference condition with four bathrooms connected to one shared shaft volume opened from above
b	Base duct opened from the bottom	Tests whether the bottom opening improves discharge from the shaft
c	Increased duct size in x and y directions	Tests whether enlarging the duct cross-section improves airflow capacity
d	Duct extended above roof level, H = 3.00 m, opened from the bottom and configured with dual bathroom windows	Tests whether increasing roof-level extension with lower air entry and dual bathroom inlet–outlet windows strengthens exhaust potential
e	Duct extended above roof level, H = 1.75 m, and opened from the bottom	Tests the combined effect of upper extension and lower air entry
f	Proposed three-channel system	Separates fresh-air supply through side channels from exhaust through the central shaft

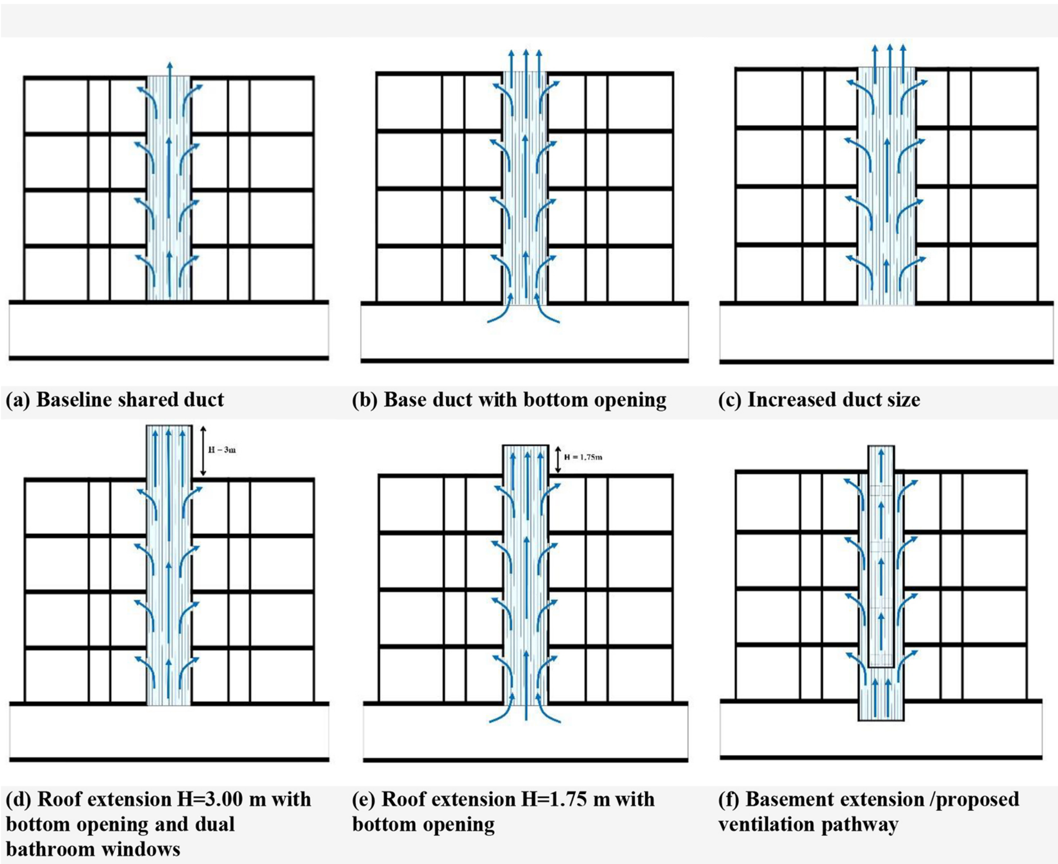

Figure 4. CFD scenario for the tested duct configurations: (a) baseline shared duct, (b) base duct with bottom opening, (c) increased duct size, (d) roof extension H = 3.00 m with bottom opening and dual bathroom windows, (e) roof extension H = 1.75 m with bottom opening, and (f) basement extension/proposed ventilation pathway

Autodesk Revit and then exported to Autodesk CFD for airflow simulation. The model included the main building geometry, four residential floors above a basement level, bathroom spaces, duct walls, roof extensions, basement connection where applicable, and the proposed separated-channel ventilation pathway. A computational air domain was generated around the building to represent the external airflow field and to minimize boundary interference with the simulated ventilation behavior. As shown in Figure 5, the domain was defined with an upstream distance of 5w from the wind-facing side of the building and a top clearance of 3h above the roof level, where w and h represent the building width and height, respectively.

Air was assigned as the fluid material within the computational domain, while the building envelope and duct components, including walls, floors, roof, shaft partitions, and basement-related duct elements, were assigned as solid materials. The wind-facing surface of the computational domain was specified as a velocity inlet with a wind speed of 3 m/s, representing a moderate wind condition for Irbid. The opposite downstream surface was defined as a pressure outlet with a zero static gauge pressure. The building and duct surfaces were treated as solid wall boundaries, while the top and lateral surfaces of the computational domain were assigned slip or symmetry boundary conditions to reduce artificial boundary effects. These boundary conditions and domain settings were applied consistently to all simulated cases so that the observed differences in airflow behavior could be attributed to changes in duct configuration rather than to variations in external wind input or computational-domain setup.

Performance indicators

The airflow performance of each configuration was evaluated using quantitative and visual CFD outputs. The main indicators were velocity magnitude, measured region area, airflow direction, local recirculation, and the visual continuity of flow paths from inlet toward exhaust. Exact readable numerical outputs were available for the baseline and final proposed configurations, while the intermediate cases were interpreted qualitatively from the visible vector and contour fields.

The baseline and proposed cases were compared quantitatively using the velocity magnitude and measured rectangular region reported in the CFD output images. The percentage increase in velocity magnitude was calculated by subtracting the baseline velocity from the proposed velocity, dividing the difference by the baseline velocity, and multiplying by 100. This comparison provided a direct indicator of airflow-strength improvement between the conventional and proposed systems (Table 2).

RESULTS

Overview of airflow behavior across configurations

The CFD simulations showed that shaft performance depended on the organization of airflow paths rather than on duct presence alone. The baseline shared duct produced weak and irregular airflow. The intermediate cases demonstrated that the bottom opening,, duct enlargement, roof extension, and lower/basement air

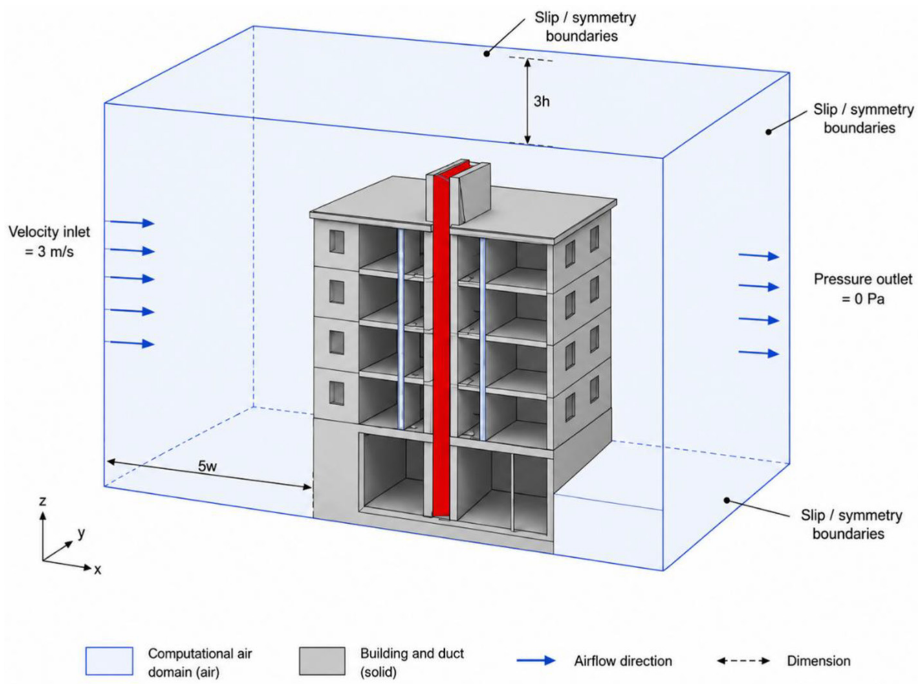

Figure 5. Computational air domain and CFD boundary conditions used for the ventilation-shaft simulations

Table 2. Performance indicators used in the CFD interpretation

Indicator	Unit	Interpretation
Velocity magnitude	m/s	Strength of air movement within the measured region
Measured region area	cm²	Area over which the velocity output was calculated
Vector direction	Qualitative	Direction of airflow relative to bathroom openings and exhaust path
Recirculation/stagnation	Qualitative	Presence of low-velocity or locally circulating air patterns
Flow-path continuity	Qualitative	Whether air follows a continuous path from supply to exhaust

entry improved certain aspects of airflow behavior but did not fully remove the limitation of a shared air volume. The proposed three-channel system produced the clearest directional pattern because it separated fresh-air supply from contaminated-air exhaust.

Figure 6 shows the six scenario images extracted from the simulation file. The vector fields indicate that configurations with lower or basement air entry supported more coherent upward movement than the baseline condition. However, the most organized pattern appeared in the proposed system, where fresh air was supplied through side channels and exhausted through the central shaft.

Baseline shared-shaft condition

The baseline case represented the conventional condition in which four bathrooms were connected to a single shared vertical duct. The CFD image showed weak and poorly organized airflow inside the duct and around the bathroom-duct interfaces. The measured velocity magnitude in the baseline case was 0.076127 m/s over a measured region area of 53,718.3 cm². This low value confirms that the baseline shaft provided weak air movement under the simulated condition.

The vector pattern suggested that the baseline design is vulnerable to local recirculation and air mixing because there is no physical separation between incoming air, exhausted air, and the air volumes connected to different bathrooms. Therefore, the baseline configuration has a higher potential for odor and pollutant transfer between bathrooms than the proposed separated system.

Performance of the proposed three-channel system

The final proposed configuration divided the vertical shaft into three separate channels. The two side channels functioned as fresh-air supply paths, while the central channel functioned as the exhaust path. Each bathroom was connected to both a supply opening and an exhaust opening. This arrangement changed the ventilation behavior from a shared, uncontrolled shaft into a directional airflow system.

The measured velocity magnitude in the proposed system was 0.147702 m/s over a measured region area of 52,890.2 cm². Compared with the baseline velocity magnitude of 0.076127 m/s, the proposed configuration increased velocity magnitude by approximately 94.0% (Table 3 and Figure 7). This means that the proposed system generated almost 1.94 times the airflow velocity of the conventional shared duct. The measured region area changed only slightly, indicating that the improvement is mainly associated with the reorganization of airflow paths rather than with a larger measurement area.

Airflow direction and effectiveness

The airflow direction in the baseline case was weak and poorly controlled. Because all bathrooms connect to the same duct volume, the baseline configuration does not provide a dedicated pathway that forces air to move from each bathroom directly to the outside. This makes the system susceptible to stagnant zones, local recirculation, and possible air exchange between bathrooms, particularly under low-pressure-difference conditions.

In contrast, the proposed three-channel system showed a more effective airflow direction. The visible vector pattern indicated that air was supplied through the side channels and exhausted through the central channel. This separation reduces the likelihood that air from one bathroom will enter another bathroom because the air no longer relies on one shared shaft volume. Instead, the proposed system creates controlled movement from supply inlet

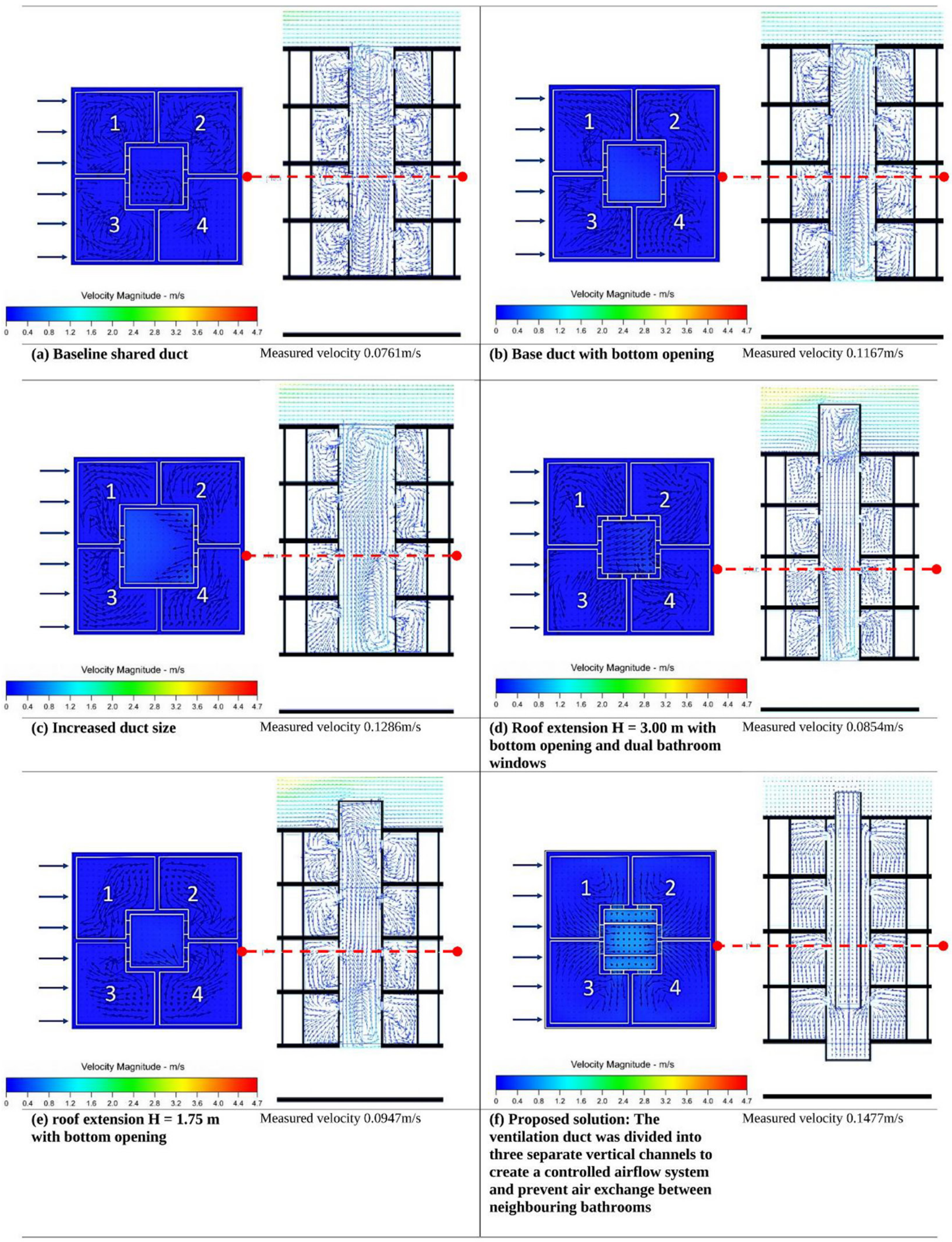

Figure 6. Progression of plan-view and section-view CFD results for the tested ventilation-shaft configurations: (a) baseline shared duct, (b) base duct with bottom opening, (c) increased duct size in the x and y directions, (d) roof extension H = 3.00 m with bottom opening and dual bathroom windows, (e) roof extension H = 1.75 m with bottom opening, and (f) proposed three-channel ventilation system

to bathroom space, then from bathroom outlet to central exhaust shaft, and finally toward the outside of the building.

The results therefore indicate that the proposed system is more effective than the baseline in three ways. First, it increases air velocity inside the duct system. Second, it creates a clearer airflow direction from inlet to exhaust. Third, it reduces the potential for uncontrolled air mixing between bathrooms by separating fresh-air supply from contaminated-air exhaust. However, the results should be interpreted as evidence of reduced likelihood of inter-bathroom air transfer rather than complete prevention, because no tracer-gas or pollutant-concentration simulation was conducted.

Table 3. Quantitative comparison between the baseline and proposed ventilation-shaft configurations

Configuration	Measured region area (cm²)	Velocity magnitude (m/s)	Change compared with baseline	Interpretation
Baseline shared duct	53,718.3	0.076127	Reference	Weak airflow; higher potential for stagnation and air mixing
Proposed three-channel system	52,890.2	0.147702	+94.0%	Stronger directional airflow; reduced likelihood of inter-bathroom transfer

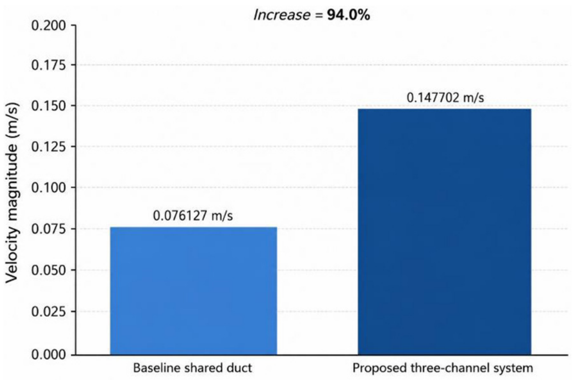

Figure 7. Comparison of velocity magnitude between the baseline shared duct and the proposed three-channel ventilation system

DISCUSSION

Interpretation of airflow performance

The baseline result is important because residential ventilation systems are expected to dilute and remove indoor pollutants while maintaining acceptable indoor air quality and limiting unnecessary energy use (Guyot et al., 2018; Mannan and Al-Ghamdi, 2021). Bathrooms are moisture- and odor-generating spaces, and ineffective air removal can increase the persistence of humidity, odors, and other indoor contaminants in residential buildings (Mannan and Al-Ghamdi, 2021; Kumar et al., 2022). In the baseline configuration, the four bathrooms were connected to one common vertical duct volume, which means that the system did not separate fresh-air supply from contaminated-air exhaust.

The baseline result supports the argument that the presence of a vertical shaft alone does not guarantee effective passive ventilation. Natural ventilation depends on the pressure relationship between inlet and outlet openings, the geometry of the flow path, and the interaction between wind-driven and buoyancy-driven forces (Jiang et al., 2023; Hajdukiewicz et al., 2024). When a shaft lacks a clear inlet-outlet sequence, air may circulate locally instead of moving continuously toward the outdoor discharge point (Zhang et al., 2020; Hajdukiewicz et al., 2024). Similar concerns have been reported in multi-family residential buildings, where bathroom ventilation ducts can act as inter-unit air-transfer pathways under unfavorable pressure conditions (Miller et al., 2026).

Effectiveness of partial and integrated duct modifications

The intermediate duct modifications provide useful evidence that partial changes to the shaft can improve some aspects of airflow behavior but cannot fully resolve the problem of shared air mixing. Opening the duct from above increases the possibility of discharge to the exterior, but it does not necessarily create a controlled ventilation path between each bathroom and the exhaust outlet. Natural ventilation studies show that the effectiveness of an opening depends not only on its presence but also on its position, pressure coefficient, wind direction, and relationship to other openings in the airflow network (Jiang et al., 2023; Zhang et al., 2020).

Increasing the duct size in the x and y directions also has limited value as an isolated intervention. A larger duct cross-section can reduce local resistance and increase the available volume for airflow, but ventilation effectiveness still depends on the pressure-driven organization of the flow path (Jiang et al., 2023; Hajdukiewicz et al., 2024). If pressure differences remain weak or if air is not guided from a defined inlet toward a defined outlet, a larger shaft may still contain low-velocity zones (Zhang et al., 2020).

The proposed three-channel system produced the strongest airflow performance because it changed the shaft from a common air void into a separated supply-and-exhaust system. Separation between air-supply and air-exhaust pathways is important because ventilation effectiveness depends on moving air from clean or less contaminated zones toward contaminated zones and then toward exhaust, rather than allowing uncontrolled mixing (Guyot et al., 2018; Mannan and Al-Ghamdi, 2021). The increase in velocity magnitude from 0.076127 m/s to 0.147702 m/s supports the interpretation that the proposed system substantially strengthened the ventilation pathway.

Design implications

The results suggest that passive bathroom ventilation shafts should be designed as directional airflow systems rather than as unpartitioned service voids. Natural ventilation performance depends on the relationship between inlet and outlet openings, pressure differences, and the continuity of airflow pathways (Jiang et al., 2023; Hajdukiewicz et al., 2024). The proposed configuration shows that separating fresh-air supply from contaminated-air exhaust can strengthen velocity magnitude and improve airflow direction.

The findings also suggest that minimum duct area alone is not sufficient as a design criterion for passive bathroom ventilation. Performance-based ventilation approaches emphasize that ventilation systems should be evaluated according to indoor air-quality and energy outcomes rather than only prescriptive dimensional requirements (Guyot et al., 2019). In multi-story residential bathrooms, performance criteria should include airflow direction, velocity magnitude, reverse-flow risk, separation between supply and exhaust, and evidence that air is discharged outdoors rather than redistributed to adjacent spaces.

Limitations

The study provides comparative evidence that the proposed three-channel system improves airflow behavior, but the interpretation has limitations. The available readable numerical outputs were limited to the baseline and proposed configurations, while the intermediate cases were interpreted qualitatively from visible CFD vector and contour patterns. CFD results are sensitive to model geometry, boundary conditions, mesh resolution, turbulence-model choice, and convergence criteria (Hajdukiewicz et al., 2024; Zhang et al., 2020).

The study assessed velocity magnitude and airflow direction but did not simulate tracer-gas concentration, odor decay, contaminant transport, or humidity removal. Ventilation studies often use tracer gas or scalar-transport methods when the objective is to quantify contaminant removal or inter-zone pollutant transfer (Lai et al., 2020; Miller et al., 2026). Therefore, the present findings support the conclusion that the proposed system reduces the likelihood of inter-bathroom air exchange, but they do not prove complete prevention of pollutant transfer. Future work should test multiple wind directions and validate the CFD results using field measurements, pressure measurements, or tracer-gas testing.

CONCLUSIONS

This study evaluated passive vertical bathroom ventilation shaft configurations in a multi-story residential building in Irbid using computational fluid dynamics. The results show that the conventional shared-shaft arrangement produced weak and poorly organized airflow, with a measured velocity magnitude of 0.076127 m/s. This finding indicates that a common unpartitioned shaft can function as a low-velocity shared air volume rather than a controlled exhaust pathway.

The intermediate design modifications showed that opening the duct from above, increasing duct size, extending the duct above roof level, and introducing lower or basement air entry can improve aspects of airflow behavior. However, these strategies do not fully solve the main limitation of the baseline configuration because the bathrooms remain connected to one common air volume.

The proposed three-channel ventilation shaft achieved the strongest airflow performance. It increased the measured velocity magnitude to 0.147702 m/s, representing an approximately 94.0% improvement compared with the baseline case. The proposed configuration also produced a clearer airflow direction by introducing fresh air through side channels and exhausting bathroom air through a central shaft. This separation reduced the likelihood of uncontrolled air transfer between bathrooms under the simulated boundary conditions.

The study concludes that separating fresh-air supply from contaminated-air exhaust is a more effective passive ventilation strategy than relying solely on a larger or taller shared duct. The proposed three-channel shaft system provides a low-energy design approach for improving bathroom ventilation, reducing stagnant airflow, and supporting healthier indoor environmental quality in multi-story residential buildings.

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