Configuring Windows and Clerestories of Bedrooms for Optimum Daylighting in Dining Spaces of Contemporary Apartment Buildings in Dhaka

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ABSTRACT

The majority of Dhaka's residential apartments contain dining spaces without windows due to their spatial organization. While large bedroom windows could improve dining space daylighting through doors and clearstories, if the bedroom is connected to the dining spaces; however, they risk glare and overheating in the bedrooms. This research explores optimal bedroom window position, shape and size, along with clerestories of varying widths in partition walls shared with dining spaces, to enhance dining space daylighting without causing glare to bedrooms. Using daylight simulations based on Leadership in Energy and Environmental Design (LEED v4.1) metrics and the daylight glare probability (DGP) index, various options were tested with ClimateStudio in Rhinoceros 7 and Grasshopper. Results show that strategically placing doors, windows and clerestories in adjacent bedrooms can significantly improve dining space daylighting. Optimally positioned rectangular windows (aspect ratio 0.3) and clerestories increased spatial daylight autonomy ($sDA_{300/50\%}$) by 2.8% and illuminance by 57% without creating glare.

1. INTRODUCTION

Buildings, particularly residences, support various human needs by serving as a place of convergence for people and societal identities. Optimal use of daylight is essential for visual comfort and well-being. Windows enhance spaces by providing daylight and views, supporting physiological and psychological health. Studies show daylight exposure reduces risks linked to vitamin D deficiency [1], boosts immunity [2], improves visual perception and mood [3], and increases occupant satisfaction [4].

The urban house form in Dhaka evolved through various phases. Initially, during the pre-Mughal period, resembling traditional rural designs (Fig. 1[a]) [5], houses were featured with rooms around courtyards for light and ventilation (Fig. 1[b]) [6]. In the Colonial period, this style merged with European bungalow designs, converting central courtyards into indoor spaces (Fig. 1[c]). Post-colonial houses became compartmentalized multistory blocks, with dining areas acting as central transition spaces to connect other rooms and balconies attached to peripheral rooms (Fig. 1[d]). The central living-dining areas, inspired by traditional courtyards, often lack adequate daylight and thermal comfort [7]. Large full-height apertures in surrounding rooms of the dining spaces may be used to improve daylight in the central dining space (Fig. 1[e]); however, it can cause indoor heat gain and glare, particularly in the rooms with south-facing facades.

Dhaka's rapid urbanization has led to severe housing challenges, prompting private developers to construct multistory apartment buildings with several units per floor. These deep-plan buildings (Fig. 1[e]), with large interior-to-external wall ratios [8], hinder natural ventilation and daylight, making them unsuitable for Dhaka's hot, humid climate [9]. An appropriate combination of window and shading systems can help extend non-cooling periods and save energy. The Bangladesh National Building Code (BNBC, 2020) [10] provides only general guidelines, lacking specificity for building function or performance targets. Dynamic daylight simulation can be used to enhance daylighting through passive features such as windows and clerestories.

Optimum window system design is essential to achieve standard illumination levels and minimize glare and even daylight distribution in interior spaces. According to Maleki [11], square and horizontal window shapes with a 30% window-to-wall ratio (WWR) in central and upper positions were optimum for south orientation in the context of Iran. The same configuration of windows with a WWR of 40% was found as optimum for the north orientation. Another study found that, a WWR of 39% in the middle position can enhance daylight and energy

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performance up to 12% [12] for an office space. Another study reported a 68% reduction in glare and a 70% increase in daylighting performance by adjusting WWR and shading in the educational space of Iran [13]. Most of these experiments are related to non-residential buildings.

A study related to residential daylight performance in warm-humid climates reported that a change in the window position could be beneficial in maintaining spatial daylight autonomy ($sDA_{300/50\%}$) and annual sunlight exposure ($ASE_{1000,250h}$) within the prescribed limit of 75% and 20% respectively [14]. Another study reported that 61% of the variability in energy consumption can be defined by changes in the WWR of residential buildings in hot-arid climatic zones [15]. These studies are limited to a specific climatic context. Little or no guideline is found on window location and WWR of bedrooms and clerestories of the peripheral walls of dining spaces to improve the overall luminous environment of the apartments by illuminating dining spaces. Multiple apertures, such as windows on two sides of a space or clerestories, can increase the distribution of daylight in a space. Against this backdrop, this research aims to find the optimum position, shape and size of windows on the bedrooms' facades and optimum clerestory configuration in the partition walls around the adjacent dining space to enhance daylight illumination of the dining space without creating glare in the bedrooms.

Fig. 1: Transformation of Courtyards and Balconies in Urban Houses Through Different Periods (After [16])

2. METHODOLOGY

This research followed a five-step methodology. First, the case space and climatic context were defined. Second, key design variables were selected, and a parametric model was developed using Rhinoceros 7 and Grasshopper. Third, dynamic daylight metrics were chosen to optimize daylight in the dining space through bedroom windows while minimizing glare in the bedrooms, with performance benchmarks set to ensure balanced lighting. In the fourth step, the impact of each variable on daylight quantity and glare probability was evaluated. Finally, a sensitivity analysis was conducted to assess the effects of window configurations, leading to the development of design guidelines.

2.1 The Case Space

Nearly 57% of Dhaka residents were classified as a mid-middle income group (monthly income 370 USD to 555 USD) and preferred two-bedroom apartments due to their financial capacity [17]. Three distinct types of living-dining layouts were identified in these middle-income group apartments: attached, continuous and separate (Fig. 2[a]. The attached type was significantly prominent in numbers [18]. Taking into account those mentioned above, a case residential apartment of 88m2 area [16,18] was selected as the case space for the simulation study (Fig. 2[b]). It had two bedrooms, one attached type living-dining space, a kitchen, two toilets and one verandah. The dining space area was 12.7 m2 without any window for direct penetration of daylighting. The average area and WWR of bedrooms were 14.4 m2 and 19%, respectively. The floor-to-ceiling height was 3.0 m, and the width of the shading device was 0.5 m [10]. To investigate the effect of the selected variables on the daylighting condition of the dining space, the interior of the case apartment and the surroundings were considered vacant. The case space was considered on the ground floor of a six-story building as the daylighting condition is expected to be the worst on ground floor. The 3D model of the case apartment was validated for daylighting in a previous study [7].

2.2 Climatic Context and Weather Data

Dhaka is located between the latitudes of 23°40' N and 23°55' N and the longitudes of 90°20' E and 90°30' E. According to the Koppen Climate Classification, it falls under Category-A, that is, Tropical Savanna. Primarily, three distinct seasons can be observed here– the hot dry (March-May), the warm humid (June-November) and the cool dry (December-February) seasons. Both clear

Fig. 2: [a] Types of Living-Dining Layout in Dhaka's Residential Apartment; and [b] Plan of the Case Apartment

and overcast sky conditions are observed in different parts of various seasons. The sky remains clear with the sun and overcast in the hot dry season. The sky remains significantly overcast during the warm humid period, including the monsoon. Only in the cool dry season, the sky remains mostly clear.

Hourly weather data BGD_Dhaka.419230_SWERA, downloaded from the website of EnergyPlus™, was used in this research. It is based on high quality solar and wind energy information developed by the Solar and Wind Energy Resource Assessment (SWERA) project, financed by the United Nations Environment Program (UNEP) [19].

2.3 Design Variables for Residential Daylighting

Daylight availability in spaces depends on different features, such as window location, placement or position, width, window head height and size [20, 21]. WWR is one of the factors that determine how much daylight enters a building's interior. Increasing the WWR to maximize daylight quantity will not always ensure an effective visual environment but may also cause glare and overheating [22]. Clerestories or combined side lighting systems permit deeper penetration of daylight while little glare and discomfort, depending on the mounting height and width [7, 26]. In this study, three independent design variables for window design: window shape, position and window size were selected for simulation study. In the case of clerestory window design, only the width of the clerestory was considered here as the mounting height (2.1 m) for clerestories in residential apartment's partition walls were fixed above the lintel and maximum window height (i.e., up to the ceiling) will not cause overheating and glare.

2.4 Benchmark of Daylighting Performance Metrics

Leadership in Energy and Environmental Design (LEED) Version 4.1 introduced a rating system to evaluate the daylight performance of buildings using the IES-LM-83-12 Standard [24]. In this standard, two dynamic metrics are used: $sDA_{300/50\%}$ and $ASE_{1000,250h}$. These two metrics are evaluated in a grid analysis on a horizontal work plane. In the $sDA_{300/50\%}$ metrics, daylight sufficiency of a specific area is measured as a percentage of the area that exceeds a target illuminance value (300 lux) for a specified amount of time of a year (50% of the annual hours). The target value of $sDA_{300/50\%}$ was considered as 75% for this study [24].

$ASE_{1000,250h}$ refers to the percentage or fraction of area that exceeds the direct sunlight level of 1000 lux more than 250 hours per year, which can cause glare over a specified daily schedule with the operable shading devices retracted. As residential tasks are less desk and screen-oriented, glare is usually less concern and the use of blinds is determined by several factors, including privacy and thermal comfort. Consequently, the target value of $ASE_{1000/250h}$ was considered as 20% for this study [25].

Besides these two metrics, a complementary approach of glare prediction assesses the probability of glare in the perceptual field of view, termed daylight glare probability (DGP). DGP is an index indicating the probability of an occupant's dissatisfaction with the difference between bright and dark areas within the visual environment caused by direct sunlight or high light source luminance [26]. It is presented as a percentage of time or space an occupant may be disturbed by glare on a four-point scale: imperceptible (DGP<35%); perceptible (35%≤DGP<40%); disturbing (40%≤DGP<45%); intolerable (DGP≥45%) on a scale between 20% to 80%. Daylight standard of the European Committee for Standardization (CEN) [27] proposed different levels for glare protection in interior spaces: minimum 45%, medium 40% and high 35%, not more than 5% of the occupied time of a space. So, the minimum accepted level of DGP for glare protection was considered 45%.

2.5 Daylight Simulation Method

The parametric model of the case space was constructed using Rhinoceros and Grasshopper (Fig. 3[a]). Then, the weather data and surface materials were assigned in the ClimateStudio (CS) plugin, regarded as the fastest and most accurate simulation tool based on EnergyPlusTM and a novel RADIANCE-based path tracing technology. Reflectance values for the ceiling, walls, floor and shading devices were 88.4%, 83.9%, 64.9% and 82.4%, respectively. The window construction was 6mm single clear glass with a solar heat gain coefficient (SHGC) value of 0.64. The sensor grid was set at 0.75m high from the finish floor level. The grid spacing was considered as 0.6 m (36 sensors in the dining space and 80 sensors in the bedrooms) (Fig. 3b). For the calculation of the DGP index simulation, ClimateStudio software considered the height of the subject's field of view in the seated position at 1.2m from the finished floor level. The daylight simulation schedule was considered from 8:00 AM to 6:00 PM. The simulation outputs of each design variable were measured to achieve a maximum amount of $sDA_{300/50\%}$ for the dining space by placing the optimum window size on the bedrooms' facades to reduce the risk of glare in the bedrooms.

The daylight performance of each selected variable was assessed based on the chosen daylight performance metrics (Section 2.4). There were three steps in the assessment process (Fig. 4). In the first step, window shapes and positions were assessed. In the second step, the variable of clerestory configuration was assessed along with the window shape and position found best in the first step. The impact of several WWRs of the ideal window shape and position, along with the best clerestory configuration, was then evaluated for the dining area and the bedrooms.

3. DAYLIGHT SIMULATION ANALYSIS AND RESULTS

3.1 Assessment of Window Shapes and Positions

The first two variables were window shape and position (Table I). Two types of window shapes- square and rectangular, were used for each of the four window positions: low, high, middle and corner. The low window begins at the bottom of the facade and the middle window is located precisely on the central axis of the facade [11, 20]. In the case of the corner window, two design options were evaluated. In the first option, windows were placed at one end of the facades just opposite the bedroom doors to provide daylight in the dining through the doors. In the second option, windows were placed away from the door. Multiple design options were created by changing these two design variables and keeping the WWR at 14% according to BNBC 2020 [10] (Table I). Aspect ratio (AR) width to height ratio (W/H) was used to define the window shapes in this study. Rectangular vertical windows with an AR value of 0.3 were the same in the case of low, middle and high positions as in this specific facade, AR 0.3 comprised the full length of the facade. These window configurations were placed on the facades (Fig. 3) to investigate their effect on the daylight illuminance of the dining space (Fig. 3[b]).

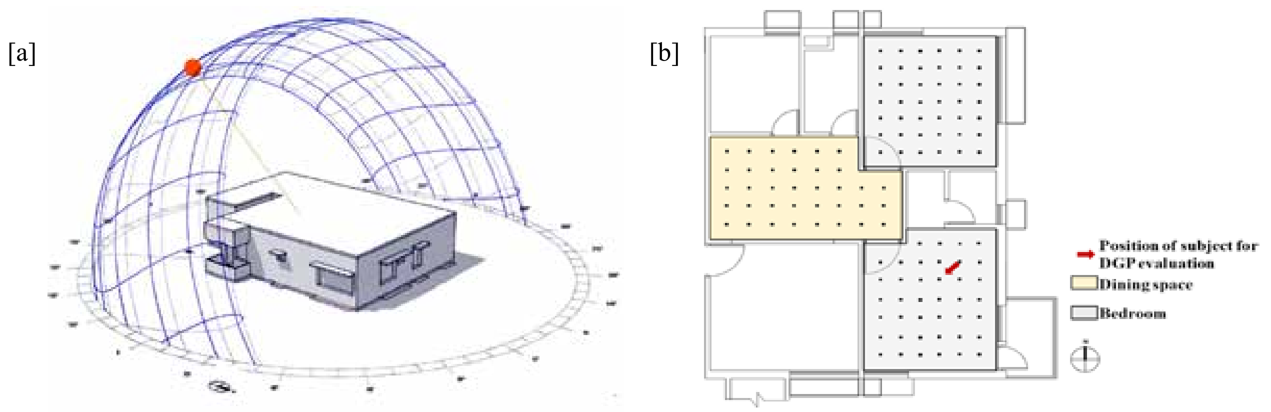


Fig. 3: [a] Three-Dimensional Model of the Case Residential Apartment in Rhinoceros; and [b] Sensor Grid Setup of Dining Space and Two Bedrooms

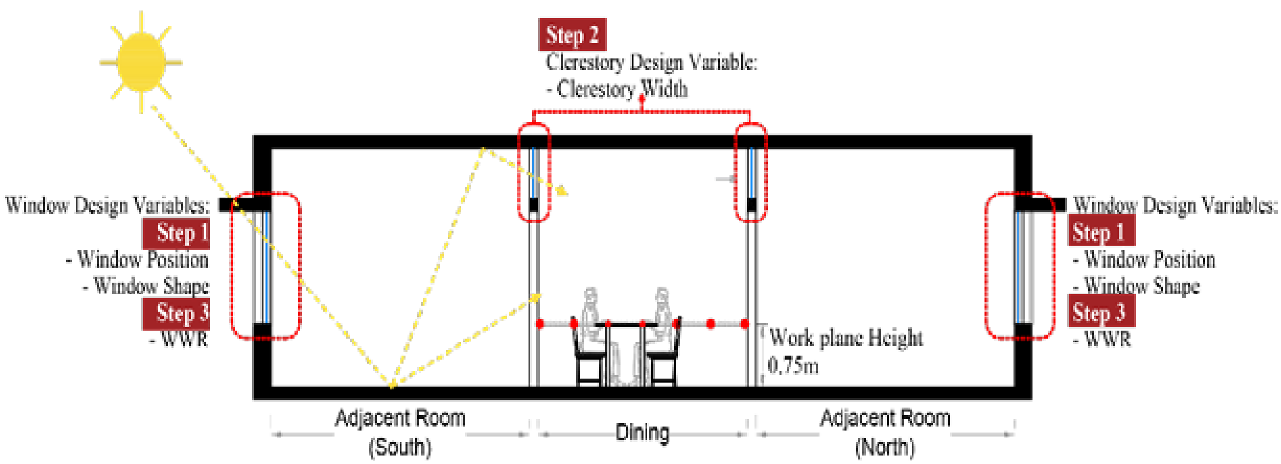


Fig. 4: Conceptual Section Showing Different Window Design Variables (Position, Shape and WWR) and Clerestory Configurations for Performance Evaluation

The results of daylight simulations for different window positions and shapes with a constant WWR of 14%, along with rating points (RPs) and ranking, are presented in Table III. The studied design options produce zero ASE$_{1000,250h}$ values in the dining space, sDA$_{300/50\%}$ values range from 0.0-1.8% and annual average illumination values from 62.5-84.8 lux. As the ASE$_{1000,250h}$ values were zero, and the sDA$_{300/50\%}$ and illumination values were below the acceptable and standard level, a rating system [25] was developed to analyze the simulation results. The rating was done considering 0 to 24 points to recommend the configurations from 1st to 25th rank. Rectangular vertical window with AR value 0.3 ranked 1st. Rectangular vertical window with an AR value of 0.5 in the low window position and a square window in the middle position of the facade, ranked 2nd and 3rd positions, respectively.

Considering the rating point distribution, rectangular vertical windows performed better than rectangular horizontal windows. In addition, the middle windows performed better than the other three window positions (Table III). This is because it can transmit more daylight by creating better reflections from the walls of bedrooms due to its central position in the facade. This indicates that vertical windows with greater height perform better than horizontal windows, and window head height has a more significant impact on the $sDA_{300/50\%}$ and illuminance values than the window width. In contrast, horizontal windows performed better in corner positions with a greater AR value.

3.2 Assessment of Clerestory Configuration

Clerestories with two different widths (Table I and Fig. 4) were inserted alternatively in the partition walls around the dining space after placing the optimum window position and shape (rectangular middle window with AR=0.3) in the bedrooms' facades. The effectiveness of the width of the clerestory was investigated only as the mounting height (above the lintel level, 2.3m) and the height of the clerestories (between lintel and ceiling, 0.6m) was fixed. The results of the simulations revealed that the $sDA_{300/50\%}$ value after inserting a clerestory C1 was not changed, the illuminance value increased by 18.9% from the previous condition. $sDA_{300/50\%}$ and annual average illumination values increased by 1.2% and 18% after inserting the clerestory C2 in the partition wall around the dining space.

3.3 Assessment of Window-to-Wall Ratio (WWR)

Optimum WWR is required in the bedrooms to balance daylight illumination of the dining space and bedrooms. The optimum WWR of the best window shape and position found in Section 3.1, along with the best clerestory configuration (Section 3.2), were investigated in this section. WWR of the base case was selected as 14%, according to BNBC 2020 [10]. The selected range of WWR for the daylighting assessment is 20%- 90% other than the base case (Fig. 5). The impact of each WWR of the test windows on the bedrooms' facades was investigated in two steps. In the first step, the impact of the nine different WWRs of bedrooms on the illumination condition of the dining space (Fig. 3[b] and Fig. 4) was investigated. Then, their effect on the illumination condition of the bedrooms (Fig. 3[b] and Fig. 4) was also assessed to avoid glare.

In the dining space, the preferred or accepted levels of $sDA_{300/50\%}$ were not achieved, even with a WWR of 90% on the bedrooms' facades. The $ASE_{1000,250h}$ and DGP values remained 0% (Fig. 5). In the case of bedrooms, $sDA_{300/50\%}$ values were increasing slowly with an increase in WWR and were in the preferred limit; however, the $ASE_{1000,250h}$ increased to 44.7% from the lowest to the highest value of WWR. WWRs from 40% and above exceeded the acceptable limit (<20%) of $ASE_{1000,250h}$, though it can provide a preferable daylight level. Considering the benchmark values of the daylight performance metrics, 30% is the optimum WWR among the studied WWR that can provide useful daylight both in dining space and bedrooms without risk of glare (Fig. 6). Although the greater value of WWRs provided the preferred $sDA_{300/50\%}$, it has the possibility of glare in the bedrooms.

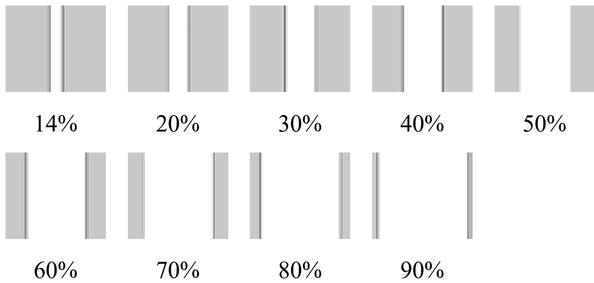


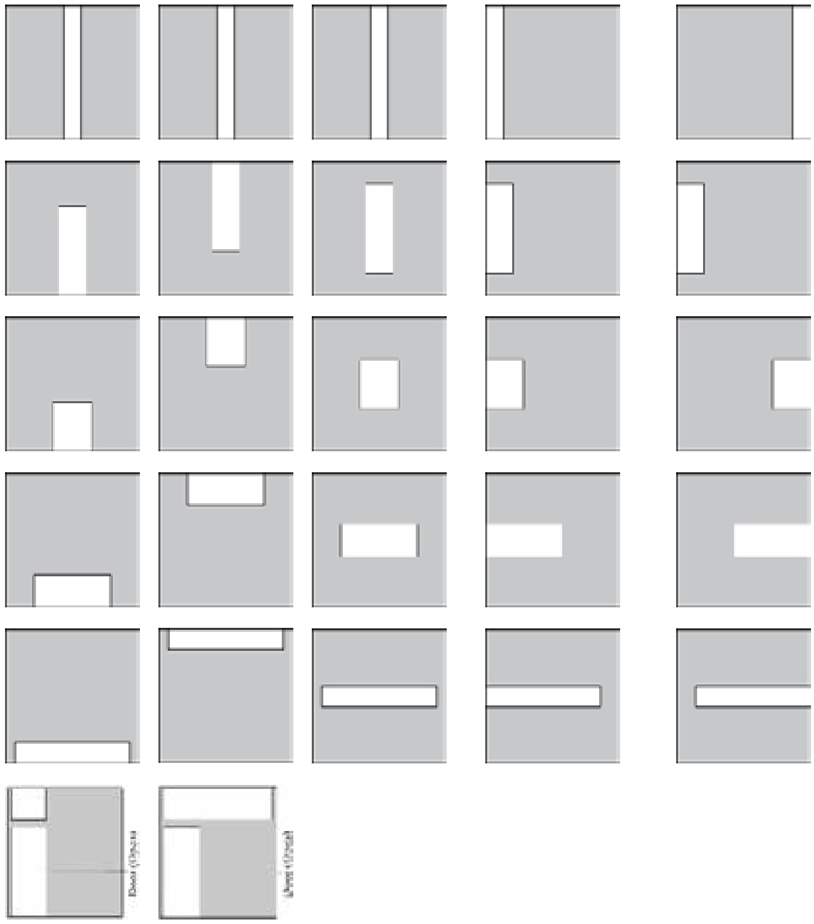
Fig. 5: Selected Range of WWR of the Test Windows on the Bedrooms' Facades for the Simulation Assessment

3.4 DGP Evaluation of Bedrooms

To determine whether discomfort glare is present in the visual field of bedrooms and to confirm the accuracy of the results computed in the preceding section, the glaring probability of the bedrooms was estimated through targeted glare analysis. The subject's location was considered in such a position that the maximum bedroom area can be visible (3[b]). It was carried out on a point-in-time basis in the critical periods of the year with the optimum WWR. Glare analysis was done on the summer solstice (21st June), autumnal equinox (22nd September), the winter solstice (22nd December) and the vernal equinox (20th March) at 9.00h, 12.00h and 15.00h, to visualize the risks of glare in a visual field. Results of the point-in-time glare analysis with the position of the subject are summarized in Fig. 7. The annual DGP value of the bedrooms with optimum WWR of 30% (opposite wall of the bedrooms' door) was 34.9%, which indicates the occurrence of

Table I: Window Position and Shape with Different Aspect Ratios for the Simulation Study

	Shape and AR \ Position		Low	High	Middle	Corner (opposite to door)	Corner (away from the door)
Window Shape and position	Rectangular (vertical)	0.3					
		0.5					
	Square	1.0					
	Rectangular (horizontal)	2.0					
		3.0					
Clerestory Width			Only over the Door (C1)	Over the Entire Length of the Partition Walls (C2)			



perceptible glare within the preferred range for this study (Section 2.4). From the point-in-time glare analysis for the south-east bedroom, imperceptible glare (DGP<35%) was found on the critical dates.

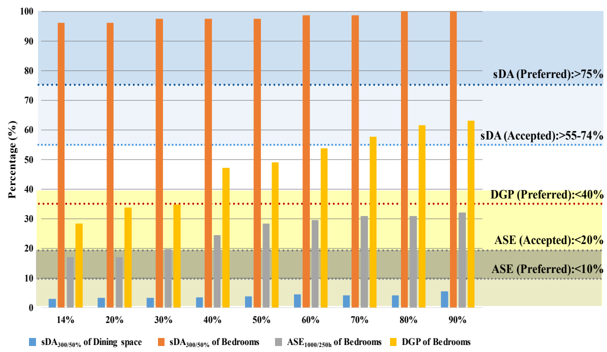


Fig. 6: Performance of Different WWRs of Bedrooms' Facades on Daylight Condition of the Dining and Bedrooms Based on SDA, ASE and DGP Metrics

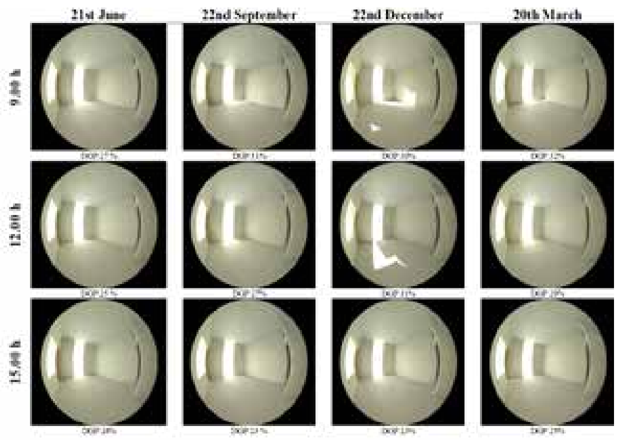


Fig. 7: Daylight Glare Probability of the Bedroom (South-East) with Optimum WWR of 30%

WWR of 30% on the bedrooms' facades opposite the doors increased the $sDA_{300/50\%}$ and annual average

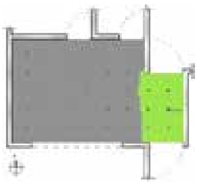
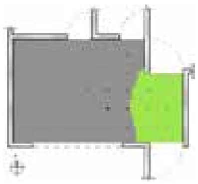
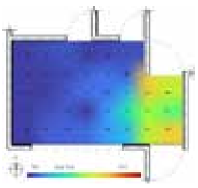
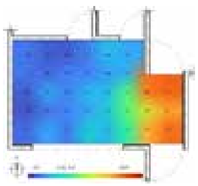
Table II: Summary of Daylight Simulation Results for Different Window Positions and Shapes with a Window Area of 14% of the Bedrooms, Along with the Rating Points and Ranking

Window position	Window shape	Aspect ratio (W/H)	Value and rating points (RP)	$sDA_{300/50\%}$ (%)	Annual average illumination (Lux)	Total RPs		Rank
Low window	Rectangular (vertical)	0.3	Value	1.8	84.8	48	155	1st
			RP	*24*	*24*			
		0.5	Value	1.5	80.2	45		2nd
			RP	*23*	*22*			
	Square	1.0	Value	0.0	62.0	4		20th
			RP	*0*	*4*			
	Rectangular (horizontal)	2.0	Value	0.5	72.0	31		10th
			RP	*17*	*14*			
		3.0	Value	0.3	71.2	27		14th
			RP	*16*	*11*			
High Window	Rectangular (vertical)	0.3	Value	1.8	84.8	48	189	1st
			RP	*24*	*24*			
		0.5	Value	1.0	71.3	32		5th
			RP	*20*	*12*			
	Square	1.0	Value	1.3	79.8	43		8th
			RP	*22*	*21*			
	Rectangular (horizontal)	2.0	Value	1.3	74.7	38		4th
			RP	*22*	*16*			
		3.0	Value	1.0	67.0	28		12th
			RP	*20*	*8*			
Middle Window	Rectangular (vertical)	0.3	Value	1.8	84.8	48	191	1st
			RP	*24*	*24*			
		0.5	Value	1.2	74.8	38		9th
			RP	21	*17*			
	Square	1.0	Value	0.8	73.3	34		3rd
			RP	*19*	*15*			
	Rectangular (horizontal)	2.0	Value	0.8	81.0	42		5th
			RP	*19*	*23*			
		3.0	Value	0.7	70.2	29		13th
			RP	*18*	*11*			
Corner Window (Opposite to door)	Rectangular (vertical)	0.3	Value	0.5	62.5	22	124	18th
			RP	*17*	*5*			
		0.5	Value	0.2	46.8	15		19th
			RP	*15*	*0*			
	Square	1.0	Value	0.5	69.5	27		14th
			RP	*17*	*10*			
	Rectangular (horizontal)	2.0	Value	0.5	63.8	23		17th
			RP	*17*	*6*			
		3.0	Value	0.7	76.8	37		6th
			RP	*18*	*19*			

Window position	Window shape	Aspect ratio (W/H)	Value and rating points (RP)	$sDA_{300/50\%}$ (%)	Annual average illumination (Lux)	Total RPs		Rank
Corner Window (away from the door)	Rectangular (vertical)	0.3	Value	0.5	79	37	153	6th
			RP	*17*	*20*			
		0.5	Value	0.5	66.2	24		16th
			RP	*17*	*7*			
	Square	1.0	Value	0.5	71.5	30		11th
			RP	*17*	*13*			
	Rectangular (horizontal)	2.0	Value	0.5	69	26		11th
			RP	*17*	*9*			
		3.0	Value	0.67	75.2	36		7th
			RP	18	18			

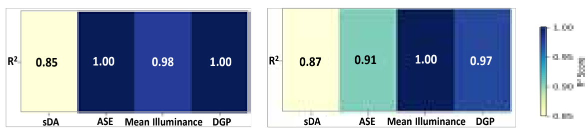
illumination values by 0.3% and 8.9%, respectively. The distribution of daylight in the dining space was also improved. Comparison of the daylight condition of the original model and updated model in terms of $sDA_{300/50\%}$ and annual average illumination are shown in Table III.

Table III: Comparison of the Original and Updated Model's $sDA_{300/50\%}$ and Annual Average Illumination Distribution

	Original model	Updated model
$sDA_{300/50\%}$		
Annual average illumination		

4. SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to evaluate the impact of window size (WWR) on four performance metrics: mean illuminance, $sDA_{300/50\%}$, $ASE_{1000/250h}$ and DGP. The coefficient of determination (R^2) from regression models was calculated and compared for both the dining space and bedrooms, as shown in Fig. 8. An R^2 value close to 1.00 indicates that WWR explains nearly all variability in a given metric. In contrast, lower values suggest the influence of additional factors. For ASE, mean illuminance, and DGP, high R^2 values (0.98–1.00 in the dining space and 0.97–0.99 in the bedrooms) confirm that WWR predominantly governs these metrics. In contrast, $sDA_{300/50\%}$ showed slightly lower R^2 values (0.85–0.87), suggesting that while WWR has a strong influence, it is not the sole determining factor.



[a] Dining space [b] Bedroom

Fig. 8: Heat Map of the Sensitivity Analysis for Dining Space and Bedroom

5. CONCLUSION

This study demonstrates how reflected or diffused daylight from adjacent bedrooms can enhance dining space illumination by adjusting key design variables-window position, shape, clerestory width and WWR, highlighting the critical role of bedroom window design in improving daylighting in deep urban residences. The optimum window position was found to be the middle of the facade, where a vertical rectangular window (AR 0.3) with increased window head height significantly boosted daylight in the dining space, improving $sDA_{300/50\%}$ by 1.3% and illuminance by 32% from the base case. Adding a full-length clerestory further improved $sDA_{300/50\%}$ by 1.2% and illuminance by 14.7%. A 30% WWR vertical window on the wall opposite the bedroom door enhanced $sDA_{300/50\%}$ and illuminance by 0.3% and 9%, respectively. While 30% WWR proved optimal, larger windows with adjustable shading could further enhance daylight without causing glare in bedrooms.

The optimum results of this study can be directly used in buildings with similar contexts to improve daylight availability. In addition, this methodology of daylight inclusion in the deepest part of the residence can be used as a basis for deriving design solutions for other climatic contexts and building types. Besides the variables presented in this paper, other variables, such as external and internal shading devices, and occupant behavior related to daylight inclusion along with surrounding context, can be investigated in future studies. On the other hand, the benchmark of daylighting metrics may not apply to all types of climates. In that case, threshold values for the daylighting metrics can be investigated for different climatic contexts.

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