RESEARCH ARTICLE
Published: 6 July 2025
doi:10.15627/jd.2025.18

Volume 12 | Issue 2 | 265-277

OPEN ACCESS

Journal of Daylighting

Journal homepage: www.solarlits.com/jd

Designing a Kinetic Façade to Control Glare: Inspiration of Long-Day Plants Pattern

Fatemeh Fallahi,[1,*] Ferial Ahmadi,[2] Mahdi Khakzand,[3] Yaser Shahbazi[4]

[1] *Faculty of Arts and Architecture, University of Mazandaran, Babolsar, Iran*
[2] *School of Public Health, University of Memphis, Memphis, USA*
[3] *School of Architecture and Environmental Design, Iran University of Science & Technology, Tehran, Iran*
[4] *Faculty of Architecture and Urbanism, Tabriz Islamic Art University, Tabriz, Iran*

Received 7 March 2025; Revised 15 April 2025; Accepted 27 April 2025; Published online 6 July 2025

Citation: *Fatemeh Fallahi, Ferial Ahmadi, Mahdi Khakzand, Yaser Shahbazi, Designing a Kinetic Façade to Control Glare: Inspiration of Long-Day Plants Pattern, Journal of Daylighting, 12:2 (2025) 265-277. doi: 10.15627/jd.2025.18*

ABSTRACT

In this study, to control glare in buildings with glass facades, a kinetic facade was designed using a pattern inspired by nature. Accordingly, in this study, due to the essential similarity of buildings with plants regarding the inability to move and location, in the first step, plants and their morphology were examined. Among them, long-day plants, which offer greater shading capacity than other plants, were selected as the basis for modeling. In the next stage, computational simulations were conducted using Rhino and Grasshopper software along with Ladybug and Honeybee plugins to analyze sunlight and daylight performance. The simulation results of annual climate-based daylight metrics and luminance-based metrics demonstrated that the kinetic facade inspired by long-day plants outperformed the Reinhart reference office room with horizontal shading in terms of glare control and useful daylight. In other words, the kinetic facade designed in this study effectively provides sufficient daylight and prevents glare as well.

Keywords: kinetic façade, long-day plants pattern, glare, bionic

1. INTRODUCTION

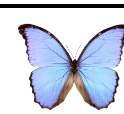
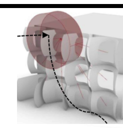
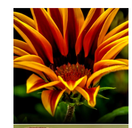
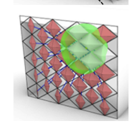
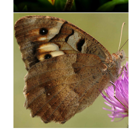
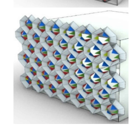
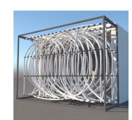
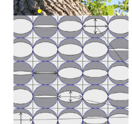
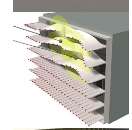
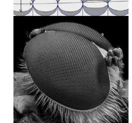
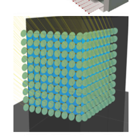
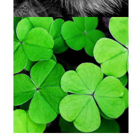
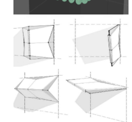
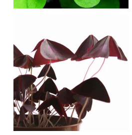
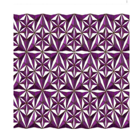
Light radiation is a common problem in modern buildings using large glass facades [1]. As mentioned by Illuminating Engineering Society of North America's Lighting Handbook (IES), glare refers to the sensation caused by light in the visual field that is greater than the brightness to which the eyes have adapted, causing discomfort or loss of vision and visual performance of people [2]. So far, many solutions have been used by architects and designers to control natural light. The set of these solutions are generally divided into passive and active approaches, including prismatic glass, laser-cut acrylic sheet, electrochromic glass, and the category of light guiding systems, such as shelves optical, internal and external shading, optical shaft, anidolic system and kinetic facade [3].

In this research, the kinetic facade is used to eliminate glare, which is in the category of active approach and flexible designs. The design of movable elements in architecture and spaces creates the possibility in architecture that buildings and structures can be more compatible with their surroundings and respond to environmental conditions and meet the needs and desires of their occupants as well [4]. The reason for using the kinetic facade in this research is the change in the sun's position during the day and throughout the year and the need for space flexibility to adapt to these changes. Through this feature, kinetic facades provide natural lighting, improve visual comfort, and control glare in interior spaces, improving environmental quality [5-7], improving the physical and mental well-being of occupants [8]. By adaptability and automatic response to daylight variations and providing natural lighting in interior spaces and also by enabling the design of complex three-dimensional movement patterns [9] they reduce reliance on artificial lighting and increasing energy efficiency and regulating indoor thermal conditions.

*Corresponding author.
f.fallahi@stu.umz.ac.ir (F. Fallahi)
ferial_ahmadi@yahoo.com (F. Ahmadi)
mkhakzand@iust.ac.ir (M. Khakzand)
y.shahbazi@tabriziau.ac.ir (Y. Shahbazi)

In particular, this research is dedicated to solving the problem of glare in office buildings with glass facades. Among the different types of buildings, office spaces require special attention because employees spend long hours working in these sorts of spaces, making them more susceptible to glare-related discomfort. The use of daylight in office buildings is important because of their special arrangement and the type of activity that takes place. Improper daylighting can result in eye strain, decreased concentration, and lower productivity. The benefit of using daylight is its impact on occupants' health including improving physical and mental well-being and increasing productivity at work [8]. From this point of view, solving the problem of glare in these buildings is highly necessary. For this reason, using a kinetic facade can be efficient to solve this problem.

Table 1. Review on bio-inspired adaptive kinetic façade.

OBJECT	METHOD	SOFTWARE	MOVEMENT MECHANISM	FORM/GRID	FUNCTION	USERS' DETECTION AND ESTIMATION	ENVIRONMENTAL TRIGGER	ARCHITECTURAL CONCEPT	BIOLOGICAL CONCEPT	FAÇADE MORPHOLOGY
Daylight control biomimetics kinetic façade [9]	B, BPS, GMA, PD, PS	LB, RH, GH, R	R, S, 3D	CF, HS/R	DP, GP, RTDC, SSD	SU, MP	S	Morpho butterfly wings nanostructure		
Light-responsive biomimetics kinetic façade [39]	B, BPS, PD, PS	LB, RH, GH, R	S, 3D	CF, HS/R	DP, GP, RTDC, SSD	SU, MP	S	Functional principles of the Gazania flower reaction to sunlight		
Improving daylight performance biomimetics kinetic façade [40]	B, BPS, GMA, PD, PS, MOO	LB, RH, GH, R	R, S, Sc, 3D	CF, HS/ H	DP, GP, RTDC, SSD	SU, MP	S	Morpho butterfly wings and integrating them with Orosi window principles		
Improving daylight performance biomimetics kinetic façade [41]	B, BPS, PD, PS	D, RH, GH, R	C, 3D	CF/ R	DP, GP, SSD, RTDC	SU, OP	S	Tree configuration		
Improving visual comfort biomimetics kinetic façade [42]	B, BPS, PD, PS	D, RH, GH, R	R, S, 3D	CF, HS/ R	DP, GP, SSD, RTDC	MU, MP	S	Plant's stomata movement		
Improving visual comfort & harvesting energy biomimetics kinetic façade [43]	B, BPS, PD, PS, F	LB, RH, GH, R	R, 3D	PS/R	T, DP, EE, EP, SSD, RTDC	S	S	Insects' eyes geometrical arrangement with Fresnel lens to concentrate solar rays		
Providing visual comfort & Enhancing energy efficiency biomimetics kinetic façade [44]	B, BPS	Re, In, E	Fo, S, 3D	CF, HS/ R	T, DP, EE, SSD, RTDC	S	S	Behavior of the Oxalis Oregana (Redwood sorrel) leaf in response to sunlight		
Light responsive biomimetics kinetic façade [45]	B, BPS, PD, PS	LB, RH, GH, R	Fo, R, S, 3D	PS/ T	DP, GP, SSD, RTDC	SU, OP	S	Photonastic movement of Irish clover flower		

Note(s):
Method_ Parametric design: PD, Parametric simulation: PS, Building Performance Simulation: BPS, Biomimetic: B, General morphological analysis: GMA, Fabrication: F, Multi-objective optimization: MOO;
Software_ Ladybug Tools: LB, DIVA: D, Ecotect: E, Insight 360: In, Revit: Re, Rhinoceros: RH, Grasshopper: GH, Radiance: R;
Movement mechanism_ Fold: Fo, Rotate: R, Slide: S, Scale: Sc, Curve: C, Three dimension: 3D;
Geometric Form_ Complex Form: CF, Hierarchical Structure: HS, Primary Shape: PS;
Grid_ Rectangular: R, Triangular, T, Hexagonal: H;
Functions_ Thermoregulation: T, Daylight performance: DP, Energy Efficiency: EE, Energy Production: EP, Glare Protection: GP, Sufficient Supply of Daylight: SSD, Real-Time Daylight Control: RTDC;
Users' Detection and Estimation_ Single User: SU, Multiple Users: MU, Space: S, One Position: OP, Multiple Position: MP;
Environmental trigger_ Sun: S

Intended for the above outcomes, in this research, nature inspired patterns are used. This is because these patterns, which are the result of the adaptation of living organisms to their surrounding environment over millions of years, are considered the most suitable ones in buildings construction [10]. For that, in this research the Biomimicry approach is employed. Biomimicry is a scientific approach that studies nature at various levels to derive or replicate its most effective solutions for architectural challenges [11-14]. Biomimicry examines nature on three levels—organism, behavior, and ecosystem— [15,16] while Badarnah categorizes it into physiology, morphology, and behavior [12]. It is worth to mention that principles of biomimicry and biological strategies are used to create facades that adapt dynamically to environmental changes [17-20] and enable diverse approaches to achieving adaptive morphological transformations [21]. Integrating bio-inspired forms with their ability to transform allow for the development of intelligent [22,23], responsive [24], and adaptive [25,26] façade systems.

In this regard, this research was inspired by the patterns found in plants because they have had to adapt to their surroundings due to their lack of ability to move and to maintain their survival with changing environmental conditions. The similarity of buildings in this feature with plants has caused them to be a suitable pattern for architects through the processes of designing [27]. Subsequently, among the different plant species, one type of long-day plant has been chosen to model in this research. It was because the morphology of long-day plants can be a suitable solution for designing a kinetic facade for solving the glare due to the need of sunlight for a long time and the existing pattern in shading on the back space of their petals [28].

From this point of view, the use of this model to eliminate glare through designing of kinetic facade, is considered the innovation of this research and puts this research among the first. Hence, the particular purpose of this research is to use the pattern of long-day plants in the design of kinetic facades of an office building with a glazed facade in Babolsar city, and its essential question is how to eliminate the glare by using the pattern of long-day plants in the design of the kinetic façade in buildings.

In recent years many studies have been conducted on the design of kinetic facades for visual comfort [5,29-38]. Among them, a small number of studies are dedicated to creating kinetic facades inspired by patterns found in nature (Table 1). The most recent research in this field was conducted by Hosseini and his colleagues (2024). By emphasizing architectural aspects and deep biomimetic investigations, in this research, researchers develop a methodology that integrated biomimetic analogies and kinetic behavior to optimize daylight performance and visual comfort in façade design. In this research, inspired by butterfly wings' nanostructure, the researchers found those simpler forms with proper kinetic behavior (e.g., a "Bookshelf" shape) outperform complex forms in daylight efficiency and glare control [9]. Another research in this year's research belongs to Sommese and his colleagues (2024). In their research, researchers, through a multidisciplinary approach, proposed a design for a light-responsive kinetic biomimetic system, inspired by the functional principles of Gazania flower. In this study, adaptive movements of the Gazania flower were studied through a morphological-functional analysis. The results of this research showed that parametric simulations, carried out for different occupant positions in an office building in a temperate Mediterranean climate show that the biomimetic kinetic system is well suited to provide the office space with variable natural daylight between 87,5 % and 100 %, promoting energy efficiency and user comfort [39]. In addition, Hosseini, S.M. and Heidari, S. in their 2022 research, drawing on biomimetic lessons from the Morpho butterfly wings and integrating them with Orosi window principles, studied a kinetic facade system to optimize daylight performance. They used General Morphological Analysis (GMA) and kinetic design strategies to examine how hexagonal modular elements adjust depth and scale in response to dynamic sunlight and occupant positions .The results of this study indicated that the use of this structure led to significant improvements in daylight metrics (UDI, EUDI, sDA) and reduced excessive daylight exposure by 91.8%, while increasing the even distribution of daylight and minimizing glare [40]. Another research in this field again conducted by Hosseini and his colleagues (2021), has been addressed by modeling the morphological changes resulting from the multi-layering and curving of trees for the purpose of regulating sunlight. Based on this and taking into account the dynamic nature of sunlight and with the approach of biomimicry morphology, the researchers extracted the formal strategies of the tree. In this process, these strategies were translated, parametrically simulated and became the basis for the design of the multi-layer kinetic facade. Finally, by evaluating the performance of daylight, they achieved a flexible form of multi-layered and intersecting skin and kinetic vectors with curvature movements [41]. The researchers of this research, in another research, designed their bionic kinetic facade by simulating the movement and distribution of the apertures of plants to receive sunlight. The aforementioned simulated facades had elastic movement and were sensitive to changes in the position of the sun and the inhabitants of the interior space [42]. Rizi and Jahangiri (2021) also designed a kinetic and adaptable facade inspired by the insects' eyes geometrical arrangement to solve the problem of glare in their studied building. The designed façade in this research included Fresnel lenses whose orientation towards the sun, in both moveable and fixed modes, happened in the most optimal possible mode and could solve the problem of glare in mentioned building [43]. In this regard, Tariq Sheikh and Asghar (2019) with modules that were inspired by the formal and physiological characteristics of Oxalis Oregana leaves and imitating the behavior of the plant in tracking the position of the sun, addressed the issue of glare in the studied building. The facade modules designed in this research consisted of 4 panels that were folded in both vertical and horizontal axes and provided visual comfort without limiting the view to the outside [44]. The latest research in this field is dedicated to Mahdavi Kochsaraei and Matini. In this research, in order to solve the problem of glare in the building by analyzing

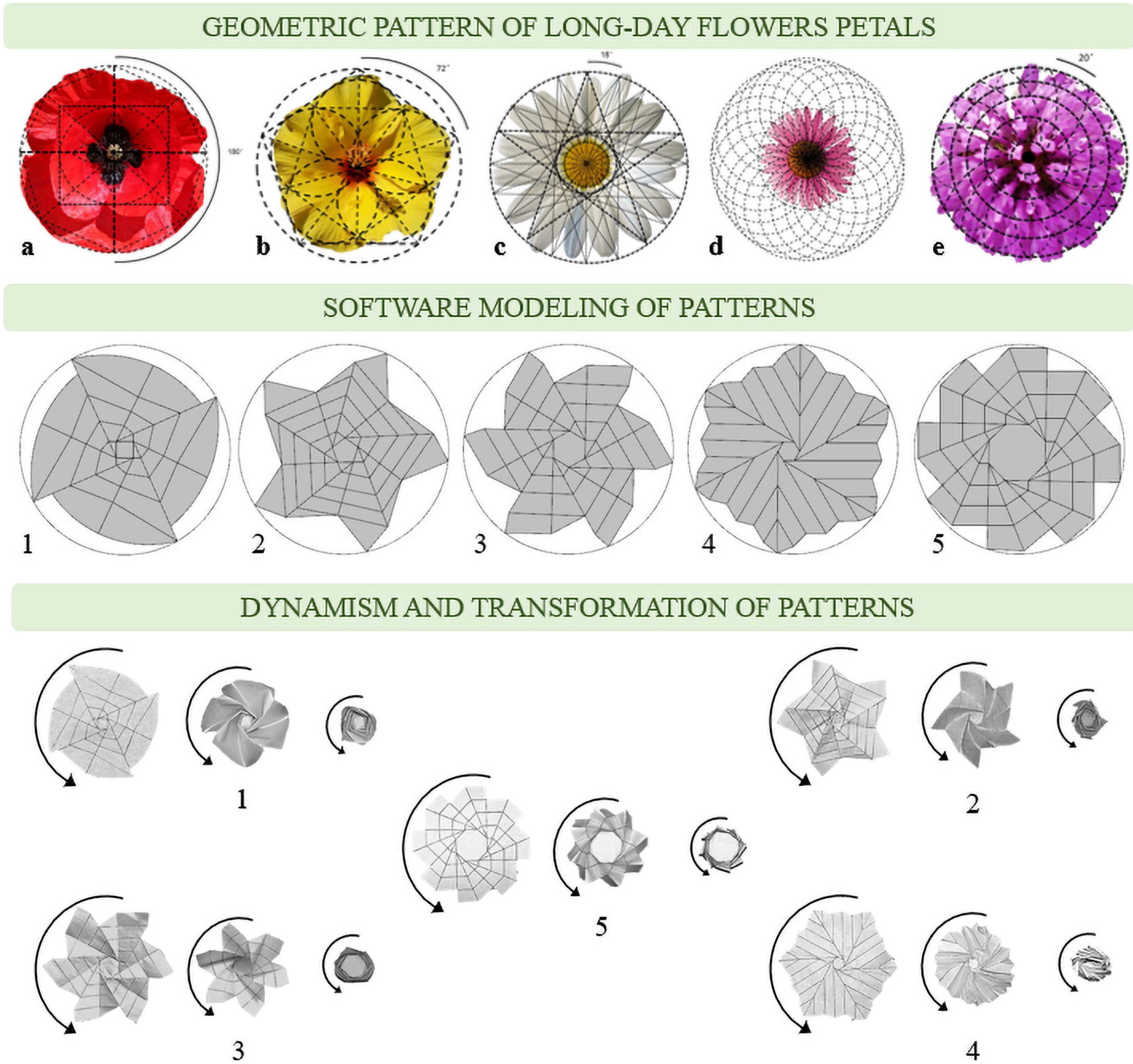


Fig. 1. Geometrical pattern of long-day flowers: (a) Poppy, (b) Alcea, (c) Aster, (d) Echinacea Angustifolia, (e) Red Clover; Software modeling of patterns: Module 5 has the highest coverage based on pixels; Dynamism and transformation of patterns: Steps of opening and closing.

the photonastic behavior of the Irish Clover, in relation to the changes in light, and inspired by the opening and closing mechanism of their petals in response to the light, the researchers designed an adaptative kinetic facade. The geometric pattern extracted for the facade panels in this research was abstracted from the formal structure of the Clover flower and its functional mechanism [45].

However, as mentioned at the beginning of this section, there are still limited studies specifically addressing nature-inspired kinetic façades for glare control. There are some clear distinction points of these studies and the present study. Hosseini et al. (2024), Sommese et al (2024), Hosseini et al (2022), Hosseini, Fadli and Mohammadi (2021) primarily emphasize presenting the general design rather than execution details, such as connections and assembly. Additionally, Rizi and Jahangiri (2021), Tariq Sheikh and Asghar (2019) and Mahdavi Kochsaraei and Matini (2015) focus solely on useful daylight provision without thoroughly analyzing glare control. In our study, the design of the kinetic modules incorporates origami techniques, which not only enhance simplicity and reduce the need for complex connections but also contribute to the aesthetic quality and the manifestation of the natural concept in the design. Furthermore, the façade's connection details have been carefully developed to ensure practical implementation.

2. METHOD

The main goal of this study is to control glare in official buildings. In this case, a kinetic facade has been designed based on inspiring long-day plants pattern. In this regard, basic etudes have been carried out using the morphology of long-day plants. The reason for using this type of plants was due to their greater need for sunlight, they have leaves and petals with wider surfaces and

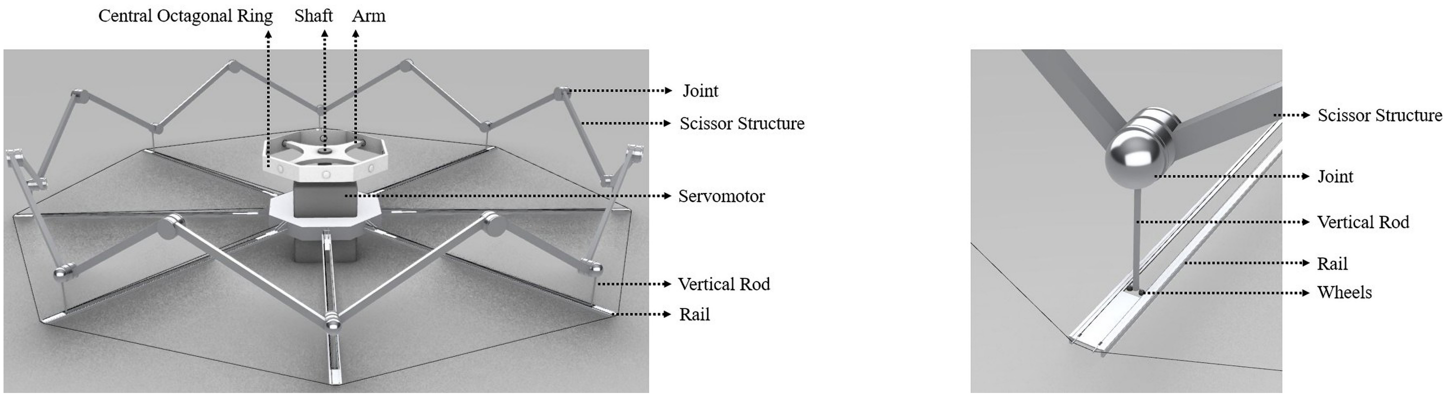


Fig. 2. Details of scissor structure connection in kinetic module.

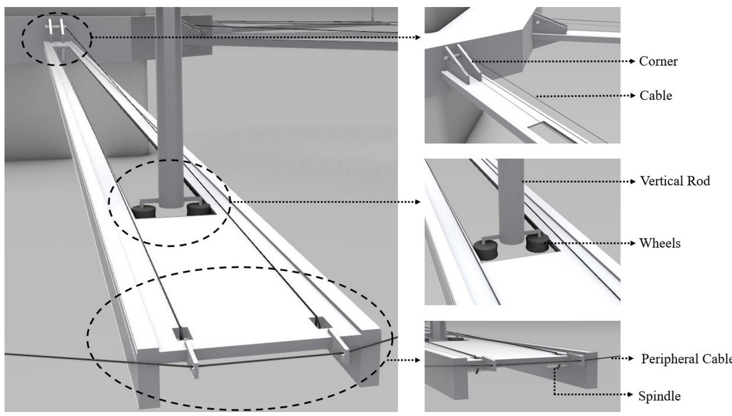


Fig. 3. Details of Rail structure in kinetic module.

therefore more shading than other types. Afterward, the weaknesses and strengths of each etude have been investigated to select the final alternative. Then, the parametric simulation of the final alternative has been done by Rhino 7 and Grasshopper software. Additionally, the movement patterns along with its implementation were designed. It is worth mentioning that Honeybee and Ladybug plugins were used to analyze the light intensity and glare.

2.1. Bionic approach

According to the aim of this study, among two general processes of architectural design based on bionic approach, as top-down (or solution-based methods) and bottom-up (or problem-based methods) [46] this research problem has been solved from the perspective of the form of the organism and through the problem-based method from top to bottom.

2.2. Finding an appropriate pattern using the morphology of long-day plants

The shape of flowers in long-day plants enables the plant to absorb the maximum amount of sunlight. At the same time, this feature prevents sunlight from reaching the part of the flower that is located behind the petals [28]. From this point of view, the patterns of petals in long-day plants can be considered the most suitable option for geometrical patterning in order to create shading in the design of facades modules. Due to this feature as well as the ability of geometrical patterning of these sorts of plants, the morphology of the petals of these flowers are examined. Among the flowers of long-day plants, those flowers which their petals covered more surface were selected for investigation and geometric patterning. In this case, Aster, Alcea, Poppy, Echinacea Angustifolia and Red Clover were selected. The geometric patterns of the above-mentioned flowers were described in Fig. 1.

2.3. Designing kinetic façade module

Based on the geometrical patterning of long-day flowers as noted in Table 1, of the kinetic facade modules was designed. In this regard, various steps were done. First, the initial sketches of the different facade modules were drawn. It should be noted that, their opening and closing pattern along with the possibility of the pattern placement was considered. Afterward, the origami method was used to minimization of rigid members and mechanical joints. The use of this flexible mechanism in designing and constructing of kinetic facades leads to the integrity of the structure, increasing accuracy, reducing the number of parts and the weight of the structure, significantly reducing the tension in the joints, reducing the cost of maintenance and repairing and finally the design financial justification [47]. Moreover, in order to folding lines

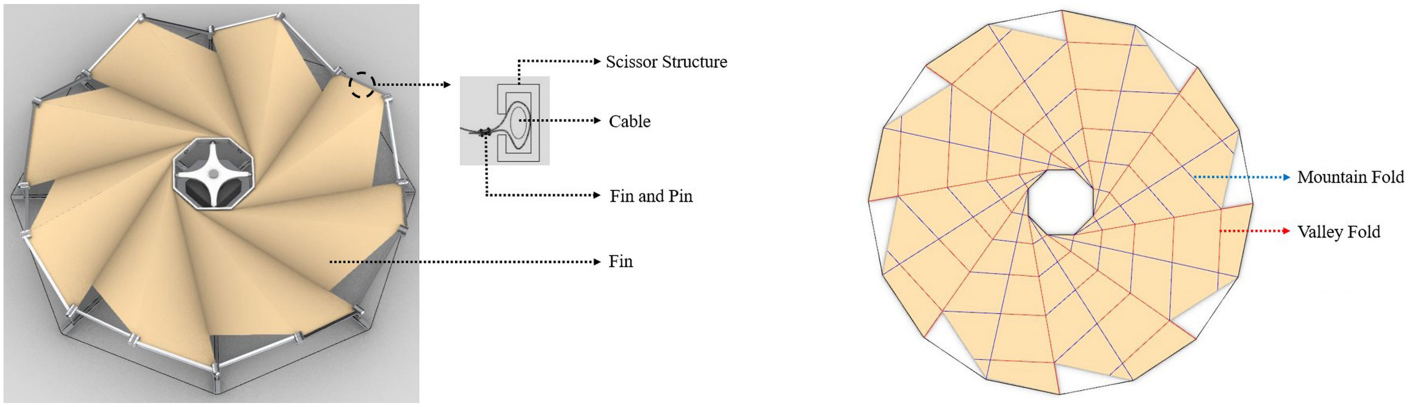


Fig. 4. Details of fins connection to scissor structure & fins folding lines.

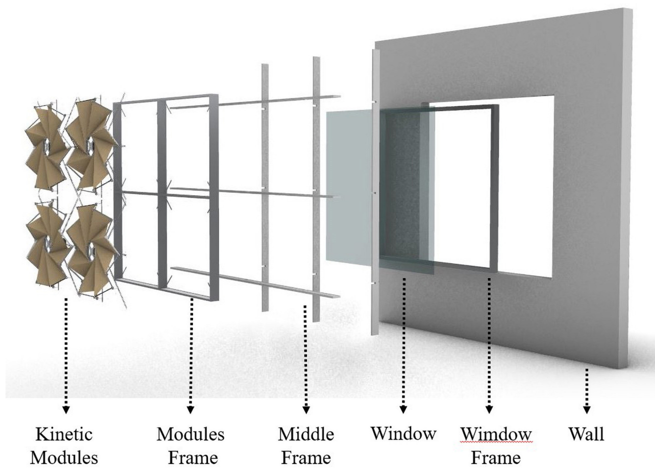


Fig. 5. Details of connection the modules of designed kinetic facade to the wall.

which were consistent in module pattern during opening and closing as well as stacking, the regular geometric shapes were used. Five patterns as facade modules and their opening and closing steps are illustrated in this stage (Fig. 1).

2.4. Module simulation process

After the geometric patterning of long-day plant flowers and the design of five alternative patterns, these modules were modeled by Rhino 7 and Grasshopper software. In order to control glare, a module with a higher coverage percentage were selected. In this case, all presented modules were simulated by Rhino software (Fig. 1) and then the coverage percentage of each of these modules was calculated with Photoshop software, so that the modules with high coverage percentage were determined. In this case, the coverage percentage of module 1-7 were 76.3%, 47.5%, 52.2%, 61.7% and 85.1%., respectively. As a result, based on the highest coverage percentage, modules 1, 4 and 5 were selected for parametric simulation.

After simulating these modules, it was found that a module with more sides in central geometry has had better performance during opening and closing. Additionally, and the fins of mentioned modules had less interference. Since, the form of folding the modules was also important; the more the fins were folded inward, the less damage the module will have against weather conditions and environmental changes such as wind. As a result, module 5 was the final and the best choice.

2.5. Module operation details

According to the initial design and the simulated parametric model, the facade module consisted of fins that rotated around the central octagonal ring. The rotation of these fins was done by the central servomotor. A servomotor was a rotary actuator or linear actuator that allowed for precise control of angular or linear position, velocity, and acceleration. This motor could rotate in both directions, clockwise and anticlockwise. This action caused the opening and closing of the fins as well as their rotation around the engine. In designed module, the engine power was applied to the fins by means of the engine shaft through its arms which were connected to the central octagonal ring. The fins were connected from one end to the central octagonal ring and at the end to the scissor structure. The scissor structure consisted of 16 metal rods that were connected to the fins. These rods were connected to each other with 16 joints and each of the joints was placed on the radial rails with a vertical rod. These rails were connected to the servomotor case and are fixed. The power of the engine was transferred to the scissor structure through the fins, and the

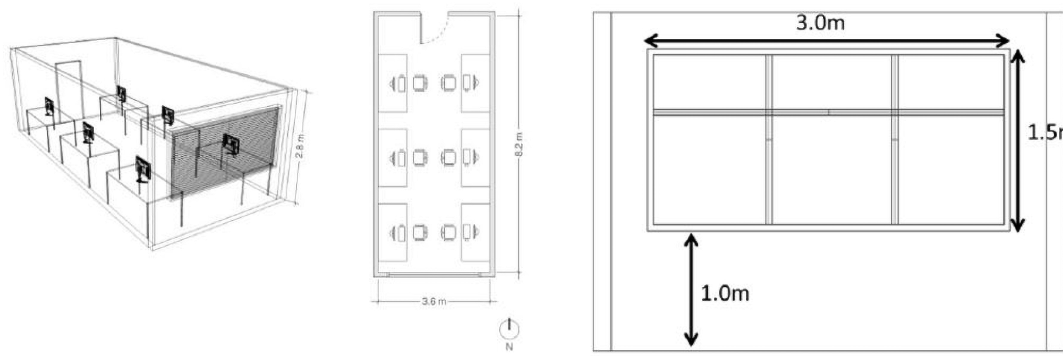


Fig. 6. The plan, perspective and dimensions of the window of Reinhart reference office space [51].

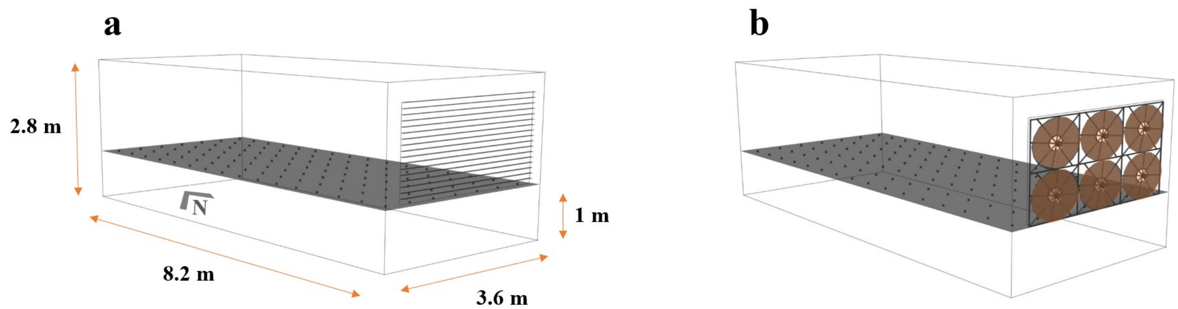


Fig. 7. The Reinhart reference office room and test points with: (a) Fixed horizontal shading and (b) Kinetic facade modules.

opening and closing of the module happens with the movement of the joints on the rail. Figure 2 illustrated this structure (without fins).

Movement of the joints of the scissor structure on the rails was such that 8 of its 16 joints were one in the middle, in the part where the folding of the fins was downwards, by means of vertical rods was located on 8 rails and the vertical rods was moved between the rails by the wheels in the groove (Fig. 2).

The rails are connected to the lower octagonal connecting piece of the engine by means of a corner. These rails are permanently installed to control the movement of the fins on the track, and cables and angles are used to increase the moment of inertia and prevent the rails from buckling. In each rail, two series of cables are connected from the top of the rail to its beginning and end. This connection is such that the beginning of the cable is connected to the bottom of the rail by the spindle and the end of the cable is connected to the corner, and for the balance of the rails and the motor, as well as to maintain the centrality and balance of the weight of the structure, all the rails are connected by a peripheral cable (Fig. 3).

Next, the modular fins are connected in the center with a pin to the octagonal ring and at the end, with a cable to the rods of the scissor structure, which act as sheaths, one in the middle (Fig. 4). This type of connection causes prestressing in the fins. The edge of the remaining fins was reinforced to prevent their vibration. Correspondingly, the color of the fins has been chosen to be matte and pale colors, so that while preventing the passage of light, they also have less heat absorption.

Following, to regularly change the shape of the fins in the desired direction, the lines are reinforced. In Fig. 4, the widest mode of the fins is indicated by folding lines; The blue lines indicate outward folding (Mountain fold) and the red lines indicate inward one (Valley fold).

Afterward, to connect the facade to the elevation wall, due to the lightness of the kinetic facade module, it can be directly connected to the window frame. The method of connection is that the kinetic module rails are connected to a square frame with dimensions of 1 × 1 meter. Then these frames are connected to the interface frames in the form tongue and groove, and the interface frame is placed between the kinetic module frame and the window frame. By connecting the intermediate frame to the window frame, the kinetic modules are connected to the wall with a distance of five centimeters, like the double skin facade. The presence of the intermediate frame allows opening and closing of the window (Fig. 5).

2.6. Daylight simulation process

The research example is a 4-story building with office use. Each office in prementioned building has a window on the south front with dimensions of 19 × 4 meters and a kinetic facade at a distance

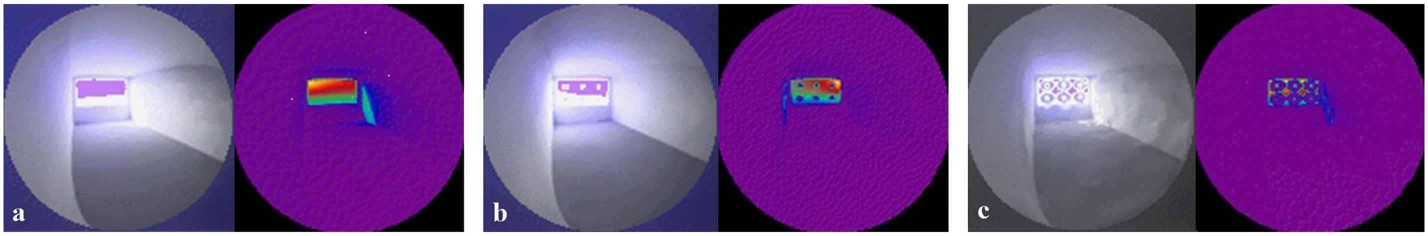


Fig. 8. Simulating the glare, 9:00 a.m., the 21th of March: (a) Fixed horizontal shading; (b) Closed kinetic façade modules; (c) Opened kinetic façade modules.

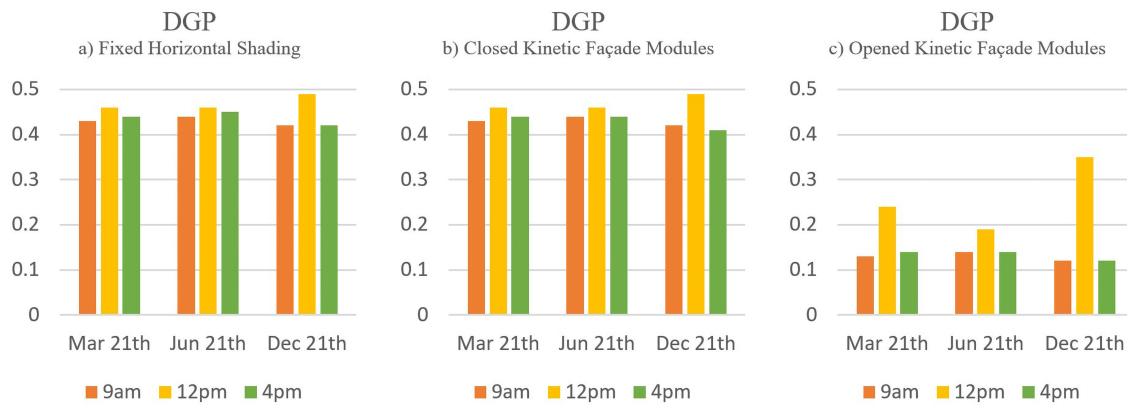


Fig. 9. Glare values (DGP) of: (a) Fixed horizontal shading; (b) Closed kinetic façade modules; (c) Opened kinetic façade modules.

of 5 cm of windows. Also, the Occupancy Kingstone Benchmark (OKB) of the windows is considered 0.25 meters in model. Subsequently, the geometry of the kinetic facade with dimensions of 1 in 1meter and its range of changes, from completely opened to completely closed was determined, and then the materials and time of occupying the space were determined. After determining the parameters related to the geometry of the basic model, the specifications related to the materials have been specified according to the climate and according to the ASHRAE standard 90.1 [48] with the reflection percentage of the roof 0.8%, the floor 0.2% and the window 0.65%.

To determine dependent and independent parameters in light simulation, a plane parallel (control points) to the floor of the space and at a distance of 75 cm from it (equal to the height of the work table) at a distance of 1 meter is considered to show the amount of light received at each point. Considering that the lighting threshold of the office space in different standards is between 300 and 500 lux, 300 lux light is considered as the lighting threshold in this space.

This designed office space with open plan located in Mazandaran province and Babolsar city. In order to implementation of the simulation process, weather information has been used annually from reliable weather files such as the weather files of the Energy Plus 10 site. This information was introduced hourly along with longitude and latitude in the appropriate format as input data to the software.

DGP index depend on the observer's vision and height and its type of performance, including standing, sitting and lying down. Therefore, simulations were repeated in different positions to get the best answer. DGP value is a number in the range of 0-1 and divided into 4 ranges: less than 0.35 (imperceptible glare), 0.4-0.35 (perceptible glare), 0.4-0.45 (disturbing glare) and more than 0.45 (intolerable glare) [49]. Finally, three dimensions user's view was chosen.

After determining the appropriate angle for the simulation, in order to have a more appropriate analysis of the space, daylight simulation has been done to reduce glare and having desirable useful daylight. In this regard, the DGP (Daylight Glare Probability) index has been determined momentarily at 9 a.m., 12 p.m. and 4 p.m. on 21th of March, June, September, and December. And then, UDI (Useful Daylight Illuminance) index was used for simulating daylight that based on standard must be in the range of 100 to 2000 lux [50]. The average amount of received light has been investigated for all hours of a year.

3. RESULTS

The finding of this research includes plenty of evidence of controlling glare by the designed kinetic façade. This segment compromises these evidences in details.

3.1. DGP and UDI analysis in Reinhart reference office room

To analyze the performance of a designed kinetic facade regarding its efficiency in controlling glare, first a comparison was made between the results of the light analysis of the Reinhart reference office room with fixed horizontal shading as the base case, and the designed kinetic facade. The dimensions of Reinhart's reference office space are 2.8 × 3.6 × 8.2 meters [51]. It is worthy to note

Table 2. Percentage reduction in Daylight Glare Probability (DGP) after applying the kinetic façade in base case.

Scenario	Office Hours		
	9:00	12:00	16:00
	DGP Reduction (%)	DGP Reduction (%)	DGP Reduction (%)
Mar 21th	71.43%	44.44%	69.77%
Jun 21th	69.8%	57.78%	70.45%
Dec 21th	73.17%	28.57%	73.17%

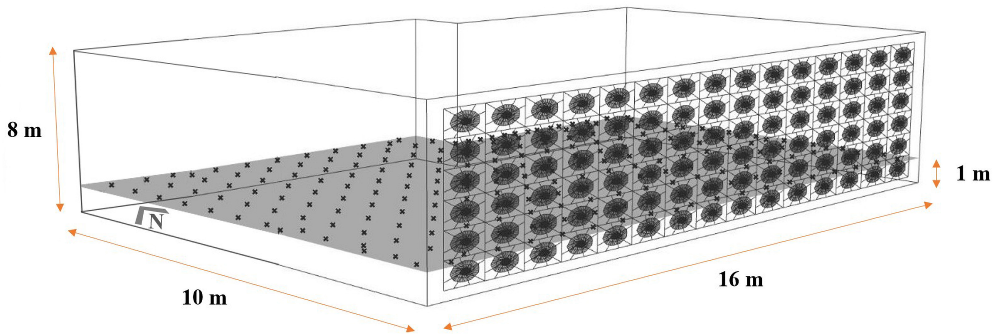


Fig. 10. Location of kinetic facade modules and test points in designed office space.

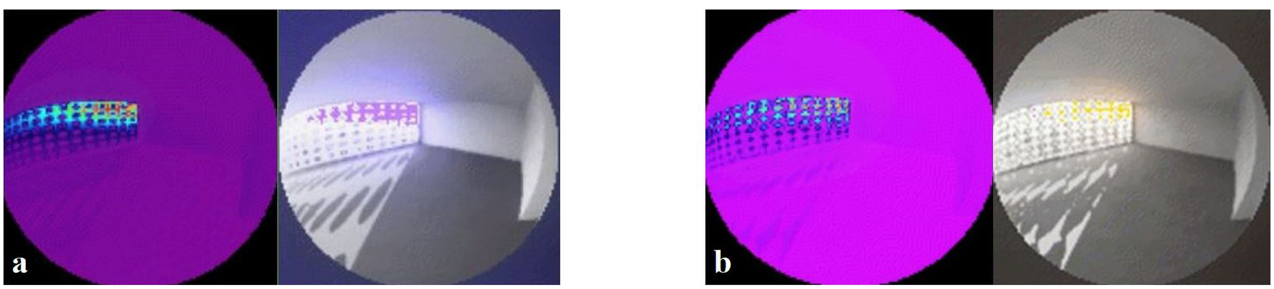


Fig. 11. Simulation the glare, 9:00 am, the 21th of September: (a) Closed kinetic façade modules; (b) Opened kinetic façade modules.

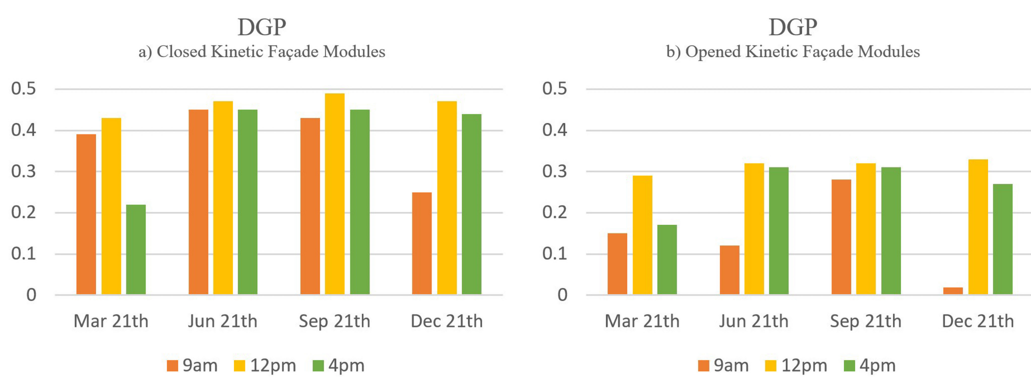


Fig. 12. DGP range of: (a) Closed kinetic façade modules; (b) Opened kinetic façade modules.

that a window of 39% of its wall area (WWR 39%) is considered (Figs. 6 and 7).

The Daylight Glare Probability (DGP) index was evaluated instantaneously at 9:00 AM, 12:00 PM, and 4:00 PM on March 21st, June 21st, and December 21st. In following Figures, outcomes of DGP analysis are presented as an example at 9:00 am on the 21st of March (spring equinox) in the office space of Reinhart reference, with two fixed horizontal shading and designed kinetic facade (Figs. 8 and 9).

The results showed that with the use of fixed horizontal shading, the predicted risk of daylight glare is within the intolerable (DGP > 0.45) and disturbing (0.40 < DGP < 0.45) ranges. This level indicates a significant amount of visual discomfort for occupants who are exposed to daylight glare throughout the year.

Table 3. Daylight Glare Probability (DGP) after applying the kinetic façade in office space.

Scenario	Office Hours		
	9:00	12:00	16:00
	DGP	DGP	DGP
Mar 21th	0.15	0.29	0.17
Jun 21th	0.12	0.32	0.31
Sep 21th	0.28	0.32	0.31
Dec 21th	0.02	0.33	0.26

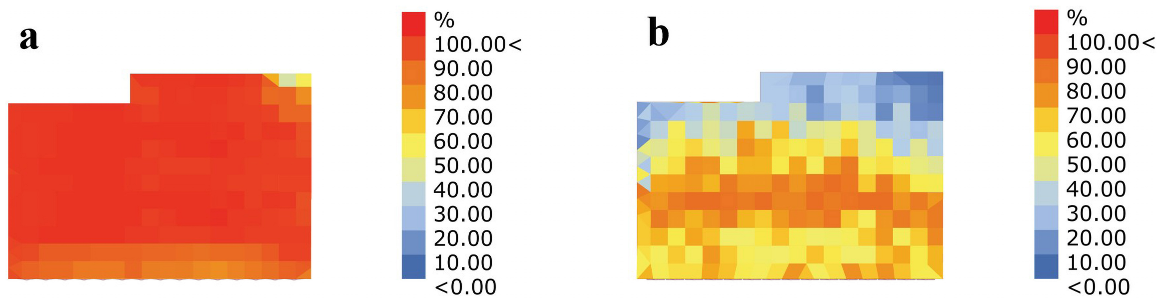


Fig. 13. UDI range of: (a) Closed kinetic façade modules; (b) Opened kinetic façade modules.

In contrast, by replacing the fixed horizontal shading with a kinetic façade, DGP values, respectively, were reduced by 71.43%, 44.44%, and 69.77% at 9:00, 12:00, and 16:00, on March 21. Likewise, on June 21, the reductions were 69.8%, 57.78%, and 70.45%, while on December 21, the values decreased by 73.17%, 28.57%, and 73.17%, respectively (Table 2). In fact, the implementation of the kinetic façade reduced daylight glare levels during peak sunlight hour (12 pm) to the range of 0.25–0.35, and generally placing it within the imperceptible glare ranges (DGP < 0.35).

3.2. Analyzing the useful daylight and glare in designed office space

In this section, a kinetic façade was considered for an office space with large windows (Fig. 10), and the Daylight Glare Probability (DGP) and Useful Daylight Illuminance (UDI) results were evaluated for both open and closed states of the modules (Figs. 11-13). The window for the office space was considered to have a Window-to-Wall Ratio (WWR) of 80% to provide an analysis of the kinetic facade performance in different conditions and configurations. While the kinetic system and module size are the same for all scenarios.

The results from the analysis phase indicated that the DGP values in this space, with the modules in the open position, at 9:00 AM, 12:00 PM, and 4:00 PM on March 21, were 0.15, 0.29, and 0.17, respectively. On June 21, the values were 0.12, 0.32, and 0.31, while on September 21, they were 0.28, 0.32, and 0.31. On December 21, the values were 0.02, 0.33, and 0.26 (Table 3). Consequently, with the implementation of the designed kinetic façade in the office space, the glare levels during peak sunlight hour (12 pm) were reduced to a range of 0.29 to 0.33, thereby generally placing them within the imperceptible glare range (DGP < 0.35).

In following Figures, outcomes of DGP analysis are presented as an example at 9:00 am on the 21st of September (autumn equinox) in the office space, using the designed kinetic façade in both open and closed states (Figs. 11 and 12).

Furthermore, the UDI for the office space, with the modules in the open position, ranged between 60% and 100%, indicating ideal daylight performance for a substantial portion of the annual occupied hours (Fig. 13).

Overall, our analyses in this study showed that kinetic facades reduce the probability of glare to an imperceptible level while still providing useful daylight to the space. This highlights the effectiveness and necessity of using kinetic facades to control glare in buildings exposed to uncontrolled daylight.

4. DISCUSSION

In recent years, research has advanced in the field of kinetic and responsive facades [32-45], which are mainly focused on conceptual design. These designs, which are often limited to simple geometry, are only developed up to the stage of ideation and form design [9,32-34,36-41]. However, by addressing the details of the designed idea system, an important step can be taken to ensure that the initial idea is efficient. Morphological adaptations in response to environmental triggers, especially those derived from plants, provide valuable insights for the design of kinetic facades. Focusing on how ideas are implemented paves the way for practical use.

In this regard, biomimicry emerges as a powerful design strategy inspired by nature-tested solutions. In particular, long-day flowers serve as a key biological reference in this study due to their unique morphology. These plants need long-term sunlight and the morphology of their petals due to their large area are able to absorb maximum light and make extensive shade behind the petals [28]. This research examines how the morphology of the long-day flowers petal can inspire the design of the light-responsive kinetic façade. A biomimetic morphological approach [12,46] is applied to enhance glare reduction and improve visual comfort.

In design of the kinetic facade modules, the origami method was used to minimize rigid members and mechanical joints. The use of this flexible mechanism in the design and construction of kinetic facades leads to structural integrity, increased accuracy, reduction in the number of parts and weight of the structure, significant reduction of tension in joints, reducing the cost of maintenance and repairing, and finally financial justification of the design [47].

This bio-inspired kinetic system is evaluated through annual climate-based daylight metrics and luminance-based metric. The simulation results show a significant reduction in the Daylight Glare Probability (DGP). On March 21, the façade reduced the DGP by an average of 61.88%, and also on June 21, a reduction of 66.01%, and on December 21, the average glare decreased by 58.30%. Overall, in all scenarios, the kinetic façade reduces glare from intolerable (DGP > 0.45) and disturbing (0.40 < DGP < 0.45) ranges to imperceptible ranges (DGP < 0.35).

In comparison with nature-inspired kinetic facades in recent years, for example, compared to studies such as Sommese et al.'s research [39], the kinetic façade designed in the present study performs better in controlling glare with an overall approximation of 19.7% in the DGP index and puts the glare levels in the imperceptible range in all scenarios. While some studies in this field have focused only on the provision of useful daylight without analyzing glare [43-45]. In addition, in the present study, in comparison with similar research [9,39-41], the executive details of the façade from idea to implementation have been discussed. In other words, this study, in addition to presenting a novel conceptual design of long-day plants as an important step in the development of kinetic façade has also dealt with its executive subtleties. This can be considered a practical basis for the integration of biomimicry and morphological logic in architecture in general.

In addition, it worth to be mentioned that the scope of the present study relies on the parametric daylight simulation based on the daylight performance prediction guidelines written by Nabil and Reinhart [50,51] that he applied to evaluate the visual comfort of the occupants. Since the prediction of glare, as an important metric in the residents' sense of comfort, depends on human sensation, it is suggested that future researches in this field investigate the performance of the interactive kinetic façade through experimental studies, in order to investigate its efficiency in its actual application from different aspects.

5. CONCLUSION

Patterns in nature have always been an inspiration in the process of buildings construction. These patterns are the results of living creatures' adaptation to their surrounding environment over long and continued time. Existing patterns in plants also has the same features of other organisms because of their adaption to their surroundings due to their lack of ability to move and to maintain their survival through changing environmental conditions. Hence their various ways of adaptation and their Instinctive solutions permanently has been a great wealth for architects and architecture knowledge. Accordingly, the aim of current study was to design a kinetic façade for controlling glare inspired by geometrical patterns of long-day flowers. Intended that, long-day flowers morphology is investigated to extract the daylight bionic principles. At the second step, those principles translate into the process of designing a kinetic facade. It worth to mention that the morphology of long-day plants can be a suitable solution for designing a kinetic facade for solving the glare due to the need of sunlight for a long time and the existing pattern in shading on the back space of their petals. Cause of this very important feature, as well as the ability of geometrical patterning of the petals of these sorts of plants, we will examine them in this point of view.

At the next stage and based on the geometrical patterning of long-day flowers in the previous section, the design of kinetic facade modules was accomplished. The initial sketches of the different facade modules, their opening and closing, and how to place them together were drawn and after reaching the initial ideas, the origami method was used to minimization of rigid members and mechanical joints and to integrity of the structure, increasing accuracy, reducing the number of parts and the weight of the structure, significantly reducing the tension in the joints, reducing the cost of maintenance and repairing and finally the design financial justification.

According to the initial design and the simulated parametric model, the facade module was designed and then, in order to connect the facade to the wall, due to the lightness of the kinetic facade module, it was directly connected to the window frame by connecting to an intermediate frame to the window frame like the double skin façade to allows opening and closing of the window.

The results showed that the simulations of the annual climate-based daylight metrics and luminance-based metric confirm the best performance of the bio-inspired kinetic façade for controlling glare and having useful daylight in comparison with the Reinhart reference office room with fixed horizontal shading as the base case. the kinetic form shows a significant performance for preventing visual discomfort by decreasing Daylight Glare Probability (DGP) compared to the base case in the solstice and equinox days. Accordingly, by replacing the kinetic facade instead of the fixed horizontal shading, the amount of daylight glare is reduced to less than 0.35 and the glare is laid in the imperceptible range.

This study definitely proves the high potential of the bionic approach for authentic inspiration and meaningful exploration for adequate mimicry aimed at finding functional solutions for resolving buildings problems or extending their possibilities.

FUNDING

This research received no external funding.

CONTRIBUTIONS

F. Fallahi: Conceptualization, Methodology, Investigation, Software, Formal analysis, Visualization, Writing—original draft; F. Ahmadi: Supervision, Formal analysis, Validation, Review & Editing; M. Khakzand: Mentoring, Review & Editing; Y. Shahbazi: Mentoring, Review & Editing.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] M. Pourahmadi, M.A. Khan Mohammadi, F. Mozafar, Optimizing building openings based on efficiency in educational buildings in Iran's hot and dry climate; Case study: university buildings in Yazd city, Architecture and sustainable urbanism, 7(1) (2018) 113-128.

[2] IESNA, The Lighting Handbook Illuminating Engineering, Society of North America, 2000.

[3] S. Rostamzad, M. Faizi, H. Sanyayan, M. Khakzand, Parametric design of movable facade with the aim of improving lighting efficiency and visual comfort, case study: office buildings in Tehran, Journal of architecture and urbanism, 13(31) (2021) 85-100.

[4] N. Afzali, S. Hamzehlou, Introducing and evaluating the performance of kinetic systems and structures in architecture, The 4th International Congress on Civil Engineering, Architecture and Urban Development, Tehran, Iran, (Dec. 2015).

[5] S.M. Hosseini, M. Heiranipour, J. Wang, L.E. Hinkle, G. Triantafyllidis, S. Attia, Enhancing visual comfort and energy efficiency in office lighting using parametric-generative design approach for interactive kinetic louvers, Journal of Daylighting, 11 (1) (2024) 69-96.

[6] S. Attia, S. Garat, M. Cools, Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive facades, Building and Environment, 157 (2019) 268-276.

[7] S.M. Al-Masrani, K.M. Al-Obaidi, N.A. Zalin, M.I. Aida Isma, Design optimisation of solar shading systems for tropical office buildings: challenges and future trends, Solar Energy, 170 (2018) 849-872.

[8] A. Luna-Navarro, R. Loonen, M. Juaristi, A. Monge-Barrio, S. Attia, M, Overend. Occupant-Facade interaction: a review and classification scheme, Building and Environment, 177 (2020)106880.

[9] S.M. Hosseini, S. Heidari, S. Attia, J. Wang, G. Triantafyllidis, Biomimetic kinetic façade as a real-time daylight control: complex form versus simple form with proper kinetic behavior, Smart and Sustainable Built Environment, (2024).

[10] A. Arabidehej, Smart shell design with a sustainable architectural approach inspired by nature (office and commercial building in Tehran), Master's thesis, University of Tehran Architecture Campus, 2013.

[11] J.M. Benyus, Biomimicry: innovation inspired by nature, New York: Perennial, 2002.

[12] L. Badarnah, Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation, Buildings, 7(2) (2017) 40.

[13] R. Vanaga and A. Blumberga, First Steps to Develop Biomimicry Ideas, Energy Procedia, 72 (2015) 307-309.

[14] G. Pohl, W. Nachtigall, Buildings, Architecture, and Biomimetics, in Biomimetics for Architecture & Design: Nature - Analogies - Technology, Eds. Cham: Springer International Publishing, 2015, pp. 9-24.

[15] C. Tavsan, F. Tavsan, E. Sonmez, Biomimicry in Architectural Design Education, Procedia - Social and Behavioral Sciences, 182 (2015) 489-496.

[16] M.S. Aziz, A. Y. El sherif, Biomimicry as an approach for bio-inspired structure with the aid of computation, Alexandria Engineering Journal, 55 (2016) 707-714.

[17] A.N.E. Houda, D. Mohamed, Advanced Building Skins Inspired From Plants Adaptation Strategies to Environmental Stimuli: A Review, 2018 International Conference on Applied Smart Systems (ICASS), Medea, Algeria, (Nov. 2018), pp. 1-7.

[18] I. Mazzoleni, Architecture Follows Nature-Biomimetic Principles for Innovative Design. CRC Press, 2013.

[19] Z. Han et al., Biomimetic multifunctional surfaces inspired from animals, Advances in Colloid and Interface Science, 234 (2016) 27-50.

[20] F. Fadli, P. Bahrami, I. Susorova, M. Tabibzadeh, S. Zaina, E.-S. El-Ekhteyar, Bio-Facades, An Innovative Design Solution Towards Sustainable Architecture in Hot Arid Zones, Qatar Foundation Annual Research Conference ARC'14, Doha, Qatar, (Mar. 2016), pp. EEPP3394.

[21] J.F.V. Vincent, Adaptive Structures - Some Biological Paradigms, in Adaptive Structures, John Wiley & Sons, Ltd, 2007, pp. 261-285.

[22] S. Li, K.W. Wang, Plant-inspired adaptive structures and materials for morphing and actuation: a review, Bioinspiration & Biomimetics, 12 (2016) 011001.

[23] O. Speck, D. Speck, R. Horn, J. Gantner, K. P. Sedlbauer, Biomimetic bio-inspired biomorph sustainable? An attempt to classify and clarify biology-derived technical developments, Bioinspiration & Biomimetics, 12 (2017) 011004.

[24] A. Körner et al., Flectofold-a biomimetic compliant shading device for complex free form facades, Smart Materials and Structures, 27 (2018) 017001.

[25] K.M. Al-Obaidi, M. Azzam Ismail, H. Hussein, A.M. Abdul Rahman, Biomimetic building skins: An adaptive approach, Renewable and Sustainable Energy Reviews, 79 (2017) 1472-1491.

[26] M. López, R. Rubio, S. Martín, B. Croxford, R. Jackson, Active materials for adaptive architectural envelopes based on plant adaptation principles, Journal of Facade Design and Engineering, 3 (2015) 27-38.

[27] D. Rezaei, M. Zare, Plants in arid climate as apattern for bionic in behavioral viewpoint, Canadian Journal on Environmental, Construction and Civil Engineering, 6 (2011) 141-146.

[28] T. Lincoln, Z. Eduardo, Plant Physiology, 3rd ed. Publisher: Sinauer Associates, 2002.

[29] H. Toodekharman, M. Abravesh, S. Heidari, Visual comfort assessment of hospital patient rooms with climate responsive facades, Journal of Daylighting, 10 (2023) 17-30.

[30] A. Tabadkani, A. Nikkhah Dehnavi, F. Mostafavi, H.G. Naeini, Targeting modular adaptive façade personalization in a shared office space using fuzzy logic and genetic optimization, Journal of Building Engineering, 69 (2023), 106118.

[31] S.S. Golzan, M. Pouyanmehr, H. Sadeghi Naeini, Recommended angle of a modular dynamic façade in hot-arid climate: daylighting and energy simulation, Smart and Sustainable Built Environment, 12 (2023) 27-37

[32] S.M. Hosseini, M. Mohammadi, T. Schr¨oder, O. Guerra-Santin, Integrating interactive kinetic façade design with colored glass to improve daylight performance based on occupants' position, Journal of Building Engineering, 31 (2020), 101404

[33] R.A. Rizi, & A. Eltaweel, A user detective adaptive facade towards improving visual and thermal comfort, Journal of Building Engineering, 33 (2020) 101554

[34] S.M. Hosseini, , M. Mohammadi, O. Guerra-Santin, Interactive kinetic façade: Improving visual comfort based on dynamic daylight and occupant's positions by 2D and 3D shape changes, Building and Environment, 165 (2019) 106396.

[35] A. Tabadkani, M. Valinejad Shoubi, F. Soflaei, S. Banihashemi, Integrated parametric design of adaptive facades for user's visual comfort, Automation in Construction, 106 (2019) 102857.

[36] P. Pilechiha, M. Mahdavinejad, M. Moghimi, M. Valitabar, Design Optimum Responsive Façade Based on Visual Comfort and Energy Performance, Learning, Adapting and Prototyping-the 23rd CAADRIA Conference, singhua University, Beijing, China, (Jun. 2018), pp. 93-102.

[37] A. Tabadkani, S. Banihashemi, M. R. Hosseini, Daylighting and visual comfort of oriental sun responsive skins: A parametric analysis, Building Simulation, 11 (2018) 663-676.

[38] Y. Yi, R. Sharston, D. Samer, Auxetic Structures and Advanced Daylight Control Systems, Journal of Facade Design and Engineering, 7 (2019) 63-74.

[39] F. Sommese, S.M. Hosseini, L. Badarnah, F. Capozzi, S. Giordano, V. Ambrogi, G. Ausiello, Light-responsive kinetic façade system inspired by the Gazania flower: a biomimetic approach in parametric design for daylighting, Building and Environment, 247 (2024) 111052.

[40] S.M. Hosseini, S. Heidari, General morphological analysis of Orosi windows and morpho butterfly wing's principles for improving occupant's daylight performance through interactive kinetic façade, Journal of Building Engineering, 59 (2022) 105027.

[41] S.M. Hosseini, F. Fadli, M. Mohammadi, Biomimetic Kinetic Shading Facade Inspired by Tree Morphology for Improving Occupant's Daylight Performance, Journal of Daylighting, 8 (2021) 65-82.

[42] S.M. Hosseini, M. Mohammadi, T. Schröder, O. Guerra-Santin, Bio-inspired interactive kinetic façade: Using dynamic transitory-sensitive area to improve multiple occupants' visual comfort, Frontiers of Architectural Research, 10 (2021) 821-837.

[43] R.A. Rizi, M. Jahangiri, Feasibility Study of Implementing a Bio-Inspired Building Envelope for Energy Harvesting and Visual Comfort Improvement, Research Square, (2021).

[44] W. Tariq Sheikh, Q. Asghar, Adaptive biomimetic facades: Enhancing energy efficiency of highly glazed buildings, Frontiers of Architectural Research, 8 (2019) 319-331.

[45] A. Mahdavi Kochsaraei, M.R. Matini, The design of a movable and adaptable shell against the light using the structural pattern and functional mechanism of the Irish Clover flower, The third international conference on new research achievements in civil engineering, architecture and urban management, Tehran, Iran, (Aug. 2015) pp. 400-421.

[46] R.M.A. El-Zeiny, Biomimicry as a Problem Solving Methodology in Interior Architecture, Procedia Social and Behavioral Sciences, 50 (2012) 502-512.

[47] K. Taghizadeh, M. Matini, E. Kakui, flexible structures; A solution to reduce the functional problems of mobile shells, Journal of architecture and urban design (fine arts), 24 (2018) 39-48.

[48] ASHRAE, Energy standard for buildingsexcept low-rise residential, Atlanta, GA, USA, 2007.

[49] Y. Bian, Y. Leng, Y. Ma, A proposed discomfort glare evaluation method based on the concept of 'adaptive zone', Building and Environment, 143 (2018) 306-317.

[50] A. Nabil, J. Mardaljevic, Useful daylight illuminances: A replacement for daylight factors, Energy and Buildings, 38 (2006) 905-913.

[51] C.F. Reinhart, A. Jakubiec, D. Ibarra, Definition Of A Reference Office For Standardized Evaluations Of Dynamic Facade And Lighting Technologies, 13th Building Simulation Conference Proceedings, Chambéry, France, (Aug. 2013) pp. 26-28.