

A Multi-Objective Optimization Framework for Designing Kinetic Shading Patterns based on Daylight and Lighting Energy Efficiency

Samin Kamalisarvestani¹, Mehdi Ashayeri¹

¹ Southern Illinois University Carbondale, Illinois, United States

Abstract

Escalating environmental issues—such as climate change, rising energy use, and poor indoor environmental quality—have made performance-driven design essential. Designers often use extensive glazing to increase daylight, but this can cause uneven distribution, overheating, glare, and visual discomfort. Kinetic shading devices offer a solution, yet their use remains limited due to the high computational demands in the design process and the complexity of multi-objective optimization. This study investigates how parametric and kinetic shading systems can improve daylight performance and reduce lighting energy use in educational buildings, following LEED v4 Platinum standards. As a proof of concept, the study compares four globally recognized shading patterns, derived from real-world building applications, to identify the most effective strategy for optimizing daylight performance. Using parametric modeling, daylight simulations, and genetic algorithms, two key metrics—Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)—are optimized. Various shading strategies are evaluated to enhance visual comfort, daylight uniformity, and indoor environmental quality. Results show that kinetic systems perform well across these metrics, supporting healthier, more energy-efficient spaces. This work lays the groundwork for integrating broader metrics such as daylight efficiency and renewable energy potential into sustainable design.

Keywords: Kinetic Shading, Energy Performance, Daylight Performance, Parametric Design, Multi-Objective Optimization

1 Introduction

Introducing spaces that utilize the attributes of daylight to improve the comfort, health, and performance of the users has remained a major challenge for the field of Architecture [1]. Moreover, lighting accounts for 31% of the overall building energy usage in U.S. colleges and universities (*U.S. National Grid, Managing Energy Costs in Colleges and Universities*). Therefore, daylight triggered the interest in using renewable energy resources to improve the potential performance of buildings used for writing and reading [3]. Visual comfort in educational buildings is an essential issue since it is directly related to students' well-being and learning process [4,5]. Daylight, due to its highly variable and uncertain characteristics, changes appearance and varies with time, making it difficult to track and predict [6]. However, it is beneficial to maximize its contribution to providing a more comfortable condition for the users [7].

Daylight is a primary design feature that provides a connection to the outdoor environment [6] and creates a dynamic indoor lighting condition [8]. Daylight can affect human health, including psychological, mental, physiological conditions [9] and visual comfort [1]. Working in daylight considerably decreases negative moods [8] and increases productivity, especially for precision, reading, and writing activities. As a result, to enhance the penetration of light into the building, architects started incorporating more glass into their façades. Although glass is helpful for allowing light into buildings, a lack of ability to control the intensity of direct natural light [10] can result in an increase in heat gain and non-uniform daylight distribution, which leads to visual problems such as glare [11]. Thus, adjusting the daylight performance level in the design process is essential to achieve the user's comfort [6]. To achieve the goal, the façade plays an integral role in controlling light penetration with relevance to the sun's movement position and adapting to the outdoor environment [8].

Façade is a term to describe the zone between architectural exterior and interior [12]. Façade, on the one hand, is an essential element to protect the building against extreme climatic conditions (e.g., glare and overheating) [10]; on the other hand, to provide interiors with essential daylight [13]. Moreover, building façades account for more than 40% of heat loss in the winter and overheating in the summer [14]. However, daylight management arises because of the problems that the traditional concept of façade has been practiced: static and pre-designed. Accordingly, high-performance building façades have become one of the primary targets for researchers and designers because of their essential roles [15], including an increase in lighting and visual comfort. By actuating the façades and making them more dynamically responsive to the environment, they can now better adapt to improve user comfort and different weather conditions [16,17]. The kinetic façade can be designed as a dynamic form to reach optimal building performance [17].

The kinetic façade is characterized by complex shapes and patterns [17], singular forms, and a dynamic process from which a range of forms and patterns manifest over time [12]. The Kinetic façade is capable of changing its geometry and patterns repeatedly and reversibly to integrate motion with environmental conditions of the context and user requirements [6,17]. For instance, it is used to allow solar heat to enter as much as possible while keeping out the glare and heat at specific periods, protecting the building, and allowing the building users to have a visual connection with the outside environment [13,18]. Generative design methods and tools by integrating parametric modeling and daylight analysis tools have facilitated various design solutions to achieve this goal [19–21]

Generative Design (GD) is a computer-based approach to designing complex shapes [22] through iterative and straightforward algorithms [23] in the early steps of design [22]. Parametric modeling is a specific GD approach with a series of design parameters [24] that generates different instances of a design, where each instance represents a particular set of values for the design parameters [25]. Therefore, this allows architects to continuously evaluate several solutions [26], which would be difficult to do with traditional design methods [27]. Parametric models can automatically adjust geometric models in response to dynamic real-time data [28]. Thus, the combination of kinetic façade and parametric modeling has the potential to improve the control of lighting in buildings to meet users' comfort by employing responsive components [29,30]. Patterns play the leading role in predicting the performance of kinetic façades through parametric modelling. Kinetic patterns are formed by multiple singular movements [18] to provide various façade compositions.

Geometric patterns have been popularly used in architectural designs, primarily due to their function as an element in adorning surfaces [31]. Due to their systematic symmetry and mathematical nature, Geometric patterns can easily be generated as single reproducible modules with parametric tools [32]. Porosity in these patterns can link the function of light to the façade as a filter between the outside and interior to create games of reflections and shadows while concealing the direct penetration of natural light [6]. Geometrical patterns have shown profound effects in ancient Architecture as an environmental solution for daylight [33]. For instance, Mashrabiya is a traditional latticework shading system in Arab countries. Hence, integrating geometric patterns with kinetic façade can strengthen the relationship between daylight and indoor conditions and, consequently, optimal building performance.

This paper aims to explore how various parametric and kinetic shading devices enhance daylight performance and reduce lighting energy use in a unified system as a suggestion tool for improving indoor health for educational spaces based on platinum LEED v4. Educational buildings are among the most important fields for daylight solutions, as optimal daylighting can improve students' mood, concentration, behavior, and learning process in general [10]. To explore this idea, kinetic shading forms will be created in Rhinoceros and Grasshopper; and daylight and glare metrics will be simulated using Radiance and OpenStudio interface [34] and optimized using Wallacei to find the best pattern solution for user comfort in terms of daylight performance. This will help designers expand the use of kinetic façades with optimum patterns with simulation in the early stage of the design.

2 Literature Review

2.1 Daylight and lighting energy

Daylight as a renewable source is a primary element that can create significant and suggestive spatial experiences for users [1]. As defined by Christoph Reinhart, daylight in architecture is the interplay of natural light and building form to provide a visually stimulating, healthful, and productive interior environment [35]. Therefore, daylit spaces are commonly considered as pleasant work environment [8]. The most obvious effect of daylight is on vision, in which the higher retinal illumination, the faster and finer will be the performance of the visual system [3]. In fact, light, other than being fundamental to visual tasks, has other effects on the process of body's living organisms [36]. The adequate light received during the natural day period synchronizes the internal biological clock, stimulates circulation, increases the production of vitamin D, regulates protein metabolism, and controls the levels of a number of hormones such as cortisol (the 'stress hormone') and melatonin (the 'sleep hormone') [37]. Moreover, daylight— with its fluctuations, spectral composition variations, and provision for external views— can enhance productivity, release stress, and reduce absenteeism in educational buildings (Altomonte, 2009).

High-potential daylight further affects users' experience in space through the view to the outside. The provision of a view to the outside is promoted in buildings through the LEED rating system as a means of relieving stress [3]. Stress can bring up emotional activities, such as arguments, uncomfortable environmental conditions, and behavioral changes such as poor productivity and performance [38]. However, entry of daylight in a space can be accompanied by direct solar incidence [39] which provides more than adequate illuminance on the task that is prone to produce excessive luminance ratios, as the luminance of the sky is usually much higher than the luminance of interior walls. According to the International Commission on Illumination (CIE) [40], this can cause an unsuitable spreading of light sources and glare, an extreme contrast that distracts the viewer from their concentration [3]. Glare can cause symptoms of eyestrain, such as sore eyes, blurred vision, double vision, and headaches [3,41]. Consequently, some daylight control techniques are required for a proper daylight design, such as a movable façade that does not block the view [42]. In a full and effective approach to daylighting, the design should control direct sunlight, create a uniform distribution of daylight, provide view and connection to the outside, and maintain ambient lighting demand [43].

The magnitude of daylight in space is determined through illuminance level. Illumination is the amount of light that reaches a point on a given plane in an interior, or the flow of light, measured in lumens, that strikes a unit surface area of one square meter and creates a unit lux(lx) illumination [6]. Illuminating Engineering Society (IES) [44] recommends the light level of 200 to 1500 lux according to the task. There are different quantitative performance metrics to assess illuminance levels such as Daylight Factor (DF). It defines the ratio of outdoor illuminance over interior spaces illuminance in percent. However, DF does not consider the season, time of day, variable sky conditions, building location, or any movable shading devices in design recommendations [39]. Today's design context requires the use of three-dimensional CAD software as well as a daylight simulation model. Therefore, dynamic daylight performance metrics should be used. These metrics are based on time series and extend over the whole calendar year. Daylight metrics show the changes of daylight over diurnal and seasonal sun's position and light [6]. Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE) are different metrics to measure interior dynamic illuminance.

DA uses work plane illuminance as an indicator of whether there is sufficient daylight in a space so that a user can work by daylight alone [35]. IES recommends the minimum required illuminance levels for different space types, as it is a threshold between 300 lx and 2500 lx. As a result, DA measures the quantity of daylight absorption on a given plane in space and identifies the intensity of direct sunlight [6]. The other factor, UDI, is defined to make it easier to interpret and read illumination levels recorded in an interior space. It explains that daylight levels are 'useful' for the user when it is associated with 500 lx (UDI

autonomous), neither too dark 100 lx (UDI fell-short) nor too bright 2500 lx (UDI exceeded) [45]. The upper threshold is meant to detect times when an oversupply of daylight might lead to visual discomfort, irritating glare, and overheating [6] (Fig. 1).

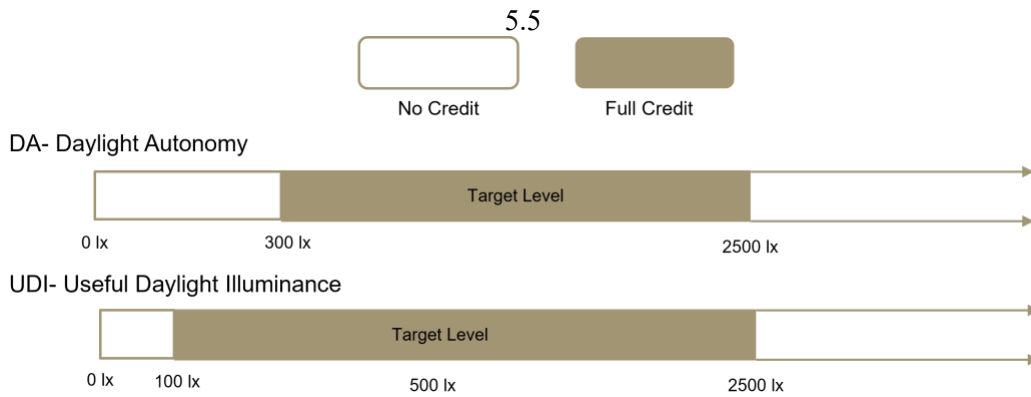


Fig. 1. DA and UDI schemes [6]

Daylight Glare Probability (DGP) is another criterion that enables evaluating the influence of both direct illuminances at the eye level and luminance contrast to determine the final glare condition for occupants. Glare is "an unpleasant sensation in human vision caused by contrast or luminous intensity that is brighter than the illumination level to which the eyes are adapted" [46]. The probability of daylight glare has been divided into four categories: imperceptible, perceptible, disturbing, and intolerable, with values ranging from $DGP \leq 0.35$, $0.35 < DGP \leq 0.40$, $0.40 < DGP \leq 0.45$, and $DGP > 0.45$, respectively [35].

sDA also defines what amount of a space collects enough daylight. Precisely, it defines the percentage of floor zone that obtains no less than 300 lx for at least 55% of the yearly inhabited hours [47]. The graphic below depicts how daylight analysis based on the sDA parameter allows for precise reading of varying conditions on the work surface, creating micro areas that allow for the differentiation of areas where the sDA has been achieved and areas where the percentage is Appreciable, required, or Inadequate [47,48] (Fig. 2).

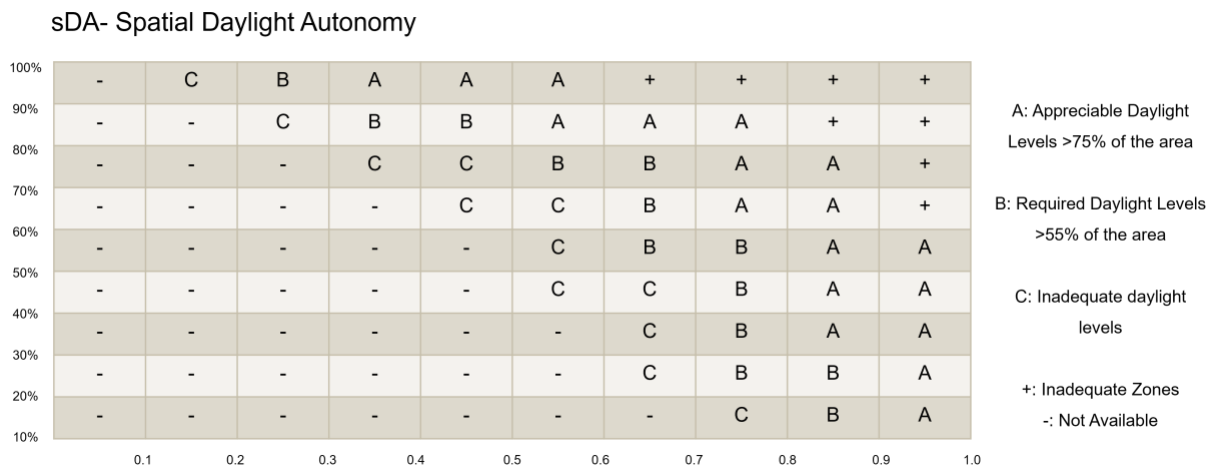


Fig. 2. sDA scheme [47]

sDA also calculates ASE which defines how much of space collects excessively direct sunlight, more than 250 hours of direct illumination per year, where 'direct illumination' means a quantity higher than 1000 lux

through the apertures [6]. ASE provide a reliable estimate of the amount of harmful radiation to which an object is subjected with reference to the presence of sources of visual discomfort (glare). Thus, according to LEED v4. [49], dynamic daylight metrics coupled with climate data at the boundary solar positions can measure illuminance levels for different design recommendations.

Providing daylight in a building is an essential factor to affect building lighting energy efficiency [45]. Since daylight illuminance data can also be used to predict a building's lighting energy and increase energy efficiency, an accurate assessment of indoor daylight illuminance is crucial to saving lighting energy. Furthermore, lighting energy usage is responsible for 20%-30% of the building energy consumption [50]. As a result, efficient daylight control can cut lighting energy use by 30%-60% annually [51,52]. Hence, to achieve an optimal use of daylight and reduce lighting energy consumption, illumination studies should be combined by daylight controls [53].

2.2 Kinetic façade

The most iconic and recognizable element of the building is its Façade. Façade traditionally describes the vertical construction plane, while envelope refers more generally to the total building enclosure. The expression building skin initially underlines the distinction between the cladding and the structural parts but has been more recently recognized as an intelligent system [12] that can adapt and interact with the environment. Generally, facades have been static systems and were not designed to change and respond to climatic conditions [13]. However, facades should control indoor comfort for users by providing enough sunlight and visual connection to the outside [13] over time. Therefore, responsive skin systems emerged in the form of kinetic technology with a predefined set of orders, with no room for processing or reasoning in response to unforeseen natural forces [8]. Over the past few decades, the use of glass in educational buildings has become dominant for transparency, view, and daylighting purposes. As a result, kinetic systems have been used widely due to their interactive abilities [8].

The kinetic façade system consists of multifunctional patterns which can change their configurations with dynamic motions in response to the surrounding environment and users [54]. The first-time *kinetic architecture* was introduced by William Zuk and Roger H. Clark in 1970. Zuk defined kinetic architecture as the ability that building components possess to adapt to climate and environmental conditions through kinetic movements that can be reversible, adjustable, deformable, incremental, and changeable through mobile modes [55]. Definitions regarding the kinetic façades are comprehensive as any research group has defined their word to describe the dynamic behaviours of kinetic architecture [14]. For instance, 'performative' [56], 'adaptive' [54], 'responsive' [57], or 'dynamics' [58] are some different terms to manifest the functional and flexible attributes of building skins based on their performance and functionality.

The kinetic structures can be classified into different approaches [12], among which two of them are significant in this study. The first approach introduced by Hoberman Associates, who developed a mechanical, light, and flexible structure that produces a singular, minimal motion as the structural component folds in on itself. The second approach was founded by the MIT Kinetic Design Group, who provided a taxonomy of control systems for kinetics [59], grouped them into three categories: deployable, dynamic, and embedded. The group describes the embedded as a fixed system in space; the deployable as a temporary one, which is easily portable; and the dynamic as a independent system controlled by a larger context. This research will focus on the embedded type. The embedded system can directly measure and comparatively analyse quantitative values; it also directly impacts the building users and their comfort by controlling factors such as light, thermal comfort, and ventilation [18].

The kinetic façade with its transformable, dynamic, and interactive components should consider both external factors and human comforts [17], regardless of building type or climate [60], as Michael Fox states:

“The primary goal of intelligent kinetic systems should be to act as a moderator responding to changes between human needs and environmental conditions” [61,62]. Some environmental conditions to ensure or improve the functional requirements of the façade are heat, air, water vapor flow, rain penetration, solar radiation, noise, and fire. Among all different environmental conditions, solar radiation affects the building more than others, approximately 80% [60]. On the other hand, human comfort factors are thermal comfort, energy performance, indoor air quality, acoustic performance, and visual performance [60]. Since the human comfort concept has evolved in this research, the kinetic façade can potentially respond repeatedly and reversibly over time [60] as a solution to improve the indoor environment, such as thermal and visual comfort of users [63].

Exploring comfort conditions lead to utilizing complex fenestration systems facilitated by the kinetic façade to achieve trade-off solutions for conflicts between visual and thermal comfort [9,64,65]). Kinetic shading forms can reduce unbalanced daylight penetration to the building and keep out the glare at specific periods [8]. These moving elements of the kinetic facade can be programmed to respond to varying environmental conditions, time, levels, and types of occupancy to improve performance and human comfort [8,63]. For instance, Al-Bahr Towers demonstrate (Fig. 3) the potential of kinetic façade systems that provide appropriate daylight levels for the indoor environment. The study also shows that the kinetic façades have an outstanding ability to enhance the daylight performance of the indoor environment over conventional façades. The central aspect of Al-Bahr Towers is the reinvention of the traditional Mashrabiya with advanced technology, the mechanism of the triangular shading panels based on a linear actuator’s response to the sun’s movement in order to provide solar and glare protection and maintain privacy [66].

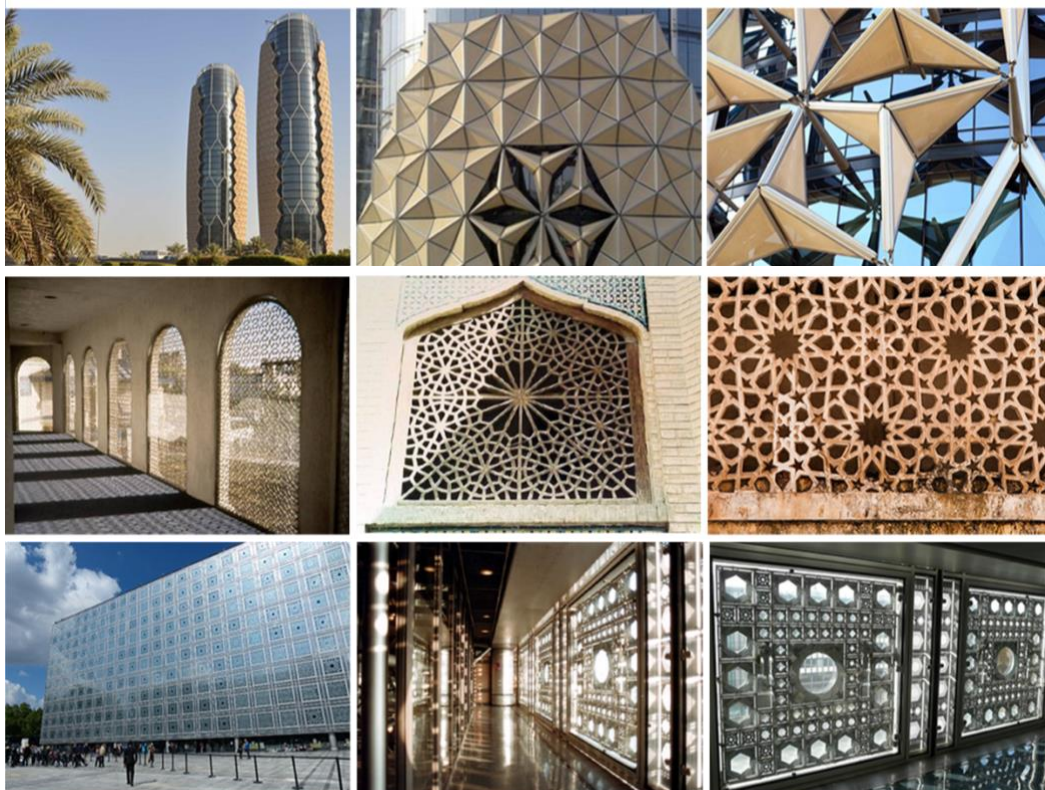


Fig. 3. Al-Bahr Towers by Aedas Architects (Top) [67], Shobak. (middle) [68], The Institute Monte de Arab by Jean Nouvel (Bottom) [67].

2.3 Geometric Pattern

Geometric patterns are widely used in building elements due to their characteristics of regularity both in nature and artificial designs [31]. Beauty, balance, and symmetry are qualities of geometric patterns which are based on the intellectual integration between mathematical and geometric science with art and architecture [69]. Geometric patterns are ornamental elements that are widely used and have evolved according to time and region [70]; however, in architecture, geometric patterns are not merely ornamental but also, due to their environmental performance, they are applied to perforated screens or shading lattice [71]. For example, daylight penetration through perforated screens can create a uniform daylight distribution over the building [71]. Therefore, actuating these geometric screens as external panels allows daylight to enter the building while controlling thermal discomfort and glare [72].

Using geometric patterns as shading screens resembles a traditional solution in Iran known as Shobak (or Shabake) (Fig. 3) that is an unglazed latticework to provide daylight control, view to the outside, space privacy, ventilation, and the reduction of glare [71]. Studying patterned shading screens includes quantitative measurement of sufficient daylight autonomy, illuminance, visual comfort, and the annual glare [71]. Several studies have assessed the quantitative aspects of these screens. For example, Francesco Ruggiero and his colleagues found that the Islamic wall allows a more uniform luminance distribution within a confined environment, which is necessary to create visual comfort conditions [73]. Another research was offered by Nermin Abdel Gelil, which studied the use of traditional latticework named Mashrabiya and the Japanese Machiya-goshi. This research proposed a new alternative to adjust the degree of privacy, airflow, and daylighting performance, which was assessed simultaneously using genetic algorithms [74]. Therefore, adding kinetic characteristics to these shading screens can enhance daylight-control capacities. For instance, the Institute Monte de Arab in Paris, designed by Jean Nouvel (Fig. 3), perfectly combined high-tech modernity with Mashrabiya to adapt to changing conditions and control daylighting performance [16,75]

2.4 Parametric Design

The parametric design is a process based on an intelligent algorithm that allows to encode, define, determine, and clarify the geometrical relationships of particular values [76]. The word parametric stems from mathematics and utilizes certain variables or parameters that can change the result of the design system [77]. Parametric models consist of two parts: variables and constraints. Variables are the model's parameters that include the geometrical relationships and numbers, while constraints are the fixed part of the geometry that needs to be achieved [78]. Parametric design is used to fine-tune the best geometrical attributes for particular parameters [18]. Parametric design method has been made on algorithmic-based approach, namely generative design [27]. The generative design is a process that explores complex forms from iterative and straightforward parameters while preserving specified qualities [23]. The essential use of generative and parametric design systems in architecture is to assist designers in discovering new designs and automating some steps of design procedure by computational means [79,80]. In addition, the advantages of parametric design are the abilities to explore larger design space, support design generation, achieve efficiency (multiple design instances in limited time), reduce cost (reduced time and labor), and optimize the design process with accuracy and consistency [81].

The parametric design facilitates multidisciplinary study in the early design stages by integrating daylighting analysis tools [19,21] to propose optimal designs and behaviors that respond to different climates and environmental conditions [82]. It creates complex adaptive systems characterized by their ability to dynamically respond to environmental changes [83–85]. For instance, parametric design and daylighting analysis tools in the kinetic façade can provide model variation while balancing between the view-out maximization and daylight harvesting. At the same time, it delivers a process of continuous deformation of kinetic facade geometric shapes to discover more functional forms or patterns [86]. Thus,

integrating the parametric design with the kinetic façade helps indoor environment to minimize glare, and simultaneously it prevents unnecessary decrease of daylight and keeps view to the outside [87]. Accordingly, a multidisciplinary design platform will be established with more flexible, generative, evaluative, and performance-based designs [63].

In 2008, architectural theorist Patrick Schumacher established the term parametricism. The parametricism explains and iterates the relation between input parameters with the help of parametric software. This kind of software automatically updates the model and facilitates making changes to the project in real-time [77]. One of the most used parametric design software in the field is Grasshopper, developed by David Rutten at Robert McNeel & Associates, as a graphical algorithm editor. Therefore, using computational design tools such as Grasshopper can provide robust operation in the design and optimization procedure via developing an environmentally-conscious architectural design in the early design stages [88,89]. In addition, to set the evaluation criteria for daylighting assessment, Honeybee for grasshopper can be used to facilitate the daylight computational simulation [90]. To further enhance the design process for high-performance solutions, optimization techniques such as the Genetic Algorithm (GA) play an essential role [81,91]. GAs by running sets of simulations in search space, populating generations of possible solutions with random parameters based on predefined criteria [92]. Therefore, the GA plugin in Grasshopper, Wallacei, as an evolutionary engine for multi-objective optimization, uses Non Dominated Sorting Genetic Algorithm-II (NSGA-2) to input different values as fitness number in search of optimal configuration, which can be used for high-performance façade-design optimizations [93].

3 Methodology

Different factors such as daylight and energy should be considered in developing a methodology to measure and enhance building performance. Therefore, various kinetic shading patterns are investigated through quantitative approaches to evaluate and optimize the design objectives dynamically, an acceptable illuminance level, minimum direct sun hours, reduced lighting energy, and the view to the outside. Consequently, five various kinetic shading patterns are tested on a modeled shoebox with a window on the south façade. The procedure is developed in the Rhino3D / Grasshopper [94] Modeling environment. Ladybug/ Honeybee [90] is used for daylight analysis and OpenStudio [34] to estimate lighting energy usage.

The research framework for this research encompasses three steps mentioned below (Fig. 4):

Step 1: This step handles various inputs to explore design space; shoebox geometry setup, adding sensor grid to the shoebox, and creating five kinetic shading patterns. A shoebox with 5m width, 10m depth, and 3m height is generated parametrically in the grasshopper, and the window is embedded on the south façade of the shoebox with an 80% window-to-wall ratio to maximize the daylight penetration into the interior space as much as possible. Materials for the shoebox are also selected with different diffuse reflectance, 50% for the wall, 80% for the ceiling, 20% for the floor, 35% for kinetic shading devices, and 50% for transmittance of the window. After modeling the core geometry, kinetic patterns are designed parametrically in the grasshopper to have seven opening angle degrees (0°, 15°, 30°, 45°, 60°, 75°, 90°). The patterns are selected among five different functional designs, namely, horizontal, and vertical louvers, Mashrabiya, a pattern from Miami City View Garage, and Shobak (Fig. 5).

Step 2: The previously generated shoebox is translated as the Honeybee model (HBM) for daylight assessment. Kinetic shading patterns are added to the HBM as shading devices with 0.1m offset from the window. The following step is to add sensor grids with a scale of 0.5*.05 (total of 200 sensors) and 0.6m offset from the floor. Chicago weather data is used for daylight analysis from the EnergyPlus website. The college building occupancy schedule which represents occupancy presence and density, is also added to run the daylight simulation effectively. Two daylight metrics are evaluated during the simulation, annual

daylight simulation and direct sun hours, to analyze spatial daylight autonomy (sDA) and annual sunlight exposure (ASE). The best practice in defining metrics is to use standard metrics published by organizations such as the US Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) [49]. The simulation aims to meet the sDA (300 lx/55%) and ASE (1000 lx/250h) criteria of platinum LEED v4. sDA illustrates the percentage of floor zone that obtains no less than 300 lx for at least 55% of the yearly inhabited hours [47], and any sDA percentage less and more than 55% defines as inadequate zones and required daylight levels, respectively. Moreover, 250 hours of direct illumination of 1000 lux to analyze the ASE should be less than 10% [6]. Another objective is lighting energy (L-Ene) analysis, which is needed HBM to be translated to OpenStudio model (OSM) and adding the college lighting usage schedule. College lighting schedule is generated form annual daylight analysis to control daylight in energy analysis.

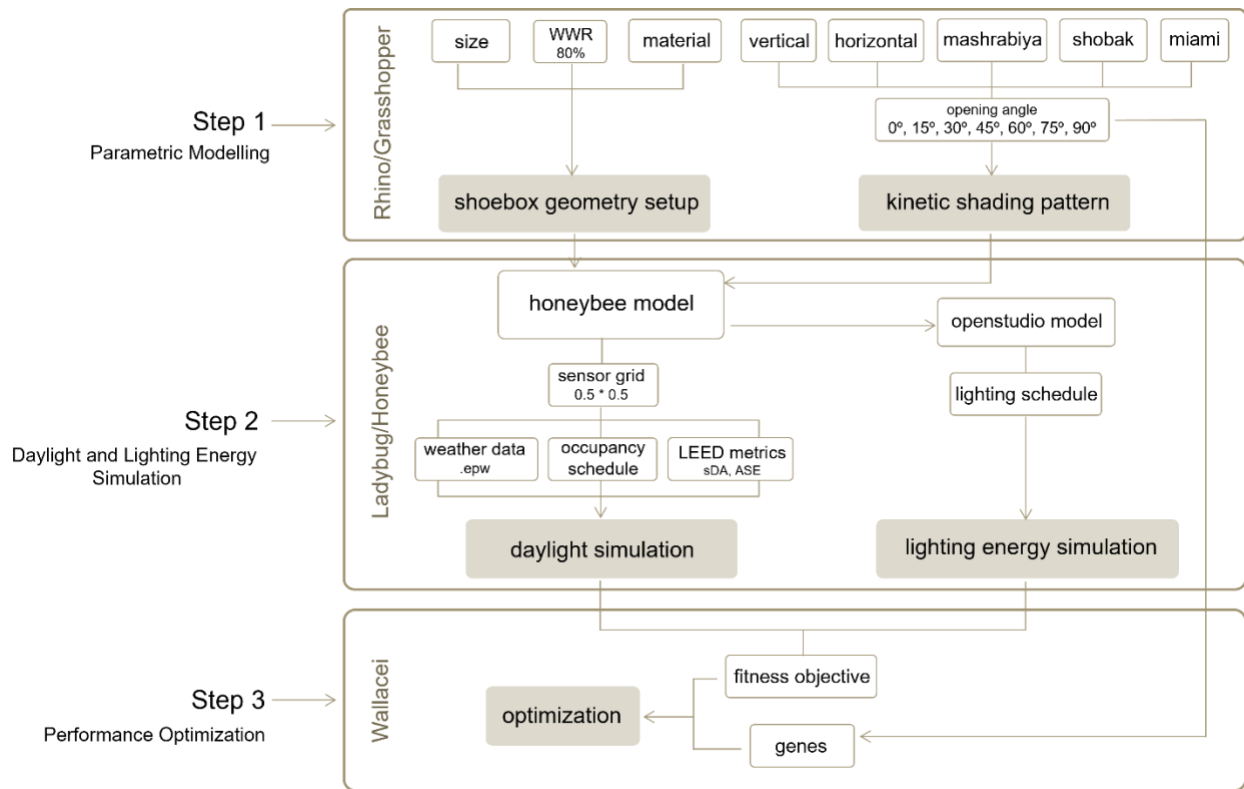
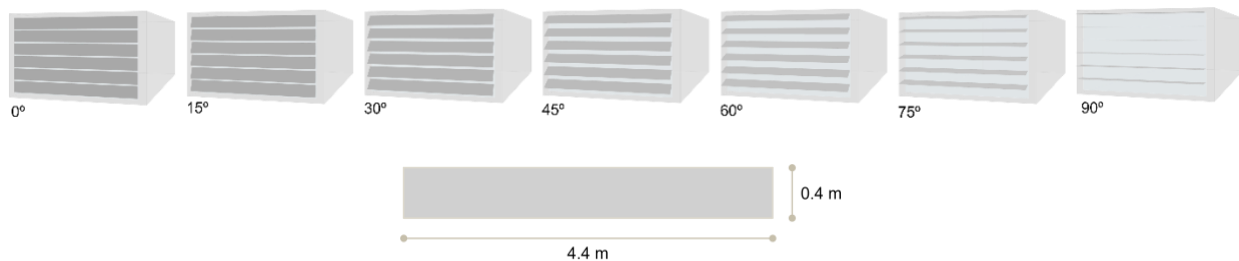


Fig. 4. Overall framework.



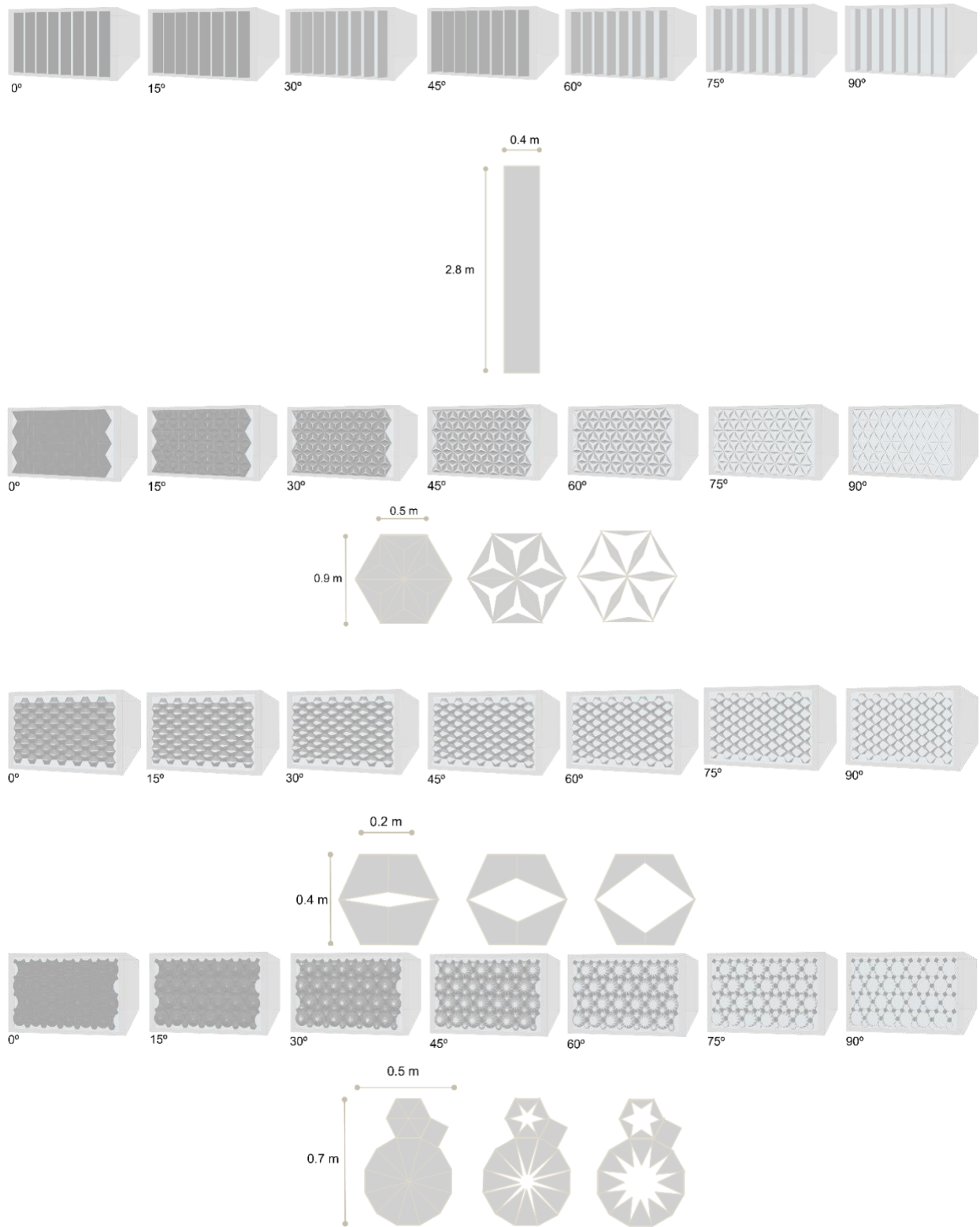


Fig. 5. Top to bottom: Horizontal louvers, Vertical louvers, Mashrabiya pattern, Miami City View Garage pattern, Shobak pattern.

Step 3: Having optimal decision-making requires multi-objective optimization and dynamic trade-offs between objectives. Therefore, daylight simulation results (sDA and ASE) and lighting energy (L-Ene) analysis output are inputted as fitness objectives (FO) and opening angles as parametric variables to run the optimization through genetic algorithms. Optimization was done in Wallacei [93] an evolutionary engine that allows users to run evolutionary simulations with a generation size of 100. The FO is to maximize sDA (300 lx/55%), minimize ASE (1000 lx/250h), and minimize L-Ene as much as possible. Simulation is done for each pattern separately, with 50 generations for the entire population of the objectives. The next step in this process is to decode and filter the simulated result based on FO to select the desired solution.

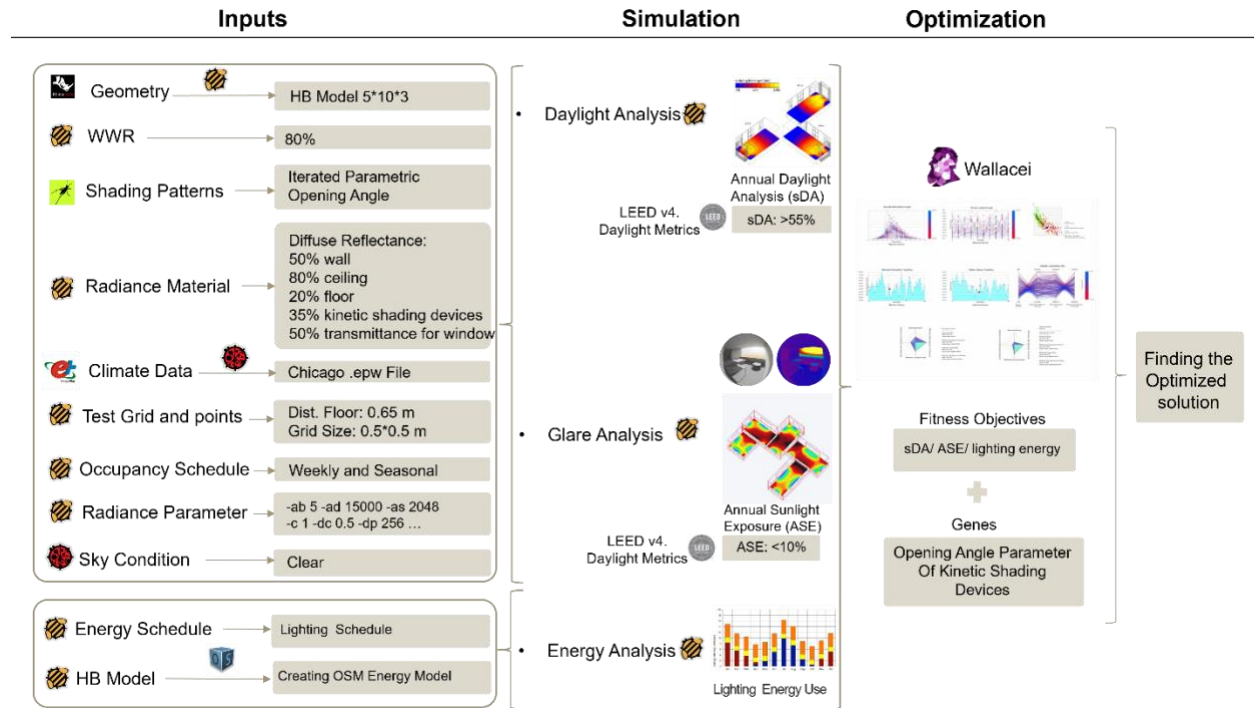


Fig. 6. Detailed workflow.

This early design decision-making framework provides sDA, ASE, and L-Ene estimates, and it can be replicated easily for any other kinetic shading patterns based on their different opening angle degrees and building typology.

4 Results

Five kinetic shading patterns are used as a case study to demonstrate this methodology. Following the methodology steps, daylight metrics (sDA and ASE) and lighting energy (L-Ene) are optimized to adequately start the processing phase with 50 generated data sets for each pattern. After decoding the results and data cleaning, five solutions per pattern were selected for further analysis. These solutions are among the best solutions for each FO which has a rank of 0, the relative difference between fitness ranks that are solutions with equally ranked (0) among the three objectives, and the average of fitness ranks which calculated the average between the three objectives.

After processing the data, a consistent behavioral pattern is determined among all fitness values with a rank of 0 of five patterns. sDA and L-Ene data have a non-linear correlation, which indicates that the higher the sDA percentage, the lower the amount of L-Ene usage is. However, they both show the same opening angles when the fitness rank is 0 for the sDA or the L-Ene, which determines the sDA directly affects the L-Ene amount. On the other hand, ASE and L-Ene have a downward trend; by decreasing the ASE and fitness

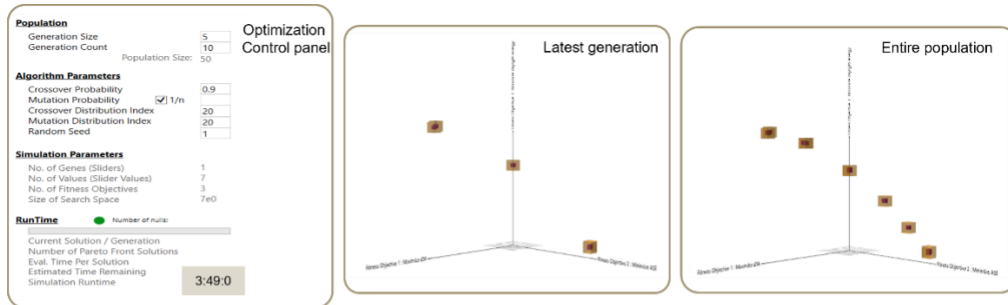
rank of 0, the L-Ene increasing slightly. Following the methodology of using different opening angles for kinetic shading patterns, results show that higher opening angles such as 75° and 90° have a higher rate of sDA and a lower rate of L-Ene. While lower opening angles like 0° and 15° indicate a lower percentage of ASE (Table. 1).

Relative differences between FOs also show moderate opening angles, relatively halfway open for each pattern, which illustrates the possible opening angle for patterns in which all the three FO ranks are 0. Rank 0 indicates an opening angle that can decrease ASE and L-Ene and increase sDA simultaneously. Moreover, the average fitness values mostly show the opening angle of 75° for the average solution between three objectives, which is the optimal solution for this methodology. Therefore, the average between FOs is the calibrated result for the research objectives (Table. 1).

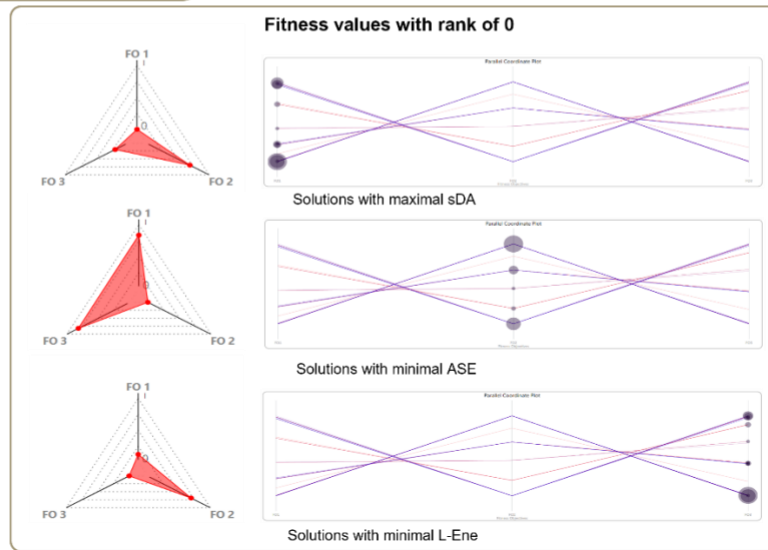
| | Fitness values with rank 0 | | | | | Relative difference between fitness ranks 0 | | | | Average of fitness ranks 0 | | | |
|------------|----------------------------|---------------|------|------|--------|---|------|-----|-------|----------------------------|------|------|-------|
| | fitness objective/rank | opening angle | sDA | ASE | L-Ene | opening angle | sDA | ASE | L-Ene | opening angle | sDA | ASE | L-Ene |
| Horizontal | sDA/0 | 90° | 62.5 | 11.8 | 1070.6 | | | | | | | | |
| | ASE/0 | 15° | 29.2 | 5.1 | 1480.2 | 60° | 54.2 | 8.2 | 1216 | 75° | 56.1 | 10 | 1134 |
| | L-Ene/0 | 90° | 62.2 | 11.8 | 1070 | | | | | | | | |
| Vertical | sDA/0 | 90° | 62 | 12 | 1064 | | | | | | | | |
| | ASE/0 | 0° | 33.6 | 7.8 | 1429 | 45° | 56.9 | 10 | 1220 | 75° | 60.7 | 11.2 | 1090 |
| | L-Ene/0 | 90° | 61.8 | 12 | 1063 | | | | | | | | |
| Mashrabiya | sDA/0 | 75° | 62.5 | 12 | 1098 | | | | | | | | |
| | ASE/0 | 0° | 22.7 | 4.8 | 1557 | 30° | 40.2 | 8.1 | 1408 | 75° | 59.7 | 9.2 | 1093 |
| | L-Ene/0 | 75° | 59.7 | 12 | 1063 | | | | | | | | |
| Miami | sDA/0 | 90° | 56.6 | 12 | 1125 | | | | | | | | |
| | ASE/0 | 15° | 40 | 8.8 | 1340 | 45° | 55.2 | 11 | 1227 | 90° | 56.6 | 12.1 | 1124 |
| | L-Ene/0 | 90° | 56.5 | 12 | 1124 | | | | | | | | |
| Shobak | sDA/0 | 75° | 56.7 | 12 | 1128 | | | | | | | | |
| | ASE/0 | 0° | 34.5 | 7.5 | 1429 | 30° | 45.7 | 9.4 | 1344 | 75° | 56.5 | 9.9 | 1124 |
| | L-Ene/0 | 75° | 56.5 | 12 | 1124 | | | | | | | | |

Table. 1. Results from optimization.

1.



2.



3.

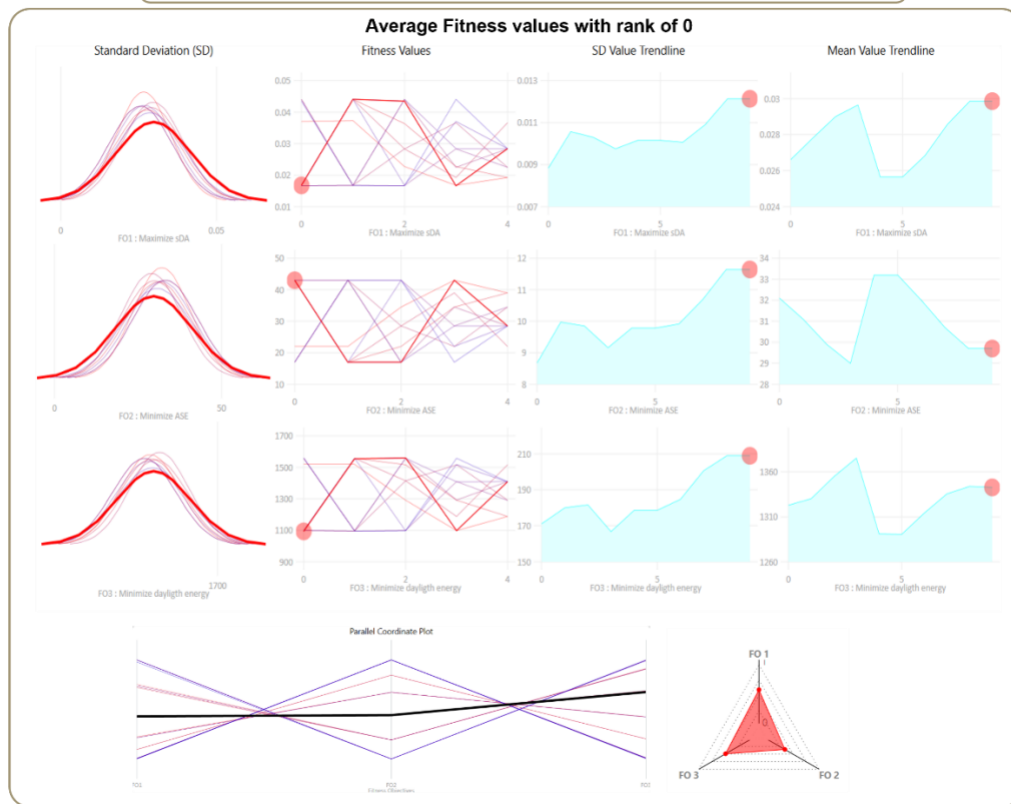


Fig. 7. Mashrabiya pattern optimization results.

Fig. 7. Indicates the optimization results of Mashrabiya pattern with simulation runtime of approximately 4 hours (section 1). Fitness values with rank of 0 indicate the number of solutions for each FO (sDA, ASE, and L-Ene). Diamond charts in section 2, show the most optimal solution for each FO and each axis on the diamond chart represents one of them. The closer the point to the center of the diamond chart the fitter the solution. Parallel coordinate plots analyze all the solutions in the population through comparing the fitness values for each solution across all FOs. The aim is to extract emergent behavior exhibited by the simulation and better understand how the solutions are optimizing throughout the simulation by showing the frequency of the repeated solutions for FOs. In section 3, average fitness values with rank of 0 orders the solutions according to their mean fitness by calculating the mean fitness rank of each solution's fitness objectives (the 'fittest' solution is the one with the rank 0) [95].

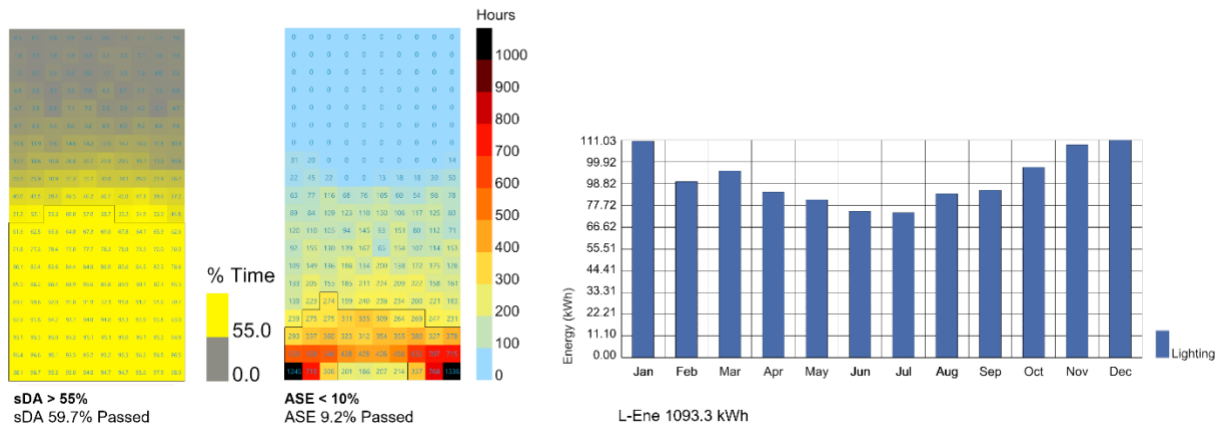


Fig. 8. Mashrabiya pattern daylight and lighting energy simulation results.

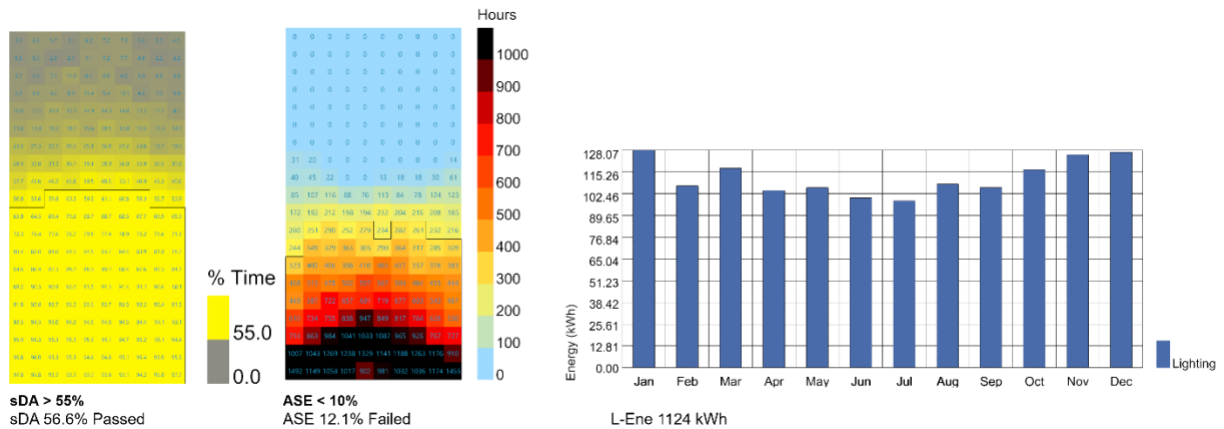


Fig. 9. The Miami pattern daylight and lighting energy simulation results.

Hence, among the five patterns' average fitness values, Mashrabiya, Shobak, horizontal louvers, vertical louvers, and Miami patterns showed the best results, respectively. Mashrabiya (Fig. 8), with an opening angle of 75°, can accomplish sDA of 59.7%, ASE of 9.2%, and L-Ene of 1093.3 kw/h to pass the platinum LEED v4. In contrast, the Miami pattern with opening angle of 90° (Fig. 9), results are sDA of 56.6% and ASE of 12.1%, a failure, which cannot pass the mentioned criteria for daylight.

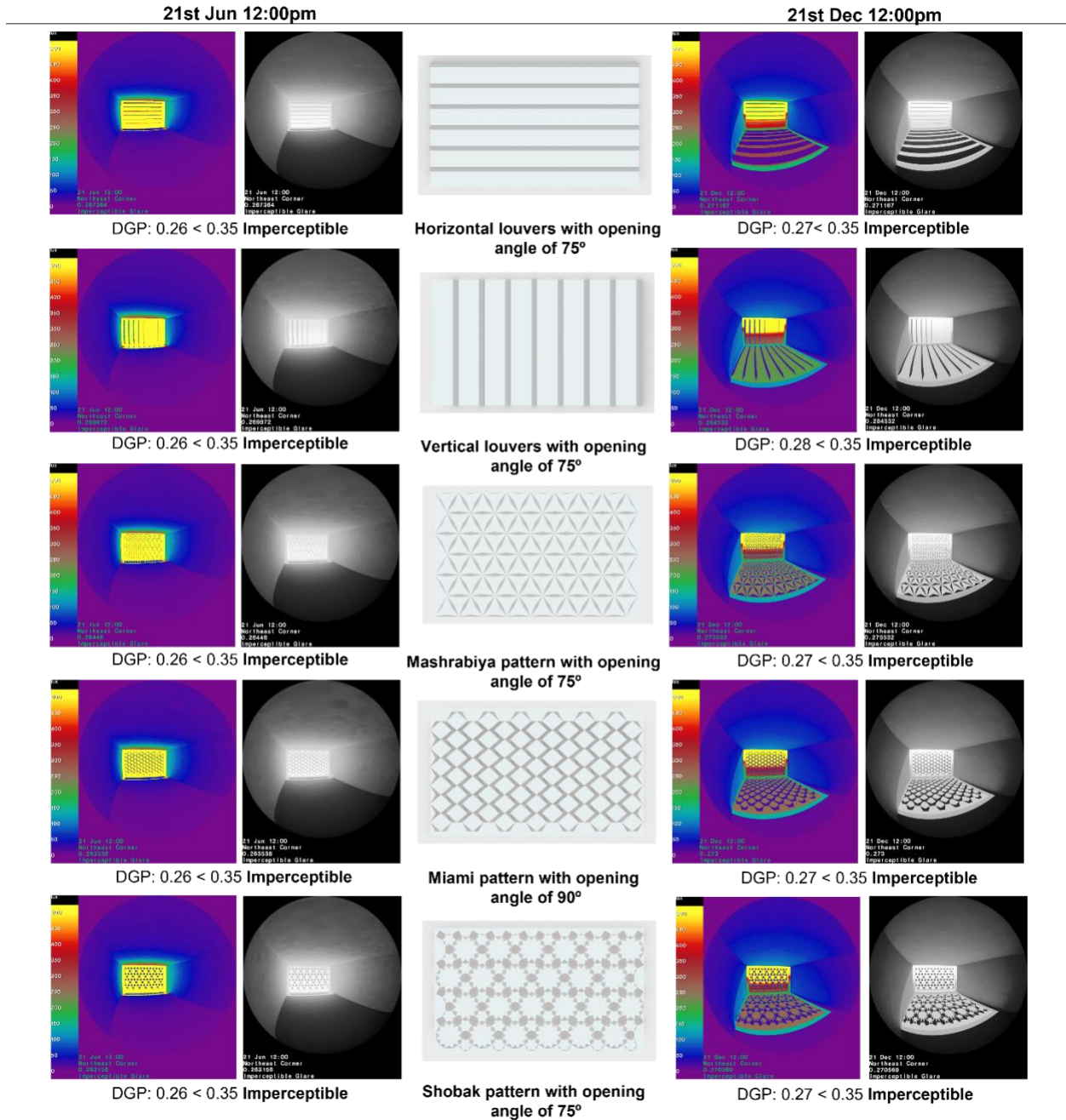


Fig. 10. DGP and façade renders.

Daylight glare probability (DGP) analysis was also done for the average optimal solutions from the optimization to visualize the risk of glare for occupants. Results found all kinetic shading patterns with opening angles of 75° and 90° in imperceptible range ($DGP < 0.35$) at 12:00 pm on the 21st of June and December, achieving complete visual comfort through LEED daylight metrics (Fig. 10).

5 Discussion and conclusion

The interaction of the building's façade with the surrounding environment significantly impacts the amount of useful daylight penetration into interior spaces. As a result, the early design of a façade with

performance-based kinetic shading devices can lead to optimal natural light quality and quantity. Because of the dynamic nature of daylight, the kinetic configuration of shading devices, in particular, can influence visual comfort and daylight performance and reduce lighting energy consumption. Kinetic shading devices with real-time motions can identify the best orientation and configuration for meeting the occupants' needs. Due to their self-shading assets, parametric and modular kinetic shading patterns redirect daylight into the interior space. These features allow for a reduction in the intensity of direct sun radiation while still allowing adequate daylight to enter the interior space. Furthermore, the transition from two to three-dimensional shape changes in the kinetic patterns is a significant decision that considerably impacts daylight performance and visual comfort requirements.

For five different kinetic shading patterns, metric simulation using climate-based daylight metrics, based on different opening angles of the kinetic forms, was performed for horizontal and vertical louvers, Mashrabiya, Shobak, and a pattern from Miami City View Garage. The optimization results show an uncomfortable level of glare (ASE) with an opening angle of 75° and 90° for most of the cases (10% and more). However, those opening angles provide appreciable daylight level (sDA) for the interior space (55% and more). Moreover, enough daylight penetration into the building showed remarkable reductions in lighting energy results.

The observation of this study validates that the accuracy of simulation models can be improved by identifying behavioral patterns using a multi-objective optimization approach. Second, the results confirmed that the proposed kinetic shading patterns could be scaled to an actual college building because of the accurate optimization. The primary outcomes of this research [96] are the optimal opening angle for each pattern with a higher amount of daylight and lower lighting energy usage and glare. The simulated results accurately visualized the shoebox daylight demand and main lighting energy load patterns. Thus, this methodology allows designers and policymakers to accurately test the lighting and energy performance of the potential future case scenarios to decide on the early steps of the design.

Future research can benefit from incorporating emerging technologies such as artificial intelligence (AI) into performance-driven design [97]. This includes the integration of machine learning (ML)-based surrogate modeling approaches [98], generative design methods leveraging deep learning predictions [99], the development of digital twins for real-time monitoring and optimization [100], and employing human feedback systems with advanced NLP analytics [101–103], among other advanced applications. These technologies have the potential to significantly enhance the efficiency, adaptability, and intelligence of design processes.

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