

Optimizing window design for natural ventilation in high-rise social housing toward livable space

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Abstract. The livability of compact high-rise social housing in tropical climates depends heavily on thermal comfort, particularly in units relying solely on natural ventilation. This study investigates how window design—specifically Openable Window Ratio (OWR) and Window Height Shading (WHS)—affects thermal comfort in naturally ventilated units of a public rental apartment in Jakarta. Using validated CFD simulations calibrated with real climate data at peak discomfort hours (13:00), thirty-six window variants were tested across three building levels (floors 4, 10, and 16). Thermal comfort was evaluated using the ASHRAE 55 standard with PMV, PPD, and thermal sensation metrics. Results show that a window design with 90% OWR and 100% WHS consistently improves thermal comfort across all heights, reducing PPD from over 80% to under 30%. Notably, even with single-sided ventilation—a common limitation in such housing—specific window configurations successfully shifted indoor conditions toward acceptable comfort thresholds. These findings provide actionable design guidelines for enhancing livable space in tropical high-rise social housing.

1 Introduction

Global climate change has increasingly intensified thermal stress in dense urban areas, particularly within tropical megacities such as Jakarta. As temperatures continue to rise, low-income vertical housing—specifically government-subsidized public rental flats (Rumah Susun Sederhana Sewa or Rusunawa)—faces significant challenges in maintaining thermal comfort. These developments typically lack mechanical cooling systems, relying entirely on passive solutions such as natural ventilation. In locations like Daan Mogot, where the Rusun Lokbin Rawa Buaya complex is situated, daily temperatures often surpass 32°C with high humidity and low wind speeds, leading to persistent indoor heat retention and inadequate airflow [1]

In hot-humid tropical environments, natural ventilation is a critical strategy for promoting indoor thermal comfort without relying on energy-intensive HVAC systems. Its success, however, is closely tied to the design geometry and operability of openings. Nugroho [2] stresses that an operable window area of at least 10% is essential for achieving effective

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airflow—whether cross or single-sided. Moreover, vertical shading devices such as overhangs and louvres not only reduce solar heat gain but also influence airflow distribution, especially in buildings with single-sided openings [3]. These considerations are central to creating livable, resilient environments in dense housing contexts.

A major issue in many existing Rusunawa units is the limited operability of their window systems, which often consist of fixed glass and small boventlight panels. This results in a low Openable Window Ratio (OWR) and the absence of solar shading features, amplifying solar heat gain and restricting indoor air exchange. Although shading elements are traditionally employed for solar control, their role in facilitating ventilation—especially in single-sided layouts—remains underexplored. Omrani [4] observes that single-sided ventilation typically contributes only 10–30% toward thermal comfort improvement, with effectiveness highly dependent on wind orientation, opening dimensions, and facade design. Nonetheless, he also notes that architectural enhancements such as balconies, overhangs, and wind deflectors may optimize airflow under constrained conditions.

Despite increased attention to adaptive passive design, relatively few studies have explored how window operability and vertical shading depth interact to influence indoor thermal conditions in compact, non-HVAC high-rise dwellings. Much of the literature to date has focused on mixed-mode or office buildings [5], leaving a knowledge gap regarding fully naturally ventilated low-income housing in tropical urban settings.

Prajongsan [5] also demonstrates that increasing the openable window area can significantly enhance air velocity and, in turn, improve thermal comfort indices such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). Computational Fluid Dynamics (CFD) simulations offer a robust framework to quantify how window geometry and shading depth influence indoor thermal conditions by modeling variables such as airspeed, operative temperature, and radiant exposure [4]

Aligned with the ISLIVAS 2025 theme of “Regenerative Livable Built Environment,” this study seeks to optimize window design as a regenerative intervention that enhances indoor livability in high-rise tropical housing. Specifically, it investigates how variations in OWR and Window Height Shading (WHShading) affect thermal comfort in a compact, west-facing bedroom unit within Rusun Lokbin Rawa Buaya. Through validated CFD analysis and cross-referencing with the CBE Thermal Comfort Tool, the study addresses the following research questions:

- To what extent do variations in window design (OWR) combined with vertical overhang depth (WHShading) affect thermal comfort in naturally ventilated rooms?
- Which combination of OWR and WHShading yields optimal comfort across different building floor levels?

This research contributes academically by addressing the overlooked intersection of operable fenestration and shading geometry in passive design. Practically, it proposes retrofit-friendly design interventions that support more livable, thermally resilient environments for low-income urban residents—advancing the goal of regenerative urban housing.

2 Materials and methods

2.1 Theoretical framework

Regenerative design in tropical urban housing increasingly emphasize passive strategies to create thermally livable environments, particularly where mechanical cooling is unavailable. Naturally ventilated buildings depend on integrated components such as operable windows, shading devices, and orientation to optimize indoor conditions. These elements play a vital

role in maintaining thermal neutrality and reducing energy dependency as a core principles aligned with regenerative and livable space agenda promoted by ISLIVAS 2025.

Olewi et al. [6] highlight that passive integration of cross ventilation, external shading, and thermal mass can significantly maintain PMV values within the optimal -0,5 to +0,5 range. Similarly, Jayalath [7] demonstrate that in low-cost housing, passive measures such as optimized window placement and overhangs can effectively improve indoor comfort and reduce PPD, contributing to energy-efficient and health-supportive environments.

This study focuses on four key variables substantiated by literature:

- The size of the openable window area plays a decisive role in determining the indoor thermal comfort in naturally ventilated buildings. Studies confirm that an openable window area ratio of at least 10% of the floor area is essential to ensure effective airflow for thermal comfort. A higher OWR improves ventilation rates, reduces indoor overheating, and contributes to lower Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) values—both of which are key indicators of thermal comfort [8]. In particular, simulation results have shown that larger operable window ratios significantly reduce overheating hours and support adaptive thermal comfort in residential buildings. Notably, the relationship between window openness and indoor temperature aligns with adaptive thermal comfort models, indicating that window operability is a critical passive design strategy in reducing reliance on HVAC systems and enhancing comfort through natural means [9, 10].
- Proper window shading in tropical climates has been shown to reduce PMV values significantly, especially for west and south orientations, with reductions up to 1.0 PMV unit [11]. Additionally, effective use of overhangs and orientation-specific shading strategies can help maintain indoor thermal comfort in glazed zones of naturally ventilated buildings [9]. Shading Dimension (WShading Ratio): Horizontal overhangs are known to reduce solar heat gain and surface temperature, ideally within 50–100% of window height [3, 12, 13].
- Thermal Comfort Metrics (PMV and PPD): These are standardized indices used to predict thermal satisfaction and dissatisfaction among occupants, integrating physical environmental variables with human thermal responses [14, 15].
- Vertical Wind Gradient: Building height affect wind speed and turbulence intensity. Wen et al. [16] and Weng et al. [17] argue that upper floors in high-rise buildings experience higher wind exposure, which may improve ventilation effectiveness. Alfaki [18] suggest that such condition can be leverage through facade optimization.

These theoretical foundation provide the scientific bases for simulating the performance of passive intervention in constrained urban housing environment. The use of computational Fluid Dynamics (CFD) in tandem with thermal comfort modelling ensures methodological rigor and relevance for retrofit applications [19].

2.2 Case study selection and context

This study focuses on a specific case: the Rusunawa Lokbin Rawa Buaya, a 16-story government-subsidized rental apartment located in West Jakarta, Indonesia. The building complex, which accommodates low-income families, is representative of the broader typology of tropical high-rise public housing in Southeast Asia. The selection of this case was motivated by multiple factors: its west-facing units are subject to intense solar radiation during the afternoon, the building employs natural ventilation with minimal operable windows, and residents frequently report discomfort due to elevated indoor temperatures and poor airflow.

The typical unit analyzed in this study measures approximately 33.5 m² and includes two bedrooms, a living area, a kitchenette, and a bathroom. Specifically, Bedroom 2—measuring

8.13 m² and located on the façade—is chosen as the simulation subject due to its direct exposure to external environmental conditions and its pivotal role in regulating indoor comfort. The unit's window configuration primarily consists of fixed glass panels with small top-hung openings (bovenlight), resulting in a low Openable Window Ratio (OWR) and no built-in shading elements.

The selected study area represents a common housing scenario in tropical megacities: compact, high-density dwellings lacking mechanical cooling systems. These constraints emphasize the importance of passive design strategies to mitigate thermal discomfort and reduce energy dependency. Furthermore, the environmental conditions at the site—characterized by high temperatures (29–32°C), high humidity (up to 90%), low wind speeds (0.13–2.2 m/s), and urban heat island effects—create a highly challenging context for achieving thermal comfort naturally [1].



Fig. 1. Public rental housing Rawa Buaya (source: writer, 2025).



Fig. 2. Existing windows with 10% OWR and 10% WHS (source: writer, 2025).



Fig. 3. Building floorplan and its orientation.

2.3 Research design

This study employs a quantitative, simulation-based approach using Computational Fluid Dynamics (CFD) to evaluate how variations in window and shading design affect indoor thermal performance [20]. The methodological framework is structured as a simulative-predictive study in which physical environmental parameters are analyzed numerically and validated through thermal comfort models.

The research analyzes 36 design scenarios combining three main variables:

- Openable Window Ratio (OWR): 10%, 30%, 60%, and 90%
- Window Height Shading Ratio (WShading): 0%, 50%, and 100%
- Floor Levels: Level 4 (16m), Level 10 (40m), and Level 16 (64m)

All simulations are conducted using Ansys Fluent, a widely used CFD software capable of modeling fluid dynamics and heat transfer in architectural environments [14, 21]. The geometry of Bedroom 2 is modeled in 3D based on on-site measurements, and local climatic data from Meteoblue is applied as boundary conditions for temperature, wind speed, and humidity.

2.4 Simulation parameters and workflow

The research method involves the following key steps:

- 3D Geometry Modeling: A physical model of the bedroom unit is created using accurate architectural dimensions. Window configurations and tritisan (shading) dimensions are parametrically adjusted for each scenario.
- Boundary Conditions: External environmental data (temperature, humidity, wind direction and speed) is input based on recorded data for the hottest days in March 2024. The unit is assumed to be occupied and ventilated passively.
- CFD Simulation: Each of the 36 scenarios is simulated under steady-state conditions. The model calculates air velocity, temperature distribution, and radiation effects within the space.
- Thermal Comfort Indexing: CFD output is used to derive environmental variables—air temperature, mean radiant temperature, relative humidity, and air speed—which are then input into the CBE Thermal Comfort Tool to calculate PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) values. This dual method ensures physical realism through CFD and perceptual validation through thermal comfort standards.
- Comparative Evaluation: Results from all simulations are compared to determine the most thermally comfortable configuration. Special attention is given to how

performance varies with floor level and whether specific combinations of OWR and WHShading consistently yield better outcomes.

2.5 Simulation calibration and validation

To evaluate thermal comfort across window configurations, this study used validated Computational Fluid Dynamics (CFD) simulation via Ansys Fluent. A 3D model of Bedroom 2 was developed based on actual measurements, incorporating local material properties and geometrical details. Climate boundary conditions – temperature, humidity, wind speed and solar intensity – were taken from hourly data during March 2025 in West Jakarta, particularly at 13:00, the peak thermal discomfort hour.

Simulations generated airflow velocity, air temperature, surface temperature, humidity and mean radiant temperature. For consistency, thermal comfort values were calibrated using data from grid point 5 (center of the room), which served as the representative one. These environmental variables were then processed through the CBE Thermal Comfort Tool (UC Berkeley) to calculate PMV and PPD values in compliance with ASHRAE 55 standard.

3 Results and discussion simulation result overview

The CFD simulations produced detailed airflow and temperature data across 36 design scenarios—comprising 4 OWR values (10%, 30%, 60%, 90%), 3 shading depths (WHShading: 0%, 50%, 100%), and 3 floor levels (4th, 10th, 16th). The analysis focused on thermal indicators at 9 grid points inside Bedroom 2, specifically air temperature (°C), air velocity (m/s), and operative temperature, which were then converted into PMV and PPD values using the CBE Thermal Comfort Tool.



Fig. 4. Windows variant 12 model and layout of 9 grid measurement points (source: writer, 2025).

Results showed that increasing the Openable Window Ratio (OWR) consistently improved airflow velocity and reduced operative temperature across all floor levels. The most significant cooling effect was observed at the 16th floor due to increased wind exposure. Shading depth (WHShading) also affected thermal performance, with 100% shading showing the best control of solar radiation while maintaining acceptable airflow.

Table 1. 36 Simulation recap data

REKAPITULASI DATA HASIL SIMULASI

Note: Level Ketinggian: A= Lantai bawah, B= Tengah dan C= Lantai Atas

OWR: 1= OWR 10%; 3= OWR 30%; 5= OWR 50% dan 9= OWR 90%. Openabel Window Ratio

WH Tritisian: X= 0; Y= 0,5 dan Z= 1. (rasio teritisian dan tinggi jendela)

NO	DATA	CFD Ansys Fluent							CBE Thermal Tools					Scoring
		V	T Room	T floor	T wall	T Ceill	T Rad	Rh %	PMV	PPD %	SET °C	Cooling Effect	Sensasi	
Lantai 4 (16m)														
1	A 1 X	0,002	33,50	33,10	34,00	35,00	34,03	65,00	3,19	100,00	33,90	-	Hot	-
2	A 3 X	0,002	33,00	33,00	34,00	34,00	33,67	65,00	3,03	99,00	34,50	-	Hot	-
3	A 5 X	0,002	32,50	34,00	35,00	33,00	34,00	65,00	3,01	99,00	35,10	-	Hot	-
4	A 9 X	0,022	33,70	34,00	36,00	33,00	34,33	65,00	3,21	100,00	36,10	-	Hot	-
5	A 1 Y	0,002	34,50	34,00	34,00	33,00	33,67	65,00	3,25	100,00	36,70	-	Hot	-
6	A 3 Y	0,003	32,00	32,00	34,00	33,00	33,00	65,00	2,74	97,00	34,30	-	Hot	-
7	A 5 Y	0,331	33,70	32,00	34,00	33,00	33,00	65,00	2,47	93,00	33,80	1,50	Warm	-
8	A 9 Y	0,220	30,50	32,00	34,00	33,00	33,00	65,00	2,28	88,00	32,70	-	Warm	1,00
9	A 1 Z	0,261	32,00	31,90	32,00	32,00	31,97	65,00	2,05	79,00	32,30	1,20	Warm	1,00
10	A 3 Z	0,210	32,50	31,90	32,00	33,00	32,30	65,00	2,35	90,00	33,40	0,80	Warm	-
11	A 5 Z	0,215	32,20	32,50	31,90	32,00	32,13	65,00	2,24	86,00	33,00	0,80	Warm	1,00
12	A 9 Z	0,419	30,20	30,90	30,60	31,00	30,83	65,00	0,96	25,00	28,50	2,70	Slightly Warm	2,00
		V	T Room	T floor	T wall	T Ceill	T Rad	Rh %	PMV	PPD %	SET °C	Cooling Effect	Sensation	
Lantai 10 (40m)														
13	B 1 X	-	31,70	32,90	33,00	32,00	32,63	60,00	2,55	94,00	33,20	-	Hot	-
14	B 3 X	0,002	31,70	33,10	32,50	31,70	32,43	60,00	2,52	94,00	33,20	-	Hot	-
15	B 5 X	0,032	31,70	33,10	32,50	31,70	32,43	60,00	2,52	94,00	33,20	-	Hot	-
16	B 9 X	0,210	31,70	31,50	32,50	31,70	31,90	60,00	2,04	79,00	31,90	0,90	Warm	1,00
17	B 1 Y	0,345	32,90	32,00	32,20	32,90	32,37	60,00	2,06	79,00	32,00	1,60	Warm	1,00
18	B 3 Y	0,314	31,70	33,60	34,00	31,70	33,10	60,00	2,37	90,00	32,80	-	Warm	-
19	B 5 Y	0,392	32,10	33,10	32,00	31,70	32,27	60,00	1,78	66,00	31,00	1,90	Warm	1,00
20	B 9 Y	0,350	32,60	28,50	30,20	31,00	29,90	60,00	1,65	59,00	30,60	2,60	Warm	1,00
21	B 1 Z	0,390	31,20	31,50	31,50	32,00	31,67	60,00	1,86	70,00	31,30	1,00	Warm	1,00
22	B 3 Z	0,319	30,80	31,20	31,00	30,70	30,97	60,00	1,43	47,00	29,90	1,60	Slightly Warm	1,00
23	B 5 Z	0,632	31,30	31,10	31,50	31,60	31,40	60,00	1,24	37,00	29,30	2,60	Slightly Warm	2,00
24	B 9 Z	0,665	30,10	31,00	31,00	30,00	30,67	60,00	0,83	19,00	27,90	2,80	Slightly Warm	2,00
		V	T Room	T floor	T wall	T Ceill	T Rad	Rh %	PMV	PPD %	SET °C	Cooling Effect	Sensation	
Lantai (64m)														
25	C 1 X	0,001	31,00	31,00	32,00	31,20	31,40	55,00	2,15	83,00	31,70	-	Warm	1,00
26	C 3 X	0,210	31,80	31,60	32,00	31,20	31,60	55,00	1,95	74,00	31,30	0,90	Warm	1,00
27	C 5 X	0,378	31,70	32,50	32,00	31,10	31,87	55,00	1,58	55,00	30,10	1,90	Warm	1,00
28	C 9 X	0,210	32,00	32,90	33,00	32,00	32,63	55,00	2,14	83,00	31,90	0,90	Warm	1,00
29	C 1 Y	0,370	31,60	31,80	32,50	32,00	32,10	55,00	1,23	37,00	29,10	3,00	Slightly Warm	2,00
30	C 3 Y	0,360	30,70	30,40	30,70	30,00	30,37	55,00	1,19	35,00	28,90	1,90	Slightly Warm	2,00
31	C 5 Y	0,530	31,30	31,70	30,70	32,00	31,47	55,00	1,17	34,00	28,80	2,70	Slightly Warm	2,00
32	C 9 Y	0,370	29,20	29,50	30,70	30,10	30,10	55,00	0,44	9,00	26,60	3,00	Neutral	3,00
33	C 1 Z	0,460	31,00	30,90	30,60	31,00	30,83	55,00	1,18	34,00	28,90	2,20	Slightly Warm	2,00
34	C 3 Z	0,358	30,80	30,40	30,70	30,00	30,37	55,00	1,13	32,00	28,70	1,80	Slightly Warm	2,00
35	C 5 Z	0,650	29,80	30,50	29,60	29,30	29,80	55,00	1,03	27,00	28,40	2,20	Slightly Warm	2,00
36	C 9 Z	0,790	29,50	30,10	30,70	30,10	30,30	55,00	0,40	8,00	26,50	3,70	Neutral	3,00

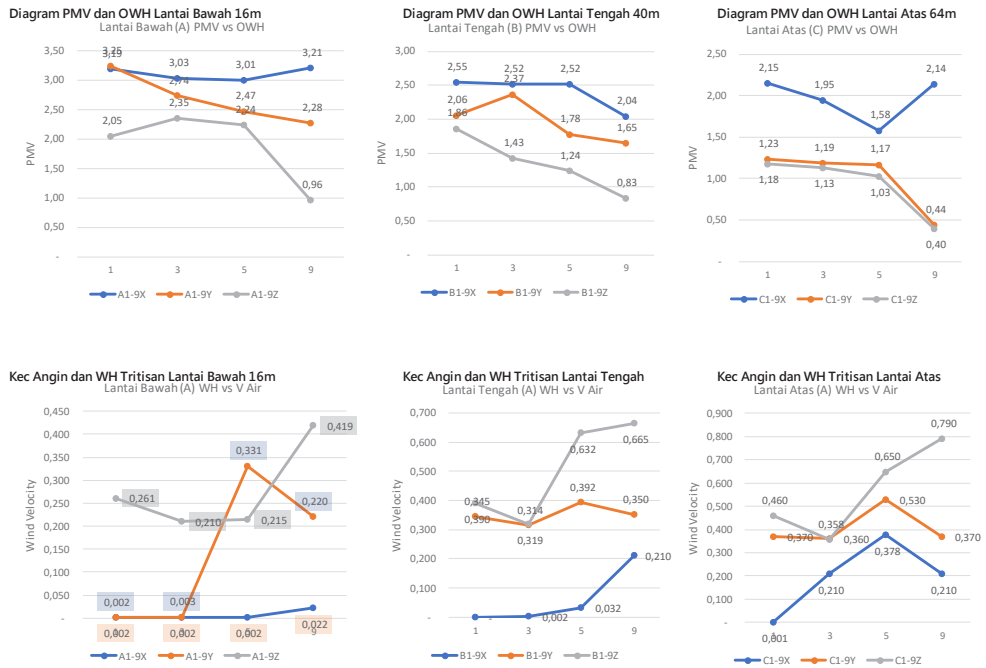


Fig. 5. Values of PMV and OWR level for each WHShading.

3.1 Airflow distribution and window design

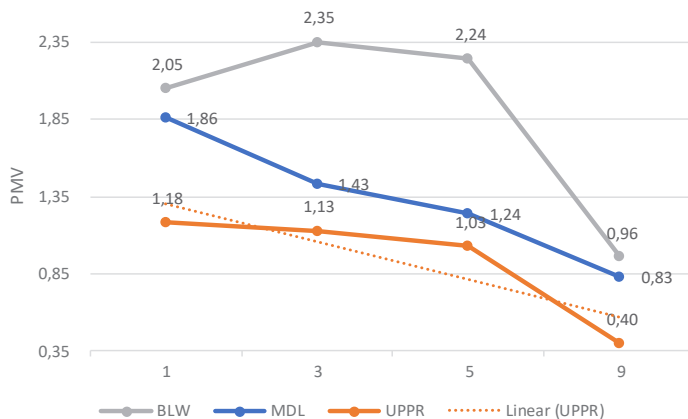
A total of 36 design scenario were simulated using CFD, combining four Openable Window Ratio (OWR: 10%, 30%, 60% and 90%), three Window Height Shading (WHShading: 0%, 50% and 100%), and three floor levels (4th, 10th and 16th). Air temperature, air velocity, and operative temperature were measured at middle grid points in Bedroom 2 as a average value and processed through the CBE Thermal Comfort Tool to derive PMV and PPD values.

Key Finding:

- Higher OWR significantly improved air velocity and reduced operative temperatures.
- WHShading of 100% performed in limiting solar heat gain without significantly impeding air flow.
- Upper Floors (especially the 16th) benefitted from higher wind exposure, resulting in more efficient passive cooling.

These finding are summarized in Table 1 and further visualized in Figure 5-6.

Comparison of PMV and OWR at 3 Floor Level



Comparison of T Rad and WH Shading at 3 Floor Level

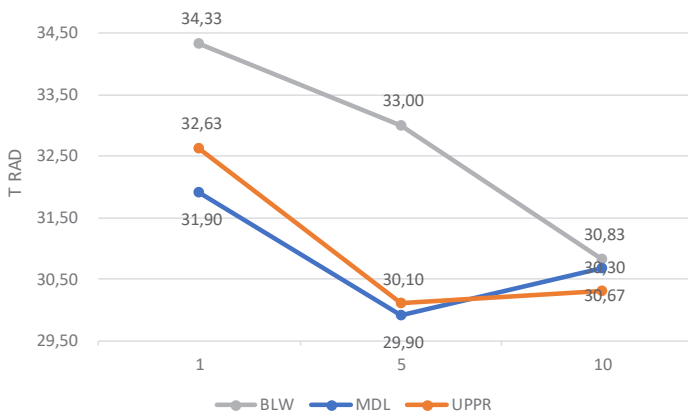


Fig. 6. OWR value effect on PMV and the effect of WHShading on Tradiant.

3.2 Airflow distribution and window configuration

Simulations revealed that rooms with 90% OWR exhibited the highest air velocities, peaking at 0.45–0.7 m/s, facilitating effective cross-room circulation even with single-sided exposure. In contrast, lower OWR values (10–30%) resulted in stagnant zones, particularly near the rear corners of Bedroom 2 and most prominently on the 4th floor.

Interestingly, configurations with large window openings but no shading (e.g., 90% OWR + 0% WHShading) demonstrated elevated solar heat gain. Although air velocity improved, operative temperatures and PMV values remained high. This underscores that ventilation alone is insufficient; solar protection is equally critical for achieving thermal comfort in tropical west-facing units.

3.3 Radiant temperature control through shading

The WHShading parameter significantly influenced radiant heat control:

- 100% WHShading reduces surface and operative temperatures by up to 2,8°C. Especially between 14.00-17.00.
- This reduction also minimized heat re-radiation from wall and glazing surfaces.
- However, WHShading at 100% marginally impeded airflow at low OWR ($\leq 30\%$).

The optimal thermal performance emerged from configuration that balanced large OWR (60-90%) with moderate-to-deep shading (50-100%), maintaining both air velocity and solar protection.

Comparison of PMV and Floor Height,

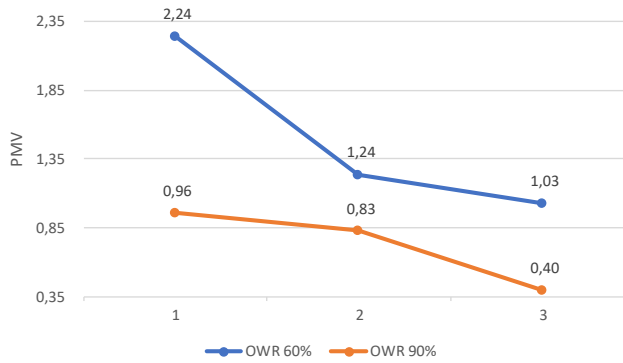


Fig. 7. The effect floor height to PMV.

3.4 Effect of floor level on ventilation performance

Height had a direct correlation with thermal performance:

- 16th floor experienced stronger wind exposure, resulting in better ventilation and lower PMV values (ranging from -0,3 to +0,2 optimal configuration).
- The 10th floor showed similar trends but with slightly weaker airflow.
- The 4th floor had the least favorable conditions due to urban obstructions, yet still showed marked improvement with 90% OWR and 100% WHShading, bringing PMV down from +2.1 to +1.1.

These results support the notion that passive design must be height-sensitive in high-rise buildings—a key aspect of regenerative and livable architecture in dense tropical urban settings.

3.5 Synthesis: Most effective passive design configuration

The most effective design configuration—based on composite PMV and PPD values, airflow velocity, and radiant temperature control—was the combination of 90% Openable Window Ratio (OWR) with 100% Window Height Shading (WHShading), particularly at the 10th and 16th floor levels. This configuration consistently yielded lower thermal stress and improved perceived comfort by enhancing air movement and reducing radiant heat gains.

While neutral comfort ($PMV \approx 0$) was not fully achieved in all scenarios, this setup demonstrated a substantial shift in thermal condition even in less favorable environments. Notably, on the 4th floor—where wind pressure is lower—the configuration still moved the PMV value from a “Hot” zone (+1.7 to +2.1) to a “Slightly Warm” range (+0.7 to +1.1). This

outcome highlights the adaptive potential of such design interventions: even modest improvements can significantly affect occupant perception. With the addition of a localized ceiling or standing fan near the window area, the thermal experience can be further moderated toward the neutral range, without mechanical cooling.

The summary of these results is presented in Table 1: 36 Simulation Recap Data, which aggregates CFD-based airflow and temperature simulations, validated using the CBE Thermal Comfort Tool (PMV/PPD). This table forms the basis for identifying high-performing design combinations and underscores the practical effectiveness of passive strategies when carefully calibrated to context.

3.6 Effectiveness of single-sided ventilation: A re-evaluation

Although the studied building layout uses a double-loaded corridor configuration, each unit has only one external façade, limiting ventilation to a single-sided airflow system. This condition is often cited in literature as suboptimal; prior studies [3, 9], suggest that single-sided ventilation contributes no more than 15% to thermal comfort improvements, compared to cross-ventilation or stack-driven systems.

However, this study reveals that even with single-sided ventilation, well-calibrated design interventions—specifically the increase of Openable Window Ratio (OWR) and the addition of horizontal shading (WHShading)—can significantly shift thermal comfort indicators. In scenarios with 90% OWR and 100% WHShading, the PMV improved by up to 1.2 points, and the PPD dropped by more than 25 percentage points compared to the baseline configuration (OWR 10%, no shading).

This finding highlights that airflow generation in single-sided systems, though limited in directionality, still benefits from increased aperture area and reduced solar heat gain. Air movement near the window and within the occupant zone increased to 0.4–0.6 m/s in upper-floor scenarios, sufficient to activate convective cooling and enhance perceived comfort.

Thus, the common assumption that single-sided ventilation is inherently ineffective should be revisited. While it may lack the efficiency of cross-ventilation, strategic enhancements to window operability and shading can unlock a much greater performance margin than previously estimated. This insight is particularly valuable for retrofit applications in existing tropical high-rise housing, where façade modifications are more feasible than structural overhauls.

3.7 Discussion: Implication for regenerative design and retrofit practice

The simulation results offer insight into how window operability and shading interact with building height to influence indoor thermal conditions. Across all 36 scenarios, higher Openable Window Ratios (OWR) consistently resulted in enhanced airflow velocities and reduced operative temperatures, confirming the assertion by Nugroho [2] that increasing window operability is critical to effective natural ventilation in tropical environments. The thermal comfort response—indicated by the PMV and PPD values—varied across floors, underlining the impact of wind pressure and boundary-layer effects at different heights.

At the 16th floor, the configuration with 90% OWR and 100% WHShading achieved the most favorable thermal comfort conditions. PMV values shifted from warm ($PMV \approx +1.5$) to slightly warm or neutral ($PMV \approx +0.5$), indicating a significant improvement in comfort level without mechanical cooling. On the 10th floor, similar trends were observed, albeit with slightly lower wind velocities. At the 4th floor, despite implementing the same optimal configuration, airflow remained more stagnant due to limited exposure to prevailing winds and urban obstructions. Yet, even at this level, thermal conditions improved from "hot" to "slightly warm"—a shift that has practical implications for occupant comfort. With the

addition of simple, localized enhancements (e.g., electric fans placed near the operable window), thermal neutrality could feasibly be achieved.

These findings challenge the consensus in literature that single-sided ventilation only yields marginal benefits. Omrani [4] estimated that such systems typically offer only 10–30% improvement in comfort, depending on opening position and orientation. However, this study demonstrates that with carefully calibrated design—particularly through maximizing OWR and integrating proportional overhang shading—single-sided configurations can meaningfully reduce thermal stress, even under west-facing solar loads.

Furthermore, this study reinforces the argument presented by Zheng & Tao [3], who noted that vertical shading elements not only control solar heat gain but also alter wind flow paths. In the simulated scenarios, WHShading reduced mean radiant temperature (MRT) by minimizing solar exposure, especially during peak afternoon hours. When combined with sufficient OWR, it created a balance between ventilation and heat rejection, supporting [5] conclusion that improved operability correlates directly with better thermal performance in naturally ventilated rooms.

From a design and retrofit standpoint, the results imply that window upgrades in public housing do not require full structural renovation to enhance comfort. The strategic enlargement of window openings (achieving 60–90% OWR) and installation of overhangs equivalent to window height (100% WHShading) can offer substantial gains. Importantly, performance varies by building height—lower floors may require deeper shading to minimize heat gain, while higher floors benefit more from larger operable areas to maximize ventilation.

In summary, these results reinforce earlier findings that window operability and shading depth strongly influence passive thermal performance in tropical buildings, as indicated by Zheng & Tao [3] and Ran et al. [8]. At the same time, the ability of optimized single-sided configurations to reduce PMV more substantially than the 10–30% margin reported by Omrani [4] suggests that this study extends the current understanding of single-sided ventilation potential in high-rise tropical housing. By aligning with and extending earlier studies, this research adds a height-sensitive perspective that has been underrepresented in prior work, showing how operability and shading interact differently across building floors to influence thermal comfort in tropical high-rise housing.

4 Conclusion

This study examined the effect of window design parameters—specifically Openable Window Ratio (OWR) and Window Height Shading (WHShading)—on indoor thermal comfort in a compact, naturally ventilated unit within a tropical high-rise social housing complex. Using 36 validated CFD simulation scenarios across various OWR and WHShading configurations, the analysis was conducted in the context of a fixed west-facing bedroom unit at Rusun Lokbin Rawa Buaya, Jakarta. Floor level, while not a manipulated variable, was considered a contextual control factor to capture variations in wind exposure typically encountered in high-rise environments.

The results confirm that increasing OWR improves air movement within the room, while proportionally applied shading (especially 100% WHShading) significantly reduces mean radiant temperature (MRT). Together, these design elements influence the overall thermal environment and drive PMV and PPD indices closer to acceptable thresholds—even under the constraints of single-sided ventilation.

Importantly, the findings highlight that adaptive window design can expand the functional boundaries of single-sided ventilation systems in tropical urban housing. The optimal configuration (90% OWR + 100% WHShading) consistently yielded significant reductions in thermal discomfort, regardless of building height. While slight performance variations

were observed across floor levels, the consistency of improvement confirms that these passive strategies are robust and replicable under diverse microclimatic conditions.

In line with ISLIVAS 2025's mission to promote regenerative livable environments, this study demonstrates that even compact, constrained urban housing can achieve improved thermal resilience through optimized passive window design. The findings reaffirm the potential of data-driven, climate-responsive strategies to deliver high-impact, low-cost interventions—especially for vulnerable populations in tropical megacities.

Furthermore, the study challenges the prevailing assumption that single-sided ventilation yields limited thermal benefit. It presents empirical evidence that, through strategic design of operability and shading geometry, such systems can perform far beyond conventional expectations. This has practical implications for public housing retrofits, where façade modifications are more feasible than full structural changes.

However, the study recognizes limitations: simulations were conducted under steady-state peak conditions and did not account for internal heat gains, occupant behavior, or seasonal variation. Future research should incorporate dynamic thermal modeling and on-site measurements. Additionally, explorations into low-cost, climate-responsive shading technologies—such as operable louvers or porous shading—could extend the impact of this research to more adaptable retrofit applications.

In conclusion, this study demonstrates that simulation-informed passive design—anchored in window operability and contextual shading—can regenerate indoor environments in tropical high-rise housing, making them more livable, resilient, and aligned with sustainable development goals.

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References

1. A.A. Sunoto, Evaluasi Rancang Bangun terkait Pengadaan Fasilitas Lingkungan pada Rumah Susun Lokbin Rawa Buaya, Jakarta Barat. *J. Arsit. Zo.* **5**, 402–410 (2022).
2. A.M. Nugroho, “Rekayasa Ventilasi Alami untuk Penyejukan Bangunan,” Universitas Brawijaya Press (2019).
3. J. Zheng, Q. Tao, “Impact of shading louvers on wind-driven single-sided ventilation in a multi-storey building” in *E3S Web of Conferences* (EDP Sciences, 2022)vol. 356.
4. S. Omrani, “Natural Ventilation in High-Rise Apartments in Hot-Humid Climates” (2018).
5. P. Prajongsan, Natural ventilation strategies to enhance human comfort in high-rise residential buildings in Thailand. University of Liverpool Liverpool (2014).
6. M.Q. Oleiwi, M.K.A.M. Sulaiman, M.F. Mohamed, Mohd Khairul Azhar Mat S, Mohamed MF. Passive Cooling Strategies in the Hot Climate: A Review Study. *Arid Int. J. Sci. Technol.*, 76–106 (2023).
7. A. Jayalath, P. Vaz-Serra, F.K.P. Hui, L. Aye, Thermally comfortable energy efficient affordable houses: A review. *Build. Environ.* **256**, 111495 (2024).
8. J. Ran, K. Xiong, M. Dou, H. Zhong, Y. Feng, M. Tang, Z. Yang, Effect of Window Openable Area and Shading on Indoor Thermal Comfort and Energy Efficiency in Residential Buildings with Various Operating Modes. *Atmosphere (Basel)*. **13** (2022).

9. A. Kabanshi, G. Choonya, A. Ameen, W. Liu, E. Mulenga, Windows of Opportunities: Orientation, Sizing and PV-Shading of the Glazed Area to Reduce Cooling Energy Demand in Sub-Sahara Africa. *Energies* **16** (2023).
10. T.S. Rajput, A. Thomas, “Analyzing the effects of passive design strategies on building ventilation performance and thermal comfort using simulation-based approach” in *E3S Web of Conferences* (EDP Sciences, 2023)vol. 396.
11. S. Pathirana, A. Rodrigo, R. Halwatura, Effect of building shape, orientation, window to wall ratios and zones on energy efficiency and thermal comfort of naturally ventilated houses in tropical climate. *Int. J. Energy Environ. Eng.* **10**, 107–120 (2019).
12. W. Liping, W.N. Hien, “The impact of façade designs: orientations, window to wall ratios and shading devices on indoor environment for naturally ventilated residential buildings in Singapore” (2006).
13. P. Zhou, C. Zhang, J. Wang, “Influence of the Passive Design of a Building Facade on the Indoor Thermal Comfort of Residential Buildings” in *E3S Web of Conferences* (EDP Sciences, 2021)vol. 237.
14. F.G. Tartarini, C. Nguyen, S. Schiavon, CBE Clima Tool: A free and open-source web application for climate analysis tailored to sustainable building design. *Build. Simul.* **17**, 493–508 (2024).
15. E. Abbaas, I. Mazran, G.M. Azhar, Impact of window shading on the thermal performance of residential buildings of different forms in Jordan. *Archit. Eng.* **8**, 25–36 (2023).
16. Q. Wen, H. Liu, Q. Zhou, Q. Guo, P. Wang, L. Zhang, The Impact of Ground-Floor Elevation of School Buildings on Courtyard Wind Environment. *Buildings* **14** (2024).
17. J. Weng, B. Luo, H. Xiang, B. Gao, Effects of Bottom-Overhead Design Variables on Pedestrian-Level Thermal Comfort during Summertime in Different High-Rise Residential Buildings: A Case Study in Chongqing, China. *Buildings* **12** (2022).
18. A. Aflaki, N. Mahyuddin, G. Manteghi, M. Rizal Baharum D, Building Height effects on Indoor Air temperature and Velocity in High Rise Residential Building in Tropical Climate. *OIDA Int. J. Sustain. Dev.* **7**, 39–48 (2014).
19. Z. Jiang, T. Kobayashi, M. Sandberg, T. Yamanaka, N. Kobayashi, N. Choi, K. Sano, K. Toyosawa, Analysis of single-sided ventilation flows of a generic isolated building using particle tracking method in LES simulation. *Build. Environ.* **235**, 110230 (2023).
20. I. Alhindawi, C. Jimenez-Bescos, Computational Approach to Predict Thermal Comfort Levels at Summer Peak Conditions in Passive House Based on Natural Ventilation. *J. Sustain. Dev. Energy, Water Environ. Syst.* **10** (2022).
21. N.A. Enteria, O.L. Cuartero-Enteria, CFD evaluation on the pre- And post-Renovation, and windows and doors opening, of a typical, walled, detached family house in the Philippines. *Infrastructures* **2** (2017).