

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**AN ALGORITHMIC APPROACH FOR DAYLIGHT
PERFORMANCE OPTIMIZATION OF OFFICE SHADING
ELEMENT DESIGN**

NEBAHAT ÖZGE ESENER

**A THESIS OF DOCTORATE
DEPARTMENT OF ARCHITECTURE**

ADVISOR: ASSOC. PROF. DR. SANİYE KARAMAN ÖZTAŞ

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T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

OFİS GÖLGELEME ELEMANI TASARIMINDA GÜN
IŞIĞI PERFORMANSININ OPTİMİZASYONU İÇİN
ALGORİTMİK BİR YAKLAŞIM

NEBAHAT ÖZGE ESENER

DOKTORA TEZİ
MİMARLIK ANABİLİM DALI

DANIŞMAN: DOÇ. DR. SANİYE KARAMAN ÖZTAŞ
2. DANIŞMAN: DR. ALFREDO CALOSCI

TEMMUZ 2025

DOCTORATE JURY APPROVAL FORM

A thesis submitted by Nebahat Özge ESENER, defended on 10 / 07 /.2025 before the jury formed with the 08/07/2025 date and 2025/35 numbered decision of the GTU Graduate Administration Board, has been accepted as a DOCTOR of PHILOSOPHY thesis in the Department of Architecture.

JURY

MEMBER

(THESIS ADVISOR) : Assoc. Prof. Dr. Saniye KARAMAN ÖZTAŞ

MEMBER : Prof. Dr. Nilay COŞGUN

MEMBER : Assoc. Prof. Dr. Togan TONG

MEMBER : Assoc. Prof. Dr. Cecilia ROSTAGNI

MEMBER : Assoc. Prof. Dr. Emilio BARCHIESI

APPROVAL

Gebze Technical University Graduate Administration Board
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*To my Loving
Family...*

ABSTRACT

Ensuring adequate daylight in office buildings is essential for reducing energy consumption, improving user health, and enhancing productivity. In this context, the doctoral research aims to develop an algorithmic approach for the design of shading layers integrated into building façades. A scenario developed in Rhino was used to simulate this condition. The research optimizes the perforation patterns of the shading system, categorized as Regular, Irregular, and Striped, using a genetic algorithm. These patterns were generated through parametric tools (Rhino, Grasshopper, Ladybug, Honeybee, Wallacei) and optimized using a multi-objective approach.

Three key daylight performance criteria were selected to guide the optimization process: Spatial Daylight Autonomy (sDA), Daylight Glare Probability (DGP), and Direct Sunlight Hours (DSH). For each pattern category, a total of 750 design variants were generated. The most successful genes, identified via Pareto front selection, were compared based on their quantitative performance across the defined metrics, and one optimal variant per pattern category was selected. These selected patterns were then evaluated to typical office working hours (08:00–17:00). Annual simulation outputs of sDA, DGP, and DSH were analyzed for two user viewpoints (seated and standing) at three times of day (08:00, 13:00, 17:00), covering both equinoxes (March 21, September 23) and solstices (June 21, December 21). The results were interpreted using false color visualizations and renderings.

In addition to quantitative evaluation, a qualitative shadow analysis was conducted based on insights from the literature, and the potential perceptual impacts were also discussed. The analyses revealed that the Regular Pattern (Regular Pattern 01) demonstrated the most consistent performance in maintaining daylight continuity while minimizing glare and direct sunlight exposure. Irregular and Striped patterns, on the other hand, enhanced spatial diversity and rhythmic light distribution, contributing to greater perceptual richness and varied interior experiences. Shadow analysis showed that most patterns provided effective shading depending on user position; however, during noon hours, some variants offered limited protection at desk height under high solar angles. These findings highlight the necessity of integrating hourly visual assessments and perceptual criteria alongside annual metrics in performance-based façade design processes, in order to achieve both technical efficiency and spatial quality.

This study presents a novel algorithmic approach to façade design that incorporates not only quantitative performance metrics but also qualitative and experiential aspects. The findings offer guidance for a design methodology that prioritizes user comfort and spatial quality in addition to environmental performance.

Keywords: Genetic Algorithm, Daylight Optimization, Facade Shading Element Design, Office Buildings.

ÖZET

Ofis binalarında yeterli gün ışığının sağlanması, enerji tüketiminin azaltılması, kullanıcı sağlığının iyileştirilmesi ve üretkenliğin artırılması açısından önemlidir. Bu bağlamda, doktora çalışması, bina cephelerinde gölgeleyici katman tasarımı için algoritmik bir yaklaşım geliştirmeyi hedeflemektedir. Bu yaklaşımın üretiminde Rhino üzerinden geliştirilen bir senaryo ile İstanbul'da konumlanan bir ofis mekanının, tamamen şeffaf güney cephesine 20 cm mesafede, binanın dışına sabitlenmiş bir perfore alüminyum gölgeleme elemanının tasarımı ve performans değerlendirmesi üzerine odaklanmaktadır. Araştırma, geometrik yapıları Düzenli (Regular), Düzensiz (Irregular) ve Şeritli (Striped) olarak sınıflandırılan gölgeleme desenlerinin boşluklarını genetik algoritma kullanarak optimize etmektedir. Bu desenler parametrik araçlar (Rhino, Grasshopper, Ladybug, Honeybee, Wallacei) kullanılarak oluşturulmuş ve çok kriterli bir algoritma ile optimize edilmiştir. Algoritmanın tasarım sürecinde gün ışığı performansının değerlendirmesinde kullanılan üç temel kriter şunlar olarak belirlenmiştir: Mekansal Günlüğü Otonomisi (sDA), Parıltı Olasılığı (DGP) ve Doğrudan Güneş Işığı Süresi (DSH).

Her desen grubu için toplamda 750 varyant üretilmiştir. Algoritmanın Pareto front ile seçtiği başarılı genler, belirlenen kriterlerde gösterdikleri nicel performansa göre birbirleriyle kıyaslanmış ve her desene ait en iyi genler seçilmiştir. Sonrasında bu başarılı üç (düzenli, düzensiz ve çubuklu) desen, ofis çalışma saatlerine (08.00-17.00) göre analiz edilmiştir. sDa, DGP ve DSH kriterlerine ait senelik simülasyon çıktıları, iki farklı kullanıcı bakış noktasına göre (oturan, ayakta) ekinoks (21 Mart, 23 Eylül) ve dönence (21 Haziran, 21 Aralık) tarihlerini kapsayan, sabah (08.00), öğle (13.00), akşam (17.00) saatlerinde gösterdikleri performans, false color görselleri ve renderlar aracılığıyla incelenmiştir. Nicel değerlendirmelere ek olarak, literatür araştırması baz alınarak, nitel gölge incelemesi yapılmıştır ve potansiyel algısal etkileri de tartışılmıştır.

Analizler, Düzenli Desen'in (Regular Pattern 01) hem günlükliğini sağlama hem de parıltı ve doğrudan güneş ışığı maruziyetini dengeli biçimde kontrol etme açısından en tutarlı performansı sunduğunu göstermiştir. Düzensiz ve Çizgisel desenler ise mekansal çeşitliliği ve ritmik ışık dağılımını zenginleştirerek algısal derinliği artırmış, dolayısıyla iç mekanda farklı deneyimler yaratmıştır. Gölge analizi sonuçları, desenlerin büyük ölçüde kullanıcı pozisyonuna bağlı olarak etkili gölgeleme sağladığını; ancak özellikle öğle saatlerindeki yüksek güneş açılarında, bazı varyantların masa hizasında sınırlı koruma sunduğunu ortaya koymuştur. Bu bulgular, performans-temelli cephe tasarımı süreçlerinin yıllık metriklerin yanı sıra saatlik görsel analizlerle ve algısal değerlendirmelerle desteklenerek hem teknik verim hem de mekânsal deneyimin bütüncül olarak ele alınması gerektiğini ortaya koymaktadır. Bu çalışma, cephe tasarımına dair sayısal verilerle desteklenen ama aynı zamanda nitel değerleri de dikkate alan yeni bir algoritmik yaklaşım sunmaktadır. Elde edilen bulgular, yalnızca teknik performansı değil, aynı zamanda kullanıcı konforunu ve mekânsal niteliği gözetilen bir tasarım anlayışı için yol gösterici niteliktedir.

Anahtar Kelimeler: Genetik Algoritma, Gün Işığı Optimizasyonu, Cephe Gölgeleme Elaman Tasarımı, Ofis Yapıları.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my Ph.D. supervisor, Assoc. Prof. Dr. Saniye Karaman Öztaş, for her unwavering support, guidance, and dedication throughout every stage of this research. Her insightful feedback and encouragement have been invaluable in shaping both the direction and depth of this work.

My sincere thanks also go to my co-supervisor, Dr. Alfredo Calosci, for introducing me to new ways of thinking and for encouraging a broader, more critical perspective on architectural research. His interdisciplinary approach and thoughtful mentorship have greatly enriched this dissertation.

I would like to extend my heartfelt gratitude to Prof. Dr. Nilay Coşgun, my former Ph.D. supervisor and current doctoral monitoring committee member. Her continuous guidance over the years, along with her dedication to academic excellence, has had a lasting impact on my development as a researcher.

Special thanks are due to Assoc. Prof. Dr. Togan Tong, whose constructive feedback and critical perspective throughout the thesis monitoring process greatly contributed to the refinement of this study.

I would also like to extend my gratitude to Assoc. Prof. Dr. Fitnat Çimşit Koş, the coordinator of the Ph.D. program, for her valuable support during the co-tutela process and for facilitating the international collaboration that made this research possible.

I am also sincerely grateful to all the faculty members at the Università degli Studi di Sassari for their kind support and assistance throughout this international doctoral journey.

My appreciation extends to Assoc. Prof. Dr. Dilek Ekşi Akbulut and Prof. Dr. Cahide İpekçi Aydın for their valuable support and insightful contributions during the earlier stages of the thesis monitoring process.

I am also deeply grateful to Architect Efe Topçu, a former undergraduate student of mine and now a colleague, for his technical support during the parametric modeling phase of this thesis. His expertise in Grasshopper and his generous collaboration made a significant contribution to the realization of the computational aspects of the study.

Finally, I would like to thank my family and friends for their constant encouragement, patience, and emotional support throughout this long and challenging journey. Their belief in me made all the difference.

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LIST OF SYMBOLS AND ABBREVIATIONS

DA	: Daylight Autonomy
sDA	: Spatial Daylight Autonomy
DGP	: Daylight Glare Probability
DSH	: Direct Sunlight Hour
ASE	: Annual Sunlight Exposure
UDI	: Useful Daylight Illuminance
IEQ	: Indoor Environmental Quality



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1. INTRODUCTION

As contemporary standards of living rise, people increasingly expect built environments to offer not only functionality but also enhanced comfort and well-being. In this context, daylight emerges as a critical component, contributing simultaneously to thermal regulation and visual comfort by delivering adequate natural illumination while minimizing glare [Rezakhani & Kim, 2024]. Moreover, natural light is known to bring numerous psychological and physiological benefits [Wen et al., 2023; Knoop et al., 2020], and it significantly enhances productivity and well-being in workspaces [Wen et al., 2023]. Nevertheless, uncontrolled sunlight exposure can lead to issues such as glare-induced visual discomfort and overheating [Beck et al., 1999; Wen et al., 2023]. Therefore, the design of the building façade becomes a key mediator of indoor daylight performance, as it represents the primary interface for daylight entry and control [Nazari et al., 2023; Rizi et al., 2021].

In developed nations, it is reported that individuals spend approximately 90% of their time indoors [Knoop et al., 2020], a lifestyle shift that correlates with higher energy demands for artificial lighting and HVAC systems [Duan et al., 2024]. Since the building sector accounts for nearly 40% of total global energy use [Alajmi et al., 2019; Elmaky & Araj, 2024; Tsangrassoulis et al., 2006], passive strategies have become increasingly vital. Depending on climate conditions, such strategies can potentially reduce energy demand by up to 80–90% [Nazari et al., 2023]. Given that lighting alone represents approximately 15% of building energy consumption, daylight utilization stands out as an effective passive solution [Pérez-Lombard et al., 2008; Wen et al., 2023].

Among the range of passive techniques, solar shading devices-such as overhangs, fins, louvers, venetian blinds, roller shades, or solar screens-play an integral role in improving energy efficiency while also addressing visual and thermal discomfort [Choi et al., 2017; Moscoso et al., 2021]. Studies have highlighted that the absence of effective shading often leads to increased glare and overheating, especially during the summer months [Chi et al., 2020; Nazari et al., 2023]. Conversely, well-designed shading systems have demonstrated the capacity to reduce a building's energy use by up to 20% [Nazari et al., 2023].

Considering both user comfort and energy conservation, the refinement of shading strategies is essential. A well-calibrated shading design not only blocks excessive solar gain during summer but also allows beneficial sunlight in winter, thereby improving both comfort and energy performance [Ishac & Nadim, 2021; Zhao & Du, 2020].

Shading design is inherently a complex and multi-objective challenge, where changes in one variable can simultaneously improve or degrade various performance outcomes. To navigate this complexity, algorithmic design methods have become increasingly relevant. These approaches provide a structured way to explore interdependent variables and performance goals in design processes.

Among such strategies, genetic algorithms (GAs)—which mimic Darwinian principles of evolution—have been widely used in architectural design problems requiring optimization. These algorithms begin with a pool of candidate solutions and, through probabilistic operations such as selection, crossover, and mutation, evolve better-performing generations over time [Goldberg, 1989; Alajmi et al., 2019]. GAs are especially suitable for cases where deterministic logic falls short, and a degree of randomness is key to finding optimal design solutions.

This doctoral research introduces a distinctive methodological approach to the algorithmic design and evaluation of external sun-shading panels integrated with fully glazed office façades. While generative design and daylight simulation tools are commonly applied in façade studies, a comprehensive review of both national theses and international publications revealed that shading panels positioned as an independent second skin—separate from the main façade surface—remain underexplored, particularly in terms of geometric variation and user-centered performance. This study addresses that gap by focusing specifically on three geometrically distinct shading grammars (Regular, Irregular, Striped), which were parametrically generated and assessed for their impact on indoor visual comfort.

The use of a multi-objective optimization process enabled the selection of high-performing design variants based on daylight sufficiency, glare control, and direct sunlight exposure. While evolutionary algorithms are gradually being introduced into architectural workflows, the integration of distinct pattern grammars into an optimization framework remains novel, especially within the context of fixed shading panels.

In contrast to many previous studies that rely solely on annual simulation metrics or abstract daylight targets, this research adopts a position-sensitive analysis that examines visual performance from two user viewpoints-standing and seated at desk height-across three times of day and four solar dates. This level of spatial and temporal resolution enabled the identification of daylight patterns and glare risks that would otherwise be masked in aggregated results.

1.1. Research Aims and Scope

Although the terms building envelope and building façade are often used interchangeably, they refer to different architectural elements. The building envelope includes all external components, walls, roofs, floors, and openings that separate the interior from the external environment. In contrast, the building façade refers specifically to the vertical exterior surfaces, encompassing both opaque and transparent elements such as solid walls, windows, and fixed glazing. This study focuses exclusively on the vertical transparent façade surface and the fixed external shading layer positioned in front of it, concerning daylight control and visual comfort. Therefore, the term building façade is used throughout to define the scope more precisely.

The primary aim of this doctoral research is to develop a generative, algorithm-driven approach for optimizing a fixed perforated shading layer applied to a fully glazed, south-oriented office façade located in Istanbul. The study explores how different shading pattern grammars-Regular, Irregular, and Striped-affect indoor daylight conditions and visual comfort. Using a multi-objective genetic algorithm (via Wallacei), each pattern type was parametrically generated and optimized based on three core daylight performance metrics: Spatial Daylight Autonomy (sDA), Daylight Glare Probability (DGP), and Direct Sunlight Hours (DSH).

The scope of the research includes both annual and time-specific simulations for selected optimal solutions from each pattern group. Quantitative analysis was conducted using false color visualizations and simulation outputs generated for two user viewpoints (standing and seated) across three key times of day (08:00, 13:00, 17:00) and four critical solar dates-equinoxes (March 21, September 23) and solstices (June 21, December 21). Additionally, shadow behavior and perceptual qualities, such

as spatial rhythm, brightness distribution, and visual complexity, were evaluated to incorporate a human-centered perspective into the performance-based design process.

1.2. Research Methodology

This study employed a parametric design and simulation-based performance evaluation workflow for office buildings. Using Rhino and Grasshopper, a parametric framework was established in which three distinct shading pattern grammars based on Chamilothoni's [2019] research, Regular, Irregular, and Striped, were encoded, and their openings were optimized through Wallacei, a multi-objective genetic algorithm plugin. For each grammar, a population of 750 design variants was generated. Wallacei's evolutionary process, based on selection, crossover, and mutation, was guided by a fitness function composed of normalized values of three key daylight performance metrics: Spatial Daylight Autonomy (sDA), Daylight Glare Probability (DGP), and Direct Sunlight Hours (DSH), calculated using Ladybug and Honeybee.

The multi-objective optimization process ensured a balanced evaluation of daylight sufficiency, glare control, and direct sunlight exposure. Pareto front analysis was used to identify the top-performing individuals for each pattern grammar. These selected variants were then subjected to detailed daylight performance evaluations under real-world conditions, considering two user viewpoints (standing and seated with side orientation) at three different times of day (08:00, 13:00, and 17:00), across both equinox (March 21, September 23) and solstice (June 21, December 21) dates.

In addition to quantitative simulations, the study integrated a qualitative evaluation framework to assess the perceptual and experiential qualities of daylight. Inspired by Chamilothoni [2019], five perceptual dimensions were considered: light distribution and brightness, temporal dynamics, glare perception and attentional load, spatial legibility, and phenomenological light quality. False color renderings and architectural rendering images were used to interpret how light interacts with space, surfaces, and users across different scenarios. Shadow behavior was also examined to understand the spatial rhythm and visual coherence created by the different pattern grammars throughout the day. This dual-layered methodology, combining simulation data with perceptual assessment, enabled a user-centered, feedback-driven design approach. While the genetic algorithm provided optimized design alternatives based on

performance criteria, perceptual evaluations served as a secondary filter to assess experiential qualities that quantitative data alone cannot capture. For example, certain patterns that ranked high in numerical performance were found to create perceptible or disturbing glare at desk height during peak sun hours, highlighting the importance of daily/hourly visual validation.

The overall workflow integrates standards-based parameterization (guided by TS EN 12464-1 and TS EN 17037+A1) [Turkish Standards Institution, 2021;2022], generative modeling, environmental simulation, and perceptual feedback into a coherent methodological framework **Figure 1.1**. This methodology supports a holistic façade design process that balances computational optimization with architectural intuition.

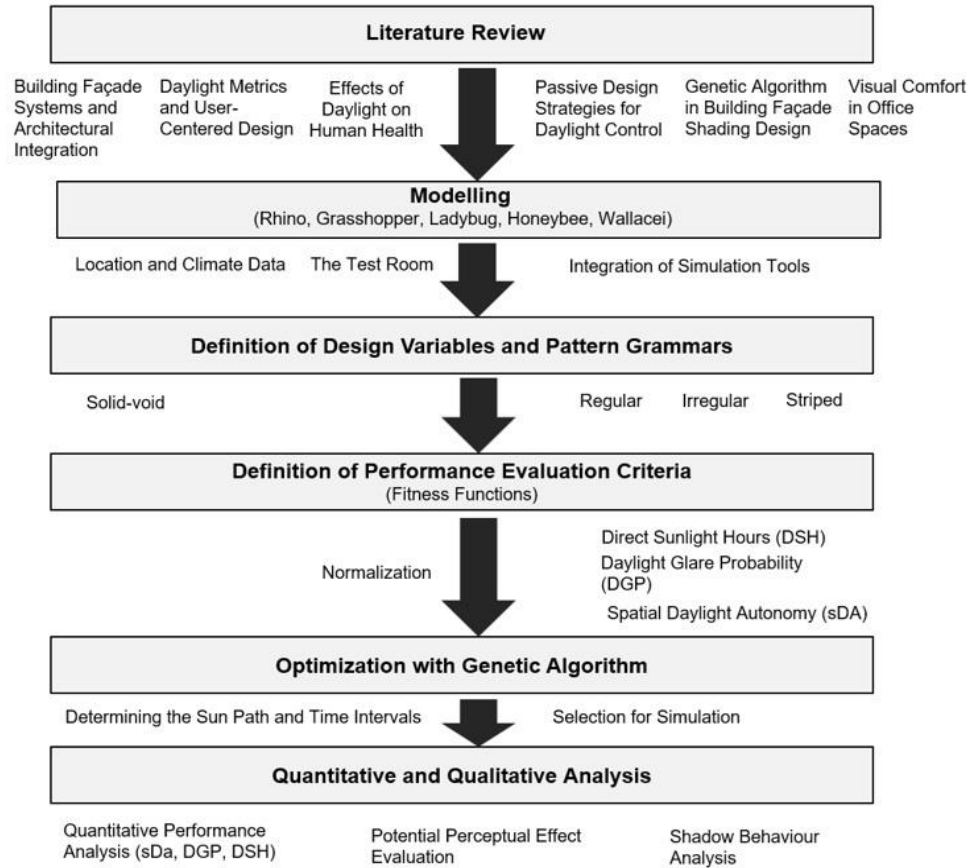


Figure 1.1: Structure of the study.

2. BACKGROUND OF THE STUDY

In this study, the term “building façade” refers specifically to the exterior vertical surfaces of a building, comprising both opaque components (such as load-bearing and non-load-bearing external walls) and transparent elements, including various types of exterior openings (e.g., windows, doors, fixed glazing, and ventilation apertures). Horizontal elements such as roofs and roof-integrated façade systems are excluded from this definition.

Beyond its physical definition, the building envelope, particularly the façade, plays a pivotal role in establishing the environmental quality of indoor spaces. As the primary interface between the interior and the external environment, the façade regulates key factors such as daylight entry, solar heat gain, and natural ventilation. Accordingly, sustainable façade design is essential not only for reducing energy demand but also for enhancing visual comfort, promoting user well-being, and ensuring the creation of healthy and comfortable interior environments.

2.1. Visual Comfort in Office Spaces

Visual comfort in office spaces is a crucial concept that highlights the importance of natural lighting in supporting employee well-being. It involves ensuring that there is sufficient natural light to meet the needs of various office tasks while promoting the health of workers. The objective is to enhance visibility for employees while minimizing issues such as glare and excessive direct sunlight, all while maximizing the availability of daylight.

This chapter focuses on the research question “How can we provide visual comfort in office spaces?”

Huang et al. discuss visual comfort in relation to the design of office building facades, indicating that facade characteristics significantly affect the level of visual comfort associated with natural lighting [Huang et al., 2025]. Their study presents specific design strategies aimed at enhancing visual comfort, demonstrating how an optimized facade can contribute to a well-lit and visually appealing indoor environment. Similarly, Rezaei et al. [2024] focus on optimizing window designs and light shelves within office interiors, which are critical for improving both visual and thermal

comfort. Their findings reveal that carefully chosen window specifications and configurations play an essential role in creating a visually comfortable office environment [Rezaei et al., 2024]. This highlights the need to integrate functionality with aesthetic elements in office design.

Kwon further emphasizes the significance of renovation practices in office buildings, arguing that improvements in indoor environmental quality, including visual comfort, directly relate to higher employee satisfaction and productivity [Kwon, 2020]. Such renovations are vital for creating workspaces that promote well-being and efficiency, reinforcing the importance of visual comfort in professional settings.

A thorough understanding of visual comfort also takes into account the complexities of lighting design. For example, Kim and Kim [2015] discuss how specific glazing and shading devices can greatly affect the visual and thermal environments in offices. Their research indicates that combining effective shading strategies with appropriate glazing can optimize comfort levels and enhance energy efficiency.

Research shows that inadequate visual comfort can lead to negative outcomes such as eyestrain and decreased productivity. Borsos et al. developed a "Comfort Map" to evaluate various indoor environmental quality (IEQ) parameters, including visual comfort, which is critical for tailoring office spaces to meet the health and comfort needs of occupants [Borsos et al., 2021]. Their survey underscores that visual comfort is essential for understanding what constitutes a hospitable workplace environment.

Factors like daylight availability and artificial light quality are vital to achieving visual comfort. For instance, poor visual conditions can negatively impact job satisfaction and disrupt circadian rhythms, suggesting that thoughtful lighting design is key to influencing mood and productivity [Tan & Majid, 2022]. This idea is supported further by Kahaki et al. (2022), who identify lighting quality, encompassing color temperature and the amount of natural light, as critical elements that affect employee alertness and comfort at work [Kahaki et al., 2022].

To sum up, visual comfort in office buildings is characterized by thoughtful design that incorporates adequate natural light, effective artificial lighting strategies, and methods for glare reduction. Collectively, these elements foster environments that enhance productivity while supporting the health and well-being of occupants.

In this study, visual comfort is defined as having sufficient natural lighting to accommodate essential office tasks and ensure user health, without considering energy consumption from artificial lighting. The focus is on reducing glare, minimizing direct sunlight exposure, and increasing daylight availability.

To ensure to provide visual comfort, there are some daylight metrics, standards, fundamental design strategies, and computer-aided technologies. These will be discussed in this chapter in the following sections.

2.1.1. Benefits of Daylight and Risks of Glare

Light helps us perceive our environment, which makes it important for various activities in our daily lives. Adequate natural daylighting enables the space to perform its function efficiently. Being able to see helps people not only to perform their activities, but it also provides a healthy environment. Daylighting affects the users' physiological and psychological health in many direct or indirect ways, such as the eyes and skin.

This literature review focuses on the research question "How does daylight affect human health and productivity?"

Lack of daylight and prolonged vision problems can have temporary or permanent effects on the eyes. Both temporary and permanent negative effects must be discussed, as architects can take measures in the early design process that can prevent them.

Temporary visual effects can be caused due to glare. Research indicates that glare can overwhelm the visual system, causing a momentary inability to focus and potentially leading to symptoms such as headaches and eye strain [Stringham et al., 2011; Maniglia et al., 2018]. Glare can not only cause eye discomfort but also affect users' psychology in the long run in an office working space, influencing workplace productivity and overall user satisfaction [Horr et al., 2016]. For example, studies have shown that average visual performance declines in environments with excessive glare, significantly impacting individuals' ability to perform tasks requiring acute vision [Stringham et al., 2011; Epitropoulos et al., 2015; Wolska & Sawicki, 2014]. Discomfort glare can arise from varying light conditions when transitioning from dark to brightly lit environments, a phenomenon known as adaptation glare [Maniglia et al., 2018]. In office spaces, managing glare through careful lighting design can help

maintain visual comfort, thus enhancing occupational performance and psychological well-being.

Permanent visual effects may arise from chronic exposure to adverse lighting conditions. Conditions like cataracts can exacerbate sensitivity to glare, leading to persistent visual disturbances [Epitropoulos et al., 2015; Wolska & Sawicki, 2014]. Another condition, Myopia, is a condition that causes difficulty in seeing distant objects. This condition is usually seen starting from childhood. In a study, a number of kids who spent more time outdoors was less likely to be diagnosed with myopia [French et al., 2013]. Furthermore, aging increases the likelihood of glare sensitivity and reduces overall contrast sensitivity, which can compound existing visual impairments in older populations [Wolska & Sawicki, 2014; Kimlin et al., 2017].

Lack of daylight can also negatively affect the visual perception of colors. Individuals born above and below the Arctic Circle in different seasons showed that reduced daylight exposure during infancy, exposure to twilight, and artificial lighting altered color sensitivity [Laeng et al., 2007]. In the study, participants born in the fall season above the Arctic Circle showed the lowest color perception performance.

In addition to eye health problems, daylight can also affect visual perception. Natural light significantly influences the ambiance of a room and affects how objects and individuals are perceived [Knoop et al., 2020]. Unlike artificial lighting, which may create overlapping shadows and visual clutter, daylight enters through windows and skylights in a more directed manner, promoting visual clarity and a sense of tranquility. Additionally, studies show that faces illuminated by daylight, especially from the side, are often perceived positively **Figure 2.1**, while soft shadows from larger windows enhance modeling. The lateral flow of daylight effectively improves the perception of both human features and objects, highlighting its importance in creating favorable lighting conditions [Knoop et al., 2020].



Figure 2.1: Spatial light distribution natural lighting (left and right), artificial lighting (center) [Knoop et al., 2020].

A larger window size can let more daylight into interiors and affect the visual effect of the space, which can result in creating an effect of readability, excitement, and openness on the users **Figure 2.2** [Knoop et al., 2020]. However, direct or reflected sunlight falling on the user may cause temporary visual discomfort due to glare [Stazi et al., 2017]. For this reason, the user may want to use curtains or sunshades. This may later cause insufficient sunlight to enter the space and create thermal problems. For this reason, consideration of glare control in the early architectural design stage is important.



Figure 2.2: Effect of window size on spatial light distribution [Knoop et al., 2020].

Environments illuminated by artificial lights indicate that maintaining a surface brightness of more than 30–40 cd/m² in a horizontal area 20° above and below the line of sight can enhance the visual lightness and appeal of office spaces [Knoop et al., 2020; Kirsch, 2015; Loe et al., 1994]. Additionally, the perceived spaciousness of a room is significantly influenced by lighting levels; wall-oriented lighting, either alone

or in conjunction with minimal overhead lighting, appears to contribute positively to a sense of spaciousness [Knoop et al., 2020; Wänström Lindh, 2012; Stamps, 2010]. A comprehensive study examining various aspects of room quality found that ample daylight from oversized windows is essential for fostering a room that feels more enjoyable, dynamic, intricate, readable, cohesive, and open [Knoop et al., 2020; Moscoso, 2015].

In addition to its visual effects and perception, natural light also has systemic effects on the human body. The biological clock creates the body's sleep and wake cycle and is associated with light. A well-designed lighting system can ensure that the user's biological clock functions healthily. Thanks to this functioning, the user's sleep quality, health, mood, and cognitive ability are positively improved [Münch et al., 2017]. The input of light to the biological clock occurs through photosensitizer retinal ganglion cells (ipRGC), which are sensitive to short-wavelength blue components of light. These cells were discovered in 2002 and affect the biological clock and non-visual functions of the brain. Therefore, exposure to bright, short-wavelength light during the day and no exposure to light at night is beneficial for melatonin release and the regulation of the biological clock [Knoop et al., 2020]. In a study conducted in the Antarctic region in 2011, it was observed that individuals exposed to natural lighting during the polar winter had better sleep quality compared to those exposed to only artificial lighting during the daylight period. In addition, when artificial lighting conditions were compared, blue-enriched light was found to be more efficient than bright white in supporting the biological clock [Mottram et al., 2011]. In a study conducted in 2014, it was reported that office workers with access to windows had better sleep quality than those without access [Boubekri et al., 2014].

It is also known that sleep quality improves with the increase in the effect of the sun in the summer [Figueiro, 2016]. In addition, the decrease in the melatonin hormone, which is effective in increasing sleep quality and whose release in the body begins with the decrease in light at night, with daylight can be beneficial in terms of feeling more vigorous during the day and concentrating on work. Daylight is important for employees working in offices to feel vigorous, concentrate, and work efficiently.

In addition, daylight may also have other cognitive effects. According to research conducted in 1991, looking at a deep space or area can relax the eye and muscle tone and free the cerebral cortex from processing information, leading to cognitive

relaxation. Looking at a view accelerates physiological recovery [Hartig, 1991; Ulrich, 1991]. According to a study conducted in 1980, patients in intensive care units with translucent windows had better memories and fewer hallucinations and delusions than those in those without windows [Keep et al., 1980]. From this, it can be understood that light and view are effective in the recovery process of patients.

Windows provide functions such as lighting, air flow, view, weather conditions, and information about outdoor activities. The characteristics of the window material and design provide control against external environmental effects (such as odor, heat, and sound). In addition, windows can provide an escape in some cases. All of these create a sense of control and security in the user's interior. A study conducted in 1976 indicated that the reason why female office workers who felt lonely, tense, and depressed did not like their offices without windows was that there was no view and they could not get weather information [Collins, 1976]. According to a study conducted in 1986, office workers in windowless spaces preferred to decorate their offices with plants and pictures of nature. Small windowless offices were decorated with these items twice as often as offices with a view [Heerwagen & Orians, 1986]. Chang and Chen's [2005] research also shows that window views and indoor plants in the office environment positively affect the aesthetic and emotional experiences of employees.

Research has highlighted the negative effects of inadequate indoor lighting on human health. As individuals spend many hours in the office, a lack of natural light can adversely affect employees' health, productivity, and mood.

2.1.2. Office Users' Needs and Indoor Environmental Quality

While technical metrics and standards provide an essential framework for design, the ultimate measure of a building's success is its ability to support the health, comfort, and productivity of its occupants. This section shifts the focus from the physics of light to the human experience, exploring the holistic concept of Indoor Environmental Quality (IEQ), the specific physiological and psychological needs of office users related to the luminous environment, and the methodologies used to evaluate how well buildings meet these needs, drawing heavily on research conducted within the Turkish context.

- **Adequate Illuminance for Tasks:** Office workers need sufficient light on their work surfaces (desktops, screens, etc.) to perform tasks without straining. Insufficient light can cause eye fatigue, whereas overly bright light can cause visual stress or require squinting. Standards (like 500 lux for reading/writing per EN 12464-1) are set based on typical needs, but individuals may have varied preferences (some prefer softer lighting, others brighter) **[European Committee for Standardization, 2021]**. Studies have found that giving occupants personal control over their lighting (e.g., task lamps or dimmable systems) increases satisfaction significantly. When users can adjust light levels to their comfort, they tend to tolerate a wider range of ambient conditions and report fewer complaints **[Hasanova et al., 2024]**.
- **Glare Prevention and Visual Comfort:** Glare, either from the sun/daylight or from luminaires, is a top complaint in offices with poor lighting design **[Bian et al., 2018]**. Discomfort glare can lead to annoyance, headaches, and avoidance behaviors (like blinds being shut continuously). Occupant surveys underscore that glare-free daylight is critical: a daylight environment that is bright but without harsh contrast improves mood and comfort **[Bian et al., 2018]**. This aligns with medical findings that excessive contrast or direct sun in the field of view causes eye discomfort. Therefore, providing operable shading (blinds, screens) that users can deploy against sun glare, or designing fixed elements (lightselves, overhangs) to reduce direct sun penetration, is important. Many workers prefer indirect daylight or diffusely lit spaces to avoid glare on monitors and in their eyes **[Park et al., 2021]**. Ensuring monitors are positioned perpendicular to windows, using low-reflectance finishes, and implementing automatic glare-control systems (e.g., electrochromic glazing that tints in response to DGP thresholds) are all strategies to protect occupants from glare while preserving daylight.
- **Uniformity and Luminance Balance:** Users feel more comfortable in spaces with relatively uniform illuminance and without extreme contrasts between bright and dark zones **[Hasanova et al., 2024]**. High uniformity (within the recommended uniformity ratio in EN 12464-1) means the eyes do not need to constantly adapt when looking around the room, reducing visual fatigue. Non-uniform lighting (patches of very bright light surrounded by very dim areas) can cause discomfort and hinder visibility **[European Committee for Standardization, 2021]**. Ensuring uniform distribution of light in offices helps prevent discomfort from

sudden changes in brightness [Jang et al., 2024]. Thus, designers strive for a balanced daylight distribution, for instance, through well-placed windows and interior surfaces that reflect light deeper into the space, and supplement with artificial lighting in darker corners to even out the illumination.

- **View Quality and Connection to Outdoors:** Beyond illumination, having a view to the outside is a significant contributor to visual comfort and overall satisfaction in offices. A view provides visual relief (far-field focus), information about time and weather, and a psychological sense of openness. TS EN 17037 standard [Turkish Standards Institution, 2022] explicitly includes view out as a component of daylight comfort, recommending that occupants be able to see a large, clear scene including sky, landscape, and ground, at a distance beyond the immediate exterior obstacles. Studies have shown that offices with windows and decent views report higher occupant satisfaction with lighting and with general working conditions (often translating to better productivity and well-being) compared to windowless spaces [Kent et al., 2020].
- **Integration with Other IEQ Factors:** Indoor Environmental Quality (IEQ) includes key factors like visual, thermal, acoustic comfort, and indoor air quality. These factors are interconnected and influence how satisfied and healthy occupants feel. Research shows that good IEQ leads to better employee productivity, mood, and fewer health complaints [İşanç et al., 2024]. This focus on IEQ is why many aim for green building certifications like LEED, as they promote healthier workspaces, boost building value, and lower owner liability [İşanç et al., 2024].

Building Information Modeling (BIM) has emerged as a critical tool in enhancing Indoor Environmental Quality (IEQ), particularly with the growing emphasis on sustainability in construction and architecture. By providing an integrated platform for data management throughout the lifecycle of a building, BIM facilitates the assessment and improvement of indoor environmental conditions, thus contributing significantly to the comfort and well-being of occupants.

The utilization of BIM allows for comprehensive monitoring and assessment of various indoor environmental parameters, such as thermal comfort, indoor air quality (IAQ), and acoustic environments. These parameters are crucial for determining acceptable IEQ standards, which are increasingly recognized as fundamental in sustainable building practices [Vilčeková & Burdová, 2015; Al-Sulaihi et al., 2015;

Heinzerling et al., 2013]. For instance, a study highlights that standards based on IEQ factors define acceptable comfort ranges, stressing the importance of occupant feedback in evaluating building performance **[Alavi et al., 2021]**. Furthermore, the correlation between good indoor conditions and productive educational environments has been documented; improvements in IEQ are associated with enhanced learning performance in educational settings **[Al-Sulaihi et al., 2015; Lee et al., 2012]**.

Moreover, the practical application of BIM in educational buildings aids not only in visualizing sensor data but also in energy management decisions **[Aguilar et al., 2022]**.

2.2. Building Façade Systems for Daylight Control

The design of a building façade extends beyond material selection and formal articulation; it involves a complex negotiation between structural logic, environmental performance, and spatial organization. A critical aspect of this negotiation lies in the morphological relationship between the structural system and the exterior skin. Understanding whether these components are integrated, separated, or hierarchically arranged provides insight into both the technical and architectural behavior of façades. This relationship directly affects constructability, energy efficiency, daylight availability, glare control, and user comfort.

2.2.1. Evolution and Role of Shading Systems in Office Buildings

Façade shading strategies have historically evolved in response to climate, culture, and material innovation. In the Middle East and Mediterranean, vernacular systems such as the mashrabiya provided solar protection, privacy, and ventilation, filtering daylight through intricate wooden lattices **[Michell, 1978; Bagasi, Calautit, & Karban, 2021]**. In southern Europe, wooden shutters, louvers, pergolas, and terracotta overhangs moderated sunlight while enabling airflow, whereas in northern Europe, shading devices remained limited until the advent of modern glass façades and mechanical cooling **[Bagasi et al., 2021]**.

Modernist architects revived and reinterpreted these traditions. Le Corbusier's brise-soleil drew explicit inspiration from Islamic screens, translating vernacular lattices into fixed concrete fins suitable for glass architecture **[Michell, 1978]**. With advances in

materials, shading systems shifted from wood to concrete and metals, later evolving into automated kinetic devices responsive to solar trajectories [Bagasi et al., 2021].

Shading practices across diverse regions and historical periods illustrate the dynamic relationship between climatic needs, cultural values, and technological advancements in architecture. In Middle Eastern contexts, shading techniques primarily prioritized thermal comfort and privacy, while Mediterranean designs emphasized adaptability and versatility in response to sun exposure. Conversely, European modernism reinterpreted shading as an architectural language that focused on solar control and environmental interaction.

To further investigate the morphological aspects of shading, Fernandez [2004] introduces a categorization system that delineates three primary envelope typologies based on their spatial relationship with the building structure: exoskeleton, structural envelope, and skin envelope **Figure 2.3**. Each envelope type offers unique design implications concerning thermal performance, spatial organization, and construction methodologies. Through this examination, we gain insight into how shading strategies influence and are influenced by architectural forms across different contexts.

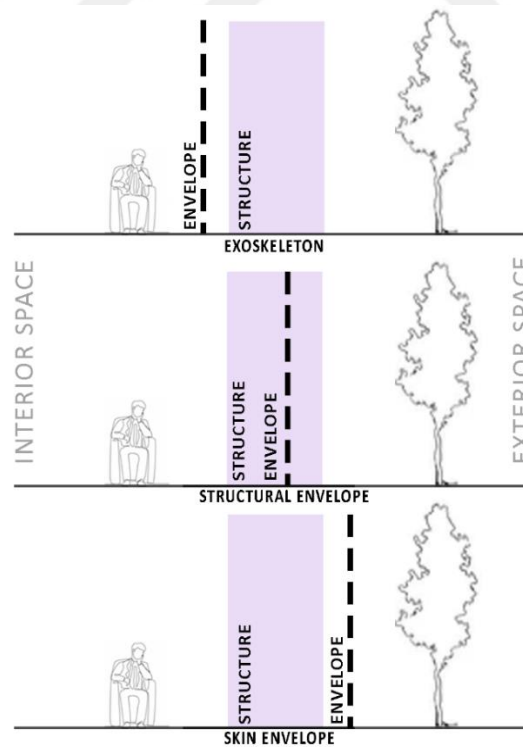


Figure 2.3: Morphology of building envelope systems according to their position in a building [Fernandez 2004].

In the exoskeleton model, the structural system is located entirely outside the envelope. This enables uninterrupted interior space and highly flexible layouts. However, the structural frame becomes exposed to external environmental conditions, requiring detailed attention to weather protection and thermal insulation. Despite these challenges, exoskeletons often contribute to a strong architectural identity by emphasizing structural expression.

The structural envelope typology places the structural frame and the envelope within the same physical layer. This integration allows for material efficiency and constructional simplicity, but can lead to systemic thermal bridging and limit flexibility in façade articulation. Examples include traditional load-bearing masonry and some monocoque systems.

In the skin envelope configuration, the envelope functions as an independent layer positioned outside the structural frame. This separation allows for improved thermal performance, greater design freedom, and enhanced adaptability in material and geometry. Curtain walls and double-skin façades are typical applications. However, the interface must be carefully designed to accommodate differential movement and ensure long-term enclosure performance.

Table 2.1 summarizes the advantages and disadvantages of each envelope type. While exoskeletons offer spatial openness and expressive structure, they introduce challenges in environmental resilience. Structural envelopes are materially efficient but limited in flexibility. Skin envelopes provide superior environmental control and design adaptability, although they require careful coordination between independent systems.

Table 2.1 Advantages and Disadvantages of Envelope Morphologies [Fernandez, 2004].

Morphology	Advantages	Disadvantages
Exoskeleton	Structural elements do not obstruct interior space Enhanced spatial flexibility Possible fire protection Clear separation between services and structure	Structure is exposed to weather and temperature variations Complex roof-envelope interface Thermal bridging Structural movement may cause envelope discontinuities
Structural Envelope	Integrated structural and envelope function Material and load-bearing efficiency Simple construction logic	Systemic thermal bridging Limited flexibility for façade articulation The interior structure is vulnerable to vapor condensation and temperature shifts
Skin Envelope	Structure protected from the external environment Envelope design flexibility Reduced thermal bridging Easier roof interface	Differential movement between structure and envelope Complex detailing to manage independent systems

These three morphological categories **Figure 2.3** provide a conceptual foundation for evaluating and designing façade systems. In this study, the proposed sun-shading components are developed as part of a skin envelope strategy, where the external layer operates independently from the structural system and can be parametrically optimized to enhance visual comfort and daylight performance.

Architectural decisions relate to the material and geometrical decision-making processes in the design and application of structural façades cannot be underestimated, as evidenced in things such as the research by Saban and Özmen [2022] which explored the design and application issues of aluminum cladding systems in Turkey, which indicates that architectural decisions are a significant part of the relationship between a façade, and the structural system, in terms of the safety and appropriateness of the façade, as representative of the structure in the architectural sense.

Exoskeleton façades that operate behind the primary structural systems of the building could be thought of as an approach to design that prioritizes movement and flexibility and its reciprocal relationship with structural loads. As an architectural condition, it can also meaningfully improve energy efficiency and the response to other external environmental stresses. In terms of a necessity to combine these designs in modern architecture in parts of the world with such varied climatic conditions, research could be found on the interaction of high-rise buildings as elements of the urban climate

[Yaliner & Begeç, 2025], which indicates the effectiveness of these approaches is bound to aesthetics, that is, a response to responsiveness within the building to the differing interior and exterior environments to achieve a more sustainable design approach.

Façades convey broader historical appreciations through narratives; these were found to relate to culture and history [Çelemoğlu & İnce, 2023]. The aesthetic and functional qualities of façades as a composite are very relevant to the user experience and the corresponding interest if the building is protected for heritage purposes as art. But beyond structural and aesthetic classifications, it is also essential to recognize the growing importance of façades in creating sustainable and healthy environments.

2.2.2. Sustainable Building Façade Design Strategies and Indoor Environmental Impact

The building façade serves not only as the external skin of a structure, but also as a critical environmental interface that directly influences the quality of the indoor environment. As a barrier and filter between interior spaces and external conditions, the façade plays a central role in regulating key environmental parameters such as daylight, thermal comfort, air quality, and acoustic performance [Evans, 2010; Baker & Steemers, 2002].

In the context of sustainable design, façades are increasingly recognized as multifunctional systems capable of improving occupant well-being while simultaneously reducing energy consumption. One of the most prominent functions of the façade is the modulation of daylight. A well-designed façade balances the admission of sufficient natural light with the need to avoid glare and excessive solar heat gain. Visual comfort is particularly sensitive to façade orientation, glazing properties, shading devices, and material reflectance [Tzempelikos & Athienitis, 2007]. If optimized correctly, façade systems can ensure high levels of spatial daylight autonomy (sDA) while maintaining acceptable levels of daylight glare probability (DGP), contributing to healthier, more productive indoor environments. Daylighting strategies, such as dynamic shading, light shelves, and double-skin façades, offer flexible control over light quality and distribution, allowing interior conditions to adjust naturally to changing exterior environments [Reinhart & Rogers, 2006].

Furthermore, the amount and quality of daylighting are influenced not only by the design of the façades but also by various external and internal contextual conditions. This interplay highlights the importance of considering both architectural and environmental factors when designing building façades to optimize indoor conditions. **Figure 2.4** illustrates this duality by categorizing the main factors into environmental and building-related parameters, highlighting how both domains interact to shape daylight access, glare risk, and visual comfort.

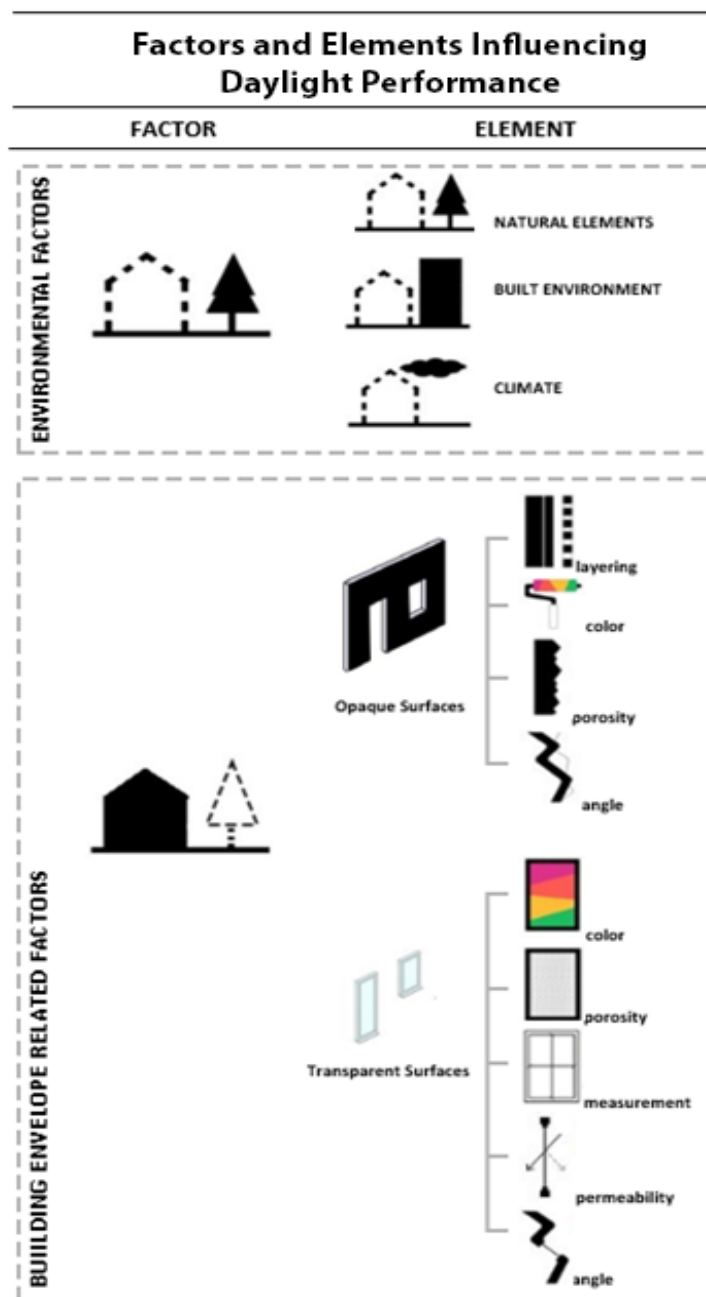


Figure 2.4: Factors and elements affecting daylight control in building façades.

Environmental factors are external conditions that influence daylight performance but do not originate from the building design itself. These include natural features such as trees, hills, and topography, as well as the built environment (neighboring structures, roads) and climatic conditions like solar angle, brightness levels, and seasonal variations [Pellegrino et al., 2017; Ámundadóttir et al., 2017]. For instance, deciduous trees can provide shading in summer while permitting solar gains in winter, illustrating how vegetation can function as a passive daylight regulator. Similarly, surrounding mountains or elevations can obstruct light penetration, as seen in the case of Rjukan, Norway, where mirrors were installed on the mountainsides to redirect sunlight into the town. Integrating building design with local topography and environmental conditions not only improves daylight accessibility but also supports energy efficiency and user comfort [Setiawan et al., 2024; Ahamadjula & Busayarat, 2024; Lee et al., 2015].

Building-related factors refer to façade-specific design decisions that directly determine the amount and quality of daylight entering indoor spaces. The façade—comprising walls, windows, and openings—is the primary mediator between exterior light and interior comfort [Esin, 1996; Sevinç & Altın, 2021]. Variations in window orientation, size, and placement significantly alter daylight distribution: vertical windows provide deeper penetration, whereas horizontal windows disperse light laterally. Raising window height can improve uniformity of illumination and reduce glare, while careful selection of non-reflective ground and façade materials can further mitigate excessive reflections [Tezel, 2007]. In addition, using multiple smaller openings instead of a single large window may result in more balanced light distribution within the space [Esin, 1996]. Ultimately, façade-related parameters, orientation, glazing ratio, window height, and materiality, are critical to balancing daylight sufficiency, glare control, and overall indoor environmental quality [Brzezicki et al., 2021; Şenel et al., 2023; Attia, 2018].

In addition to visual performance, façades significantly influence thermal comfort through their capacity to insulate, buffer, or ventilate the building envelope. Sustainable façades are designed to mitigate temperature extremes by using thermal mass, insulation layers, or ventilated cavity systems that respond to seasonal and diurnal changes in climate. Particularly in temperate and hot climates, shading devices such as louvers, brise-soleil, or responsive kinetic elements can reduce cooling loads

by minimizing direct solar gains during peak hours [Bessoudo et al., 2010]. At the same time, transparent elements such as low-emissivity glazing can be used strategically to harness passive solar heat gains in colder seasons, reducing the demand for artificial heating.

The façade also influences indoor air quality and occupant health by mediating the exchange of air between the indoor and outdoor environments. Strategies such as operable windows, breathable materials, and hybrid ventilation systems contribute to better air circulation and help reduce reliance on mechanical ventilation [Ghaffarian Hoseini et al., 2018]. Moreover, bioclimatic façade approaches, such as green walls or integrated photovoltaic systems, introduce additional environmental benefits, including carbon reduction, shading, and natural cooling.

From a broader perspective, sustainable façade design supports the principles of environmental justice, occupant equity, and long-term resilience. By enhancing daylight access and indoor environmental quality (IEQ), façades contribute to the psychological and physiological health of occupants, especially in office, educational, and residential settings. Numerous studies have shown that improved daylight exposure correlates with increased productivity, mood enhancement, and better sleep regulation [Knoop et al., 2020; Li & Sullivan, 2016]. As such, façade systems should not be viewed solely as passive protective layers but rather as active mediators of environmental quality that shape the everyday experiences of building users.

In contemporary architectural practice, parametric and algorithmic tools enable designers to evaluate and optimize façade systems across multiple performance metrics simultaneously. Through simulations and generative design processes, architects can predict how specific façade configurations impact daylight levels, glare indices, energy use, and occupant comfort. These tools support an evidence-based approach to sustainable design, bridging architectural intent with environmental performance.

In conclusion, the façade is a key component of sustainable building design, with direct implications for indoor environmental quality, energy performance, and user comfort. Its role as a dynamic mediator of external and internal conditions places it at the forefront of climate-responsive architecture. As buildings are increasingly required to meet higher performance and health standards, façade design must be approached

holistically, integrating visual, thermal, and ecological considerations to support long-term sustainability and occupant well-being.

2.2.3. Shading Typologies and Pattern Grammars

2.2.3.1. Shading Typologies

There are many different types of solar shading, and it is crucial to know which type is applicable for each facade for effective usage of these systems. The effectiveness of any shading system is rooted in a set of fundamental physical and geometric principles. The core purpose of a shading device is to intercept solar radiation, particularly on glazed surfaces, before it can be transmitted into the building's interior and contribute to the cooling load [Abuelzein, 2020].

A primary principle established throughout the literature is the superior thermal performance of external shading systems compared to their internal counterparts. The physical mechanism underpinning this advantage is direct and compelling: external devices block solar energy before it penetrates the building's thermal façade [Onwuzuligbo et al., 2025]. In contrast, internal shading devices such as blinds or curtains, even those with highly reflective surfaces, deal with solar radiation that has already passed through the glazing. This energy is then absorbed by the shading material and converted into thermal energy, which is released into the conditioned space, thereby contributing to the heat gain it was intended to prevent [Kumar et al., 2005]. This distinction is not merely theoretical; research quantifies this performance gap, suggesting that external shading systems are generally about 35% more efficient than internal ones [Kumar et al., 2005]. This establishes a clear design imperative: to achieve the most significant impact on thermal performance and cooling load reduction, design efforts and resources should be prioritized for the exterior of the building façade.

The design of any effective fixed shading system is fundamentally predicated on a precise understanding of solar geometry. The sun's path across the sky varies predictably with the time of day, the season, and the building's geographic latitude. The performance of a shading device is therefore inextricably linked to its ability to respond to these specific solar angles. Two key parameters, the Vertical Shadow Angle (VSA) and the Horizontal Shadow Angle (HSA), are derived from solar geometric

analysis and form the basis of rational shading design **[Wijaya, 2024]**. The VSA dictates the necessary vertical projection of a horizontal shading element, while the HSA informs the design of vertical fins. A design that overlooks basic geometric principles is likely to be less effective, or even entirely ineffective. This shows that the effectiveness of a shading system does not depend solely on the device itself; instead, it results from how well it interacts with its environment, which includes factors like climate, the orientation of the building, and the solar path.

The most fundamental classification of fixed, or passive, shading devices is based on their primary geometric form. This geometry is not arbitrary but is a direct response to the solar angles the device is intended to block, making its effectiveness highly dependent on the façade's orientation.

- **Horizontal Systems (Overhangs, Louvers):** This category includes simple roof overhangs, cantilevered slabs, and systems of horizontal louvers. These devices are most effective on façades that face the equator, south-facing in the northern hemisphere and north-facing in the southern hemisphere. On these orientations, the sun travels at a high altitude for most of the day, especially during the summer months **[Khadijah et al., 2024]**. Horizontal elements are ideally suited to intercept this high-angle sun, casting a shadow over the glazing below. A significant advantage of this geometry is its seasonal selectivity; it effectively blocks the high-angle summer sun to prevent overheating while allowing the low-angle winter sun to penetrate the building, providing desirable passive solar heating **[Onwuzuligbo et al., 2025]**. However, their performance is highly sensitive to their projection depth. As noted, an excessively deep overhang can block too much daylight, particularly in the deeper parts of a room, potentially increasing the demand for artificial lighting and offsetting some of the cooling energy savings **[Kim et al., 2017]**.
- **Vertical Systems (Fins, Vertical Louvers):** This typology consists of vertical elements, often called fins, that project perpendicularly from the façade, or systems of vertical louvers. They are the logical solution for east- and west-facing elevations, where the primary challenge is blocking the low-angle sun of the early morning and late afternoon **[Khadijah et al., 2024]**. During these times, the sun's horizontal bearing angle changes rapidly, and vertical elements are effective at interrupting its path before it strikes the glass. While they are the preferred solution

for east and west orientations, they are may be ineffective for the high-angle midday sun on south-facing elevations.

- **Egg-Crate Systems (Brise-Soleil):** This typology, famously championed by Le Corbusier under the term brise-soleil, is a hybrid that integrates both horizontal and vertical elements into a grid-like structure **[Khadijah et al., 2024]**. By combining the strengths of both geometries, egg-crate systems offer more comprehensive solar protection across a wider range of sun angles. This makes them particularly suitable for orientations that are not perfectly cardinal (e.g., southeast or southwest) or in climates where robust shading is required for most of the day. Research confirms their effectiveness; studies have found that egg-crate shading can lead to greater energy savings and a more significant reduction in thermal discomfort hours when compared to purely horizontal or vertical systems used in isolation **[Abuelzein, 2020]**. **Table 2.2** discusses the advantages and disadvantages of different fixed shading typologies.

Table 2.2: Comparative Analysis of Fixed Shading Typologies [Khadijah et al., 2024; Ofluoğlu, 2018; Robinson et al., 2013; Tezel, 2007; Lechner, 1991].

Typology	Optimal Orientation(s)	Primary Function	Advantages	Disadvantages / Trade-offs
Horizontal (Overhang, Louvers) 	South (in N. Hemisphere), North (in S. Hemisphere)	Blocks high-angle summer sun	Effective for summer cooling, allows winter passive heating; architecturally simple.	Ineffective against low-angle sun (east/west); can obstruct views; may reduce daylight, increasing lighting loads.
Vertical (Fins, Louvers) 	East and West	Blocks low-angle morning/afternoon sun	Effective glare control for low sun angles; enhances facade aesthetics.	Can obstruct panoramic views; ineffective for high-angle sun (south).
Egg-Crate (Brise-Soleil) 	All orientations, especially SE/SW, or where comprehensive protection is needed	Blocks the sun from a wider range of angles	Highly effective solar control, significant energy savings, strong architectural expression.	Can appear heavy/obtrusive; higher material/installation cost; potential for significant daylight reduction.
Perforated Screens (Jali) 	All orientations	Filters direct sunlight, reducing intensity and glare	Provides diffuse daylight; maintains a degree of visual connection; allows for air movement.	Less effective at complete solar blockage compared to solid elements; performance depends on perforation density.

The choice of material for a fixed shading device has a significant impact on its performance, durability, cost, and aesthetic expression. Traditional materials like cast-in-place concrete or heavy timber create a sense of permanence and thermal mass. More contemporary designs frequently employ lightweight materials like aluminum, which can be easily extruded into complex louver profiles, or steel for more slender structural supports [Khadijah et al., 2024]. An increasingly popular approach involves the use of perforated screens, sometimes referred to by the traditional term “jali” [Chockalingam et al., 2021]. These screens, made from materials like metal,

composite panels, or glass-reinforced concrete (GFRC), offer a nuanced approach to solar control. They work by filtering rather than completely blocking sunlight, reducing its intensity and mitigating glare while still allowing for a degree of diffuse daylight penetration and visual connection to the outside [Khadijah et al., 2024].

2.2.3.2. Pattern Grammars in Shading Systems

This section bridges the conceptual gap between the physical typologies of shading systems and the abstract, rule-based computational methodologies used to design them. It establishes a clear intellectual lineage from the formal theory of Shape Grammars, developed in the 1970s, to the contemporary, widespread practice of parametric and generative design in architecture, demonstrating how algorithmic thinking is used to create complex, performance-optimized façade patterns.

The theoretical foundation for rule-based generative design in architecture was laid in the early 1970s with the introduction of Shape Grammars (SG) by George Stiny and James Gips [Acosta-Zazueta et al., 2022]. A Shape Grammar is a formal production system designed to generate a language of designs through geometric computation. It is defined by a specific set of components: an initial shape, which serves as the starting point for the generation process, and a finite set of shape rules [Acosta-Zazueta et al., 2022].

The generative process is one of recursive rule application. Beginning with the initial shape, rules are applied iteratively to transform the design. The essence of this process is not the direct drawing of a final form, but rather the definition of a precise, logical procedure that produces a family of related forms, all of which share a common underlying logic [Acosta-Zazueta et al., 2022]. This approach allows for the exploration of a vast "design space" of possibilities that are all coherent within the defined language.

Two key concepts are central to the power of Shape Grammars. The first is shape emergence, a phenomenon where the application of a rule can create new shapes, patterns, and spatial relationships that were not explicitly defined in the initial shape or the rules themselves. This allows for genuine novelty and surprise in the generative process. The second key concept is that of a design language. The complete collection of all possible designs that can be generated by a given grammar constitutes a language

of design, which is characterized by a recognizable and coherent style. A famous early example was Stiny's parametric shape grammar for generating a language of Hepplewhite-style chair-back designs [Acosta-Zazueta et al., 2022].

Chamilothori [2019] conducted research in her doctoral thesis that examined 20 different shading examples **Figure 2.5**, categorizing them into three types: regular, irregular, and striped **Table 2.3**. Her study focused on the unique characteristics of each shading type and their applications in various contexts. Regular patterns consist of repetitive and symmetrical geometries, creating a predictable and balanced light environment. In contrast, irregular patterns feature more random or organic configurations, resulting in variability and unpredictability in light distribution. Striped patterns, which typically involve vertical or horizontal bands, produce strong directional light effects that enhance spatial orientation.

Chamilothori's [2019] research included immersive virtual reality experiments where participants experienced different daylight interior scenarios. These scenarios were generated from façade configurations with a constant aperture ratio but varying geometrical designs. The study aimed to assess both subjective impressions and physiological responses, measuring concepts such as visual interest, spatial complexity, pleasantness, and calmness. Results showed that irregular façade patterns were associated with higher ratings of interest and complexity, implying that non-uniform light distributions are perceived as more dynamic and engaging **Figure 2.5**. Participants often described these patterns as visually rich and diverse, contributing to greater cognitive engagement. In contrast, regular patterns were generally seen as calming and orderly, aligning with expectations of clarity and coherence in visual perception. While these patterns received lower excitement or novelty ratings, they were valued for their stability. Responses to striped configurations were mixed; participants found them rhythmically engaging and easy to understand, especially due to their strong directional filtering of daylight. These patterns effectively articulated space and were often described as energizing when sunlight came through at oblique angles.

Overall, the findings highlight the importance of façade design in influencing not only lighting performance but also psychological and emotional reactions to space. This research provides a framework that emphasizes the need to consider geometrical

variation in architectural daylight design for its qualitative effects on user experience, rather than focusing solely on quantitative lighting outcomes.

Table 2.3: Shading pattern classification [Chamilothori, 2019].

Pattern Type	Perceptual Attributes	User Feedback
Irregular	High in interest and complexity	The variability and unpredictability of light patterns made the space feel more dynamic and aesthetically engaging.
Striped	Rhythmic, attention-grabbing, creates a sense of direction	The movement of shadows provided varied spatial experiences throughout the day, enhancing perceptual richness.
Regular	Calming and balanced, sometimes perceived as monotonous	Offered visual stability, though some users associated it with lower stimulation and predictability.

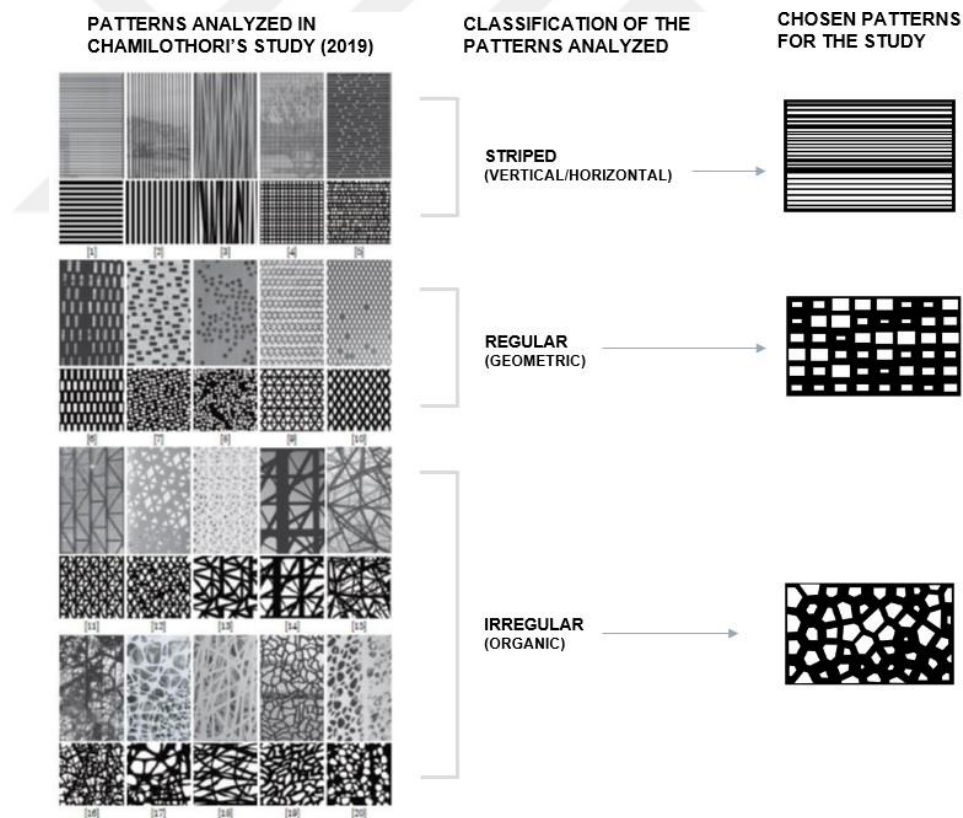


Figure 2.5: Classification of the grammars, and choosing the patterns for the study [Chamilothori, 2019].

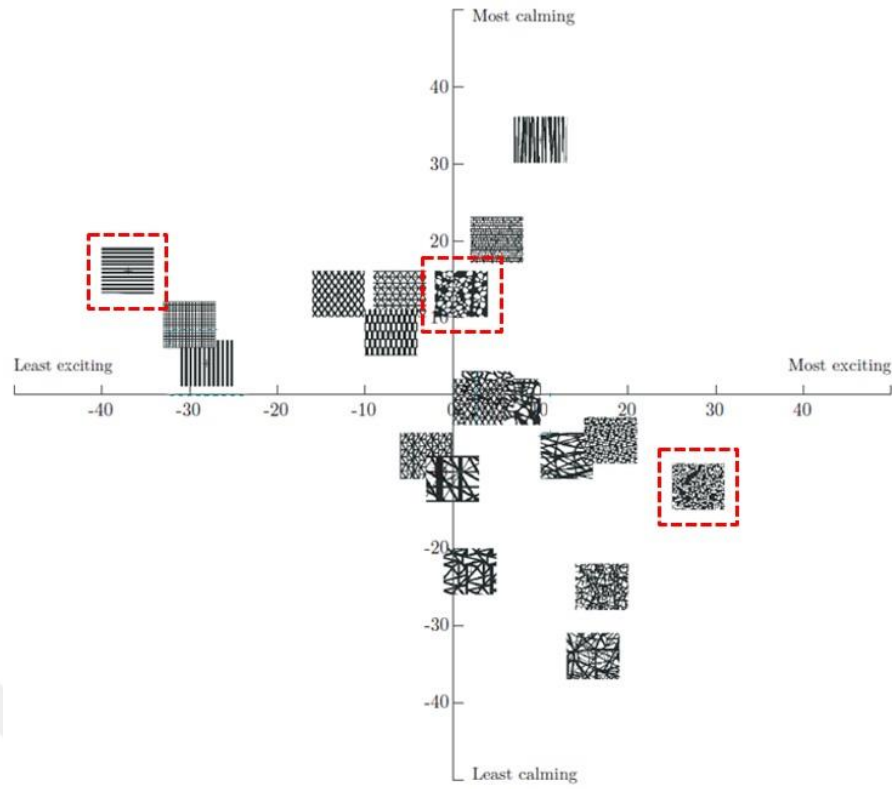


Figure 2.6: Perceptual effects of the chosen patterns on the users [Chamilothori, 2019].

2.3. Metrics and Evaluation Methods for Daylit Spaces

The methods used to measure and assess daylight performance in buildings have significantly changed over time. They have evolved from basic models to advanced simulations that take climate into account. This change shows a better understanding of how building design, climate, and occupant experience are connected. This section will look closely at this evolution, highlighting important metrics that have been developed and how they are used in global green building standards and Turkey's specific regulations.

Historically, the assessment of daylight in buildings was dominated by the Daylight Factor (DF). Introduced in the late 19th century, the DF is a static, ratio-based metric defined as the illuminance at a point inside a room relative to the unobstructed horizontal illuminance outdoors under a standardized, uniformly overcast sky (CIE Overcast Sky) [Tabadkani et al., 2021].

However, the very simplicity of the DF constitutes its most significant limitation. By assuming a single, static sky condition, it fails to account for the dynamic and variable

nature of real-world daylight, including the position of the sun, changes in weather, and the influence of building orientation [Tabadkani et al., 2021]. Consequently, it is a poor predictor of actual daylight availability and visual comfort throughout the year. Despite these well-documented shortcomings, the DF has not been entirely abandoned. It continues to be referenced in some building regulations and is still used by some practitioners for preliminary design analysis [Dervishaj et al., 2022]. In the Turkish academic context, for example, some studies still reference Illuminating Engineering Society (IES) recommendations for DF values in offices, where a DF below 1% is considered poor, 2-5% is deemed good, and values exceeding 10% are seen as increasing the risk of visual discomfort and glare. A study on an office in Ankara, for instance, used the DF as a baseline metric for comparison [Kılıç&Yener, 2017].

The limitations of the DF and other static methods led to the development and widespread adoption of Climate-Based Daylight Modelling (CBDM). This represents a fundamental paradigm shift in daylighting analysis [Tabadkani et al., 2021]. Instead of relying on a single sky model, CBDM utilizes annual, site-specific weather data files that contain hourly values for solar radiation and sky conditions. By running simulations for every hour of the year (or for occupied hours), CBDM provides a dynamic and highly detailed prediction of indoor illuminance levels, offering a far more accurate and realistic assessment of a building's daylight performance [Boubekri&Lee, 2017]. This approach enables designers to understand how a space will perform under a full spectrum of conditions, from clear sunny days to overcast winter afternoons, making it an indispensable tool for high-performance building design.

The shift to CBDM has given rise to a new suite of dynamic metrics that form the backbone of modern daylighting analysis and are integral to the credit requirements of leading international green building rating systems such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method).

Daylight Autonomy (DA): One of the earliest dynamic metrics, Daylight Autonomy is defined as the percentage of annual occupied hours during which a single point in a space meets a minimum illuminance threshold (e.g., 300 or 500 lux) from daylight alone [Tabadkani et al., 2021]. While a significant improvement over the DF, DA has a critical flaw: it is a "one-tailed" metric. It only measures when daylight is sufficient,

failing to penalize for periods when daylight is excessive, which can lead to significant problems with glare and unwanted solar heat gain. Research has also shown that DA can have a poor correlation with occupant satisfaction for this reason **[Tabadkani et al., 2021]**.

Spatial Daylight Autonomy (sDA): To address the point-based limitation of DA and provide a whole-room assessment, Spatial Daylight Autonomy was developed. sDA is an area-based metric that describes the percentage of floor area that meets a minimum illuminance level (e.g., 300 lux) for a specified fraction of annual occupied hours (e.g., 50% of the time). This metric is a cornerstone of the LEED v4.1 daylighting credit, which awards points based on achieving specific sDA thresholds. For instance, achieving an sDA_{300/50%} of 55% or more can earn two points towards certification **[Sun et al., 2020]**.

Usability and Discomfort Metrics provide a more nuanced understanding of daylight quality, acknowledging that too much light can be as problematic as too little.

Useful Daylight Illuminance (UDI): UDI moves beyond a single sufficiency threshold to report the percentage of occupied time that illuminance at a point falls within a series of "useful" ranges **[Boubekri&Lee, 2017]**. While the specific bins can be adjusted, a common scheme includes:

- **Insufficient:** Illuminance is below a minimum threshold (e.g., <100 lux), indicating that electric lighting is required.
- **Supplementary:** Daylight provides a useful contribution but likely needs to be supplemented with artificial light (e.g., 100–500 lux).
- **Autonomous (or Useful):** Daylight levels are within a desired range, and artificial lighting is likely not needed (e.g., 500–2500 lux).
- **Excessive:** Illuminance levels are very high (e.g., >2500 lux), indicating a potential risk of visual and thermal discomfort.

The great strength of UDI is its ability to simultaneously identify under-lit and over-lit conditions, providing a more holistic picture of daylight usability.⁶ Studies have shown that UDI has a strong correlation with occupant visual satisfaction **[Tabadkani et al., 2021]**.

- **Annual Sunlight Exposure (ASE):** Developed specifically to address the potential for visual discomfort from direct sunlight, ASE is the companion metric to sDA in

the LEED rating system. It is defined as the percentage of the floor area that receives more than a certain high level of direct sunlight (e.g., 1000 lux) for more than a specified number of occupied hours per year (e.g., 250 hours). To meet the LEED credit, the ASE_{1000/250} value must typically be kept below 10% of the space's area. ASE acts as a balancing metric, penalizing designs that achieve high sDA scores through large, unshaded windows that would create unacceptable glare [Farivar & Teimourtash, 2023; Ahmed, 2021].

While ASE indicates the risk of discomfort from direct sun, more sophisticated metrics have been developed to predict the subjective sensation of glare.

Daylight Glare Probability (DGP): DGP is one of the most widely accepted metrics for predicting discomfort glare from daylight in an occupant's field of view. It is a complex index that accounts for the total vertical illuminance at the eye (E_v) as well as the luminance, size, and position of glare sources **Table 2.4**. The resulting value is expressed as a probability, with established thresholds for perceived glare: <0.35 is considered imperceptible, 0.35-0.40 is perceptible, 0.40-0.45 is disturbing, and >0.45 is intolerable. While DGP is considered highly accurate in many conditions, research acknowledges the immense complexity of glare as a phenomenon. Finding a single, universally reliable glare index that performs perfectly under all conditions, especially in the presence of direct sun, remains an ongoing challenge for the scientific community [Tabadkani et al., 2021]. To facilitate a clearer understanding, the primary daylight performance metrics are compared in **Table 2.4**.

Table 2.4: Comparative Analysis of Primary Daylight Performance Metrics.

Metric	Definition	Purpose	Typical Thresholds (Example)	Key Limitations
Daylight Factor (DF)	Ratio of internal illuminance to external horizontal illuminance under a CIE standard overcast sky.	Static, early-stage assessment of daylight potential.	>5% = Well-lit; 2-5% = Adequately lit.	Ignores climate, orientation, sun position, and time. Poor predictor of actual performance. (Tabadkani et al., 2021).

Table 2.4 Continued: Comparative Analysis of Primary Daylight Performance Metrics

Spatial Daylight Autonomy (sDA)	Percentage of floor area meeting a minimum illuminance for a specified fraction of occupied hours.	Quantifies the annual sufficiency of ambient daylight.	LEED v4.1: sDA _{300/50%} ≥ 55% for 2 points.	One-tailed metric; does not account for excessive daylight or glare. Can be misleading in shared spaces (Tabadkani et al., 2021).
Useful Daylight Illuminance (UDI)	The percentage of occupied hours that the illuminance at a point falls within a defined "useful" range.	Quantifies usability of daylight, identifying underlit, useful, and overlit conditions.	UDI _{useful} (e.g., 500-2500 lux).	Thresholds can be subjective. May not fully align with specific visual task requirements (Kılıç&Yener, 2017).
Annual Sunlight Exposure (ASE)	Percentage of floor area exceeding a high illuminance level for a specified number of occupied hours.	Quantifies the potential for visual discomfort from direct sun.	LEED v4.1: ASE _{1000/250} ≤ 10%.	An indicator of risk, not a direct measure of glare perception. Sensitive to simulation inputs (Boubekri&Lee, 2017).

In Turkey and across Europe, baseline visual comfort requirements for workplaces are formalized in standards such as TS EN 12464-1 [Turkish Standards Institution, 2021], which addresses the lighting of indoor workplaces. TS EN 12464-1 (the Turkish adoption of EN 12464-1) specifies quantitative requirements for illuminance, glare control, and lighting uniformity to support visual comfort and performance in offices [Hasanova et al., 2024]. For typical office tasks (reading, writing, computer work), a maintained illuminance of 500 lux on the workplane is recommended, with higher levels for more visually demanding tasks [Park et al., 2021]. The standard also limits discomfort glare from luminaires using the Unified Glare Rating (UGR) system (for offices, usually UGR ≤19) and emphasizes sufficient lighting uniformity [Hasanova et al., 2024]. While EN 12464-1 [European Committee for Standardization, 2021] primarily focuses on electric lighting, it implicitly assumes that daylight will be utilized as much as possible – indeed, it is generally accepted that daylight should be

the primary source of illumination in daylight hours for reasons of visual comfort, occupant preference, and energy efficiency **Table 2.5**.

Table 2.5: Prescriptive Lighting Requirements for Office Spaces per TS EN 12464-1 [Turkish Standards Institution, 2021;Öztürk Gül et al., 2023].

Area/Task	Maintained Avg. Illuminance (E _m , lux)	Uniformity (U _o)	Glare Limit (RUGL)	Min. Color Rendering (Ra)	Notes
Filing, copying, etc.	300	0.60	19	80	General office tasks.
Writing, typing, reading, and data processing	500	0.60	19	80	Standard for desk-based work.
Technical drawing	750	0.70	16	80	Higher requirements for visually demanding tasks.
CAD workstations	500	0.60	19	80	Specific requirement for computer-aided design.
Conference and meeting rooms	500	0.60	19	80	Assumes flexible use, including reading/writing.
Circulation areas and corridors	100	0.40	28	80	Lower requirement for transient spaces.

Recently, TS EN 17037+A1 [Turkish Standards Institution, 2022] – the Turkish standard “Daylight in Buildings”, based on the European standard with the same title, EN 17037 [European Committee for Standardization, 2018] – has been adopted to provide a comprehensive, climate-based approach to daylighting and visual comfort. This standard covers four aspects of daylight in interiors: daylight provision, view out, exposure to sunlight, and protection from glare [Konuk Taştan et al., 2024]. Unlike older methods that relied on a static daylight factor, TS EN 17037+A1 uses climate-based daylight modeling to ensure adequate daylight availability throughout the year, especially under the sunny sky conditions characteristic of many Turkish climates [Turkish Standards Institution, 2022] . It sets performance targets for illuminance that must be achieved for at least half of the daylight hours, at both a median point of

the space (50% of the reference plane area) and near the darkest points (95% of the area). For example, the minimum daylight provision level requires at least 300 lux over 50% of the space and a minimum of 100 lux over 95% of the space for at least 50% of the annual daylight hours [Konuk Taştan et al., 2024]. Higher performance tiers (medium and high) increase these targets – e.g., a medium level expects 500 lux over 50% of the area (and 300 lux over 95% area for 50% of the time) [Konuk Taştan et al., 2024].

2.4. Genetic Algorithms in Building Façade Shading Design

A systematic literature analysis begins with formulating a clear and well-defined research question. This study focuses on the research question: “What are the current trends and scientific gaps in the algorithmic design of building facade shading systems for daylight control using GAs?”

The Genetic Algorithm (GA), commonly used as a generative algorithm in shading design, also called the Evolutionary Algorithm, is inspired by Natural evolution as described by Darwin’s theory [Darwin, 1964], where stronger individuals survive over generations. These coding techniques are commonly used in situations where the problem to solve is not easily breakable into a chain of logical decisions and allows randomness to play a key role in the generation of the expected result. Alajmi et. al. [2019] explain GA as it starts with a group of alternative possible solutions for a given problem. It uses three key processes: selection, crossover, and mutation [Goldberg, D.E., 1989]. The role of natural selection is absolved by a "testing function" that measures the performance of the different alternatives against some Key Performance Indicators (KPI) and selects the most performative alternatives for the next generation of possible solutions, while those with below-average fitness are eliminated. The crossover process randomly mixes the "genetic materials" of the selected alternatives into a new generation of individuals. Finally, the mutation process introduces small changes to the new chromosomes [Alajmi et al. 2019] before the new iteration of the overall algorithm.

There are some other review studies published in the field. For example, Machairas et al. [2014] conducted a comprehensive review of algorithms applied to design buildings. Costa-Carrapiço et al. [2020] also published a systematic review that

examined genetic algorithm-based Multi-Objective Optimization Methods (MOOM) for building retrofitting with the objective of energy performance improvements. In a somewhat overlapping area, Alexakis et al. [2024] published a review of studies examining GA-based MOOM applied to building retrofitting that covered the scope of 175 studies. They concluded that the most preferred algorithm, judging by the studies examined, was the NSGA-II method based on efficiency and quality of solution.

Liu et al. [2023] published a review paper that was developed to provide a systematic review to serve as a reference for choosing and tuning machine learning algorithms (MLAs) for daylight prediction applications. Al-Masrani et al. [2018] also published a review in 2018 of solar shading systems applied to office buildings in the tropics by establishing three different categories: passive, active, and hybrid. The review of solar shading systems emphasized adaptive, low-energy shading responses for tropical climates, which also need to consider the increased humidity present in tropical climates, as well as the non-uniformity of sky luminance.

Nazari et al. [2024] published a comprehensive review focusing on challenges with accuracy and validation in architectural research related to digital daylighting simulations. The study stressed that the uncertainties associated with input data quality, computational algorithms, and validation are very important to the reliability of results.

Madan et al. [2024] conducted a systematic review examining the restorative effects of daylight in indoor environments. A review of 33 studies revealed that a total of about 42% of the examined relationships were positively associated with the presence of natural daylight on restorative outcomes, especially affective and clinical outcomes. Their review concluded that direct sunlight was an important factor to restorativity, as well as acknowledging that a not insignificant factor was within the variability of the current literature on links with orientation and availability of daylight, and noting the constraints of the methods studied.

Özlük et al. [2025] undertook a systematic literature review of artificial intelligence algorithms, simulation tools, and software for optimizing the performance of adaptive building facades. The result of their review was that GAs were the most applied AI optimization method, and the software tools of emerging importance were Grasshopper, EnergyPlus, and Rhino.

2.5. Summary of the Current State of the Art

Recent research highlights the growing importance of daylight as a determinant of both environmental performance and user well-being in office spaces. Studies consistently emphasize that daylight contributes not only to energy efficiency but also to visual comfort, cognitive performance, and health [Knoop et al., 2020; Wen et al., 2023; Rezakhani & Kim, 2024]. Inadequate daylight or uncontrolled sunlight, however, can result in glare, discomfort, and overheating [Stringham et al., 2011; Horr et al., 2016; Nazari et al., 2023]. Consequently, ensuring optimal indoor daylight quality has become a critical research field.

Façade design stands out as the primary architectural mediator of daylight access and distribution. Investigations into façade systems demonstrate that both environmental factors, such as topography, vegetation, and surrounding buildings [Pellegrino et al., 2017; Ámundadóttir et al., 2017], and façade-related parameters—such as orientation, window height, glazing type, and material reflectance—are decisive in shaping daylight performance [Esin, 1996; Tezel, 2007; Sevinç & Altın, 2021]. While conventional systems like overhangs, fins, or light shelves provide partial control [Khadijah et al., 2024; Robinson et al., 2013], external fixed devices generally outperform internal shading in terms of thermal and visual performance [Kumar et al., 2005; Onwuzuligbo et al., 2025]. Historical precedents such as mashrabiyas and brise-soleil show the long-standing cultural and climatic relevance of shading systems [Michell, 1978; Bagasi et al., 2021].

Recent advances increasingly employ computational methods to design and evaluate shading systems. Parametric and algorithmic tools enable architects to simulate and optimize daylight conditions in early design stages [Reinhart & Rogers, 2006; Tzempelikos & Athienitis, 2007]. Within these methods, genetic algorithms (GAs) have proven effective in addressing the multi-objective nature of shading design, where daylight autonomy, glare control, and direct sunlight exposure must be balanced simultaneously [Goldberg, 1989; Alajmi et al., 2019]. Studies applying GAs in façade optimization show promising results, yet they are often limited to simplified geometries, conventional shading typologies, or annual metrics without consideration of user position or perceptual qualities [Moscoso et al., 2021; Chi et al., 2020].

Pattern-based design approaches, inspired by shape grammars and computational rule sets, have introduced new opportunities for developing complex façade geometries [Chamilothori, 2019]. However, their application to fixed perforated shading panels remains underexplored, especially in relation to user-centered evaluation. While existing literature covers energy savings and daylight sufficiency, relatively few studies integrate both quantitative metrics and qualitative, experiential factors such as spatial rhythm, temporal dynamics, or phenomenological qualities of light [Brzezicki et al., 2021; Şenel et al., 2023].

In summary, the current state of the art reveals significant progress in understanding the relationship between daylight, user comfort, and façade design. Yet, research gaps persist in three areas: the integration of distinct shading grammars beyond conventional typologies, the simultaneous evaluation of quantitative and perceptual criteria, and position-sensitive and time-specific performance analysis. Addressing these gaps requires methodological frameworks that combine generative design, evolutionary optimization, and multi-layered evaluation techniques, thereby advancing façade design toward more holistic, user-centered solutions.

3. METHODOLOGY: AN ALGORITHMIC APPROACH TO PARAMETRIC DESIGN AND OPTIMIZATION OF FACADE SHADING SYSTEMS

This chapter discusses the scientific method and process of developing a design approach for building facade shadings, specifically the south-facing second layer of a curtain wall, for office buildings in Istanbul.

The research **Table 3.1** describes an integrated methodology that consists of parametric modeling, environmental simulation, and optimization through genetic algorithms. The primary aim of the approach is to establish a pool of high-performing design alternatives and analyze these options through a multi-objective optimization process that operates within specified pattern grammars.

Table 3.1: Steps of the development of the design approach.

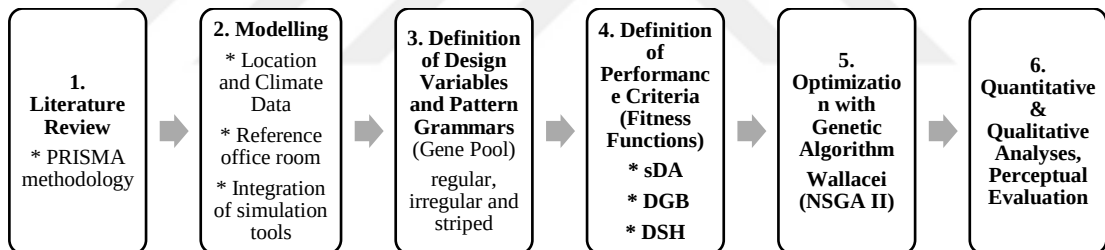


Figure 3.1 presents the development process of the optimization and evaluation of façade shading systems using a generative design approach. The process begins with the definition of design parameters and constraints, which are informed by standards such as TS EN 17037+A1 and TS EN 12464-1 [Turkish Standards Institution, 2022;2021], and include factors such as building function, plan typology, usage hours, orientation, location, pattern grammar, material properties, and shading element positioning. These parameters are encoded into a parametric model developed in Rhino and Grasshopper, where environmental performance is simulated using Ladybug and Honeybee, and optimization is carried out via the Wallacei genetic algorithm. The fitness function is based on normalized outputs of sDA (Spatial Daylight Autonomy), DGP (Daylight Glare Probability), and DSH (Direct Sunlight Hours). The algorithm

iteratively generates and ranks design alternatives through processes of selection, crossover, and mutation, and selects representative patterns from each grammar. Both quantitative data (metric-based outputs and simulation results) and qualitative data (rendered views and false color images) are analyzed based on two different user positions. The final design is evaluated according to whether it satisfies daylight performance standards. If the outputs meet the criteria, the design is presented to the user; if not, the data are stored for future refinement and the optimization loop is repeated. This iterative and user-informed design process bridges environmental performance, generative algorithms, and perceptual design evaluation in facade shading systems.

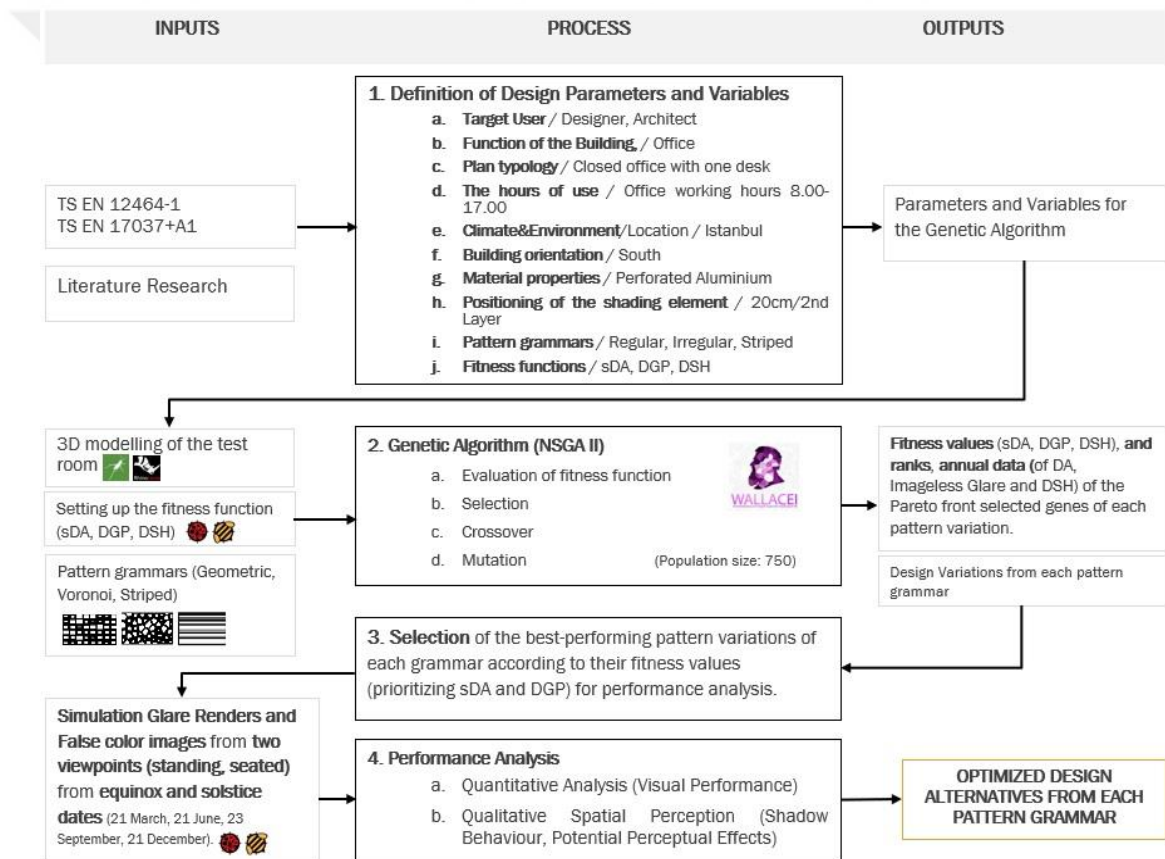


Figure 3.1: Development process of the algorithmic approach.

3.1. Literature Review

Firstly, to understand the effects of daylight on human health, comfort, and strategies to provide visual comfort in indoors, a broad literature review was conducted. A broad

variety of conference proceedings, journal papers, articles, books, book chapters, and graduate theses from different countries were included. The literature review study shows insight into the “2. Background of the Study” chapter, and understanding the state of the art supported the decision-making of setting the parameters and variables for the model. The study aimed to systematically review the literature focusing on shading design with GA to identify the current research gaps and trends. The PRISMA method was chosen due to its widespread use and established credibility in conducting systematic analyses. While many studies focus on holistic building design or optimization methods for energy efficiency, this review specifically targeted shading design using GA for more than one performative criterion. Functional performance, which includes visual comfort, thermal comfort, and user interaction, was analyzed in addition to energy efficiency and aesthetics.

In this chapter, a systematic literature review approach was implemented to explore the research question and methodically achieve the intended objectives. To maintain a structured and transparent review process, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was adopted, as proposed by Moher et al. [2010]. The PRISMA 2020 flow diagram utilized in this research was adapted from the official PRISMA website [Web 1, 2020].

PRISMA serves as a standardized guideline specifically designed for conducting systematic reviews and meta-analyses, offering a framework that promotes methodological clarity and consistency [Moher et al., 2010]. The PRISMA process involves evaluating academic publications through clearly defined stages, which include the selection of a research topic, database searching, application of eligibility criteria, systematic data extraction, and subsequent analysis.



Figure 3.2: PRISMA Method steps.

The PRISMA methodology in this study was implemented through the following sequential steps **Figure 3.2**.

- **Formulating the Research Question:** The main thematic areas of the study were clearly defined to guide the review process within a structured scheme.
- **Identifying Data Sources:** The literature search was carried out using Scopus, a reputable and widely used academic database.
- **Establishing Inclusion and Exclusion Criteria:** Studies that did not meet the scope and relevance of the research were eliminated based on pre-established criteria.
- **Data Collection and Evaluation:** The articles meeting the criteria were systematically reviewed, and the extracted data were analyzed to inform the research findings.

Firstly, the study began with the formulation of a research question. The main research question was “What are the current trends and scientific gaps in the algorithmic design of building facade shading systems for daylight control using GA?”. It was decided that the study would focus on shading design with GA.

Then the database was set to Scopus, which is well well-known and reliable academic database. During the Scopus search, the query for the study was set to:

“(TITLE-ABS-KEY ("algorithm" OR "algorithmic design" OR "parametric design") AND ("pattern" OR "pattern design") AND ("daylight optimization" OR "daylight control" OR "daylighting")) AND ("building façade" OR "building skin" OR "facade"))”

To increase the likelihood of retrieving relevant studies, the search query was constructed using commonly used keywords within the field. However, terms such as "genetic algorithm," "shading," and "sun shade" did not yield relevant and sufficient results during the database search. Although some studies did address GA to shading design, these specific keywords failed to retrieve them through the Scopus search engine. Consequently, broader and more general terms from the field were utilized, and a manual filtering process—first by titles, then by abstracts—was applied to eliminate irrelevant results. After this two-step screening, 23 publications remained, all of which were closely aligned with the research objectives. Moreover, to reflect the dual focus on performance and form, additional keywords related to pattern design were included, allowing the search to encompass aesthetic considerations alongside optimization.

As presented in **Figure 3.3**, the query initially yielded 293 publications. The results were first filtered by language, with only English-language documents retained, which removed 2 records. The next filtering step limited the document type to peer-reviewed journal articles, review papers, and conference proceedings, eliminating 9 additional documents. Subject areas were also narrowed to disciplines relevant to the study, namely, Engineering, Energy, Social Sciences, Computer Science, Environmental Science, Materials Science, Arts and Humanities, and Multidisciplinary studies, which led to the exclusion of 10 more records. In total, 21 documents were excluded through these predefined criteria.

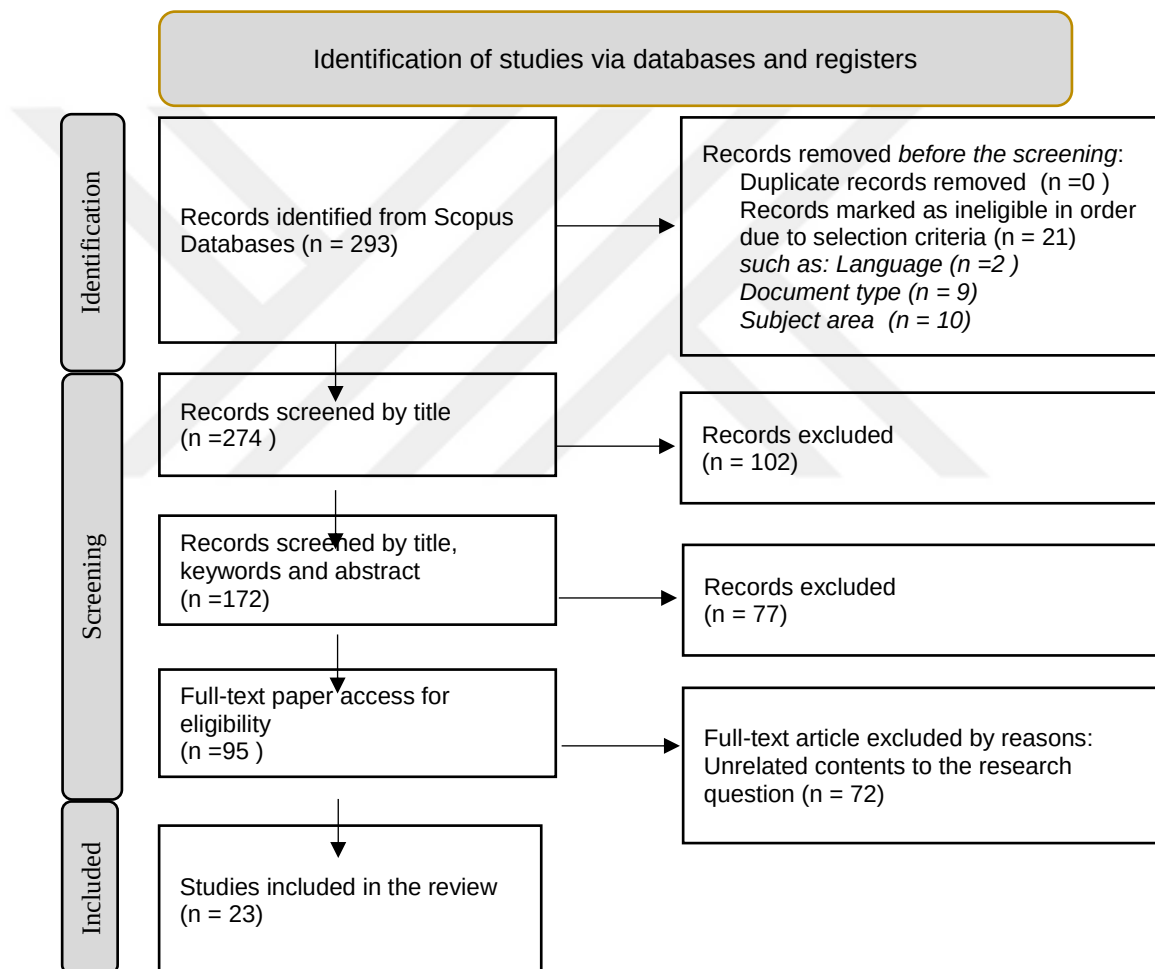


Figure 3.3: PRISMA flow diagram [Esener et al., 2025].

The literature review focused on publications from the years 2003 to 2024, with the search conducted between October 13 and 25, 2024. No relevant records were found before 2003, and only two publications were identified between 2003 and 2005,

indicating that research in this specific area has become more prominent in recent decades.

The initial screening phase was conducted using Microsoft Excel. From a total of 274 records, an initial title-based screening led to the exclusion of 102 entries deemed unrelated to the research scope. The remaining 172 records were further examined based on their titles, keywords, and abstracts, resulting in the removal of 77 additional studies. One record was inaccessible. At the next stage, 95 documents underwent manual full-text screening, and 62 studies were excluded due to a lack of direct relevance to genetic algorithms and shading design. As a result, 23 publications were selected for inclusion in this systematic review.

Following the elimination of non-relevant studies, the remaining 23 articles were analyzed in detail. To support a systematic review framework, these documents were categorized according to their treatment of facade shading performance, focusing on three primary performance dimensions:

- Functional performance,
- Energy and environmental performance, and
- Aesthetic considerations (excluding material durability).

The functional performance category encompasses three key subtopics: visual comfort, thermal comfort, and user interaction.

- Visual comfort is essential for protecting ocular health, supporting circadian rhythms, and ensuring work efficiency **[Knoop et al., 2020]**.
- Thermal comfort contributes to users' physiological well-being and is a well-established consideration in building design.
- User interaction relates to the adaptability and controllability of the shading system by occupants. As highlighted by Tabadkani **[2018]**, offering users the ability to control shading elements can enhance their psychological comfort and satisfaction with the space. Especially for static shading systems, the possibility of manually adjusting elements according to varying daylight conditions during different working hours can be beneficial, both in terms of visual access to the outside and psychological well-being **[Knoop et al., 2020]**.

The energy and environmental performance category included studies focusing on daylight-based energy savings and reductions in cooling loads. Although aesthetic quality is a more subjective issue, it was still considered in terms of whether the authors explicitly addressed aesthetics in their work, rather than through evaluative critique.

Each of the 23 reviewed studies was also classified based on methodology **Table 3.1**. The identified categories include:

- Optimization studies,
- Simulation-based analyses,
- Comparative studies,
- Novel approach development, and
- Hybrid methodologies (e.g., simulation combined with optimization or comparative studies with modeling).
- Optimization refers to research where performance criteria of shading systems were enhanced using computational methods.
- Simulation analysis covers studies evaluating daylight performance through digital tools.
- Comparative research involves side-by-side evaluation of different shading systems or strategies.
- New approaches relate to original frameworks or models developed for daylight control.
- Combined studies integrate two or more of these methods in a single research setup.

Among the 23 articles analyzed:

- 19 studies focused on visual comfort,
- 8 addressed thermal comfort,
- 3 examined user interaction,
- 17 explored energy and environmental performance, and
- 4 touched upon aesthetic concerns, **Table 3.2**.

The importance of visual comfort emerged as a dominant theme across the reviewed literature. For example, Rezakhani et al. [2024] proposed façade designs with irregular and widened patterns near windows to reduce glare and reflections, which led to improved user satisfaction. Rizi et al. [2021] investigated an adaptive façade system that adjusted in real-time to occupant position, enhancing comfort by optimizing shading coverage—resulting in a 76% improvement in visual conditions. Baghoolizadeh et al. [2023] analyzed the performance of Venetian blinds in office environments and found that their proper control significantly boosted both thermal and visual comfort. Alajmi et al. [2019] evaluated various window shading systems in Kuwait’s hot climate, showing that well-designed solutions could provide maximum daylight without excessive glare, improving visual comfort overall. Similarly, Stevanović et al. [2018] studied curvilinear shading systems and demonstrated that these not only enhanced visual comfort but also contributed to energy savings and environmental performance by lowering cooling demands.

Table 3.2: Classification of the reviewed studies by study type, year and the performance criteria.

Study type	Authors	Year	Functional Performance			Energy Efficiency and Environmental Performance	Aesthetics
			Visual Comfort	Thermal Comfort	User Interaction		
Optimization	Rezakhani, M., & Kim, S. A.	2024	●				●
	Baghoolizadeh, M., Rostamzadeh-Renani, M., Rostamzadeh-Renani, R., & Toghraie, D.	2023	●	●		●	
	Rizi, R. A., & Eltaweel, A.	2021	●	●	●	●	
	Alajmi, A., Abaalkhail, F., & Alanzi, A.	2019	●	●		●	
	Stevanović, S., & Stevanović, D.	2018				●	
	Negendahl, K., & Nielsen, T. R.	2015	●	●		●	
	Tsangrassoulis, A., Geros, V., & Bourdakos, V.	2006				●	
Simulation Analysis	Wanas, A., Aly, S., Farghal, A., & El-Dabaa, R.	2015	●				
Comparison	Vojdani, B., Rahbar, M., Fazeli, M., Hakimazari, M., & Samuelson, H. W.	2024	●			●	
	Nazari, S., Keshavarz Mirza Mohammadi, P., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Doan, D. T., & Almhafdy, A.	2023	●	●		●	
	Lee, K. S., Han, K. J., & Lee, J. W.	2016	●			●	
New Approach	Duan, Y., Zhang, T., Yang, Y., Li, P., Mo, W., Jiao, Z., & Gao, W.	2024	●	●		●	
	Elmalky, A. M., & Arajji, M. T.	2024				●	●
	Tabadkani, A., Banihashemi, S., & Hosseini, M. R.	2018	●			●	
	Choi, S. J., Lee, D. S., & Jo, J. H.	2017	●	●		●	
	Caldas, L., & Santos, L.	2016	●		●		
	Von Buelow, P.	2016					●
Comparison and Optimization	Wen, S., Hu, X., Hua, G., Xue, P., & Lai, D.	2023	●			●	
New Approach and Simulation Analysis	Xiao J., Liu Y., Deng Q.	2022	●				
Simulation Analysis and Optimization	Sorooshnia, E., Rashidi, M., Rahnamayiezekavat, P., Rezaei, F., & Samali, B.	2023	●				
	Tabadkani, A., Dehnavi, A. N., Mostafavi, F., & Naeini, H. G.	2023	●		●	●	
	Taveres-Cachat, E., & Gola, F.	2020	●	●		●	
	Fathy, F., Sabry, H., & Faggal, A. A.	2017	●			●	●

Thermal comfort is inherently linked to effective daylight management, as optimizing natural light can reduce the dependency on mechanical cooling systems. For instance, Rizi et al. [2021] not only considered visual comfort but also integrated façade geometry into their optimization process, resulting in reduced heat gains and improved overall thermal conditions. Similarly, Alajmi et al. [2019] assessed window shading systems in hot climates, focusing on their ability to regulate daylight while simultaneously reducing cooling demands and enhancing thermal comfort. Baghoolizadeh et al. [2023] emphasized that strategic control of Venetian blinds significantly contributes to thermal comfort, reinforcing the interconnectedness between light control and heat regulation. In another study, Stevanović et al. [2018] explored curvilinear shading elements, showing that they effectively minimize cooling loads while supporting thermal balance between heating and lighting needs in office spaces.

User interaction, defined as the occupant's ability to influence or adjust building systems according to changing conditions, also plays a critical role in enhancing comfort and satisfaction. According to Knoop et al. [2020] and Duan et al. [2024], allowing users to interact with shading systems promotes psychological well-being and perceived environmental control. Rizi et al. [2021] incorporated this aspect into their adaptive façade by integrating occupant position tracking, thus enabling shading adjustments tailored to users' locations. Baghoolizadeh et al. [2023] also acknowledged the impact of occupant behavior in managing shading systems, concluding that user-based modifications could improve both thermal and visual comfort. Alajmi et al. [2019] discussed how understanding user interaction is essential for evaluating the effectiveness of shading solutions in different climatic contexts. Stevanović et al. [2018] pointed to the potential of user involvement in future adaptive design strategies, implying that flexibility and user agency could increase functional efficiency.

When it comes to energy efficiency and environmental performance, these aspects are among the most frequently examined within sustainable façade design. Baghoolizadeh et al. [2023] reported that optimizing the control logic for Venetian blinds could yield substantial energy savings—up to 40–50%—thereby improving both building performance and user comfort. In a similar vein, Alajmi et al. [2019] recorded energy

savings of 24–27%, underscoring the importance of climate-responsive design. Stevanović et al. [2018] demonstrated that their curvilinear shading system successfully reduced cooling loads while achieving a balance between heating and lighting demands, contributing positively to overall energy performance. Rezakhani et al. [2024] highlighted that visually optimized façade patterns not only enhanced occupant comfort but also improved energy efficiency. Meanwhile, Rizi et al. [2021] showed how adaptive façade designs, responsive to both environmental factors and occupant behavior, could significantly boost energy efficiency.

Aesthetic quality, although less frequently emphasized, was addressed in a few studies. Rezakhani et al. [2024] designed façade elements that balanced technical performance with visual appeal, achieving both efficiency and architectural expression. Alajmi et al. [2019] discussed the importance of aesthetic considerations in window shading design, noting that appealing forms can contribute to user satisfaction while supporting sustainability goals. Rizi et al. [2021] aimed to create adaptive shading systems that were not only effective but also visually engaging. Stevanović et al. [2018] highlighted the potential of curvilinear designs to provide both energy benefits and visual interest, showcasing how performance and design quality can be integrated seamlessly. Collectively, these studies emphasize the interdependence of aesthetics and performance in contemporary architectural design.

Following the systematic analysis, the reviewed literature from 2003 to 2024 revealed a thematic distribution as follows:

- Visual comfort: 37%
- Thermal comfort: 16%
- User interaction: 6%
- Energy efficiency and environmental performance: 33%
- Aesthetics: 8% **Table 3.2.**

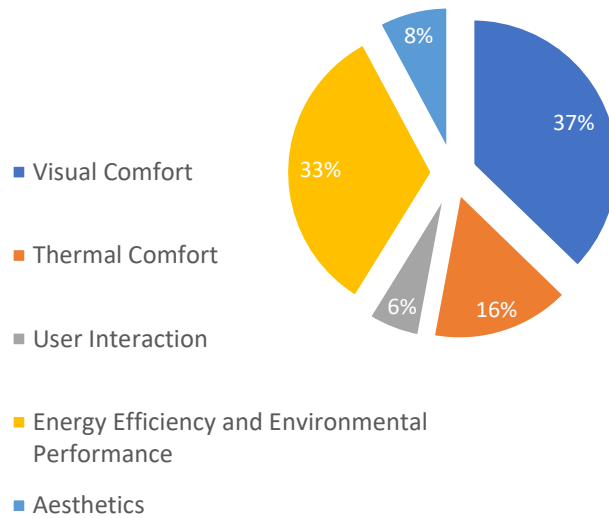


Figure 3.4: The percentages of the reviewed studies that researched performance criteria.

As illustrated in **Table 3.3**, research on visual comfort has seen a noticeable increase in recent years, although interest in the topic has been present consistently over time. Similarly, studies focusing on energy efficiency and environmental performance have remained relevant both historically and in more recent scholarly work. In contrast, thermal comfort has received steady attention throughout the years without significant fluctuation in interest. However, investigations addressing aesthetic considerations within the context of shading and façade design continue to be relatively limited.

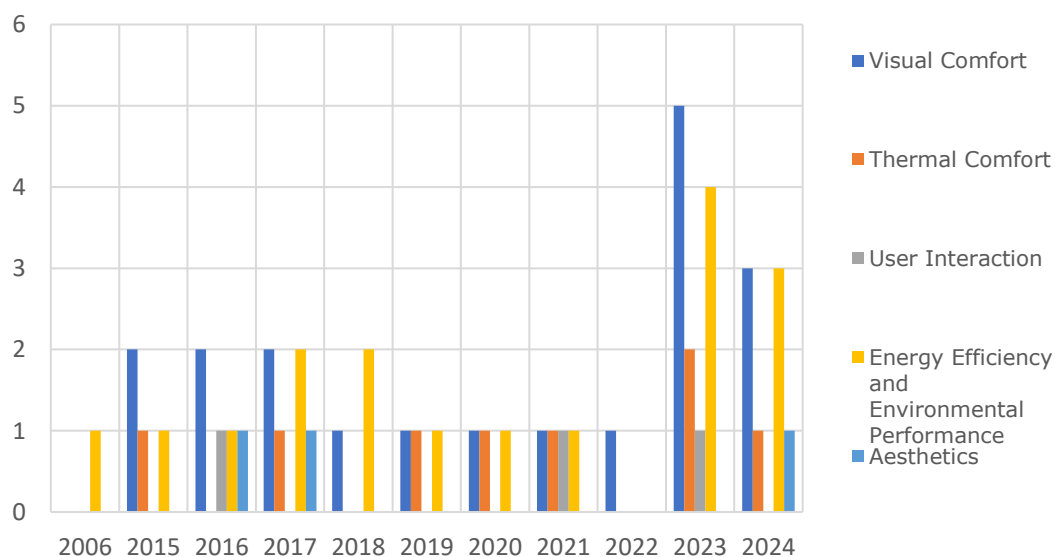


Figure 3.5: The performance criteria researched over the years.

Based on the data presented in **Table 3.2**, research addressing energy efficiency and environmental performance was limited in the earlier years, with only a single study recorded in 2006. By 2015 and 2016, however, the emphasis in the literature shifted, and visual comfort emerged as the most frequently studied performance criterion. A modest increase in energy-focused studies occurred in 2017, indicating renewed attention to environmental concerns. A noticeable decline in publication volume was observed during the pandemic years (2019–2021), likely influenced by global disruptions. In contrast, 2023 witnessed a sharp rise in studies on visual comfort, with five publications released that year. This increase was accompanied by greater scholarly activity on both thermal comfort and energy-related performance. In 2024, research trends continued to center primarily on visual performance and energy efficiency.

Regarding methodological approaches, optimization studies have existed in the field for some time, with early examples dating back to 2006 **Table 3.4**. From 2016 onward, there has been growing interest in the development of innovative design methodologies. While comparative studies and simulation-based analyses have remained widely used, 2023 marked a notable peak in optimization research, paralleled by increases in both comparative evaluations and simulation work. The trend toward new design approaches gained momentum again in 2024, reinforcing a continued shift toward more integrative and computationally driven research strategies.

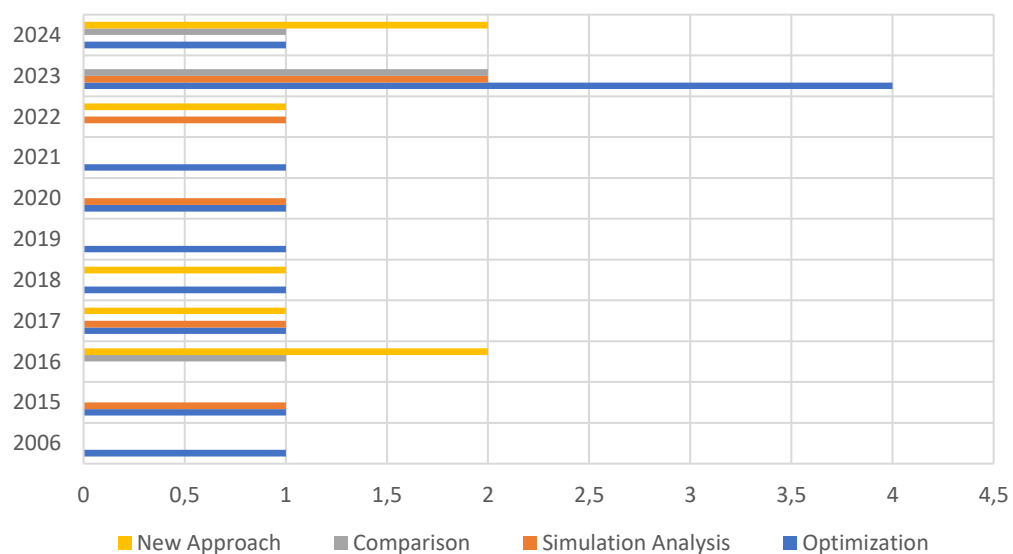


Figure 3.6: Study types researched over the years.

Table 3.3: The reviewed studies by study type, the country the study was conducted, the year of publication, and the tools used.

Study type	Country	Authors	Year	Tools
Optimization	South Korea	Rezakhani, M., & Kim, S. A.	2024	Rhinoceros, Grasshopper, Galapagos, Karamba
	Iran	Baghoolizadeh, M., Rostamzadeh-Renani, M., Rostamzadeh-Renani, R., & Toghraie, D.	2023	EnergyPlus, JEPLUS, JEPLUS+EA, Morris Sensitivity Analysis
	Iran	Rizi, R. A., & Eltaweel, A.	2021	Rhinoceros, Grasshopper, Octopus, Ladybug, Honeybee
	Kuwait	Alajmi, A., Abaalkhail, F., & Alanzi, A.	2019	EnergyPlus, JEPLUS+EA
	Serbia	Stevanović, S., & Stevanović, D.	2018	Rhinoceros, Grasshopper, Octopus, Ladybug
	Denmark	Negendahl, K., & Nielsen, T. R.	2015	Rhinoceros, Grasshopper, Honeybee, Termite, HQSS
	Greece	Tsangrassoulis, A., Geros, V., & Bourdakis, V.	2006	Radiance, Summer-Building, TRNSYS, DOE-2, ESP-r
Simulation Analysis	Egypt	Wanas, A., Aly, S., Farghal, A., & El-Dabaa, R.	2015	Rhinoceros, Grasshopper, DIVA, Radiance
Comparison	USA, Iran	Vojdani, B., Rahbar, M., Fazeli, M., Hakimazari, M., & Samuelson, H. W.	2024	Rhinoceros, Grasshopper, MATLAB
	Iran, New Zealand	Nazari, S., Keshavarz Mirza Mohammadi, P., Ghaffarianhoseini, A., Ghaffarianhoseini, A., Doan, D. T., & Almhafdy, A.	2023	Rhinoceros, Grasshopper, Ladybug
	South Korea	Lee, K. S., Han, K. J., & Lee, J. W.	2016	Rhinoceros, Grasshopper, DIVA
New Approach	China	Duan, Y., Zhang, T., Yang, Y., Li, P., Mo, W., Jiao, Z., & Gao, W.	2024	Rhinoceros, Grasshopper, Octopus
	Canada	Elmalky, A. M., & Arajji, M. T.	2024	Rhinoceros, Grasshopper, MATLAB
	Iran	Tabadkani, A., Banihashemi, S., & Hosseini, M. R.	2018	Phyton
	South Korea	Choi, S. J., Lee, D. S., & Jo, J. H.	2017	Shading calculation tool (polygon method)
	Portugal	Caldas, L., & Santos, L.	2016	Rhinoceros, Grasshopper, Radiance
	USA	Von Buelow, P.	2016	Rhinoceros, Grasshopper, Digital Project (by CATIA), Autodesk Inventor, Generative Components (Bentley Systems)
Comparison and Optimization	China	Wen, S., Hu, X., Hua, G., Xue, P., & Lai, D.	2023	Rhinoceros, Grasshopper, Wallacei X (NSGA II Algorithm)
New Approach and Simulation Analysis	China	Xiao J., Liu Y., Deng Q.	2022	Rhinoceros, Grasshopper, DIVA, Radiance
Simulation Analysis and Optimization	Australia	Sorooshnia, E., Rashidi, M., Rahnamayezekavat, P., Rezaei, F., & Samali, B.	2023	Rhinoceros, Grasshopper, Wallacei
	Australia	Tabadkani, A., Dehnavi, A. N., Mostafavi, F., & Naeini, H. G.	2023	Phyton
	Norway	Taveres-Cachat, E., & Goia, F.	2020	Rhinoceros, Grasshopper, EnergyPlus
	Egypt	Fathy, F., Sabry, H., & Faggal, A. A.	2017	Rhinoceros, Grasshopper, DIVA, Radiance, Daysim, Galapagos

According to **Table 3.3**, the majority of studies in the reviewed literature utilized Rhinoceros and Grasshopper, as these platforms provide a robust foundation for parametric and algorithmic design workflows. Although these tools are commonly used for generative optimization studies, some researchers applied alternative software and methods. For instance, Choi et al. [2017] developed a new shading approach using a polygon-based calculation tool. Alajmi et al. [2019] and Baghoolizadeh et al. [2023] employed EnergyPlus, while Tsangrassoulis et al. [2006] used Radiance. Tabadkani et al. [2018; 2023] conducted two studies using Python, one focused on a new shading approach in Iran, and the other involved simulation and optimization in Australia.

The growing focus on indoor environmental quality has underlined the importance of daylight control, which influences both visual and thermal comfort, as well as general well-being and productivity [Knoop et al., 2020; Duan et al., 2024]. Effective

daylighting strategies not only support user comfort but also reduce dependence on artificial lighting and air conditioning. Among passive design strategies, solar shading systems stand out for their capacity to enhance daylight control and energy savings [Choi et al., 2017; Moscoso et al., 2021]. The choice of shading form and material often varies according to climate, but high-performance outcomes today increasingly rely on digital and algorithmic tools. Genetic Algorithms (GAs), rooted in Darwin's theory of evolution, allow the generation of diverse design alternatives based on the principle of survival of the fittest.

This study conducts a systematic analysis of research trends and gaps related to shading systems and façade design, with a particular emphasis on the use of genetic algorithms. The initial dataset included 293 publications retrieved from Scopus (2003–2024), and after applying the PRISMA screening method, only 23 studies met the inclusion criteria. These were then classified according to publication year, design tools used, research type, and performance criteria.

The findings indicate that Rhinoceros and Grasshopper are the dominant tools used in the field, while a smaller number of studies utilized Python or EnergyPlus. Grasshopper, with its visual programming interface, is particularly attractive for designers and architects who may lack coding experience. Its intuitive drag-and-drop logic simplifies the creation and testing of complex algorithms. In contrast, while Python provides greater flexibility and control, it requires more advanced programming skills, making Grasshopper a more accessible option for early-stage exploration and prototyping.

Recent literature shows an increasing interest in developing new design methods and systems, as well as in conducting comparative studies. Although simulation and optimization have long been part of this field, their usage continues to grow thanks to user-friendly software plug-ins. The emergence of artificial intelligence (AI) tools within parametric platforms is also regarded as a major turning point for the discipline. To ensure a structured review, the performance criteria for shading systems were categorized into four main themes:

- Functional performance (visual comfort, thermal comfort, and user interaction),
- Energy efficiency and environmental performance,

- Aesthetic quality, and
- Tool-based design methodology.

The literature highlights a significant gap in aesthetics-related studies, especially in those that focus on quantitative metrics such as glare or illuminance, often neglecting qualitative and perceptual dimensions. While Buelow [2016] addressed pattern aesthetics, the work did not directly relate to shading systems. Likewise, Rezakhani [2024] and Elmalky [2024] referenced visual appeal, but did not systematically analyze aesthetics as a design parameter. There is a clear need to evaluate both functional and aesthetic performance concurrently.

The interplay between aesthetics and performance also remains underexplored. Although some studies, such as those by Rezakhani et al. [2024], touch upon the relationship between design appeal and usability, they fall short of investigating how aesthetics impact user satisfaction and comfort.

Another underdeveloped area in the literature is the integration of user feedback into the design process. Collecting such data remains challenging due to the dynamic nature of user-shading interactions. Efficient and early-stage user involvement strategies are needed to capture feedback that can meaningfully inform design decisions.

Although the reviewed literature has contributed valuable insights into comfort, interaction, and energy performance, several gaps persist. For example, while Rezakhani et al. [2024] addressed visual comfort, the psychological and physiological implications of façade patterns have not been fully examined.

Understanding how occupant behavior affects performance is another area lacking in-depth analysis. While Baghoolizadeh et al. [2023] and Rizi et al. [2021] acknowledged its importance, they did not fully explore how user routines and preferences shape shading effectiveness.

Furthermore, evaluating overall indoor comfort should go beyond light and temperature. While Alajmi et al. [2019] focused on daylight and energy metrics, their study did not consider acoustics, air quality, or psychological factors. A more holistic framework, ideally developed in collaboration with experts in building science and environmental psychology, is necessary for comprehensive comfort analysis.

The practical implementation of high-performance façade systems also warrants attention. Although Rizi et al. [2021] and Stevanović et al. [2018] demonstrated strong

performance metrics, they did not assess real-world feasibility, including installation, maintenance, or lifecycle costs.

Finally, although many studies focus on energy performance, there is a lack of attention to how shading design responds to local climate conditions, cultural context, and building typology. The field would benefit from research that investigates context-sensitive design reasoning, potentially supported by field data and climate-based design simulations.

3.2. Modelling

The second step of the process is the modeling phase, which involves the creation of the test room and the pattern configurations in Rhinoceros and Grasshopper **Appendix-A**. In this step, firstly, the location and climate data were defined. Later, the test room and three pattern grammars were modelled, and simulation tools were integrated into the design with coding in Grasshopper, enabling the model to support environmental performance simulations.

3.2.1. Location and Climate Data

Istanbul Atatürk Airport, one of Turkey's well-documented meteorological measurement infrastructures, was selected as the location. The primary reason for this choice is the reliability and level of detail of the Typical Meteorological Year (TMY) climate data, which is critical for building performance simulations. This data, in EnergyPlus Weather (EPW) format, was imported into the simulation environment using the Ladybug tool. The use of reliable and measurement-based climate data enhances the accuracy and scientific validity of daylighting and energy analyses [Crawley, Lawrie, & Winkelmann, 1999].

In the study, the south-facing façade of the office building was identified as a critical orientation due to its high exposure to solar radiation throughout the year, and the analyses were conducted on this façade. The hours were chosen as working hours of 08.00-17.00, and the yearly data is calculated in **Figure 3.7**.

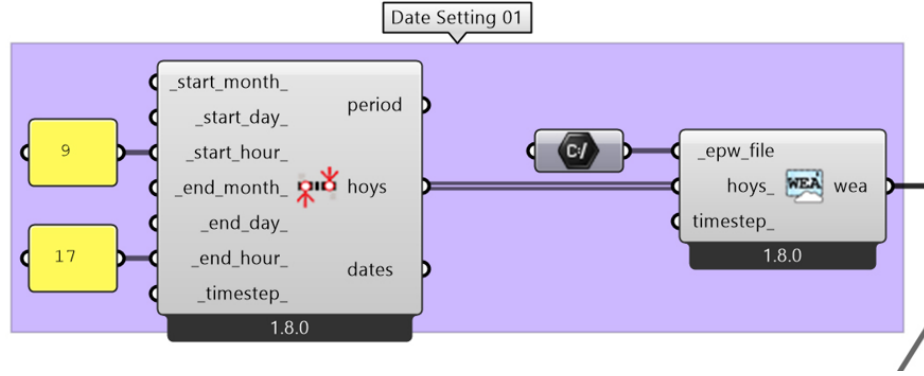


Figure 3.7: Hours and the climate data in the model.

3.2.2. The Test Room

For the simulations, a reference model representing a standard office room was created **Figure 3.8**. The model geometry, material properties, and usage scenario were defined based on international standards and common assumptions in the literature.

The test room was chosen as a closed-plan office, aligned with the requirements of TS EN 17037+A1 standard [Turkish Standards Institution, 2022]. As the genetic algorithm was planned to change the solid-void ratios during creating variations of the pattern grammars chosen, the width of the office space does not make an important change in the void sizes. Yet, the depth of the space and the ceiling height affect the amount of daylight entering to space. So these measurements were treated as important design parameters in the genetic algorithm and daylight control, more than the width of the space, which affects the typology of the office.

As the TS EN 17037+A1 [Turkish Standards Institution, 2022] standard requires daylight simulations for the desk 1 meter away from the transparent layer of the facade, the study will be based on a single desk configuration consistent with the methodology employed by Konuk Taştan et al. [2024].

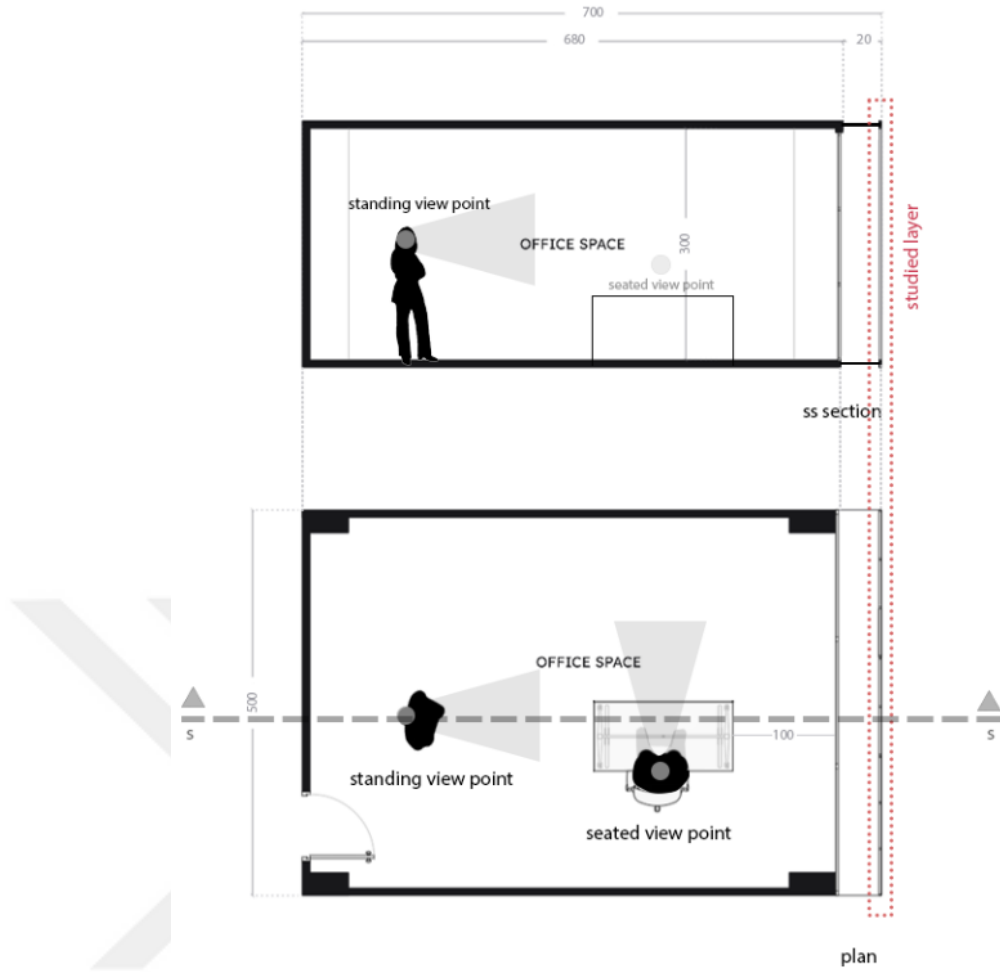


Figure 3.8: Test room plan and section.

- **Geometry:** The office room was modeled with dimensions of 5.0m x 7.0m x 3.0m (Width x Depth x Height) as based on the literature review in the previous chapter, it was well understood that for a 3.0-meter ceiling -which is common in Turkish building practices and the standards TS EN 17037+A1[**Turkish Standards Institution, 2022**] - the daylight could reach maximum to 7.0 meters in depth, following the 2.5h rule as mentioned in the previous chapter. The Window-to-Wall Ratio (WWR) was set to 95% for the primary transparent layer of the curtain facade. The second layer of the facade, which is created after the genetic algorithm process, stands 20 cm, similar to the work of Nazari et al. [2023] and Erkan [2024], in front of the primary layer to create space for cleaning and maintenance.
- **Material Reflectance Values:** The reflectance values of the interior surfaces directly affect visual comfort and daylight distribution. These values were defined

based on TS-EN:17037+A1 [2022] and the CIBSE Lighting Guide LG10: Daylighting and Window Design **Table 3.4**.

Table 3.4: Reflectance Values of Interior Surface in the Reference Office Model.

Surface		Reflectance (%)	Source
Ceiling		80	TS-EN:17037+A1 (2022)
Interior Walls		50	TS-EN:17037+A1 (2022)
Floor		40	TS-EN:17037+A1 (2022)
Window (VT)	Glass	80	Konuk Taştan et al. 2024

Figure 3.9 illustrates the initial phase of the parametric modeling workflow in Grasshopper, which involves the generation of the room geometry and the assignment of material properties for daylight simulations. The process begins with the definition of a base geometry of the office room, including its zoning, floor height, and orientation. Using the Honeybee components, room volumes are generated and linked to construction sets that define the thermal and optical properties of elements such as interior walls, glazing surfaces, shading devices, and window systems. Adjustable number sliders are used to control critical geometric parameters, including room dimensions, window height, window-to-wall ratio, and shading offset distances, providing flexibility in formulating different design alternatives. These parameters are then connected to Honeybee's energy model components, which define the boundary conditions and material performance characteristics essential for simulating daylight performance. This step forms the foundational model setup used in subsequent simulation and optimization phases, ensuring that spatial and material definitions are consistently integrated into the generative design process.

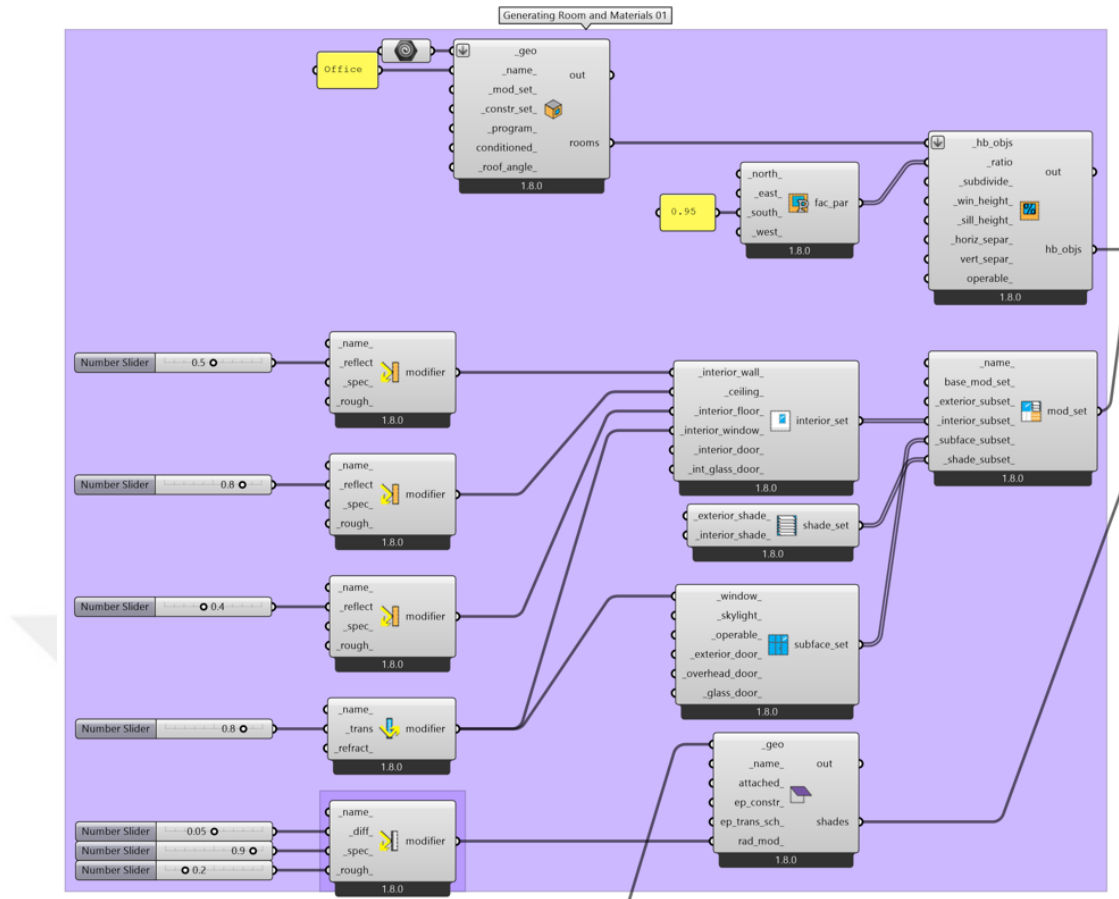


Figure 3.9: Modelling of the test room in Rhino, Grasshopper.

Perforated aluminum was selected for the second layer of the shading system generated through a genetic algorithm because of its lightweight structure and performance [Khadijah et al., 2024]. The research has shown that perforated shadings like “jali” show effective performance in daylight control [Chockalingam et al., 2021]. In addition to it, perforated sun shading elements can support visual interaction with the outdoor environment [Khadijah et al., 2024].

Analysis Plane and Sensor Grid: The sensor grid used in the simulations was placed on a plane positioned 0.85m above the floor, which is considered the work plane. The distance between sensors was set to 0.5m x 0.5m. This arrangement complies with the methodology recommended for lighting calculations by the TS EN 12464-1 [Turkish Standards Institution, 2021] and IES LM-83-12 standards **Figure 3.10**.

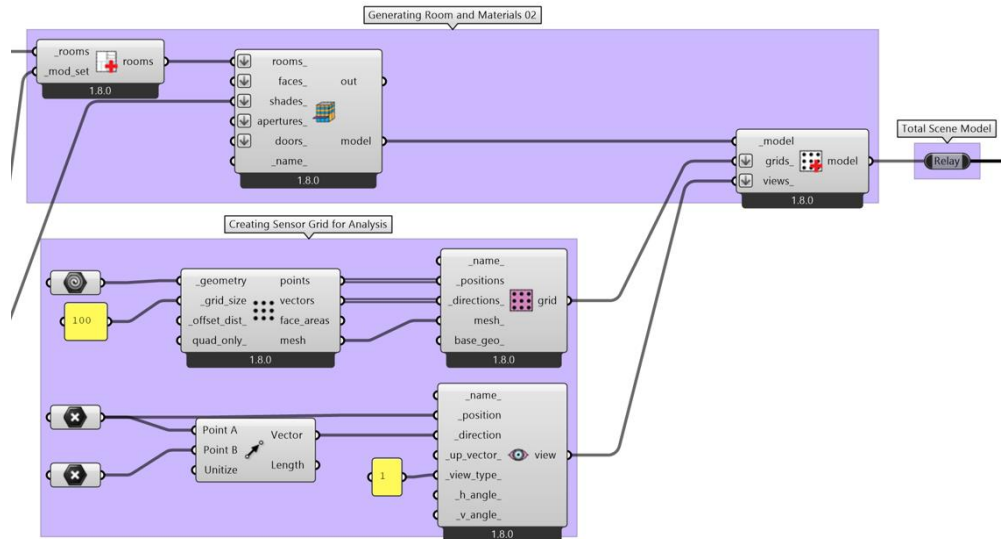


Figure 3.10: Grids of the sensors.

3.2.3. Integration of Simulation Tools

The research was conducted on the Rhinoceros 3D modeling program and its plugin, the Grasshopper parametric design platform. The following tools and libraries were used in the process:

- Ladybug & Honeybee: These open-source libraries allow building energy and daylighting simulations within the Grasshopper environment. Ladybug was used to import and visualize EPW climate data, while Honeybee was used for transferring 3D model data to validated simulation engines like Radiance and Daysim and for retrieving the results [Roudsari & Mackey, 2013].
- Wallacei: A Grasshopper plugin developed for multi-objective evolutionary optimization. Wallacei uses the NSGA-II (Nondominated Sorting Genetic Algorithm II) algorithm to search for the optimal solutions according to defined design objectives (fitness criteria) [Deb, Pratap, Agarwal, & Meyarivan, 2002].

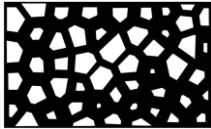
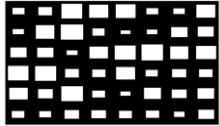
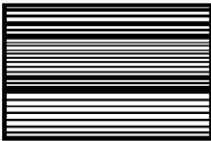
3.3. Definition of Design Variables and Pattern Grammars (Gene Pool)

The third step of the process in the development of the proposed approach is defining design variables and pattern grammars. The gene pool for the optimization process is

composed of geometric parameters that define the porous structure of the shading element on the façade.

The pattern grammars that are used in this study were set according to a thesis related to the topic, in École polytechnique fédérale de Lausanne (EPFL) by Chamilothoni [2019]. In her research, she investigated the perceptual impacts of facade patterns on users with surveys made in Greece and Switzerland, and she also classified facade patterns as regular, irregular, and striped. Similarly, in this study, the selected pattern grammars are also examined within these three categories **Table 3.5**.

Table 3.5: Defining the pattern grammars studied in the research.

Pattern Grammar (Gene Pool)	Modelling	Icon
Irregular	Irregular patterns appear to be more organic in structure, as they do not reflect clear order or repetition. The irregular form is examined as Voronoi in Grasshopper.	
Regular	Regular patterns show an apparent geometric order, but the proportion of the solid-void ratio may vary; they are orderly and arranged spatially, consistently in proportion and shape with either solid or void blocks. The sample geometrical shape for the regular pattern grammar was chosen square in this study.	
Striped	Striped appeared to reference patterns with horizontal and vertical bars. Because this study is made for a south-facing facade, only horizontal bars are considered in the Striped category.	

For each grammar, the numerical parameters (genes) that control the scale of the void parts and distribution were defined as the variables to be changed by Wallacei during the optimization process. For the modelling of regular and irregular pattern grammars, randomized points on the layer were set, and the pattern's void parts were shaped around them. The stripes, on the other hand, due to their linear nature, were shaped by extrusion of the horizontal bars on the vertical axis.

Figure 3.11 presents the simulation setup used to evaluate annual daylight performance metrics within the parametric workflow. The process is structured in three main sections.

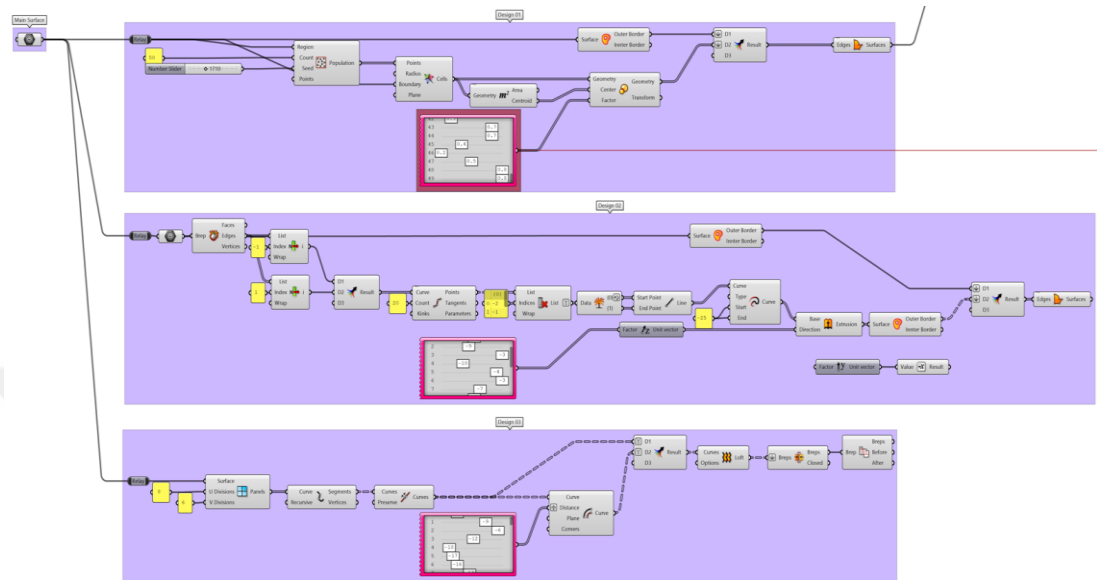


Figure 3.11 Modelling of the pattern grammars.

In the top section, the Annual Daylight Simulation is configured using Honeybee components, where weather data, room model, and sensor grids are connected to generate simulation results such as Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE).

The middle section focuses on Glare Analysis, employing the Daylight Glare Probability (DGP) metric. Here, specific viewpoints, previously defined based on user positions, are linked to simulate and quantify glare levels for various hours throughout the day using Honeybee Radiance-based tools.

The lower section is dedicated to Direct Sunlight Hour (DSH) calculations, which assess the cumulative exposure to direct sunlight over the year. This analysis is crucial for evaluating both visual comfort and the risk of overheating.

Each simulation block uses the same environmental and geometric inputs to ensure consistency across all performance criteria. The resulting data serves as the input for optimization and comparative evaluation among different shading pattern grammars.

Table 3.6: Inputs for the algorithmic approach.

Input	Description	Rationale
Target User	Designer, Architect	Defined to reflect the perspective of professional users who design and evaluate office environments.
Function of the Building	Office	Represents a standard office scenario for daylight and visual comfort studies.
Plan Typology	Closed office with one desk	Chosen to model a simple, scalable office unit typology.
The Hours of Use	Office working hours 08:00–17:00	Reflects realistic use conditions for daylight and glare analysis.
Climate & Environment	Location: Istanbul (Atatürk Airport EPW)	Selected as the most reliable and widely used climatic dataset for Istanbul.
Building Orientation	South	Maximizes solar exposure, making shading evaluation more critical.
Material Properties	Perforated Aluminium	Commonly used façade shading material, durable and realistic for second-skin façades.
Positioning of the Shading Element	20 cm distance, second façade layer	Represents a detached, double-skin façade approach frequently applied in practice.
Pattern Grammars	Regular, Irregular, Striped	Incorporated to compare different geometric logics, following Chamilothoni's classification.
Fitness Functions	sDA, DGP, DSH	Selected to jointly evaluate daylight sufficiency, glare control, and direct sunlight exposure.
Standards	TS EN 12464-1; TS EN 17037+A1	Ensure compliance with international requirements for office lighting and daylighting.
Simulation Tools	Rhino + Grasshopper, Ladybug, Honeybee, Wallacei	Provide integrated parametric modeling, climate-based daylight simulation, and evolutionary optimization.
Glare & False Color Simulations	Standing/Seated viewpoints, solstice and equinox dates (21 March, 21 June, 23 Sept, 21 Dec)	Enable seasonal and positional evaluation of visual comfort through qualitative and quantitative analysis.

Table 3.6 introduces the set of inputs defined as the foundation of the algorithmic workflow developed in this study. Since the design and evaluation process is based on climate-responsive performance and user-centered daylight assessment, it was necessary to clearly identify all initial conditions before the optimization stage. These inputs include environmental and geometric factors, façade configuration, material properties, and pattern grammars, as well as the standards and tools adopted for

simulation and validation. By systematically outlining the rationale behind each choice, the table establishes a transparent basis for the subsequent parametric modelling, simulation, and optimization steps.

3.4. Definition of Performance Evaluation Criteria (Fitness Functions)

The fourth step in the development of the design approach is defining the performance evaluation criteria. Within the framework of the genetic algorithm's "fitness" evaluation, three fundamental performance criteria that define visual comfort in the indoor environment were identified. These criteria cover both insufficient daylighting and the negative effects of excessive sunlight. The criteria were set to daylight autonomy, glare, and direct sunlight exposure **Figure 3.12**. In the optimization process, success scores were set to 1 and 0 **Figure 3.13**.

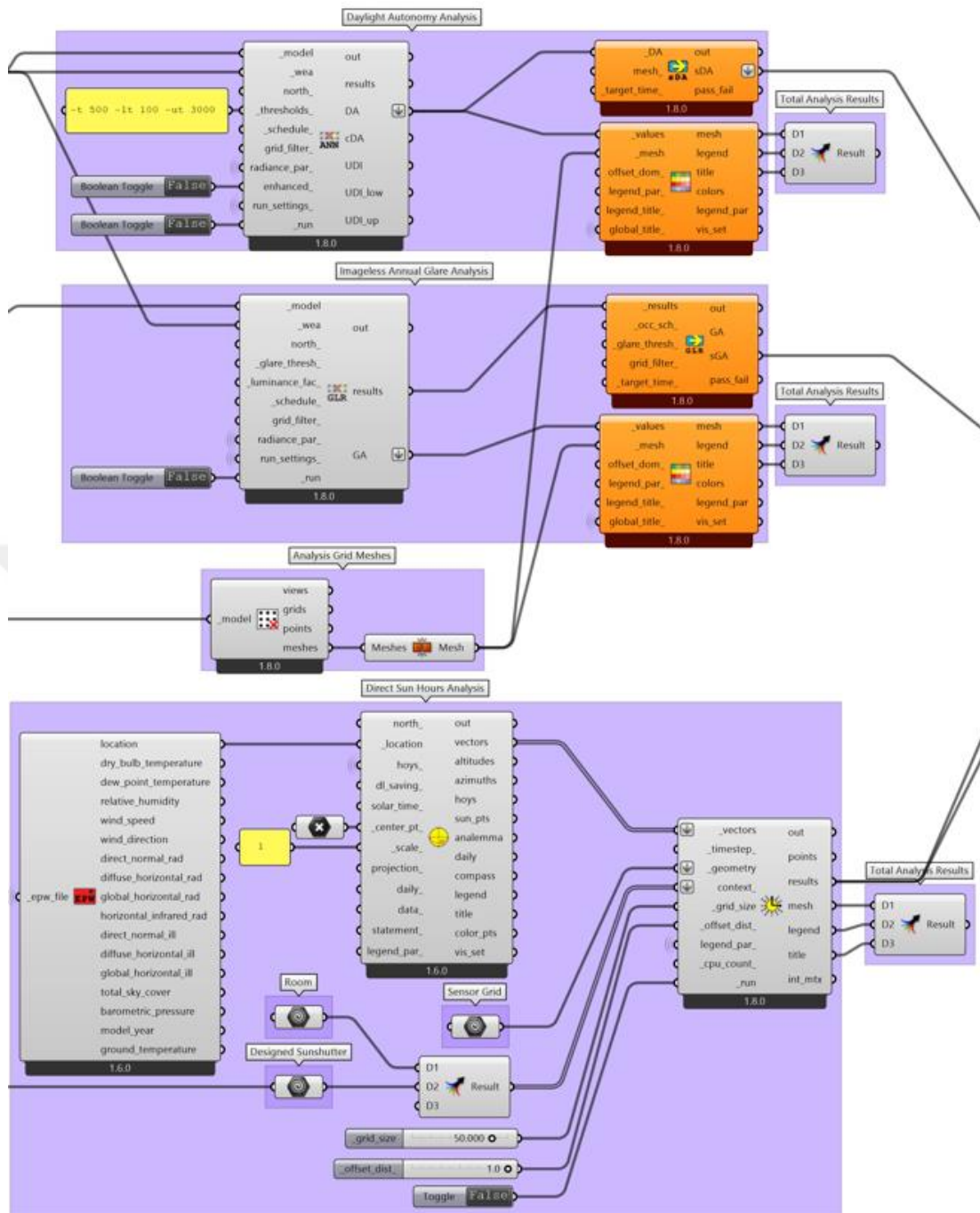


Figure 3.12: Performance analyzing criteria.

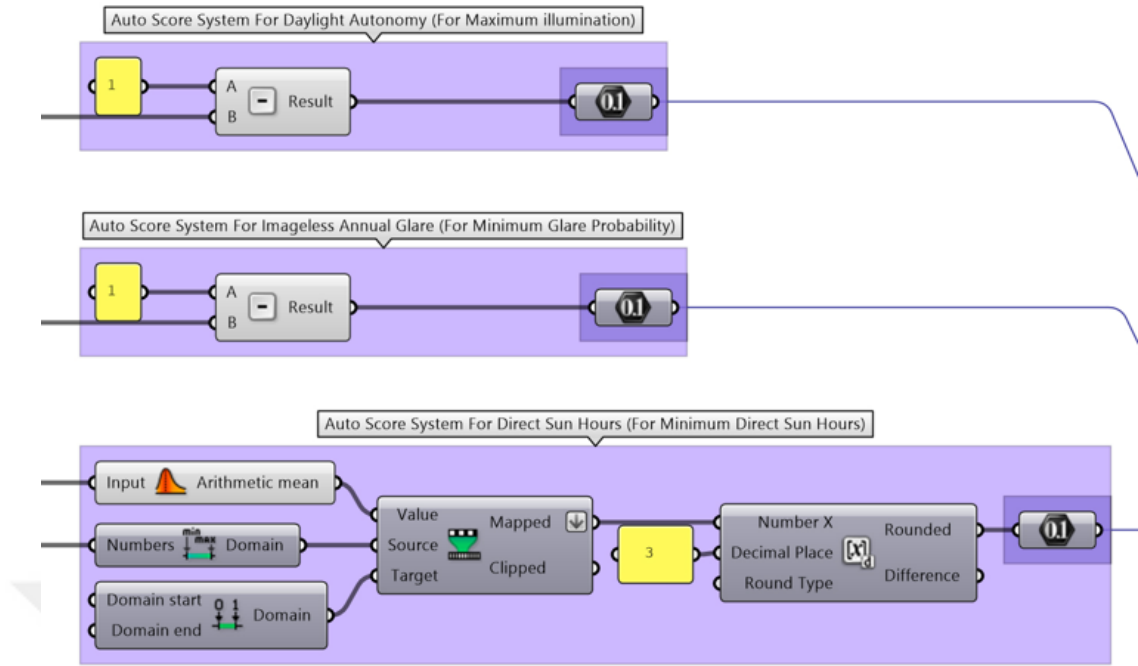


Figure 3.13: Success scores in the model.

3.4.1. Spatial Daylight Autonomy

A metric that expresses as a percentage of how long the sensor points in space reach a specified illuminance level target (e.g., 500 lux) with daylight alone. In this study, the goal is to achieve the "Medium" performance level of 500 lux illuminance on desk height, recommended for offices by the TS-EN 12464-1 standard for more than %55 of the space during working hours [Turkish Standards Institution, 2021]. This metric is expressed as a percentage. For example, if $sDa(500/55\%)=75\%$, then the corresponding fitness value would be 0,75, 1 counting as success.

3.4.2. Direct Sunlight Hours

Especially in task-oriented spaces like offices, direct sunlight impairs visual comfort by creating excessive contrast and thermal discomfort. The TS-EN:17037+A1 [Turkish Standards Institution, 2022] recommends that workspaces not be exposed to direct sunlight for more than a certain period. In this study, the optimization objective is to ensure that no point on the work plane is exposed to direct sunlight for more than 25 hours per year and to minimize this duration.

3.4.3. Daylight Glare Probability

Glare is the discomfort or reduction in the ability to see caused by excessive brightness in the field of view. DGP is a scientifically validated metric developed to predict daylight-induced glare [Wienold & Christoffersen, 2006]. According to the study, DGP values were classified as follows:

- $DGP \leq 0.35$: Imperceptible Glare (Desired)
- $0.35 < DGP \leq 0.40$: Perceptible Glare
- $0.40 < DGP \leq 0.45$: Disturbing Glare
- $DGP > 0.45$: Intolerable Glare

The optimization objective is to minimize disturbing glare by ensuring that the DGP value remains below 0.40 for 95% of the working hours, which is set to 08.00-17.00 every day for a year. Yet only for December 21st, 16.00 was analyzed due to the earlier sunset.

3.4.4. Normalization

To be able to compare sDA, DGP, and DSH, it was necessary to normalize them into a similar type of value. It is set to 0 for success and 1 for failure. sDA and DGP were the opposite. 1 was success and 0 was failure, so subtracting the values from 1 was enough for normalizing.

DSH required a different calculation. It is calculated with an arithmetic ratio. For example:

- $DSH_{max} = 100$
- $DSH_{min} = 20$

For a DSH value of 50, the fitness value would be calculated as:

$(20+100)/2=60$ (mid value) if DSH 60 refers to 0,5 fitness value, then what is 50's fitness value?

Fitness value = $(50 \times 0,5) / 60 = 0,41$ (fitness value of 50)

3.5. Optimization with Genetic Algorithm

The fifth step involves optimization with GA in Grasshopper. The design alternatives were subjected to an evolutionary process using the NSGA-II algorithm with the Wallacei plugin **Figure 3.14**.

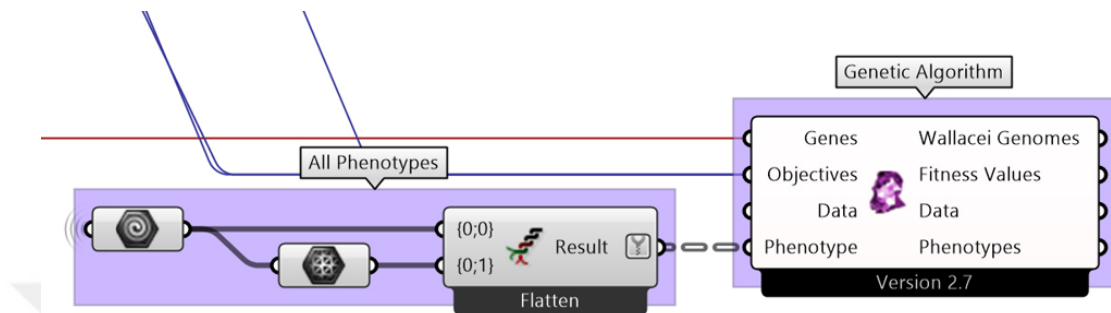


Figure 3.14: Wallacei, Genetic Algorithm modelling.

The performance of the optimization depends on basic parameters such as population size and the number of generations. In selecting these values, a balance was sought between sufficiently exploring the solution space and maintaining a reasonable computation time. A review of similar building performance optimization studies in the literature shows that populations of 20-100 individuals and 50-200 generations generally yield effective results [Duan et al., 2024; Sorooshnia et al., 2023].

Accordingly, the following parameters were set for this study:

- Generation size: 20. In each generation, 20 different design alternatives (individuals) will be generated and evaluated.
- Number of generations: 35. The evolutionary process will continue for a total of 35 generations. This means a total of $20 \times 35 = 750$ unique design alternatives will be simulated.
- Selection: The "tournament selection" and "non-dominated sorting" mechanisms, which form the basis of NSGA-II, were used.
- Crossover and Mutation Rates: Wallacei's default settings (90% and 10%, respectively) were used [Duan et al., 2024; Sorooshnia et al., 2023].

3.6. Quantitative and Qualitative Analysis

The last step of the development of the approach involves the analysis of the findings and the discussion of the outcomes. Upon completion of the optimization process, a Pareto Front, which contains a set of optimal solutions rather than a single "best" solution, was obtained. Each solution on the Pareto front represents a "non-dominated" alternative that is better than the others in at least one objective and not entirely worse in any objective.

This final solution set was visualized and analyzed on a parallel coordinate plot with axes for the three performance criteria (DA, Direct Sunlight Exposure, DGP). As a result of this analysis, representative design alternatives with different priorities (e.g., maximum illumination, minimum glare, or balanced performance) were selected.

The quantitative data of DA, Direct Sunlight Exposure, and DGP were gathered from the model, and the performance was discussed as the genetic algorithm does not always provide perfect results, but a variety in design.

Later, for the quantitative and qualitative analysis of the results, render and glare maps **Figure 3.15** of the working space of 3 pattern grammars in 3 different hours involving sunrise, midday, and sunset on equinox dates will be produced.

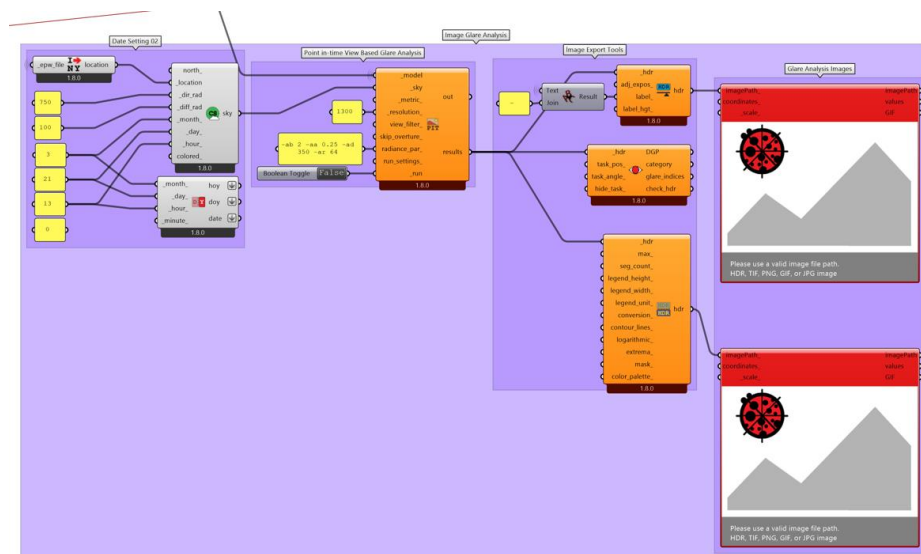


Figure 3.15: Simulation render and glare map of the outcomes.

3.6.1. Determining the Sun Path and Time Intervals

Using the latitude and longitude information of Istanbul Atatürk Airport (EWP), an annual sun path diagram is generated via Ladybug's Sunpath component.

Critical date ranges are selected from the working hours (08:00–17:00), namely: winter solstice (December 21), spring equinox (March 21), summer solstice (June 21), and autumn equinox (September 23). These dates are representative due to their significant variation in shadow length and direction (IES LM-83-12).

3.6.2. Selection for Simulation

In order to evaluate and select shading patterns based on their contribution to indoor visual comfort, a weighted scoring model was developed. Among the three daylight-related performance metrics—Annual Daylight Autonomy (sDA), Daylight Glare Probability (DGP), and Direct Sunlight Exposure (DS)—only the first two were prioritized due to their direct impact on visual perception and occupant well-being. The European standard EN 17037 [European Committee for Standardization, 2018] and similarly the Turkish standard TS EN 17037 [Turkish Standards Institution, 2022] further prioritise balancing sufficient daylight with glare control to ensure occupant comfort. While DS is useful for assessing thermal comfort, it was considered less relevant for the scope of this study, which focuses specifically on visual performance in office spaces. It is taken into consideration when DA and DGP performances are equal.

The evaluation and selection of facade shading patterns were conducted using a rule-based multi-criteria decision-making process prioritizing visual comfort. The assessment relied on three key daylight performance metrics:

- Annual Daylight Autonomy (DA): indicating daylight sufficiency
- Daylight Glare Probability (DGP): indicating the risk of visual discomfort
- Direct Sunlight Exposure (DS): associated primarily with thermal performance

Given the focus on visual comfort, DA and DGP were assigned equal importance, while DS was used only as a secondary tiebreaker.

Let:

- DA_i : normalized daylight autonomy score for pattern i
- DGP_i : normalized glare probability score for pattern i
- DS_i : normalized direct sunlight exposure score for pattern i
- VCS_i : visual comfort score for pattern i

Step-by-step selection process:

Assign weights (3.1):

$$w_1 = 0.5 \text{ (for DA)}, w_2 = 0.5 \text{ (for DGP)}, w_3 = 0 \text{ (for DS)} \quad (3.1)$$

Compute the Visual Comfort Score (VCS) for each pattern (3.2):

$$\begin{aligned} VCS_i &= w_1 \cdot DA_i + w_2 \cdot DGP_i + w_3 \cdot DS_i \\ &\rightarrow VCS_i = 0.5 \cdot DA_i + 0.5 \cdot DGP_i \end{aligned} \quad (3.2)$$

Sort patterns in ascending order of VCS_i . A lower score indicates better performance in visual comfort (higher daylight availability with lower glare).

Tiebreaker rule: If multiple patterns have the same VCS_i , compare their DS_i values; the pattern with the lower DS_i (less direct sunlight) is preferred, indicating more effective shading and potentially enhanced thermal comfort.

This rule-based algorithm ensured a consistent and transparent selection of shading patterns based on their quantitative daylight performance, while maintaining alignment with the study's core goal: the maximization of indoor visual comfort in office spaces.

3.6.3. Generation of Renders and False Colors

Ladybug's Glare Analysis components are used to produce hourly false color visuals for each selected date.

Shadow distribution on the working plane of the model (at 0.85 m height) is visualized separately for each time interval and exported in graphic format [Roudsari & Mackey, 2013].

3.6.4. Potential Perceptual Effect Evaluation

The qualitative analyses in this study are informed by the research conducted by Chamilothoni [2019] in Switzerland and Greece, where VR simulations were used to allow users to understand the perceptual effects of facade patterns on users. Based on this framework, genetic algorithm results will be classified according to their possible perceptual effects, and it will be discussed whether future works can involve perceptual effects in the algorithm, maybe with an AI integration.

After an analytical review of Chamilothoni's thesis [2019], it is understood that she provided a comprehensive framework for analyzing the perceptual effects of daylight in architectural spaces by identifying and operationalizing a set of five key perceptual attributes: Light Distribution & Brightness, Temporal Dynamics, Glare Perception & Attentional Load, Spatial Legibility, and Phenomenological Light Quality **Figure 3.16**. These attributes served as evaluative dimensions for understanding how façade geometry and daylight patterns influence users' spatial experience. Adopting a similar analytical structure in the current research is methodologically and conceptually significant, particularly due to the shared focus on human-centered daylight performance in office environments with algorithmically generated sun-shading systems.

Light Distribution & Brightness was assessed by examining the spatial gradient and balance of light as it appears in false color images and renderings. Following Chamilothoni's [2019] emphasis on luminance variability and spatial contrast (mSC), the analysis focused on detecting areas of overexposure (e.g., >2000 lux), abrupt transitions between lit and shaded zones, and imbalances in the illumination of key functional surfaces such as desks, walls, and floors. Uniformity and continuity of brightness were interpreted as enhancing perceived comfort and spatial openness.

Temporal Dynamics were evaluated by comparing daylight patterns across different times of day and seasonal contexts. In line with Chamilothoni's [2019] observations, attention was given to how the shifting position and intensity of sunlight affected perceptual stability. For each pattern, the images at 08:00, 13:00, and 17:00 were compared to determine whether the pattern allowed for a consistent and adaptive daylight atmosphere throughout office hours. Changes in the location and shape of

sunlight patches on interior surfaces served as visual indicators of temporal adaptability.

Glare Perception & Attentional Load was examined by correlating DGP simulation outputs with visual cues from the images, particularly in relation to user view direction. As highlighted by Chamilothoni, glare perception is not only about intensity but also about aesthetic context and attention. Therefore, this study analyzed whether high-intensity zones were located within the user's primary visual field, especially near eye level, and whether such zones were potentially disruptive or engaging. Bright vertical surfaces, reflections, or sunlight entering the eye zone were interpreted as contributing to visual distraction and discomfort.

Spatial Legibility was interpreted through render images that illustrated the interplay between light, shadow, and space. Drawing on Chamilothoni's discussion of spatial coherence and Lynch's notion of environmental legibility, this dimension focused on whether the lighting scheme helped users intuitively understand the layout, depth, and orientation of the space. Visual order, perceptual zoning, and clarity of spatial boundaries were considered signs of strong legibility, while fragmented lighting and inconsistent articulation of edges were viewed as disruptive.

Phenomenological Light Quality was assessed through the atmospheric and emotional tone conveyed by the renderings. Inspired by Chamilothoni's [2019] references to subjective well-being and emotional affect—as well as theoretical contributions by Pallasmaa and Salingaros—this evaluation focused on whether the light evoked calmness, stimulation, warmth, or tension. The softness of shadows, richness of light texture, and overall spatial mood were interpreted as expressions of the affective and embodied experience of daylight. Patterns that generated serene or inspiring atmospheres were seen as enhancing the phenomenological dimension of indoor space.

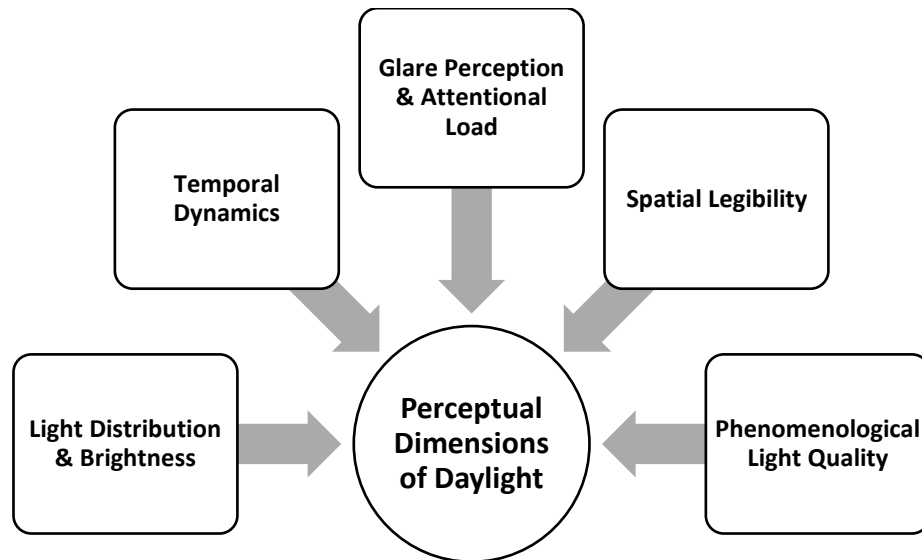


Figure 3.16: Perceptual dimensions of daylight identified by [Chamilothori, 2019].

By translating these conceptual themes into a structured set of perceptual categories, this study creates a bridge between subjective visual experience and objective performance metrics. Each dimension provides a specific lens to assess the spatial impact of geometrically varied shading devices, extending beyond functional daylight parameters toward a more holistic architectural evaluation. Yet it should be noted that qualitative analysis was conducted using gathered data and literature; user feedback was not included in this study.

This conceptual framework goes beyond the traditional boundaries of visual comfort by aiming to identify and classify the sensory and cognitive factors that shape spatial experience. Rather than evaluating daylight solely through quantitative metrics, the research adopts perceptual dimensions that reflect how light influences users' emotional responses, spatial understanding, and overall sense of atmosphere. In this context, the integration of qualitative categories such as brightness perception, temporal variation, and phenomenological quality enables a more holistic architectural assessment of daylight-responsive façade systems.

3.6.5. Shadow Behaviour Analysis

In this study, shadow behaviour was assessed through qualitative visual interpretation of rendered simulation images produced at three key times of day (08:00, 13:00, and 17:00) across four seasonal dates. The evaluation did not rely on quantitative

photometric data or geometric shadow tracing, but instead adopted a perceptually oriented framework aimed at understanding the experiential and spatial effects of shadows generated by different shading grammars.

For each pattern, renderings were reviewed from two predefined user perspectives (standing and seated). Within each image, shadows cast by the external shading system onto interior surfaces—such as the floor, work desk, back wall, and side surfaces—were visually analyzed according to four general criteria:

- The extent and location of shaded areas (coverage),
- The visual quality of shadow transitions (sharpness or softness),
- The direction and order of shadow projections relative to user orientation, and
- The variation in shadow patterns across different hours of the day (temporal change).

Although the specific classification of shadow performance into the four criteria, Coverage and Depth, Sharpness and Softness, Directionality and Orientation, and Temporal Adaptability, does not originate from a single source, this framework is developed by synthesizing concepts from daylighting theory, visual comfort studies, and architectural perception literature [**Tregenza & Wilson, 2011; Reinhart, 2004; Zumthor, 2006; Andersen, 2015**]. The classification is adapted to serve the methodological needs of the current research, offering a structured lens for analyzing shadow behaviour from a perceptual and spatial standpoint.

These criteria were not measured numerically, but served as consistent visual reference points to guide interpretation. Each set of images was compared within and across daily timeframes to observe how the geometry of the shading system influenced shadow presence, composition, and movement throughout the space. Patterns were evaluated based on how effectively they prevented direct sunlight in critical zones (such as the desk), how visually coherent or distracting the shadows appeared, and whether the shadows contributed to or disrupted spatial legibility and perceptual comfort. Rather than seeking precision or classification, this shadow analysis aimed to complement the daylight and glare simulations by offering a visual-perceptual reading of how each pattern shaped the interior atmosphere. The results were used to support broader interpretations in the perceptual evaluation of the shading grammars.

4. RESULTS AND DISCUSSION

4.1. The Data Gathered from the Genetic Algorithm Process

This section presents the outcomes of the genetic algorithm process, including the generated pattern variations, their performance metrics, and the selection criteria for simulation analysis.

4.1.1. Pattern Variations

A genetic algorithm was employed to optimize shading device geometries according to three performance-based criteria: sDA, DGP, DSH. The Pareto Front, a key outcome of multi-objective optimization, identifies non-dominated solutions, meaning no other solution in the population is better in all objectives simultaneously (Deb et al., 2002). Unlike traditional single-objective optimization, the Pareto Front does not produce a single “best” solution, but rather a spectrum of equally valid trade-off options across objectives.

In the resulting set of selected alternatives, a notable variation was observed in the distribution of grammar types: Striped and irregular patterns were more frequently represented than regular patterns. This outcome is consistent with the inherent nature of Pareto-based evolutionary algorithms, which tend to retain solutions that exhibit higher diversity, adaptability, and geometric flexibility [Zitzler et al., 2000]. Regular patterns, due to their formal symmetry and lower parametric complexity, often present limited responsiveness to conflicting objective criteria, reducing their likelihood of survival across generations. By contrast, striped and irregular grammars offer a richer solution space with greater phenotypic variation, allowing more effective negotiation of trade-offs between daylight availability and glare control. Therefore, the unequal distribution of selected patterns across grammatical categories is not only expected but also reinforces the validity of the evolutionary selection process. As highlighted by Coello Coello et al. [2007], variation in typological frequency within Pareto-optimal sets is a natural consequence of the convergence-diversity balance that governs multi-objective evolutionary search strategies.

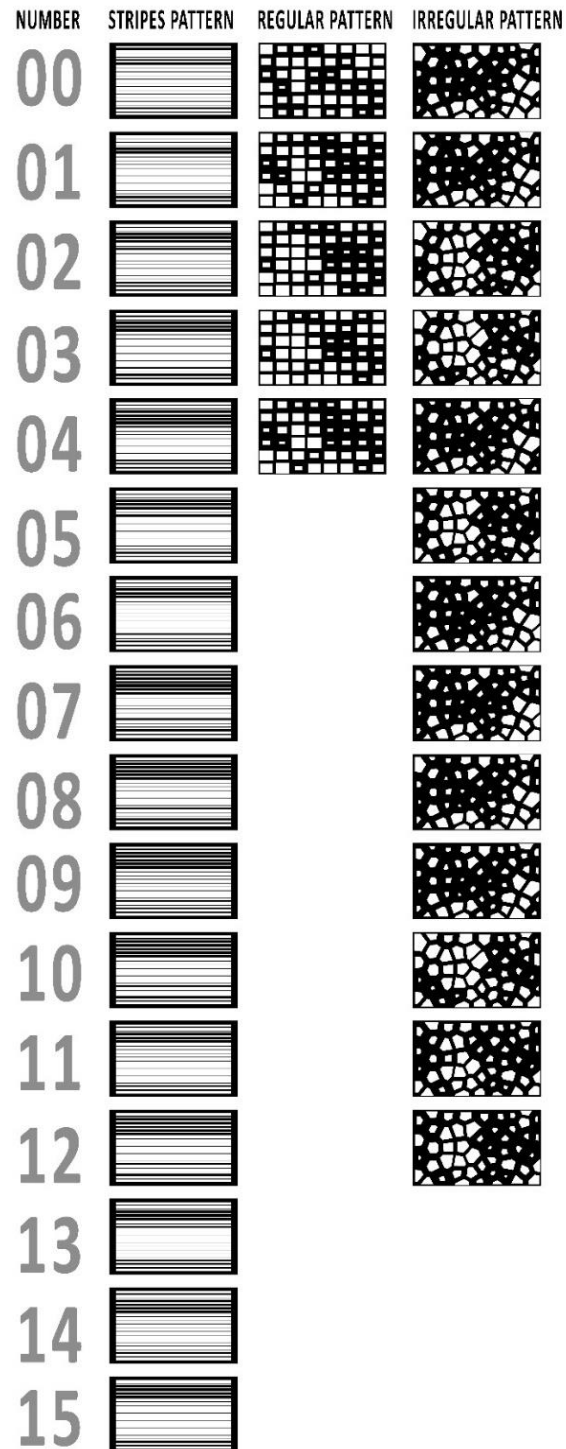


Figure 4.1: Wallacei output, design alternatives chosen by the Pareto front.

4.1.2. Performance Values and Ranks

The performance values in Wallacei for each criterion were normalized between 0 (most favorable) and 1 (least favorable), and corresponding ranks were assigned from

0 (best) to 749 (worst). This ranking system enabled a comprehensive evaluation of how each pattern balances daylight availability, glare risk, and solar control.

To ensure comparability and uniform directionality of all performance metrics used in the optimization process - namely, sDA, DGP, DSH - each variable was normalized between 0 and 1 **Table 4.1**. Given that lower values were defined as preferable across all criteria, an inverted min-max normalization was applied. This ensured that a value of 0 represented the best performance, while 1 indicated the worst.

Daylight Autonomy measures the percentage of the occupied area on desk height receiving at least 500 lux of daylight for at least 50% of the occupied hours. The analysis revealed that some patterns achieved significantly better performance across all criteria, particularly those with lower average scores and rankings.

From the parameterised dataset, Regular Pattern 01, Irregular Pattern 10, and Stripe Pattern 01 emerged as strong candidates for further analysis **Figure 4.2**. Each exhibited high DA levels while maintaining low DGP values, indicating effective daylight utilisation without excessive glare. Specifically, Regular Pattern 1 provided spatial uniformity and visual stability; Irregular Pattern 10 showcased the capacity of complex, non-repeat forms to perform competitively; and Stripe Pattern 1 delivered directional shading that mitigated glare while preserving daylight quality. By selecting these three diverse grammar-based patterns, the study enables a systematic comparison of how geometric form influences visual comfort under varying daylight conditions.

Table 4.1: Performance values and ranks of the design alternatives.

Grammar	Pattern Number	Annual Daylight Autonomy Score		Daylight Glare Probability Score		Direct Sunlight Score	
		value	rank	value	rank	value	rank
STRIPE PATTERN	00	0.036	26	0.196	442	0.429	0
	01	0	0	0.2	524	0.429	0
	02	0.071	102	0.187	180	0.5	268
	03	0.107	223	0.19	291	0.429	0
	04	0.143	328	0.182	55	0.536	486
	05	0.071	102	0.187	180	0.5	268
	06	0.036	26	0.19	291	0.464	113
	07	0.179	469	0.177	0	0.571	611
	08	0.179	469	0.181	33	0.5	268
	09	0.179	469	0.18	25	0.536	486
	10	0.179	469	0.181	33	0.5	268
	11	0.071	102	0.189	245	0.464	113
	12	0.143	328	0.181	33	0.571	611
	13	0.143	328	0.187	180	0.464	113
	14	0.107	223	0.184	104	0.5	268
	15	0.071	102	0.187	180	0.5	268
REGULAR PATTERN	00	0.321	113	0.217	719	0.536	0
	01	0.357	269	0.145	41	0.571	27
	02	0.321	113	0.149	205	0.571	27
	03	0.286	0	0.158	367	0.571	27
	04	0.393	432	0.142	0	0.571	27
IRREGULAR PATTERN	00	0.464	458	0.127	72	0.607	381
	01	0.464	458	0.127	72	0.607	381
	02	0.393	167	0.14	315	0.571	0
	03	0.357	86	0.147	382	0.571	0
	04	0.5	590	0.121	7	0.643	551
	05	0.429	227	0.133	180	0.571	0
	06	0.536	693	0.116	0	0.679	723
	07	0.536	693	0.117	3	0.643	551
	08	0.536	693	0.125	67	0.607	381
	09	0.571	735	0.121	7	0.607	381
	10	0.321	0	0.151	486	0.671	0
	11	0.429	227	0.129	121	0.607	381
	12	0.429	227	0.133	180	0.571	0

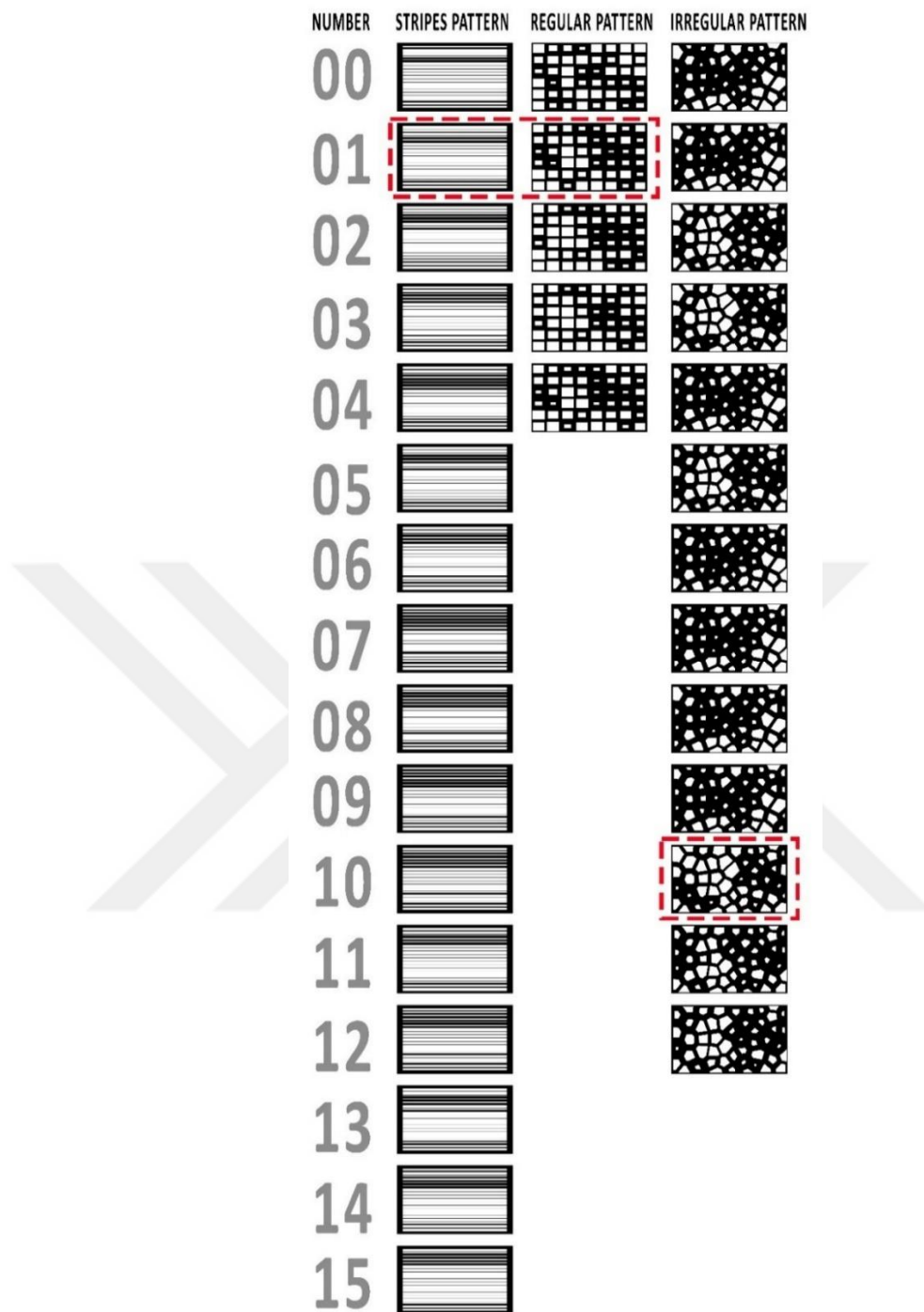


Figure 4.2: Manually chosen alternatives considering their performance values.

4.2. Performance Analysis of Regular Pattern 01

In this section, a detailed evaluation of daylight performance for Regular Pattern 01 focuses on its effectiveness in providing visual comfort across different user viewpoints within the office space.

4.2.1. Annual Spatial Metric Analysis for Regular Pattern 01

To further evaluate the daylighting performance of Regular Pattern 01, spatially mapped visual comfort indicators were analyzed using three key simulation outputs: Daylight Autonomy (DA), Imageless Annual Glare, and Direct Sun Hours (DSH). These metrics provide a comprehensive understanding of how effectively the shading system balances daylight access, mitigates glare, and controls solar exposure across the occupied space.

Table 4.2 summarizes the annual spatial metrics for Regular Pattern 01, illustrating its effectiveness in providing balanced daylight performance. High daylight autonomy near the façade, along with acceptable values in deeper zones, confirms sufficient daylight availability. The system ensures over 90% glare-free conditions annually, particularly excelling in the rear zones, which reinforces its capability to maintain visual comfort. Additionally, the controlled range of direct sun hours—limited to façade-adjacent areas—demonstrates effective mitigation of harsh solar exposure, contributing to a visually stable and comfortable indoor environment throughout the year.

Table 4.2: Annual analysis of Regular Pattern 01.

Metric	Observation	Implications for Visual Comfort
Daylight Autonomy (sDA)	sDA exceeds 75% near the facade; central zones maintain >30%	Ensures adequate daylight levels for most work areas; supports energy savings and visual comfort.
Annual Glare Control	Glare-free conditions >90% of the year; >95% in rear zones	Minimizes discomfort glare; supports consistent visual performance across space.
Direct Sun Hours (DSH)	DSH remains <700–900 hours/year in most areas; facade-adjacent zone up to ~1500 hours/year	Controls excessive solar penetration; prevents overheating and harsh contrast on work surfaces.

Daylight Autonomy: **Figure 4.3** demonstrates a high percentage of time during which the illuminance levels exceed the predefined task threshold (commonly 300 lux). Most of the floor area maintains DA values exceeding 75%, especially in zones closer to the façade. This indicates that the system provides ample daylight throughout the year, reducing the reliance on artificial lighting and contributing to both energy efficiency and visual comfort.

The gradient observed in the diagram, from high DA near the perimeter to lower values deeper in the room, is expected in single-sided daylighting strategies. Nonetheless, even the areas furthest from the glazing show acceptable daylight availability (typically >30%), supporting adequate visual performance under normal working conditions.

Imageless Annual Glare (Glare Control Rate): The glare performance of the system is illustrated through the percentage of time discomfort glare is not perceived (i.e., the DGP remains below threshold values). The diagram reveals a strong glare control performance, with most of the space achieving values above 90%, and large zones exceeding 95–100%, particularly in the rear parts of the room. This confirms that the perforated shading geometry is successful in mitigating glare during most of the daylight hours throughout the year.

Combined with earlier point-in-time DGP evaluations, this metric supports the conclusion that Regular Pattern 01 consistently ensures user-centered visual comfort, particularly when task orientation and user positioning are considered.

Direct Sun Hours (DSH): The DSH diagram quantifies the annual number of hours during which direct sunlight reaches specific interior points. For optimal visual comfort, lower values are desirable, as they reduce the risk of both glare and thermal discomfort. The analysis shows that the majority of the space remains under 700–900 hours/year, with only the zone adjacent to the façade reaching higher exposure levels (~1200–1500 hours/year). This localized exposure is limited to the immediate perimeter and is effectively filtered by the shading pattern.

The significant reduction in direct solar penetration—especially in the rear and central zones of the room—indicates a well-controlled daylight environment that minimizes the likelihood of visual strain or overheating, while still maintaining dynamic daylight access.

The combined results of spatial metrics and point-in-time analyses affirm that Regular Pattern 01 performs well across all key visual comfort indicators. It successfully achieves high daylight autonomy, excellent annual glare control, and moderate control over direct sunlight exposure. This pattern is particularly effective in maintaining a comfortable and visually balanced interior environment, aligning with the performance expectations for south-facing office spaces in Istanbul's climate.

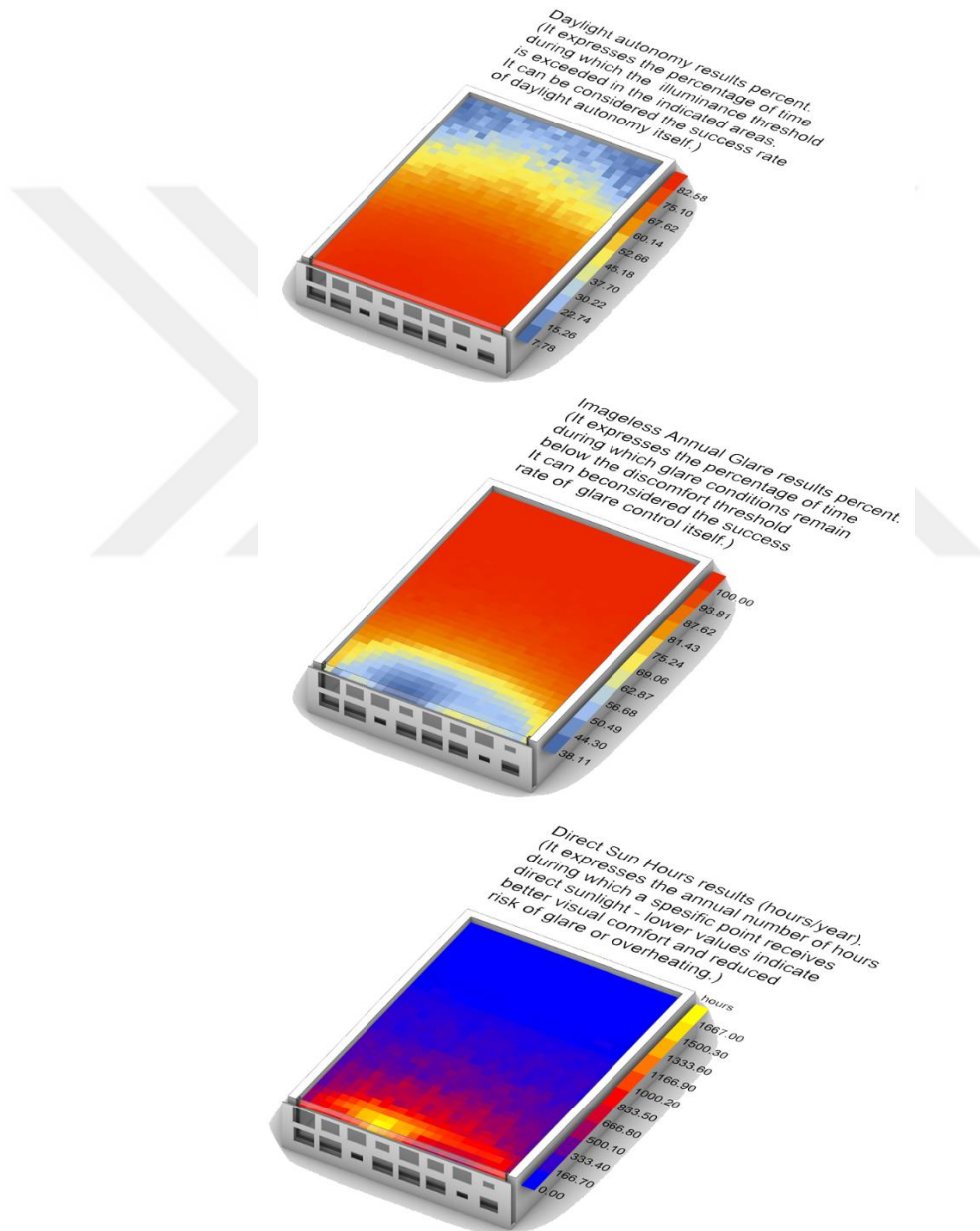


Figure 4.3: Annual analysis maps of Regular Pattern 01.

4.2.2. Visual Performance Assessment Based on User Position for Regular Pattern 01

Visual performance was measured with glare levels in the room from two viewpoints -seated and standing. Renders from morning (08.00), midday (13.00), and evening (17.00) from four different dates (equinox and solstice dates) were evaluated in **Figure 4.4**.

On March 21st, Regular Pattern 01 provided consistently imperceptible glare levels across all time intervals for standing users, with DGP values of 0.313 (08:00), 0.364 (13:00), and 0.275 (17:00). This suggests that the shading geometry successfully regulates luminance exposure throughout the equinox day. In the seated position, glare remained imperceptible at midday and evening. However, an intolerable glare level ($DGP = 1.00$) was recorded at 08:00, likely due to low-angle sunlight directly entering through lower apertures aligned with the user's line of sight. This condition represents an extreme case, possibly amplified by modeling constraints such as the absence of interior elements or reflectance-moderating furnishings. Overall, the system achieved high glare protection, with one early morning exception for the seated user.

On June 21st, Regular Pattern 01 demonstrated outstanding performance under high solar altitude conditions. All simulations for both standing and seated users yielded imperceptible glare values ($DGP < 0.35$) across 08:00, 13:00, and 17:00. The regular, grid-like aperture geometry successfully prevented direct sunlight from reaching sensitive viewing angles. Despite localized high luminance levels on the shading surface (above 5000 cd/m^2), glare discomfort was effectively avoided due to the even spatial distribution of light. This performance underscores the robustness of the pattern as a passive shading solution for summer conditions in fully glazed, south-facing offices.

On September 23rd, glare remained imperceptible in all time intervals for standing users. However, at 13:00, the seated view recorded an intolerable glare level ($DGP = 0.458$), while morning and evening conditions remained comfortable. The midday discomfort for seated users is likely due to a combination of low eye level intersecting with sun patches penetrating the lower façade openings and reflected luminance from the desk surface. This highlights the importance of evaluating shading performance from multiple user perspectives and suggests the need for further optimization in seated zones, particularly around midday during equinox periods.

On December 21st, Regular Pattern 01 effectively mitigated glare in the morning (08:00) and late afternoon (16:00 due to earlier sunset) hours, with DGP values in the imperceptible range for both user positions. However, midday (13:00) simulations for both standing and seated views showed disturbing glare levels ($DGP \approx 0.40\text{--}0.43$). This was attributed to the winter sun's higher midday altitude, allowing concentrated direct sunlight through the upper openings, increasing luminance on eye-level surfaces. Particularly for seated users, the glare was more intense due to direct exposure to bright patches on the workplane.

Regular Pattern 01 demonstrates overall strong performance in glare mitigation throughout the year, maintaining visual comfort in most cases. Seasonal and positional variations—especially around midday for seated users—indicate that while the pattern is highly effective as a passive shading strategy, further refinements in aperture placement or size may be required to optimize comfort under specific user conditions and solar positions.

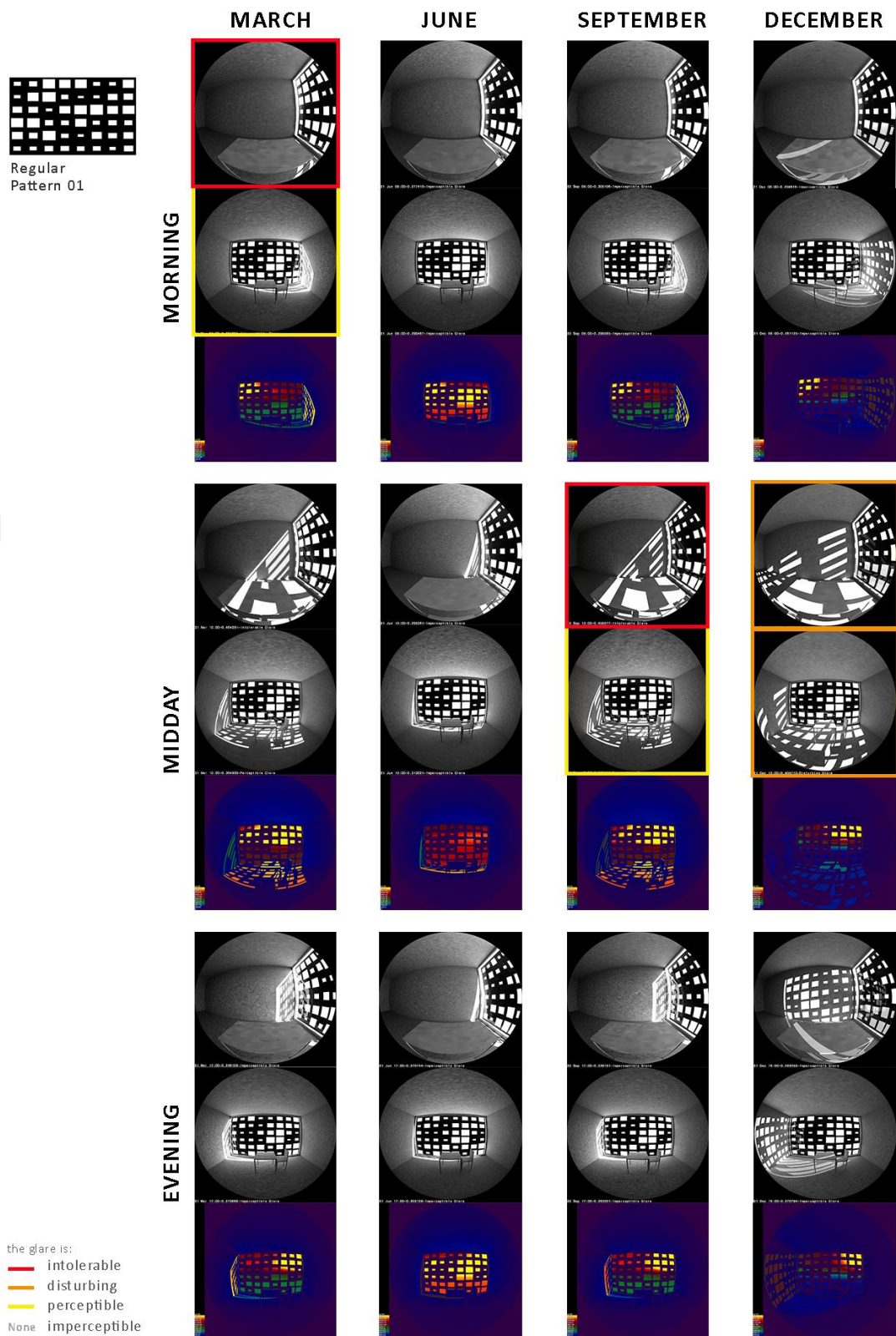


Figure 4.4: Annual analysis maps of Regular Pattern 01.

4.3. Shadow Behaviour of the Regular Pattern 01

This analysis provides a detailed discussion of the specific characteristics of shadows generated by the Regular Pattern 01. It focuses on shadow lengths and directions, the geometric impact of the shading surfaces, and the resulting spatial and temporal distribution of shaded areas within the interior.

The fundamental principle governing shadow behavior is that shadow length is inversely proportional to the sun's altitude, while shadow direction is opposite to the sun's azimuth. The shadows produced within the interior by the Regular Pattern 01 exhibit distinct seasonal variations based on this principle.

Summer Solstice (June 21): During this period of highest solar altitude, shadows are short and well-defined. At midday (13:00), shadows cast by interior objects like the table and chair are at their minimum length, falling almost directly beneath the objects. The shadows cast by the facade grid itself are similarly short, falling either on the lower portions of the facade or on a narrow strip of floor just inside the aperture. Shadow directions follow the sun's wide azimuthal path, pointing southwest in the morning and southeast in the afternoon.

Winter Solstice (December 21): The sun's very low trajectory on this day results in extremely long shadows. The shadows come to define the character of the space. The shadow of the facade grid is projected deep into the room as a distinct pattern. The shadows of interior objects become elongated and distorted, losing their distinct form and stretching far across the floor. The low solar altitude means even the smallest obstructions cast long shadows. Shadow directions reflect the sun's narrower azimuthal range, pointing northwest in the morning and northeast in the afternoon.

Equinoxes (March 21 / September 23): During these transitional periods, shadow lengths exhibit an intermediate character, falling between the summer and winter extremes. The shadows are neither as short and contained as in summer, nor as long and dominant as in winter. This balanced state creates a more dynamic yet manageable play of shadows within the space.

The effectiveness of the 'Regular Pattern 01' facade is determined by the geometry of its horizontal and vertical shading elements and their relationship to the incident angle of the sun.

Effect of Horizontal Elements: The facade's shading performance is primarily reliant on its horizontal elements. These elements function as a series of fixed overhangs, and their effectiveness is directly tied to the sun's vertical altitude. In summer, the high-angle solar rays are effectively intercepted by these horizontal surfaces, minimizing the entry of direct radiation. However, as the sun's altitude decreases (during the equinoxes and winter), solar rays begin to pass underneath these horizontal barriers. At the lowest solar altitude in winter, the shading effect of the horizontal elements is almost entirely negated, which constitutes the primary performance failure of the system.

Effect of Vertical Elements: The vertical elements, or fins, provide some protection against low-angle sun coming from the sides (east or west), particularly in the early morning and late afternoon. The simulation images show that light patterns on the side walls are broken up by these vertical members. However, their effect against a low-angle sun arriving frontally at midday in winter is marginal. Therefore, the facade's design relies heavily on the performance of its horizontal elements.

The factors discussed below determine which interior areas are shaded at specific times and seasons.

- **Shaded Areas in Summer:** The majority of the space remains continuously shaded throughout the day. At midday (13:00), except for a narrow strip of floor just inside the window, the entire room—including all walls and the interior core—is under deep shade. This creates a cool and visually comfortable refuge. In the morning and evening, the side of the room opposite the sun (the west wall in the morning, the east wall in the evening) and the central core remain shaded.
- **Shaded Areas in Winter:** Shaded areas are minimized and highly fragmented. At midday (13:00), direct sunlight penetrates to the rear half of the room. The shaded zones in this scenario are ironically the areas closest to the window, which are shaded by the lower portion of the facade and the thin strips between the projected light patches. The center and rear of the space are fully sunlit. In the morning and evening, the side of the room where the sun is located remains almost entirely shaded, while the opposite side is fully illuminated.
- **Shaded Areas during the Equinoxes:** The distribution of shaded areas is dynamic. There are no large, static shaded zones as seen in summer. Instead, the shaded areas move across the space throughout the day. For example, while the eastern part of

the room is shaded in the morning, this shaded zone gradually shifts westward as the day progresses. This allows different parts of the space to experience periods of both shade and sun.

4.4. Perceptual Evaluation of Regular Pattern 01: Potential User Effects

The Regular Pattern 01 variant demonstrates a façade-integrated daylight modulation strategy based on regular perforation geometry. Beyond its quantitative daylighting performance, its spatial and perceptual implications play a key role in shaping occupant experience, particularly in work-oriented environments.

Table 4.3 summarizes the potential perceptual impacts of the Regular Pattern 01 shading configuration based on simulated performance and literature-supported perceptual criteria. The regularity of the perforation geometry contributes to a stable and legible daylight environment, reinforcing spatial orientation and reducing visual ambiguity. Uniform light distribution across the working plane supports sustained task performance and minimizes cognitive load. Although momentary glare is recorded at midday, the overall daylight modulation introduces mild temporal dynamics that foster visual interest without overstimulation. The filtered sunlight yields soft contrasts and nuanced shadow patterns, enhancing the spatial atmosphere and contributing positively to the user experience. These findings suggest that Regular Pattern 01 is not only technically effective but also perceptually attuned to human comfort in daylight-driven spaces.

Table 4.3: Perceptual Analysis of Regular Pattern 01.

Perceptual Dimension	Observation	Effect on User Experience
Light Distribution & Brightness	Homogeneous illumination in the morning and evening; balanced DA near the desk	Supports visual stability; reduces cognitive load and fatigue
Temporal Dynamics	Predictable but varying shadow rhythms; legible luminance gradients	Maintains visual interest without overstimulation
Glare Perception & Attentional Load	DGP 0.464 (seated) at 13:00; tolerable due to lunch hour context	Momentary discomfort, mitigated by timing and user activity patterns
Spatial Legibility	Regular geometry enhances the predictability of light behavior	Improves spatial orientation and visual control
Phenomenological Light Quality	Filtered sunlight creates soft contrast and surface gradients	Enhances atmosphere; contributes to a pleasant working ambiance

4.4.1. Perception of Light Distribution and Brightness

According to the findings in Chamilothoni's research [2019], uniformity of daylight distribution and avoidance of excessive contrast are critical for occupant satisfaction and task performance. In Regular Pattern 01, the consistent perforation rhythm generates homogeneous shadow casting during early morning and late afternoon hours, fostering a sense of visual stability across the space. The spatial distribution diagrams show balanced daylight autonomy (>75%) near the desk zone without hotspots, which enhances perceived lighting quality and reduces cognitive fatigue.

4.4.2. Temporal Dynamics and Visual Interest

The pattern's rhythmic structure creates visually dynamic yet predictable shadow patterns throughout the day. According to perceptual studies referenced in Chamilothoni's thesis [2019], occupants tend to appreciate lighting environments that exhibit temporal variation—as long as glare and overheating are controlled. Regular Pattern 01 achieves this by delivering changing yet legible luminance textures,

especially noticeable in the midday shadow renderings, thereby contributing to a mild stimulation effect without discomfort.

4.4.3. Glare Perception and Attentional Load

From a perceptual standpoint, glare is not merely a physical luminance threshold but also a psychological phenomenon linked to control and attention [Chamilothori, 2019]. At 13:00, seated users may experience discomfort due to intense contrast zones near the desk ($DGP = 0.464$). However, since this time aligns with lunch breaks or reduced task activity, the cognitive impact of glare is likely mitigated by contextual expectations. For the standing user, DGP remains within a perceptible but tolerable range (0.364), ensuring that task-related visual load is not overwhelmed by daylight intrusions.

4.4.4. Spatial Legibility and Visual Comfort

Regular geometries are generally associated with predictable light behavior, which improves spatial legibility and reduces visual ambiguity. Chamilothori's [2019] perceptual mapping studies suggest that such characteristics can enhance user orientation and well-being, particularly in open-plan offices. Regular Pattern 01 contributes positively to this through its orderly luminance modulation, allowing occupants to anticipate changes in brightness while maintaining task focus.

4.4.5. Phenomenological Quality of Light

Although primarily a technical solution, the pattern indirectly enhances the phenomenological quality of interior light. Morning and evening light filtered through the perforated layer creates gentle gradients on surfaces, particularly the desk and back wall, adding aesthetic softness and depth to the spatial experience. These effects align with human preference for non-uniform but coherent light fields, as discussed in the thesis.

To conclude, Regular Pattern 01 not only satisfies quantitative performance benchmarks in daylight autonomy and glare mitigation but also supports positive perceptual outcomes. Its regularity, filtered daylight behavior, and visual consistency contribute to an environment that is legible, comfortable, and cognitively manageable.

While midday glare poses a momentary challenge for seated users, this is contextually offset and does not undermine the system's broader experiential quality. Therefore, this pattern offers strong potential for human-centered daylighting design in office applications.

4.5. Performance Analysis of Irregular Pattern 10

4.5.1. Annual Spatial Metric Analysis for Irregular Pattern 10

To evaluate the daylighting efficiency of Irregular Pattern 10, three spatial performance metrics were analyzed: Daylight Autonomy (DA), Imageless Annual Glare, and Direct Sun Hours (DSH). These indicators provide a holistic view of the daylight access, glare mitigation, and direct sunlight control achieved by the façade system across the occupied space.

Table 4.4. summarizes the annual spatial metrics for Irregular Pattern 10. The daylight autonomy map **Figure 4.5** shows that this configuration maintains a high level of daylight penetration near the south-facing façade and ensures moderate daylight availability in the rear parts of the room. The imageless glare control performance is also relatively high, indicating that the irregular geometry is successful in reducing visual discomfort throughout the year. Additionally, the direct sun exposure is limited to the immediate façade-adjacent areas, suggesting a controlled distribution of sunlight without extensive overheating or harsh contrast.

Table 4.4: Annual analysis of Irregular Pattern 10.

Metric	Observation	Implications for Visual Comfort
Daylight Autonomy (DA)	DA >65% near the façade; rear zones remain >30%	Provides adequate daylight for most work areas; maintains ambient brightness across spatial depth.
Annual Glare Control	Glare-free conditions >83% annually; highest control near the back of the room	Indicates successful glare mitigation; supports visual comfort across task zones.
Direct Sun Hours (DSH)	DSH <600 h/year for most areas; ~1100–1300 h/year near the glazing	Restricts excessive solar ingress; improves comfort by avoiding overheating and strong reflections.

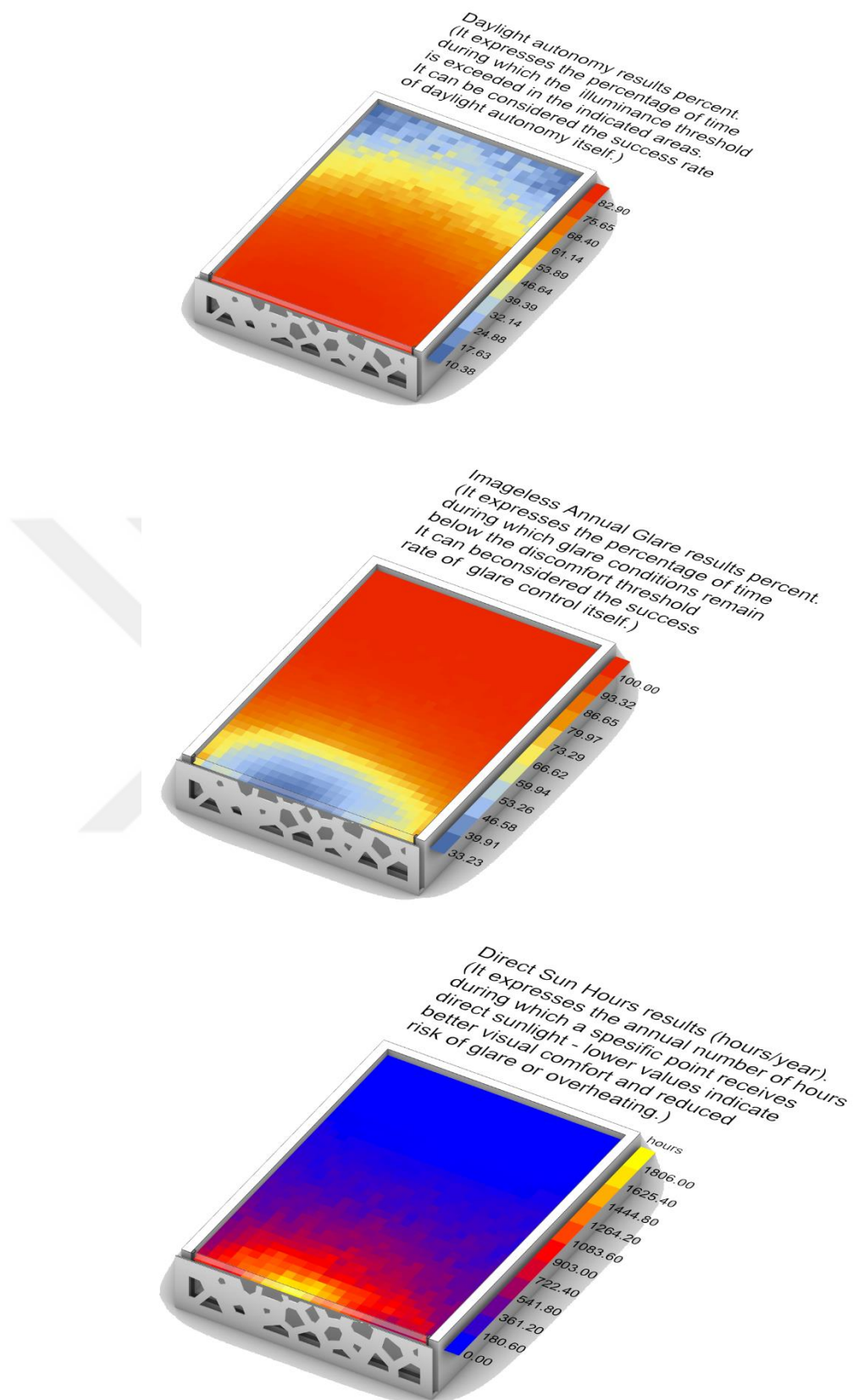


Figure 4.5: Annual analysis maps of Irregular Pattern 10.

The performance of Irregular Pattern 10 reveals a strong balance between daylight access and visual protection. While its daylight autonomy values are slightly lower than those of the Regular Pattern 01, it compensates with a softer distribution of direct sunlight and acceptable glare control in critical working areas. The irregular perforation geometry contributes to a dynamic but controlled lighting environment, making it well-suited for tasks requiring diffuse and stable illumination.

4.5.2. Visual Performance Based on User Position for Irregular Pattern 10

Visual performance was measured with glare levels in the room from two viewpoints -seated and standing. Renders from morning (08.00), midday (13.00), and evening (17.00) from four different dates (equinox and solstice dates) were evaluated **Figure 4.6.**

The glare performance assessment of the Irregular Pattern 10 configuration across four representative dates, March 21st, June 21st, September 23rd, and December 21st, demonstrates a generally successful outcome in terms of visual comfort, particularly from the standing user perspective. Throughout most time intervals, Daylight Glare Probability (DGP) values remained within imperceptible or perceptible ranges, indicating effective mitigation of direct solar glare. The performance is especially notable during the summer solstice (June 21st), when solar angles are highest and glare risks tend to peak; Irregular Pattern 10 maintained imperceptible glare levels for both standing and seated users during all hours, underscoring its suitability under high solar exposure conditions.

However, several limitations emerged when evaluating glare from the seated user position. On March 21st and December 21st, the midday condition exhibited intolerable glare for seated users, while the same time slots remained within acceptable ranges for standing users. Similarly, on September 23rd, seated users experienced intolerable glare in the early morning and midday hours, despite perceptible or imperceptible results from the standing perspective. These discrepancies highlight the sensitivity of glare perception to user height and viewing angle.

The seated glare issues are primarily attributed to lower eye-level alignment with incoming sunlight through the perforated shading geometry. As sunlight enters through lower apertures during early morning and midday hours, seated users are more

prone to direct glare exposure, particularly when horizontal surfaces such as desks reflect light into the visual field. Moreover, due to the simplified nature of the simulation model, which does not include internal furniture, ceiling baffles, or adjacent architectural elements, the reflected luminance distribution may be overrepresented in these cases.

Irregular Pattern 10 exhibits commendable performance, particularly in challenging daylight conditions commonly encountered during the summer months. While a few glare issues arise in the seated position during specific times of the year, these are addressable through targeted refinements and pose opportunities for further optimization in future iterations of the façade design.



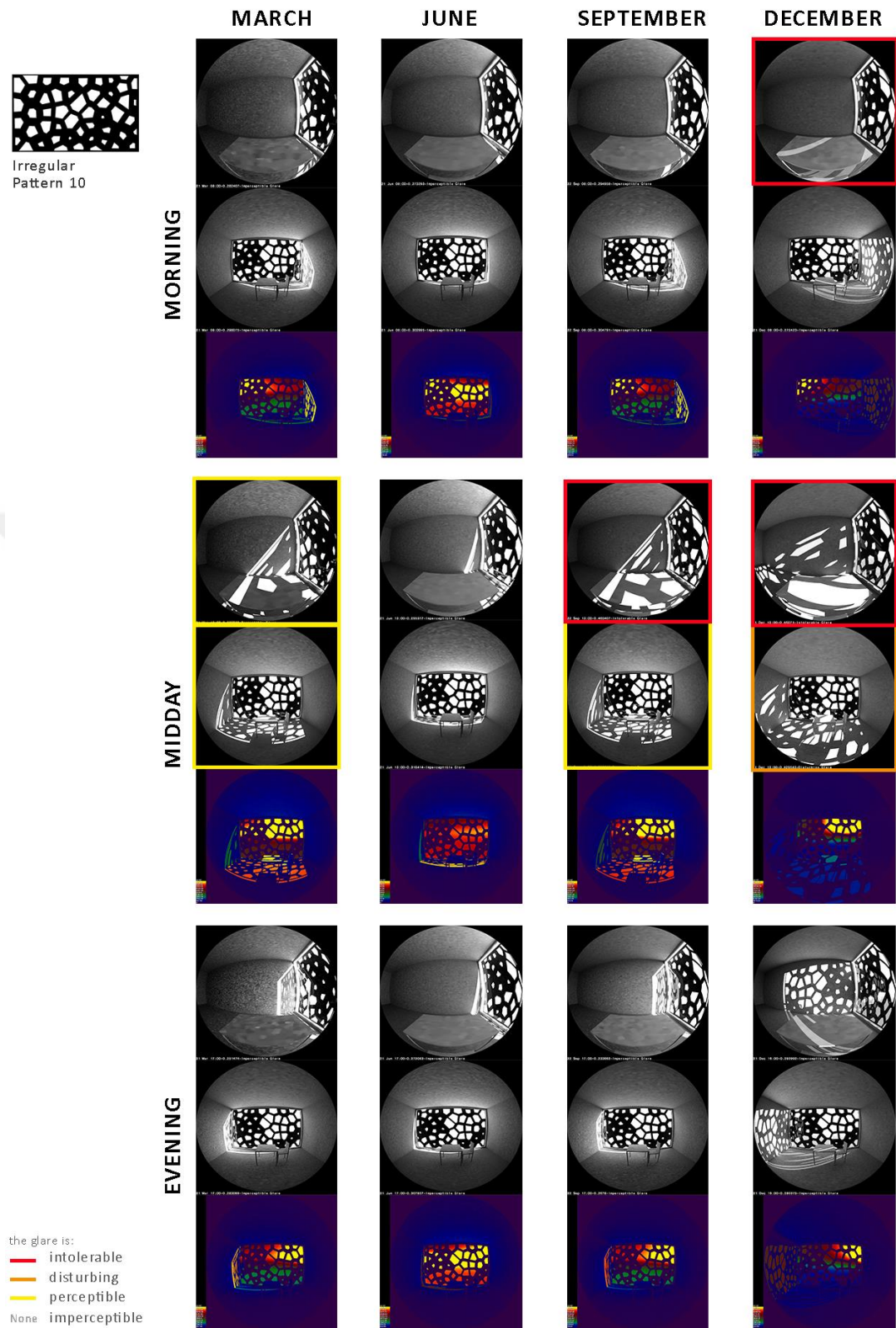


Figure 4.6: Annual analysis maps of Irregular Pattern 10.

4.6. Shadow Behaviour of Irregular Pattern 10

This analysis discusses the qualitative and geometric characteristics of the shadows produced by the Irregular Pattern 10 shading under different seasonal conditions. It focuses on shadow lengths and directions, the effect of the facade's shading surfaces, and the resulting distribution of shaded areas within the interior space.

The form of the shadows is defined by the facade's organic, non-directional pattern, but their length and direction follow the fundamental principles of solar geometry.

Summer Solstice (June 21): At the sun's highest position, shadows are short. The few patches of light that enter the space create minimal shadows. Shadows cast by interior objects are also short and compact. The form of the light patches is not rectangular but organic and soft-edged, reflecting the cellular shapes of the facade.

Winter Solstice (December 21): The sun's lowest position causes shadows to reach their maximum length. During this period, the entire Voronoi pattern is projected as a large-scale shadow deep into the interior. This creates a high-fidelity shadow replica of the facade on the floor and walls. The shadows of objects in the room are also extremely long and distorted, altering the perception of the space.

Equinoxes (March 21 / September 23): On these dates, shadow lengths exhibit an intermediate character. The shadow of the Voronoi pattern extends significantly into the room but is not as dominant as in winter. The key characteristic is its dynamic movement, as the oblique pattern sweeps across the floor and walls from morning to evening.

The shading performance of the irregular pattern results from its cellular geometry, which functions very differently from a regular grid. Unlike a regular pattern, the irregular pattern has no distinct horizontal or vertical shading elements. This means the pattern lacks a directional optimization. Its ability to shade relies on two main factors:

The ratio of solid material to open voids provides a baseline level of light reduction, regardless of the sun angle.

The thickness (depth) of the facade creates angled inner surfaces within each cell. In summer, high-angle sun rays strike these deep, angled surfaces and are blocked,

preventing direct penetration. This is the primary mechanism behind its success in summer.

The system's weakness is exposed by the low-angle winter sun. Low-angle rays are more parallel to the central axis of the cells, allowing them to pass through directly with minimal interaction with the angled inner walls. The absence of strong horizontal "overhangs" means the facade has no effective defense against this low-angle sun. In short, the shading surfaces are not "tuned" to the sun's altitude.

The effectiveness of the shading mechanism directly determines the distribution of shaded areas in the room.

Shaded Areas in Summer: Nearly the entire space is under deep and continuous shade. At midday, only a small area near the windowsill receives "dappled light." This represents a complete shading success, turning the interior into a visually comfortable and cool space.

Shaded Areas in Winter: During this season, it is difficult to speak of a defined "shaded area." The space is flooded with a "carpet of light" composed of bright Voronoi shapes. The only shaded areas are the thin, dark lines of the pattern projected onto the interior surfaces. The center and rear of the room are fully exposed to direct sun, causing significant glare.

Shaded Areas during the Equinoxes: The shaded areas are dynamic and transient. A large, moving pattern of light covers about half of the space. This creates a constantly changing environment where no single area remains consistently shaded for long during the main hours of the day, which can be challenging for visual comfort in a workspace or living area.

4.7. Perceptual Evaluation of Irregular Pattern 10: Potential User Effects

The perceptual dimension of Irregular Pattern 10 reveals a spatial experience shaped by complexity, contrast, and temporal richness. Its non-repetitive geometry allows for constantly shifting light patterns that contribute to dynamic visual effects across the workspace. Based on Chamilothon (2019), perceptual comfort and user preference increase when spatial diversity is paired with controlled glare conditions. The following sub-sections detail the five key perceptual categories observed in this study.

Table 4.5 summarizes the key perceptual attributes of Irregular Pattern 10, providing a clear overview of its spatial and experiential impacts on users. The heterogeneous light distribution is noted for enhancing spatial depth and avoiding perceptual monotony, particularly through evolving luminance gradients. Temporal dynamics, characterized by shifting shadows and light rhythms, contribute to sustained visual interest and help mitigate sensory fatigue in office settings. While glare is moderately present around midday, it remains controlled during most of the working hours, thereby supporting attentional stability. Despite its geometric irregularity, the pattern maintains spatial legibility, aiding user orientation and task efficiency. Finally, the phenomenological quality of the filtered daylight reinforces the atmospheric identity of the space, inviting multisensory engagement and contributing positively to the psychological and emotional comfort of occupants.

Table 4.5: Perceptual Analysis of Irregular Pattern 10.

Perceptual Dimension	Observation	Impact on User Experience
Light Distribution	Heterogeneous brightness; evolving gradients	Enhances spatial depth; avoids monotony
Temporal Dynamics	Changing shadow rhythms throughout the day	Stimulates visual interest and reduces fatigue
Glare Management	Moderate glare only at midday; otherwise, well-controlled	Maintains visual comfort and attentional balance
Spatial Legibility	Predictable despite irregularity	Supports orientation and task efficiency
Phenomenological Quality	Fragmented, atmospheric light	Strengthens identity and multisensory engagement

4.7.1. Perception of Light Distribution and Brightness

Irregular Pattern 10 provides a heterogeneous distribution of brightness levels, with a mix of high and low luminance zones that evolve throughout the day. Users are exposed to soft transitions between light and shadow, enhancing perceptual depth

without inducing excessive contrast. Such variation promotes spatial engagement and reduces perceptual flatness, especially near the rear and side zones of the room.

4.7.2. Temporal Dynamics and Visual Interest

The temporality of light in Irregular Pattern 10 is one of its defining characteristics. Shadow movements, direction changes, and light gradients offer a high degree of visual interest. This temporal variety supports attentional restoration and helps reduce sensory fatigue in long-term workspaces.

4.7.3. Glare Perception and Attentional Load

Despite the irregular nature of the pattern, glare remains generally within tolerable limits, with only moderate peaks recorded around noon for seated users. These peaks are not persistent and align with typical office inactivity periods. The irregular apertures break up direct sun exposure, reducing the likelihood of high-contrast, eye-level glare.

4.7.4. Spatial Legibility and Visual Comfort

Although the pattern lacks geometric regularity, its daylight behavior is spatially legible due to the repeatable logic of contrast distribution. Users can anticipate areas of brightness and shade, which supports spatial navigation and task orientation.

4.7.5. Phenomenological Quality of Light

From a phenomenological standpoint, Irregular Pattern 10 contributes to a heightened atmospheric experience. The fragmented daylight creates subtle visual textures on surfaces, invoking material depth and spatial variability. These effects stimulate multisensory engagement with the space and help transform functional daylight into a source of spatial identity.

4.8. Performance Analysis of Striped Pattern 01

4.8.1. Annual Spatial Metric Analysis for Striped Pattern 01

The annual daylight simulation results for Striped Pattern 01 indicate a well-balanced performance in terms of daylight availability, glare mitigation, and solar exposure. Daylight Autonomy (DA) values exceed 65% in most areas, particularly near the façade and in the central working zones, ensuring adequate natural illumination throughout the year. The linear configuration effectively distributes daylight in parallel bands, enhancing uniformity while avoiding excessive contrast between lit and shaded areas **Figure 4.7**.

Annual Glare Control performance is also favorable **Table 4.7**, with glare-free conditions achieved in over 85% of annual working hours across the majority of the space. Only localized areas close to the glazing present marginal risks of visual discomfort during midday hours, yet these remain within perceptible but not intolerable levels. This suggests that the pattern maintains a low glare profile, supporting sustained visual comfort across task zones.

Regarding Direct Sun Hours (DSH), most parts of the space receive less than 300–600 hours/year of direct sunlight, with only minor increases in proximity to the lower window regions. This controlled solar exposure minimizes thermal gains and avoids strong reflections on work surfaces, contributing to both visual and thermal comfort. Overall, Striped Pattern 01 demonstrates an effective balance between daylight access and comfort criteria, making it a viable solution for south-oriented office environments.

Table 4.6 highlights the annual spatial performance of Striped Pattern 01, revealing its effectiveness in promoting visual comfort. Daylight Autonomy (DA) exceeds 65% across most of the space, particularly near the façade and side zones, ensuring sufficient daylight and reducing reliance on artificial lighting. Annual Glare Control results indicate over 85% glare-free conditions, with only minor discomfort risks near the façade edges, demonstrating strong glare mitigation while maintaining occupant visual clarity. Direct Sun Hours (DSH) remain below 300 hours/year in the majority of the room, with a slight increase (400–600 hours/year) near lower window regions,

successfully limiting excessive solar gain and enhancing both thermal and visual comfort.

Table 4.6: Annual analysis of Striped Pattern 01.

Metric	Observation	Implications for Visual Comfort
Daylight Autonomy (DA)	DA >65% across the majority of the room; higher values near the façade and side zones	Ensures sufficient daylight throughout the space, reducing dependency on artificial lighting.
Annual Glare Control	Glare-free conditions are observed over 85% of the year; minor risk zones near the façade edges	Demonstrates effective glare control while preserving visual clarity and occupant comfort.
Direct Sun Hours (DSH)	DSH <300 h/year in most areas; small rise (~400–600 h/year) near lower window regions	Minimizes excessive solar exposure; contributes to thermal comfort and limits visual discomfort.

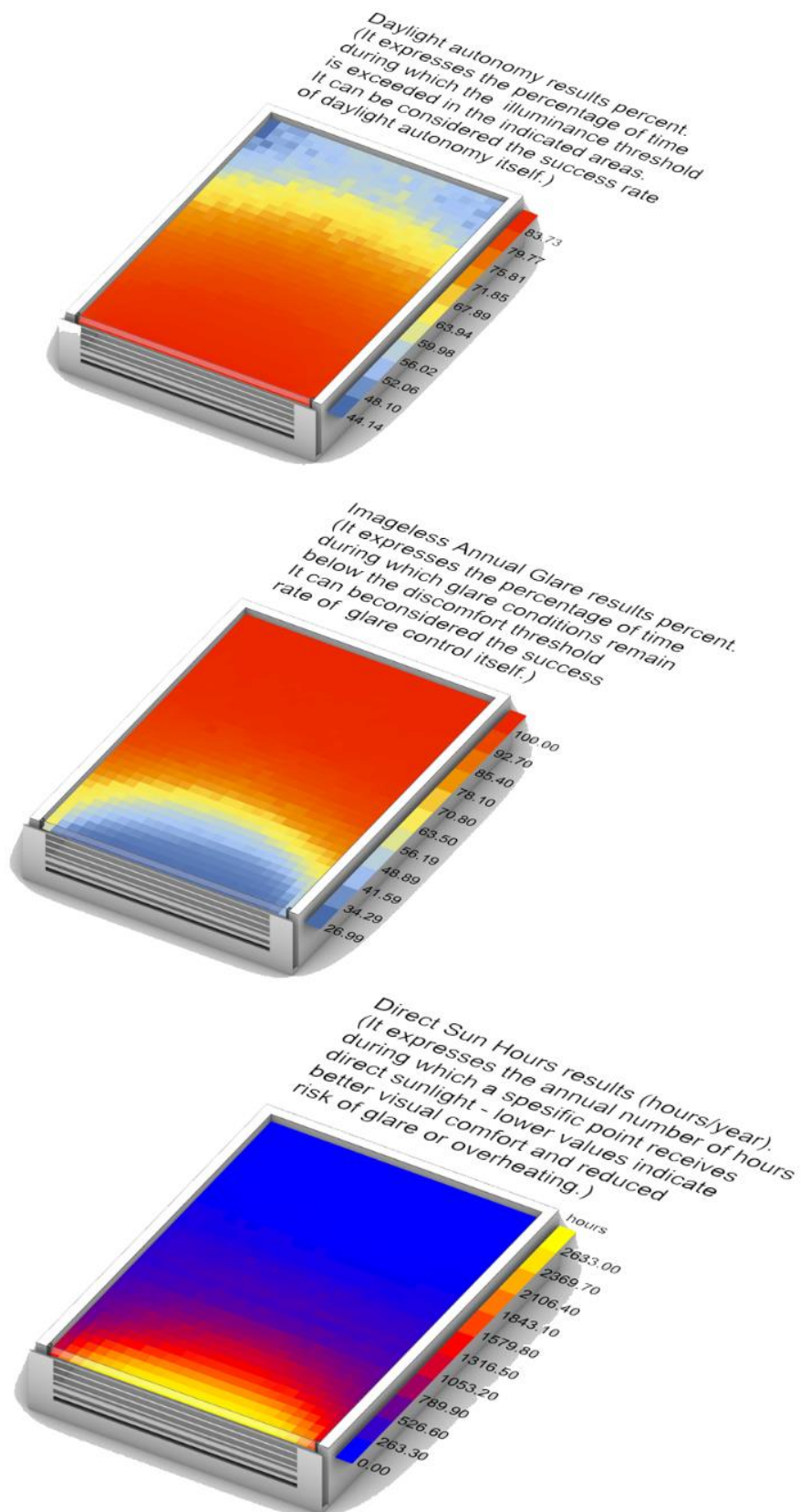


Figure 4.7: Annual analysis maps of Striped Pattern 01.

4.8.2. Visual Performance Based on User Position for Striped Pattern 01

The visual comfort performance of Irregular Pattern 10 was assessed on four key seasonal dates—December 21st, March 21st, June 21st, and September 23rd—at three time intervals (08:00, 13:00, 17:00), from both standing and seated user perspectives. This dual-perspective analysis allows for a more comprehensive evaluation of how solar conditions interact with user position and façade geometry in a typical south-facing office scenario.

From the standing user's viewpoint, the shading system exhibits strong and consistent performance across the year **Figure 4.8**.

- During the summer solstice (June 21st), all DGP values remain within the imperceptible glare range ($DGP \leq 0.318$), confirming the system's ability to manage high solar altitudes effectively.
- On equinox dates (March 21st and September 23rd), glare levels are mostly imperceptible, with only midday values reaching the perceptible range ($DGP \approx 0.38$), yet still within acceptable limits.
- On December 21st, glare is imperceptible in the morning and late afternoon (DGP : 0.272 and 0.280), while disturbing glare occurs at 13:00 (DGP : 0.429) due to low winter sun angles and direct light penetration through upper apertures.

From the seated user's perspective, performance is generally acceptable throughout the year, with the majority of cases falling within imperceptible or perceptible glare categories. However, three isolated instances show intolerable glare ($DGP > 0.45$):

- 08:00 and 13:00 on December 21st
- 13:00 on September 23rd

These exceptions appear to be related to geometric alignment between the user's lower eye level and the solar incidence angle, causing direct sunlight to fall into the field of view through upper perforations. Although material properties were correctly defined according to daylight standards, some modeling limitations (e.g., absence of interior elements, furnishings, side panels) may have exaggerated glare effects in seated conditions.

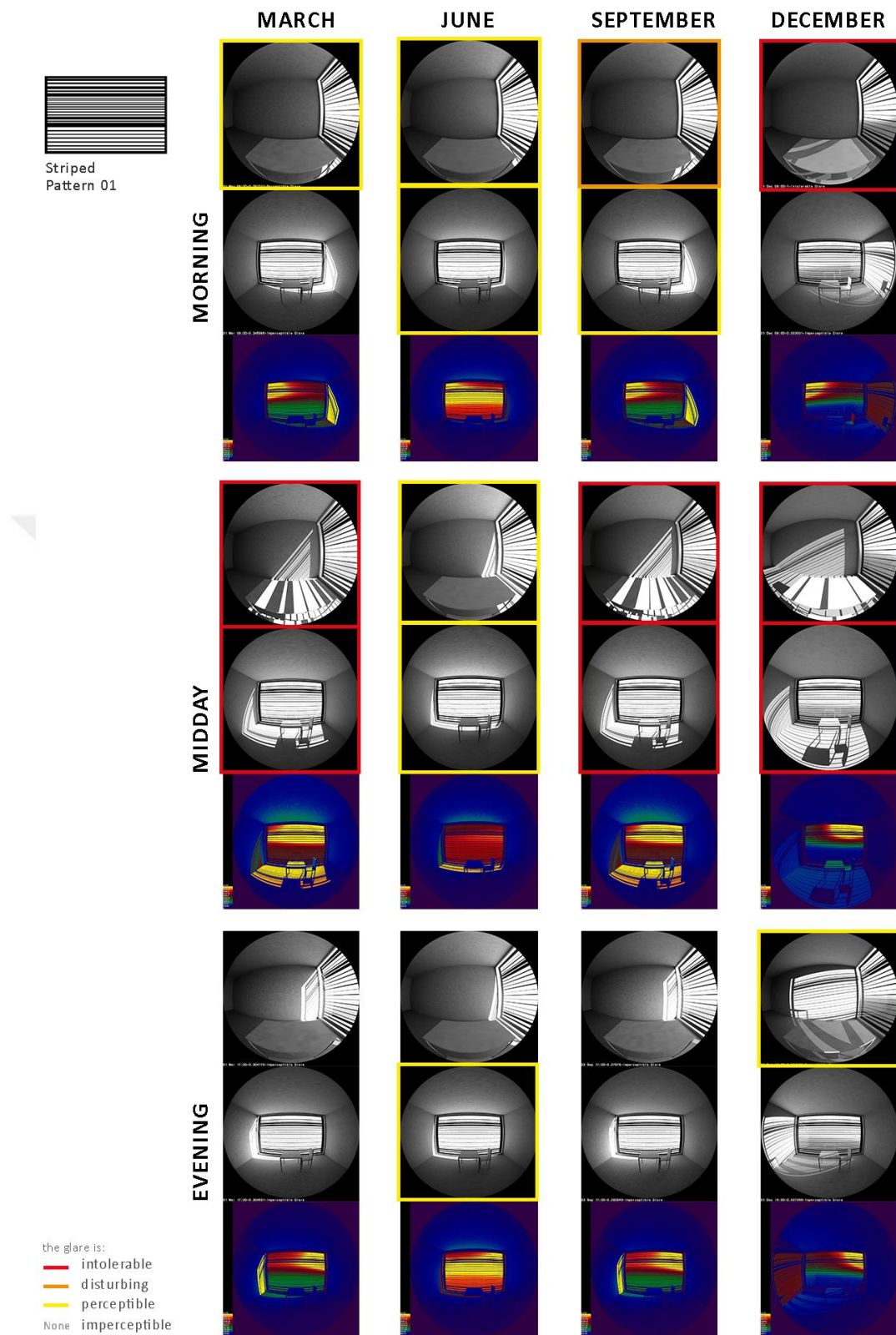


Figure 4.8: Annual analysis maps of Striped Pattern 01.

4.9. Shadow Behaviour of the Striped Pattern 01

The shadows created by this pattern have a simple, predictable geometry, but their manifestation within the space changes dramatically with the seasons.

- Summer Solstice (June 21): At the sun's highest altitude, the system completely blocks direct sunlight from entering the interior. As a result, no distinct shadows are cast on the floor or walls. The only visible shadows are the faint and short ones cast by the furniture under diffuse light. During this period, shadow as a design element is absent.
- Winter Solstice (December 21): The sun's lowest position causes shadows to reach their maximum length and dominance. The facade projects its entire pattern deep into the space, creating shadows in the form of long, sharp, and uninterrupted horizontal stripes. The shadows of interior objects also become extremely long but are largely lost within the overwhelming "zebra pattern" cast by the facade.
- Equinoxes (March 21 / September 22): On these dates, shadow lengths are moderate. Due to the oblique angle of the midday sun, the projected shadows appear as curved or bowed stripes on the floor and side walls. The most distinct feature of these shadows is their dynamic movement, sweeping across the room from morning to evening.
- The "Altitude Switch" Mechanism: The facade acts like a binary switch that operates in two distinct modes based on solar altitude:
- High-Altitude Mode (Summer): When the sun's angle is steeper than the line-of-sight through the louvers, the system functions as a 100% effective shading device. The sun's rays hit the top surface of one louver and are blocked from passing through the next gap. This explains the complete absence of direct sun patches in summer. However, this same mechanism causes the louvers themselves to become intensely bright, creating a secondary glare source.
- Low-Altitude Mode (Winter & Equinox): When the sun's angle is lower than the line-of-sight through the louvers, the system becomes a 0% effective shading device. The sun's rays pass directly between the slats with almost no obstruction. This is what creates the high-contrast bands of light and results in "Intolerable Glare".

- **The Impact of No Vertical Elements:** The critical flaw of this design is the complete absence of vertical elements. This absence means that when the system fails in low-altitude mode, the stripes of light stretch uninterrupted across the entire width of the facade. This creates an aggressive visual pattern that floods the field of view and maximizes the negative impact of glare, unlike the Grid pattern, which at least breaks the light into smaller patches.

The shading mechanisms described above result in opposite spatial conditions depending on the season.

- **Shaded Areas in Summer:** Throughout the entire day, all interior surfaces (floor, walls) are 100% shaded from direct sunlight. The room is filled with uniform, diffuse light. In this scenario, the "shaded area" in terms of direct radiation is the entire room.
- **Shaded Areas in Winter & Equinox (Midday):** The opposite is true. The concept of a defined "shaded area" almost ceases to exist. The entire room, from floor to ceiling, is flooded with alternating bands of intense light and sharp shadow. The only shaded areas are the narrow, dark stripes themselves. The deepest parts of the interior are exposed to the most aggressive light pattern.
- **Shaded Areas in Morning/Afternoon (All Seasons):** Half of the room where the sun is located (e.g., the east side in the morning) remains shaded from direct light. The opposite wall is illuminated with an oblique projection of the horizontal lines, creating a pattern of angled stripes. The core of the room is largely shaded from this sidelight.

4.10. Perceptual Evaluation of Striped Pattern 01: Potential User Effects

Striped Pattern 01 presents a structured and rhythmically dynamic lighting environment that aligns well with visual comfort goals for office users. The linear shading configuration successfully balances daylight distribution, maintaining spatial brightness during morning and afternoon hours while introducing expressive light patterns at midday. Although glare perception peaks at 13:00, particularly for seated users, the system generally performs within tolerable thresholds across the day. Its capacity to deliver temporal variety, reinforce spatial legibility, and evoke a phenomenologically engaging atmosphere supports its effectiveness not only as a

daylighting strategy but also as a perceptual design intervention. The findings are consistent with previous literature emphasizing the cognitive and emotional relevance of temporally dynamic daylight environments [Chamilothori, 2019].

Table 4.7 provides a synthesized evaluation of Striped Pattern 01 across five perceptual dimensions. The linear configuration of the pattern delivers a consistent distribution of daylight that reinforces spatial clarity while promoting temporal variation in light experience. Despite a temporary midday glare peak, the overall visual environment remains comfortable and supportive of user activities. The horizontal rhythm of the slats enhances spatial legibility, and the evolving interaction between daylight and form offers a phenomenologically rich atmosphere that strengthens emotional engagement and temporal awareness.

Table 4.7: Perceptual Analysis of Striped Pattern 01.

Perceptual Dimension	Observation	Impact on User Experience
Light Distribution	Consistent luminance bands; increased brightness at midday	Supports visual stability and spatial clarity
Temporal Dynamics	Pronounced light variation across daily cycle	Enhances engagement through rhythmic daylight change
Glare Management	Intolerable glare only at 13:00; minimal elsewhere	Generally maintains comfort; requires mitigation at peak hours
Spatial Legibility	Strong directional rhythm from horizontal slats	Reinforces spatial orientation and visual coherence
Phenomenological Quality	Dynamic light atmosphere shaped by time and geometry	Evokes temporal awareness and emotional resonance

4.10.1. Perception of Light Distribution and Brightness

Striped Pattern 01 demonstrates a visually ordered distribution of daylight, with linear shadow bands contributing to both spatial clarity and brightness consistency. Particularly in the morning (08:00) and late afternoon (17:00), the façade-mounted horizontal slats diffuse incoming sunlight effectively, resulting in softly modulated

light across working surfaces. While brightness increases significantly at 13:00, especially near the window, the pattern's directional uniformity helps maintain perceptual balance rather than causing disorientation. However, zones of intensified luminance may still introduce mild perceptual strain for users engaged in focused tasks.

4.10.2. Temporal Dynamics and Visual Interest

The striped geometry introduces a strong temporal variation in daylight distribution, which shifts perceptibly throughout the day. At noon, the renderings show sharply defined light bands traversing the interior, creating dynamic contrasts on floors, desks, and walls. These changes enhance spatial animation and can enrich the visual experience. However, as noted by Chamilothoni [2019], repetitive shadow patterns, though initially stimulating, may lose novelty over time and reduce visual interest with prolonged exposure.

4.10.3. Glare Perception and Attentional Load

Simulated glare levels for Striped Pattern 01 indicate a notable peak in visual discomfort at midday. At 13:00, Daylight Glare Probability (DGP) values reach "intolerable" thresholds for the seated user, with direct light reflections impacting both frontal and peripheral vision. While early morning and late afternoon hours remain within perceptible or imperceptible glare levels, the midday peak can disrupt task concentration and visual endurance. According to Chamilothoni (2019), such fluctuations in glare risk contribute to cognitive load and may affect sustained visual comfort.

4.10.4. Spatial Legibility and Visual Comfort

The horizontal rhythm established by the striped shading system reinforces spatial orientation by guiding the eye along façade-parallel axes. This directional emphasis, combined with consistent luminance gradients during non-peak hours, supports spatial legibility and user orientation. However, zones with intensified contrast during midday can potentially impair visibility in critical task areas, such as the work desk, leading to localized discomfort. Nevertheless, the overall predictability and structure of the pattern contribute positively to spatial comprehension.

4.10.5. Phenomenological Quality of Light

Striped Pattern 01 offers a phenomenologically rich light environment, where the interaction of daylight and architectural form creates a temporal narrative within the space. Morning and afternoon periods yield calm and balanced shadow textures, whereas midday introduces dramatic light intensities and contrast. This evolving quality of light not only enhances environmental awareness but also marks the passage of time, echoing Chamilothon's [2019] findings on temporal light perception. The spatial mood transitions across the day provide users with a psychologically engaging and atmospherically varied experience.

4.11. Comparative Evaluation of Regular 01, Irregular 10, and Striped 01 Patterns

4.11.1. Performative Comparison

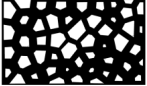
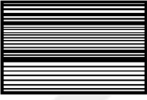
This section presents a comparative evaluation of the three shading configurations—Regular Pattern 01, Irregular Pattern 10, and Striped Pattern 01, concerning their visual comfort performance, particularly glare control, across four key dates of the year: March 21, June 21, September 23, and December 21 **Table 4.8**. Simulations were conducted for both standing and seated user perspectives at three daily time intervals: 08:00 (morning), 13:00 (midday), and 17:00 (evening). The Daylight Glare Probability (DGP) was used as the primary metric to assess visual comfort in each scenario.

Regular Pattern 01 exhibits the most consistent performance, maintaining imperceptible glare levels for most time slots, especially from the standing viewpoint. Only two deviations were observed: a seated morning glare on March 21 and a midday glare on December 21. These were linked to specific low solar angles interacting with direct sightlines at seated eye height.

Irregular Pattern 10 shows successful glare mitigation overall, especially in summer and equinox conditions, thanks to its diffuse geometry. Most seated and standing simulations yield imperceptible or perceptible glare. However, three exceptions were found: midday glare on December 21 (seated), September 23 (seated), and March 21 (standing), where intolerable or disturbing glare occurred, primarily due to horizontal solar penetration and lack of secondary shading in the model.

Striped Pattern 01 demonstrates the least favorable glare performance, with multiple midday intolerable glare values for both user positions, particularly during March and June. The continuous horizontal bands allow higher luminance contrast and deeper solar penetration, especially at low shading angles. Although early morning and evening performance is better, midday glare remains a critical weakness.

Table 4.8: Performative comparison.

Pattern	March 21	June 21	September 23	December 21
Regular 01 	Excellent (all standing); seated glare at 08:00	Excellent (all views)	Excellent except seated at 13:00	Minor midday glare (standing + seated)
Irregular 10 	Standing midday glare; otherwise successful	All hours successful	Seated midday glare	Seated 08:00 & 13:00 glare
Striped 01 	Midday glare (both views), seated AM perceptible	Midday glare (both views)	More balanced, seated at 13:00 glare	Successful except seated at midday

User position significantly influences glare outcomes. Most intolerable values were found in seated midday positions, especially when horizontal sightlines align with bright interior surfaces (floor, desk) or direct solar beams. Regular Pattern 01 benefits from its grid-based consistency, offering uniform shading and minimal contrast zones. This makes it the most robust solution in terms of visual comfort across seasonal and positional variations. Irregular Pattern 10, though geometrically complex, manages glare efficiently through light diffusion. Its sporadic failures are typically localized and can be mitigated through design refinements like denser upper apertures or side reveals. Striped Pattern 01, due to its wide horizontal gaps, allows substantial solar ingress and high luminance zones. Its design may benefit from angular reorientation of the stripes or added internal diffusing layers to alleviate critical glare issues.

In light of the annual performance simulation results, Regular Pattern 01 emerges as the most balanced and effective shading strategy for static south-facing office façades.

Irregular Pattern 10 also provides strong performance but may require adjustments for sensitive times of the year. Striped Pattern 01 is currently the weakest performer and demonstrates a clear need for geometric or material refinement to meet visual comfort expectations in real-world applications.

4.11.2. Comparative Perceptual Analysis of Regular 01, Irregular 10, and Striped 01 Patterns

This section compares the perceptual daylight qualities of the three tested shading patterns, Regular 01, Irregular 10, and Striped 01, based on five key perceptual dimensions derived from Chamilothoni [2019]: Light Distribution & Brightness, Temporal Dynamics, Glare Management, Spatial Legibility, and Phenomenological Quality **Table 4.9**. The evaluation synthesizes visual simulation outputs (false color images and renderings) along with performance observations.

Table 4.9: Perceptual comparison.

Perceptual Dimensions	Regular 01	Irregular 10	Striped 01	Strengths	Weaknesses
Light Distribution & Brightness	Balanced and uniform	Diffused with spatial depth	Moderate contrast	Irregular: diffused daylight; Regular: balanced spread	Striped: uneven under high sunlight
Temporal Dynamics	Stable through the day	High variation by hour	Moderate variation	Irregular: dynamic character	Regular: lacks temporal variation
Glare Management	Generally effective	Mostly effective	Frequent perceptible glare	Regular: strong in summer; Irregular: strong annually	Striped: critical glare midday
Spatial Legibility	Clear pattern & rhythm	Visual interest with complexity	Dominated by horizontal rhythm	Regular: clarity; Irregular: spatial richness	Striped: repetitive visual load
Phenomenological Quality	Neutral and consistent	Rich shadows & atmosphere	Directional emphasis	Irregular: experiential quality	Striped: lacks visual warmth

4.11.3. Shadow Behavior Comparison Among Pattern Variants

In addition to visual comfort metrics, the comparative analysis includes an evaluation of shadow behavior based on the rendered images captured at three key times (08:00, 13:00, and 17:00) for each seasonal date.

Regular Pattern 01 demonstrates relatively stable shadow castings throughout the year. Due to its grid-based structure, the shadows are distributed uniformly on the floor and work surfaces, effectively avoiding sharp contrasts. Especially in summer, it creates deep and layered shadows that enhance spatial legibility.

Irregular Pattern 10 generates more complex and scattered shadow compositions. The fragmented layout results in dynamic shadow patterns that change dramatically across different times of day. While this offers a strong phenomenological quality, it occasionally leads to shadow gaps that allow direct light penetration.

Striped Pattern 01 exhibits strong directional shadows due to its horizontal band configuration. In the morning and afternoon, the long stripes cast elongated shadows, creating a distinct rhythm in interior surfaces. However, in midday conditions, particularly in summer, the parallel alignment may lead to partial exposure and reduced shading efficiency.

Overall, the Regular Pattern provides the most consistent shadow coverage, whereas the Irregular Pattern introduces rich phenomenological variation. The Striped Pattern shows pronounced temporal dynamics but needs geometric refinement for improved midday protection.

5. CONCLUSION

5.1. Summary of the Study

This doctoral study investigated the design, optimization, and evaluation of a second-layer perforated shading system positioned 20 cm in front of a fully transparent south-facing office façade. Conducted within a parametric and simulation-based workflow in the Grasshopper environment, the research utilized genetic algorithms (via Wallacei) to explore how different pattern grammars, Regular, Irregular, and Striped, affect indoor visual comfort conditions.

The primary objective was to identify sunshade configurations that improve visual comfort through three key daylight performance criteria: Spatial Daylight Autonomy (sDA), Daylight Glare Probability (DGP), and Direct Sunlight Hours (DSH). Each of these parameters was normalized and equally weighted within a multi-objective fitness function to ensure balanced performance assessment. The study focused on an idealized office model and simulated occupant viewpoints (standing and seated) at three different times of the day (08:00, 13:00, 17:00) on the equinox date (March 21st).

Three distinct pattern types were algorithmically generated and evaluated in terms of their impact on daylight metrics, glare control, and shadow behavior. In addition to quantitative analysis, the study also included a perceptual framework inspired by Chamilothoni [2019], examining qualitative aspects such as brightness distribution, temporal dynamics, and the atmospheric qualities of light.

Through iterative environmental simulations and false color renderings, the research offered a comparative performance-based evaluation of façade grammars and demonstrated the architectural value of algorithmically designed shading devices. The approach aimed to bridge performance-based design with human-centric considerations in contemporary office environments.

5.2. Key Findings

The Grasshopper model (Appendix-A) was created to test the design approach in a virtual environment. Some key findings include:

- **Pattern Grammar Strongly Influences Visual Comfort Performance:** The geometry of the shading pattern significantly affects daylight distribution, glare control, and exposure to direct sunlight. Regular patterns provided the most balanced performance across all visual comfort metrics, while Irregular patterns enhanced spatial dynamics at the cost of higher glare risks. Striped patterns produced time-dependent daylight effects that enriched spatial experience but introduced varying levels of luminance contrast.
- **Regular Pattern 01 Showed the Best Overall Performance:** Among the optimized solutions, Regular Pattern 01 achieved the highest combined scores in annual DA, lowest DGP values, and reduced DSH exposure. It offered a uniform light environment with low glare risk throughout the year, making it the most visually stable option across all user positions and time scenarios.
- **User Position Affects Daylight Perception and Glare Risk:** Analysis based on occupant positions (standing vs. seated with side orientation) revealed that glare perception and light intensity vary significantly depending on the user's viewpoint. This highlights the importance of multi-positional evaluation in visual comfort studies, especially in workplace design.
- **Irregular Patterns Enhance Perceptual Interest:** Although irregular patterns did not perform best in terms of objective metrics, they were perceived as more visually engaging due to their complex light patterns and spatial variability. These configurations created a dynamic indoor atmosphere and received the highest scores for interest and complexity in perceptual analysis.
- **Striped Patterns Emphasize Temporal Dynamics:** The rhythmic quality of Striped patterns contributed to temporal legibility and spatial rhythm throughout the day. However, the same time-dependent variation also introduced inconsistency in glare control, especially during critical sun angles in the afternoon.
- **Multi-Objective Genetic Algorithm is Effective in Shading Design:** The use of Wallacei for multi-objective optimization proved successful in balancing competing criteria such as daylight sufficiency and glare mitigation. The normalized fitness function enabled fair comparison among design variants and supported the identification of high-performance solutions.
- **Perceptual Analysis Adds Depth Beyond Quantitative Metrics:** Incorporating perceptual criteria such as brightness distribution, spatial complexity, and light-

induced mood supported a more holistic understanding of shading performance. This approach acknowledged that optimal solutions are not only technically efficient but also experientially rich.

- **Visual and Temporal Evaluation Is Essential for Model Validation:** Genetic Algorithm creates randomized variations of the pattern grammars set, and eliminates them according to their fitness values to the fitness criteria for generations. Yet, it is understood that visual analysis is necessary. Especially from the desk, sitting eye height. In this study, after the creation of 750 genes for each pattern grammar, the best ones were picked. Annual graphics and fitness values showed them successful, yet one of the patterns failed in visual analysis (via Ladybug), at 13.00 on the 21st of March, Equinox on desk height. It was successful in every hour for standing height and morning and evening for sitting height. This shows the importance of daily values and visual analysis. It is understood that visual analysis and daily/hourly values should be added to the approach, and the model should work with feedback.

5.3. Contribution to Knowledge

This doctoral research makes several key contributions to the field of daylight-responsive architectural design, particularly in the context of façade-integrated sunshade systems for office environments:

- **Development of a Generative, Multi-Objective Workflow for Shading Design:** The study presents a novel design-to-evaluation workflow that combines parametric modeling, environmental simulation, and evolutionary optimization. By integrating Wallacei with Ladybug and Honeybee in the Grasshopper environment, it enables the systematic generation and assessment of shading geometries based on user-defined performance goals.
- **Integration of Pattern Grammar Logic into Performance-Based Optimization:** Unlike many existing studies that treat sunshade geometry as a generic parametric surface, this research categorizes shading devices into three geometrically distinct grammar types (Regular, Irregular, Striped) and examines their differentiated impact on visual comfort metrics. This taxonomy enriches the understanding of how formal logic in design affects environmental performance.

- **Inclusion of User Position and Perceptual Evaluation as Design Parameters:** The study incorporates two distinct user perspectives, standing and seated with side orientation, to simulate realistic visual comfort conditions. It also integrates a perception-informed evaluation framework based on previous research, emphasizing not only performance metrics but also experiential factors such as spatial rhythm, visual complexity, and brightness distribution.
- **Highlighting the Need for Hourly and Visual Validation Beyond Annual Metrics:** A significant contribution of this research is the identification of limitations in relying solely on annual simulation outputs for design decision-making. The study demonstrates that a pattern may appear successful in aggregate metrics yet fail in critical hourly scenarios—particularly at desk height—emphasizing the necessity of integrating daily/hourly visual simulations into generative design workflows.
- **Proposal of a Feedback-Responsive Model Structure:** The findings support the development of an iterative model that not only optimizes based on predefined criteria but also evolves through visual and temporal feedback. This feedback-informed generative loop contributes to the emerging paradigm of human-centered performance-based design in architecture.

In summary, the thesis bridges computational environmental design with perceptual and user-based considerations, offering a comprehensive and replicable framework for the design of façade sunshades that are optimized not just for numerical efficiency but also for experiential quality and contextual relevance.

5.4. Limitations of the Research

While this study offers a comprehensive approach to performance-based façade shading design, it also presents several limitations that should be acknowledged:

- The simulations were conducted exclusively for a south-facing façade located in Istanbul. While this provides a realistic and climatically relevant scenario, the results are context-specific. Future research could enhance generalizability by applying the same approach to various geographic locations, orientations, and climates, using local weather files and solar angles for comparative analysis.
- The office model used in this study was intentionally kept idealized ($5 \times 7 \times 3$ meters), excluding internal furniture, partitions, and occupancy-related elements

that might influence daylight behavior. While this allowed for focused analysis of façade performance, future studies could integrate more realistic spatial configurations and variable user activities to test adaptability under diverse conditions.

- The study focuses on fixed, non-responsive shading panels. Although these are commonly used in practice, adaptive systems—such as movable louvers or dynamic façades—may offer enhanced performance in environments with variable daylight conditions. Incorporating kinetic or sensor-based responsive models into the algorithmic framework is a promising direction for future work.
- The optimization process concentrated solely on visual comfort parameters (DA, DGP, DSH), without evaluating thermal comfort or energy efficiency. While this was a deliberate focus, integrating thermal simulations (e.g., operative temperature, solar heat gain) into the multi-objective fitness function would yield a more holistic understanding of façade performance and could better align with sustainable design goals.
- The perceptual assessments in this study were based on simulated false color images and design logic informed by literature. However, actual user feedback through surveys, interviews, or immersive VR testing could validate the perceptual outcomes and strengthen the human-centered aspects of the design approach. Future research could implement such methods to bridge simulation with real-world experience.
- Daylight simulations were conducted at three key times (08:00, 13:00, 17:00) on March 21st, the equinox. While this offers balanced daylength conditions, additional analysis across different seasons and finer time intervals would capture more complex daylight dynamics. Expanding the temporal scope would improve the model's reliability and responsiveness to annual variability.
- The optimization algorithm employed equal weighting for DA, DGP, and DSH in the fitness function. However, in practical applications, different stakeholders may prioritize these metrics differently depending on context. Future models could allow user-defined or adaptive weighting strategies, enabling more customized and scenario-specific optimization.

5.5. Recommendations for Future Work

Building upon the findings and limitations of this research, several recommendations are proposed to guide future investigations and enhance the methodological and practical scope of façade-integrated shading design:

- Future studies should apply the generative workflow to different geographic contexts and façade orientations to test the adaptability and robustness of the approach under diverse solar conditions. Comparative analyses across climates could reveal regional design strategies and context-specific shading grammars.
- Introducing furniture layout, material reflectance, interior partitions, and user activity patterns would improve the accuracy of simulations and better reflect real-world conditions. This would also allow the evaluation of shading effects on visual tasks, spatial zoning, and occupant movement throughout the day.
- To further improve visual and thermal comfort, future research should include dynamic shading devices that respond to real-time daylight conditions using sensors or programmable logic. Such systems can be evaluated within the same generative framework by adding kinetic parameters and control strategies to the optimization model.
- Expanding the optimization criteria to include thermal metrics and building energy performance (e.g., cooling loads, lighting energy savings) would enable more holistic, performance-driven design solutions that support sustainable architecture goals.
- The current study used equally weighted fitness criteria; however, stakeholders in different building projects may prioritize daylight, glare, or sunlight differently. Allowing flexible or adaptive weighting mechanisms would make the model more customizable and stakeholder-responsive.
- Incorporating immersive virtual reality (VR), augmented reality (AR), or real-scale mock-up studies with human participants would provide empirical data on user comfort, mood, and perception. Such feedback would enhance the reliability of perceptual evaluation and support evidence-based design decision-making.
- The algorithm can be modified in a modular way and applied at a larger building scale, and also maybe for different types of buildings. The patterns that are

generated can be built in a modular fashion, allowing for flexibility in their construction.

- Future versions of the model could benefit from incorporating real-time feedback—both quantitative (e.g., simulation re-runs based on failure cases) and qualitative (e.g., user perception mismatches)—into the generative loop. This would support a truly adaptive and learning-based design system capable of refining itself through iterative cycles.
- Given the growing interest in health-centered design, future studies could examine how algorithmically generated shading systems influence circadian rhythm and biological lighting quality. Metrics such as melanopic lux, circadian stimulus (CS), or equivalent daylight illuminance (EDI) can be added to the optimization framework.
- In the study, regular patterns were defined as squares, while irregular patterns were defined as Voronoi shapes. However, different shapes that fit this grammar can be tested, and qualitative analyses can be conducted.

These recommendations aim to broaden the research impact and applicability of the current model while encouraging interdisciplinary collaboration among computational designers, environmental engineers, and building performance experts. As digital tools become increasingly integrated into architectural practice, the refinement of performance-driven, perception-informed design strategies will be essential in creating responsive, healthy, and sustainable built environments.

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BIOGRAPHY

N. Özge Esener received her Bachelor of Science degree in Architecture from Yeditepe University in 2015 and completed her Master of Science in Building Science at Mimar Sinan Fine Arts University in 2018.

From 2015 to 2017, she worked as a teaching assistant in the Department of Architecture and Design at F.M.V. Işık University, where she contributed to undergraduate courses such as Architectural Design Studio, Building Science, and Building Theory. In 2017, she joined the Department of Architecture at Gebze Technical University as a research assistant, where she is currently employed. Since 2018, she has been pursuing a Ph.D. in Building Science at the same institution as well. In the Spring semester of 2023, she participated in the Erasmus+ program at the Università degli Studi di Sassari, Italy, where she undertook coursework on coding in architecture. This experience laid the foundation for her subsequent research direction. As a result, a co-tutelle agreement was established between Gebze Technical University and the Università degli Studi di Sassari, under which she is currently conducting her doctoral research.

Her international collaborations have contributed significantly to the development of her language skills. A native speaker of Turkish, she completed her bachelor's degree in English and is fluent in English (C1 level). During her studies at the Università degli Studi di Sassari, she also acquired proficiency in Italian (B1 level).

Her research focuses on the application of algorithmic and performance-based approaches in architectural design, with particular emphasis on generative methods for building façade systems, daylight optimization, and visual comfort in office environments.

PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

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APPENDICES

APPENDIX-A: GRASSHOPPER MODEL

