Parametric Optimization of Window-to-Wall Ratio to Reduce Thermal Discomfort in Naturally Ventilated Multi-Storied Residential Building in Dhaka

Maria Jebin[1*], Humayra Anan[1] and Md. Mashuk-Ul-Alam[2]

[1]Department of Architecture, Dhaka University of Engineering & Technology, Gazipur, Bangladesh
[2]Department of Architecture, Ministry of Housing and Public Works, Bangladesh

ABSTRACT

Rapid urban population growth in Dhaka has led to dense high-rise housing, often characterized by poor window design, which causes indoor overheating and a greater reliance on air conditioning, thereby escalating energy consumption. This study addresses thermal discomfort in multi-unit residential buildings by optimizing Window-to-Wall Ratios (WWR) using a performance-based, single-objective optimization approach. A case study of a typical Dhaka apartment with four rooms of different orientations was analyzed using parametric modeling in Rhinoceros 3D and Grasshopper, with Galapagos optimizer, using Predicted Percentage of Dissatisfied (PPD) as the primary thermal comfort metric. The results indicate that a WWR between 69% and 70% minimizes PPD across all orientations, improving comfort by 9–13%. The findings highlight the importance of early-stage design optimization for thermal performance and recommend considering window placement, shading, and other metrics for comprehensive building improvements.

1. INTRODUCTION

The ongoing rapid urbanization of Dhaka, the capital city of Bangladesh, is attracting approximately 2000 migrants daily, resulting in a substantial rise in population density [1]. Facing the challenges of land scarcity, soaring land prices, and rising construction costs, high-rise multi-unit residential buildings have gained popularity to meet the ever-increasing housing demand of the growing population [2]. Vertical expansion is a viable solution for an urban area as densely packed as Dhaka. However, the design of these tall structures tends to focus on increasing density, resulting in inadequate provision for natural ventilation. Consequently, high-density buildings trap heat and moisture indoors, causing the internal temperature to rise to intolerable levels [3].

In recent years, Dhaka has experienced unprecedented heat waves, frequently causing overheating in buildings [4]. This rising temperature, driven by climate change, can have adverse effects on residents' health and productivity due to extended exposure to heat [5]. As temperatures continue to rise, air conditioners are being perceived as daily necessities to maintain a comfortable living environment in residential buildings. Market reports show that AC sales in Bangladesh have increased by 25% annually since 2015, with Dhaka accounting for 70% of the national demand [6]. The residential sector accounts for more than one-third of global energy use [7, 8], much of which is dedicated to maintaining suitable thermal conditions within buildings [9, 10].

One of the critical parameters affecting the thermal comfort of the indoor environment is the Window-to-Wall Ratio (WWR) of the building [11-12]. The WWR indicates the percentage of the building's exterior surface occupied by windows or openings compared to solid wall surfaces [13]. Typically, increasing the WWR enhances the thermal exchange between the interior and exterior, which can affect the indoor comfort levels and result in higher energy consumption for cooling or heating [9]. Passive design strategies aim to maximize views while minimizing heat gain and energy loss through the proper sizing and placement of windows and openings [14]. Simulation tools and performance analysis are crucial in aiding architects to assess the impact of various WWR values on energy usage, indoor environmental quality, and overall building performance [15-16]. The size, position, and orientation of a window play a crucial role in determining a building's ability to maintain comfortable indoor temperatures through natural ventilation. Addressing these design elements early in the design development process can reduce reliance on mechanical cooling systems, and the required thermal comfort can be achieved. Early studies have underscored the potential of courtyards and natural ventilation in Dhaka's context, citing improved daylight and airflow through the introduction of courtyard typologies [17].

*Corresponding author's email: mariajebin2013@duet.ac.bd

In recent studies, the focus has shifted towards optimal plan layout, WWR, window design, and shading design to maintain thermal comfort through natural ventilation in apartments in Dhaka [18-20]. It was noted that most existing research on the thermal comfort of residential buildings in Dhaka remains descriptive, adopting manual optimization methods.

In recent literature, several studies have attempted to determine the suitable window-to-wall ratios for different climates and building types [8-10, 13, 16]. Comparative examinations in similar climates such as Butwal in Nepal [21], Guwahati in India [22], Katuanyake in Sri Lanka [23] show strong links between WWR, orientation, and thermal comfort under natural ventilation. However, these studies often target single-unit houses or courtyard typologies and don't utilize parametric optimization frameworks to establish optimal WWR values.

Through literature review, a research gap emerged concerning natural ventilation and thermal comfort using parametric optimization, specifically in multi-unit residential buildings in the context of Dhaka. To address the identified research gap, the study aims to analyze the impact of varying window-to-wall ratios on the thermal performance of multi-unit residential apartment buildings within the climatic context of Dhaka. The primary objective is to optimize the WWR to achieve improved thermal comfort, as measured by the Predicted Percentage of Dissatisfied (PPD), a metric that quantifies occupants' thermal discomfort. Considering recent advancements in building performance optimization techniques [24], this research employs a single-objective optimization algorithm implemented through computer simulations. The simulations are based on prototypical design models representative of typical multi-unit residential buildings in Dhaka. This study aims to provide insights that can help architects and building designers make informed decisions about WWR, ultimately contributing to the development of more energy-efficient and thermally comfortable residential buildings in Dhaka.

2. METHODOLOGY

This study employs a parametric optimization approach to enhance the thermal performance of window designs in residential buildings. In architectural and environmental design, a parametric approach involves the use of computational tools to systematically vary design parameters—here, the WWR—and analyze resulting performance outcomes through iterative simulations. This method enables the identification of optimal design solutions that effectively respond to environmental conditions. A typical residential building located in Dhaka, Bangladesh, was selected as the basis for the study. This building represents standard construction practices commonly found in the region. Four rooms within the building, each facing a different direction, were selected for detailed analysis. These orientations were chosen to represent the varying effects of solar exposure on thermal performance throughout the building envelope. The selected rooms were modeled using Rhinoceros 3D (version 8), a precision modeling tool widely used in architectural workflows. The thermal performance of the base case models was analyzed using ClimateStudio 2.1, an environmental simulation platform that integrates the EnergyPlus engine to evaluate indoor thermal comfort conditions. Input parameters for the simulation included local climate data, material properties, internal heat gains, and occupancy schedules relevant to the climatic context of Dhaka. To explore the performance implications of varying the WWR, the Galapagos evolutionary solver, integrated within the Grasshopper plugin for Rhinoceros, was utilized. Galapagos enables automated parametric optimization by iteratively modifying the WWR and evaluating the performance of each configuration. The fitness function was defined based on thermal comfort metrics, such as PPD, derived from ClimateStudio.

The research process was organized into four primary phases, including (1) field measurements to assess current thermal conditions, (2) development of base case models based on field data and typical construction details to serve as the baseline for performance evaluation, (3) thermal performance analysis of the base case models, and (4) parametric optimization to identify design solutions that improved thermal performance for the studied rooms. This methodology integrates empirical data collection, validated simulation tools, and algorithmic design exploration to ensure a rigorous and reproducible approach to performance-driven design.

2.1 Thermal Performance Metric

The PPD index is used as the primary metric for thermal analysis because it provides a precise estimate of the number of occupants likely to be dissatisfied with thermal conditions. According to recognized standards such as ASHRAE 55 and ISO 7730, keeping PPD below 10% and 15% in occupied spaces is crucial for ensuring thermal comfort. This makes PPD the most effective tool for assessing and optimizing indoor environments.

2.2 Case Study Description

A multistoried government residential apartment building is considered as the case study for the research (Table I). The purposeful selection resembles typical criteria and maximum challenges required for qualitative reflection of housing characteristics and adequate accuracy of expected outcome. It is a 12-storied building with 4 dwelling units in each floor measuring approximately 1250 square feet in area. Each dwelling unit consists of four bedrooms, three bathrooms, two verandas, and combined living-dining space which is the standard Government 'E-Type Apartment' Typology. The layout is also commonly used in multi-unit residential projects for mid to upper middle-income communities in Dhaka. It is situated at the 'Architecture and Public Works Department Officers Quarters, Jigatola', near Dhanmondi-2, Dhaka, established within the urban residential zone and surrounded by one of the most complex and dense built fabric. The location exposes the building and its inhabitants to almost every microclimatic challenge of Dhaka such as elevated ambient temperature, reflected heat and obstructed wind-flow caused by surrounding structures, lack of natural shading elements and cooling agents, compromised air quality and intensive noise pollution. The studying units are located on the fourth floor, standing approximately 45 feet above ground level, representing mid-level environmental condition offering balanced condition of urban exposure and potential for natural ventilation and cooling. All these parameters set an ideal context for studying the impact of WWR on occupants' thermal comfort. Moreover, having built on a government housing complex, within the direct design service, construction supervision, and occupancy opportunities by the authorities responsible for the public building construction sector (Department of Architecture and Department of Public Works under Ministry of Housing and Public Works), the building complies with every construction regulation, codes, and ethics. Besides its institutional importance, the building also exemplifies the concurrent standards and prevailing practices in both public and private residential architecture. The apartment unit size also corresponds to the average dwelling size of the area mentioned in Detailed Area Plan (DAP) 2016-2035. The configuration and orientation reflect the expectation from middle-income urban housing in Dhaka city. Thus, the selection of the building intends to ensure meaningful findings extended to both the public and private sectors of multi-unit high-rise residential.

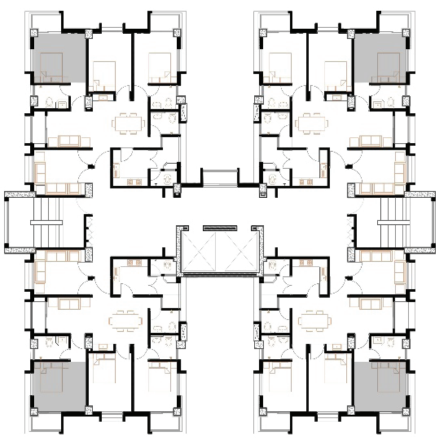
Table I: Parameters of the Case Studies

Parameters	Case 1 (A4)	Case 2 (B4)	Case 3 (C4)	Case 4 (D4)
Room Dim.	12′×11′			
Window Orientation	South-West, North-West	North-West, North-East	North-East, South-East	South-East South-West
Window Width	SW: 5′0″ NW: 5′5″	NW: 5′5″ NE: 5′0″	NE: 5′0″ SE: 5′5″	SE: 5′5″ SW: 5′0″
Window Height	7′0″			
Sill Level	0′0″			
Lintel Level	7′0″			
Window Type	Sliding glass window with 50% operable area			
Wall	150mm brick plaster wall, off-white color			
Ceiling	Concrete slab, white color			
Floor	Tile floor, beige color			

(a) (b)

Fig. 1: (a) Exterior View of the Case Study. (b) Interior View of the West-Facing Bedroom

Case 1 (A4) Case 2 (B4)



Case 4 (D4) Case 3 (C4)

Fig. 2: Floor Plan of the Case Building

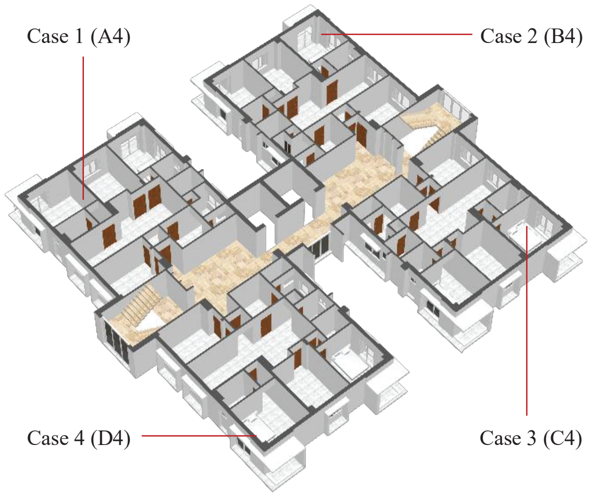


Fig. 3: 3D Model of the Case Building

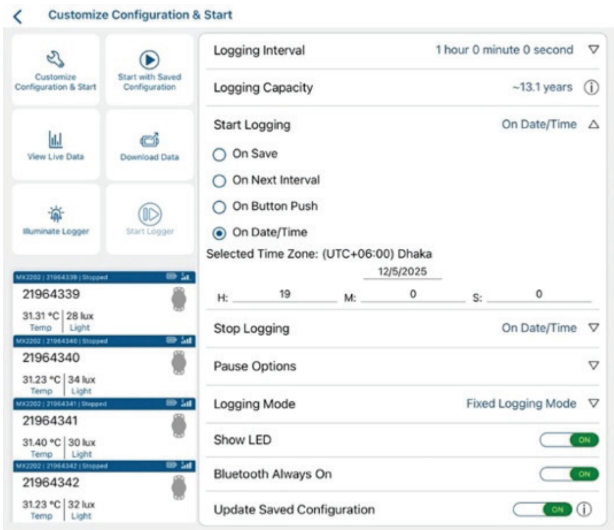
2.3 Experimental Protocol for Field Measurements

To evaluate the thermal performance of the test room envelope, field measurements were conducted. Air temperature data were recorded over 24 hours from May 9 to May 10, 2025, at the center of the room at a height of 1 meter above the floor, following ASHRAE Standard 55-2010 [25]. Four HOBO MX2202 pendant data loggers shown in Fig. 4(a) were employed for temperature monitoring. This waterproof device, featuring Bluetooth connectivity, allows for direct data transfer to mobile devices or Windows computers via a dedicated application, as shown in Fig. 4(b). It offers temperature measurement accuracy suitable for both air (ranging from -20°C to 70°C) and water (ranging from- 20 °C to 50°C). Table II shows the detailed configuration set for the data logging activity.

Table II: Deployment Information

Configure Date	2025/05/09 14:48:11 Bangladesh Standard Time
Logging Interval	1 hour 0 minutes 0 seconds
Logging Mode	Fixed - Normal
Start Logging	On Date/Time 2025/05/09 16:00:00 Bangladesh Standard Time
Stop Logging	On Date/Time 2025/05/10 15:00:00 Bangladesh Standard Time

(a)



(b)

Fig. 4: (a) Hobo MX2202 Pendant Data Loggers. (b) App Interface and Configuration Settings

2.4 Base Case Model

Building simulation models of the case study rooms were developed based on the existing building design and material characteristics (Table III). Room geometries were created using Rhinoceros 3D (v8), and parametric control was handled via Grasshopper. Thermal simulations were conducted using ClimateStudio (v2.1), which employs the EnergyPlus engine. Each room was modeled as a single thermal zone, using Dhaka's climate data (.epw format). Internal loads assumed an occupancy density of 0.16 persons/m², with 0.1 ACH infiltration and no mechanical heating or cooling systems, reflecting naturally ventilated conditions. Temperature ranges for the natural ventilation are 22° C and 28° C for indoors and 17° C and 28° C for outdoor conditions, based on EN 15251 (Fig. 5).

The base case models were used to evaluate the performance of the base case rooms, considering overall thermal performance over an entire year. The thermal condition was calculated by assessing the PPD.

Table III. Materials used for base Model Simulation

Element	Material									
	Name	Type	Reflectance [%]	Specular [%]	Diffuse [%]	Roughness	U-value [W/m²K]	SHGC*	Tvis*
Ceiling	White painted room ceiling	Glossy	82.20	0.44	81.76	0.200	-	-	-
Floor	Beige floor tile	Glossy	36.83	1.10	35.72	0.200	-	-	-
Wall	Offwhite plaster wall	Glossy	84.07	0.43	83.64	0.200	-	-	-
Window glazing	Solarban 72 on starphire	-	-	-	-	-	3.16	0.31	0.743

*SHGC- Solar Heat Gain Coefficient; Tvis- Visible Light Transmission

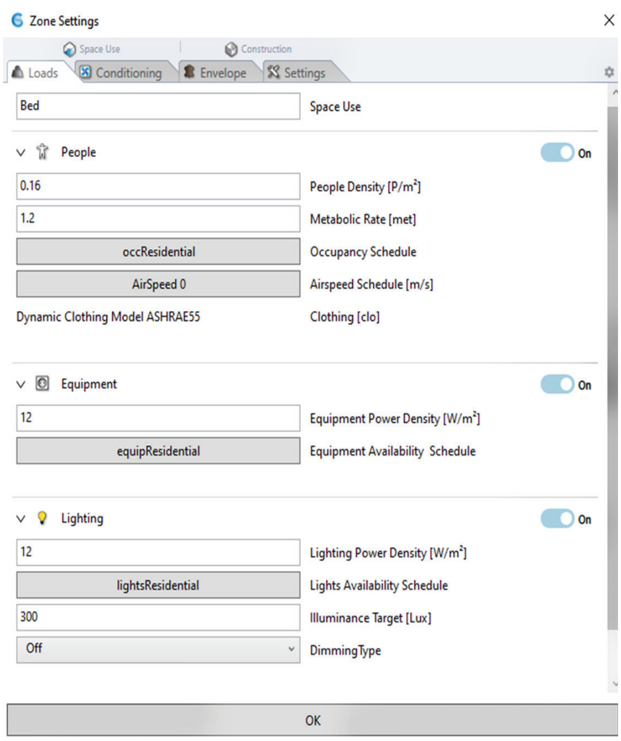


Fig. 5: Zone Settings

2.5 Optimization Approach for Building Performance

Recent developments in building optimization have led to its widespread adoption in architecture, particularly for addressing complex design challenges [24]. Optimization refers to the process of identifying the maximum or minimum value of a function by manipulating certain variables within predefined constraints [26]. Performance-based optimization involves tools such as parametric design, building performance simulations, and Genetic Algorithms [27]. Qingsong and Fukuda state that parametric design involves systematically varying design parameters within a defined space to explore multiple potential solutions. This approach supports informed decision-making by identifying options that satisfy, or closely approach, a set of predefined criteria [28]. Consequently, architects increasingly employ these methods to address complex environmental design issues [24]. Typically, the optimization framework consists of two key components: design variables and objective functions [27]. In the building performance optimization, variables refer to the parameters that define the design's geometry or physical characteristics, while objective functions represent performance indicators that are typically assessed through simulation tools [26]. When optimization targets a single performance criterion, the process is referred to as single-objective optimization, which is the approach adopted in this study.

2.6 Single-Objective Optimization

The main purpose of this step is to use the base case rooms and optimize their window design in terms of WWR for achieving the goal of minimizing PPD, which quantifies thermal discomfort as a percentage. The Grasshopper plugin Galapagos was used to optimize the design parameters for the single-objective optimization approach. Figure 6 shows the grasshopper script developed for single-objective optimization. In the script, there are six parts. The first part is developed for creating the surfaces of the room geometry, including the parametric components of the window, which will be used for the optimization process. The second part comprises selecting the materials for each surface defined in the room geometry from a wide range of material libraries from the ClimateStudio. The third part is the thermal model, which includes the detailed zone setting for the indoor environment in terms of load, conditioning, envelope, and additional settings. The fourth part is the Galapagos optimization tool, which is the primary basis of this study. It functions by connecting the design variables as the genomes, and performance metrics as the fitness objective. The final part is the data exportation component, which extracts detailed data derived from optimization in a structured Excel format, which is essential for intuitive analysis of the results.

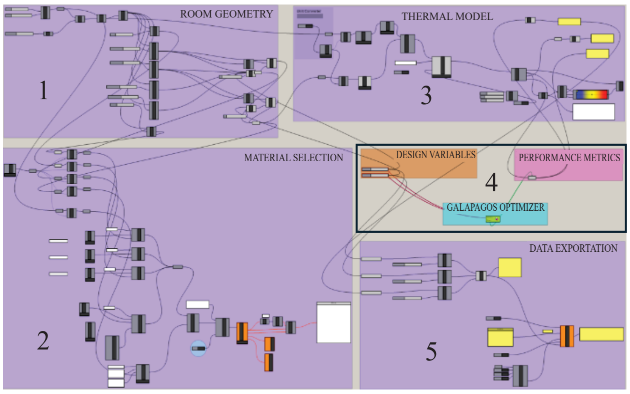
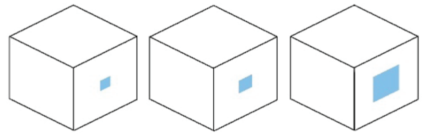
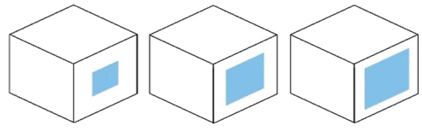


Fig. 6: Grasshopper Script Developed for Single-Objective Optimization

2.7 Optimization Parameters

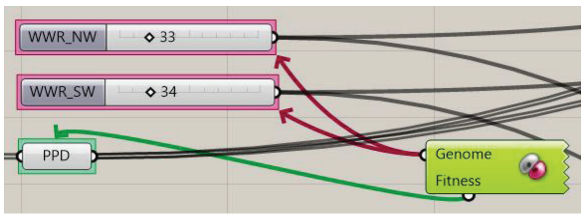
Windows significantly influence a building's thermal performance and energy use due to their higher heat transfer coefficients compared to opaque envelope components [29]. According to Lee et al. [30], window U-values are typically five times greater than those of walls or doors, accounting for 20–40% of energy loss in buildings. Poor window design can lead 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 [24]. In this study, WWR is used as a design parameter to evaluate its impact on PPD and identify optimal solutions. As per the Bangladesh National Building Code (BNBC), in mechanically ventilated and air-conditioned buildings across all occupancy types, the allowable WWR must be determined in relation to the glazing performance, specifically the Solar Heat Gain Coefficient (SHGC) or Shading Coefficient (SC) of the installed glass. As the SHGC of the window used in the case building is 0.31, the range of WWR was set to 10% to 70% for the optimization study. Table IV shows the WWR parameters adjusted during the optimization process.

Table IV: Parameters Adjusted During Optimization Process

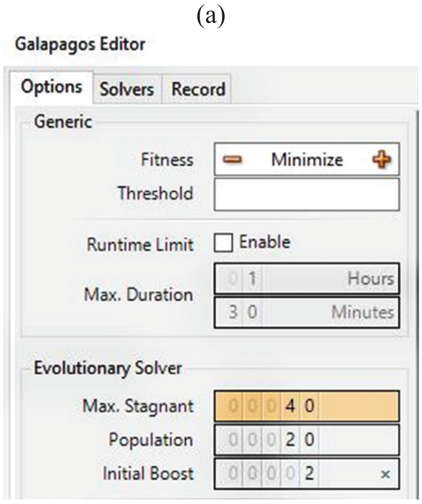
Window-Wall-Ratio (WWR)			Attributes
			
10%	20%	30%	10%-70%
			
40%	60%	70%	

2.8 Optimization Process

The Galapagos plug-in in Grasshopper was employed for single-objective optimization, generating parameter combinations based on a defined fitness goal. It adjusts one or more genomes to either minimize or maximize a specific performance metric. In this study, the WWRs of individual rooms were used as genomes, with PPD serving as the fitness objective (Fig. 7). The optimization was configured with a maximum of 50 generations, a population size of 20, and an initial boost of 2x (equivalent to 40 individuals).



(a)



(b)

Fig. 7: (a) Galapagos Genomes and Fitness Objectives; (b) Optimization Settings in Galapagos Editor

3. RESULTS AND DISCUSSION

3.1 Field Measurement

From the field measurement data, it is identified that, case 2 (B4) has the highest average temperature, and case 1 (A4) has the lowest average temperature. However, case 4 (D4) exhibits both the highest maximum temperature and the lowest minimum temperature, indicating the most significant fluctuations in thermal conditions throughout the day among all the rooms studied (Table V).

Table V: Field Measurement Data of Temperature

Case Study (Flat no.)	Max	Min	Average
Case 1 (A4)	33.46	31.01	31.86
Case 2 (B4)	33.03	31.74	32.54
Case 3 (C4)	33.07	31.57	32.15
Case 4 (D4)	33.63	30.59	31.99

Figure 8 shows the 24-hour temperature data for each case study room, derived from field measurements. In nearly all cases, the maximum temperature is observed between 4:00 AM and 6:00 AM. After that, the temperature starts to rise, reaching the peak between 1:00 PM and 2:00 PM.

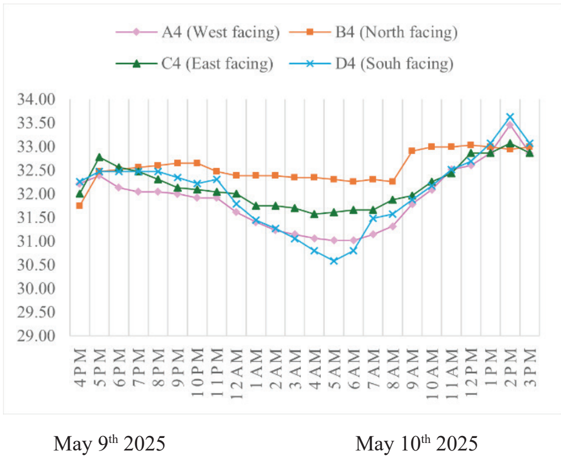


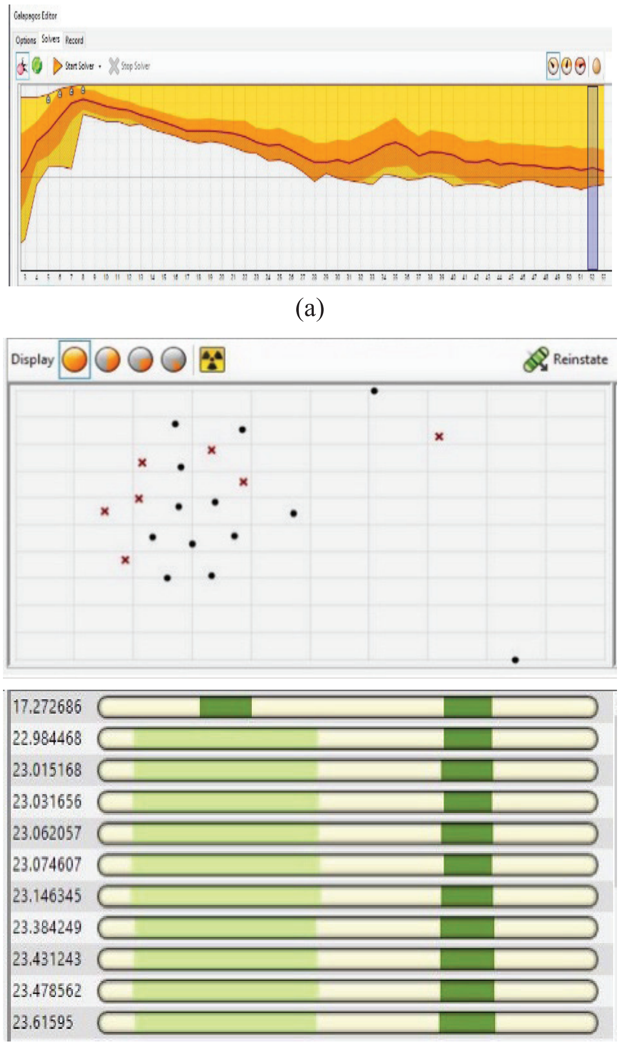
Fig. 8: Temperature data for 24 hours from Field Measurements.

3.2 Base Case Performance

The base case performance was evaluated by setting the WWR the same as the actual studied rooms for each unit of the case building and running the simulation with the EnergyPlus shoebox model. Table VI shows the simulation results of the PPD for the base case in all the different rooms on the same floor level. It is seen that case 2 (B4) has the highest level of PPD, indicating a higher percentage of dissatisfied occupants within that room. Again, case 4 has the lowest level of PPD, meaning better comfort conditions than the other three rooms. The results from the simulation study correlate with the field measurement data, indicating the validity of the simulation model. Table VI also indicates that the Mean Radiant Temperature (MRT) is lower in each optimized case compared to its respective base case, demonstrating improved thermal performance as a result of the optimization.

Table VI: Simulation Results of the PPD and MRT

Case Study	PPD	MRT
Case 1 (A4)	29.97%	27.47 °C
Case 2 (B4)	30.66%	27.53 °C
Case 3 (C4)	29.86%	27.47 °C
Case 4 (D4)	29.02%	27.53 °C



(a)

(b)

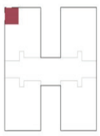
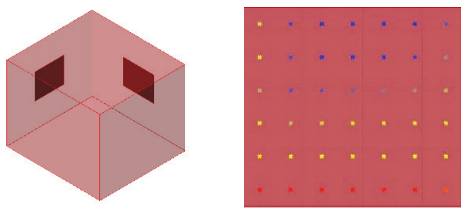
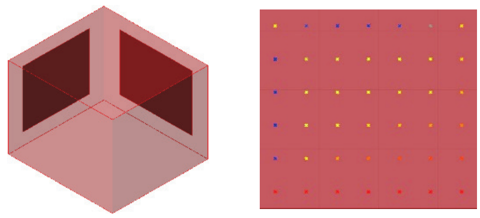
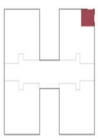
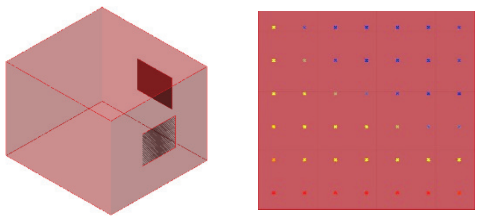
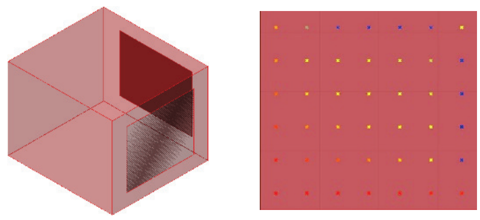
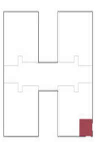
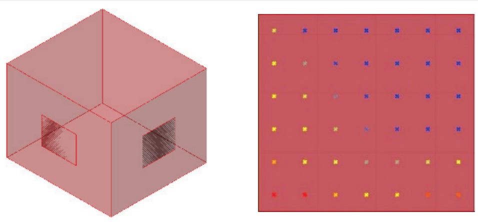
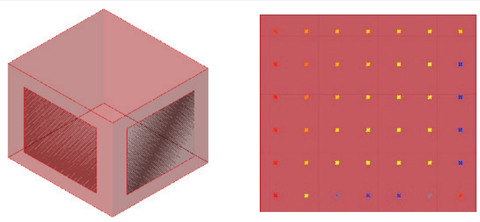
Fig. 9: (a) Galapagos Genomes and Fitness Objectives; (b) Optimization Settings in Galapagos Editor

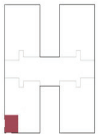
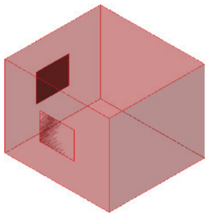
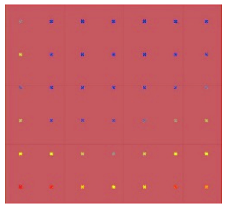
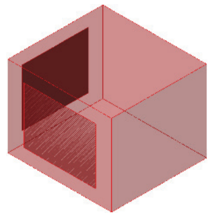
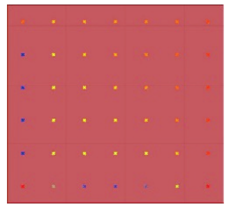
3.3 Optimization Solution for the Case Studies

A single-objective optimization algorithm was utilized to parametrically analyze various combinations of WWR using the PPD as a measure of thermal comfort. The goal of this analysis was to identify design options that offer the best thermal performance by minimizing PPD. Figures 9(a) and 9(b) illustrate how the Galapagos optimizer progressively filters out less effective solutions over successive generations during the simulation process.

Furthermore, all simulation outputs generated by the Galapagos optimizer were exported in .xlsx format for post-processing and cross-checking the identified optimal solutions. A summary of the results, highlighting WWR, PPD, and thermal comfort improvements achieved through optimization, is presented in Table VII. The analysis revealed that a WWR between 69% and 70% consistently yielded the lowest PPD values across all orientations, indicating a notable reduction in thermal discomfort and enhanced indoor environmental quality. Specifically, the optimized PPD values for the case 1, 2, 3 and 4 were 19.75%, 21.07%, 17.27%, and 16.31%, respectively. Compared to the baseline models, these results represent substantial improvements of 10.22% (case 1), 9.59% (case 2), 12.59% (case 3), and 12.71% (case 4) in thermal comfort performance.

Table VII: Summary of the Major Findings

Case	Attributes	Base Model	Test Model
Case 1 (A4)			
	WWR	SW: 34%; NW: 33%	SW: 69%; NW: 70%
	MRT	27.47° C	26.36° C
	PPD	29.97%	19.75%
	Remarks	Improved 10.22%	
Case 2 (B4)			
	WWR	NW: 33%; NE: 34%	NW: 70%; NE: 69%
	MRT	27.53° C	26.49° C
	PPD	30.66%	21.07%
	Remarks	Improved 9.59%	
Case 3 (C4)			
	WWR	NE: 34%; SE: 33%	NE: 69%; SE: 70%
	MRT	27.47° C	26.12° C
	PPD	29.86%	17.27%
	Remarks	Improved 12.59%	

Case	Attributes	Base Model	Test Model
Case 4 (D4)		 	 
	WWR	SE: 33%; SW: 34%	SE: 70%; SW: 69%
	MRT	27.39° C	26.01° C
	PPD	29.02%	16.31%
	Remarks	Improved 12.71%	

However, it is essential to assess these results in the context of several factors critically. As illustrated in Table VII, among the four rooms oriented in different directions, the southeast-southwest facing corner room (D4) achieved the lowest PPD and the most significant improvement in thermal comfort. In contrast, the northeast-northwest facing corner room (B4) recorded the highest PPD and the least improvement, indicating orientation has a considerable impact on thermal performance outcomes. The improvements observed were more pronounced in the northeast-southeast (C4) and southeast-southwest facing rooms (D4), suggesting that WWR optimization is particularly effective in rooms that experience direct sunlight for extended periods. The northeast-northwest (B4) and northwest-southwest (A4) facing rooms, although showing improvement, exhibited less enhancement compared to the northeast-southeast (C4) and southeast-southwest (D4) orientations, indicating that the design variable had a relatively smaller influence on thermal comfort for these facades. Figure 10 presents a comparative analysis of the PPD values for all four rooms, alongside their corresponding baseline PPD figures.

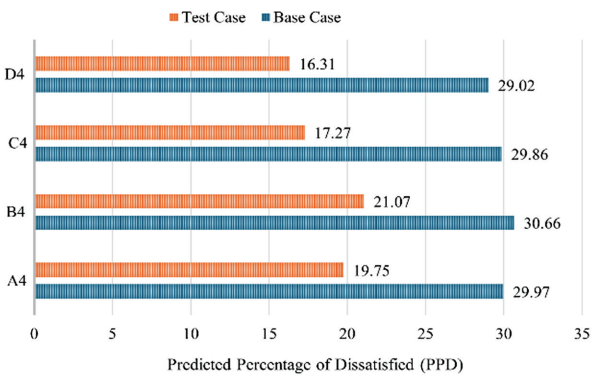


Fig. 10: Comparative Analysis of the Predicted Percentage of Dissatisfied (PPD)

Additionally, while the PPD improvements are notable, the achieved PPD values (ranging from 16.31% to 21.07%) remain above the commonly accepted comfort threshold of 10%. This indicates that while optimizing the WWR contributes to reduced thermal discomfort, it alone may not be sufficient to ensure optimal comfort. Further strategies such as incorporating shading devices or enhancing natural ventilation may be required, particularly for heat-sensitive occupants. Nonetheless, the observed reductions, ranging from 9% to 13%, represent a meaningful enhancement in occupant comfort achieved solely through adjustments to the window-to-wall ratio. It is essential to note that this study did not account for the effects of window placement or shading strategies, which could potentially influence thermal performance and should be explored in future research. Additionally, incorporating other building performance criteria, such as visual comfort and energy efficiency, alongside thermal performance, would provide a more comprehensive evaluation of design effectiveness.

4. CONCLUSION

This study demonstrates the potential of a parametric, single-objective optimization approach to enhance thermal comfort in residential buildings by optimizing the Window-to-Wall Ratio (WWR). Using the Predicted Percentage of Dissatisfied (PPD) as the primary performance metric and employing tools such as Rhinoceros 3D, EnergyPlus, and Galapagos, the research identified that a WWR between 69% and 70% consistently minimizes thermal discomfort across different room orientations. The optimized models showed notable improvements in PPD, ranging from 9% to 13%, compared to baseline scenarios, validating the effectiveness of the method despite PPD values remaining above the ASHRAE-recommended 10% threshold.

The findings underscore the importance of orientation-specific design strategies in warm-humid climates like Dhaka. However, the study acknowledges limitations, particularly the exclusion of window placement and shading strategies. Future research should integrate these factors and extend the optimization to include multi-objective criteria, such as energy efficiency and visual comfort, to support more holistic building performance improvements.

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