IMPACT OF WINDOW-TO-WALL RATIO, GLASS VISIBLE TRANSMITTANCE, AND SURFACE REFLECTANCE ON INDOOR ILLUMINANCE: A SIMULATION STUDY USING DIALUX

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ABSTRACT

The growing adoption of window facades in buildings has enhanced the use of daylighting, which has generally been well-received by occupants. However, the effectiveness of daylighting in interior spaces can be influenced by several factors, including the window-to-wall ratio (WWR), glass visible transmittance (VT), and the reflectance of walls, ceilings, and floors. This study investigates how these factors affect indoor average illuminance. To model the indoor lighting environment and adjust these factors, a simulation method using DIALux software was employed. Multiple linear regression analysis was then used to assess the impact of each factor on average illuminance. The results reveal that WWR and VT are the most significant variables, with their increases leading to substantial improvements in illuminance, though the benefits diminish at higher levels. In contrast, ceiling and floor reflectance have minimal effects, with ceiling reflectance being the least impactful. The regression analysis validates the model's high predictive accuracy and highlights the critical role of WWR and VT in achieving optimal lighting conditions.

Keywords: daylighting, indoor illuminance, simulation analysis, WWR, surface reflectance

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1. INTRODUCTION

In recent times, there has been a notable rise in the adoption of window facades in buildings, with glass curtain walls becoming increasingly prevalent. There is a growing emphasis on harnessing daylight to create a visually comfortable indoor environment, leading to more active exploration in this regard [1]. Buildings abundant in natural light typically foster a more favorable work atmosphere compared to those reliant on artificial lighting. Human beings tend to react more positively to natural light, which enhances the functionality of their eyes and brains, resulting in heightened concentration and overall better performance [2]. Studies conducted on office buildings have demonstrated that elevated levels of daylight can enhance employees' working performance and their capacity to recall information. Research focusing on educational buildings has revealed that optimal daylighting is associated with improved student performance and lead to heightened satisfaction and morale among both students and teachers [3].

A more sustainable lighting solution can be realized using a three-stage design approach. The first stage consists of adjusting geometric shapes and surface colors or reflectances, the second aims to maximize natural light use, and the third incorporates artificial lighting. In tropical countries with abundant daylight, effectively harnessing this light presents a valuable opportunity for design implementation [4]. Nasrollahi & Shokry in [5] suggest implementing windows with a maximum height to width ratio of 35 to 45%, and reflection coefficient for the roof, floor, walls with windows, and walls of two other fronts are 0.6, 0.4, 0.4, and 0.6, respectively, to achieve optimum visual comfort in the building. Changing the color of room surfaces (walls, ceiling, and floor) to white or brighter colors has been proved able to improve lighting quality [6]. Katunský et al. in [2] indicated that white, gray, green, or yellow walls, along with a white ceiling and brown floor, were perceived as the most suitable choices for the interior surfaces in the hall under consideration. Makaremi et al. in [7] investigated how surface color reflectance relates to lighting efficiency and discovered a strong correlation between the reflectivity of the ceiling and lighting system performance. Enhancing indoor surface reflectance is crucial for improving visual comfort and can lead to potential electrical energy savings of up to 45%. However, according to Roy et al. in [8], the ideal combination of room surface reflectance should strike a balance, avoiding surfaces that are excessively absorptive or overly reflective.

Related to the openings, a study in three rooms of an office in Jakarta revealed that daylight openings facing the same orientation but differing in type, position, size, and material, yield varying quantities and qualities of light across different spaces. In addition, the reflective surfaces both inside and outside the rooms significantly influence the effectiveness of natural lighting in each workspace [9]. Tahbaz et al. in [10] assesses how architectural design details—such as window size and frame, glass size and color, and ceiling shape and height—affect daylighting, using simulations to modify or remove these elements. The results show that alterations in design features like ceiling shape, window height and size, and glass specifications significantly impact light distribution and intensity in different seasons within the room. Cammarano et al. in [11] alters architectural features of a room—such as its orientation, window size, depth, and external obstructions—and analyzing how these modifications affect daylight performance. This helps to understand how daylight availability within a space varies because of these changes. The findings of this study can help determine how room depth and window size affect the availability of daylight in a space. They can also be used to adjust window dimensions and room layout to achieve the desired level of daylight.

Because numerous factors, including the room's geometry, the ratio of windows to walls, window component, such as glass ratio, glazing materials and shading devices, and internally reflected component, which is the lighting component originating from reflections of surfaces within the room, such as the ceiling, room, and floor, surface material, and color affect the quantity of natural light that enters indoor areas, it's essential to grasp the significance of each element in indoor lighting [3], [8]. Nasrollahi & Shokry in [5] suggest investigating those factors and how each element contributes to the lighting environment to provide a fundamental strategy for designing daylighting systems in buildings. Therefore, this study seeks to investigate the impact of window design and the reflectivity of interior surfaces on the dispersion of light withing buildings.

2. METHOD

Research into indoor lighting generally combines experimental field measurements with computational simulations. This approach employs various metrics and indices such as illuminance, illuminance uniformity, daylight factor, luminance, and visual comfort probability [12], [13]. Advances in technology have greatly enhanced the role of digital tools in architectural design, especially in lighting simulation. Modern simulation software is crucial in the design process, providing a comprehensive foundation for tackling multiple challenges simultaneously. These tools not only offer a visual representation of a building's lighting environment but also supply critical parameters needed for design [14].

To examine the relationship between room lighting levels, window design, and interior surface reflectance, the software DIALux Evo was chosen for its suitability. This tool excels in simulating, calculating, and visualizing both natural and artificial lighting, making it ideal for the analysis [12]. As a free software, DIALux Evo is well-regarded for its capability to simulate lighting conditions both externally and internally within buildings. Verification results confirm that DIALux Evo's outputs closely match reference values from experimental tests under various lighting conditions, including both artificial and daylighting [12], [15]–[17]. Comparisons between experimental data and simulation results showed that the percentage error did not exceed 10%, demonstrating that the accuracy of DIALux Evo's model is generally acceptable [12].

A baseline model was created using DIALux Evo with dimensions of 3.5 meters in width, 6 meters in depth, and 2.8 meters in height, featuring a window on the north-facing facade. The model's depth is more than twice its height to promote effective daylighting [18]. It has a Window-to-Wall Ratio (WWR) of 0.5, glass visible transmission (VT) of 0.4, and surface reflectances for the ceiling, walls, and floor set at 0.7, 0.6, and 0.3, respectively (Figure 1a). The model includes 45 light sensors to measure illuminance, shown by the blue color in Figure 1c. The simulation takes place on March 21st at 09:20 under clear sky conditions, coinciding with the sun's position during the equinox [19].

Initially, the impact of each variable—WWR, glass visible transmission (VT), ceiling reflectance (CR), wall reflectance (WR), and floor reflectance (FR)—is analyzed individually. Each variable is adjusted while keeping the others constant. For example, to assess the effect of WWR, it is varied from 0.1 to 0.75, while the other parameters remain unchanged. The same approach is used for the other variables, with the average illuminance on the workplane, positioned at a height of 0.8 meters, being assessed from the simulations (Figure 1). The variable input ranges are presented in Table 1 and Figure 2.

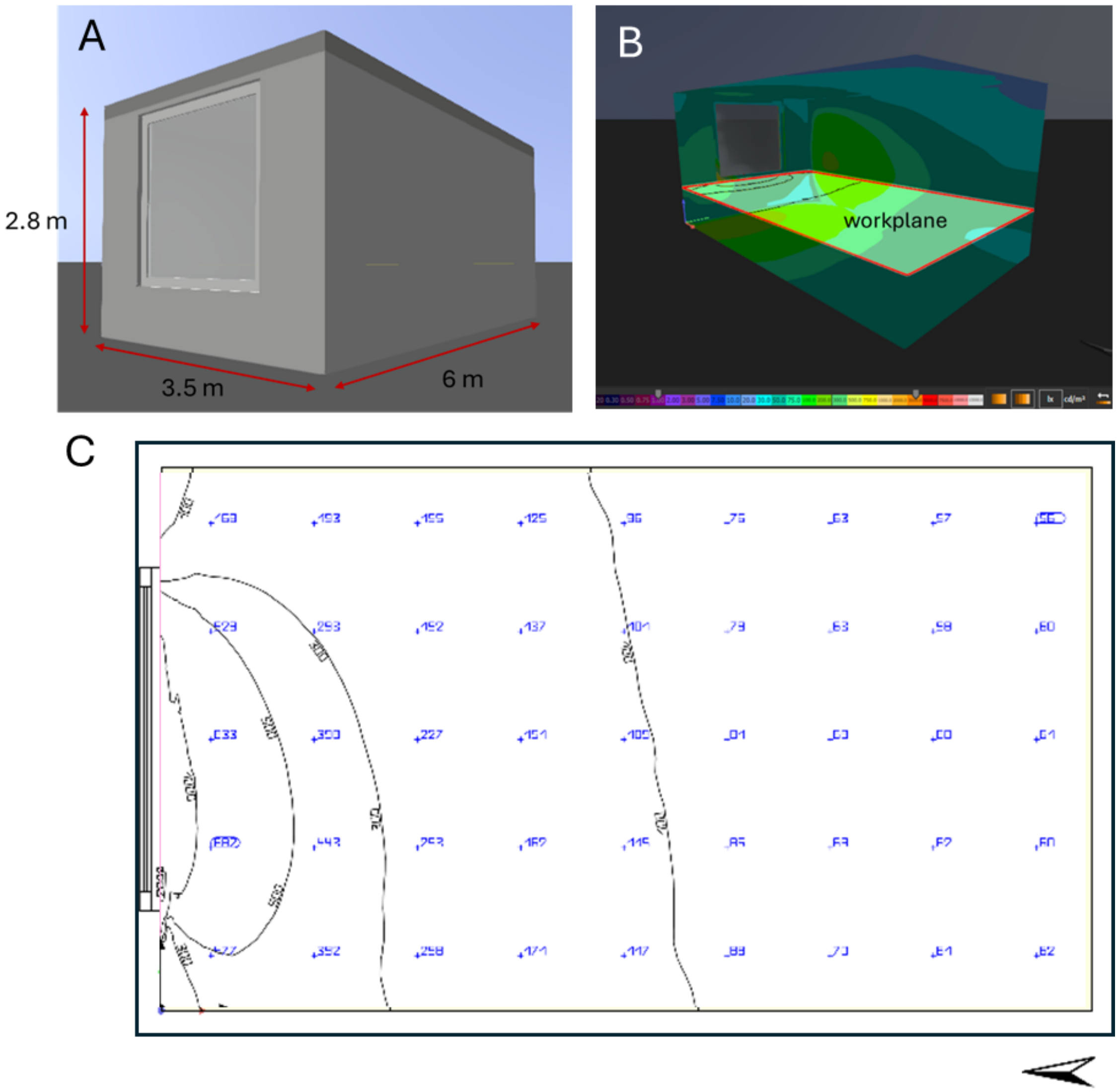

Figure 1. The model of the building created in DIALux Evo (a), the luminance on workplane (b), and the position of the sensor (c).

Table 1. Variable input range

Variables	Input Range
WWR	0.1 – 0.75
VT	0.1 – 0.75
CR	0.1 – 0.75
WR	0.1 – 0.75
FR	0.1 – 0.75

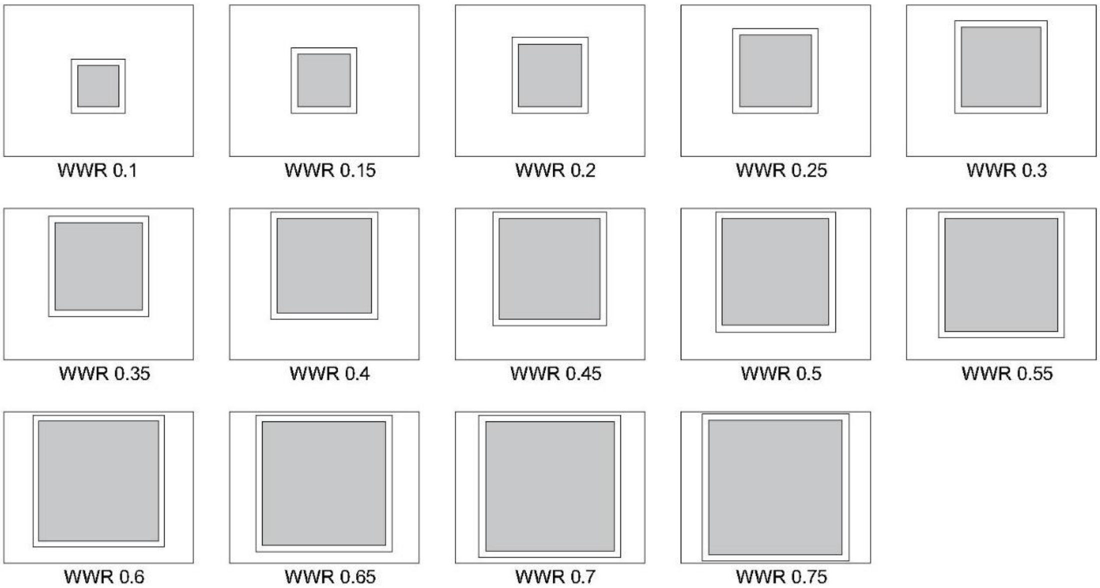

Figure 2. The elevation views of model with different WWR.

Subsequently, the combined effects of these variables are examined. A total of 150 models are constructed to explore various combinations of WWR, VT, CR, WR, and FR ranging from 0.1 to 0.75. The average illuminance values from these models are analyzed using multiple linear regression (MLR), with SPSS software employed for this analysis [20], [21]. Given the five variables and the sample size, the data meet the requirements for multiple linear regression analysis, with a confidence level of alpha = 0.05 and an R-value of 0.8 [22].

In addition of the illuminance, the uniformity of the illuminance will be analysed. The illuminance uniformity ratio (U_o) is a key architectural design metric that reflects the even distribution of light throughout a space, serving as an indicator of daylight quality. It is calculated as the ratio of the minimum illuminance (E_{min}) to the average illuminance level (E_{ave}) within that area. To determine this uniformity, daylight is measured on a designated work plane [23].

3. RESULT

The relationship between each variable—WWR, VT, CR, WR, and FR—and E_{ave} (measured in lux) is depicted in Figure 3. The analysis clearly indicates that WWR and VT play a more prominent role in influencing E_{ave} levels compared to the other variables. This is particularly evident from the steeper slopes associated with these two variables, which suggest a more pronounced effect on the overall lighting environment. The E_{ave} for baseline model is 340 lux. As both the WWR and VT increase, there is a marked increase in E_{ave}—from 52.5 lux to 456 lux with rising WWR, and from 85 lux to 638 lux with increasing VT. This clearly demonstrates their substantial impact on lighting levels. However, the rate of increase in E_{ave} begins to taper off once the WWR surpasses a threshold of 0.45, suggesting a diminishing return in illuminance gains beyond this point.

In contrast, changes in WR exhibit a more moderate influence on E_{ave}, from 251 lux to 386 lux, indicating that while WR does contribute to the overall lighting, its effect is not as substantial as that of WWR or VT. On the other hand, CR and FR appear to have the least impact on E_{ave}, from 297 lux to 344 lux with rising CR, and from 322 lux to 391 lux with rising FR. Their relatively shallow slopes in the analysis suggest that variations in these reflectance values result in minimal changes to the illuminance levels, making them less critical factors in the overall lighting design.

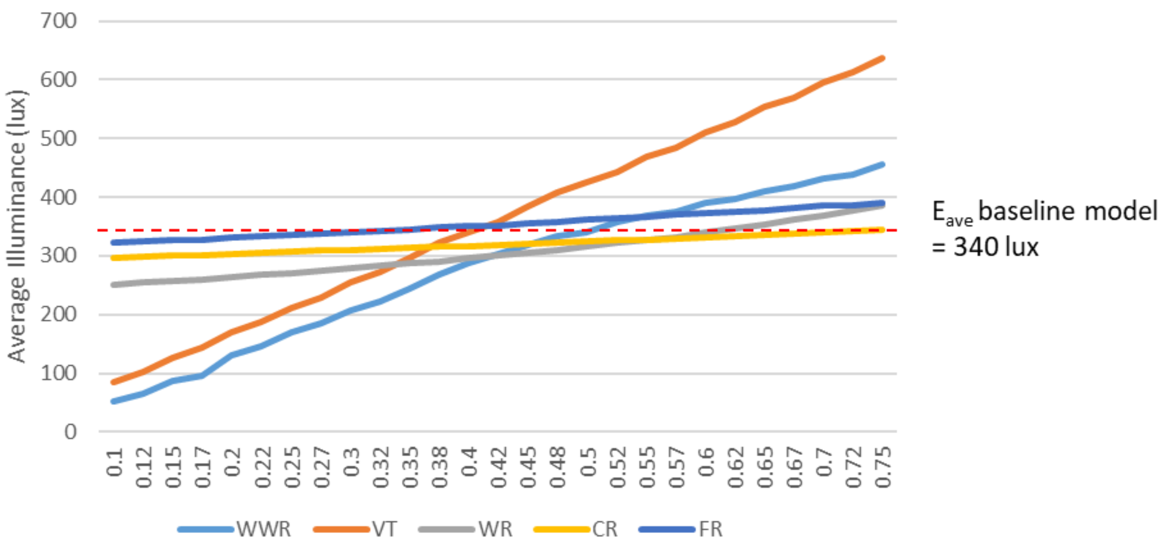

Figure 3. Average illuminance of the model with various variable values.

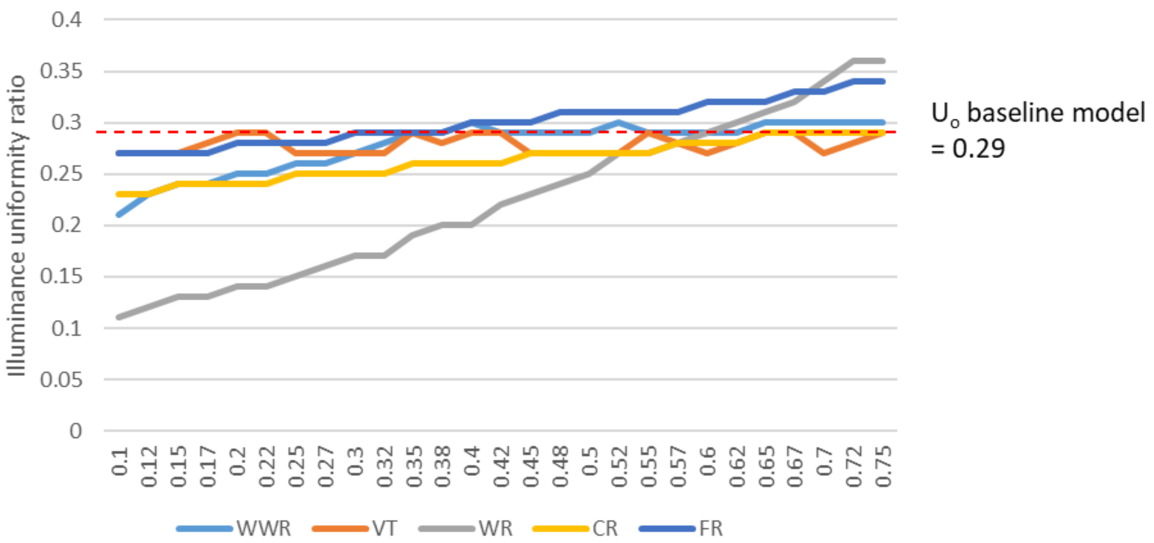

Figure 4. Illuminance uniformity ratio of the model with various variable values.

Regarding the U_o, the U_o of baseline model is 0.29. Increasing the WWR from 0.1 to 0.35 leads to a rise in the U_o from 0.21 to 0.29. In contrast, raising the WWR from 0.35 to 0.75 only increases the U_o slightly, from 0.29 to 0.30. Variations in VT, CR, and FR do not significantly impact the U_o; it fluctuates only slightly, ranging from 0.27 to 0.29 for VT changes, 0.23 to 0.29 for CR changes, and 0.27 to 0.34 for FR changes. These minimal changes in the U_o can be attributed to both E_{min} and E_{ave} increasing as WWR, VT, CR, or FR values rise. However, WR has a substantial effect on the Uo, which increases from 0.11 to 0.36 as WR rises from 0.1 to 0.75 (Figure 4).

After analyzing the effects of each individual variable, the next step is to evaluate their combined effects. Figure 5 displays the simulation results for various models with different combinations of WWR, VT, CR, and FR values. The results indicate that varying these combinations leads to different illuminance levels.

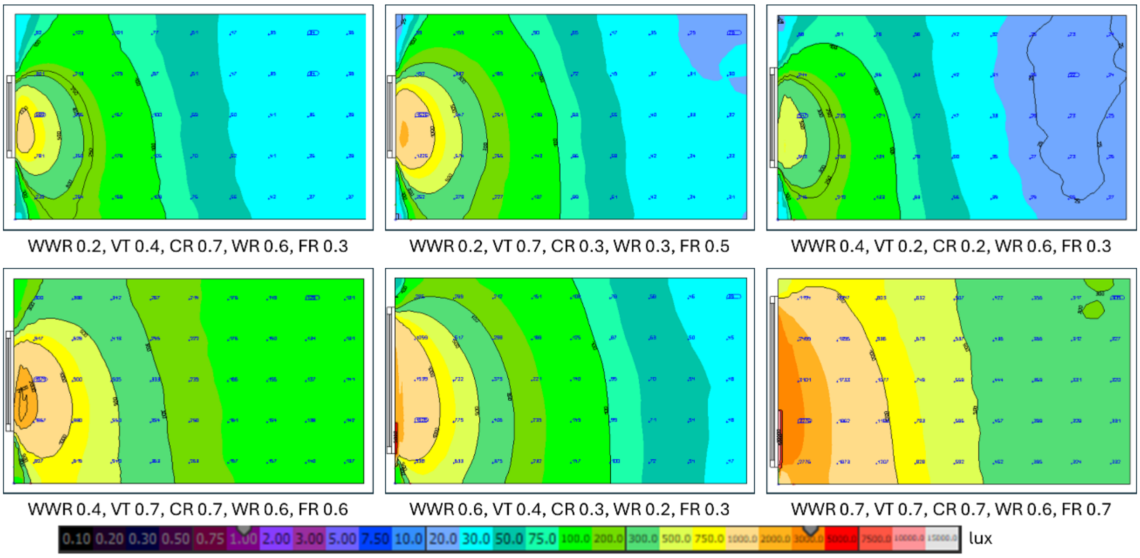

Figure 5. Average illuminance of the model with various variable values.

Before conducting the MLR analysis, the dataset underwent a thorough examination, including normality test, autocorrelation test, heteroscedasticity test, and multicollinearity test to ensure its suitability for multiple regression, with the goal of achieving accurate and valid results [24], [25]. Initial findings, however, indicated nonlinearity within the regression model, which required corrective measures to meet the assumption of linearity. To address this issue, logarithmic transformations were applied to both the independent and dependent variables, as referenced in [20]. This transformation was essential to aligning the data with the linear assumptions necessary for a valid MLR analysis. However, for the U_o in the MLR analysis, the normality test, autocorrelation test, and heteroscedasticity test do not satisfy the necessary conditions, even after transforming the independent and dependent variables. This suggests that the regression model is nonlinear, making uniformity ratio MLR analysis inappropriate.

The MLR analysis revealed that all variables significantly predicted E_{ave}, with $F(5, 150) = 1067.290$, $p < 0.001$, an R value of 0.987, and an R^2 of 0.974, underscoring the model's strong predictive capability. Each of the five variables contributed significantly to the model, as indicated by p-values <0.05, with all p-values registering <0.001, as shown in Table 2. This outcome aligns closely with the individual variable analysis presented in Figure 3, reinforcing the consistency of the findings across different analytical approaches.

The unstandardized coefficients—raw coefficients directly produced by the regression—reveal that WWR and VT have higher values compared to the other variables, suggesting that these factors exert a more substantial influence on average illuminance. Notably, VT slightly surpasses WWR, indicating it has a marginally greater impact on the illuminance levels. In contrast, the coefficients for CR and FR are lower, highlighting their relatively minor effect on E_{ave}.

However, a different perspective emerges when examining the standardized coefficients, which are typically used to assess the relative strength and direction of the relationships between variables. Here, WWR stands out as having a more significant effect on E_{ave} than VT, even though VT showed a higher unstandardized coefficient. A similar trend is observed between CR and FR, with CR having a lower standardized value than FR, positioning it as the variable with the least influence on E_{ave} within the model. This nuanced interpretation underscores the importance of considering both unstandardized and standardized coefficients to fully understand the dynamics at play in the regression analysis.

Table 2. Variable coefficients

Variables	Unstandardized Coefficients	Standardized Coefficients	t Statistic	p Value
log WWR	0.936	0.798	59.076	<0.001
log VT	1.043	0.515	34.985	<0.001
log CR	0.125	0.076	4.960	<0.001
log WR	0.428	0.194	13.044	<0.001
log FR	0.113	0.124	8.495	<0.001

4. DISCUSSION

The results of this study reveal intricate relationships between WWR, VT, CR, FR, and E_{ave}. As depicted in Figure 3, WWR and VT emerged as the most influential variables, significantly affecting E_{ave}. The substantial increases in E_{ave} —ranging from 52.5 lux to 456 lux for WWR and from 85 lux to 638 lux for VT—demonstrate their critical role in optimizing lighting environments. This aligns with findings from previous research that emphasize the importance of WWR and VT in daylighting design, indicating that higher values enhance both the quantity and quality of natural light in indoor space [5], [26].

The analysis indicated that illuminance gains began to decline when the WWR exceeded 0.45. This trend reflects the principle of diminishing returns in architectural daylighting, where an overabundance of glazing can lead to issues such as glare and overheating, ultimately negating the benefits of a higher WWR [27]. In line with this, previous study suggests an optimal WWR of 0.35 to 0.45 for maximizing daylight utilization in buildings [5].

In contrast, the influence of CR and FR on E_{ave} was minimal, with their changes producing only slight variations in illuminance levels. The modest range of illumination provided by CR (from 297 lux to 344 lux) and FR (from 322 lux to 391 lux) suggests that while they contribute to overall light reflectance, their impact on enhancing natural daylighting is less significant compared to WWR and VT. This finding is in line with previous research indicating that reflectance values play a secondary role in daylighting performance compared to direct contributions from fenestration, leading the optimization of window design as the first strategy in daylighting optimization [28], [29].

The analysis of the illuminance U_o further underscores the dominant role of WWR. The notable improvement in U_o when increasing WWR from 0.1 to 0.35, and the minimal gains, thereafter, point to the complex interplay between distribution and quantity of light. While variations in CR and FR showed negligible effects on U_o, WR demonstrated a marked influence, indicating that it plays a critical role in achieving uniform lighting conditions. This suggests that designers should prioritize WWR and WR when aiming for both sufficient illuminance and uniformity in lighting design [30].

The subsequent MLR analysis confirmed the predictive strength of the combined variables on Eave, with an R^2 of 0.974 underscoring a robust model. Each variable's contribution was significant, particularly WWR and VT, which were indicated as primary drivers in both unstandardized and standardized coefficient analyses. Notably, the slightly higher unstandardized coefficient for VT compared to WWR highlights its impact when isolated, yet the standardized analysis reveals WWR's dominance in the overall context of illuminance prediction. This dual perspective emphasizes the importance of considering both types of coefficients to appreciate the complex dynamics among the variables involved [31].

Despite the robust findings, the study faced limitations, particularly with the nonlinearity observed in the U_o regression model. These limitations suggest potential avenues for further research, including exploring nonlinear modeling approaches or examining additional variables that could influence lighting performance. While WWR, VT, CR, and FR do not significantly affect U_o, another study in [32] suggests that window design and sill height have a considerable impact on the uniformity ratio. Future investigations could also focus on the interaction effects among WWR, VT, CR, and FR to gain a more comprehensive understanding of their collective impact on lighting design.

5. CONCLUSION AND RECOMMENDATION

This study investigated the impact of various factors—WWR, VT, CR, WR, and FR—on indoor average illuminance. The analysis reveals that WWR and VT are the most influential variables affecting E_{ave}. Both factors demonstrate a strong and statistically significant impact, as reflected by their steeper slopes and higher coefficients, whether in unstandardized or standardized form. These results suggest that increasing WWR and VT leads to significant gains in E_{ave}. However, it is important to note that the effect of WWR begins to plateau once it exceeds a value of 0.45, indicating diminishing returns at higher WWR levels.

While wall reflectance also contributes to changes in E_{ave}, its impact is more moderate compared to WWR and VT. On the other hand, CR and FR are shown to have the least effect, indicating that these variables play a minimal role in influencing E_{ave}.

The MLR analysis further confirmed the significance of all the variables in predicting E_{ave}, with the model demonstrating a high degree of predictive accuracy. These results emphasize the critical role of WWR and VT in designing spaces that achieve optimal lighting conditions, with WWR having a greater effect on E_{ave}. In contrast, the effects of CR and FR, although statistically significant, are comparatively minimal and less impactful in influencing overall illuminance levels, with CR being the least significant.

This study has several limitations. Firstly, it concentrates on a specific range of variables—WWR, VT, CR, WR, and FR —while excluding other potentially influential factors such as window orientation, shading devices, and external conditions like cloud cover or nearby buildings. Secondly, this study did not analyze the U_o regression model due to its nonlinearity. These limitations highlight opportunities for further research, such as investigating nonlinear modeling techniques or considering additional variables that might affect lighting performance. Future studies could also explore the interaction effects among WWR, VT, CR, and FR to achieve a more thorough understanding of their combined influence on lighting design.

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