Assessing Window Design's Impact on Daylight Uniformity in Classrooms in Patna, India

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ABSTRACT

Windows play a vital role in daylight infusion, significantly impacting indoor visual comfort. Various metrics exist for evaluating visual comfort in which the uniformity ratio falls under the distribution category and is as crucial as illuminance levels. This ratio effectively reduces the likelihood of glare and the need for artificial lighting. The primary objective of this research is to assess the impact of window design on daylight uniformity ratio in a classroom setting. In pursuit of this objective, a study investigated the uniformity ratio (U_o) of north-oriented and south-oriented classrooms of Kendriya Vidyalaya (KV) Khagual, Patna. The study considered five common shapes of windows (excluding the existing base cases) at different window-sill levels. Ninety simulations were run in the DesignBuilder software under overcast, intermediate, and clear sky conditions. To assess the uniformity ratio on three dates: March 21st, June 21st, and December 21st, which correspond to the highest, equinox, and lowest solar availability during the year under intermediate and clear sky conditions at three distinct times. The omission of the specific time and date for overcast conditions and the particular year for clear and intermediate sky conditions is justified as the outcome remains consistent throughout all years. The results show that the window design and sill level significantly affect the uniformity ratio. The research findings show that window design in Case 9 at a sill of 1230 mm and lintel of 3050 mm (just below the slab) consistently produces the best uniformity ratio across all sky conditions, independent of classroom orientation. This paper offers valuable design recommendations by comparing the uniformity ratio for five commonly used window designs. This is one of the first studies of window design and position to evaluate the uniformity ratio in the classrooms at Patna.

Keywords-window design; uniformity ratio; daylight; classroom; simulation

I. INTRODUCTION

Window design is a crucial aspect of daylighting in buildings. Well-designed windows can significantly impact the distribution of natural light, enhancing visual comfort and reducing the need for artificial lighting during daylight hours. Positioning, size, and shape of windows influence the amount of daylight that enters the space and the way it is distributed. Strategic window design allows optimal daylight penetration while minimizing glare and unwanted heat gain. In comparison to artificial electric light, natural daylight provides occupants with enhanced visual comfort [1]. As a result, daylight plays a pivotal role in window design, offering the potential for passive solutions that improve energy efficiency and visual comfort [2]. The effective utilization of daylighting in buildings can be ensured by conducting daylight performance analysis and integrating the results into the building facade design process [3]. Additionally, it represents a notable architectural strategy in creating visually comfortable classrooms, enhancing circadian activity and reading-writing speed, and positively influencing the well-being of students and teachers [4]. A well-lit building with natural light and solar radiation for heating and cooling reduces electricity demand, offers comfortable indoor temperatures, and lowers energy consumption and greenhouse gas emissions [5-7]. Efficiently utilizing solar radiation allows buildings to create a comfortable and productive indoor environment while promoting energy saving and sustainability [8].

In classrooms, daylight evaluation encompasses several metrics, including static evaluation (illuminance and daylight factor) and dynamic evaluation (useful daylight illuminance, daylight autonomy, continuous daylight autonomy, spatial daylight autonomy), based on the analysis period (point-in-time vs. annual), sky model (standard vs climate based) [6], and distribution (illuminance uniformity) [9]. Out of these, the uniformity ratio is especially critical for classrooms, as insufficient uniformity can lead to glare and increased dependence on artificial lighting [10]. Research demonstrates a preference for classrooms with uniform daylighting, even if the illuminance levels are lower, as opposed to an uneven distribution of light with higher illuminance. Achieving a uniformity ratio in a side-lit classroom is challenging. The illuminance levels decline as one walks away from the window, and there is a considerable drop in illuminance at the opposite corner of the classroom, reducing the uniformity ratio.

This paper focuses primarily on the north and south orientations due to the substantial differences in daylight supply between these two directions in the northern hemisphere. The southern orientation receives abundant direct sunlight, while the northern orientation benefits from diffused sunlight. These two orientations present a notable contrast for investigation. The current study is limited to north and south-oriented classrooms. The East-West orientations remain open to future exploration and research. The study at hand is one of the first studies of window design and position (sill level) to evaluate the uniformity ratio in the south and north-oriented classrooms in composite climate at KV Khagual, Patna, which previous researchers ignored. This research introduces a new perspective to investigate the impact of window design and position (window-sill) on the uniformity ratio and adds existing knowledge of daylight uniformity. The findings of this research are specific contributions in this field.

II. LITERATURE REVIEW

Table I provides a concise overview of the past research on design proposals of varying categories and building types.

TABLE I. WINDOW/FACADE CONFIGURATION LITERATURE

Design proposal	Category	Building type	References
Energy, thermal, visual performance	Window configuration	Office	[11-14]
Energy and visual performance	Window configuration	Classroom	[15-17]
Energy, thermal, visual performance	Window configuration	Residential	[18-20]
Energy and visual performance	Window configuration	Non-residential	[21]
Energy, thermal, visual performance	Facade configuration	School	[22]
Energy and visual performance	Facade configuration	Residential	[23]
Energy and visual performance	Facade configuration	Office	[24]
Energy and visual performance	Window configuration	-	[25-26]

This research aimed to improve the visual performance of buildings using static and dynamic metrics. The literature review revealed that window/facade configurations significantly impact the buildings' visual performance. The climate and window orientation influence the outcomes, leading to varying results. Horizontal windows exhibited superior illuminance uniformity and increased energy savings for electrical lighting. On the other hand, higher-positioned (sill) windows facilitated deeper penetration of daylight into indoor spaces. Furthermore, centrally placed windows at eye level provided favourable outside views. The daylight factor also gives more residential satisfaction [27, 28].

III. METHODOLOGY

This study examines daylight uniformity resulting from window design and position (sill level). It specifically focuses on investigating the effects of commonly utilized window shapes and positions in classrooms situated within the composite climate of India. The research process involves several steps. Firstly, it entails creating a model of the classroom geometry, including all window configurations ranging from case 1 to case 10, within the DesignBuilder software. In the second step, simulations are conducted under three distinct conditions: clear, intermediate, and overcast sky. The simulations were performed for March 21st, June 21st, and December 21st, corresponding to the highest, equinox and lowest solar availability during the year for the intermediate and clear sky conditions at three distinct times: 9:00 a.m., 12:00 p.m., and 3:00 p.m. The impact of different window designs and position (sill level) on uniformity ratios are analyzed. A total of 10 cases were investigated, with 5 cases featuring centrally located windows while maintaining the existing sill and lintel levels and the other 5 cases having windows at elevated positions (sill level). Figure 1 depicts the opted research workflow.

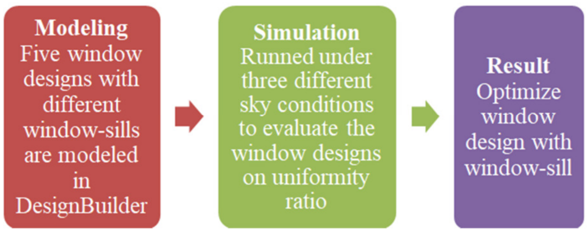
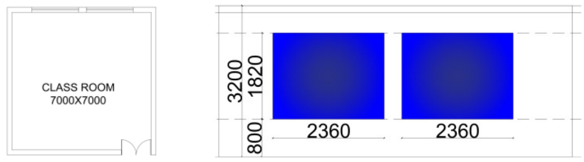


Fig. 1. Research workflow.

A. *Window Design and Position*

This study involves selecting various window designs and window sills for the classrooms under investigation. Five commonly used window designs were considered. Figure 2 illustrates the window design (plan and elevation) with sill and lintel level. Figure 3 illustrates the 10 cases of window design of the same window-to-wall ratio (WWR) of 40.23% with alternative 01 from Case 1 to 5 and alternative 02 from Case 6 to 10. In alternative 01, the sill and window height are kept fixed to match the existing conditions, creating what is referred to as a centrally located window. In alternative 02, the windows are elevated, with the top positioned just below the classroom ceiling. For Cases 1 to 5, the window sill is 800 mm, and the lintel is kept at 2620 mm, whereas from Cases 6 to 10, the window sill is 1230 mm, and the lintel is 3050 mm (just below the slab).

The KV Khagul classrooms adhere to the standards and guidelines regarding area and dimension, which are common throughout the country. The selected KV school is located in Khagul, Patna, Bihar, India, with coordinates of 25°35'05.00"N and 85°01'56.80"E. The classroom has dimensions of 7 m × 7 m, covering an area of 49 m^2, with floor-to-floor height equal to 3.30 m. It is situated on the ground floor, has side lighting, and is oriented towards the south. Figure 2 displays the typical plan and the elevation of the window side wall of a classroom. The single-pane clear glass windows in this classroom has dimensions of 2360 mm × 1820 mm and a WWR of 40.23%.



(a) (b)

Fig. 2. (a) Class design, (b) elevation (window side wall).

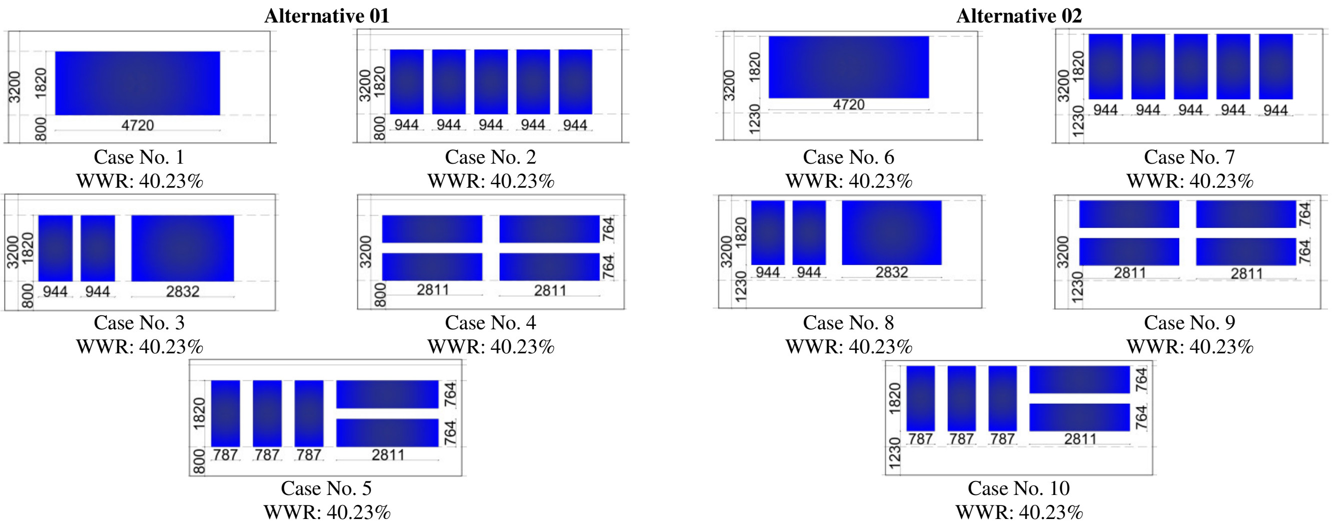


Fig. 3. Window design and position (sill level).

TABLE II. MATERIAL REFLECTANCE AND TRANSMITTANCE

Particular	Reflectivity
Walls	0.75
Ceiling	0.80
Floor	0.20
Glass (transmittance)	0.80 (transmittance)

The CIE [29] model is more accurate than the Perez model [30] in predicting sky luminance in Indian tropical conditions, provided the correct CIE sky type is known. This model's capability to match the actual sky conditions in the region enhances the reliability of daylight simulations and analysis [31]. For this study, the CIE clear day, CIE intermediate day, and CIE overcast day sky conditions were chosen for simulation. These sky conditions were selected to replicate the typical sky conditions experienced in India throughout the year.

B. *Uniformity Metric*

Illuminance Uniformity or Uniformity Ratio (U_O) is a metric expressed as the ratio between the minimum illuminance value on a given plane (E_{min}) and the average illuminance (E_{avg}) at that specific moment. Alternatively, in certain cases, the ratio can be defined as the ratio between the minimum (E_{min}) and maximum (E_{max}) illuminance values on the same plane, so it is essential to specify the definition used [32].

$$U_{O,avg} = \frac{E_{min}}{E_{avg}} \quad (1)$$

$$U_{O,max} = \frac{E_{min}}{E_{max}} \quad (2)$$

According to the guidelines set by the Building Research Establishment Environmental Assessment Method (BREEAM), the uniformity ratio can be expressed as the Minimum Daylight Factor (DF_{Min}) divided by the Average Daylight Factor (DF_{AVG}). Table III outlines the prescribed threshold values for the uniformity ratio in the classroom.

TABLE III. RECOMMENDED ILLUMINANCE UNIFORMITY STANDARDS FOR CLASSROOMS

Particular	Uniformity ($U_{O,avg}$)	Reference
Classrooms, tutorial rooms	> 0.6	[33]
General teaching	0.8	[34]
Task area	> 0.6	[35]
Side lit classroom	0.3-0.4	[34]

IV. RESULTS AND DISCUSSION

Figures 4-7 illustrate the uniformity ratio for south and north-oriented classrooms under clear and intermediate sky conditions on 21st of March, 21st of June, and 21st of December, at 9:00 a.m., 12:00 p.m., and 3:00 p.m. The omission of the specific year is justified as the outcome remains consistent throughout all years. Figures 8 and 9 illustrate the uniformity ratio for south and north-oriented classrooms under overcast sky. By analyzing the data depicted in Figures 4-9, one can gain valuable insights into the daylight performance of the south and north-oriented classrooms and the impact of window design and position (sill level) on achieving uniform illumination throughout the space under all three sky conditions. Window design and position in Case No. 9, as shown in Figure 3 achieve the highest uniformity ratio in all conditions. Additionally, specific window shapes and positions yield elevated uniformity ratios when placed at higher sill levels, resulting in values slightly exceeding 0.6 for the north-oriented classroom under clear sky condition. The window design and position shown in Case No. 1 give the lowest uniformity ratio among all cases.

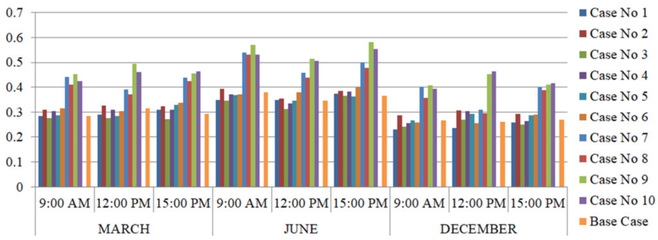


Fig. 4. Uniformity ratio for a south-oriented classroom under clear sky.

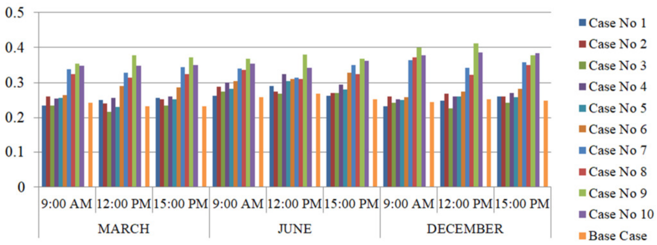


Fig. 5. Uniformity ratio for a south-oriented classroom under intermediate sky.

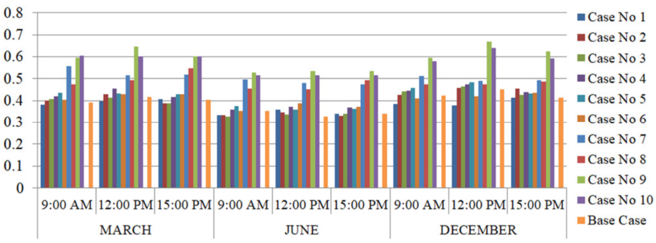


Fig. 6. Uniformity ratio for a north-oriented classroom under clear sky.

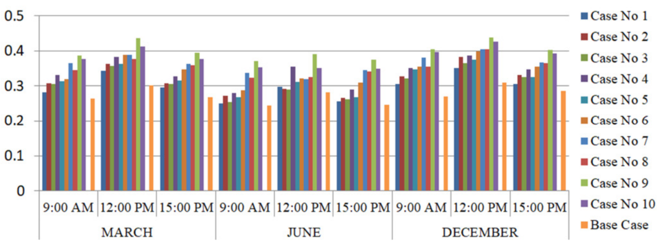


Fig. 7. Uniformity ratio for a north-oriented classroom under intermediate sky.

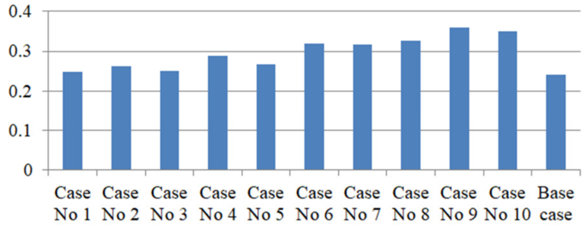


Fig. 8. Uniformity ratio for a south-oriented classroom under overcast sky.

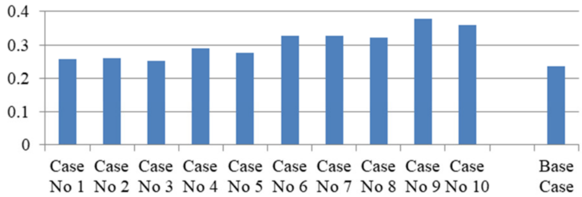


Fig. 9. Uniformity ratio for a north-oriented classroom under overcast sky.

A. Impact of Window Design and Position on the Uniformity Ratio

In Case 9, where the windows are placed at a higher sill level of 1230 mm, the north-oriented classroom under clear sky achieves a 0.6 or more uniformity ratio in March and December and more than 0.5 in June. Window design in Case 10 exhibits almost the same uniformity ratio as in Case 9. The same window design with a higher sill level achieves a more uniformity ratio than a lower sill level. The window designs in Cases 6-10 with higher sill level (1230 mm) achieve approximately 0.3 or more uniformity ratio in all three-sky conditions in both orientations. From Case 1 to Case 5, centrally located windows yield uniformity ratios ranging from 0.21 to 0.48 at various times and months. Case 7 ranks third in providing higher uniformity ratios for both orientations.

B. Impact of Sky Condition on the Uniformity Ratio

The uniformity ratio (U_o) obtains a value of 0.67 under clear sky, which is characterized by dominating radiation, which is the greatest among the other sky situations in the north-oriented classroom. The highest uniformity ratio under intermediate sky was 0.438 and 0.411 and was observed for Case 9 on the 21st of December in the north-and south-oriented classroom, respectively. Conversely, the lowest U_o value of 0.234 was recorded for Case 1 on the 21st of March at 9:00 a.m. in the south-oriented classroom. Under overcast sky, where direct radiation is absent, the highest U_o of 0.37 is observed for the north-oriented classroom in Case 9. Conversely, the lowest U_o value of 0.248 is recorded for Case 1 in the south-oriented classroom under the same sky conditions.

C. Impact of Orientation on the Uniformity Ratio

The impact of the classroom orientation on the uniformity ratio is apparent; north-oriented classrooms achieve approximately more U_o value than south-oriented classrooms under all three sky conditions. The impact of orientation on the U_o is more evident, particularly when comparing north-oriented classrooms with south-oriented classrooms under clear sky conditions. In north-oriented classrooms, there is more variation in the uniformity ratio. Under intermediate sky conditions, the variation in uniformity ratio between north and south-oriented classrooms is less pronounced compared to the clear sky conditions. This suggests that the distribution of daylight is more consistent in both orientations when a mix of direct and diffused sunlight characterizes the sky condition. Under overcast sky, the impact of orientation on the uniformity ratio is minimal, as both north and south-oriented classrooms tend to exhibit similar trends, because the sky is heavily clouded, with no direct sunlight in overcast sky conditions. Instead, the sky acts as a significant diffused light source, providing relatively uniform lighting across the space.

V. CONCLUSION

The present study has assessed the impact of window design on daylight uniformity and uniformity ratio in a classroom setting. A comparative experiment was conducted using simulations to analyze the impact of window design and sill on three typical days and times for north-oriented and south-oriented classrooms of KV Khagual, Patna. Various configurations of rectangular window forms were examined, with two sill heights (800 mm and 1230 mm) while maintaining a consistent window-to-wall ratio (WWR). The research findings show that window design in Case 9 at a sill of 1230 mm and lintel of 3050 mm (just below the slab) consistently produces the best uniformity ratio for all sky conditions, independent of classroom orientation. This research emphasizes the importance of window sill in improving daylight distribution and visual comfort in a classroom. Placing windows strategically at high sill heights allows for equal dispersion of natural light, resulting in a comfortable and well-lit learning environment for students and teachers. This method improves homogeneity and optimizes lighting performance in educational areas.

It is important to note that the results of this study are based on a limited set of sky conditions, window shapes, and placements. Therefore, future research should investigate a broader range of window designs of east and west orientations under varying sky circumstances to assess their influence on the uniformity ratio while considering elements like WWR, window sill, and other architectural solutions. Researchers may get deeper insights into the link between window design, daylight uniformity, daylight performance, and visual comfort by performing more extensive studies, allowing them to develop more successful daylighting techniques for various building types contexts.

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