Biophilia in Classrooms Through Daylight and Fractal Patterns

by

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THESIS ABSTRACT

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Title: Biophilia in Classrooms Through Daylight and Fractal Patterns

Designing K-12 classrooms with proper daylighting is imperative to the development and educational enrichment of children. The benefits of daylight in buildings have been vastly researched and have demonstrated positive impacts on student performance (Heschong et al.,1999). Out of all design parameters in the classroom, including temperature, acoustics, and air quality, daylight has the highest impact on overall student progress (Barrett et al., 2015). Daylight positively contributes to higher academic performance in reading and science (Barrett et al., 2015). It also supports focus, the stability of the circadian cycle, and overall mental health (Walker et al., 2020). While daylight alone is a great element that supports biophilic design within classrooms, it can also be utilized in creative ways to introduce other natural phenomena that exist in nature, such as fractals. This study will evaluate the benefits of daylight fractal patterns for students' visual comfort and daylight exposure in classrooms. The goal is to demonstrate the positive impact of daylight fractal patterns on students and to add to the body of knowledge related to biophilia in architecture and its benefits to building occupants. The results of this study suggest that fractal patterned screens offer better performance when aiming for better daylight exposure in classrooms, prompting better circadian rhythm regulation and overall well-being of students. Ultimately, the performance examined from fractal patterned screens in this study encourages the use of daylight and fractals combined as biophilic design elements within classrooms.

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CHAPTER 1 – INTRODUCTION

1.1 Problem Statement

Being in close contact with nature in a school environment can have significant benefits towards stress and boredom, student engagement, and academic success (Browning & Determen, 2024). However, modern school design has provided fewer opportunities for students to experience substantial contact with nature as an integral part of their education. It is especially important to study spaces in which children spend a considerable amount of their time, as most states in this country require an average of 1,231 hours per year to be spent in K-12 classrooms (Kraft & Novicoff, 2025). This can impact student comfort and engagement throughout the day, which can be affected by the classroom they are required to take part in for at least 160 days of the year (Kraft & Novicoff, 2025).

By introducing biophilic elements in K-12 school classrooms, designers can help students feel more engaged and ready to learn. One significant element of introducing biophilic design in schools is daylight, as it plays a key role in overall focus and alertness within classrooms (Barrett et al., 2015). It is known that biophilia and daylight within buildings can have significant positive impacts on human health (Elzeyadi, 2011). Therefore, digging deeper into how designers can use daylight to produce biophilic design attributes in classrooms may be pertinent.

One way that daylight can be utilized in a creative way, and has not been researched before, is by applying fractal patterns on perforated screens. Fractal patterns can introduce captivating and visually interesting light patterns within the interior space of a classroom, as seen in Figure 1.1. Fractals are self-repeating patterns that exist in various forms of nature and have been studied by psychologists to quantify their effects on stress levels. Past studies have demonstrated that when participants viewed fractal patterns with mid-D values stress was reduced by 60%

(Taylor, 2021). The D value of a fractal is related to the pattern's complexity and how the human visual system efficiently processes the intricacy and geometrical shapes of a pattern. This study will evaluate the benefits of daylight fractal patterns for students' visual comfort and daylight exposure in classrooms and will add to the body of knowledge related to biophilia in architecture and its benefits to students.

Figure 1.1. Architectural rendering exhibiting the application of perforated solar screens with fractal patterns in a kindergarten classroom.

1.2 Research Questions

This study will evaluate the visual comfort and daylighting performance of fractal patterns on solar screens as biophilic design elements within a classroom. The fractal patterns will be compared against traditional uniform patterns and randomized patterns. Uniform patterns on solar screens have been more widely used, therefore, evaluating this pattern type against a fractal pattern can add to existing research on solar screens. In addition, Huang et al.'s (2024) previous study on randomized solar screens concluded that non-uniform perforated screens have better daylight uniformity, therefore, to add to this research, randomized patterns will also be evaluated in this study to examine the performance against fractal patterns. The questions that will be examined in this study are: 1. How will fractal patterned screens impact visual comfort and daylight exposure? 2. Will there be significant differences in glare and visual comfort between fractal, uniform, and random patterned screens? 3. Are fractal patterns applied on solar screens a practical solution for providing biophilic characteristics within a classroom?

1.3 Research Objectives

The objective of this study is to evaluate the performance of different fractal patterns within the complexity factor of D = 1.4 - 1.6 on dynamic daylighting metrics such as Annual Sunlight Exposure (ASE), Useful Daylight Illuminance (UDI), Spatial Daylight Autonomy (sDA), and Daylight Glare Probability (DGP). The goal is to demonstrate how daylight fractal patterns introduced by shades or screens inside a classroom can impact visual comfort and daylight exposure. By understanding the performance of each pattern, this study can also provide evidence or support for selecting specific solar screen patterns to achieve definitive results.

1.4 Research Significance

If the results are meaningful, then it could provide a solution for introducing biophilic design elements in educational environments. In addition, if students or academics are interested in biophilic design, daylight, fractals, or solar screens, they may utilize the results of this study to develop their research. The expected results would present viable data to use in architectural practice. For designers with experience and aspirations in the K-12 education sector, this could present further knowledge on daylighting design in the field and everyday practice. Ultimately, this study could provide architectural and interior designers with empirical evidence to substantiate their design choices, allowing them to demonstrate action in their practice by utilizing research for creating spaces that serve occupants in a meaningful way.

1.5 Research Scope

The scope of this study is limited by the following parameters:

1. Location: The simulation setup was tested in Phoenix, Arizona, to maximize sunlight exposure.
2. Model Setup: A rectangular standard classroom size with a 100% window-to-wall ratio on only one side of the room is studied. All other sides are completely windowless.
3. Orientations: Only south and west orientations were simulated.
4. Typology: This study is analyzed in relation to classrooms and young students.
5. Metrics: The daylight metrics that are simulated are intended to study factors that will impact student connection with the outdoors and reinforce circadian rhythms.

1.6 Conceptual Framework

The conceptual framework is broken down into four steps as seen in Figure 1.1. The first describes the independent variables that will be applied in the studies. These variables are the varying patterns that will be applied on solar screens within the simulation model, along with the base case. The controlled variables are related to the classroom setting that will be modeled, which includes the classroom size and the window-to-wall ratio. The next step is the mediational variables that describe the specific metrics that will be analyzed. Lastly, the dependent variables will present the outcomes of this study and provide clarity regarding the research questions.

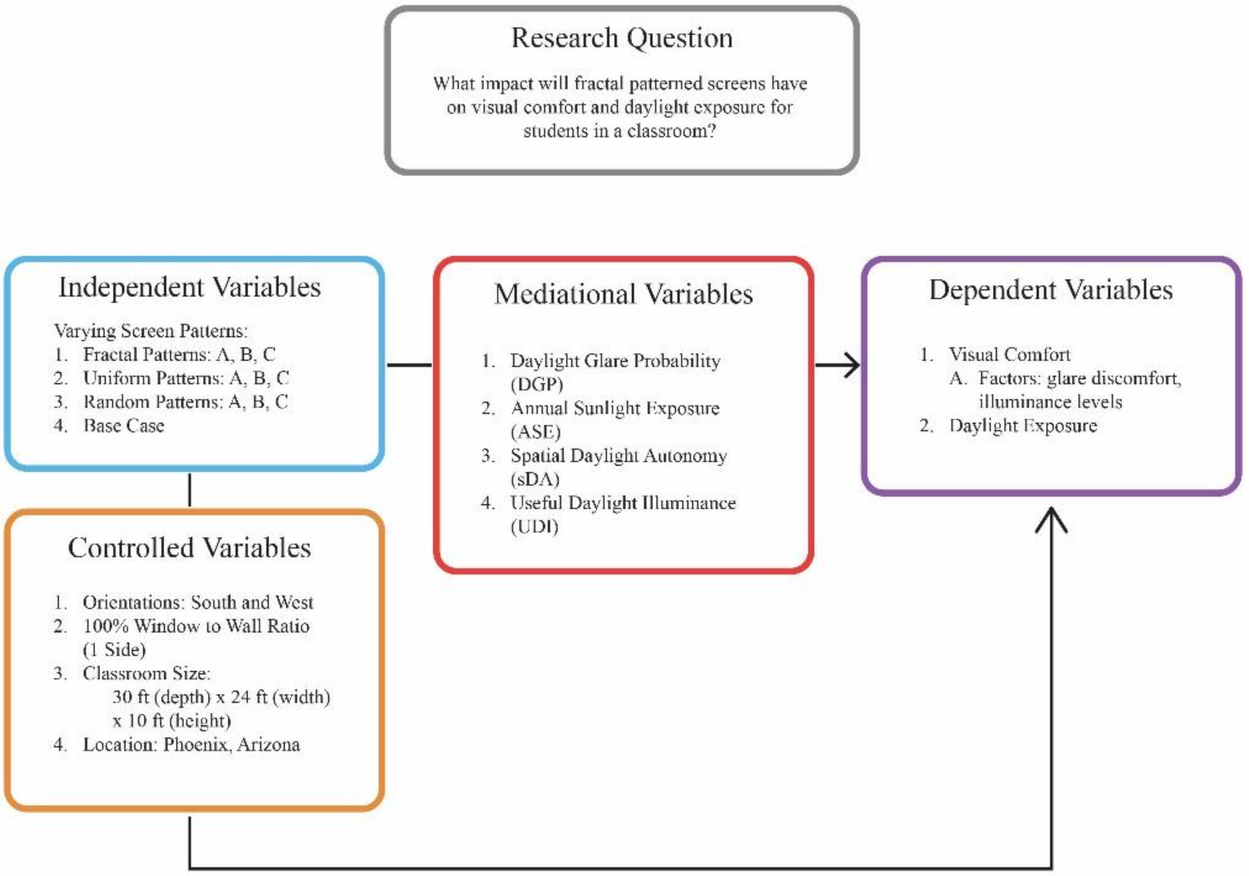


Figure 1.2. Conceptual Framework

CHAPTER 2 – LITERATURE REVIEW

2.1 Impact of Classroom Design on Student Learning

Spaces in which children spend most of their time, such as classrooms, are important places to study. The research completed by Barrett et al. (2015) suggests that differences in the physical characteristics of primary school classrooms explain approximately 16% of the variation in learning progress. They argue that individual classroom environments have a bigger impact on students and faculty than design elements within other areas of a school campus (Barrett et al., 2015). One important factor that this study highlights is that daylight was seen to have the highest impact on overall student progress, especially when considering optimum glazing and any glare risk mitigation.

In addition, addressing glare control is one aspect of lighting that is evaluated in a post-occupancy evaluation (POE) completed by Elzeyadi et al. (2019), where daylight and visual comfort are analyzed through field measurements. This study was intended to bridge a gap between daylighting simulations and actual space performance. It argues that the main factor influencing daylighting design in schools is the need to provide a diversity of illumination sources within a classroom (Elzeyadi et al., 2019). This argument supports the research proposed in this study, as the investigation being presented will add to the literature and design solutions for mitigating glare and providing an illumination source within classrooms.

2.2 Biophilia

Biophilia is the hypothesis that humans have an innate desire and need to connect with the natural world (Wilson, 1984). Classroom design must draw a connection to nature for the healthy development of children, as nature plays a crucial role in human evolution, particularly during childhood (Kahn & Kellert, 2002). Biophilic characteristics in classrooms have been proven to improve student mood and increase performance in standardized tests (Browning & Determen, 2024). This study, conducted by Browning and Determen (2024), also indicated that introducing daylight in classrooms improved academic performance. Another important aspect of nature that is highlighted in the study is that objects in nature often have statistical fractal patterns, such as snowflakes, fern leaves, or flames in a fireplace. These patterns can be so common that even when used in human-designed objects, the brain can process them easily and even lower stress levels (Robles et al., 2021). Furthermore, introducing fractal patterns through daylight in a classroom environment is one method that has not been carefully studied. It can pose a solution towards creating biophilic design elements for young students as a means of having a better connection to nature in their learning environment.

2.3 Daylight and Fractal Patterns

Irregular patterns on perforated facades have been proven to have perceptual effects on spatial distribution in luminance patterns (Chamilothori et al., 2016). The study conducted by Chamilothori et al. (2016) tested three varying facade patterns: two with uniform patterns, and one with an irregular or non-uniform pattern. Following the results, the facade with an irregular pattern demonstrated significant differences in four of the scales tested. Participants found the irregular pattern to be measurably more exciting, complex, interesting, and pleasant than the other two uniform patterns (Chamilothori et al., 2016). A similar study conducted by Huang et al. (2024), indicated that non-uniform solar screens could provide solutions for solar shading in facades with greater daylighting performance compared to uniform solar screens. Both studies looked at facade patterns, however, the former study only focused on the overall satisfaction of the patterns. The latter study went into further detail by investigating daylight availability quality and uniformity, glare discomfort, and overall daylight performance.

Another study conducted by Abboushi et al. (2019) specifically looked at projected fractal light patterns to examine what complexity level would elicit visual interest and mood response. The results indicated that medium to medium-high complexity light patterns were the most preferred and visually interesting to participants. This study projected light patterns onto a projection wall and had participants complete a rating procedure that assessed relaxation and excitement from the patterns. While this is an effective way to test responses to varying patterns, it may be pertinent to further investigate performance on overall visual comfort and daylight exposure through model simulations.

2.4 Screens and Perforations

Some studies have been conducted to test exterior solar screens in architectural applications. The study completed by Chamilothori et al. (2016), investigated daylight patterns as a means of influencing spatial ambiance. In this study, perforated facades resulting in daylight patterns are analyzed to examine the impact on perceived spatial ambiance. Other studies, such as the one conducted by Naik and Elzeyadi (2020), take a further look at how exterior solar screens may impact an occupant's thermal comfort within architectural spaces. It should be noted that through their investigation, solar screen panels with a 30 to 50 percent ratio were tested. The ratios examined are important to note because of glare impacts within interior spaces that will be examined in the research presented in this study. While past research has investigated the thermal impacts of varying screen perforation ratios, the impacts on visual comfort, daylight exposure, and circadian rhythm have not yet been investigated.

A study conducted by Huang et al. (2024), explored various non-uniform solar screen perforations against a uniform solar screen perforation as the base case to investigate factors that may impact overall daylight performance. The findings of this study suggest that non-uniform solar screens offer better daylighting performance for solar shading in façade design compared to traditional uniform screens. The findings indicate that several additional factors—including non-uniform perforation patterns, variations in aperture size and orientation, and differences in perforation density—significantly impact indoor daylight uniformity. A comprehensive evaluation of various design variables in non-uniform screens revealed that the perforation pattern has the most pronounced effect, particularly in terms of daylight availability and uniformity. Aperture size follows as the second most influential factor, especially regarding daylight uniformity. Orientation also plays a notable role, aligning with previous research, though its impact is more substantial in daylight availability and glare discomfort in non-uniform screens. A potential avenue for further research in relation to this study involves examining different climatic zones, given that the simulations in this study were conducted in a subtropical region of China. Additionally, testing of other non-uniform solar screen prototypes can be expanded. Although this study evaluated overall daylight performance, including glare, annual sunlight exposure, and spatial daylight autonomy, it did not address the impact on the circadian rhythm of occupants.

2.5 Circadian Rhythm and Wellbeing

Light plays an active role in human behavior and physiology through the influence of retinal illumination, which is a response that the eye produces for regulating the human circadian system. This biological response is separate from the image-forming responses of the eye. It is a non-visual or non-image-forming response that is crucial in resetting the internal circadian clock. The effects of circadian rhythmicity can have significant physiological, metabolic, and behavioral responses in the human state (Lucas et al.,2014). This study describes how light aids in the suppression of melatonin, increased heart rate, stimulation of cortisol production, and acts as a neurophysiological stimulant, which affects alertness and reaction time. Moreover, light has been proven to have anti-depressant properties and has been applied therapeutically to aid with sleep disorders and circadian disruptions, such as jetlag (Lucas et al., 2014). Circadian desynchrony, or circadian disruption, not only has mental health effects but also has been proven to lead to increased risk of obesity, metabolic disease, cardiovascular disease, addiction, Alzheimer's disease, and even specific types of cancer (Soler, 2019).

Soler's article (2019) also addresses circadian photoreceptor metrics that have been developed to quantify circadian effectiveness since the discovery of the circadian photoreceptor by Dr. George Brainard, known as "intrinsically photosensitive retinal ganglion cells" (ipRCGs) (Brainard et al., 2001). Soler (2019) contends that circadian rhythms are kept in sync when the human body responds to light by way of ipRCGs. The two metrics that are introduced for quantifying circadian effectiveness are melanopic lux and the circadian stimulus model (Soler, 2019). The Equivalent Melanopic Lux (EML) model was first proposed by Lucas et al (2014) and is based on spectral power distribution rather than the visual intensity of light. The melanopic lux model has a peak sensitivity of 490 nm, which is the blue-green part of the light spectrum (Soler, 2019).

According to Walker et al. (2020), blue light deriving from sunlight during the day most strongly stimulates melanopsin photopigment in the eye's ganglion cells, which is needed to set the circadian molecular clock in the brain and contributes to mood-related structures in the brain. Having a healthy circadian system is important for everyone, and circadian rhythm disruption early in life can have significant neurodevelopmental effects and may promote aging-related mental health disorders later in life (Berman, 2022). Daylight plays an important role in circadian rhythm and should be addressed through building design solutions. Buildings at schools should especially implement good-quality daylight, as young students spend a good portion of their day engaging in educational activities in their classrooms. Not having appropriate daylight within their classrooms can ultimately affect student performance and their overall well-being.

CHAPTER 3 – METHODOLOGY

3.1 Simulation Setup

The simulation model used in this study was a side-lit open-plan classroom with dimensions of 30 ft (depth) × 24 ft (width) × 10 ft (height). The size of the classroom was determined based on average K-12 classroom sizes in the U.S., ranging anywhere between 700 and 1,100 sq. ft. (Haapanen, 2024). The model was simulated on the ground floor level based on previous sensitivity studies that evaluated differences in daylight performance between first, second, or third floor levels. The analysis did not conclude any significant differences per floor level. Therefore, the final simulations were completed on the ground level. Furthermore, one side of the classroom had a 100 % window-to-wall ratio, while the other walls were windowless. To maximize daylight exposure, only south and west orientations were examined in this study. A perforated solar screen was modeled on the interior side of the glass facade, positioned 1 inch away from the surface. The solar screen was 24 ft (width) × 10 ft (height). A total of 9 perforated solar screens were simulated for daylight performance, along with a standard glazed opening with no shading as a base case for comparison, shown in Figure 3.1.

The site chosen for the simulation was Phoenix, Arizona, with a severely hot summer period. Previous sensitivity analyses tested two other site locations: Eugene, Oregon, and Los Angeles, California. However, Phoenix, Arizona was concluded to have the highest sensitivity regarding sun exposure. Phoenix, with a mean altitude of 1,086 ft, has the highest altitude out of all the cities evaluated. Therefore, it generally receives more intense sunlight, allowing this study to maximize daylight exposure to test the solar screens' performance. Lastly, ASHRAE design weather database v7.0 was used for simulation through the Integrated Environmental Solutions Virtual Environment (IES-VE) software.

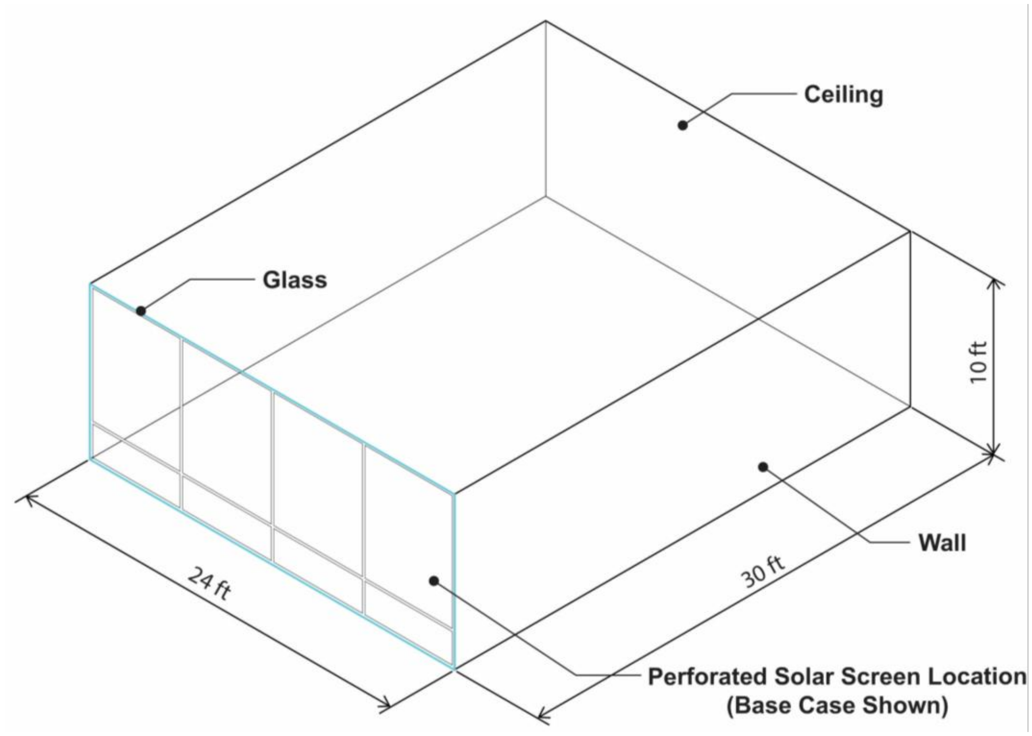


Figure 3.1. Simulation Model

3.2 The Patterns and Perforation Ratios

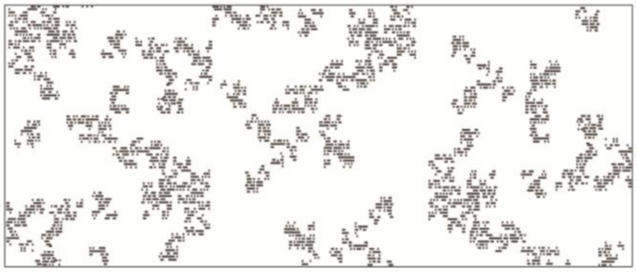
A series of patterns were selected to test out the performance of varying daylight patterns within the controlled room setting previously mentioned. This set of 9 patterns, along with the room, was modeled in Rhino 3D and then transferred to Integrated Environmental Solutions Virtual Environment (IES-VE) simulation software via Pollination for Rhino. The patterns were grouped by equal perforation ratios to isolate the analysis by pattern type. Each group contains a fractal pattern, a uniform pattern, and a random pattern. Group A has a perforation ratio of 19%, Group B has a perforation of 12%, and Group C has a perforation ratio of 38%. The following sections will explain the reasoning behind the pattern selection in detail and the methods for creating the patterns.

3.2.1 Fractal Patterns

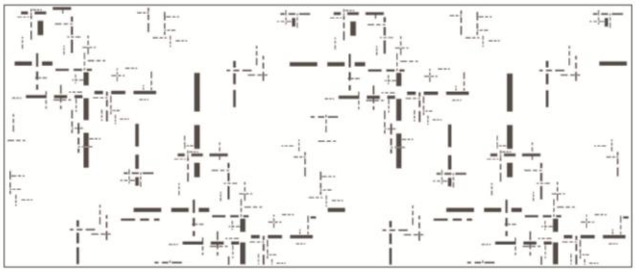
Fractals are self-repeating patterns found in nature, such as clouds, tree branches, and ocean waves. Taylor's (2021) research, initially funded by NASA to help astronauts manage stress, reveals that our visual system has adapted to these natural fractals. This adaptation occurs at multiple stages, from how our eyes scan fractal patterns to how our brain processes them. This led to the development of the "fractal fluency" model, which suggests that our visual system efficiently processes mid-range complexity fractals, enhancing our aesthetic experience and reducing physiological stress (Taylor, 2021).

Psychologists utilize a parameter developed by mathematicians to assess the visual intricacy resulting from the fractal pattern repetition (Mandelbrot, 1982). The fractal dimension (D) quantifies how patterns at different scales organize into the fractal image projected on the retina (Robles et al., 2021). For simple shapes, D has a value of 1, while a filled area has a value of 2. The repeating patterns fixed within a fractal line then begin to occupy space. At this point, the fractal's D value lies between 1 and 2. As the fractal line increases in complexity, it gradually fills in the 2-dimensional surface of the retina, and the fractal's D value begins to approach 2. As the D values move closer to 2, the increase in fine structure content creates a much more intricate and detailed shape. Behavioral research confirms that people's perception of complexity increases with D and when research participants viewed mid-D fractals stress was reduced by 60% (Taylor, 2021).

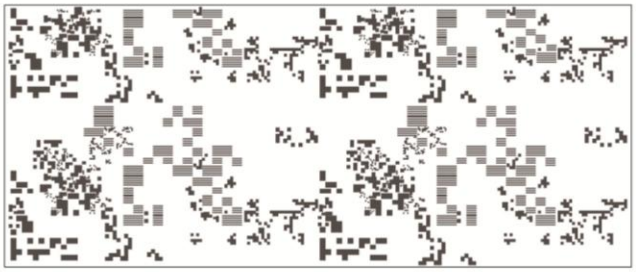
The 3 fractal patterns utilized in this study were accessed through the Science Design Lab, a collaboration between the product design studio 13&9 Design and fractals research. Each fractal pattern shown in Figure 3.2 was specifically selected to study varying perforation ratios as a perforated solar screen application. Fractal pattern A has a D value of 1.47 and a perforation ratio of 19%. Fractal pattern B has a D value of 1.35 and a perforation ratio of 12%. Fractal pattern C has a D value of 1.6 and a perforation ratio of 38%.



Fractal A - 19% Perforation Ratio



Fractal B - 12% Perforation Ratio



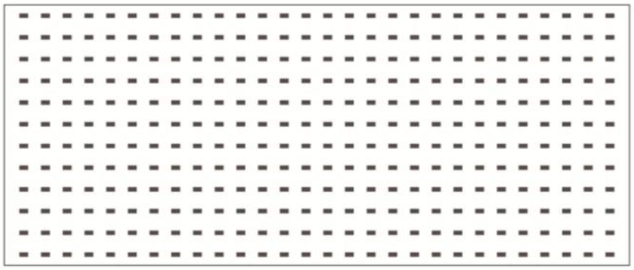
Fractal C - 38% Perforation Ratio

Figure 3.2. The Fractal Patterns Tested from the Science Design Lab's Fractal Library

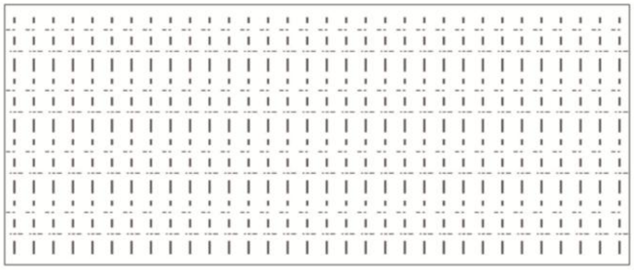
3.2.2 Uniform Patterns

While traditional uniform perforated solar screens have been widely used, the increasing adoption of non-uniform perforated screens highlights their potential to enhance architectural aesthetics through diverse perforation patterns on building facades. However, the impact of these non-uniform screens on daylighting performance has been infrequently studied (Huang et al., 2024). Non-uniform fractal patterns have not been studied before in solar screen applications; therefore, this study will comparatively analyze how fractal pattern screens perform against traditionally used uniform pattern screens.

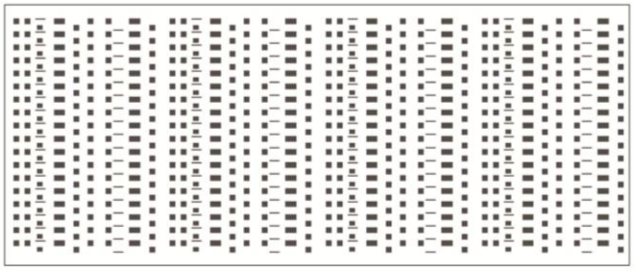
After each fractal pattern was selected in the process described previously, 3 uniform perforated patterns were created using the same perforation ratios as their corresponding fractal perforated patterns to adequately compare daylight performance. A small sample was retrieved from each fractal pattern to create a repeated uniform pattern that would ultimately have the same perforation ratios as the 3 fractal perforated patterns selected. Figure 3.3 demonstrates the uniform patterns created.



Uniform A - 19% Perforation Ratio



Uniform B - 12% Perforation Ratio

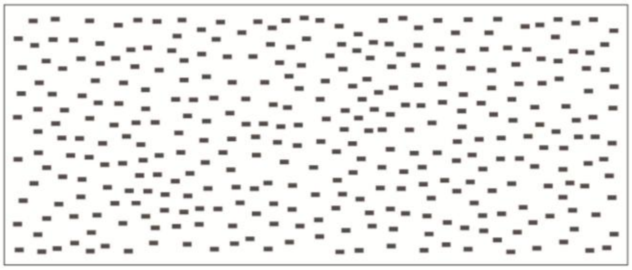


Uniform C - 38% Perforation Ratio

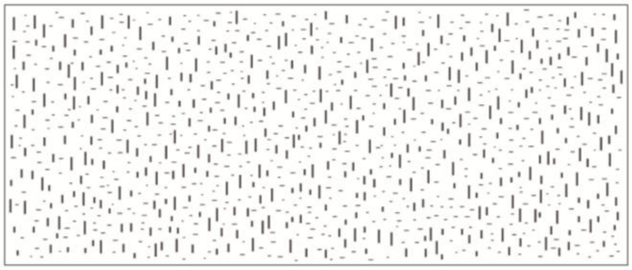
Figure 3.3. Uniform Patterns

3.2.3 Random Patterns

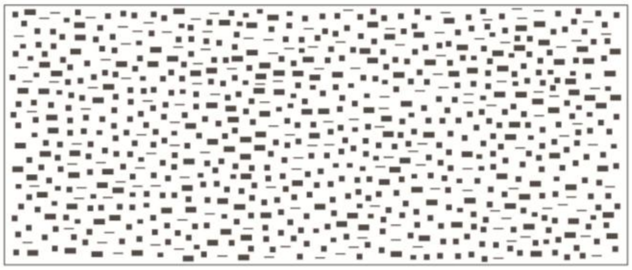
A study completed by Huang et al. (2024) utilized a uniform perforated pattern against non-uniform perforated patterns using an application in which the perforation patterns were randomized within linear and radial gradient patterns. The results of the study suggest that non-uniform perforated solar screens significantly outperform uniform screens with respect to daylighting performance, even at equal perforation ratios. Therefore, to add to the research and compare against non-uniform fractal patterns, 3 random patterns were also created as part of this study (Figure 3.4). The random patterns in this study were created using the exact perforations used in the corresponding uniform patterns but were randomized using the Grasshopper parametric function through Rhino, as seen in Figure 3.5. The grasshopper parametric function utilized the populate 2D component to randomize the perforation geometry selected.



Random A - 19% Perforation Ratio



Random B - 12% Perforation Ratio



Random C - 38% Perforation Ratio

Figure 3.4. Random Patterns

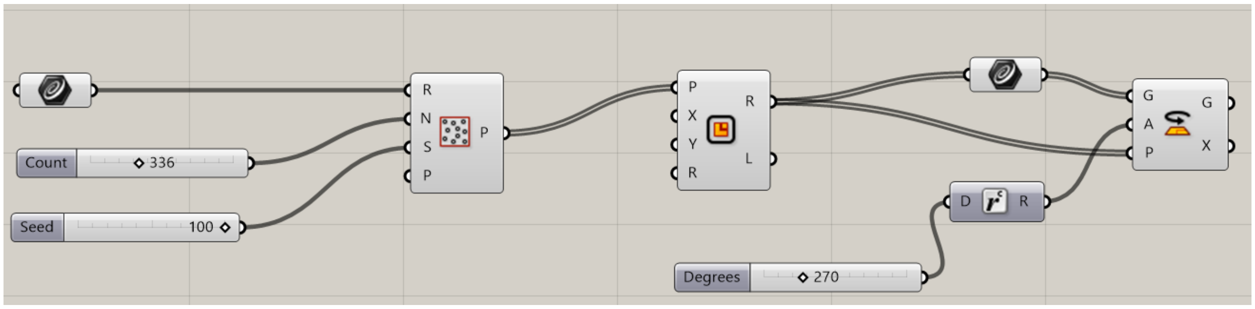


Figure 3.5. Grasshopper Parametric Function for the Randomized Patterns

3.3 Experimental Design and IES-VE Simulation Software

This study adopts an experimental design methodology, utilizing computational simulation as the primary investigative tool. Computational simulations provide a controlled environment that allows for the manipulation and analysis of individual variables, facilitating a detailed examination of their effects. For this study, the Integrated Environmental Solutions Virtual Environment (IES-VE) software has been selected, specifically, its RadianceIES module, which is recognized for its capability to perform dynamic annual simulations. RadianceIES employs sophisticated ray-tracing techniques to generate accurate representations of light distribution within architectural spaces. This tool is instrumental in evaluating daylight, thereby aiding in the optimization of daylight to enhance visual comfort.

3.3.1 Daylight Simulation Specifications

To assess illuminance values within the modeled space, the view plane height was set at 3 ft above the finish floor, and a grid spacing of 1.64 ft was used, as shown in Figure 3.6. The view plane height was selected to accommodate the average sitting heights of children with ages ranging between 2 to 18 years old (Hawkes, 2020). The simulation analysis period covered the occupancy hours from 8:00 am to 6:00 pm for the entire year, except weekends. Although most schools end earlier than the occupancy hours examined, these hours may also account for any after-school programs that students may engage in after regular school hours. The illuminance values extracted for Useful Daylight Illuminance, Annual Sunlight Exposure, and Spatial Daylight Autonomy are annual averages computed within the parameters previously described.

3.3.2 Glare Simulation Specifications

For Daylight Glare Probability (DGP) values, the position (P) examined for visual discomfort between perforation patterns was placed 10 ft away from the wall and had a diagonally focused view towards the opposite edge of the classroom, as seen in Figure 3.6. The months of March, June, and December were simulated to consider the shift in seasons during the summer and winter solstice and spring equinox. In addition, the simulation times selected for this metric varied depending on the specific orientation evaluated. When evaluating the south orientation, the simulation was completed at 12 pm, for the west it was completed at 3 pm. These specific times were selected to maximize daylight exposure within the classroom for each orientation.

The DGP metric utilizes a formula that typically involves a logarithmic relationship between the vertical illuminance and the source luminance, with the solid angle and position index also playing a role. A source luminance (Ls) refers to the brightness of the light sources within the field of view, such as the sky or a sunlit surface. A solid angle of source (ωs) indicates the size of the glare source relative to the observer's field of view. A position index (P) is a factor that accounts for the observer's position and orientation, influencing how they perceive glare. These factors are combined in a formula to determine the DGP value. Ultimately, the RadianceIES module within IES-VE computes these values and provides the DGP percentage of glare within the modeled space.

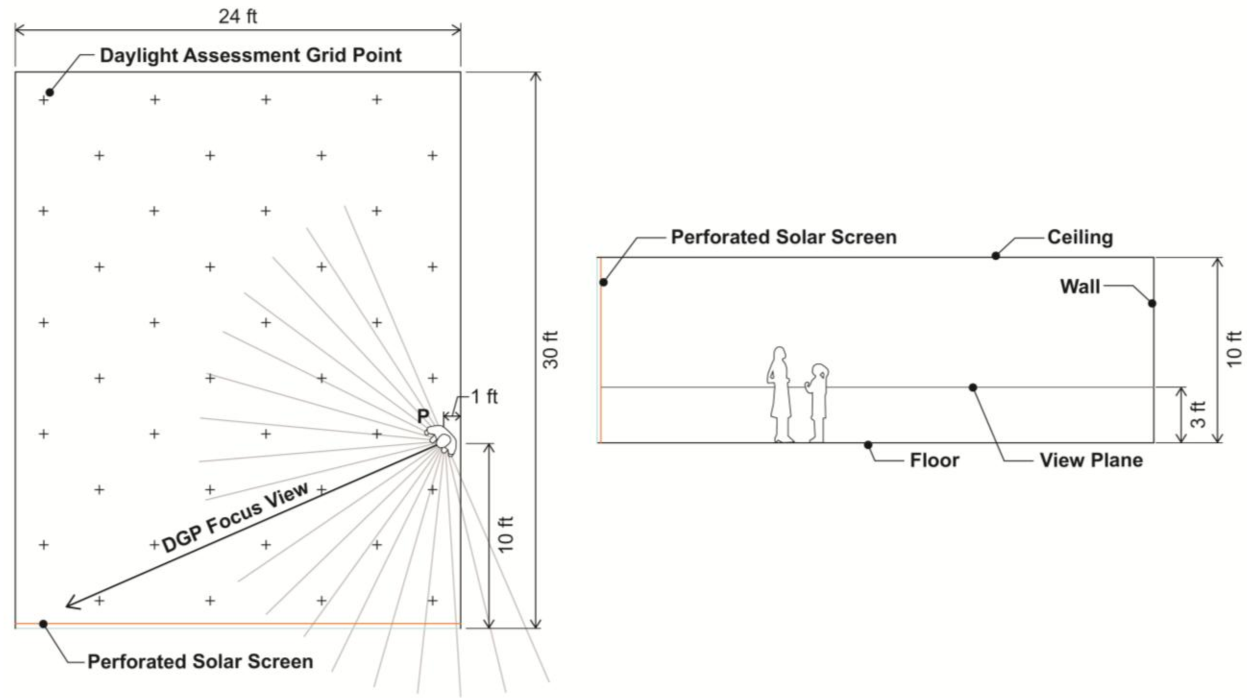


Figure 3.6. Plan and Section of the Simulation Model[NC1]

3.4 Metrics of Performance Evaluation

To evaluate the performance of the perforated solar screens, this study examined four aspects related to daylight availability and visual comfort. The following sections will explain each metric evaluated and its significance in this study.

3.4.1 Useful Daylight Illuminance (UDI)

Useful Daylight Illuminance (UDI) is the temporal distribution of various illuminance levels at a given point. It is measured as a percentage of time where the points' illuminance falls within the following lux values:

1. Below a minimum lux threshold where full electric lighting is needed:
   ("Failing": below 100 lux)

2. Between a range of lux values where supplementary electric lighting is required: ("Supplementary": between 100-300 lux)
3. Between a useful minimum and maximum value where no electric lighting is needed: ("Autonomous": between 300-3,000 lux)
4. Above a maximum value, which could result in glare: ("Excessive": above 3,000 lux)

This study deployed simulations using autonomous levels between 300 to 3,000 lux. This threshold would provide adequate daylight within a space that is useful to students within a classroom and is within a comfortable range that will not cause glare or disruption to the visual environment. Achieving a high percentage of autonomous UDI indicates that a classroom is predominantly daylit during occupied hours, reducing the need for artificial lighting. This can lead to improved student well-being due to the positive effects of daylight.

3.4.2 Annual Sunlight Exposure (ASE)

Annual Sunlight Exposure (ASE) is a percentage of an analyzed area that exceeds a specified direct sunlight illuminance level (1000 lux) for more than a specified number of hours (250 hours) per year. ASE is meant to complement Spatial Daylight Autonomy (sDA), as a metric to help designers limit excessive sunlight in a space. A higher percentage of ASE suggests a higher risk of glare but is not a definite metric for glare or visual discomfort occurring. A common ASE threshold is 10%, which means that no more than 10% of the regularly occupied space should receive more than 1,000 lux for 250 hours each year. The purpose of ASE in this study is to demonstrate if a classroom is over-lit.

3.4.3 Spatial Daylight Autonomy (sDA)

Spatial Daylight Autonomy (sDA) is a percentage area of the analyzed space that is above a certain lux level (300 lux) for a certain percentage of the time (50% of the time) or more during occupied hours (e.g., 8:00 am to 6:00 pm). It is a metric describing the annual sufficiency of daylight levels in an interior environment. It also helps designers quantify the success of a building's daylighting strategy and assess its impact on occupant well-being. Adequate daylight exposure can positively impact student well-being by aligning with circadian rhythms and potentially reducing stress and fatigue (Al Awadh and Elzeyadi, 2020). Daylight can improve mood, focus, and overall student productivity (Barrett et al, 2015). By quantifying the extent of daylight exposure, sDA provides valuable insights into how a building's design influences occupant experience and performance. It is often used in conjunction with ASE to allow designers to find a balance between maximizing daylight benefits and minimizing the potential negative impacts of excessive daylight.

3.4.4 Daylight Glare Probability (DGP)

Daylight Glare Probability (DGP) is a metric developed to quantify the likelihood of discomfort glare experienced by occupants due to daylight exposure in interior spaces. DGP accounts for both the intensity and contrast effects of light sources within the visual field. The metric is influenced by factors such as the luminance of light sources, the observer's eye-level illuminance, and the spatial characteristics of the light sources. This approach enables a comprehensive assessment of glare by considering the cumulative impact of multiple light sources and their spatial distribution relative to the observer's line of sight. DGP values typically range from 0% to 100%, with higher values indicating a greater probability of glare. The classification of DGP values is as follows:

1. Imperceptible Glare: DGP ≤ 35%
2. Perceptible Glare: 35% < DGP ≤ 40%
3. Disturbing Glare: 40% < DGP ≤ 45%
4. Intolerable Glare: DGP > 45%

These thresholds assist in evaluating the potential discomfort glare occupants might experience in a classroom setting. DGP serves as a valuable metric to predict and potentially mitigate glare issues in daylighted classrooms.

CHAPTER 4 – DATA ANALYSIS AND FINDINGS

4.1 Simulation Results

4.1.1 Useful Daylight Illuminance (UDI) Analysis

All fractal patterns A, B, and C outperformed the other corresponding patterns for UDI values in both south and west orientations. Fractal pattern C, with a 38% perforation ratio, performed the best out of all patterns and obtained a 49% UDI value, as seen in Figures 4.1 and 4.2. The high UDI values in group C are most likely attributed to the higher perforation ratio in the perforated patterns, resulting in a higher daylight illuminance distribution. Since this simulation study was measured at autonomous levels between 300-3,000 lux, this means that fractal pattern C can provide a 49% UDI within a classroom without the need to use electric lighting or cause glare discomfort. In addition, the base case analyzed in the south simulation had a lower UDI value than group C, this could be due to excessive glare levels that may have exceeded 3,000 lux within the simulated space.

In addition, random patterns A and B outperformed uniform patterns A and B in the south and west simulations. However, uniform pattern C had a better UDI value than random pattern C in both orientations. Although it was by a very small margin. The base case in the west had the highest UDI value overall. However, in the south simulation, all of the group C patterns outperformed the base case. This demonstrates the efficacy in enhancing daylight availability and uniformity with the use of perforated solar screens when glazing is facing south. Out of all the patterns evaluated, the fractal patterns demonstrated the best results in evenly distributing daylight availability within the simulated space.

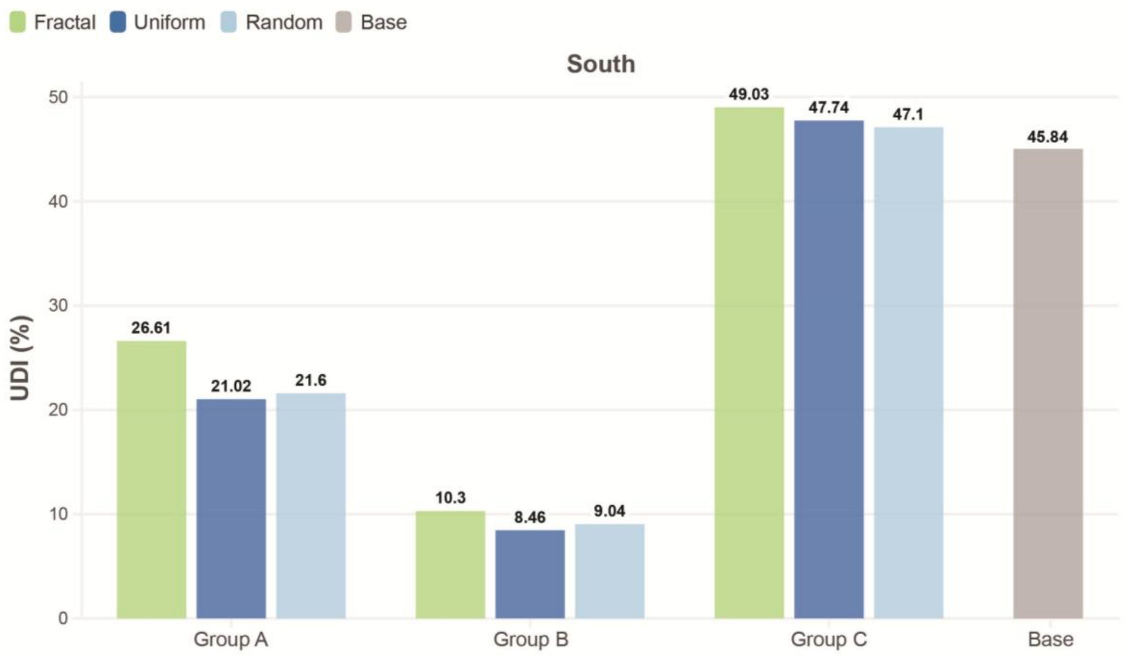


Figure 4.1. UDI values for the south simulations at autonomous levels between 300-3,000 lux.

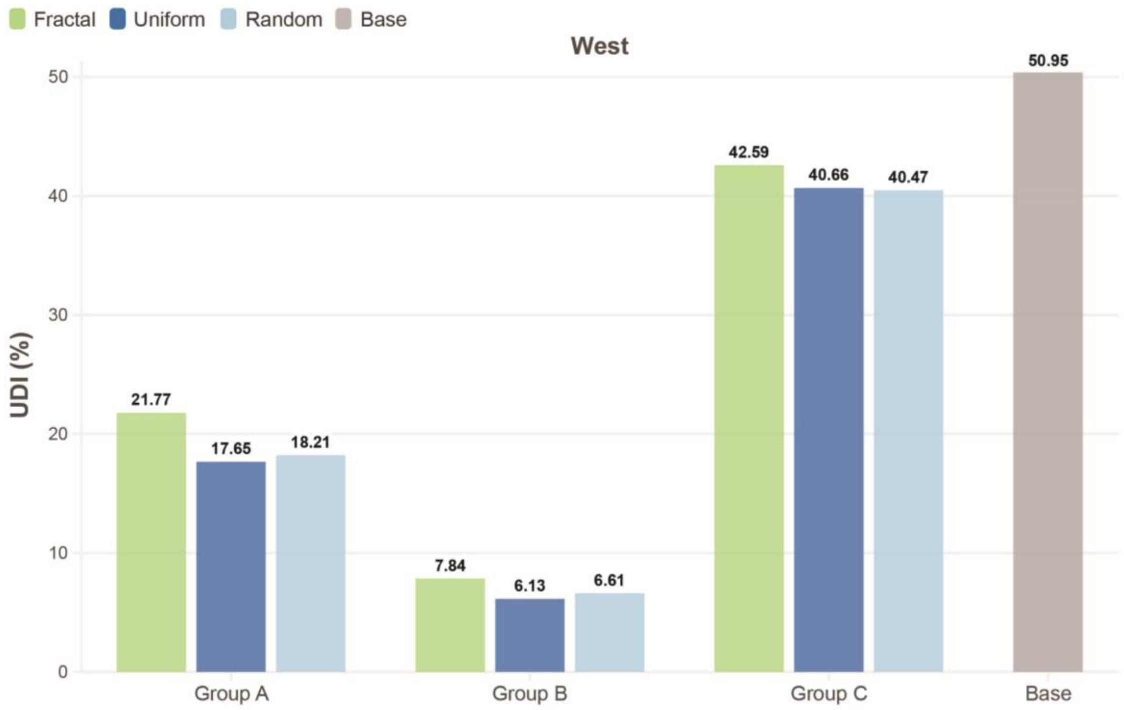


Figure 4.2. UDI values for the west simulations at autonomous levels between 300-3,000 lux.

4.1.2 Annual Sunlight Exposure (ASE) Analysis

The fractal patterns predominantly outperformed all other patterns in groups B and C for both south and west simulations, except for group B in the west, where the random pattern had a lower ASE value than the fractal pattern. However, group B had exceptionally low ASE values due to the small perforation ratio in this group of solar screens. For group A, in the south, the fractal pattern outperformed the random pattern but had a higher value than the uniform pattern case studied. Fractal pattern C did particularly better than the other corresponding patterns in both orientations, as shown in Figures 4.3 and 4.4. Only groups A and B mostly stayed under the 10% excessive threshold, this is most likely attributed to the lower perforation ratios of these groups. When accounting for ASE values, it may be important to consider a lower perforation ratio for better performance when using fractal patterns on perforated solar screens.

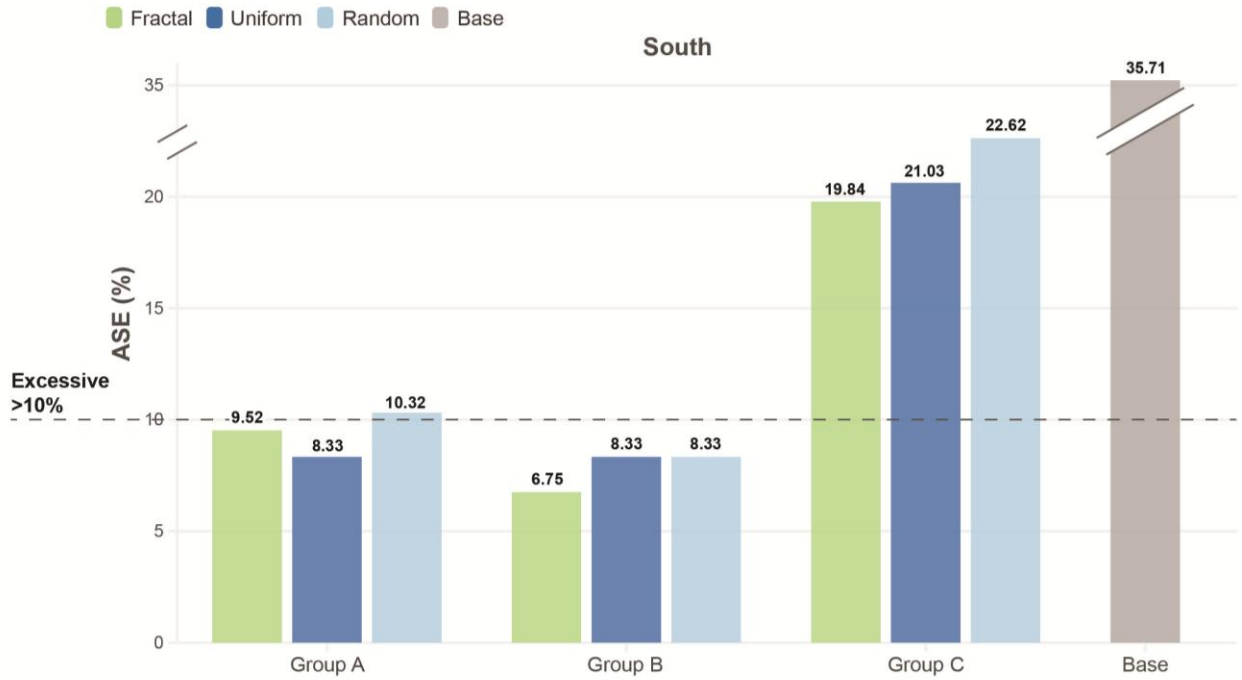


Figure 4.3. ASE values simulated facing south at 1,000 lux for 250 hours per year, where a value of more than 10% is excessive.

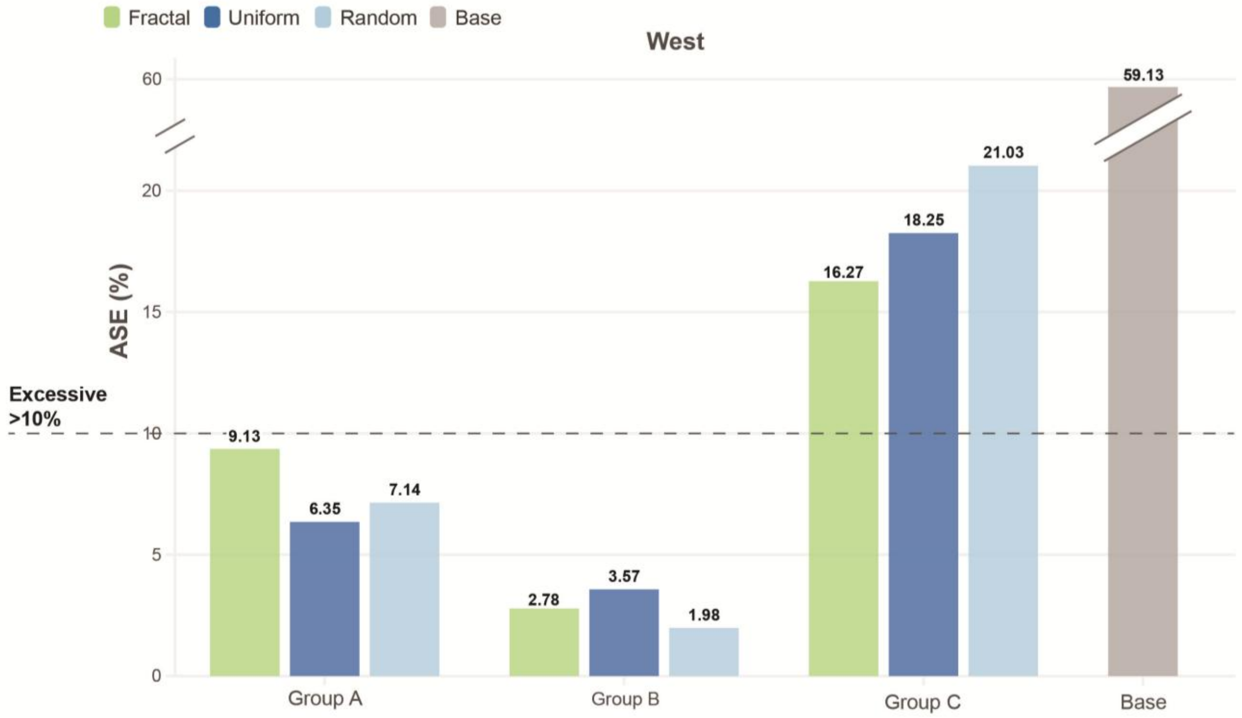


Figure 4.4. ASE values simulated facing west at 1,000 lux for 250 hours per year, where a value of more than 10% is excessive.

4.1.3 Spatial Daylight Autonomy (sDA_{300}) Analysis

Group C performed particularly well in both south and west simulations with regard to sDA_{300}. This group's better performance is most likely due to its higher perforation ratio, which allowed a higher amount of daylight distribution. Out of this group, the fractal pattern C performed the best. It did exceptionally well in the west orientation, compared to the other patterns in the group. Fractal pattern A also exceeded the sDA_{300} values of the other corresponding uniform and random patterns when applied in the south. All patterns did quite poorly in group B, with almost all receiving a 0% sDA_{300} value. This was due to the group's low perforation ratio. Although fractal pattern B was able to obtain a 2.38% sDA_{300} value in the south simulation. This value is still quite low; however, it demonstrates the benefits of using fractal patterns for solar screens when trying to optimize sDA values. Only in the west was random pattern A able to outperform fractal pattern A. In addition, the base case exceeded the sDA_{300} simulation threshold in the south and west and outperformed all other cases. These results are likely attributed to the base case having an unshaded opening, which allowed full distribution of daylight into the space. Overall, the fractal patterns evaluated in the sDA simulations outperformed the other patterns, as seen in Figures 4.5 and 4.6.

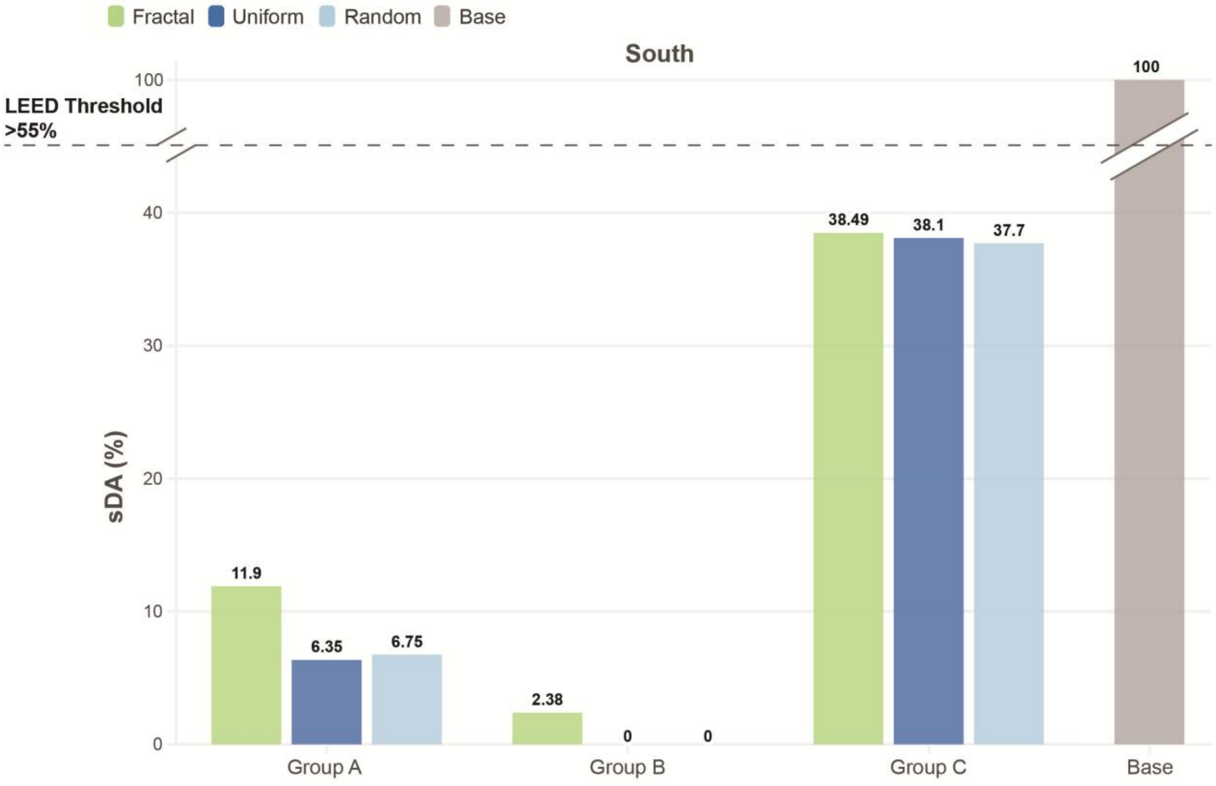


Figure 4.5. sDA values simulated facing south at 300 lux for at least 50% of the annual occupied hours.

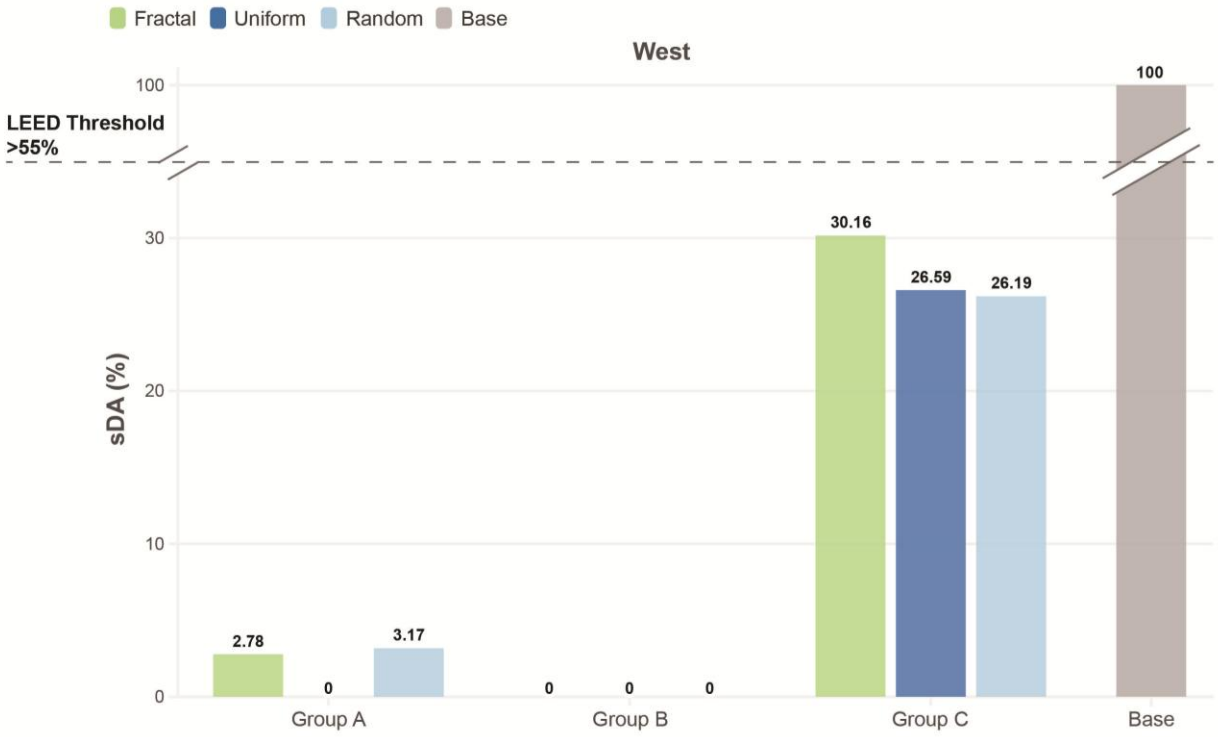


Figure 4.6. sDA values simulated facing west at 300 lux for at least 50% of the annual occupied hours.

4.1.4 Daylight Glare Probability (DGP) Analysis

For the west DGP simulations, fractal pattern A outperformed uniform A by a small margin in the month of June, however, random pattern A outperformed fractal pattern A for that same month by a small margin as well. Fractal pattern A outperformed the corresponding uniform and random patterns in March and December. However, fractal patterns B and C did not demonstrate lower DGP values than the uniform and random patterns B and C for all months in the west.

When observing the south simulations, fractal pattern A and random pattern A performed the same for June; however, uniform pattern A performed slightly better for that month. Fractal pattern A performed the best for March and December, and fractal pattern B performed the best for December. However, for all other months, uniform and random patterns B performed the best. Uniform pattern C and random pattern C performed the best for all months when compared to the fractal pattern C performance in the south simulations.

Fractal pattern A had the lowest DGP values for March and December in both the south and west simulations. All other fractal patterns did not outperform the uniform nor random patterns for DGP values in the south or west, except for a few cases. For example, fractal pattern B outperformed in the month of December in the south simulation. However, since the DGP values fell within the imperceptible and tolerable range, the higher values may offer more visually interesting daylight patterns within the classroom. If a DGP value was too low, then the daylight patterns would be quite monotonous and dull. This particularly supports the results of fractal pattern C, which resulted in higher DGP values than the other patterns evaluated.

For all the groups evaluated, the DGP values fell under “imperceptible” percentages, except for the base case showing “intolerable” percentages in all cases, as shown in Figures 4.7 - 4.9. This demonstrates the benefit of using perforated solar screens to mitigate glare effects on students within a classroom space. In addition, this specific metric evaluation demonstrated the benefit of using a fractal-patterned perforated screen in March and December.

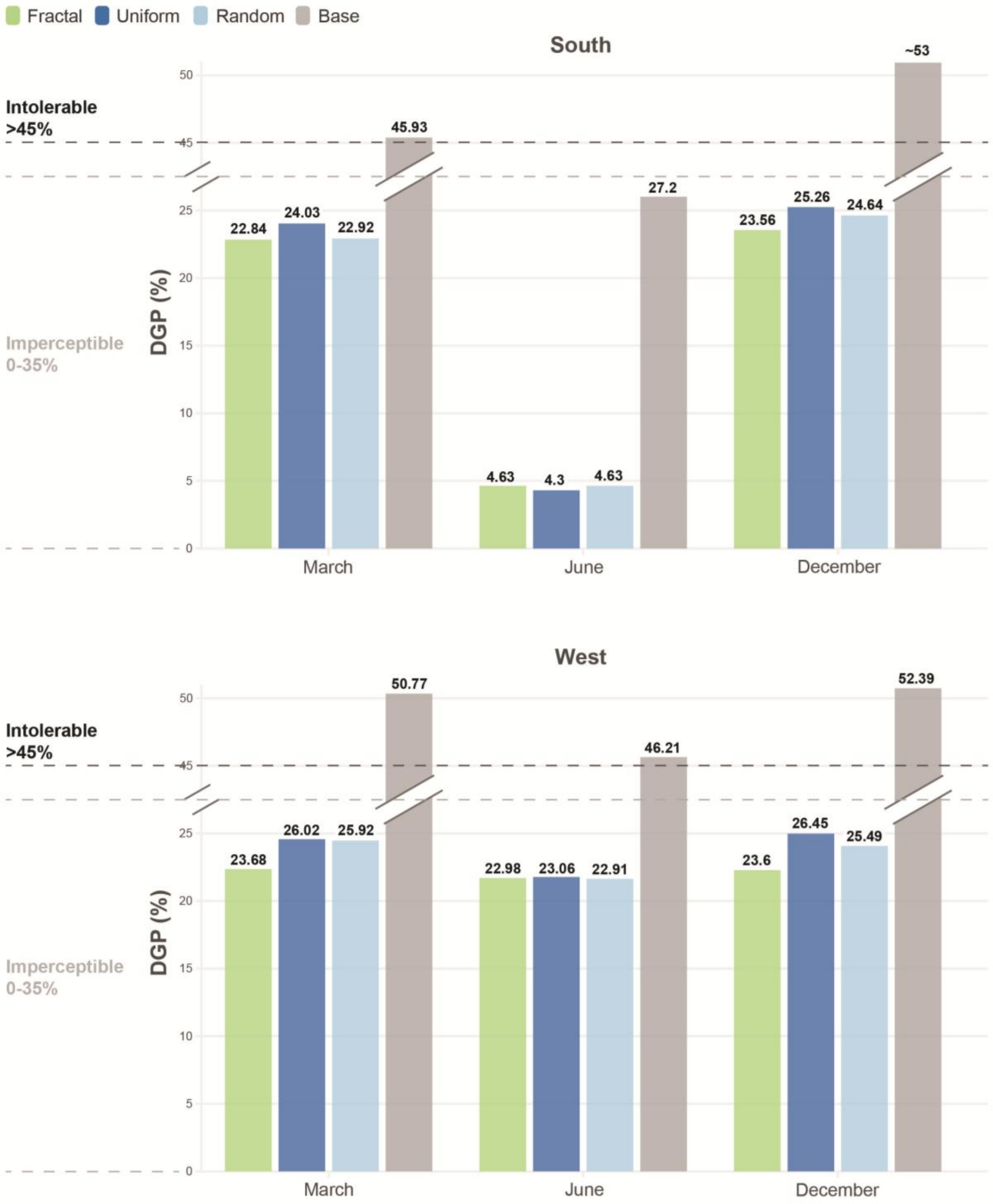


Figure 4.7. DGP values for group A. Simulated for March, June, and December.

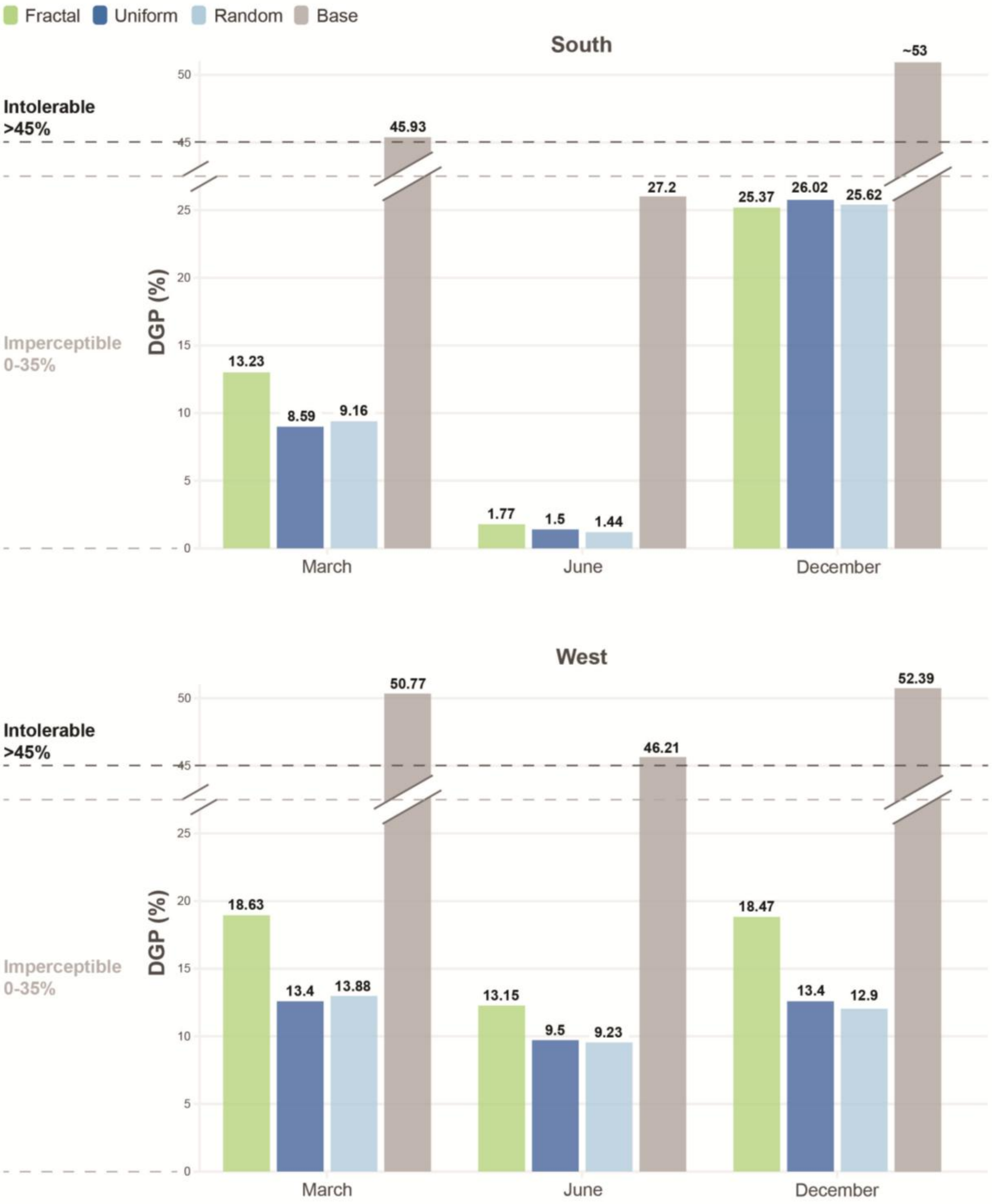


Figure 4.8. DGP values for group B. Simulated for March, June, and December.

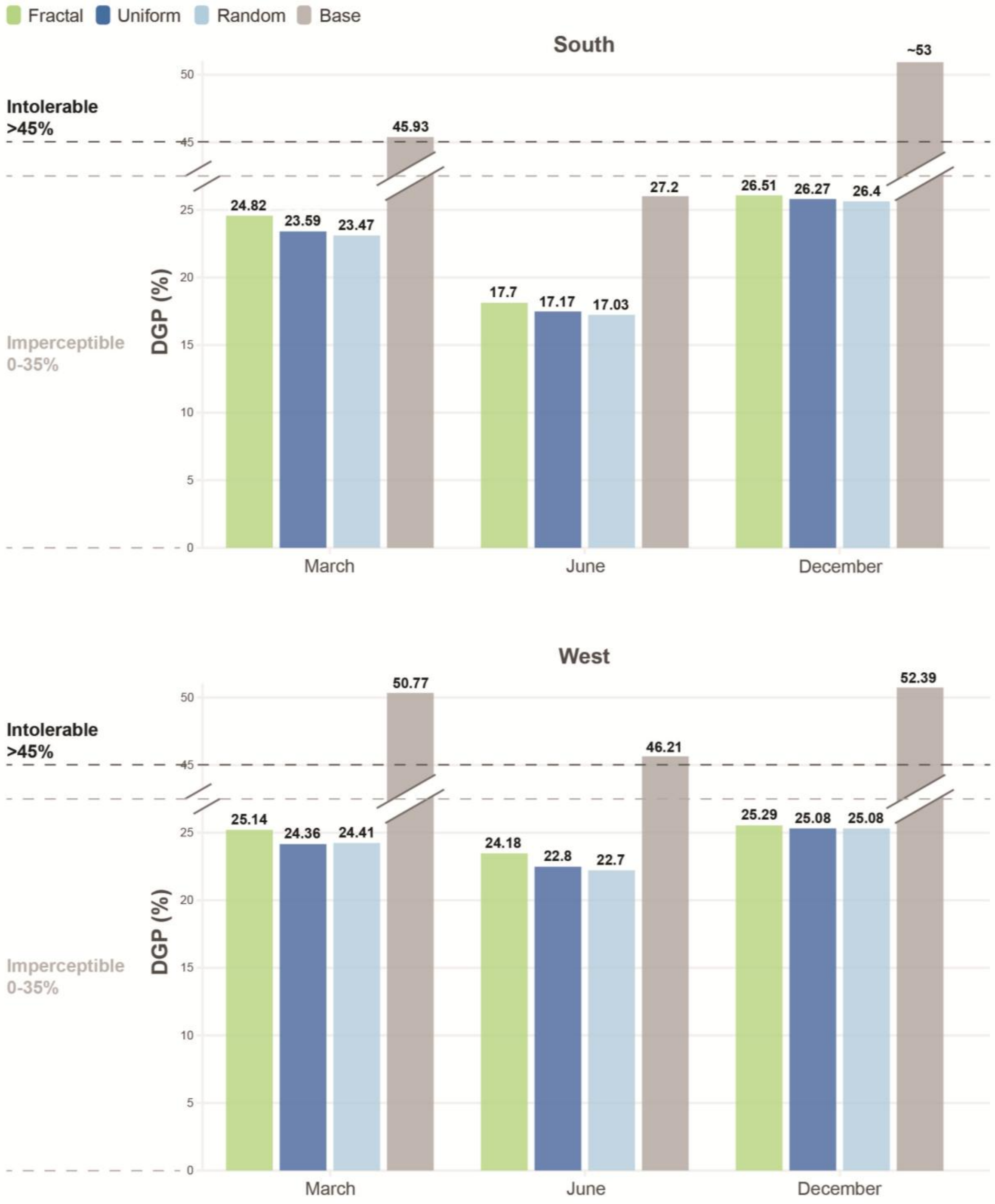


Figure 4.9. DGP values for group C. Simulated for March, June, and December.

4.2 Overall Daylight Performance

The box plots demonstrated in Figures 4.10 and 4.11 show all the corresponding daylighting metrics plotted per group and per pattern type. The data points shown are each individual simulation value per daylighting performance metric evaluated, south and west values are combined in each chart. For example, the box plot containing DGP values per group, the data points shown are both south and west simulation values for all the fractal, uniform, and random patterns within that group; and it includes the results for March, June, and December. In the box plots containing sDA, UDI, and ASE values per group, each point is the value obtained in the simulations for both south and west orientations, plotted within their corresponding group. The values are similarly plotted in the box plots shown in Figure 4.11, however, these values are arranged by pattern type. For example, the sDA values plotted in the box plot for pattern types, contain the simulation values of pattern types A through C.

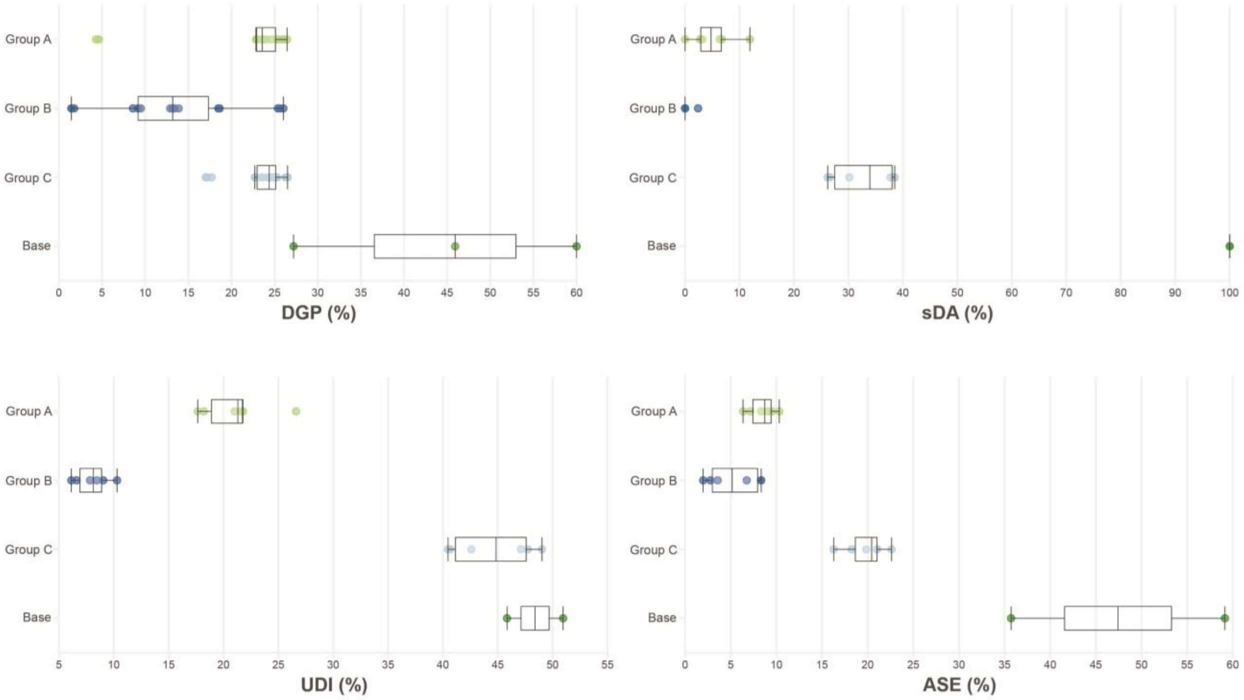


Figure 4.10. Daylight Performance Comparisons – Per Group

Furthermore, group C, with a 38% perforation ratio, had the best daylight performance for sDA and UDI values. Figure 4.10 demonstrates the highest median and interquartile range for this group when observing sDA and UDI values. Group C did not demonstrate lower glare mitigation values for DGP and ASE, however, it did have more consistent DGP values. In comparison, group B had varying DGP values and was less predictable. Group A had a very similar overall DGP performance when compared to group B. However, it had much lower ASE values than group C.

Additionally, the fractal patterns obtained the highest median value for sDA and UDI performance, as shown in Figure 4.11. When observing ASE and DGP performance, the fractal pattern's median was exceptionally close to the median of the other pattern values and even demonstrated a couple outlier values for DGP. Overall, each pattern type had similar mean values, except for sDA and UDI performance values.

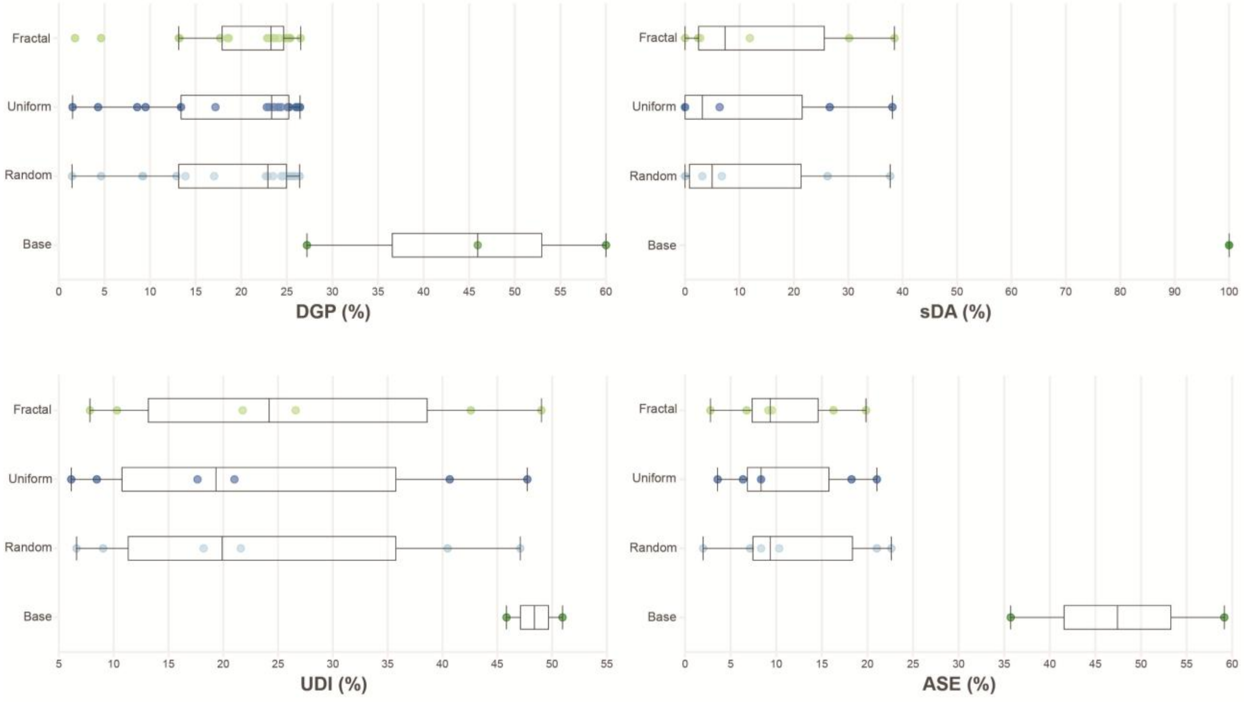
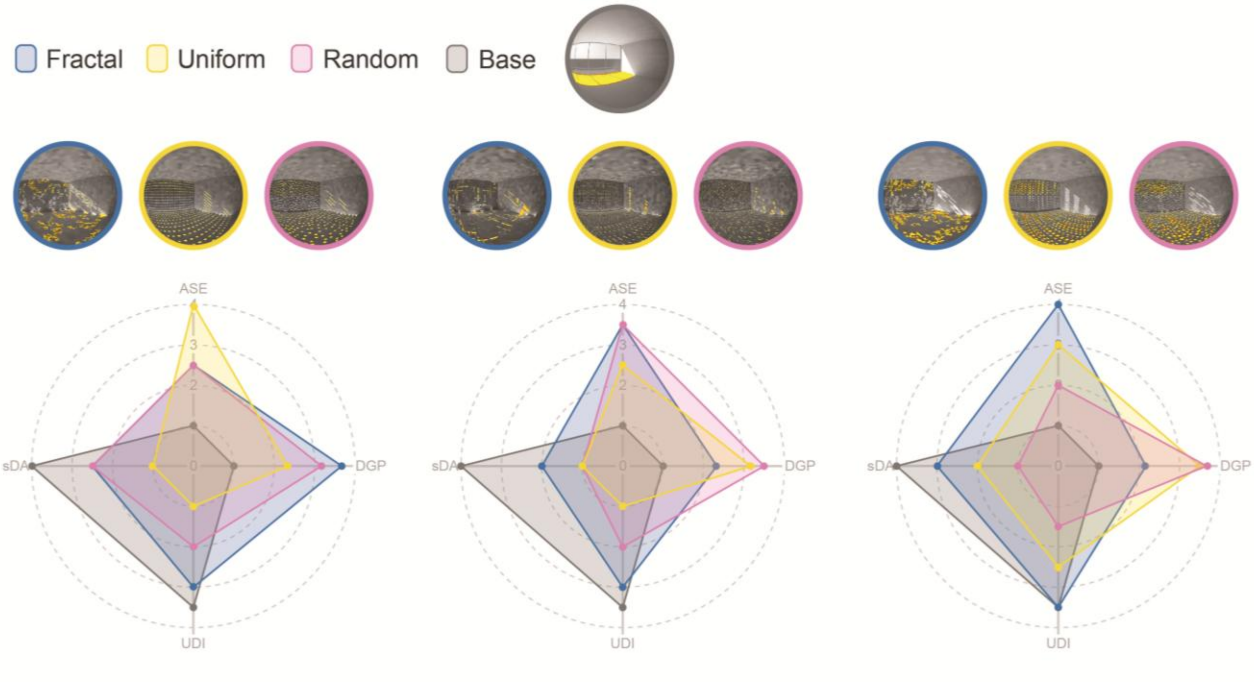


Figure 4.11. Daylight Performance Comparisons – Per Pattern Type

The spider chart shown in Figure 4.12 demonstrates the overall daylighting performance rankings of each pattern type per group. The inner circle with a value of 1 would have the lowest ranking, while the outer circle with a value of 4 would have the highest ranking. The daylight performance metrics are displayed on each axis of the chart. If a pattern type had the worst performance in the specific daylighting metric evaluated then it received a ranking of 1, and if it performed the best then it was given a ranking of 4. A similar system was used for the spider chart shown in Figure 4.13, however, this chart displays the rankings of only the fractal patterns examined to compare each fractal performance.

Overall, fractal pattern C with a 38% perforation ratio ranked the best for almost all variables, except for underperforming DGP values. Although all values fell under "imperceptible" margins. The base case also demonstrated better sDA and UDI values when compared to fractal pattern C, however, the base case performed poorly in ASE and DGP values. Whereas fractal pattern C did comparably well in these metrics. Fractal patterns B and C at 12% and 38% perforation ratios also ranked fairly well in all daylight variables. As Figure 4.12 demonstrates, a trend that can be observed is an evenly distributed ranking for all fractal patterns when compared to the other patterns studied. The uniform and random cases, along with the base case, have skewed rankings. Whereas the fractal patterns demonstrate a more consistent performance in each daylight category studied.

When observing the performance of the fractal patterns in comparison to each other, fractal pattern A had the most evenly distributed rankings. Fractal patterns B and C had skewed rankings. Pattern B demonstrated better ASE and DGP values and pattern C had better sDA and UDI values, as seen in Figure 4.13. The consistency of fractal pattern A is most likely due to the perforation ratio.



A - 19% Perforation Ratio

B - 12% Perforation Ratio

C - 38% Perforation Ratio

Figure 4.12. Performance Rankings [1 (Low): 4 (High)] – Per Group

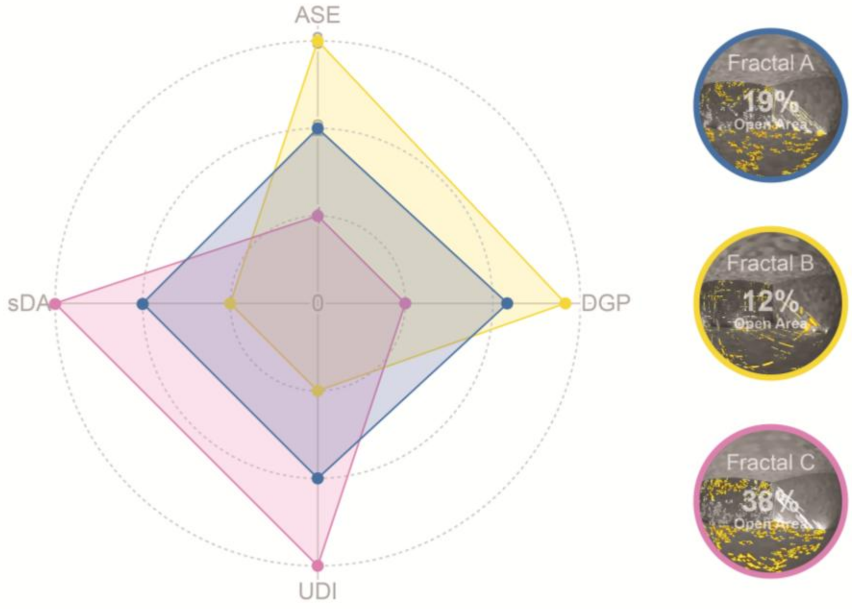


Figure 4.13. Performance Rankings [1 (Low): 3 (High)] – Per Fractal Pattern

4.3 Discussion

The solar screens with fractal patterns achieved better daylighting performance overall, in comparison to traditional uniform patterns and randomized patterns. In addition, the fractal screens contributed greater daylight exposure within the specified classroom parameters and demonstrated similar glare and visual comfort values as the other pattern types used. Consequently, fractal patterns applied on solar screens have been proven to be a practical solution for providing biophilic characteristics within a classroom. Overall, this pattern type will provide more exposure to daylight within a classroom and create a more enriching educational experience as the patterns of light create appealing biophilic characteristics within the classroom. While DGP values of the fractal patterns were occasionally higher than the other patterns examined, this may be preferred as the collection of light creates moments of wonder for students to admire and connect with. Additionally, the higher DGP values were mostly observed during summer months, and for this study having higher moments of glare in the summer may not have a great impact as students are out of school during this season.

Furthermore, fractal light patterns could be introduced in classrooms in various ways. Depending on what a designer is trying to achieve, a solar screen or shading device can be applied to any type of window or skylight. These various applications should be examined further to test the daylight potential of fractal patterns used at different building openings. However, the potential for optimizing daylight exposure and mitigating glare with fractal patterns in various architectural openings are proven to be a viable option. In addition, dynamic solar screens may also be a practical option when aiming for specific movement of light patterns within an interior space and could help mitigate distraction on classroom displays. This design application could be studied further, as dynamic screens could change the light patterns projected into a space every hour as the sun's position moves in the sky.

As this study suggests, the geometry of the perforations applied on a solar screen matters when aiming for specific daylighting performance, along with the perforation ratios used. For example, if daylight exposure was a priority within a space and glare was not as much of a concern then selecting a fractal pattern with a higher perforation ratio, and most likely a higher D value, would be best in this scenario. However, if mitigating glare was the most important factor, then selecting a fractal pattern with a lower perforation ratio would be best in this case. In addition, it is important to note that fractal patterns with higher D values would most likely have a higher perforation ratio, as the more complex and fuller a pattern becomes the more area of perforation there is to work with. The scale of the fractal patterns may be reduced or enlarged to accommodate various shading devices. Since the pattern template used for this study was fixed at 24 ft x 10 ft, scaling down or scaling up to fit within specific screen dimensions could be feasible, as long as the fractal is not distorted and maintains the same level of complexity (D value).

This study applied the patterns on a fabric-based blind. However, it may be applied to other types of solar screen materials, such as metal perforated screens. An example of this can be seen in the library rendering in Figure 4.14. In addition, there may be moments when the light patterns may diffract or get distorted within a space, as seen in Figure 4.15. However, this type of phenomenon can also happen within the natural world, for example, light patterns or shadows projected from a tree can undergo diffraction as they project onto a park bench or other nearby objects. This should not take away from the beauty of the patterns as this can also be naturally recognized within nature. Providing fractal light patterns within a classroom can create beautiful moments in which students and teachers alike can direct their attention during moments of rest, reflection, or contemplation.

Lastly, while the solar screens examined in this study targeted daylighting performance metrics regarding students within classrooms, they may also be applied in other building typologies. Solar screens are a universal design solution and are used in highly creative ways to optimize daylight exposure and mitigate glare effects within any building. Ultimately, solar screens with fractal patterns could be a viable solution in any design that might need to optimize daylight exposure, but in the end, it is up to a designer to determine the best solutions for a building design.

Figure 4.14. Architectural renderings exhibiting the application of perforated solar screens with fractal patterns in a science classroom and library.

Figure 4.15. Architectural renderings exhibiting the application of perforated solar screens with fractal patterns in a kindergarten and science classroom.

CHAPTER 5 – CONCLUSION

This study examined the effects of varying perforated patterned screens in relation to daylight metrics such as UDI, sDA, DGP, and ASE. The following sections will examine how these metrics may affect students within a classroom setting and what other related factors need further investigation.

5.1 Daylight and Fractal Patterns in Classrooms

After observing the results of the dependent variables, all fractal patterns had the best performance in UDI and sDA values when compared to the other patterns examined, even when having equal perforation ratios. Only in some cases do the DGP and ASE values demonstrate better results. Although all DGP values examined fell within an "imperceptible" threshold, glare might become an issue in summer months when using fractal patterned screens with higher perforation ratios. As observed in the previous chapter, the fractal patterns performed well in the months of March and December in most cases but had slightly higher values in June. However, it may be important to note that students will most likely be out of school in the summer months.

For daylight design purposes, fractal patterned screens offer better performance when aiming for better daylight exposure in classrooms, prompting better circadian rhythm regulation and overall well-being of students. However, to achieve the required Spatial Daylight Autonomy from various certification processes, such as LEED, a higher perforation ratio will be required. Ultimately, a designer will have to consider the use of perforation ratios and specific solar screen patterns to achieve specific daylighting results within a classroom.

5.2 Limitations and Future Research

This study was limited by the specific daylighting metrics examined in relation to solar screens and the perforated pattern types. Additionally, the DGP simulations only analyzed the glare values from one position and height. Future research may need to examine various height levels, sitting vs standing heights, and different age group heights. Also, while this study was intended to examine Equivalent Melanopic Lux (EML) values, which is related to the biological response of light on humans and the circadian system in the brain, it was limited by the lack of fully developed architectural software for simulation. This study tested the EML variable in a beta version of ClimateStudio 2.2, however, the results did not show any differences for each pattern type. Once the software is fully developed, further research can investigate the effects of different solar screen patterns on circadian rhythm and occupant alertness. In addition, this study was limited to the location of Phoenix, Arizona, to examine the daylight potential in bright and clear climates. Future research can explore varying locations with different climates. Other factors that could be examined in future research are the psychological response of fractals and daylight in interior spaces and different shading devices with fractal perforated patterns. Overall, the positive results of fractal patterned screens determined in this study encourage the further study of solar screens with fractal patterns as biophilic design elements within classrooms.

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