Decoding the Interplay of Lighting and Spatial Dynamics: A Simulation-Based Case Study Analysis across Diverse Building Orientations

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Abstract: In contrast to artificial light sources, which can be calibrated for specific luminous effects, daylight is a dynamic source that generates varying shadow patterns and brightness levels. Despite the diversity in scale and complexity of daylight studies, this research extended spatial and temporal dimensions. This research predicts the interplay of spatial-temporal dynamics and daylight in replicated buildings across diverse orientations. This study employs integrated measurement tools, Autodesk Revit simulation, statistical analysis, and Heliodon simulations. Results have shown that spatial dimensions consistently affect daylighting levels, underscoring the importance of architectural design and orientation. Seasonal effects on daylighting vary spatially, impacting daylight inconsistently, while time intervals appear non-significant, possibly causing regional daylighting differences. In conclusion, building orientations significantly influence daylight distribution, and architectural choices are crucial in maintaining consistent daylight throughout varied spatial-temporal dynamics. This study advances the scientific comprehension of spatial-temporal elements in sustaining consistent lighting patterns across diverse building orientations.

Keywords: Lighting Patterns; Revit Simulation; Building Orientations; Spatial-temporal Dynamics.

1. Introduction

Daylight provides functionality as well as aesthetic value to architecture, by providing energy-efficient [1] and natural illumination [2] for indoor activities and infusing the indoor environment with shadows, light, and texture. Daylight is influenced by some dynamic factors, in contrast to artificial light sources, that can be modified to suit a desired luminous effect despite the climate, time of day, or latitude. The duration and intensity of daylight hours vary throughout the year depending on latitude, although their strength and consistency vary hourly depending on the local climate [3]. Due to these variable circumstances, a highly dynamic driver of illumination and visual phenomena [4] is produced. The significance of these phenomenological impacts on how individuals perceive space has been recognized by numerous experts [5-7]. The daylight design and spatial-temporal parameters that may assess the advantages of daylight variations within the visual field are disproportionally scarce, if non-existent. Light's interaction with space has an immediate impact on how that space is perceived. Light's interactions with the environment and with the occupant have an impact on what they perceive, feel, and interpret the elements. The indoor building environment is largely dependent on the lighting conditions that affect both the object and the viewer [8], regardless of the dimension it can be, such as space, material, or colour [9] [10].

The beneficial characteristics of daylight go beyond energy savings for buildings, and researchers as well as building scientists have become aware of its significance [11, 12]. This highlights the question of what constitutes good design of buildings or daylighting efficiency. This question is intricate to answer from the perspective of daylighting, because it's imperative to optimize daylight inside buildings to cut down the use of energy as well as improve occupant wellness, there are a few visual comfort concerns that aren't necessarily in line with the basic concept of optimizing daylight [13]. Specific daylight features and their relevance to building design must be taken into consideration to maximize the design solution. This might be a challenging and time-consuming task due to numerous factors.

The exploration of daylight availability and variable patterns requires a thorough understanding of the dynamic interactions between spatiotemporal dynamics. The necessity to move past static studies has been highlighted by researchers on the spatial-temporal fluctuations that impact daylight penetration and variability into the spaces. Researchers have used these dimensions in numerous studies.[14, 15]. Early studies in this field were conducted to compare the design outcomes of various measures and to describe their characteristics. Researchers demonstrate the temporal, spatial, spectral, and angular variations of daylight by introducing a portable spectral high dynamic range (HDR) cubic illumination system and generating metrics based on perception from cubic samples. The method is verified using data from real-world scenes, which reveals significant differential impacts and provides a new understanding of the prediction of light appearance [16]. In the same manner, a study on the daylight perceptual effects of contrast and temporal variability in architectural design was undertaken by Rockcastle & Andersen. The authors suggest image processing-based approaches for evaluating spatial contrast and brightness variability, increasing daylit architecture analysis, and unveiling two novel metrics annual spatial contrast and annual luminance variability [17]. Similarly, another study uses cubic spectral irradiance metering to investigate the interaction of temporal and spatial dynamics in daylight within natural landscapes. The study highlights the impact of spatial context on the quality of lighting by revealing temporal shifts of light and substantial spatial variations in light intensities [18]. The spatial dimension is potentially the most significant factor to consider when evaluating a space or building's potential for daylight availability [19]. The daylight availability and variation measurements for evaluating building efficiency will be made possible by a method that employs a zonal computation [20]. This is a crucial factor to take into account while optimizing designs and setting building codes. Additionally, this improvement will make it possible to compare daylight to other zonal building performance parameters such as height, forms, orientations, etc. A follow-up study simulated the spatial and temporal effects of several daylight models of architectural settings. The study also focused on the temporal variability of daylight in an indoor environment as well as the significance of spatial variability [14]. Similarly, the van Duijnhoven et al. [21] shed light on how office workers are affected by lighting unpredictability. It was noted that the lighting conditions varied at different times and locations. Similarly, Chamilothori et al. [22], explore the effect of façade perforations on spatial ambiance through daylight. The study investigates variations in the distribution of daylight and, through empirical research, establishes a connection between daylight patterns and spatial dynamics.

Although daytime is changing and dynamic, it also follows cycles and patterns resulting in a variety of illumination conditions in an area. Static methods are important since they may be used to predict how space will function over time by an expert, such as when computing daylight factors or examining typical sky conditions [23]. By increasing the simulation's temporal resolution, it is possible to perceive lighting in a space with less complexity. When not obfuscated by complex measurements, climate-based daylight modeling is the finest approximation for the real circumstances in a building and can give the layperson a clear understanding of how a building will function [24]. According to studies by Chamilothori et al. [25], and Houser [26], the sense of space, rating of preference, and affiliation with nature are all affected by the temporal dynamics of natural or artificial light patterns. Similarly, to conduct a more comprehensive investigation of daylight performance, Rockcastle and Andersen developed a novel typological system that defines architectural space according to contrast and time-segmented variations of a daylight simulation-based method [27]. Similarly, Ruben Pastilha and Anya Hurlbert, focus on the perception and detection of temporal variations within natural daylight. It explains people's perceptions of changing lighting conditions over time and how these variations influence perception [28]. In short, it is essential to be able to quantify both the spatial and temporal dynamics of light pattern variability.

The intricate arrangement of internal inputs for daylight simulations [29] consists of space geometry, surrounding context, orientation [30], opening configuration, location, and optical properties of components [31]. Moreover, these factors depend substantially on determining external inputs like weather data and sky models that are relevant to a specific location [32]. Analyzing the amount of daylight that enters an area has become an intricate procedure because of the emergence of computer simulation techniques. A hand-held light meter's error rate is quite comparable to that of computer programs and others that analyze how much daylight penetrates an area [33]. To determine the influence of a few or several factors on daylighting in recent years, simulation-driven analytical techniques have frequently been used [34, 35].

Building information modeling (BIM) creating applications are broadening their functionality to facilitate lighting design study of buildings. The effectiveness of indoor lighting design is increasingly being evaluated using BIM-based simulations [36]. Several earlier studies suggested approaches for integrating lighting analysis methods into the BIM model. For instance, BIM was used to analyze the concepts of green building for instructional purposes by Zhang, Jie, et al. [37]. This study examines the energy performance of an academic building as a case study to reduce energy consumption in diverse orientations. Moreover, Yan et al. [38] and Kota et al. [39] created a system to link the BIM database and building energy modeling (BEM) to facilitate thermal and daylighting simulations known as Physical BIM (PBIM). Stavrakantonaki et al. [40] offered a methodology for choosing several BIM tools for daylighting assessment. In addition, the radiance daylight simulation, which takes into account the material properties of surfaces and objects as well as the effect of light reflections, was validated by Dalumo and Lim [41]. Given this, Suncast and Radiance IES-VE modeling outcomes have demonstrated similar comparability with measurement output acquired from the heliodon and artificial sky, respectively, with little variances in accuracy. This illustrates how this type of computational simulation program may estimate solar shading and daylight performance in structures.

Although such tools allow for the analysis and visualization of indoor illumination on a quantitative and qualitative level [42, 43]. Studying the various dimensions or variables quantitatively and qualitatively that can impact daylight can be classified in light of this, and a statistical technique can be used to analyze a variety of diverse and substantial data sets [33]. The integration of BIM simulation and statistical approaches can be used in a building [44], to provide optimized daylighting design solutions. These statistical methods, for instance, might primarily offer a framework for correlating data, determining interactions, and forecasting potential alternates derived from existing data. Using input and output data may be primarily utilized to demonstrate relationships between variables and to develop and assess daylighting dynamics attributes [45, 46].

Daylight is a highly diverse natural source of illumination and served as the foundation for research on the threshold characteristics of lighting and its effects. In research, where ideal orientation and optimized daylighting design take prominence, the capacity of daylighting to induce variation—and, as a result, spatiotemporal dynamics, influences on characteristics of daylight with varying building orientations—is often overlooked. However, notable gaps exist, including the need for insights into regional differences, understanding unexplained variability in specific orientations, incorporating qualitative aspects, generalizing findings across diverse building types, and exploring sustainable design strategies for daylight optimization. Addressing these gaps, the main goal of this study is to investigate the significance of daylight variation, which is evaluated in terms of spatial (areas and height levels) and temporal dynamics (the time of day and season of the year). The main contributions of the study are (i) the use of the statistical techniques, applied to spatial-temporal dimensions influencing the daylight in the replicated blocks with the varying building orientation; (ii) the creation of a status of spatial-temporal factors that impact the daylighting intensity in a space, which would be of great help to building practitioners and scientists (iii) Integrating building performance simulation tools with statistical and Heliodon data, to enhance the accuracy of energy simulations and predict the building's daylighting conditions under various settings. This study underscores the critical role of spatial dimensions in predicting daylighting variability, emphasizing the significance of architectural design and building layout and contributing to the fields of architecture and lighting studies.

2. MATERIAL AND METHODS

Seven replicated buildings across diverse orientations are used in this study. These buildings, featuring diverse architectural styles, typologies, and more, are spread across the main campus of the University of Gujrat in Gujrat, Pakistan. Hence, seven replicated blocks have been designated for the database. These are situated on an open area of land that is directly exposed to the climate and basic parameters are presented in Table 1.

Table 1. Research Study Model Parameters

Building Parameters	Description
Location	32.6389° N, 74.1649° E
Building Type	Academic Building
Timings	8:00 a.m. to 4:00 p.m.
Stories	3
Floor Area	23533.7square feet. (Each floor)

These blocks are built using radial planning, and each is duplicated at regular intervals at 45-degree angles to the academic circle's center at varying seven orientations as presented in Figure 1. Table 2 exhibits the nomenclature and orientations of the seven replicated blocks to examine daylighting variation patterns.

Figure 1. Replicated buildings across various orientations

Table 2. Orientation Model of Replicated Blocks

Replicated Blocks		Orientation
Existing Nomenclature	Used Nomenclature	
Al-Jazairi Block	Block-A	N81^{o}W
Ibn-E-Sina Block	Block-B	N37^{O}W
Al-Farabi Block	Block-C	N9^{O}E
Arfa Karim Block	Block-D	N53^{O}E
Al-Khwarzami Block	Block-E	S81^{O}E
Umar Al-Khayyam Block	Block-F	S37^{O}E
Jabir Bin Hayan Block	Block-G	S9^{O}W

These buildings exhibit diverse orientations, leading to variations in their exposure to direct sunlight. Some receive abundant sunlight, while others do not due to their differing orientations. Due to the repeated planning, zones are identical in terms of the area and type of usage on every floor of each academic block. Additionally, the academic buildings boast robust architectural designs, featuring massive tapered walls and substantial concrete construction for aesthetic purposes. These elements serve as prominent front-facing features for each block as shown in Figure 2.

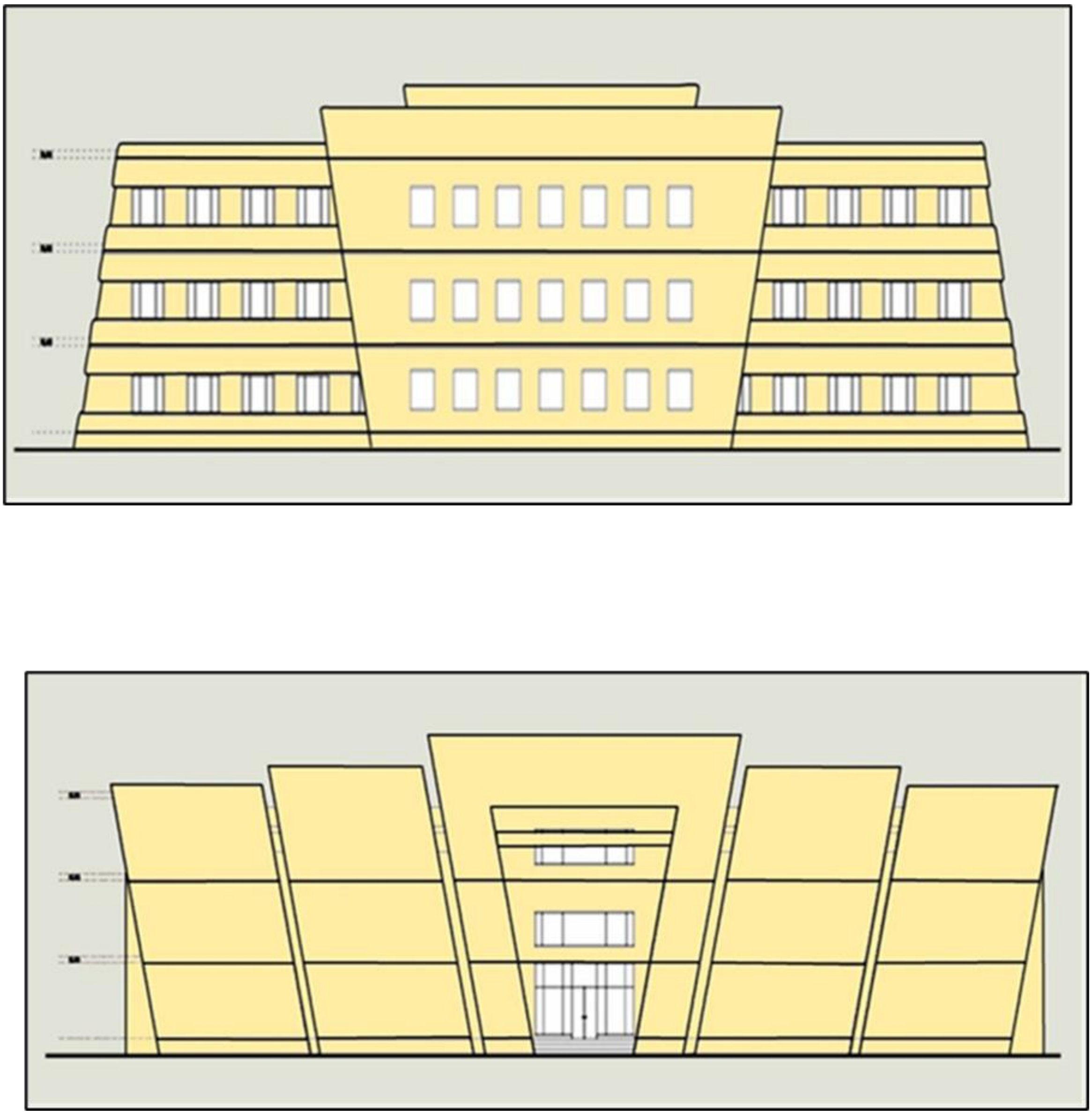


Figure 2. Front and Rear Facade of Replicated Blocks

The replicated buildings across diverse orientations are analyzed in three stages. The first step involves the database creation for the study and the collection of background information regarding these blocks, and these seven replicated blocks are considered as a base case model for this study. Autodesk Revit® 2022, a building information modeling program, is used for the modeling phase [47], to perform daylighting simulations. Autodesk Revit's “Lighting Analysis and Solar Analysis” plugins are added to enable interoperability at the highest possible level [48], used to simulate daylighting illumination (lux). The simulation model is developed quite near to the original parameters in terms of the spatial characteristics, materials, occupational classifications, and schedules of the sample study area. The default materials with typical surface reflectance, 20% for the floor, 70% for the ceiling, and 35% for the walls, are assumed in this study. The windows are chosen with single-pane tinted glass with brownish hues 50%. Figure 3 displays a base case model interface for Autodesk Revit. The average value of each analysis surface is used as the outcome of each daylighting level (lux). For occupancy schedules, occupied hours are defined as being from 8:00 AM to 4:00 PM daily during a typical year.

Based on Pakistan's geographic location in the Northern Hemisphere, the daylighting simulation of various zones of the base case model is carried out at three different times of the day, at three different heights, and during three different seasons. The simulations' goal is to investigate daylight indicators such as illuminance (lux) in various zones throughout morning, afternoon, and evening during the summer solstice, winter solstice, and equinox seasons of the year at the three distinct height levels.

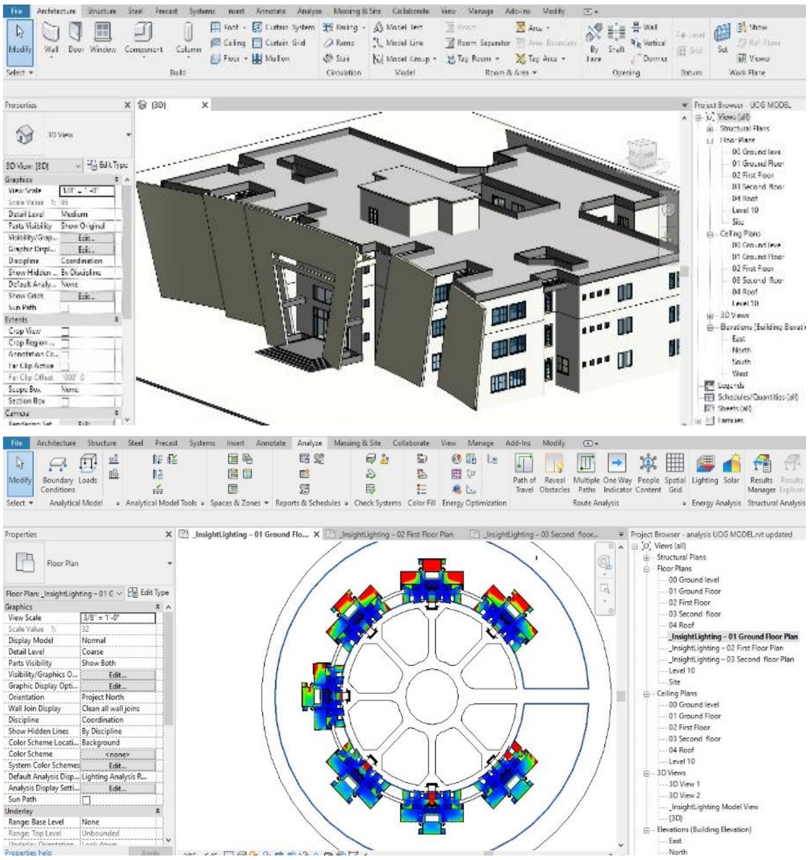


Figure 3. Autodesk Revit Study Model Interface

The second stage involves the analysis, using the statistical program "R" to perform factorial ANOVA analysis[49]. The factorial approach offers accurate feedback to the input and extracts valuable data from the input [50]. This analysis involves comparing the means of replicated academic blocks with varying orientations to determine the daylighting interaction with spatial-temporal dynamics such as time, areas (zones), and height for identifying the factors that may have an impact on daylight intensity variability. The following spatial-temporal dimensions are considered in this research.

Spatial-temporal dynamics include:

a. Multiple time steps (time of the day and time of the year) intended to depict a continuous period;

b. Multiple locations (multiple zones and height levels) intended to depict continuous distribution throughout an area or building;

c. Multiple orientations are to depict an adaptive position from one perspective.

- Analyzed the daylight metric across the evaluated spatial-temporal dimensions

For examining the sun's interaction with academic buildings of various orientations, a detailed solar analysis was also carried out using a simulation tool called "Heliodon" [41]. To precisely depict the academic buildings' architectural configurations and orientation, a three-dimensional physical model of each one was built. The final stage entails optimization and daylight design guidelines based on temporal dynamics features obtained through statistical analysis and solar interaction with academic blocks of different orientations using the Heliodon. Overall, the goal of this study is to comprehend how several spatial-temporal variables, including time, season, area, height, and orientation, affect the variability of daylighting in academic buildings of varied orientations. This research is carried out utilizing a combination of computer-aided simulations and statistical analysis while applying the requisite parameters. The analysis is given in stages illustrated in Figure 4.

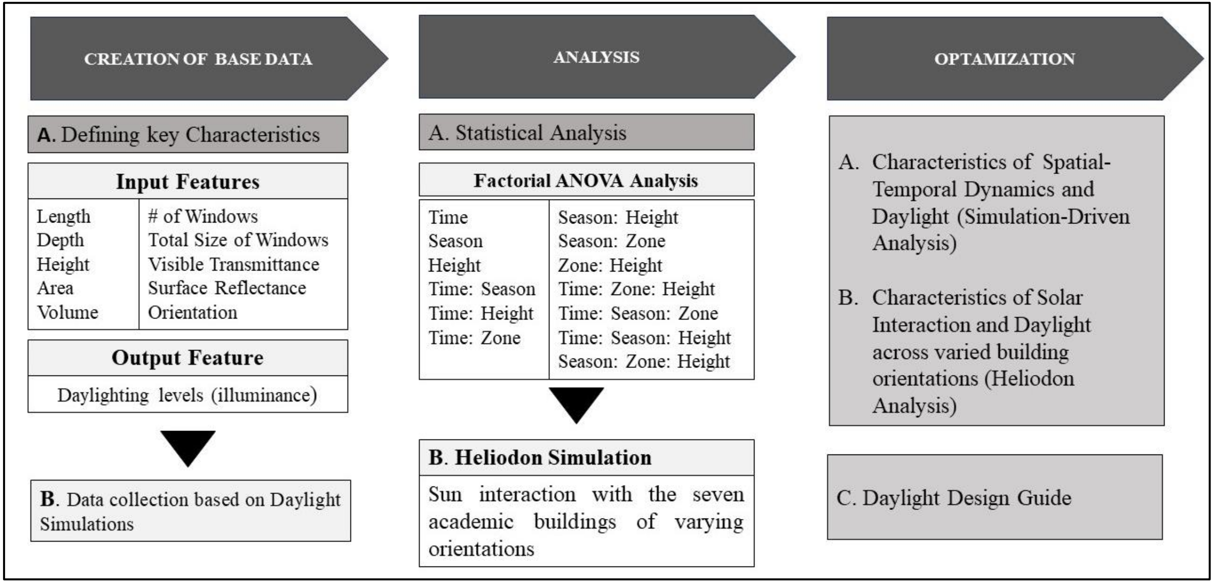


Figure 4. Research Study Model

3. RESULTS

3.1. ANALYSIS THROUGH SOFTWARE SIMULATION

A BIM program, such as Autodesk Revit, is used to construct a 3D BIM model [51] of the replicated blocks across diverse orientations that contain virtual versions of actual building components. The realistic daylighting predictions made possible by Autodesk Revit's accurate geometry, shading analysis, and solar movement simulation optimize the quality and performance of designs [52]. Through the BIM program, building elements (such as floors, walls, ceilings, light fixtures, and items of furniture), include their geometric and non-geometric characteristics (such as material and properties). For illuminance analysis, the Perez sky model is used and exhibits precise results for daylighting simulation in a range of sky situations, from fully cloudy skies to clear skies [53]. Using weather data sources for sky condition information is automatically set from the predefined city list at 32.5731° N, 74.1005° E (Gujrat, Punjab Pakistan). The information on sky conditions for lighting simulations with 0% sky cover is mentioned in Table 3.

Table 3. Sky Condition Information for Autodesk Revit Model

Day of the Year (Seasons)	Time of the Day	Irradiance Values (W/m^2)		
		Global Horizontal Irradiance (GHI)	Normal Irradiance (DNI)	Diffuse Horizontal Irradiance (DHI)
Summer Solstice	Morning	864	810	90
	Mid-day	793	785	90
	Afternoon	478	632	85
Winter Solstice	Morning	405	600	87
	Mid-day	332	539	82
	Afternoon	82	185	48
Equinox	Morning	709	767	92
	Mid-day	651	741	92
	Afternoon	322	520	80

These academic blocks share identical layouts, and each building encompasses office spaces, classrooms, lecture halls, and meeting rooms. Due to the consistent planning, zones on each floor of every replicated block have identical areas and usage types. Each floor of the study model is divided into various zones/spaces as per function and named accordingly for lighting simulation through Autodesk Revit. Refer to Figure 5 for details on the types and numbers of zones on each floor of the replicated blocks.

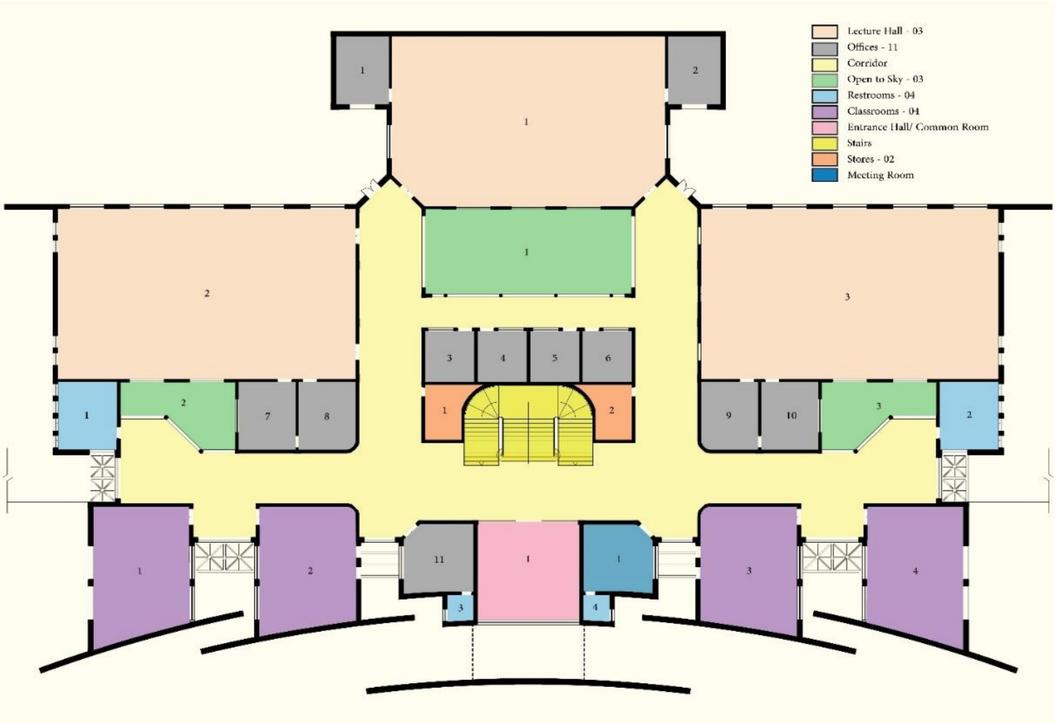
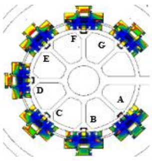
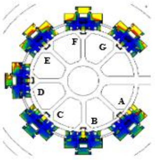
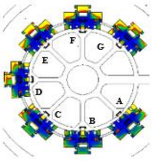
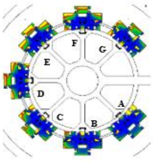
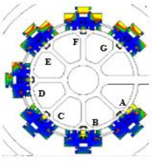
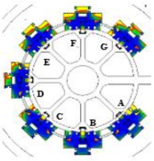
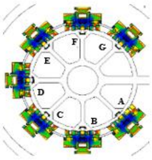
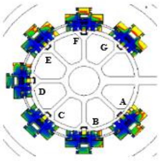
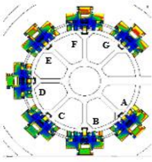
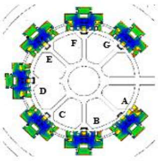
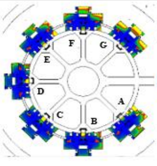
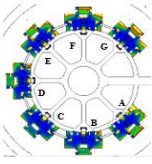
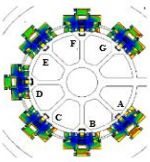
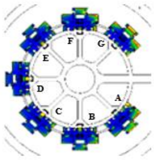
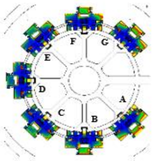
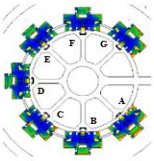
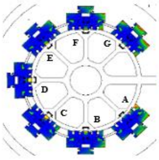
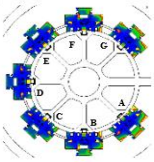
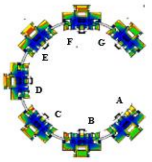
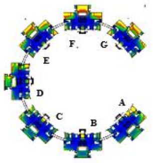
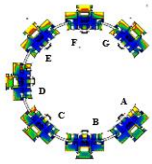
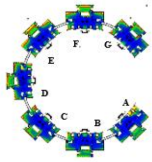
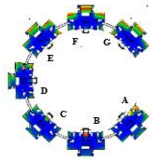
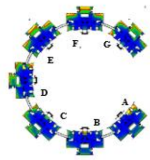
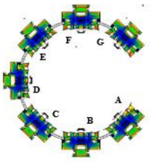
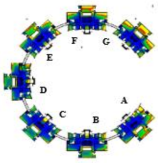
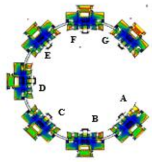
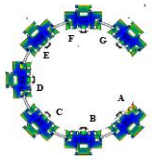
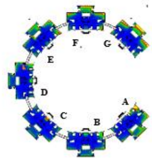
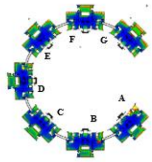
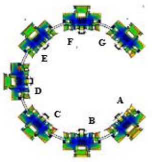
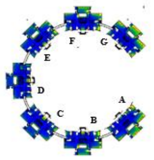
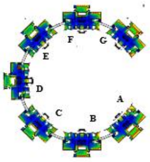
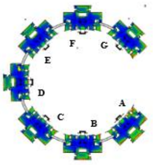
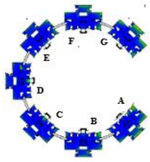
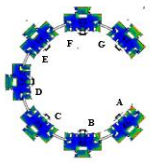
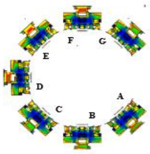
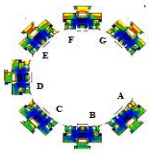
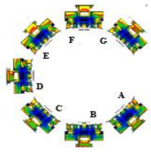
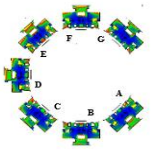
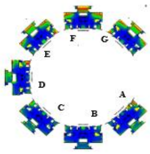
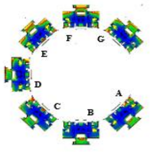
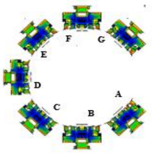
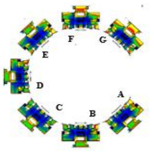
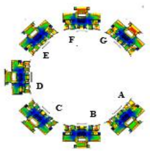
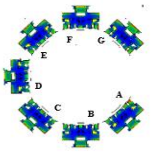
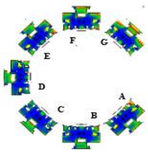
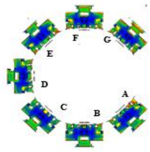
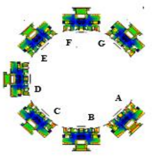
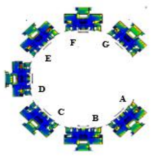
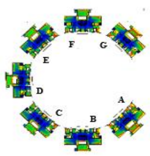
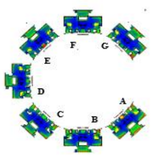
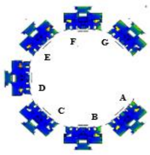
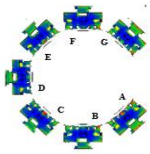


Figure 5. Area Distribution of a Typical Replicated Block

The daylighting analysis is carried out at different nine heights (chosen based on working heights, i.e., the commonly used desk or table working height of 3 feet, whiteboard mounting height is seven feet above the base of the floor), at three times of day (selected based on working hours of the day: Morning, mid-day, and afternoon, and on three different days of the year (selected based on altitude angles of Sun). Table 4 shows daylight variability patterns across diverse building orientations as simulated by the Autodesk Revit software. However, due to the almost identical daylighting pattern, the simulation for the third height is not shown.

Table 4. Daylight variability pattern in replicated blocks across diverse building orientations

Floor	Time of the Day	Daylight (lux) Summer Solstice	Daylight (lux) Winter Solstice	Daylight (lux) Equinox	Daylight (lux) Summer Solstice	Daylight (lux) Winter Solstice	Daylight (lux) Equinox
		Used desk or table working height			Whiteboard mounting height		
Ground Floor	Morning						
	Mid-day						
	Afternoon						
First Floor	Morning						
	Mid-day						
	Afternoon						
Second Floor	Morning						
	Mid-day						
	Afternoon						

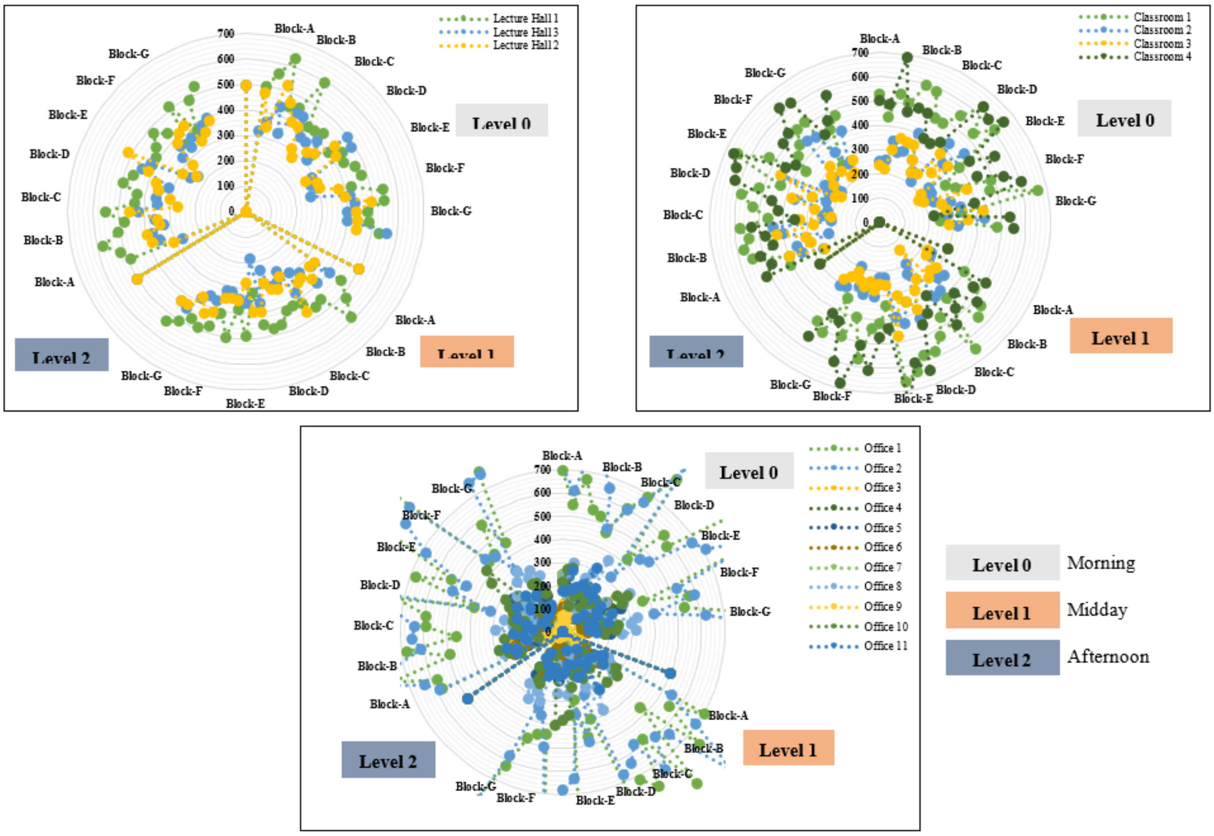


Figure 6. Daylight Intensity Variability in Lecture Halls, Classrooms, and Offices at Desk/ working table heights in Summer Solstice

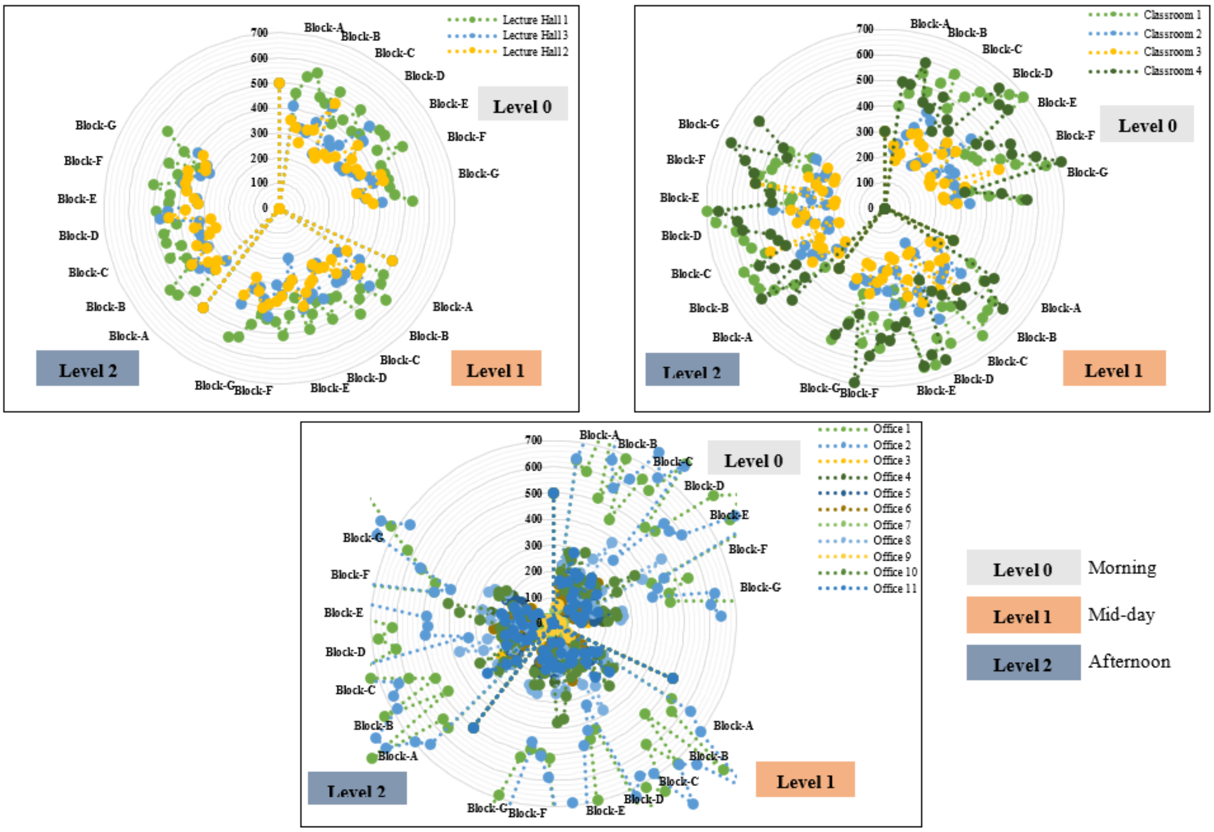


Figure 7. Daylight Intensity Variability in Lecture Halls, Classrooms, and Offices at Desk/ working table heights in Winter Solstice

The European Committee for Standardisation (CEN) and the Illuminating Engineering Society of North America (IESNA) are mostly responsible for the development of lighting codes [54]. In 2011, the Chartered Institution of Building Services Engineers (CIBSE) published The Lighting Guide 5: Lighting for Education, which recommended a target illuminance of 500 lx for classrooms and lecture halls and 300 lx for offices [55]. In contrast, the EN 17037 standard, published by CEN, recommended that the high target illuminance on vertical and inclined daylight openings should not exceed 750 lx [56].

Through a comparative analysis between the outcomes derived from Autodesk Revit lighting simulations and the guidelines outlined in CIBSE Lighting Guide 5: Lighting for Education, the daylight intensity in the various spaces such as offices, lecture halls, classrooms, meeting rooms, etc., on each floor within each replicated academic block across diverse orientations to assess whether the spaces meet the recommended lighting standards for educational spaces.

Figure 6 demonstrates the variations in daylight intensity experienced at desk or working table heights in lecture halls, classrooms, and offices during the morning of the summer solstice. Figure 7, on the other hand, illustrates the fluctuations in daylight intensity at similar heights in these spaces during the morning of the winter solstice. It appears that Lecture Halls in Block-A and Block-C meet the lighting standard at a desk/ working table height, but the lux levels drop below the standard at a board mounting height. Lecture Halls in Block-B consistently fall short of the standard at both heights. Most offices in Block-A, Block-B, Block-C, Block-D, and Block-E meet lighting standards on many floors and orientations at used desk/working plane heights. However, there are some variations within each block, with certain locations having illuminance levels slightly below the recommended standards, especially above the working plane height. Offices in Block-G, on the other hand, consistently have lower illuminance levels, especially on the first and second floors, which may require additional artificial lighting to meet standards. This behavior suggests that the lecture halls, offices classrooms, etc. may require adjustments in their lighting systems, especially at a board mounting height, to ensure they meet the specified lighting standards uniformly across different blocks and heights.

In short, a building's design can be appropriate and conceptually sound in showing the depth of its existence, but due to its changing orientation and same-sized windows, absence of shading, it does not fit the fundamental requirements for an efficient daylighting design in educational settings.

3.2. ANALYSIS THROUGH STATISTICAL SOFTWARE

To find interactions between the factors, Pandey et al. [57] suggest the Factorial Analysis as a potential method. ANOVA is a statistical method for testing differences between means in multiple groups and detecting interactions between factors, making it ideal for studying the impact of lighting conditions in factorial design experiments [58]. All factors changed together in the Factorial Analysis while the number of variables and experimentation levels will indicate the total variety of factors [59] [50]. For statistical analysis, the daylighting data was obtained through Autodesk REVIT simulations of the various zones of academic blocks at specific nine heights and three time periods during the summer solstice, equinox, and winter solstice. Factorial ANOVA (Analysis of Variance) is used in this analysis, which is conducted using the statistical program "R". Factorial ANOVA is chosen as the most suitable approach due to the diversified levels of the data collected. It is quantitative and normally distributed and enables the examination of the interaction between various factors, such as time, heights, and seasons, to identify their respective impacts on the variability of daylighting intensity in the various areas for changing the orientation of replicated blocks.

The outcomes of statistical analysis for various variables and their interactions on the daylighting levels are shown in an ANOVA table. For each factor and interaction, the table displays the degrees of freedom (Df), sum of squares (Sum Square), mean square (Mean Square), F-value (F Value), and corresponding p-values (Pr (>F)). In this study, the primary variables under investigation are Time, Season, Zone, and Height.

3.2.1. Northwest-Oriented Blocks

1. The Al-Jazairi Block referred to as Block-A, is oriented towards N81oW. In the ANOVA analysis represented in Table 5 for Block-A, it is observed that both the Time and Season factors have p-values greater than 0.05, specifically p = 0.26387 and p = 0.13187, respectively. There is no strong evidence to support that Time and Season significantly influence daylighting. The Zone factor shows a highly significant effect on daylight with a p-value of < 2e - 16 (***). The F-value of 7.135 indicates that the variability between different zones is significantly larger than the variability within each zone. This suggests that the zones have a considerable impact on the daylight, and there are likely significant differences in the daylighting intensity across different zones. The Height factor also has a statistically significant effect on the daylighting level with a p-value of 0.00244 (**). This suggests that there are significant differences in the daylighting intensity at different heights.
2. The Ibn-E-Sina Block, designated as Block-B, is situated at N37OW. Upon examining the ANOVA results presented in Table 5 for Block B, it is evident that the Time, Season, Zone, and Height factors, as well as all the interactions between these factors, have p-values greater than 0.05. This suggests that none of these individual factors nor the combined effects of these factors in any interaction have a significant influence on the daylighting levels in this block. In conclusion, the analysis indicates that daylighting levels within Block-B, located at N37OW, remain consistent across different periods and heights. This stability is attributed to the absence of significant interactions between the various factors considered. Furthermore, there is also insignificant interaction observed between specific months of the year, different heights, and distinct zones within Block-B, emphasizing that these factors do not play a substantial role in influencing daylighting levels in this particular block.

Table 5. ANOVA for Northwest-Oriented Replicated Blocks

Dimensions	**Block-A (N81^{o}W)**			**Block-B (N37^{O}W)**	
	F Value	**Pr (>F)**		**F Value**	**Pr (>F)**
Time	1.334	0.26387		1.007	0.366
Season	2.03	0.13187		0.991	0.371
Zone	7.135	< 2e - 16	***	1.01	0.452
Height	3.006	0.00244	**	1.017	0.421

Significance Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3.2.2. Northeast-Oriented Blocks

1. The Al-Farabi Block (Block-C) located at N9OE, refer to Table 6 summarizes that the time factor has a non-significant effect on daylighting (p = 0.172505). The F-value of 1.76 indicates that the variability of daylight between different time periods is not significantly different from the variability within each time period. The Season factor shows a significant effect on the daylight (p = 0.001398). The F-value of 6.616 suggests that the daylight variability between different seasons is significantly larger than the variability within each season. The Zone and height factor has a highly significant effect on the daylighting levels (p < 2e-16). The F-value of zone factor 148.958 and 36.351 of height factor indicates that the daylight variability between different zones and heights is significantly larger than the variability within each zone and height. This suggests that the zones and heights have a considerable impact on daylight, and there are significant differences in the outcome across different zones and height levels.
2. Block-D, which is referred to as the Arfa Karim Block, is positioned with an orientation of N53O E. In line with the ANOVA results presented in Table 6, show that the Time and season factors have a non-significant effect on the daylighting levels (p = 0.588546) and (p = 0.281862) respectively. The F-value of 0.53 and 0.281862 of time and season factors indicate that the variability of daylighting levels between different time periods and seasons is not significantly different from the variability within each time period and season. The Zone and Height factors show a highly significant effect on daylighting (p < 2e-16). The F-value of Zone

and Height 19460.41 and 589.279 respectively indicates that the daylighting level variability between different zones and Heights is significantly larger than the variability within each zone and height. This suggests that the zones and the height levels have a considerable impact on the daylight, and there are significant differences in the daylighting levels across different zones and at different height levels.

Table 6. Analysis of Variance for Northeast Oriented Replicated Blocks

Dimensions	**Block-C (N9^{O}E)**			**Block-D (N53^{O} E)**		
	F Value	**Pr (>F)**		**F Value**	**Pr (>F)**	
Time	1.76	0.172505		0.53	0.588546	
Season	6.616	0.001398	**	10268	0.281862	
Zone	148.958	< 2e - 16	***	19460.41	< 2e - 16	***
Height	36.351	< 2e - 16	***	589.279	< 2e - 16	***

Significance Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3.2.3 Southeast-Oriented Blocks

1. The Al-Khwarzami Block, denoted as Block-E, is oriented in the direction of S81^{O}E. Table 7 illustrates that the Time factor exhibits a nearly significant effect on daylighting, with a p-value of 0.08549. The F-value of 2.465 indicates that the variability of daylighting levels between different periods is marginally larger than the variability within each time period. However, the p-value is above the typical significance level of 0.05, so the effect is not considered statistically significant in daylight. The Season factor shows no significant effect on the daylighting ($p = 0.26226$). The F-value of 1.34 suggests that the variability between different seasons is not significantly larger than the variability within each season. The Zone and height factor has a significant effect on the daylighting ($p < 5.22e-09$) and ($p = 0.00327$). The F-value of zone and height factors 3.303 and 2.909 indicate that the daylight variability between different zones and height levels is significantly larger than the variability within each zone and height level. This suggests that the zones and height levels have a considerable impact and there are significant differences in the daylighting levels across different zones at different height levels.
2. The ANOVA analysis of the Umar Al-Khayyam Block, designated as Block-F, which is oriented towards S37^{O}E as depicted in Table 7, reveals that the Time factor does not have a significant effect on the daylighting levels, as indicated by a p-value of 0.420991. The F-value of 0.866 indicates that the daylight variability between different time periods is not significantly different from the variability within each time period. The Season, Zone, and height factors show a highly significant effect on the daylighting levels ($p = 0.000241$) and ($p < 2e-16$). The F-values of Season, Zone, and height factors 8.403, 15854.524, and 425.936 respectively suggest that the variability between different seasons, zones, and height levels are significantly larger than the variability within each season, zone, and height. This indicates that the seasons, zones, and height levels have a considerable impact on the daylighting levels, and there are significant differences in the daylighting levels across different seasons, and zones at different height levels.

Table 4. Analysis of Variance for Southeast-Oriented Replicated Blocks

Dimensions	Block-E (S81^{O}E)			Block-F (S37^{O}E)		
	F Value	Pr (>F)		F Value	Pr (>F)	
Time	2.465	0.08549	.	0.866	0.420991	
Season	1.34	0.26226		8.403	0.000241	***
Zone	3.303	5.22e -09	***	15854.524	< 2e-16	***
Height	2.909	0.00327	**	425.936	< 2e-16	***

Significance Codes: 0 ' *** ' 0.001 ' ** ' 0.01 ' * ' 0.05 ' . ' 0.1 ' ' 1

3.2.4 Southwest-Oriented Blocks

The Jabir Bin Hayan Block (Block-G) is oriented towards S9^{O}W. As shown in Table 8, it is evident that the Time factor has no significant effect on daylighting (p = 0.382065). The F-value of 0.963 indicates that the daylight variability between different time periods is not significantly different from the variability within each time period. The Season, Zone, and Height factors show a highly significant effect on the daylighting levels (p = 8.55e-10) and (p < 2e-16). The F-value of Season, Zone, and Height factors are 21.327, 16622.458 and 472.797 respectively suggesting that the daylight variability between different seasons, zones, and height levels are significantly larger than the variability within each season, zone, and height level. This indicates that the seasons, zones, and heights have a considerable impact on daylighting, and there are significant differences in the daylighting levels across different seasons, zones, and at different height levels.

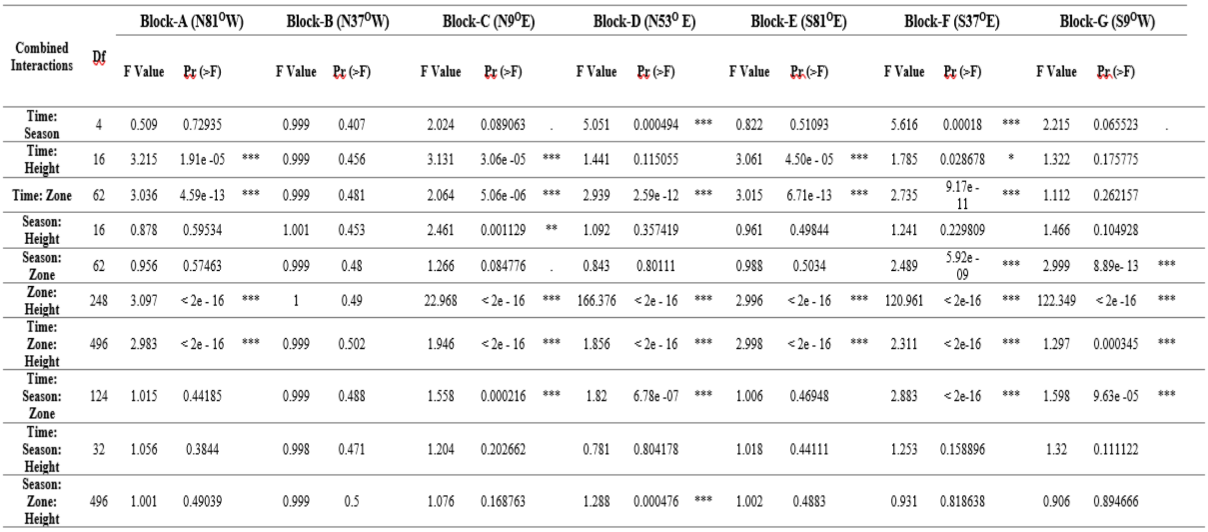
Table 5. ANOVA for Southwest-Oriented Block

Block-G (S9^{O}W)			
Dimensions	F Value	Pr (>F)	
Time	0.963	0.382065	
Season	21.327	8.55e -10	***
Zone	16622.458	< 2e-16	***
Height	472.797	< 2e-16	***

Significance Codes: 0 ' *** ' 0.001 ' ** ' 0.01 ' * ' 0.05 ' . ' 0.1 ' ' 1

Several combined interactions are also tested in this study. Referring to Table 9, results reveal varying behaviors of different blocks and orientations through the combined interactions of spatial-temporal dimensions concerning daylighting. Notably, interactions involving Time and Height, Time and Zone, Zone and Height, Time Zone and Height, and Time Season and Zone consistently exhibited statistical significance ($p < 0.05$) in influencing daylighting intensity in Block-A (N81^{O}W), Block-C (N9^{O}E), and Block-D (N53^{O} E). These interactions consistently played a significant role across various scenarios. In contrast, interactions like Time Season and Height and Season Zone and Height consistently showed p-values greater than 0.05, indicating their lack of statistical significance and limited impact on daylighting levels. Additionally, all the combined interactions between spatial and temporal dynamics in Block-B (N37^{O}W) are non-significant. In conclusion, the daylighting levels of the different zones are not changing regardless of analysis time periods and heights due to the highly non-significant interactions between the factors. The study thus highlights the non-uniform influence of certain interactions across different blocks, orientations, and settings, underscoring the complex and context-specific nature of daylighting dynamics.

Table 9. Combined interactions of spatial-temporal dimensions in replicated blocks across diverse orientations



Combined Interactions	Df	Block-A (N81^{O}W) F Value	Block-A (N81^{O}W) Pr (>F)		Block-B (N37^{O}W) F Value	Block-B (N37^{O}W) Pr (>F)	Block-C (N9^{O}E) F Value	Block-C (N9^{O}E) Pr (>F)		Block-D (N53^O E) F Value	Block-D (N53^O E) Pr (>F)		Block-E (S81^{O}E) F Value	Block-E (S81^{O}E) Pr (>F)		Block-F (S37^{O}E) F Value	Block-F (S37^{O}E) Pr (>F)		Block-G (S9^{O}W) F Value	Block-G (S9^{O}W) Pr (>F)	
Time: Season	4	0.509	0.72935		0.999	0.407	2.024	0.089063	.	5.051	0.000494	***	0.822	0.51093		5.616	0.00018	***	2.215	0.065523	.
Time: Height	16	3.215	1.91e -05	***	0.999	0.456	3.131	3.06e -05	***	1.441	0.115055		3.061	4.50e - 05	***	1.785	0.028678	*	1.322	0.175775	
Time: Zone	62	3.036	4.59e -13	***	0.999	0.481	2.064	5.06e -06	***	2.939	2.59e -12	***	3.015	6.71e -13	***	2.735	9.17e - 11	***	1.112	0.262157	
Season: Height	16	0.878	0.59534		1.001	0.453	2.461	0.001129	**	1.092	0.357419		0.961	0.49844		1.241	0.229809		1.466	0.104928	
Season: Zone	62	0.956	0.57463		0.999	0.48	1.266	0.084776	.	0.843	0.80111		0.988	0.5034		2.489	5.92e - 09	***	2.999	8.89e- 13	***
Zone: Height	248	3.097	< 2e - 16	***	1	0.49	22.968	< 2e - 16	***	166.376	< 2e - 16	***	2.996	< 2e - 16	***	120.961	< 2e-16	***	122.349	< 2e -16	***
Time: Zone: Height	496	2.983	< 2e - 16	***	0.999	0.502	1.946	< 2e - 16	***	1.856	< 2e - 16	***	2.998	< 2e - 16	***	2.311	< 2e-16	***	1.297	0.000345	***
Time: Season: Zone	124	1.015	0.44185		0.999	0.488	1.558	0.000216	***	1.82	6.78e -07	***	1.006	0.46948		2.883	< 2e-16	***	1.598	9.63e -05	***
Time: Season: Height	32	1.056	0.3844		0.998	0.471	1.204	0.202662		0.781	0.804178		1.018	0.44111		1.253	0.158896		1.32	0.111122	
Season: Zone: Height	496	1.001	0.49039		0.999	0.5	1.076	0.168763		1.288	0.000476	***	1.002	0.4883		0.931	0.818638		0.906	0.894666	

Significance Codes: 0 ' *** ' 0.001 ' ** ' 0.01 ' * ' 0.05 ' . ' 0.1 ' ' 1

3.3. ANALYSIS THROUGH HELIODON

The Heliodon is a robust tool for generating solar-responsive design solutions [41] and shows results with barely perceptible variance in accuracy to computer simulations [60]. The mobility of the light source (sun) is a defining feature of the Heliodon that is used in [61]. Heliodon comprises the key components for analyzing the sun's position based on time and location [62]. A fixed horizontal platform for positioning models, a variable light source emulating sunlight direction, moveable metal hoops with electrical lighting simulating solar geometry, and a double-ring frame for inclination modification based on geographic latitude are some of these components. The Sun Emulator Heliodon is utilized (Figure 8) for its automation of light sources and arcs, enhancing result consistency [63].

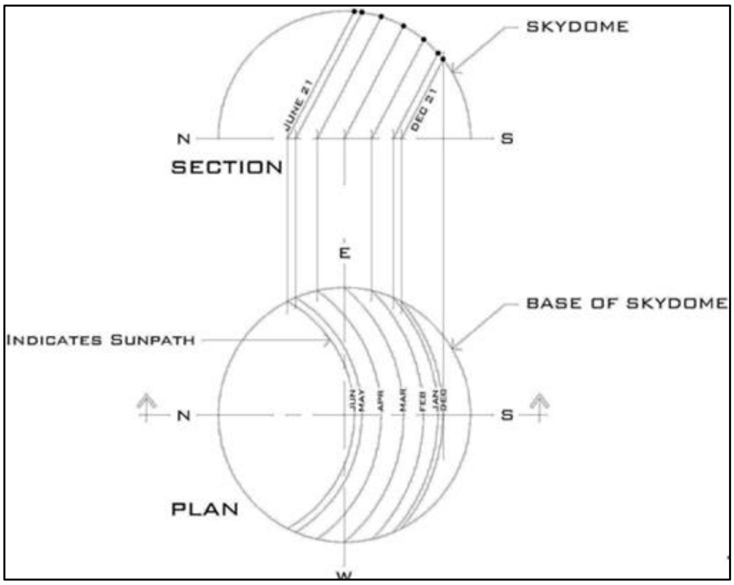


Figure 8. Structure of Heliodon

A physical base case study model is positioned at the center of the Sun Emulator heliodon as illustrated in Figure 9, with the light source inside simulating the sun. To evaluate illumination patterns and shadows created by the sun in various parts of the building. The daylight simulation is observed at various times of day and seasons by changing the position and orientation of the study model to the light source. The position of the sun's rays as they travel across the sky changes as the seasons vary from winter to spring through summer to autumn [64]. Variations occur in the length of the daytime, the sun's altitude, and the intensity of the sunlight. These changes are minimal at the equator, but they become far stronger closer to the poles. The investigations are made on the spring equinox, and winter and summer solstice. For all dates, morning, midday, and afternoon were chosen as the time. The findings from the study highlight the significance of solar geometry and its impact on the interaction between the Sun and the formulated design of buildings.

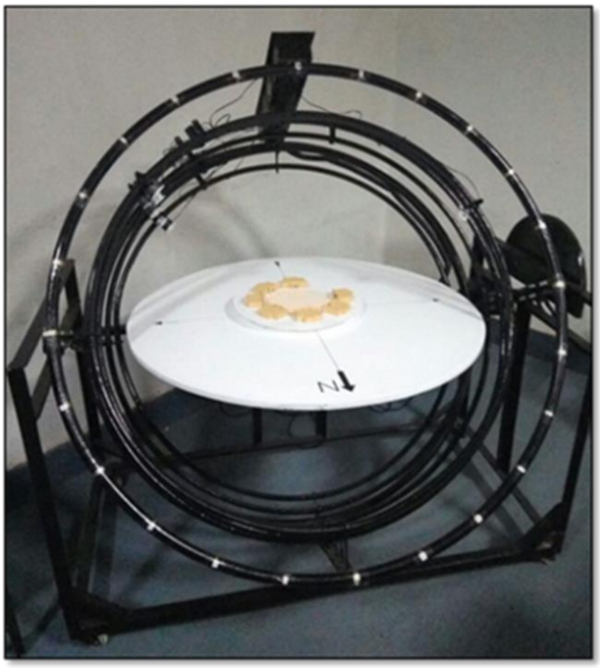


Figure 9. Heliodon with Physical Model of Replicated Blocks across Various Orientations

During the Summer Solstice, the east and west facades of Block-E and Block-A are observed to receive the strongest and most direct sunlight, contributing to higher solar exposure. Conversely, the south facade of Block-G and the front face of Block-C experienced shading due to the high Sun altitude angle. Furthermore, the roofs of the replicated blocks received the maximum and most potent sunrays throughout the day, with peak intensity observed around noon. As a result, during this period, the blocks cast small and warm shadows, indicating a reduced shading impact compared to the Spring/Autumn Equinox and Winter Solstice. Hence, the replicated blocks' orientations interact with the Sun's position during the Summer Solstice, affecting sunlight exposure and shading patterns.

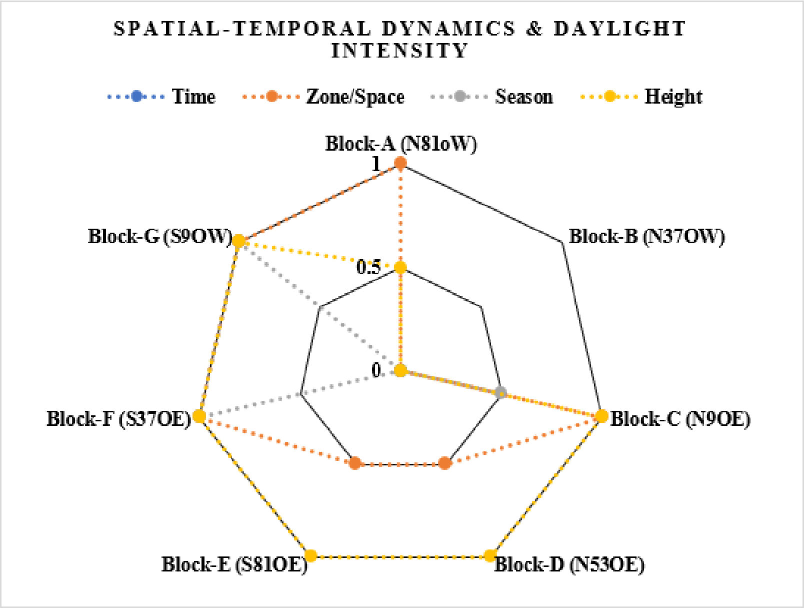
During the Spring and Autumn Equinox, when the sun rises from due east and sets in due west, the orientation of the Sun creates different lighting conditions for the replicated blocks. In the morning, during the Spring and Autumn Equinox, the rear facades of Block-G, Block-F, and Block-E, along with the front facades of Block-A, Block-B, and Block-C, are well exposed to the morning Sun, ensuring ample natural lighting. However, certain blocks, such as Block-B, experienced back shadows, while Block D produced minimal front and side shadows. At noon, the Sun is positioned directly above Block-G, resulting in rear shadows cast by buildings-Block-D, Block-C, and Block-B, while Block-E and Block-A displayed side shadows. The shadows during the Spring and Autumn Equinox were comparatively larger than those observed during the summer Solstice noon Sun, indicating variations in solar exposure and angles during these seasons. In contrast, during the Winter Solstice, the rear facades of Block-G, Block-F, and Block-E receive daylight with long front shadows, leading to distinct lighting conditions. Conversely, the front facades of Block-A and Block-B are well exposed to the Sun, generating long back shadows. Block-C and Block-D experience daylight at the front, resulting in large overlapping shadows at the side and rear facades. The Sun's position during the Winter Solstice allows direct and strong sunlight on the south facades, particularly on Block-G. However, academic blocks with east and west-facing windows, such as Block-A and Block-E, receive only minimal solar radiation due to the Sun's proximity to the horizon, resulting in glancing angles at the windows. Consequently, during this period, all blocks cast long and cool shadows, distinguishing them from the Summer Solstice and Equinox conditions.

In short, the results stress the importance of solar geometry in academic blocks during different seasons. During the Summer Solstice, it affects sun exposure and shading. In the Equinox and Winter Solstice, it's crucial for optimizing daylighting and thermal comfort. Hence, the study of the replicated blocks using Heliodon was performed for a comprehensive assessment of techniques to optimize the collection of high-quality daylight throughout the year, ensuring the creation of solar-responsive building blocks. Furthermore, building orientation and facade design play a crucial role in optimizing daylighting and solar heat gain, impacting building energy performance. Overall, Heliodon simulation confirms the link between spatiotemporal dynamics and illuminance changes with varying sunlight angles.

4. DISCUSSIONS

In this study, the daylighting and solar interaction assessment within the replicated buildings in various orientations is conducted by integrating Revit modeling, Heliodon simulation, and statistical software R as measurement tools. The acquisition of lux level data from Revit modelling to quantify daylight levels in different building areas, and derived solar exposure data from Heliodon simulations, elucidates the dynamic interaction of sunlight with the building's surfaces across various seasons. Concurrently, temporal data is meticulously recorded to monitor fluctuations in daylight and solar exposure throughout the day and across the year. The statistical analysis, facilitated by ANOVA and performed using the statistical software R, interprets the intricate relationships between daylighting, solar exposure, time, season, and the different areas and height levels within the building. This multifaceted approach offers a comprehensive understanding of the dynamics influencing daylighting and solar interactions in the studied building. First, it is worth noting that the approach of using these techniques has been described in previous literature. For example, Salgado-Conrado, Lizbeth, et al. [63] evaluate Autodesk Revit and Heliodon software, highlighting their strengths, limitations, and features. Heliodons lack standardized calibration and error analysis, while computational tools like Revit have steep learning curves due to their multifunctionality. This approach lays a robust foundation for BIM development.

This study offers valuable insights into the impact of spatial-temporal dimensions on daylighting levels within the replicated blocks, arranged in radial planning with varied orientations. Upon analyzing the results, referring to Figure 10, it becomes evident that this study solution introduces a novel dimension to the existing research findings [65-69]. Additionally, this article, in each of the mentioned aspects, presents additional values such as:



Highly Significant-1, Significant- 0.5, Non-significant-0

Figure 10. Spatial-Temporal Dynamics Interaction with Daylight Intensity

- In Block-F (S37OE) and Block-G (S9OW) blocks, daylighting variability is significantly influenced by height levels, zones, and seasons, resulting in direct and consistently high levels of illumination. The southwest and southeast-oriented replicated blocks exhibit uniform daylighting across all seasons and height levels due to factors such as the sun's high altitude, longer daylight hours, and limited shading during the summer solstice. Equally, during the equinox and winter solstice, the symmetrical sun's path, balanced solar altitude, minimal shading, and equal day-night duration maintain consistent daylighting [70], unaffected by the time of day, as indicated by Heliodon analysis.
- In Block-E (S81OE) and Block-D (N53OE) duplicated blocks, statistical analysis reveals that Zone and Height levels exert significant and highly significant influences on daylighting variability, respectively. The Heliodon simulation reinforces these statistical findings, revealing that Block-E (S81OE) maintains consistent daylighting throughout the year due to its extended early morning sunlight during the summer solstice, ensuring a steady supply of daylight even in the shorter days of winter solstice, and achieving a balanced daylight distribution throughout the day during the equinox, regardless of the time or season. Block-D (N53OE), receiving sunlight from both the north and east directions, benefits from a symmetrical sun's path, resulting in a consistently balanced distribution of daylight regardless of the season or time of day.
- The statistical analysis of Block-C (N9OE) indicates that Area and Height levels exert a highly significant influence, while season demonstrates a nearly significant impact on daylighting variability. Heliodon simulations further support these findings, illustrating that solar interaction with Block-C (N9OE) leads to consistent daylighting, regardless of the time of the year. This consistency arises from the building's orientation, which avoids the direct path of the sun. As the sun moves from east to west, Block-C (N9OE) receives minimal direct sunlight during the day. Instead, it benefits from dim, diffuse, and evenly distributed light originating from the northern sky, creating a uniform and stable indoor illumination. Throughout the year, Block-C (N9OE) maintains its consistent daylighting, with minimal impact from seasonal variations, owing to its well-balanced orientation for daylight exposure.
- In Block-B (N37OW), the statistical analysis indicated that the interactions examined in the study were not statistically significant. This suggests that spatial-temporal factors have minimal influence on daylighting levels in the academic block at North-west orientation. The

heliodon simulation corroborated these findings, demonstrating that Block-B's (N37OW) daylighting intensities remain consistent and unaffected by season, time, height levels, and building areas, primarily due to its northwest orientation. The diffuse nature of northern and western daylight further contributes to the stability of daylighting levels, resulting in a relatively constant daylighting environment in Block-B (N37OW).

- In the case of Block-A (N81OW), the statistical analysis revealed that height levels and building areas have significant and highly significant impacts, respectively, on daylighting variability. The heliodon analysis further illustrates that Block-A (N81OW) benefits from direct sunlight in the afternoon and evening. However, the penetration and distribution of daylight inside this building are notably influenced by the building's areas and to a lesser extent by its height configuration. This influence stems from the lower altitude angle and intensity of the sun's rays.

Notably, the time interval was found to be statistically non-significant for all blocks, indicating consistent daylighting levels throughout the day in Summer Solstice, Equinox, and Winter Solstice. The building orientation, absence of significant external obstructions, and the time of the year when the observations were recorded (e.g., solstices and equinox) might have minimized seasonal variations in daylight levels, resulting in relatively consistent daylighting throughout the day may limit the effectiveness of uniform daylight distribution and penetration deep into the area in the blocks. However, some blocks lack effective shading devices, leading to potential glare and discomfort for occupants during specific seasons.

The analysis of daylighting variation across different seasons in various blocks provided intriguing findings. Daylight levels vary significantly throughout the year due to factors such as the number of daylight hours, climatic conditions, the sun's height above the horizon, and more [70]. Notably, Block-B, Block-D, and Block-G exhibited statistically non-significant differences in daylighting variability during the Summer Solstice, Equinox, and Winter Solstice. This indicates that seasonal changes have minimal impact on daylight levels in these blocks. One possible reason for this consistency is the diffusion and reflection of daylight. The orientation of these blocks also plays a crucial role in maintaining consistent daylight levels year-round, regardless of seasonal variations. However, it's important to note that these blocks lack effective shading mechanisms to control direct sunlight during specific seasons. This could lead to potential issues with glare and discomfort for the occupants.

Furthermore, the study also revealed that certain combinations of factors had a statistically significant impact on daylighting levels in the duplicated blocks. These combinations include interactions such as Time: Height, Time: Zone, Zone: Height, Time: Zone: Height, and Time: Season: Zone. In simple terms, these interactions represent how different factors together affect the amount of daylight. Conversely, interactions like Time: Season, Time: Height, Time: Zone, and Season: Height were found to be statistically non-significant. This means that these combinations of factors had a limited or negligible impact on the variation in daylight levels. In essence, they didn't significantly influence the amount of daylight in the replicated blocks.

Therefore, based on these findings (highlighting the significance of spatial dimensions; Area, and Height), it is evident that the orientation of these replicated buildings plays a pivotal role in shaping the distribution and exposure of daylight, and this influence varies across different academic blocks. Baydoğan, Murat Çağlar, and Vildan Özkantar [66] and Alkhatatbeh, Baraa J. et, al. [69] offered a representative case of such research. They focused on the daylight performance of educational spaces and highlighted how spatial and temporal dynamics shape space in terms of daylighting.

5. CONCLUSION

The study investigated the influence of spatial-temporal dynamics, encompassing factors such as time, height levels, areas, and seasons, on daylight intensity of replicated buildings across diverse orientations, each with twenty-eight rooms of its three floors, and arranged in radial planning at regular intervals of 45 degrees. The employed methodology was the combination of simulation, statistical techniques, and the utilization of a Heliodon to assess its effects on replicated academic blocks featuring diverse orientations.

The following conclusions are drawn from an extensive simulation-driven study:

- The analysis revealed that spatial dimensions (Area and Height) are critical factors affecting daylighting levels across all replicated blocks and can predict daylighting variability consistently, indicating the importance of architectural design, orientation, and building layout.
- The influence of temporal dimensions such as Season appears to vary spatially and can predict the variation in daylighting inconsistently. However, the non-significance of another temporal dimension; Time interval suggests that this factor does not play a significant role in determining the daylighting levels, indicating potential regional differences in daylighting exposure.
- The study also revealed that the interactions tested for the northwest-oriented block (Block-B) did not exhibit statistically significant results for any of the spatial-temporal dimensions. This suggests that the factors considered in these interactions have an insignificant impact on daylighting levels in this particular block. The large residual variance further emphasizes that there is a considerable amount of unexplained variability in the data after accounting for the effects of the factors and interactions studied.
- The overall tendency of the results shows that orientation has been identified as a highly influential factor that distinctly impacts the distribution and exposure of daylight in each replicated block. Moreover, the specific design and architectural choices of the replicated academic blocks play a crucial role in determining the observed consistency in daylight intensity across spatial-temporal dimensions.

Optimization and daylight design guide

- The South-West (Block-G), South-East (Block-F & Block-E) and North-West (Block-A) oriented academic blocks require proper shading design. The consistent daylighting levels may limit the effectiveness of uniform daylight distribution and penetration deep into the area indicating the high probability of excessive light and glare. This problem can be solved by installing shading inside or outside of a window.
- The absence of shading design in North-East oriented (Block-C) may be advantageous in most cases.

Using one single metric may not result in a better daylight environment in all scenarios, highlighting the need for more extensive future research to support these conclusions. The integration of simulation, statistical, and heliodon tools, can guide design decisions and enable building practitioners and scientists to evaluate different design scenarios effectively. Given the complexity of the observed interactions and the potential influence of unexplored spatial-temporal factors, future research should delve into these findings and explore additional variables to enhance the daylighting study. Investigating these factors has the potential to provide a more comprehensive understanding of the phenomenon and advance knowledge in the field.

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