

Multi-Objective Optimization of Window-to-Wall Ratio for Thermal and Visual Comfort: The Impact of Vertical Spatial Positioning in Hot-Humid Climates

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ABSTRACT

In university dormitories, residents occupy identical rooms for extended hours with little control over their environment. The problem arises when identical rooms on different floors behave differently. Solar exposure, wind access, and proximity to the roof all shift with height, meaning a window configuration suited to one floor may underperform on another. This study takes that variation seriously. The case study is a five-storey dormitory in Gazipur, Bangladesh. Corner rooms were selected from each floor as they share the same geometry and orientation. Window to Wall Ratio (WWR) was treated as the primary design variable, tested between 10% and 100%. Parametric models were built in Rhinoceros 3D and Grasshopper, daylight and thermal simulations were run using Climate Studio and Energy Plus, and multi-objective optimization was carried out through the Octopus plugin. The objectives were to maximize Spatial Daylight Autonomy (sDA), Mean Illuminance, and Percentage of Comfort and minimize Percentage of Discomfort. sDA stayed below 10% on all floors, and mean illuminance ranged from just 98 to 127 lux for base case. Adaptive discomfort was high too, affecting 57.98% to 59.83% of occupied hours. After optimization, the Pareto-balanced solutions raised sDA to 83.33–100% and mean illuminance to 569.17–744.21 lux, while cutting adaptive discomfort down to 25.25–27.54%. The optimal WWR shifted by floor: 70% for the ground floor, 60% for the first floor, and 65% for the second through fourth floors. These results show that a single WWR cannot deliver the best daylight–thermal balance across every floor. Floor-specific WWR configurations are therefore necessary for naturally ventilated dormitories in hot-humid climates.

Keywords: Window-to-wall ratio, multi-objective optimization, thermal comfort, spatial daylight autonomy, hot-humid climate, naturally ventilated dormitory.

1. INTRODUCTION

Windows are one of the typical building elements, yet decisions about their size and placement can determine whether a room feels habitable or insufferable. In hot-humid climates like Bangladesh, where solar radiation is intense, ambient humidity is persistently high, and mechanical cooling remains inaccessible to much of the population, window size and placement becomes a matter of great concern. In university dormitories especially, where occupants spend hours studying, sleeping, and resting in identical rooms they cannot modify, the indoor thermal environment is a topic directly associated with learning.

Studies state that adaptive thermal comfort is a concept where occupants tend to feel more comfortable with a wider range of indoor conditions, linked to outdoor climate conditions and their own ability to adapt. It suggests that window-to-wall ratio is not merely a geometric design

variable but a key determinant of adaptive thermal comfort, because it shapes ventilation potential, solar exposure, and occupants' ability to regulate indoor conditions through behavior and opening control [1]. A larger window admits more daylight, supporting variable daylight quality and reducing dependence on artificial lighting. But at the same time, windows increase solar heat gain, pushing indoor temperatures toward discomfort. On the contrary, a smaller window limits overheating but may leave a room dim and poorly cross-ventilated. Neither extreme serve occupants well, which is why identifying the appropriate WWR for a given climate and building type matters. Work across hot and dry climates has placed optimal WWR values roughly between 20% and 50%, varying by facade orientation [2]. In tropical residential buildings, shape, orientation, and glazing ratio together determine indoor thermal conditions in ways that no single factor can address in isolation [3]. Controlling these parameters has been shown to cut annual cooling loads and lighting

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energy demand substantially, with associated reductions in CO₂ emissions [4]. Daylighting and thermal comfort do not optimize in the same direction, and this is what makes window design genuinely difficult. More glass means better daylight autonomy but also higher heat gain and potential glare, a conflict noted repeatedly in the literature [5], [6]. Single-objective approaches cannot resolve this; they simply shift the problem elsewhere. Multi-objective optimization, particularly using genetic algorithms, is better suited to the task. Rather than converging on one solution, genetic algorithms generate a Pareto front- a set of designs where no metric can be improved without degrading another, allowing designers to make informed trade-off decisions based on actual building conditions [7], [8]. Studies applying such frameworks to buildings in hot humid climate have demonstrated simultaneous gains in energy efficiency, daylight quality, and thermal comfort [9], [10]. The BNBC (2020) provides prescriptive glazing selection criteria, SHGC and SC; based on Window-to-Wall Ratio (WWR) alone, without accounting for floor-level variation, orientation, or the specific demands of naturally ventilated typologies [11].

Naturally ventilated dormitories in South Asia, however, appear rarely in this body of work. This study attempts to fill that gap. A five-storey university dormitory in Gazipur, Bangladesh, forms the case study, with five identical corner rooms in each floor was selected to isolate the effect of vertical positioning on performance. Using Rhinoceros 3D and Grasshopper for parametric modelling, EnergyPlus with a Dhaka weather file for thermal simulation, and the Octopus plugin for multi-objective optimization, the study tests WWR values between 10% and 100%. Metrics that frame the assessment are Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), Mean Illuminance, Adaptive Comfort Hour Percentage and Adaptive Discomfort Hour Percentage. The result is a set of floor-specific configurations that reflect the genuine thermal and daylight conditions of each level, offering a grounded, evidence-based reference point for dormitory window design in Bangladesh's climate.

2. METHODOLOGY

A parametric approach is adopted in this study to optimize window design with particular emphasis on daylight and thermal performance. A representative university dormitory building in Gazipur served as the basis for investigation, from which corner rooms across five floors were selected for detailed parametric analysis. The Window-to-Wall Ratio is used as the primary

design variable. Building geometry was modelled using Rhinoceros 3D along with Grasshopper, and optimization was carried out through the Octopus plugin operating within the Grasshopper environment.

The study is organized into three main parts: (1) development of the base case models, (2) performance evaluation of the base case rooms, and (3) parametric optimization to identify potential design solutions for the studied rooms.

2.1 Daylight Metric

Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), proposed by the Illuminating Engineering Society of North America [12], are widely used dynamic metrics that describe daylight quality in architectural spaces more effectively than point-based evaluations [13]. sDA measures the percentage of floor area achieving a minimum illuminance of 300 lux for 50% of occupied hours annually, with thresholds of 40%, 55%, and 75% earning one, two, and three LEED credits respectively. ASE is a codified LEED v4.1 metric representing conditions of potential visual discomfort from excessive direct sunlight. The IES recommends that no more than 10% of the floor area receive 1000 lux for 250 or more occupied hours per year to qualify for LEED recognition [12, 14]. Along with sDA and ASE, mean illuminance was used to provide an additional quantitative description of daylight distribution within the room and to support the comparison of base and optimized cases. Mean illuminance, expressed in lux, is commonly used as the average illuminance over a defined plane or area and serves as a supplementary indicator of overall light availability in daylighting studies [15].

2.2 Thermal Performance Metric

As the dormitory rooms in this study are naturally ventilated, the Adaptive Thermal Comfort Model was used. Occupants in naturally ventilated buildings tend to accept a wider range of indoor temperatures. This depends on outdoor conditions and how much air movement is available. ASHRAE 55 and EN 16798 both define comfort bands using the running mean outdoor temperature [16]. Hours are then classified as comfortable or uncomfortable based on how far indoor conditions fall from these bands. Based on this, two metrics were used: Percentage of Comfort Hours and Percentage of Discomfort Hours. These capture how much of the occupied time falls within, or outside, the adaptive comfort zone. Dormitory rooms are occupied for long stretches of the day, and thermal comfort has a direct bearing on occupant wellbeing.

For this reason, these metrics were considered more suitable than static comfort indices for this study. They also allow the effect of different WWR configurations to be compared directly, since WWR influences solar heat gain and, in turn, indoor air temperatures relative to the outdoor benchmark.

2.3 Case Study Description

A five-storied residential dormitory building located in Gazipur, Bangladesh was selected as the case study (Fig. 1). The building follows a repetitive floor plan in which individual rooms share identical design characteristics, including orientation, window configuration, and spatial layout, but differ in their positional context within the building (Fig. 2). This quality made the building particularly well suited for isolating the effect of vertical positioning on indoor thermal conditions, separate from any variation in room geometry or envelope design. Five rooms were selected from the same vertical stack, each situated on a different floor from ground to fifth level (Fig. 3). Table I describes the major parameters of the studied rooms.

Table I: Parameters of the case studies

Parameters	Case 1 (101)	Case 2 (201)	Case 3 (301)	Case 4 (401)	Case 5 (501)
Room Dim.	4.1m x 3.6m				
Window Orientation	North				
Window Size	1.27m X 1.29m				
Sill Level	0.91 m				
Lintel Level	2.20 m				
Window Type	Sliding glass window with 50% operable area				
Wall	150mm brick plaster wall, off-white color				
Ceiling	Concrete slab, white color				
Floor	Mosaic floor, beige color				



Fig. 1: (a) Exterior view of the case building; (b) Interior view of the corner room

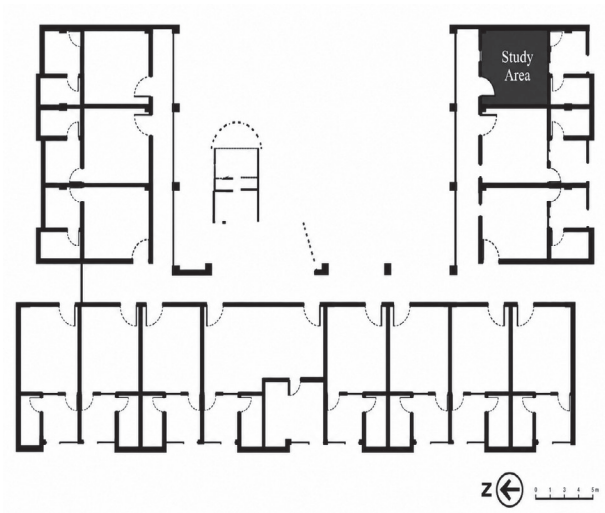


Fig. 2: Floor plan of the case building.

The selected rooms were a corner unit because corner rooms have greater exposure to the outdoor environment than internal rooms. The north-south orientation of opening was chosen to reflect a typical dormitory condition allowing natural airflow, while also keeping the room geometry consistent for comparison across floors. Since boundary conditions remain consistent across these rooms in plan, observed differences in lighting and thermal performance can reasonably be attributed to factors that vary with floor level, primarily solar exposure, wind availability, and proximity to the roof, all of which influence indoor temperatures in meaningfully different ways within the Bangladeshi climatic context.

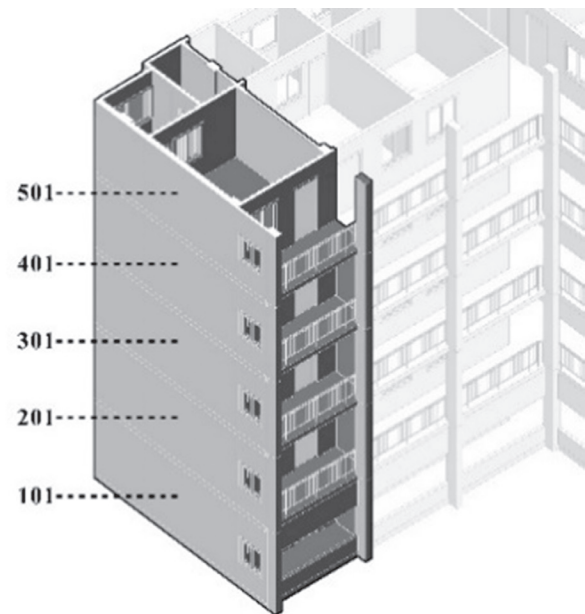


Fig. 3: 3D model of the case building.

2.4 Base Case Model

Simulation models were built based on the actual building design and documented material properties. Rhinoceros 3D with the Grasshopper plugin was used to model building surfaces and assign EnergyPlus material properties to envelope components. The Dhaka .epw climate file provided the weather dataset. Full-year daylight and thermal simulation was conducted with sDA, ASE, Mean Illuminance, and Percentage of Comfort and Discomfort Hours as the primary output. Occupancy density was set at 0.16 persons per square meter. Natural ventilation operated between indoor temperatures of 22°C and 28°C and outdoor temperatures of 17°C and 28°C, following EN 15251 thresholds.

2.5 Optimization Approach for Building Performance

Building performance optimization has become a standard part of architectural practice for addressing complex design challenges [17]. The process identifies maximum or minimum values of a function by manipulating variables within defined constraints [18]. Performance-based optimization typically combines parametric design, building simulation, and Genetic Algorithms [19]. A parametric design systematically varies parameters across a defined range to explore multiple solutions, supporting informed decision-making by identifying designs that meet predefined criteria [20]. The optimization framework consists of two components: design variables, defining geometric or physical characteristics, and objective functions, representing performance indicators assessed through simulation [21]

2.6 Multi-Objective Optimization

This step aims to optimize the WWR to simultaneously improve visual comfort by maximizing sDA, Mean Illuminance, Percentage of Comfort Hours and minimizing Percentage of Discomfort Hours. Since these objectives can conflict with one another in practice, the optimization produces a range of trade-off solutions rather than a single answer, from which appropriate design decisions can be drawn.

2.7 Optimization Parameters

Windows significantly influence a building's thermal performance due to their higher heat transfer coefficients compared to opaque envelope components. Window U-values are typically five times greater than those of walls or doors, accounting for 20% to 40% of building energy

loss. Poor window design leads to thermal discomfort and increased energy consumption. While prior studies have explored optimal WWR for various climates, they often prioritize energy efficiency over thermal comfort. WWR ranging from 10% to 100% was used as the primary design parameter to evaluate its impact on visual and thermal environment.

2.8 Optimization Process

Multi-objective optimization was performed using the Octopus plugin within Grasshopper. Octopus uses an evolutionary algorithm that encodes design variables, in this study WWR, as genome within a population of candidate solutions. Each generation is evaluated against the fitness objectives, and through selection, crossover, and mutation, successive generations progressively move toward better-performing solutions across all criteria simultaneously. Figure 4 shows the script developed to run the optimization for each floor. The fitness objectives were defined as maximizing sDA, Mean Illuminance, Percentage of Comfort Hours and minimizing Percentage of Discomfort Hours.

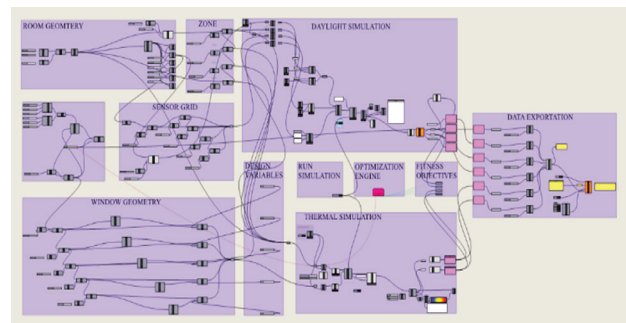


Fig. 4: Grasshopper script for optimization

The algorithm was configured with a population size of 50 and a maximum of 5 generations. the study used only one design genome, WWR, within a fixed range of 10–100%, so the search space was relatively small. A population size of 50 and 5 generations generated 250 candidate solutions per floor. This was used as a manageable Pareto-based design exploration rather than a claim of complete global convergence. The design variable and fitness objectives used for the optimization are shown in Fig. 5.

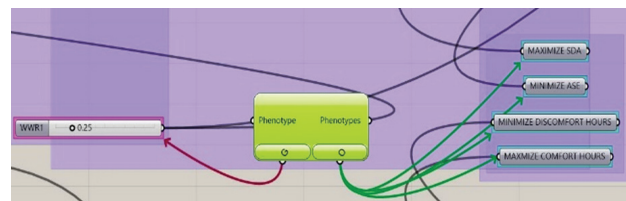


Fig. 5: Octopus genomes and fitness objectives

3. RESULTS AND DISCUSSION

The results were evaluated floor by floor to examine whether the same WWR can provide similar daylight and thermal performance across the vertical stack of the dormitory. Since the selected rooms have the same geometry, orientation, and spatial configuration, the variation in performance can mainly be attributed to differences in vertical position, including floor height, solar exposure, and thermal response. This directly supports the main objective of the study: to test whether WWR should be uniform across all floors or adjusted according to floor level.

3.1 Base Case Performance

Before optimization, the building's baseline performance was assessed for all five floors using daylight and adaptive thermal comfort indicators. Daylight levels were poor: sDA ranged from 4.76% to 9.52% and average illuminance was only 98 to 127 lux. ASE was 0% on every floor, indicating that direct sunlight was minimal, primarily because the existing windows allowed very little daylight into the spaces.

Adaptive comfort results were also unsatisfactory, with comfort scores between 40.17% and 42.02% and adaptive discomfort at 57.98% to 59.83%. Although the upper floors fared a little better, more than half of occupied hours still fell outside the adaptive comfort band.

Table II: Base case performance across each floor

Floor	sDA (%)	ASE (%)	Mean illuminance (lux)	Adaptive comfort (%)	Adaptive discomfort (%)
Ground floor	7.14	0	102	40.17	59.83
1 st floor	4.76	0	98	41.11	58.89
2 nd floor	9.52	0	102	41.48	58.52
3 rd floor	9.52	0	123	41.78	58.22
4 th floor	7.14	0	127	42.02	57.98

Overall, the base case provided inadequate daylight and offered poor thermal performance. This justified optimizing the window-to-wall ratio to increase daylight availability and reduce adaptive discomfort across the floors.

3.2 Best Daylight Performance Solutions

The first stage of the results analysis identified the best daylight solution for each floor. The goal was to find the smallest window-to-wall ratio (WWR) that produced

100% sDA while also keeping mean illuminance at a strong level. Larger WWRs, such as 100%, did increase mean illuminance but are not ideal design recommendations because too much glazing can worsen thermal comfort. For that reason, the preferred daylight solution was the minimum WWR that achieved full daylight autonomy, not the largest possible glazing area. Since ASE remained 0% for all tested WWR configurations across all floors, it showed no performance variation and was therefore excluded from the final optimization analysis.

Table III: Best daylight performance solutions for all floors

Floor	WWR (%)	sDA (%)	Mean Illuminance (lux)	Adaptive comfort (%)	Adaptive discomfort (%)
Ground floor	65	100	680.39	71.42	28.58
1 st floor	71	100	715.13	70.09	29.91
2 nd floor	70	100	733.98	72.78	27.22
3 rd floor	68	100	717.00	74.08	25.92
4 th floor	66	100	693.89	74.70	22.46

All The results indicate that every floor can achieve full sDA, but each floor requires a different window-to-wall ratio (WWR) to do so. The necessary WWRs span from 65% to 71%, showing that daylight performance changes with floor level. Level 1 reaches 100% sDA at a WWR of 65%, whereas Level 2 needs 71%. Levels 3, 4, and 5 hit full sDA at 70%, 68%, and 66% WWR respectively.

This spread is important because it shows that a single WWR cannot be relied to deliver the same daylight outcome throughout the building. Even when room types are identical and stacked vertically, the minimum WWR needed for full daylight autonomy shifts depending on the floor. Looking at the cases that maximize daylight, Level 3 recorded the highest average illuminance, 733.98 lux at a 70% WWR. Level 1 reached full sDA with the smallest required WWR, 65%, and had an average illuminance of 680.39 lux. From a daylight-only perspective, the ideal WWR therefore lies roughly between 65% and 71%, varying by floor height.

The comfort analysis reveals that the brightest daylight solutions aren't always the most comfortable thermally. For example, even though Level 2 achieves 100% sDA at 71% WWR, its adaptive discomfort remains relatively high at 29.91%. This highlights the trade-off between maximizing daylight and keeping thermal conditions acceptable.

3.3 Best Thermal Performance Solutions

The second phase identified the optimal thermal strategy for each floor using the ASHRAE 55 adaptive comfort model. Strategies were selected to maximize occupants' adaptive comfort and to minimize adaptive discomfort percentage. Because the dormitory relies on natural ventilation, the adaptive approach is more appropriate than a fixed PMV/PPD metric; occupants in naturally ventilated settings generally accept a wider comfort range influenced by outdoor conditions and airflow.

Table IV: Best thermal performance solutions for all floors

Floor	WWR (%)	sDA (%)	Mean illuminance (lux)	Adaptive comfort (%)	Adaptive discomfort (%)
Ground floor	70	100	744.21	73.03	26.97
1 st floor	60	83.3	569.17	72.46	27.54
2 nd floor	65	97.6	659.57	73.57	26.43
3 rd floor	65	97.6	668.18	74.17	25.83
4 th floor	65	97.6	679.43	74.75	25.25

The best thermal solutions fall mostly within a WWR range of 60% to 70%. Level 1 achieved its top thermal result at 70% WWR, registering 73.03% adaptive comfort and 26.97% adaptive discomfort. Level 2 reached its best thermal performance at a lower WWR of 60%, with adaptive comfort at 72.46%. Levels 3, 4, and 5 each showed their strongest thermal outcomes at 65% WWR.

This pattern shows that thermal behavior varies by floor: a WWR that works well on one level may not be ideal on another. At 65% WWR, Level 5 recorded the highest adaptive comfort, 74.75%, and the lowest adaptive discomfort, 25.25%. Level 4 was close behind at the same WWR, with 74.17% adaptive comfort. By contrast, Level 2's reduced WWR of 60% lowered discomfort but weakened daylight performance, producing only 83.3% sDA.

Taken together, the results imply that increasing WWR improves thermal performance only up to a limit. More glazing does not consistently lower discomfort and can raise heat gain. The best thermal results therefore occur within a controlled WWR band of roughly 60% to 70%, not at the maximum WWR values.

3.4 Pareto-Optimal Balanced Solutions

The final stage found Pareto-optimal balanced solutions by evaluating the four main objectives together: Maximizing sDA, Maximizing mean illuminance, maximizing

adaptive comfort hour percentage and minimizing adaptive discomfort hour percentage

These objectives pull in different directions. Raising the WWR tends to improve daylight metrics and average illuminance, but it can also increase solar heat gain and reduce thermal comfort. Therefore, the best answer is not simply the largest WWR or the highest daylight reading. The Pareto-optimal solutions instead represent the best compromise between daylight performance and adaptive thermal comfort for each floor.

Table V: Pareto-optimal balanced solutions for all floors

Floor	WWR (%)	sDA (%)	Mean illuminance (lux)	Adaptive comfort (%)	Adaptive discomfort (%)
Ground floor	70	100	744.21	73.03	26.97
1 st floor	60	83.33	569.17	72.46	27.54
2 nd floor	65	97.62	659.57	73.57	26.43
3 rd floor	65	97.62	668.18	74.17	25.83
4 th floor	65	97.62	679.43	74.75	26.97

The Pareto analysis makes clear that a single WWR across all floors is not appropriate. The best WWRs lie between 60% and 70%, and they change with floor height. Level 1 needed 70% WWR to reach the best combined daylight and thermal result. Level 2 performed best at 60% WWR. Levels 3, 4, and 5 each found their optimum at 65% WWR.

This pattern backs the study's main point: daylight and thermal responses change with vertical position, even when room geometry and WWR are unchanged. For example, 65% WWR gives a balanced outcome on Levels 3–5, but Level 1 does better at 70% and Level 2 at 60%. Put differently, floor height alters daylight access, solar exposure, and thermal behavior, so the ideal WWR shifts by level. Level 5 at 65% WWR provides the best overall thermal balance: adaptive comfort 74.75%, adaptive discomfort 25.25%, and sDA 97.62%. Level 4 at 65% WWR is also strong, with 97.62% sDA, mean illuminance 668.18 lux, and 74.17% adaptive comfort. Level 3 shows a similar balanced result at 65% WWR. These outcomes indicate 65% WWR is a reliable choice for the upper floors, while the lower floors need different WWR settings.

Overall, the analysis recommends varying WWR by floor rather than using a single value across the whole façade. A floor-by-floor WWR approach lets the design respond to each level's specific daylight and thermal conditions.

3.5 Comparison of Base Case and Optimal Case

After optimization, daylight performance improved markedly on every floor. sDA rose from 4.76–9.52% in the base case to between 83.33% and 100% in the optimized scenarios, and mean illuminance increased from 98–127 lux to 569.17–744.21 lux. Thermal comfort also got better. Comfort hours climbed from 40.17–42.02% up to 72.46–74.75%, while discomfort hours fell from 57.98–59.83% down to 25.25–27.54%. Figure 6-8 shows the comparison of the daylight and thermal performance of the base case and optimal test case.

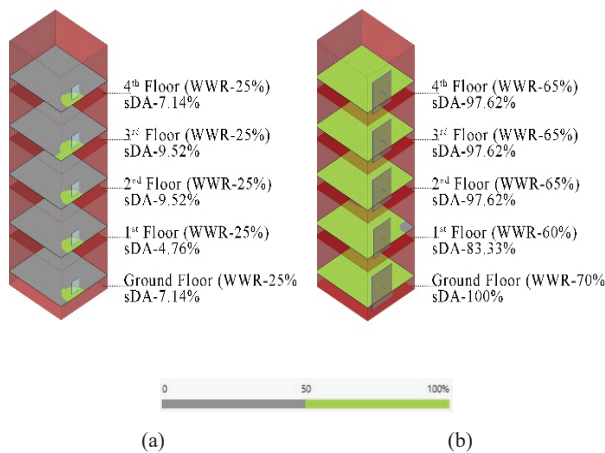


Fig. 6: (a) Base case sDA; (b) Test case sDA

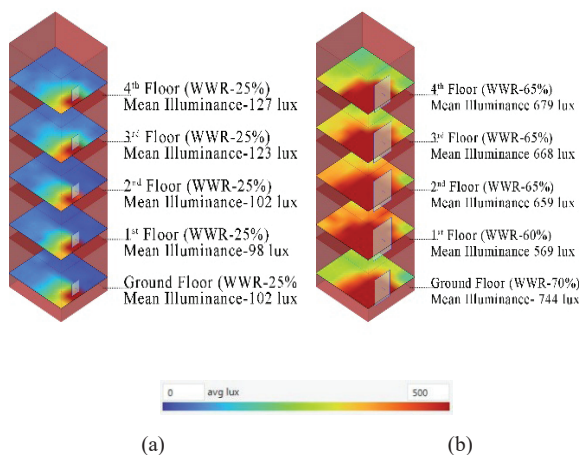


Fig. 7: (a) Base case Mean Illuminance; (b) Test case Mean Illuminance

Overall, the comparison demonstrates that optimizing WWR for each floor significantly enhances both daylighting and adaptive thermal comfort, showing that a single, uniform WWR is not appropriate across all floors.

Comparison of Adaptive Comfort (%)

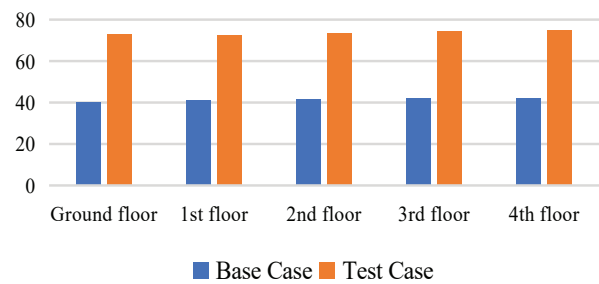


Fig. 8: Comparison of Adaptive Comfort Percentage between Base Case and Test Case

4. CONCLUSION

This research investigated whether a single, uniform window-to-wall ratio (WWR) can satisfactorily provide both daylight and thermal comfort for rooms on different floors of a naturally ventilated dormitory in a hot-humid climate. The study found that it cannot. Even though the selected rooms shared the same geometry, orientation, and layout, their daylighting and thermal outcomes differed with floor level, showing that vertical position matters when optimizing WWR.

The base case left every level underlit and thermally uncomfortable: sDA stayed under 10 percent, mean illuminance never exceeded 127 lux, and occupants spent more than half of their hours outside the adaptive comfort band. Once WWR was tuned for each floor, sDA climbed to between 83 and 100 percent, illuminance rose into the 569–744 lux range, and comfort hours nearly doubled to 72–75 percent, with discomfort cut to roughly a quarter of occupied time.

The improvement did not come from one universal setting. The ground floor needed a 70 percent WWR to balance daylight and heat gain, the first floor settled at 60 percent, and floors two through four converged on 65 percent. Although all of the rooms were built with the same template, the vertical position of the rooms in the building mattered in practice.

These findings push gently against how the BNBC (2020) currently treats windows: Solar Heat Gain Coefficient (SHGC) and Shading Coefficient (SC) limits are tied to WWR, but not to floor level. Our results indicate that incorporating floor-specific SHGC/SC limits, rather than applying a uniform requirement, could improve thermal performance and occupant comfort in naturally ventilated dormitories under this climate.

It needs to be added that, the five floors if Gazipur do not speak for every climate, orientation, or dormitory typology, and everything reported here comes from simulation rather than measurements inside occupied rooms. WWR was also the only variable in play; shading devices, glazing specification, infiltration, and how occupants actually operate their windows were all held constant. Future research should include field validation and examine a broader range of facade parameters and building typologies.

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