Biomimetic kinetic façade as a real-time daylight control: complex form versus simple form with proper kinetic behavior

Smart and Sustainable Built Environment

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Abstract

Purpose – This study aims to develop a methodology that extracts an architectural concept from a biological analogy that integrates forms and kinetic behavior to identify whether complex forms work better or simple forms with proper kinetic behavior for improving visual comfort and daylight performance.

Design/methodology/approach – The research employs a transdisciplinary approach using several methods consisting of a biomimetic functional-morphological approach, kinetic design strategy, case study comparison using algorithmic workflow and parametric simulation and inverse design, to develop an interactive kinetic façade with optimized daylight performance.

Findings – A key development is the introduction of a periodic interactive region (PIR), which draws inspiration from the butterfly wings' nanostructure. These findings challenge conventional perspectives on façade complexity, highlighting the efficacy of simpler shapes paired with appropriate kinetic behavior for improving visual comfort. The results show the façade with a simpler "Bookshelf" shape integrated with a tapered shape of the periodic interactive region, outperforms its more complex counterpart (Hyperbolic Paraboloid component) in terms of daylight performance and glare control, especially in southern orientations, ensuring occupant visual comfort by keeping cases in the imperceptible range while also delivering sufficient average spatial Daylight Autonomy of 89.07%, Useful Daylight Illuminance of 94.53% and Exceeded Useful Daylight Illuminance of 5.11%.

Originality/value – The investigation of kinetic façade studies reveals that precedent literature mostly focused on engineering and building physics aspects, leaving the architectural aspect underutilized during the development phase. Recent studies applied a biomimetic approach for involving the architectural elements besides the other aspects. While the biomimetic method has proven effective in meeting occupants' visual comfort needs, its emphasis has been primarily on the complex form which is difficult to apply within the kinetic façade development. This study can address two gaps: (1) the lack of an architectural aspect in the

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kinetic façade design specifically in the development of conceptual form and kinetic behavior dimensions and (2) exchanging the superficial biomimetic considerations with an in-depth investigation.

Keywords Kinetic façade, Biomimetic, Daylight control, Façade form, Parametric design

Paper type Research paper

Nomenclature

PIR	Periodic Interactive Region	E	Illuminance Matrix
UFV	User Field of Vision	S	Sky Matrix
HP	Hyperbolic Paraboloid	CBDM	Climate-Based Daylight Modeling
BS	Book-shelf	sDA	spatial Daylight Autonomy
HP_C	Hyperbolic Paraboloid component and circular PIR	UDI	Useful Daylight Illuminance
BS_T	Bookshelf component and tapered PIR	EUDI	Exceeded Useful Daylight Illuminance
DC	Daylight Coefficient	DGP	Daylight Glare Probability

1. Introduction

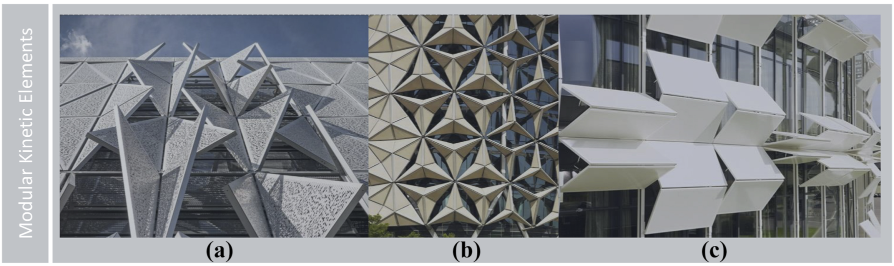
Buildings' façades play a significant role in providing sufficient adequate useable daylight within interior spaces. This significance arises from the profound impact of incident solar radiation, which varies based on the specific angle at which the receiving surface interacts with the direction of sunlight (Ostermeyer, 2010). Given the continuous variability in daylight's dynamic features over time, it becomes imperative to address this by employing an appropriate kinetic form and behavior for the façade. There is a high potential to use interactive kinetic façades (Hosseini *et al.*, 2019a), adaptive (Loonen, 2015; Tabadkani *et al.*, 2019) and responsive building skins (Shahin, 2019) to modify their morphologies in real-time with respect to the dynamic sun-timing positions and occupant activities. Given the numerous advantageous effects of daylight on the physical, psychological and mental well-being of occupants' health, implementing an interactive kinetic façade can offer a visually comforting and friendly design, leading to increased productivity and well-being of the occupants (Luna-Navarro *et al.*, 2020). Parametric modeling enables the design of interactive kinetic facades with intricate three-dimensional motions. The interactive kinetic façade holds significant promise and effectiveness for buildings with glazed curtain walls. These buildings frequently encounter challenges related to dynamic daylight, visual discomfort and overheating in close proximity to the façade (Al-Masrani *et al.*, 2018; Attia *et al.*, 2019; Hosseini *et al.*, 2024).

The Kiefer Technic Showroom's facade, located in Bad Gleichenberg, Austria and designed by Ernst Giselbrecht + Partner, and a responsive kinetic façade located in Kolding, Denmark (Kuipers, 2015), are examples of responsive facades that provide optimal visual comfort and daylight performance by regulating solar heat gain and preventing glare using modular kinetic components. Additionally, the Al Bahar Towers in Abu Dhabi (Hosseini *et al.*, 2019a) are other examples of responsive facades that utilize similar mechanisms to enhance the building's performance and sustainability (Figure 1).

1.1 The state of the art

The adaptive kinetic façade represents a highly advanced and interdisciplinary element within building design, encompassing the realms of architecture, building physics and engineering. This innovative feature incorporates a range of cutting-edge design techniques, materials and control strategies, including complex fenestration systems, operable solar shading, switchable windows and non-conventional façades. By harnessing these technologies, the façade aims to achieve multiple objectives, primarily centered around optimizing visual comfort for occupants and improving daylight performance within the space (Kim and Clayton, 2020; Taveres-Cachat *et al.*, 2021).

Reviewing prior studies (Table 1) indicates that the majority of research studies extensively rely on parametric and algorithmic methodologies to investigate kinetic facades through several methods consisting of building performance simulation (Kim, 2023), kinetic façade design strategy (Megahed, 2017), biomimetic (Hosseini, 2021a, Hosseini and Heidari, 2022; Kim, 2023; Kuru *et al.*, 2021; Soliman and Bo, 2023), advanced genetic algorithms (Le-Thanh *et al.*, 2021; Rizi and Eltaweel, 2021; Sadegh *et al.*, 2022), brute force analysis and comprehensive comparative scrutiny (Hosseini *et al.*, 2020; Hosseini and Heidari, 2022) and multi-faceted optimization techniques (Kim and Clayton, 2020). Moreover, on the one hand, the exploration of the kinetic facade subject has predominantly focused on engineering and building physics aspects, consequently leaving the architectural aspect, specifically conceptual form design and kinetic behavior dimensions, largely overlooked and underutilized during the development phase. A recent study (Hinkle *et al.*, 2022), for instance, demonstrated an automated optimization through parametric modeling and simulation to investigate building geometry and façade material. They improve energy saving by up to 19% by manipulating standard architectural elements such as window fraction, sill height, head height, site location, building rotation and location, volume fraction and length-wide aspect ratio. The parametric study lacks an underlying architectural concept for form-finding. Another study by Le *et al.* (2022) integrated parametric simulation and sensitivity analysis for developing multi-criteria decision-making to optimize view, daylighting, energy use and thermal and visual comfort. The study uses Grasshopper and ClimateStudio to conduct a parametric simulation to explore advanced façade systems with roller blinds and Low-E coating glazing. The authors stated that the roller blinds "were either fully opened or fully closed," and there is no intermediate option (Le *et al.*, 2022). The study combines principles from building physics and engineering to formulate an innovative logic for kinetic façades while omitting any input from architectural perspectives regarding the façade's design and form. Wang *et al.* (2022) applied questionnaires, Convolutional Neural Networks and parametric modeling to develop a control system for adaptive façade according to occupants' postures and positions in the space. Incorporating occupant behavior into the façade adjustment improves personalized thermal and visual comfort (Wang *et al.*, 2022). The study used a complex form as the adaptive façade form that can rotate between 180 and −180. There is no architectural design concept behind the choice of this form, the authors addressed the façade form as the area which needs more investigation and development. Valitabar *et al.* (2022) proposed an advanced control to adjust the tilt angles of multiple sections of a Venetian blind independently to improve visual comfort,



Source(s): Figure courtesy of Kuipers (2015), Hosseini *et al.* (2019a)

Figure 1. (a) SDU Campus (Kuipers, 2015), (b) Al Bahr Tower (Hosseini *et al.*, 2019a) and (c) Kiefer Technic showroom (Kuipers, 2015)

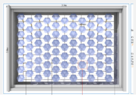
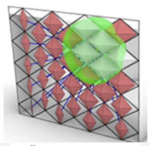
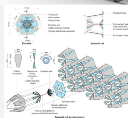
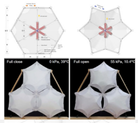
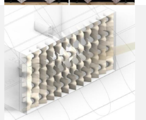
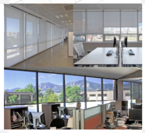
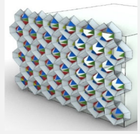
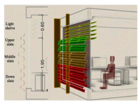
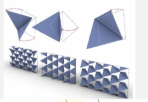
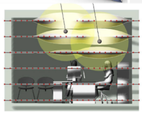
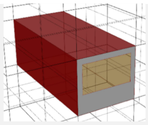
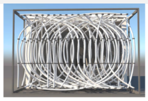
KINETIC FAÇADE DAYLIGHT CONTROL SYSTEM	CLIMATE	METHOD	SOFTWARE	ARCHITECTURAL CONCEPT	MOVEMENT MECHANISM	FORM/GRID	MATERIAL	FUNCTION	USERS' DETECTION AND ESTIMATION	INFLUENTIAL PARAMETERS	ENVIRONMENTAL TRIGGER	CONTROL LOGIC	FAÇADE MORPHOLOGY
NOVEL VARIABLE BUILDING SKIN (WANG *ET AL.*, 2024)	Cwa	PM, PS, BPS, MOO	LB, RH, GH, R	-	R, 3D	CF/ H	VT	DP, GP, RTDC, SSD, EP	SU, MP	Integrating hexagonal module with Fresnel lens to concentrate solar rays, Sun Tracking system	S	DC, IE	
LIGHT-RESPONSIVE BIOMIMETICS KINETIC FAÇADE (SOMMESE *ET AL.*, 2024)	Cfb	PD, PS,B PS, B	LB, RH, GH, R	Functional principles of the Gazania flower reaction to Sun light in macro scale	S, 3D	HS, CF/ R	SM	DP, GP, RTDC, SSD	SU, MP	Identification of Focal and Peripheral regions on facade	S	DC, IU	
ADAPTIVE BUILDING ENVELOPE BY MERGING BIOLOGICAL MECHANISMS (SOLIMAN & BO, 2023)	BWh	B, BPS		Lessons from multiple plants including Mimosa pudica, Cactus, Stone Plant in macro scale	SS, R, Fo, 3D	CF/ H	PG	T, RTDC, EE	S	Foldable surfaces with hexagonal shapes, multiple layers, self-shading features, and symmetrical triangular fins	T	DC, IE	
FLEXIBLE DAYLIGHT-ADAPTIVE SHADING FAÇADE (KIM, 2023)	Dwa	B, PD, BPS, FEA, F		Lessons from honeycomb shapes and plant breathing through stomata	C, 3D	CF/ H	SM	DP, RTD	S	Real-time façade shape change, Flexural hexagonal shapes	S	CC, IE	
ADAPTIVE FAÇADE BASED ON OCCUPANT-CENTRIC DESIGN (WANG *ET AL.*, 2022)	Dwa	S, PM, BPS, ML, MOO	LB, RH, GH, R, EP	-	R, 3D	CF, HS/ R	VT	DP, T, GP, SSD, RTDC, EE	SU, P, OP	Posture definition, adjusting shading unit, sun angle, temperature	S	CC, IU	
MULTI OBJECTIVE OPTIMIZATION OF ADAPTIVE FAÇADE (LE *ET AL.*, 2022)	Aw, Cfa, Cfa, Dfb, BSk	PS, MOO , SA	RH, GH, CS, R, EP	-	Ro, 2D	RB	VT, OF	DP, T, GP, SSD,R TDC, EE, VCE	S	Window to wall ratio, glazing, blind, threshold, either fully opened or fully closed without intermediate change	S	CC, IE	
INTERACTIVE KINETIC FAÇADE (HOSSEINI, 2022)	BWh	B, GMA , PM, PS, BPS, MOO	LB, RH, GH, R	Lessons from butterfly wing's nano structure and Orosi windows	R, Sc, S, 3D	CF, HS/ H	CG	DP, GP, SSD, RTDC	SU, MP	Geometrical changes (different depth and scales), composition of colored glass, periodic changes based on sun-timing positions and user positions/ DC	S	DC, IU	
ADVANCE CONTROL OF INDOOR AND OUTDOOR VENETIAN BLIND (VALITABAR *ET AL.*, 2022)	Csa	PD, PS, MOO	LB, RH, GH, R	-	R, 3D	VB/ R	VT	DP, GP, SSD, VCE	MU, MP	Integration of interior light-shelves and exterior venetian blind, independently adjustable tilt	S	DC, IU	

Table 1.
Review on kinetic façade characteristics based on forms, control logics and function of daylighting systems

(*continued*)

										angles of multiple sections of facade			
FORM-FINDING OF KINETIC FACADE (SADEGH *ET AL.*, 2022)	Csa	PD, PS, MOO	LB, RH, GH, R	-	R,S,3D	PS/R	C	DP	S	Shape changes, Tessellated form	S	CC, IE	
BIO-INSPIRED KINETIC FAÇADE (HOSSEINI, 2021)	BWh	B, PM, PS, BPS	D, RH, GH, R	Plant's stomata movement and kinetic behavior principles	R, S, 3D	CF, HS/R	VT	DP, GP, SSD,RTDC	MU, MP	dynamic transitory-sensitive area Symmetrical element, hierarchical arrangement, Immediate reconfiguration	S	DC, IU	
ADAPTIVE SHADING CONTROL (TABADKANI *ET AL.*, 2021)	Af, BSh, Cfb, BWh, Csa, Dfb	PM, PS, BPS	LB, RH, GH, R, EP	-	R, 3D	VB/R	VT	DP, T, GP, SSD, RTDC, EE	S	Climate zone, window-to-wall ratio, building orientation, shading control strategy and its activation threshold, Rotating range from 0◦ to 90◦	T	CC, IE	
BIOMIMETIC KINETIC SHADING FACADE (HOSSEINI, 2021B)	BWh	B, PM, PS, BPS	D, RH, GH, R	Inspiration from Tree configuration	C, 3D	CF/R		DP, GP, SSD,RTDC	SU, OP	Multilayered skin, Kinetic curvature movement, Intersected element	S	IE	

Note(s): Climate_ Tropical rainforest: Af, Humid continental: Dfb, Humid continental climate: Dwa. Temperate: Cfb, Humid Subtropical Climate: Cfa, Warm desert: BWh, Marine West Coast: Cfb, Mild, semi-humid: Csa, monsoonal humid subtropical climate: Cwa, Tropical savanna: Aw, Semi-arid: BSh; **Method_** Parametric design: PD, Parametric simulation: PS, Building Performance Simulation: BPS, Biomimetic: B, General morphological analysis: GMA, Fabrication: F, Multi-objective optimization: MOO, Survey: S, Machine Learning: ML, Sensitivity analysis: SA, Finite element analysis: FEA; **Tools/ Software_** Ladybug Tools: LB, DIVA: D, Climate Studio: CS, Design Builder: DB, Rhinoceros: RH, Grasshopper: GH, WUFI Plus: WP, Energy Plus: EP, Radiance: R; **Movement type**:_ Flap:F, Fold: Fo, Rotate: R, Retractable: Ret, Rolling: Ro, Pivot: P, Slide: S, Scale: Sc, Swelling and Shrinking: SS, Curve: C, Three dimension: 3D, Two dimension: 2D; **Geometric Form_** Complex Form: CF, Hierarchical Structure: HS, Roller blind: RB, Venetian Blind: VB, Primary Shape: PS; **Grid_** Rectangular: R, Triangular, T, Hexagonal: H; **Material_** Constant: C, Smart material: SM, Visible transmittance: VT, Openness Factor: OF, Colorful glass: CG, Photochromic glazing: PG; **Functions_** Thermoregulation: T, Daylight performance: DP, Energy Efficiency: EE, Energy Production: EP, Aesthetic: A, Glare Protection: GP, Sufficient Supply of Daylight: SSD, Real-Time Daylight Control: RTDC, Visual Contact to Exterior: VCE; Users' **Detection and Estimation_** Single User: SU, Multiple Users: MU, Space: S, Postures: P, One Position: OP, Multiple Position: MP; **Environmental trigger_** Sun: S, Temperature: T; **Control Logic_** Decentralized control: DC, Centralized control: CC, Interactive to Environment: IE, Interactive to User: IU
Source(s): Authors' own creation

Table 1.

daylight performance and visual contact with the exterior. However, the system has individual control on each piece to find the proper configuration for the whole façade which needs to consume more time and energy to reach the optimal configuration (Valitabar *et al.*, 2022).

On the other hand, some recent studies in the field have concentrated on the application of biomimetic approach, origami and floral patterns for the creation of facade forms. Although top-down (Hosseini and Heidari, 2022) and bottom-up (Sokhandan and

Monadjemi, 2016) approaches are two different ways of applying biomimicry in design, most of the precedent studies applied the top-down approach. The approach involves identifying a specific design problem and then searching for existing biological models or analogies that can provide a solution. The developed studies that used a top-down approach employ a variety of unique geometric forms, including complex and flexible designs (Globa *et al.*, 2022), convertible and hierarchical configurations (Le-Thanh *et al.*, 2021), each with its specific benefits. Applying the architectural concept extracted from the biomimetic approach leads to shortening the size of the problem and creating a meaningful exploration area by eliminating irrelevant parameters. Thus, the studies can benefit from the Brute-force algorithm to evaluate every possible solution or combination of parameters and reach the most optimal results with the highest accuracy. While these methods have proven effective in meeting occupants' visual comfort needs, their emphasis has been primarily on the complex form, particularly in the realm of biomimetics. As an illustration, multiple biomimetic kinetic facades studies use complex forms to achieve high performance in the building, including the identification of focal and peripheral regions on the façade (Sommese *et al.*, 2024), multilayer and multiscale interference (Hosseini and Heidari, 2022), foldable surfaces in multiple layers (Soliman and Bo, 2023), decentralized-hierarchical rotatable elements (Hosseini, 2021a), flexural hexagonal shapes (Kim, 2023), swelling and shrinking rib-structure (Kuru *et al.*, 2021) and kinetic curvature movement and intersected element (Hosseini, 2021b). However, these studies extracted the biomimetic principles by superficial considerations, not an in-depth investigation, resulting in neglecting some bio-inspired principles that can provide unique features for developing kinetic façade design interactions. To solve this problem, there is a need to develop an approach to identify functional convergences between buildings and nature in order to uncover special features of biological phenomena, such as form and behavior, for reaching environmental adaptation (Badarnah, 2017). This approach focuses on identifying the functional requirements and constraints of a system before searching for relevant biological analogies. By doing so, the approach aims to avoid the pursuit of irrelevant or overly complex biological analogies in the initial stages of the process, allowing for a more efficient exploration of potential solutions (Hosseini *et al.*, 2019b). Furthermore, a thorough exploration of biological analogies has resulted in the emergence of a novel attribute that integrates simple form and appropriate kinetic behavior, thereby enabling prompt reaction to environmental stimuli. This feature has not been previously explored in literature, making it a promising avenue for further research. Considering everything, this study aims to develop a methodology that extracts an architectural concept from a biological analogy that integrates forms and kinetic behavior to identify whether complex forms work better or simple forms with proper kinetic behavior for regulating dynamic daylight. The resulting kinetic principles are then translated into design solutions for the development of a biomimetic interactive kinetic facade aimed at improving occupant visual comfort. As such, the research seeks to address the following questions:

(1) How can a biomimetic functional-morphological approach be defined for detecting a proper biological analogy to extract suitable bioinspired principles for controlling dynamic daylight?

(2) How can the extracted biomimicry principles contribute to the development of kinetic facade forms and movement mechanisms?

(3) What is the improvement of daylight performance according to a case study comparison between a complex form and a simple form with proper kinetic behavior?

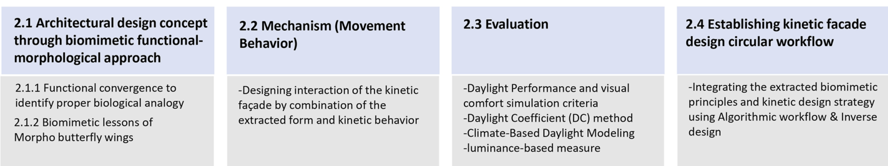
The paper uses several methods in three phases involving architectural design concepts, mechanisms and evaluation to establish a circular workflow of kinetic façade design (Section 2). Then, the study provides information about building typology, climate context, modeling settings and details of the case study used in the parametric simulation workflow (Section 3). (Section 4) represents the output of the parametric simulation study using required diagrams and tables for base case (Section 4.1), Hyperbolic Paraboloid component (Section 4.2) and Bookshelf (BS) component (Section 4.3). Section 4.4 rounds off this section with a performance comparison between the various case studies. Following that, the discussion and conclusion sections are presented as Sections 5 and 6, respectively.

2. Methods

The kinetic design strategy presents a robust framework for the systematic development of a kinetic facade, encompassing architectural design conceptualization, mechanism and evaluation stages for establishing a circular workflow of kinetic façade design (Figure 2). The methodology aims to address two gaps: (1) the lack of an architectural aspect in the kinetic facade design, specifically in the development of conceptual form and kinetic behavior dimensions and (2) exchanging the superficial biomimetic considerations with an in-depth investigation. This approach focuses on identifying the functional requirements and constraints of a system before looking for relevant biological analogies. This is to avoid searching for irrelevant or overly complex biological analogies in the initial phase of the process, allowing for a more efficient exploration of potential solutions. We can highlight the transdisciplinary approach of this study and emphasize the architectural design concept through the biomimetic functional-morphological approach in Section 2.1, which uses functional convergence to identify a proper biological analogy (Section 2.1.1). Then it conducts a comprehensive literature review analysis for detecting multiple biomimetic principles of forms and kinetic behavior within the chosen analogy (Section 2.1.2). In the next step, the extracted principles are applied to create a novel kinetic façade interaction in Section 2.2 as a mechanism. The evaluation Section 2.3 defines appropriate metrics and acceptable thresholds for assessing and comparing kinetic facades' alternatives based on daylight performance and visual comfort criteria (Section 2.3). The collected materials from the previous sections are arranged in a reliable framework to establish a circular kinetic facade design algorithmic workflow (Section 2.4).

2.1 Architectural design concept through biomimetic functional-morphological approach

2.1.1 Functional convergence to identify a proper biological analogy. The transformation of façades can enhance daylight performance and visual comfort by regulating daylight through scattering, redirecting and reflecting. To effectively explore nature and identify the appropriate analogy, this research focuses on living organisms with specific morphologies (i.e. functional convergence) that can redirect and reflect light. Numerous examples of geometric, symmetrical, regular and irregular spatial patterns can be observed in nature. For



Source(s): Authors' own creation

Figure 2. Methodological framework for establishing kinetic façade design circular workflow

instance, the iridescence of Morpho butterfly wings, the bright metallic reflection of a jewel beetle's elytron and the brilliant eye pattern of a peacock feather are some notable examples (Freyer and Stavenga, 2020; Hariyama, 2005; Yoshioka, 2013). In certain species, the phenomenon of structural color is observed, wherein the colors of the organism are generated by the interaction of light with microscopic structures on their surface rather than through pigments. These structures can be arranged in a way that selectively reflects and absorbs specific wavelengths of light, resulting in the appearance of color. The resulting colors can possess high reflectance qualities and vividness and may exhibit iridescence, wherein their hue changes depending on the angle of light and the observer's perspective (Song *et al.*, 2014; Thomé *et al.*, 2020; Yoshioka, 2013).

Real-time daylight control needs immediate action and morphological adaptation, which is frequently observed in living organisms. The functional convergence can lead to finding a relevant analogy resulting in valuable kinetic movements and behavior for responding to dynamic daylight features. Redirecting, scattering and reflecting the light contribute to optical characteristics such as iridescence and high reflectance, especially in Morpho butterfly wings. Thus, the study determines a functional convergence between visual comfort and iridescence (structural color) (Table 2). Investigating the iridescence phenomena of Morpho butterfly wings leads to achieving various morphological adaptations and kinetic behavior for controlling dynamic light.

Consequently, it is imperative to investigate the iridescence phenomenon exhibited by Morpho butterfly wings at the nano-scale. This investigation will involve a thorough analysis of existing literature, aiming to identify various biomimetic principles related to the role of forms, shapes and kinetic behavior in redirecting, scattering and reflecting light.

2.1.2 Biomimetic lessons of Morpho butterfly wings. The Genus Morpho butterfly comprises multiple species, including Rhetenor and didius, known for their brilliant blue color that exhibits iridescent coloration with high reflectivity and low angle dependence. The notable characteristics of the Morpho butterfly's color have attracted significant scientific attention (Chung *et al.*, 2012; Song *et al.*, 2014; Yoshioka, 2013). The high reflectivity of the blue color can be explained by interference among the multilayers and multi-scale wing elements, geometric forms and movement behavior (Kawabe *et al.*, 2020; Köchling *et al.*, 2020; Steindorfer *et al.*, 2012; Wang *et al.*, 2013). Table 3 analyzes Peacock feathers and jewel beetle's elytron, mostly the Morpho butterfly wings to investigate the constitution of the structural color through geometric form, movement behavior in different layers and scales.

The optical properties of the Morpho butterfly wing include iridescence, high reflectance, strong polarization, thermoregulation, mating and camouflage (Kawabe *et al.*, 2020; Köchling *et al.*, 2020; Siddique *et al.*, 2013; Yoshioka, 2013). These features have been made by reflecting, diffusing and scattering light in multilayer and multi-scale nanostructures existing in Morpho butterfly wings (Li *et al.*, 2010; Thomé *et al.*, 2020). The most crucial factors influencing the optical properties are morphology (geometrical form) and kinetic behavior (Figure 3). Regarding the optical properties, several morphological approaches have been employed, consisting of lattice frames, roof tiles, hexagonal tiles, treelike structures (Christmas tree), BS structures, grating-like structures, ridge and saddle shape

Table 2. Identifying a proper biological analogy for investigation through functional convergence

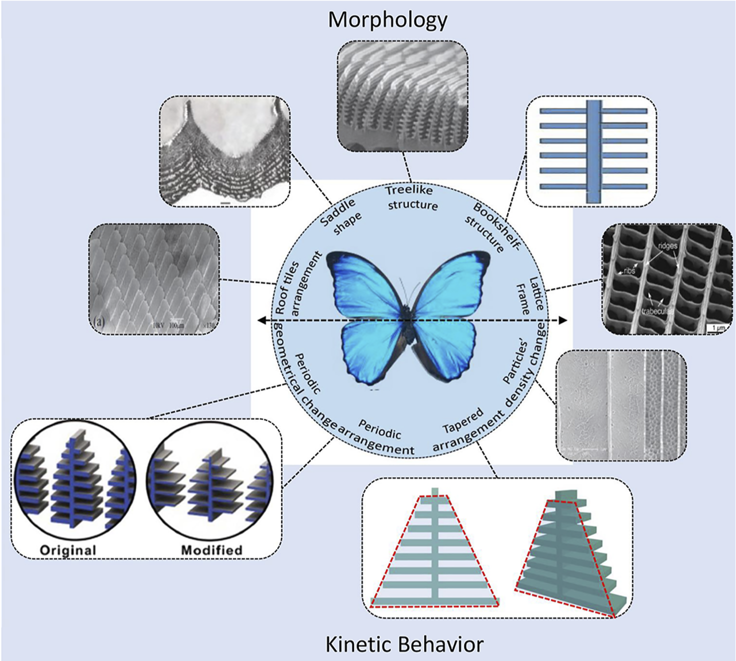
Intended function	Functional convergence compliance Building elements	Natural phenomenon
Redirecting, reflecting, scattering light	Glazing Unit and Shading Devices	Iridescence and high reflectance phenomenon of Morpho Butterfly Wings in nano-scale

Source(s): Authors' own creation

Table 3. Analyzing the Morpho butterfly wings based on their influential elements, functions, geometric form, movement behavior and relation with the iridescence phenomenon and structural colors

References	Creature name	Function	Processes	Geometric form	Influential element	movement's behavior	Geometry type/scale
Yoshioka (2013)	Morpho Cypris Butterfly	Ir	S, D, R	RT, RS, SS	The regular arrangement, Structural irregularity in the height of the ridges	PA	MLI, MSC
Wang *et al.* (2013)	Morpho butterflies	Ir	S, D, R	TS	lamellae distribution	PA, TA	MSC
Steindorfer *et al.* (2012)	*Morpho rhetenor* butterfly	Ir	S, R	BS	Structure distance, Shelf width, Shelf distance, Shelf height and offset	PGC	MLI
Song *et al.* (2014)	Morpho butterflies	Ir	S, R	BS	Ridge structure	PGC	MLI
Chung *et al.* (2012)	*Morpho rhetenor* butterfly	Ir	S, D, R	RS, SS	Ridge structure	PA	MLI, MSC
Kawabe *et al.* (2020)	Morpho butterfly	T	S, D, R	RS	Surface structure	PGC	MLI
Jiang *et al.* (2012)	Morpho butterfly	Ir	S, D, R	GS	Transparent cover scale asymmetrically arranged layers with different widths	PA	MLI, MSC
Thomé *et al.* (2020)	Morpho butterfly	Ir	S, D, R	LF	The architecture of the lamellae, The presence of micro ribs	PA	MLI
Li *et al.* (2010)	*Papilio peranthus* Fabricius	Ir	S, D, R	HT, RS, TS	The presence of micro ribs	PA, TA	MLI
Köchling *et al.* (2020)	Morpho butterfly	M, C, T	S, D, R	RS, TS	The architecture of the ridges, Densities of the ridges, The importance of cover scales	PGC, PDC, TA	MSC
Shen *et al.* (2015)	Morpho butterfly	Ir	S, D, R	RS, BS	Hierarchical nanostructure, offset in layer positions	PGC	MLI, MSC
Siddique *et al.* (2013)	*Morpho butterfly*	*Ir*	*S, D, R*	*TS*	*Alternating lamellae layers and Offsets between neighboring ridges*	*PGC, TA*	*MLI, MSC*

Note(s): *Function*_ Iridescence: Ir, High reflectance: HR, Strong polarization: SP, Thermoregulation: T, Mating: M, Camouflage: C
*Processes*_ Scattering: S, Diffusing: D, Reflecting: R
*Geometric form*_ Lattice Frame: LF, Roof Tiles: RT, Hexagonal Tiles: HT, Treelike Structure (Christmas tree): TS, Bookshelf Structure: BS, Grating-like Structure: GS, Ridge Structure: RS, Saddle Shape: SS
*movement's behavior*_ Periodic arrangement: PA, Periodic geometrical change: PGC, Particle's density change: PDC, Tapered Arrangement: TA
*Geometry type/scale*_ Multilayer interference: MLI, Multiscale components: MSC
Source(s): Authors' own creation



Source(s): Figures courtesy of Yoshioka (2013), Thomé *et al.* (2020), Köchling *et al.* (2020); Shen *et al.* (2015), Siddique *et al.* (2013)

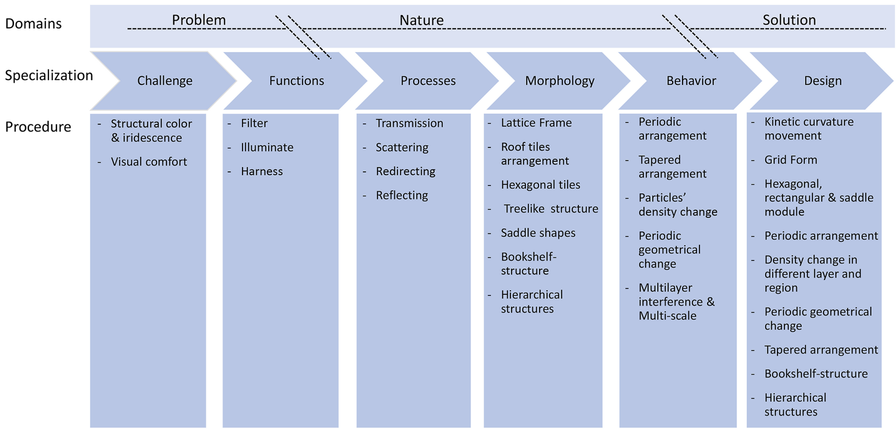
Figure 3. Extracted biomimicry principles from Morpho Butterfly wings based on the morphology and kinetic behavior adapted from Yoshioka (2013), Thomé *et al.* (2020), Köchling *et al.* (2020), Shen *et al.* (2015) and Siddique *et al.* (2013)

structures (Freyer and Stavenga, 2020; Jiang *et al.*, 2012; Köchling *et al.*, 2020; Thomé *et al.*, 2020; Yoshioka, 2013). Likewise, kinetic behaviors empowered the optical properties through periodic arrangement (Yoshioka, 2013), periodic geometrical change (Steindorfer *et al.*, 2012), particle density change (Freyer and Stavenga, 2020) and tapered arrangement (Köchling *et al.*, 2020). For example, Köchling *et al.* (2020) (Köchling *et al.*, 2020) mentioned that periodic geometrical and particle density changes in a tapered shape transform the architecture of the ridges inside the wing's nanostructure. Similarly, Steindorfer *et al.* (2012) explained BS structure and its periodic geometrical change using lamellae distribution in a tapered shape.

The extracted forms and movement behavior can be abstracted and translated to design solutions for developing a new generation of interactive kinetic façade. Based on Figure 4, a new generation of kinetic facades can benefit from the geometric form of roof tiles, BS structure and saddle shape modules in a grid form. Moreover, these forms can interact with dynamic stimuli by using periodic geometrical change, tapered arrangement and particle density change. Undoubtedly, the control logic of the façade has been enhanced to enable efficient communication between dynamic and effective parameters during real-time operation.

2.2 Mechanism

Two alternatives for biomimetic façade are developed by a combination of design solutions (Figure 5). Based on the morphological viewpoint, the options can be divided into kinetic façades with Hyperbolic Paraboloid (HP) and BS components. Considering the kinetic behavior, integration of periodic geometrical change, periodic arrangement and particle



Source(s): Authors' own creation

Figure 4. Exploring and abstracting biomimicry principles of Morpho butterfly wings and translating them to design solutions, adapted from Badarnah (2017)

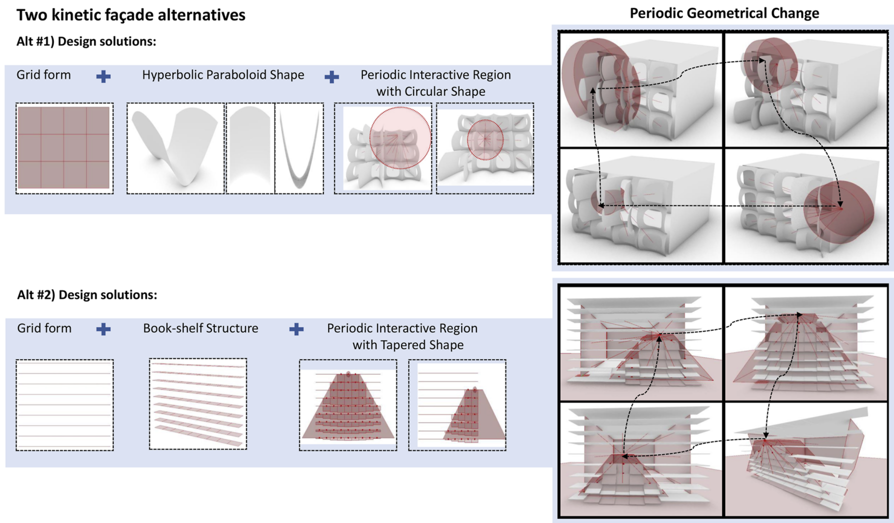


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Figure 5. Developing two alternatives of biomimetic interactive kinetic façade by combining the design solutions

density change leads to identifying a periodic interactive region (PIR) of the façade. The shapes of the region are circular and tapered based on the biomimicry procedure (Figure 5). Therefore, the biomimetic kinetic façade alternatives can benefit from PIR in circular and tapered shapes. The kinetic elements inside the PIR have periodic geometrical changes and arrangements based on the rapid fluctuations of dynamic stimuli such as sun timing positions and dynamic occupant's position. As Figure 5 displays, the area of PIR is changed in different situations so that the number of kinetic elements in operation would be increased or decreased. The facades can avoid the extra movement of the kinetic components by employing PIR logic. Therefore, it consumes less energy for operation while providing more useful daylight in the interior space.

The design of the kinetic façade draws inspiration from the nano-scale structure and kinetic behavior of the Morpho butterfly wing. It transforms the façade into an interactive and responsive medium that adapts to the dynamic features of daylight and occupants. The three-phase design process enables the transition from a static to an interactive-kinetic state. Phase 1) The wing's nanostructure's lattice frame and grating-like shape allow for the use of a grid form and the placement of kinetic components on the façade (Figure 5).

Phase 2) Establishing the logic for dynamic attraction points in the facade involves a two-step process (Figure 6a): (1) Creating a UFV line that connects the position of the sun at various times with the positions of occupants within an office; and (2) Identification of the attraction points by determining the intersections between the UFV lines and the façade surface.

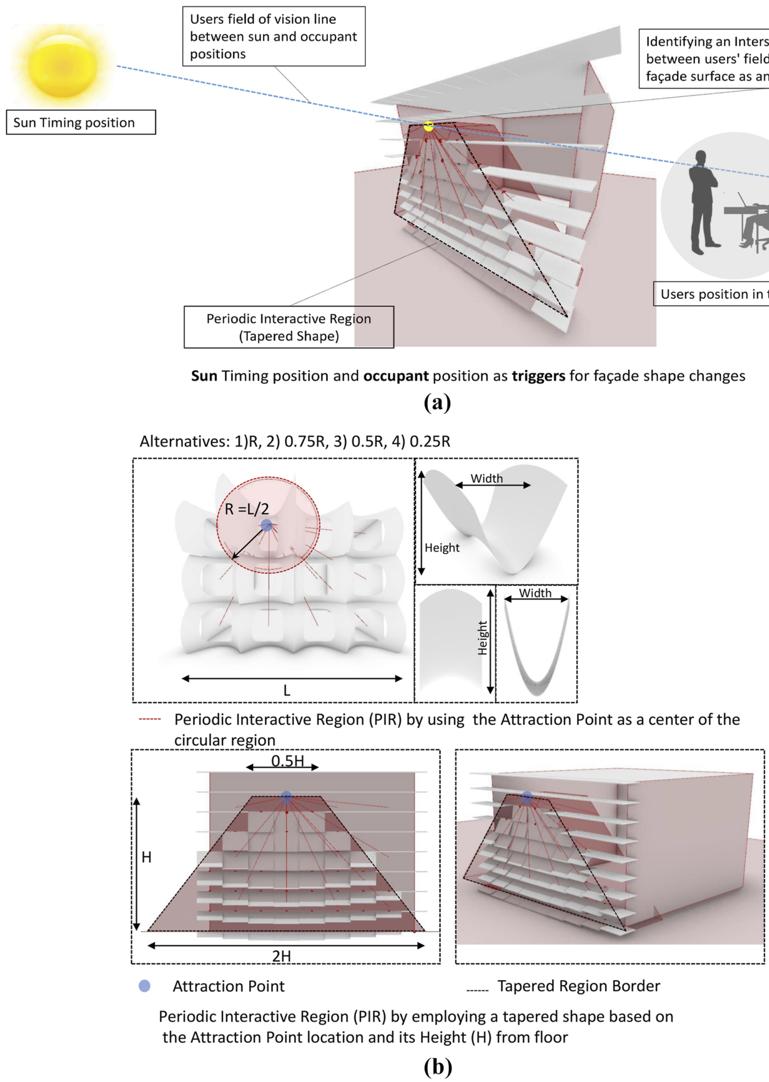

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Figure 6.
Establishing the logic of interaction of façade with dynamic occupant's position and sun timing position: (a) creating a UFV line that connects the position of the sun at various times with the positions of occupants within an office and identification of the attraction points by determining the intersections between the UFV lines and the surface of the façade (b) defining the logic of PIR with tapered and circular regions

Phase 3) Defining the logic of PIR on a façade in two shapes (Figure 6b):

(1) Using the attraction point as a center of the circular region for HP modular components. The geometry (width and height) of HP components is periodically changed according to the distance between the attraction point position and their central points' location. The amount of R is defined as half of the width of the office room. Moreover, the radius of the PIR can be changed in the range of 0.5R–2R with an interval of 0.5.

(2) Employing a tapered shape for BS modular components based on the attraction point location and its height (H) from the floor. The height (H) of the tapered shape comes from the distance between the attraction point location and its projection point position on the ground. The lower width of the tapered shape equals 2H, while the upper width is 0.5H.

2.3 Evaluation

The developed kinetic façade provides real-time daylight control to improve daylight performance and occupants' visual comfort. This section outlines the utilization of climate-based and luminance-based metrics to establish the criteria for daylight performance simulation. These metrics are derived from the daylight performance prediction guidelines provided by Reinhart (2019). The study then conducts extensive parametric daylight performance simulations of numerous kinetic facades to examine their visual comfort improvements. The alternatives are three distinguished options consisting of the base case (Plain window room), kinetic façade with Hyperbolic Paraboloid component and circular PIR (HP_C) and kinetic façade with BS component and tapered PIR (BS_T). To evaluate daylight performance, widely recognized software and plugins such as Rhino 7, Grasshopper, Honeybee, Ladybug and Design Explorer are employed. These powerful tools enable comprehensive analysis and assessment of various aspects related to daylighting. The Honeybee and Ladybug use the RADIANCE-based daylight simulations that are validated by Brembilla and Mardaljevic (2019), Reinhart and Walkenhorst (2001).

The research involves an extensive exploration that encompasses both annual daylight simulations and point-in-time evaluation for a range of proposed dynamic building facade configurations. In conducting climate-based daylight modeling assessments, a detailed analysis is carried out, spanning an entire year with time intervals of an hour or less. This approach effectively captures the intricate nuances of daily and seasonal daylight variations. Furthermore, the study includes point-in-time simulations utilizing a luminance-based metric on solstice and equinox days. These simulations assess the degree of visual comfort satisfaction experienced by occupants.

Climate-based daylight modeling assessments are conventionally undertaken for an entire year, employing time intervals of 1 h, to capture the intricate daily and seasonal fluctuations in daylight accurately. The widely used Daylight Coefficient (DC) method (Tregenza and Waters, 1983) offers an efficient computational approach for simulating a wide array of diverse daylight scenarios, and this is achieved through the application of the following formula:

$$E = DC \times S \tag{1}$$

where the DC matrix stores the values describing the relationship between the virtual sensor points (n) and the 145 sky patches (plus one for the external ground), the sky matrix (S) stores the luminance values for each of the sky patches at each hour of the year (8,760 h for hourly time steps), and the resulting illuminance matrix (E) is obtained by multiplication of the previous two matrices. The DC matrix has been obtained through the computationally expensive lighting simulation. After that, the rest of the process (i.e. the derivation of illuminances) largely includes the relatively rapid multiplication of matrices. Both Climate-Based Daylight Modeling (CBDM) and Radiance-based techniques draw their foundation from the Radiance software platform and contain distinct modifications of the DC method (Brembilla and Mardaljevic, 2019) (Table 4).

To evaluate the daylight performance of the interactive kinetic facade, we employed climate-based metrics such as spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), Exceeded Useful Daylight Illuminance (EUDI), as well as a luminance-based measure, namely, Daylight Glare Probability (DGP) (Reinhart, 2019). sDA is a metric that calculates the percentage of occupied hours during a year in which a minimum illuminance threshold is achieved exclusively through daylight. A point is considered "daylit," if its sDA value is equal to or greater than 50% or sDA 300 lux [50%] (Reinhart, 2019). UDI refers to the presence of daylight that falls within the range of 100–3,000 lx in the back two-thirds of a space. When the UDI exceeds 80%, the space is considered to have sufficient useful daylight. On the other hand, EUDI is a metric that indicates the presence of excessive daylight near the façade, with values exceeding 3,000 lx (Reinhart, 2011, 2019). Glare is a human sensation that occurs when there is a bright light source within the field of vision that exceeds the brightness to which the eyes have adapted (Reinhart, 2011). DGP is a metric that has gained popularity in recent years, as suggested by Reinhart (2019), Wienold and Christoffersen (2006). It utilizes CCD camera-based luminance mapping technology to assess glare. DGP values are classified into four groups: imperceptible (30–35), perceptible (35–40), disturbing (40–45) and intolerable (45–100) (Table 4) (Reinhart, 2011).

2.4 Establishing kinetic facade design circular workflow

Figure 7 showcases research exploration through the integration of kinetic design strategy, biomimetic functional-morphological approach and parametric workflow using inverse design. The kinetic design strategy, comprising three steps – design concept, mechanism and evaluation – offers a reliable cycle to transition from static to dynamic. The extracted principles from the biomimetic section are utilized to support the design concept. Subsequently, the appropriate morphology and movement behavior are translated into kinetic logic and specific morphologies, including PIR, periodic geometrical change, circular and tapered shapes of the region, the dynamic region based on the sun-timing positions and occupant's position, grid form with Hyperbolic shape and BS structure. According to the logic mentioned above and mechanisms, two kinetic façade alternatives are developed. A parametric workflow for conducting a daylight simulation is applied in the last step.

3. Case study

The case study is an open office on the second floor of an office building called Parmida (Figure 8c). The architectural team designed a second façade layer using a triangular grid to

Table 4. Radiance ambient parameters were used for simulation

Method	Ambient bounces (-ab)	Ambient divisions (-ad)	Ambient super-samples (-as)	Ambient accuracy (-aa)	Ambient resolution (-ar)	Limit weight (-lw)
Daylight coefficient	5	4,096	512	0.15	512	0.002

Source(s): Authors' own creation

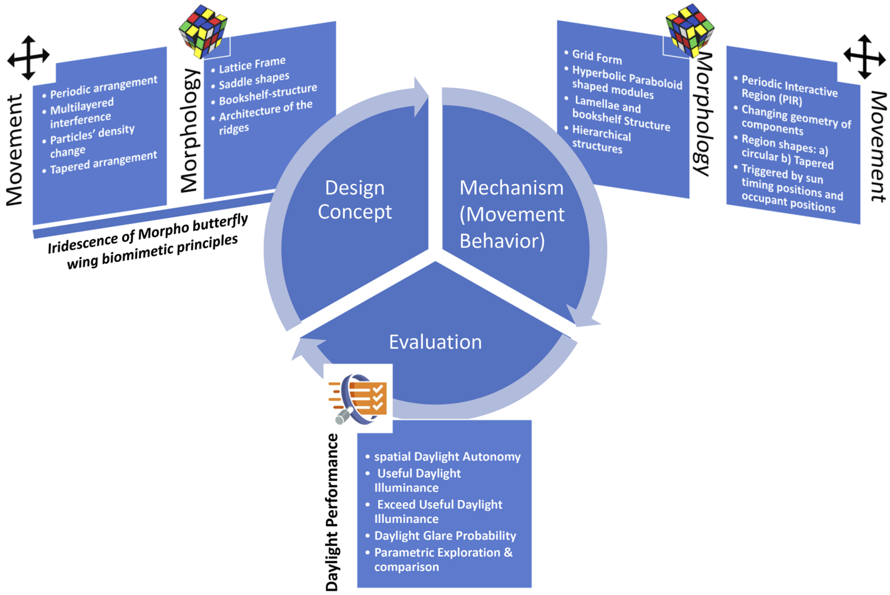

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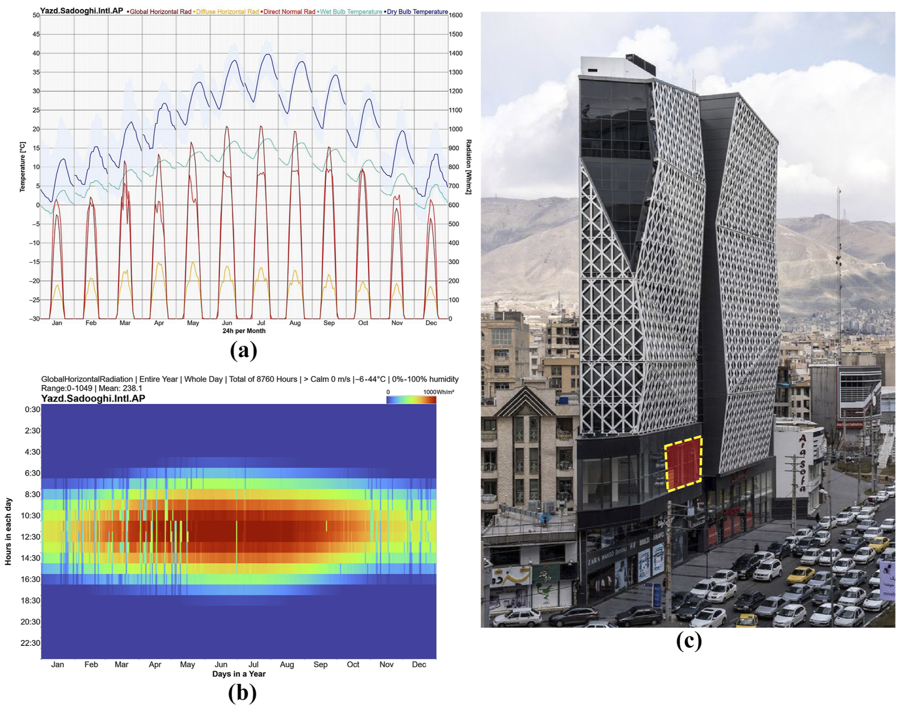
Figure 7.
Research exploration through the integration of kinetic design strategy and biomimetic functional approach



Source(s): Authors' own creation

Figure 8.
(a) Diurnal averages (global horizontal radiation, diffuse horizontal radiation, direct normal radiation, wet bulb temperature and dry bulb temperature); (b) hourly heatmap of global horizontal radiation; and (c) case study building: second-floor plan of Parmida building (highlighted area represented the selected office room)

control the intense daylight of the south orientation. However, office spaces located in the small part of the second floor have a fully glazed façade which causes glare and visual discomfort within the space. Thus, the space needs a façade design to control glare and increase daylight performance. The model is a “shoebox” office that represents a south-facing side-lit office that is not obstructed by neighboring buildings according to Reinhart’s recommendation for daylighting study (Reinhart, 2018). The developed biomimetic façade alternatives are applied to the case study. To conduct the simulation, the location chosen for the office building is Yazd, Iran, which is characterized as having a hot desert climate (BWh) with clear skies, as per the Köppen climate classification (Hosseini *et al.*, 2019a). To accurately simulate the environmental conditions in Yazd, weather data specific to the region is acquired from the EnergyPlus website (Figures 8a and b) (National Renewable Energy Laboratory, 2024). Based on a standard office layout, the floor plan dimensions are determined to be 4.4 m in width and 4.1 m in depth (Neufert and Neufert, 2000; Reinhart, 2018). The building elements, such as walls, ceilings and floors, are modeled with a thickness of 0.2 m and 0.3 m, respectively (Figure 9). The height of the room, measured from the top of the floor to the bottom of the ceiling, is determined to be 2.8 m. Additionally, the window is situated on the south-facing façade with a window-to-wall ratio of 0. 85.

Climate-based metrics are calculated annually for each distinct façade configuration. The DGP is calculated using the kinetic façade options on the solstice and equinox days, including the 21st of December, the 21st of March and the 21st of June (Reinhart, 2011, 2019). This outlines the essential parameters for conducting a daylight performance simulation, which assumes a clear sky with sun, a minimum illuminance level of 300 lx on the work plane at a height of 0.85 meters from the floor, an occupancy schedule of 8–16, a sensor grid spacing of 0.5 m, the absence of shading and no use of electrical light (Reinhart, 2011). All modeling settings of the case study used in the parametric simulation have been listed in Table 5.

Figure 10 illustrates the interior spaces that are perceived by each alternative as well as kinetic façade elements comprising grid form, rail profile, kinetic louvers and rotatable joints. To initiate the grid divisions of the alternative hyperbolic paraboloid design, we took into consideration the façade of the *Kiefer Technic Showroom*, which was divided into four sections. According to *Construction Specialties* company, the louver system can use blades’ depth around 30 cm. Different alternatives are simulated according to daylight performance criteria. The study performed individual comparisons between alternatives and the base case Figure 11 represents the inverse design and algorithmic workflow of interactive kinetic façade during parametric modeling and simulation using biomimetic lessons of Morpho butterfly wings as input drivers.

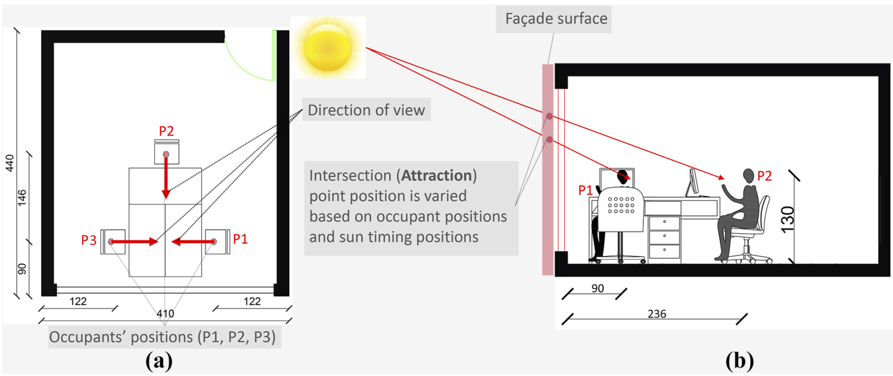


Figure 9. Test room, occupant positions, the direction of views and attraction points

Source(s): Authors’ own creation

Performance criteria Parameters		Name	Unit	Range
Daylight-related parameters (Annual daylight simulation metrics)		Useful daylight Illuminance (UDI) (100–3,000 lux)	Percentage	[0–100]
		Exceed Useful daylight Illuminance (EUDI) (>3,000 lx)	Percentage	[0–100]
		Spatial daylight autonomy (sDA)	Percentage	[0–100]
Visual comfort relate parameters		Daylight Glare Probability (DGP)	$X < 0.35$: Imperceptible $0.35 < x < 0.4$: Perceptible $0.4 < x < 0.45$: Disturbing $x > 0.45$: Intolerable	Normalized range: [0–100]
Model driving parameters	Hyperbolic Paraboloid	Periodic arrangement (Circular shape radius: R = Spece width (L)/2); L = 4	Float	0.25, 0.5, 0.75, 1R
		Opening Width	Floating point number	0.30, 0.35, 0.40, 0,45, 0.50
		Opening Height	Floating point number	0.30, 0.35, 0.40, 0,45, 0.50
		Grid division	Integer	4×3
	Bookshelf component	Periodic arrangement (Tapered shape) Short side: 0.5 H, Long side: 2 H, Height: H	m	H: Height of the dynamic Attraction Point from floor
		Lamella Depth	m	0.3
		Lamella Rotation	Degree	Domain [0–90] °
		Grid division	Integer	9×8
Model fixed parameters		Glazing Ratio	Percentage	90
		Task Area Height	m	0.85
		Sensor Grid Spacing	m	0.5
		Space Width	m	4.10
		Space Length	m	4.40
		Space High	m	2.8
		Single glazing direct visual transmittance	Percentage	90
		Int. Wall Reflectance	Percentage	50
		Int. Ceiling Reflectance	Percentage	80
		Int. Floor Reflectance	Percentage	20
		Ext. Ground Reflectance	Percentage	20
Sun timing positions (For Glare analysis and form changing parameters)		Month	Integer	6-9-12
		Day	Integer	21
		Hour	Integer	9–12-15
Climate parameters		Weather File for analysis	user-defined	Hot desert climate (BWh)

Table 5. Modeling settings of the case study used in the parametric simulation

4. Results

4.1 Base case (plain window room)

The investigation of the daylight performance of a base case using climate-based daylight metrics demonstrates that the amount of usable daylight provided is insufficient to meet

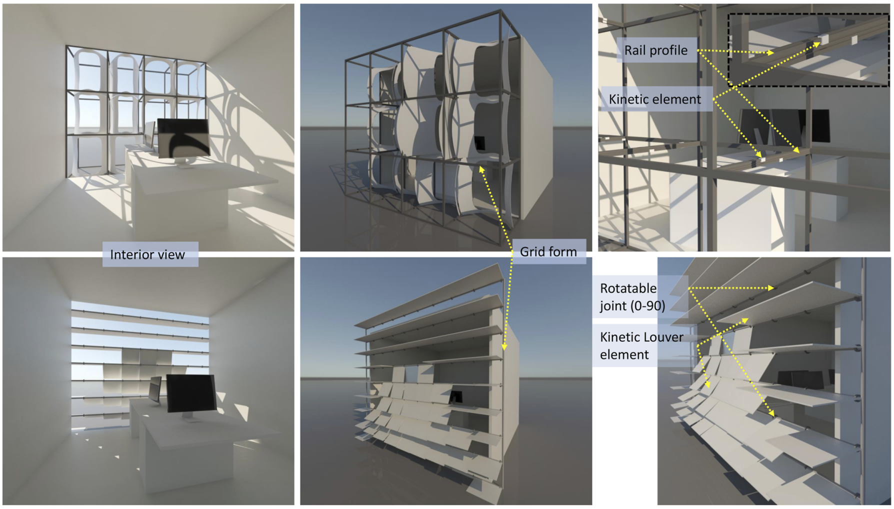


Figure 10. Interior spaces are perceived by each alternative and kinetic façade elements including grid forms, rail profiles, kinetic louvers and rotatable joints

Source(s): Authors' own creation

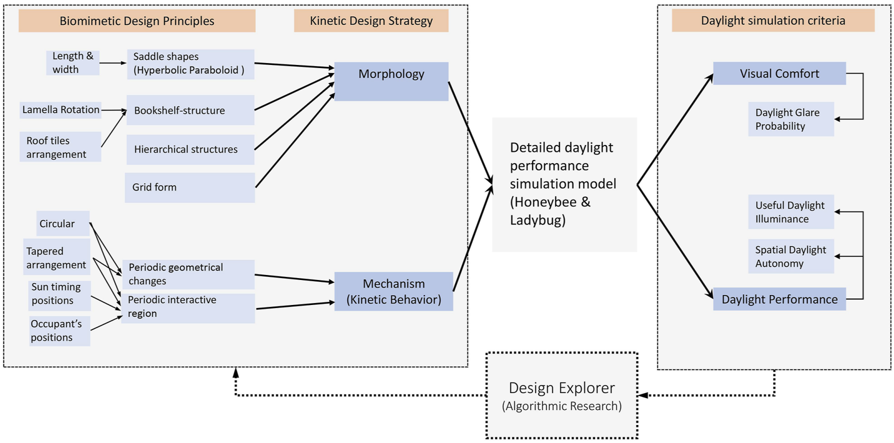


Figure 11. Inverse design of interactive kinetic façade using biomimetic lessons of Morpho butterfly wings

Source(s): Authors' own creation

occupants' requirements. Despite the room receiving an adequate amount of daylight (sDA 94%), the UDI analysis (17%) reveals that most of the incoming light exceeds 3,000 lx, leading to visual and thermal discomfort. The analysis revealed that the EUDI metric had a value of 77%, indicating that a significant amount of daylight in the room was above the recommended threshold of 3,000 lx. Most cases are at the intolerable zone due to DGP evaluation (Table 6). Table 5 presents the overall visual discomfort experienced by occupants who are exposed to sun glare throughout the year.

4.2 Biomimetic kinetic façade with hyperbolic paraboloid component and circular periodic interactive region (HP_C)

Table 7 displays the extensive investigation conducted on the daylight performance of the kinetic façade, focusing on different areas of PIR during solstice and equinox days at 9:00, 12:00 and 15:00.

The data extracted from Table 5 provides compelling evidence of the positive daylight performance exhibited by the kinetic façade alternatives, as indicated by the ranges of UDI, EUDI and sDA values, which fall within the respective range of (52.7_74.26), (25.73_47.3) and (96.88_98.95). Notably, these improvements are achieved while varying the window-to-wall ratio (WWR) between 0.2349 and 0.4790. The alternative design demonstrates significant potential in delivering ample daylight into the interior space, with the UDI increasing up to 3.47 times compared to the base case. Furthermore, the façade effectively reduces the EUDI levels in the room by 66.48%, further enhancing visual comfort for occupants. Parametric simulation of the façade (Figure 12) shows that the façade with PIR (2R) has the best daylight performance by an average UDI and EUDI of 72.59 and 27.4. Regarding Figure 13, we can conclude that there is no significant difference between regions with a radius of 2R, 1.5R, R. The PIR with a radius of 0.5R has lower daylight performance than the other alternatives

	Office hours		
	9:00	12:00	15:00
Scenario	DGP	DGP	DGP
Person 1/Mar 21st	0.43	0.52	0.58
Person 1/Jun 21st	0.41	0.48	0.44
Person 1/Dec 21st	0.53	1	1
Person 2/Mar 21st	0.34	0.36	0.31
Person 2/Jun 21st	0.29	0.33	0.29
Person 2/Dec 21st	0.46	0.53	0.36
Person 3/Mar 21st	0.72	0.69	0.45
Person 3/Jun 21st	0.49	0.59	0.42
Person 3/Dec 21st	1	1	0.4

Source(s): Authors' own creation

Table 6. Basecase daylight performance evaluation and DGP prediction for multiple occupants' positions in the room

Orientation	South							
	Office hours							
	9:00		12:00		15:00			
Scenario	UDI	EUDI	UDI	EUDI	UDI	EUDI	sDA	WWR
PIR (0.5)/Mar 21st	53.47	46.53	74.04	25.96	52.70	47.30	98.83	0.47902
PIR (0.5)/Jun 21st	74.22	25.78	74.26	25.73	73.92	26.07	97.03	0.2448
PIR (0.5)/Dec 21st	69.44	30.55	70.57	29.43	73.88	26.12	98.42	0.2845
PIR (1.0)/Mar 21st	66.09	33.91	73.11	26.88	65.33	34.67	98.95	0.3272
PIR (1.0)/Jun 21st	74.22	25.78	73.37	26.63	73.92	26.07	96.88	0.2456
PIR (1.0)/Dec 21st	68.92	31.08	70	29.99	72.99	27	98.60	0.2612
PIR (1.5)/Mar 21st	66.17	33.83	73.04	26.95	68.41	31.59	98.87	0.3002
PIR (1.5)/Jun 21st	73.84	26.15	73.28	26.71	72.90	27.09	97.33	0.2412
PIR (1.5)/Dec 21st	69.63	30.37	70	29.99	72.97	27.02	98.40	0.2786
PIR (2.0)/Mar 21st	74.11	25.89	73.35	26.65	73.80	26.19	97.63	0.2349
PIR (2.0)/Jun 21st	74.10	25.89	74.04	25.96	72.90	27.09	97.24	0.2395
PIR (2.0)/Dec 21st	69.23	30.76	68.85	31.14	72.97	27.02	98.46	0.2732

Source(s): Authors' own creation

Table 7. Daylight performance investigation of biomimetic kinetic façade with hyperbolic paraboloid component and circular PIR (HP_C) for the South direction through climate-based daylight metrics

(Figures 14–17). Even though all options provide extremely high UDI and sDA, the average amount of EUDI (29.21) emphasizes the overheating problem just near the façade.

Table 8 represents DGP and climate-based metric evaluation of the best biomimetic kinetic façade with Hyperbolic Paraboloid component and circular PIR (HP_C) for the South direction. Evaluation of DGP proves the facades' exceptional performance for providing occupants visual comfort in given directions. All the cases are in the imperceptible range (DGP < 0.35) except for one scenario on the 21st of December at 12:00. In this scenario, the DGP amount equals 1, which means the occupant P2 faces an intolerable situation. The results point out the geometry of the façade has some problems in avoiding glare that happens at the lowest height in front of the occupant position.

4.3 Biomimetic kinetic façade with Bookshelf component and tapered periodic interactive region (BS_T)

Analyzing the results of daylight performance simulation approves the extraordinary performance of the biomimetic kinetic façade with Bookshelf component and tapered PIR

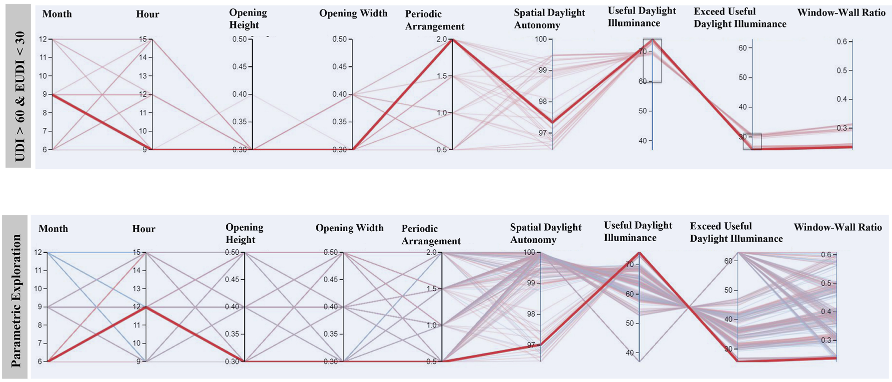


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Figure 12. Parametric exploration of biomimetic interactive kinetic façade with hyperbolic paraboloid module and circular PIR through climate-based daylight metrics (a parallel coordinated graph)

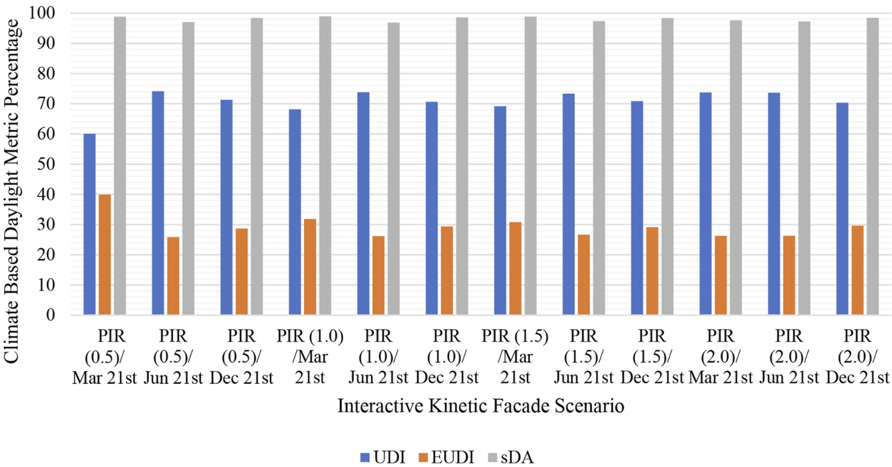

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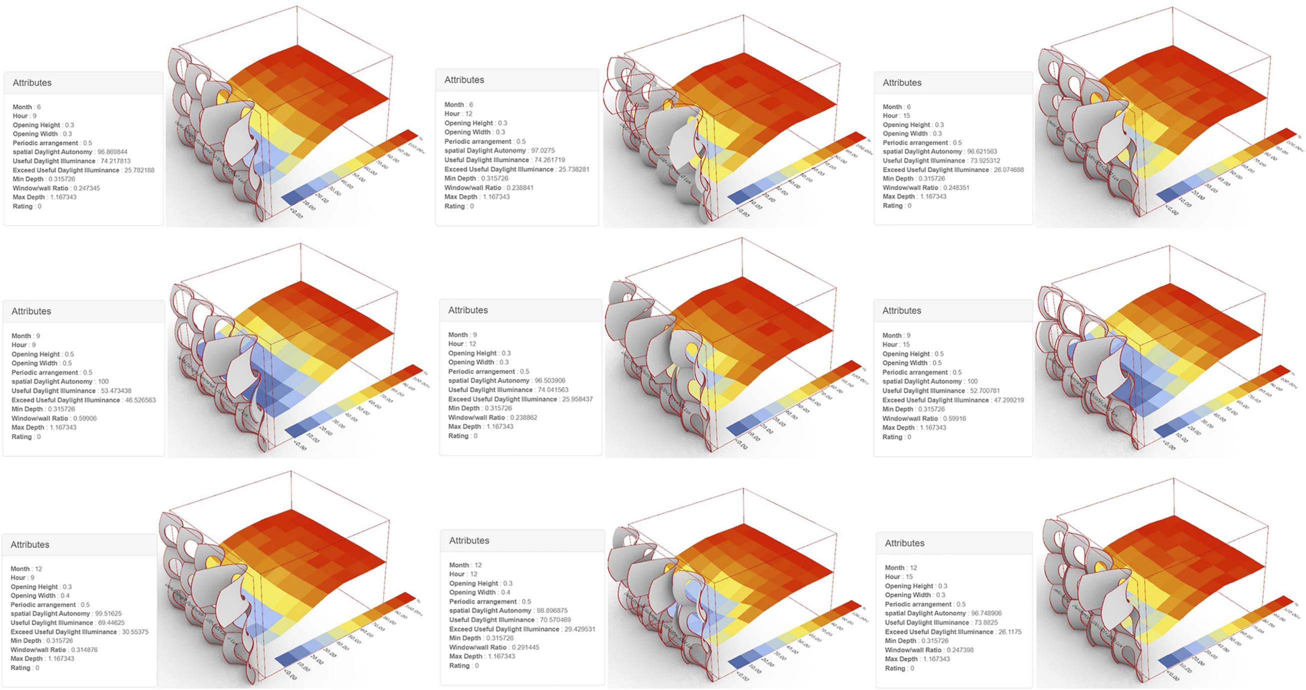
Figure 13. Annual daylight performance evaluation of biomimetic interactive kinetic façade with hyperbolic paraboloid module and circular PIR through climate-based daylight metrics

Figure 14. Daylight performance evaluation of best scenarios of hyperbolic paraboloid façade with PIR of 0.5 m through climate-based daylight metrics



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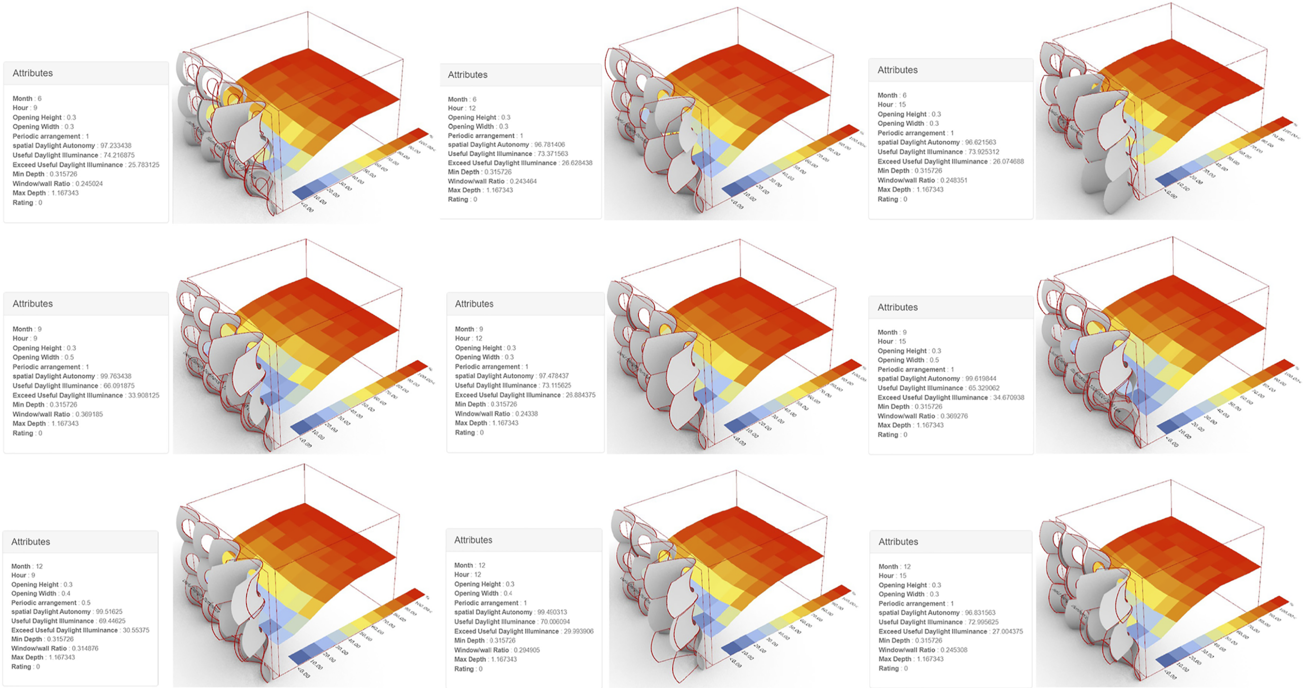

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Figure 15.
Daylight performance evaluation of best scenarios of hyperbolic paraboloid façade with PIR of 1 m through climate-based daylight metrics

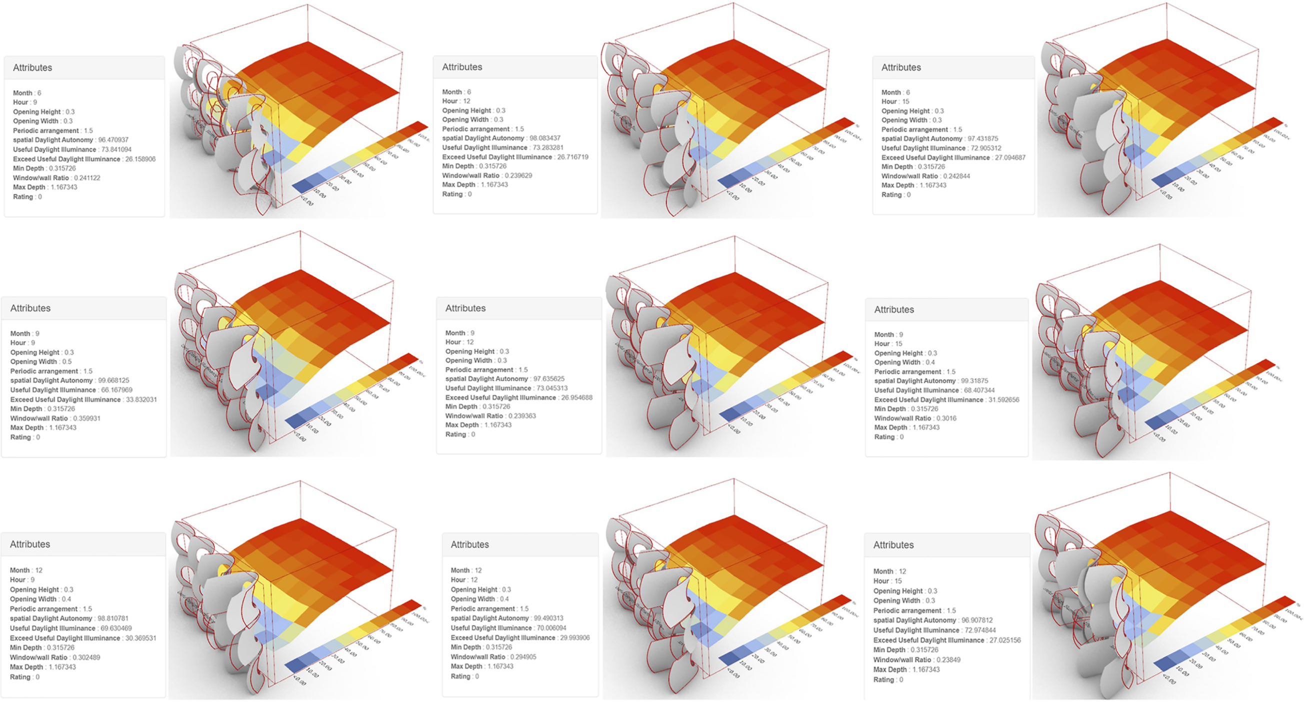

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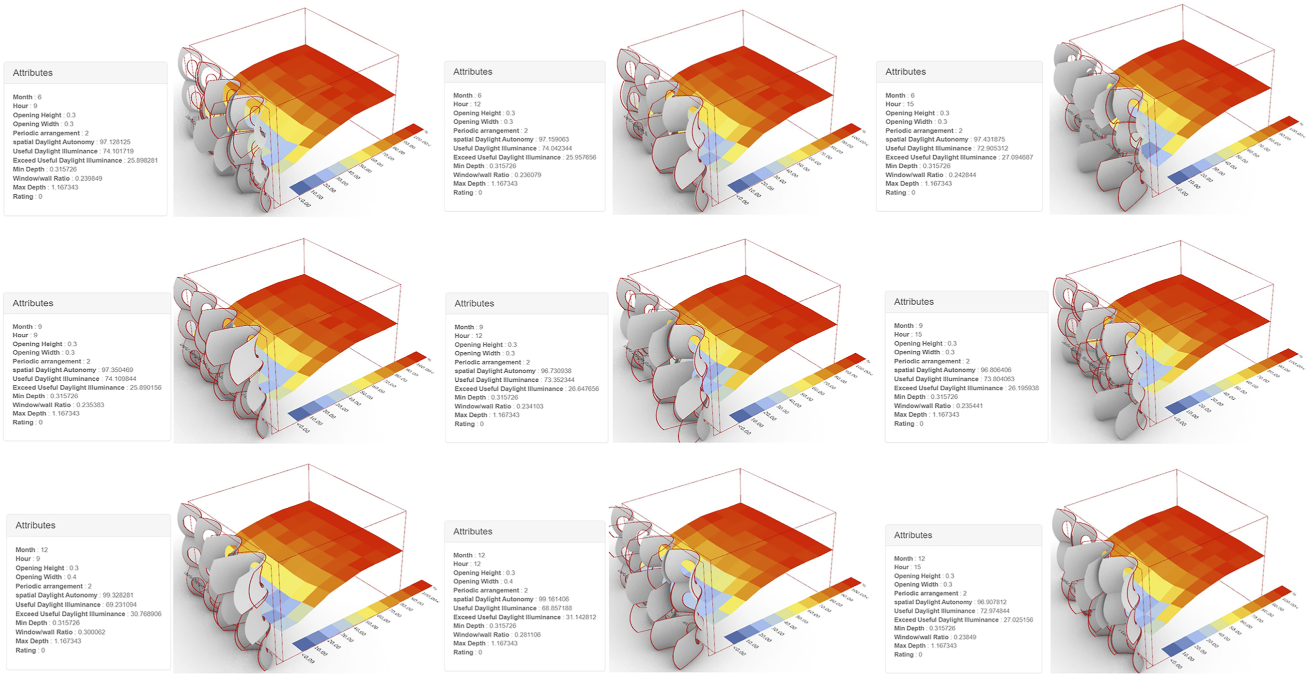
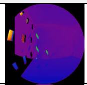
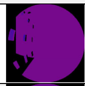
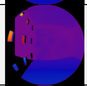
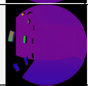
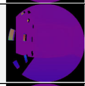
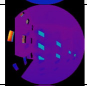
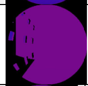
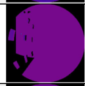
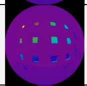
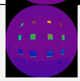
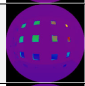
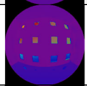
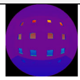
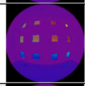
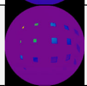
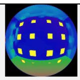
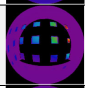
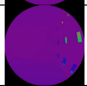
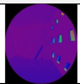
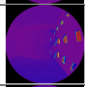
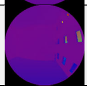
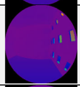
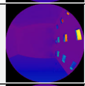
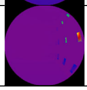
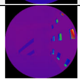
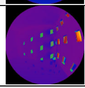
Figure 16. Daylight performance evaluation of best scenarios of hyperbolic paraboloid façade with PIR of 1.5 m through climate-based daylight metrics



Source(s): Authors' own creation

Figure 17. Daylight performance evaluation of best scenarios of hyperbolic paraboloid façade with PIR of 2 m through climate-based daylight metrics

Orientation	*South*												
Scenario	Office Hours												sDA
	9:00				12:00				15:00				
	UDI	EUDI	DGP	PHOTO	UDI	EUDI	DGP	PHOTO	UDI	EUDI	DGP	PHOTO	
Person 1/ Mar 21st	74.11	25.89	0.23		73.35	26.65	0.26		73.80	26.19	0.28		97.63
Person 1/ Jun 21st	74.10	25.89	0.23		74.04	25.96	0.24		73.92	26.07	0.24		97.24
Person 1/ Dec 21st	69.23	30.76	0.22		68.85	31.14	0.27		72.97	27.02	0.3		98.46
Person 2/ Mar 21st	74.10	25.89	0.3		74.04	25.96	0.33		73.80	26.19	0.28		97.13
Person 2/ Jun 21st	74.10	25.89	0.28		74.04	25.96	0.3		73.92	26.07	0.29		97.24
Person 2/ Dec 21st	69.63	30.37	0.29		70.57	29.43	1		73.88	26.12	0.29		96.75
Person 3/ Mar 21st	74.10	25.89	0.26		74.04	25.96	0.27		72.90	27.09	0.25		96.50
Person 3/ Jun 21st	73.84	26.15	0.25		74.04	25.96	0.25		72.90	27.09	0.23		98.89
Person 3/ Dec 21st	69.63	30.37	0.27		70.57	29.43	0.26		73.88	26.12	0.22		96.75

Source(s): Authors' own creation

Table 8. DGP and climate-based metric evaluation of the best biomimetic kinetic façade with Hyperbolic Paraboloid component and circular PIR (HP_C) for the South direction

(BS_T) to improve visual comfort compared to the base case (Figure 18). Table 7 shows the daylight performance investigation of the kinetic façade with the tapered shape of PIR in solstice and equinox days at 9:00, 12:00 and 15:00. Analyzing the data of Table 6 proves the daylight performance of the kinetic façade alternatives with the amount of UDI, EUDI and sDA in the range of (89.51_98.63), (1.28_10.49) and (65.61_99.24), respectively. The BS component with tapered PIR has the potential to supply remarkably high useful daylight in the interior space by increasing the amount of UDI up to 4.92 times, with respect to the base case. Moreover, the façade decreases the amount of EUDI in the room by 99.33%, with respect to the base case.

Table 9 presents the DGP value of the biomimetic kinetic façade with the BS component and tapered PIR of the South direction based on the occupant's position in the room on the solstice and equinox days (Figure 9). The evaluation of DGP reveals the remarkable performance of the façade in mitigating visual discomfort by effectively reducing DGP compared to the base case. This improvement is consistently observed across various times of the day and days. The facade indicates the substantial improvement of DGP values while

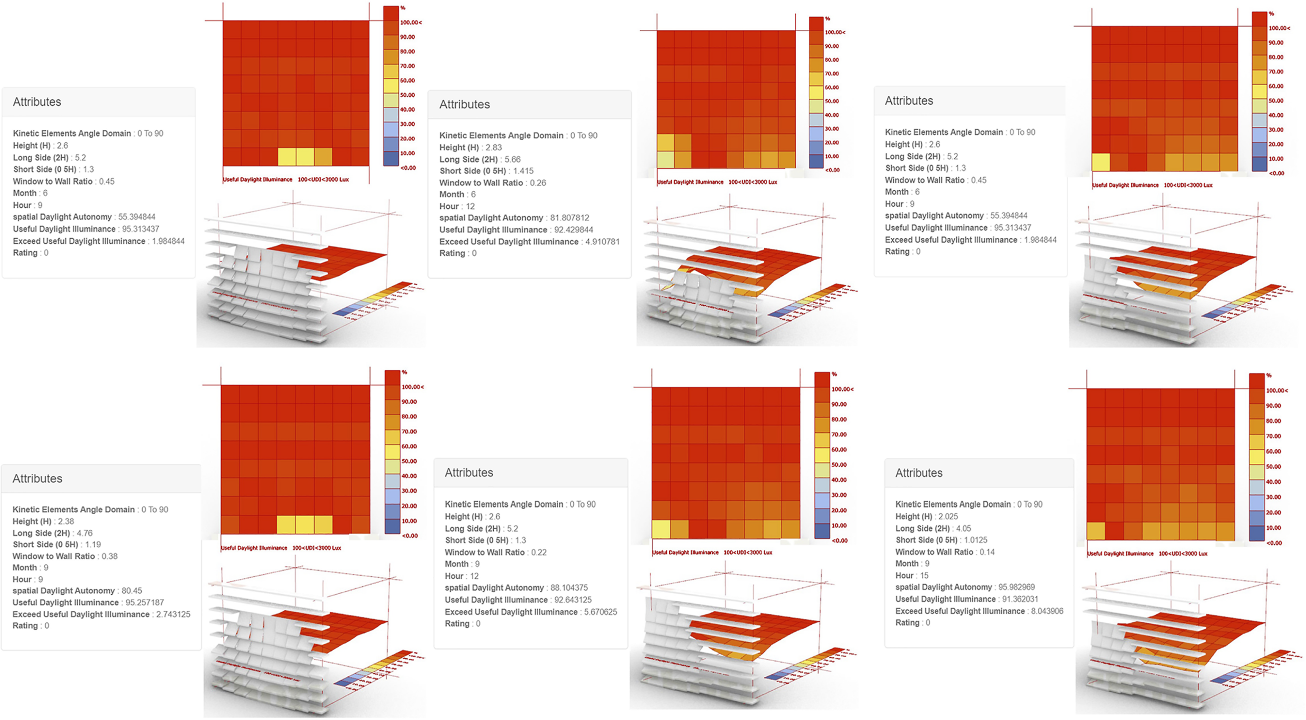
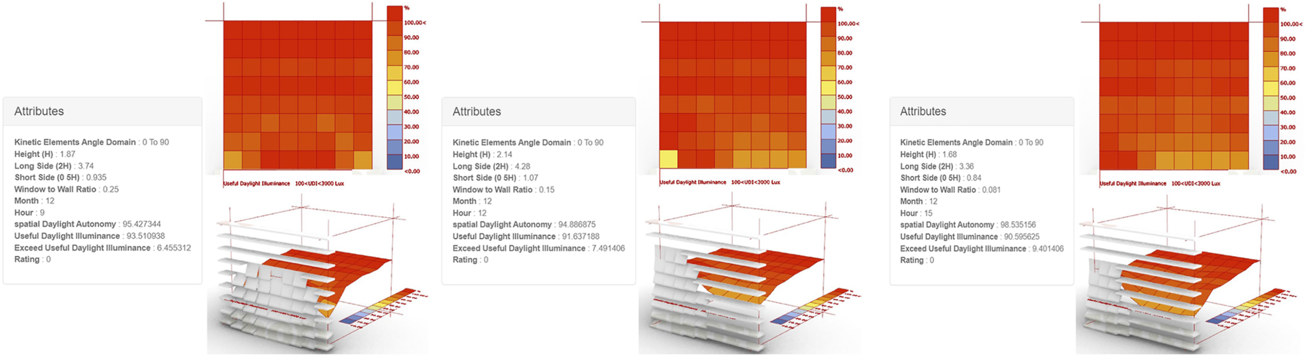


Figure 18. Daylight performance evaluation of the biomimetic kinetic façade with Bookshelf component and tapered periodic interactive region (BS_T)

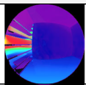
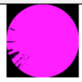
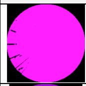
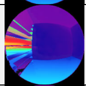
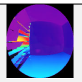
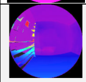
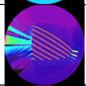
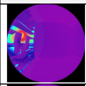
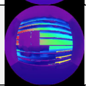
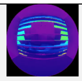
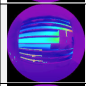
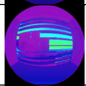
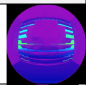
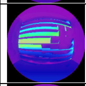
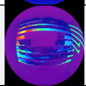
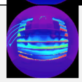
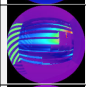
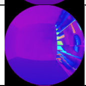
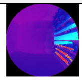
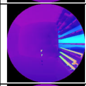
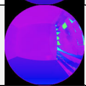
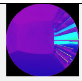
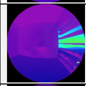
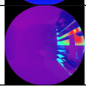
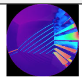
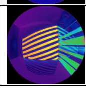
(continued)



Source(s): Authors' own creation

Figure 18

Table 9.
DGP evaluation of the biomimetic kinetic façade with Bookshelf component and tapered periodic interactive region (BS_T)

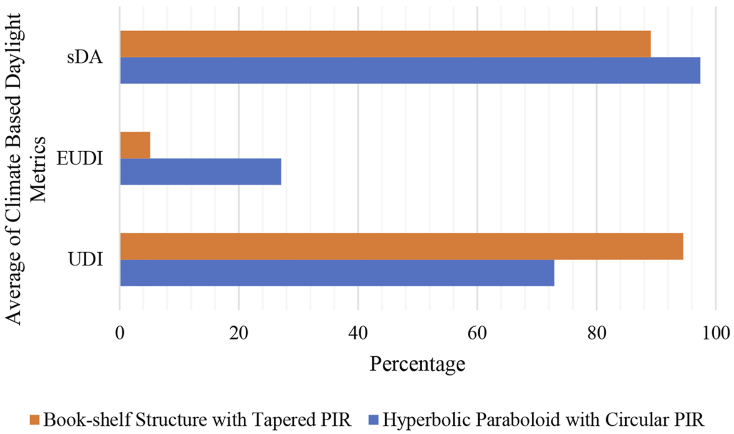
Orientation	*South*												
Scenario	Office Hours												sDA
	9:00				12:00				15:00				
	UDI	EUDI	DGP	PHOTO	UDI	EUDI	DGP	PHOTO	UDI	EUDI	DGP	PHOTO	
Person 1/ Mar 21st	96.72	3.13	0.24		94.90	5.09	0.27		93.37	6.62	0.29		93.85
Person 1/ Jun 21st	97.13	2.17	0.25		95.14	4.62	0.25		94.32	5.68	0.22		85.93
Person 1/ Dec 21st	93.74	6.18	0.32		93.41	6.58	0.27		92.94	7.05	0.28		98.66
Person 2/ Mar 21st	94.68	4.44	0.33		97.3	2.09	0.3		95.53	4.37	0.30		84.5
Person 2/ Jun 21st	95.05	3.85	0.27		97.75	1.28	0.26		93.98	2.15	0.27		65.61
Person 2/ Dec 21st	94.48	5.36	0.34		96.43	3.02	0.34		94.61	5.39	0.32		95.09
Person 3/ Mar 21st	96.91	3.09	0.25		93.61	6.39	0.32		91.26	8.74	0.27		95.3
Person 3/ Jun 21st	98.63	1.29	0.22		94.99	5	0.29		92.89	7.11	0.24		83.48
Person 3/ Dec 21st	92.18	7.82	0.32		91.01	8.98	0.35		89.51	10.49	0.35		99.24

Source(s): Authors' own creation

keeping the sDA in a very satisfactory range. The kinetic façade demonstrates exceptional performance across all scenarios, consistently remaining within the imperceptible domain. To summarize, the incorporation of a tapered PIR in the facade design yields remarkable results. It successfully provides much useful daylight to the interior space while mitigating visual discomfort and overheating near the facade, particularly when facing south.

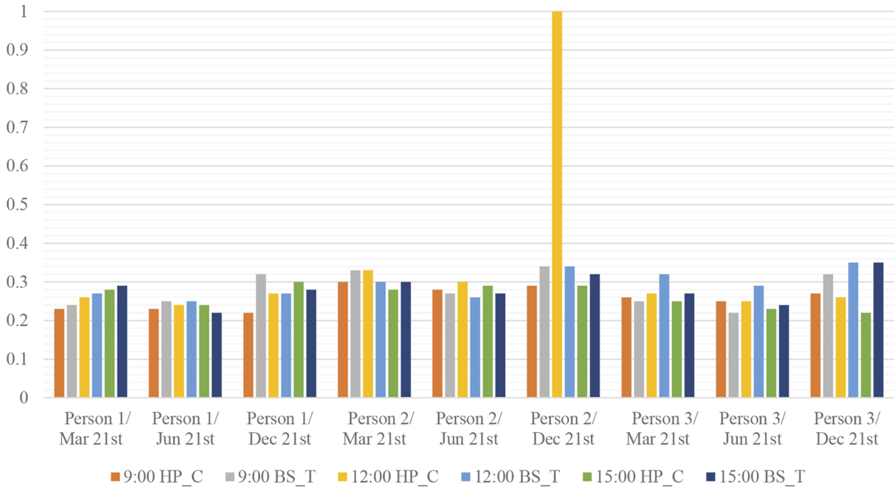
4.4 Daylight performance comparison between Bookshelf structure with tapered PIR (BS_T) and hyperbolic paraboloid with circular PIR (HP_C)

Both facades keep an sDA amount of more than 90% and meet the daylight standard requirements at a remarkably high rate. However, comparing the UDI and EUDI records specifies the high daylight performance of the book-shelf component with tapered PIR. BS_T provides 29.65% useful daylight illuminance more than HP_C while dramatically decreasing EUDI by more than 31.5%, as Figure 19 demonstrates. Although both facades have a similar performance regarding DGP evaluation, BS_T keeps all scenarios in the imperceptible range while HP_C has a case in the intolerable area (Figure 20). It clearly shows the potential of BS_



Source(s): Authors' own creation

Figure 19. Daylight performance comparison of Bookshelf structure with tapered PIR and hyperbolic paraboloid with circular PIR using climate-based daylight metric evaluation



Source(s): Authors' own creation

Figure 20. Daylight glare probability comparison of Bookshelf structure with tapered PIR (BS_T) and hyperbolic paraboloid with circular PIR (HP_C)

T for providing the maximum useful daylight in the interior spaces while keeping Exceed UDI under 6.4%.

5. Discussion

Integrating biomimetic and the kinetic design strategy through parametric workflow enables the development of high-performance interactive kinetic façades. The results provide sufficient evidence to determine whether complex forms or simple forms with proper kinetic behavior are more effective in regulating dynamic daylight, which is the main aim of the study. This biomimetic methodology supports kinetic façade design by integrating morphology and kinetic behavior inspired by Morpho butterfly wings. The findings of this study strongly suggest that an optimal combination of morphology and kinetic behavior is the most effective way to achieve excellent visual comfort. Using a biomimetic functional-morphological approach reveals that Morpho butterfly wings benefit from both simple and complex forms, along with exceptional kinetic behavior that allows for interactivity with various stimuli. Although façade morphologies have a profound influence, kinetic behavior can significantly enhance or mitigate their impact on visual comfort. For example, the Hyperbolic Paraboloid (HP_C) components, which have a complicated shape, perform exceptionally well in terms of boosting occupant's visual comfort. However, considering the performance of Book-shelf (BS_T) components with the same kinetic behavior (PIR) reveals that using a simple shape integrated with an appropriate kinetic behavior provides more adaptability and improvement in visual comfort comparing the complex geometry. As results approve, BS_T provides 29.65% useful daylight illuminance more than HP_C while remarkably decreasing EUDI by more than 31.5%.

The current study introduces PIR inspired by Morpho butterfly wings. The result is consistent with that of Hosseini (2021a), which discovers a transitory sensitive area retrieved from plant stomata. The comparison of the climate-based daylight metrics shows that the BS_T façade provides more useful daylight than the Bio-inspired façade with an improvement of 28.57% and 4.06% of sDA and UDI, respectively. Both solutions work equally well in terms of reducing overheating near the facades. Through a comprehensive analysis of DGP metrics, considering both occupant positions and dynamic daylight scenarios, it becomes evident that the BS_T outperforms the alternative design. Notably, the BS_T consistently maintains all cases within the imperceptible range, indicating its superior performance in preventing glare-related visual discomfort. The same functions in plant stomata and Morpho butterfly wings lead to acceptance of the PIR on the façade as major control logic for achieving more occupant visual comfort.

In comparison to studies that lack architectural concepts, such as the works by Wang *et al.* in 2022 involving a complex form and the study by Le *et al.* in 2022 focusing on adaptive roller blinds, the Bookshelf component (BS_T) achieves equivalent visual comfort conditions and superior daylight performance by providing several intermediate options of façade form transformation not only fully opened or fully closed. It achieves these outcomes through a straightforward design characterized by the appropriate combination of kinetic behavior and form, in contrast to the use of genetic algorithms or other probabilistic methods. Indeed, the utilization of a biomimetic approach strengthens the architectural design concept by avoiding irrelevant variables in the initial stages of the process, allowing for a more efficient exploration of potential solutions. Consequently, the algorithmic workflow can employ a brute force algorithm to evaluate all possible solutions within an efficiently defined exploration area, achieving high accuracy in finding the global optimum. In this study, our methodology introduces novel design variables, including PIRs, particle density adjustments and a tapered arrangement of kinetic elements on the façade. However, existing research, such as the works by Tabadkani *et al.* (2021), Valitabar *et al.* (2022), has primarily focused on optimizing users' daylight performance using conventional parameters like slat rotation, orientation and slat depth in Venetian blinds and using a hexagonal module and sun tracking system in unconventional façade (Wang *et al.*, 2024). In contrast to existing methods, where Valitabar *et al.* (2022) and Wang *et al.* (2024) independently adjust tilt angles for all façade modules—a process that is complex and computationally expensive—our BS_T façade system takes a different approach. Specifically, our system dynamically adjusts its elements exclusively within the PIR, following a tapered pattern while keeping the remaining elements stationary. By avoiding the need for intricate tilt angle adjustments across all elements, our system achieves energy efficiency and reduces maintenance demands. This adaptability enables swift transformations based on dynamic user positions and sun angles. Studies that incorporate architectural concepts, such as those involving multilayer and multiscale interference (Hosseini and Heidari, 2022), foldable surfaces in multiple layers

(Soliman and Bo, 2023), flexural hexagonal shapes (Kim, 2023), focal and peripheral regions on façade (Sommese *et al.*, 2024), swelling and shrinking rib-structure (Kuru *et al.*, 2021) result in complex and three-dimensional forms similar to HP_C which provide centralized and decentralized control for users in the space. Furthermore, there are many criticisms due to their complexity, energy consumption and capital costs for operating these types of facades (Al-Masrani *et al.*, 2018). However, the BS_T demonstrates superior daylight performance and enhanced visual comfort for occupants. Moreover, the BS_T's advantage lies in its simple lamella shape and interactive control logic, making it the optimal choice for practical applications owing to its ease of manufacturing, control and maintenance. As a result, the BS_T can be implemented in buildings with a louver system, enhancing adaptability to dynamic sun positions and occupants' positions in a room. Despite the superficial consideration of the biomimetic approach in the studies above, the current study conducts a thorough exploration of the biological analogy (Morpho Butterfly wing). This exploration has resulted in detecting both simple and complex forms within the same analogy. The finding demonstrates that natural phenomena offer multiple approaches for adaptation, including a simple form with appropriate kinetic behavior and a complex form simultaneously. These forms can be utilized based on specific applications and conditions.

The analysis of the daylight performance of existing kinetic facades, including Al Bahr Towers and Helio Trace Centre of Architecture building, demonstrates their high potential for meeting daylight performance criteria. In general, they have the same daylight performance as BS_T. However, based on the comparison of the detailed results, by incorporating PIRs, the BS_T design effectively reduces solar heat gain by over 99% compared to the base case. Al Bahar Towers and the Helio Trace Centre of Architecture have demonstrated remarkable abilities in reducing solar heat gains, achieving respective reductions of 50% and 81% (Hosseini *et al.*, 2019b). The comparison confirms the critical role of PIR in significantly improving occupants' visual comfort through interactive kinetic facades.

Several limitations must be considered while evaluating the study's findings. This study utilized a parametric daylight simulation approach according to the guidelines of daylight performance prediction (Reinhart, 2019). However, because glare prediction relies strongly on human perception, the function of the biomimetic interactive kinetic façade must also be examined experimentally. Furthermore, since the study is based on modeling, a collaboration with laboratory or field data is required. Occupants' participation in future studies will be critical for testing research assumptions and formulating interaction with façades based on post-occupancy evaluations. In addition, it would be advantageous to investigate diverse types and mechanisms of the kinetic façade and compare their daylight performance with standard solar shadings such as louver façade and roller shading. The primary objective of this study is to investigate the iridescence of the Morpho butterfly wing to extract efficient morphology and kinetic motions for regulating light. The scale of the façade system and the ideal size of elements are beyond the focus of this study. This optimization option can be developed as a future study using a proper algorithmic method such as an evolutionary algorithm and machine learning process. Given the focus of this study on the form and function of façades, particularly in terms of daylight performance and visual comfort, the topics of structure and material fall outside the scope of this work. However, future research should explore materialization to propose optimal combinations of material and structure that achieve the desired form and function (Reichert *et al.*, 2015). Notably, the material-dependent behavior of structures can be geometrically modeled using discretization methods and Finite Element Analysis techniques (Vergauwen *et al.*, 2017). As we do not possess a biological laboratory, the exploration of Morpho butterfly wing characteristics within the biomimetic approach has primarily relied on a thorough review of existing literature.

It is imperative to thoroughly investigate the control logic governing kinetic components, particularly, the PIR. This exploration should encompass various aspects, including sensor correlation, interpositions and an analysis of their interactions with other dynamic internal and external features. Additionally, incorporating occupant behavior into the design process is crucial. To achieve this multidisciplinary approach, close collaboration among biologists, structural and architectural engineers and computer science specialists is essential. Ultimately, this collaborative effort will contribute to the development of versatile façade components with multiple functions. The enhancement of the periodic interactive zone can be achieved through the application of a reinforcement learning approach, primarily driven by optimization objectives. Leveraging evolutionary algorithms, we can optimize the functions of a kinetic façade, considering various dynamic stimuli. These stimuli include occupant detection, estimation and interaction, as well as factors related to location, dynamic environmental features, orientations, space functions and architectural design elements. Furthermore, as a recommendation for future research, investigating material compatibility with the façade typology, actuation type and rotational/movement speed of the elements holds promise.'.

6. Conclusion

The study's output reveals that incorporating the biomimetic functional-morphological approach within the kinetic design strategy phases leads to the establishment of a circular algorithmic workflow of kinetic façade design. Furthermore, the results confirm that simple forms with proper kinetic behavior outperform the counterpart complex forms for improving visual comfort and daylight performance.

(1) The research employs a multidisciplinary methodology through a distinctive blend of methods as a biomimetic functional-morphological approach, kinetic design strategy, case study comparison and using algorithmic workflow, parametric simulation and inverse design to engineer an interactive kinetic facade with optimized performance.

(2) The functional-morphological convergence of the biomimetic approach leads to finding the iridescence and high reflectance phenomenon, especially in Morpho butterfly wings that are made by redirecting, scattering and reflecting the light through a combination of forms and kinetic behavior.

(3) A key development is the introduction of a PIR, which draws inspiration from the butterfly wings' nanostructure. This unique feature leverages periodic geometrical changes, tapered arrangements and particle density modifications to enhance the facade's adaptability to environmental stimuli.

(4) Two distinguished forms are extracted from the Morpho butterfly wing's nanostructure: Saddle shape as Hyperbolic Paraboloid and BS structure. The research provides a comparative analysis of two biomimetic kinetic facades, revealing that the facade with a simpler "Bookshelf" shape integrated with a tapered shape of the PIR outperforms its more complex counterpart (Hyperbolic Paraboloid component) in terms of daylight performance and glare control, especially in southern orientations.

(5) As results approve, BS_T provides 29.65% useful daylight illuminance more than HP_C while dramatically decreasing EUDI by more than 31.5%. In particular, the Book-shelf component with the tapered PIR demonstrates exceptional daylight performance in the south direction, ensuring occupant visual comfort by keeping cases in the imperceptible range while also delivering sufficient average sDA of 89.07%, UDI of 94.53% and EUDI of 5.11%.

(6) Compared to studies that incorporate architectural concepts that result in complex forms, the BS_T demonstrates outstanding daylight performance and enhanced visual comfort for occupants. Furthermore, the BS_T stands out due to its straightforward lamella shape and interactive control system, rendering it the top choice for practical applications due to its ease of manufacture, control and maintenance.

The results reveal that there is an immense potential for finding adaptive solutions for kinetic façade design through the biomimetic functional morphological approach. The next step would be initiating a multidisciplinary collaboration with biologists, material science experts and structural designers to construct a kinetic façade as a multi-functional building component. In addition, some parameters such as occupant behavior and preferences, space function and adaptation in the long term are important subjects for further research.

References

Al-Masrani, S.M., Al-Obaidi, K.M., Zalin, N.A. and Aida Isma, M.I. (2018), "Design optimisation of solar shading systems for tropical office buildings: challenges and future trends", *Solar Energy*, Vol. 170, pp. 849-872, doi: 10.1016/j.solener.2018.04.047.

Attia, S., Garat, S. and Cools, M. (2019), "Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive facades", *Building and Environment*, Vol. 157, pp. 268-276, doi: 10.1016/j.buildenv.2019.04.054.

Badarnah, L. (2017), "Form follows environment: biomimetic approaches to building envelope design for environmental adaptation", *Buildings*, Vol. 7 No. 2, p. 40, doi: 10.3390/buildings7020040.

Brembilla, E. and Mardaljevic, J. (2019), "Climate-based daylight modelling for compliance verification: benchmarking multiple state-of-the-art methods", *Building and Environment*, Vol. 158, pp. 151-164, doi: 10.1016/j.buildenv.2019.04.051.

Chung, K., Yu, S., Heo, C.-J., Shim, J.W., Yang, S.-M., Han, M.G., Lee, H.-S., Jin, Y., Lee, S.Y., Park, N. and Shin, J.H. (2012), "Flexible, angle-independent, structural color reflectors inspired by morpho butterfly wings", *Advanced Materials*, Vol. 24 No. 18, pp. 2375-2379, doi: 10.1002/adma.201200521.

Freyer, P. and Stavenga, D.G. (2020), "Biophotonics of diversely coloured peacock tail feathers", *Faraday Discussions*, The Royal Society of Chemistry, Vol. 223 No. 0, pp. 49-62, doi: 10.1039/D0FD00033G.

Globa, A., Costin, G., Tokede, O., Wang, R., Khoo, C.K. and Moloney, J. (2022), "Hybrid kinetic facade: fabrication and feasibility evaluation of full-scale prototypes", *Architectural Engineering and Design Management*, Vol. 18 No. 6, pp. 791-811, doi: 10.1080/17452007.2021.1941739.

Hariyama, T. (2005), "The leaf beetles, the jewel beetle, and the damselfly; insects with a multilayered show case", in *Structural Colors in Biological Systems-Principles and Applications*, Osaka University Press, pp. 153-176.

Hinkle, L.E., Wang, J. and Brown, N.C. (2022), "Quantifying potential dynamic façade energy savings in early design using constrained optimization", *Building and Environment*, Vol. 221, 109265, doi: 10.1016/j.buildenv.2022.109265.

Hosseini, S.M. and Heidari, S. (2022), "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*, Vol. 59, 105027, doi: 10.1016/j.jobe.2022.105027.

Hosseini, S.M., Fadli, F. and Mohammadi, M. (2021b), "Biomimetic kinetic shading facade inspired by tree morphology for improving occupant's daylight performance", *Journal of Daylighting*, Vol. 8 No. 1, pp. 65-85, doi: 10.15627/jd.2021.5.

Hosseini, S.M., Heiranipour, M., Wang, J., Hinkle, L.E., Triantafyllidis, G. and Attia, S. (2024), "Enhancing visual comfort and energy efficiency in office lighting using parametric-generative design approach for interactive kinetic louvers", *Journal of Daylighting*, Vol. 11 No. 1, pp. 69-96, doi: 10.15627/jd.2024.5.

Hosseini, S.M., Mohammadi, M. and Guerra-Santin, O. (2019a), "Interactive kinetic façade: improving visual comfort based on dynamic daylight and occupant's positions by 2D and 3D shape changes", *Building and Environment*, Vol. 165, 106396, doi: 10.1016/j.buildenv.2019.106396.

Hosseini, S.M., Mohammadi, M., Rosemann, A., Schröder, T. and Lichtenberg, J. (2019b), "A morphological approach for kinetic façade design process to improve visual and thermal comfort: review", *Building and Environment*, Vol. 153, pp. 186-204, doi: 10.1016/j.buildenv.2019.02.040.

Hosseini, S.M., Mohammadi, M., Schröder, T. and Guerra-Santin, O. (2021a), "Bio-inspired interactive kinetic façade: using dynamic transitory-sensitive area to improve multiple occupants' visual comfort", *Frontiers of Architectural Research*, Vol. 10 No. 4, pp. 821-837, doi: 10.1016/j.foar.2021.07.004.

Hosseini, S.M., Mohammadi, M., Schröder, T. and Guerra-Santin, O. (2020), "Integrating interactive kinetic façade design with colored glass to improve daylight performance based on occupants' position", *Journal of Building Engineering*, Vol. 31, 101404, doi: 10.1016/j.jobe.2020.101404.

Jiang, X., Shi, T., Zuo, H., Yang, X., Wu, W. and Liao, G. (2012), "Investigation on color variation of Morpho butterfly wings hierarchical structure based on PCA", *Science China Technological Sciences*, Vol. 55 No. 1, pp. 16-21, doi: 10.1007/s11431-011-4528-4.

Kawabe, M., Maeda, H. and Kasuga, T. (2020), "Heat transfer properties of Morpho butterfly wings and the dependence of these properties on the wing surface structure", *RSC Advances*, Vol. 10 No. 5, pp. 2786-2790, doi: 10.1039/C9RA09990E.

Kim, H. and Clayton, M.J. (2020), "A multi-objective optimization approach for climate-adaptive building envelope design using parametric behavior maps", *Building and Environment*, Vol. 185, 107292, doi: 10.1016/j.buildenv.2020.107292.

Kim, M.j., Kim, B.g., Koh, J.s. and Yi, H. (2023), "Flexural biomimetic responsive building façade using a hybrid soft robot actuator and fabric membrane", *Automation in Construction*, Vol. 145, 104660, doi: 10.1016/j.autcon.2022.104660.

Köchling, P., Niebel, A., Hurka, K., Vorholt, F. and Hölscher, H. (2020), "On the multifunctionality of butterfly scales: a scaling law for the ridges of cover scales", *Faraday Discussions*, The Royal Society of Chemistry, Vol. 223 No. 0, pp. 195-206, doi: 10.1039/D0FD00038H.

Kuipers, N. (2015), "From static to kinetic - the potential of kinetic façades in care-hotels", aE-Intecture-Studio14.

Kuru, A., Oldfield, P., Bonser, S. and Fiorito, F. (2021), "Performance prediction of biomimetic adaptive building skins: integrating multifunctionality through a novel simulation framework", *Solar Energy*, Vol. 224, pp. 253-270, doi: 10.1016/j.solener.2021.06.012.

Le, D.M., Park, D.Y., Baek, J., Karunyasopon, P. and Chang, S. (2022), "Multi-criteria decision making for adaptive façade optimal design in varied climates: energy, daylight, occupants' comfort, and outdoor view analysis", *Building and Environment*, Vol. 223, 109479, doi: 10.1016/j.buildenv.2022.109479.

Le-Thanh, L., Le-Duc, T., Ngo-Minh, H., Nguyen, Q.-H. and Nguyen-Xuan, H. (2021), "Optimal design of an Origami-inspired kinetic façade by balancing composite motion optimization for improving daylight performance and energy efficiency", *Energy*, Vol. 219, 119557, doi: 10.1016/j.energy.2020.119557.

Li, J., Li, X., Yu, F., Chen, Y. and Huang, W. (2010), "Mechanism and analysis of structural color in two typical butterfly scales", *2010 IEEE 5th International Conference on Nano/Micro Engineered and Molecular Systems*, pp. 723-727, doi: 10.1109/NEMS.2010.5592256.

Loonen, R.C.G.M. (2015), "Bio-inspired adaptive building skins", in Pacheco Torgal, F., Labrincha, J.A., Diamanti, M.V., Yu, C.-P. and Lee, H.K. (Eds), *Biotechnologies and Biomimetics for Civil Engineering*, Springer International Publishing, Cham, pp. 115-134, doi: 10.1007/978-3-319-09287-4_5.

Luna-Navarro, A., Loonen, R., Juaristi, M., Monge-Barrio, A., Attia, S. and Overend, M. (2020), "Occupant-Facade interaction: a review and classification scheme", *Building and Environment*, Vol. 177, 106880, doi: 10.1016/j.buildenv.2020.106880.

Megahed, N.A. (2017), "Understanding kinetic architecture: typology, classification, and design strategy", *Architectural Engineering and Design Management*, Vol. 13 No. 2, pp. 130-146, doi: 10.1080/17452007.2016.1203676.

National Renewable Energy Laboratory (2024), "EnergyPlus", available at: https://energyplus.net/weather-location/asia_wmo_region_2/IRN/IRN_Yazd.408210_ITMY (accessed 3 June 2024).

Neufert, E. and Neufert, P. (2000), *Neufert Architect's Data*, 3rd ed., Wiley-Blackwell.

Ostermeyer, Y. (2010), "2.3 solar gain in context", in *MOVEArchitecture in Motion - Dynamic Components and Elements*, Birkhäuser, Berlin, Basel, doi: 10.1515/9783034608541.132.

Reichert, S., Menges, A. and Correa, D. (2015), "Meteorosensitive architecture: biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness", *Computer-Aided Design*, Vol. 60, pp. 50-69, doi: 10.1016/j.cad.2014.02.010.

Reinhart, C. (2011), *Daylight Performance Predictions, Building Performance Simulation for Design and Operation*, Routledge, London.

Reinhart, C. (2018), *Daylighting Handbook II*, Building Technology Press, Cambridge, MA.

Reinhart, C. (2019), "Daylight performance predictions", in *Building Performance Simulation for Design and Operation*, 2nd ed., Routledge, London, Vol. 792, pp. 221-269.

Reinhart, C.F. and Walkenhorst, O. (2001), "Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds", *Energy and Buildings*, Vol. 33 No. 7, pp. 683-697, doi: 10.1016/S0378-7788(01)00058-5.

Rizi, R.A. and Eltaweel, A. (2021), "A user detective adaptive facade towards improving visual and thermal comfort", *Journal of Building Engineering*, Vol. 33, 101554, doi: 10.1016/j.jobe.2020.101554.

Sadegh, S.O., Gasparri, E., Brambilla, A. and Globa, A. (2022), "Kinetic facades: an evolutionary-based performance evaluation framework", *Journal of Building Engineering*, Vol. 53, 104408, doi: 10.1016/j.jobe.2022.104408.

Shahin, H.S.M. (2019), "Adaptive building envelopes of multistory buildings as an example of high performance building skins", *Alexandria Engineering Journal*, Vol. 58 No. 1, pp. 345-352, doi: 10.1016/j.aej.2018.11.013.

Shen, Q., He, J., Ni, M., Song, C., Zhou, L., Hu, H., Zhang, R., Luo, Z., Wang, G., Tao, P., Deng, T. and Shang, W. (2015), "Subtractive structural modification of morpho butterfly wings", *Small*, Vol. 11 No. 42, pp. 5705-5711, doi: 10.1002/smll.201500502.

Siddique, R.H., Diewald, S., Leuthold, J. and Hölscher, H. (2013), "Theoretical and experimental analysis of the structural pattern responsible for the iridescence of Morpho butterflies", *Optics Express*, Vol. 21 No. 12, pp. 14351-14361, doi: 10.1364/OE.21.014351.

Sokhandan, A. and Monadjemi, A. (2016), "A novel biologically inspired computational framework for visual tracking task", *Biologically Inspired Cognitive Architectures*, Vol. 18, pp. 68-79, doi: 10.1016/j.bica.2016.09.006.

Soliman, M.E. and Bo, S. (2023), "An innovative multifunctional biomimetic adaptive building envelope based on a novel integrated methodology of merging biological mechanisms", *Journal of Building Engineering*, Vol. 76, 106995, doi: 10.1016/j.jobe.2023.106995.

Sommese, F., Hosseini, S.M., Badarnah, L., Capozzi, F., Giordano, S., Ambrogi, V. and Ausiello, G. (2024), "Light-responsive kinetic façade system inspired by the Gazania flower: a biomimetic approach in parametric design for daylighting", *Building and Environment*, Vol. 247, 111052, doi: 10.1016/j.buildenv.2023.111052.

Song, B., Eom, S.C. and Shin, J.H. (2014), "Disorder and broad-angle iridescence from Morpho-inspired structures", *Optics Express*, Vol. 22 No. 16, pp. 19386-19400, doi: 10.1364/OE.22.019386.

Steindorfer, M.A., Schmidt, V., Belegratis, M., Stadlober, B. and Krenn, J.R. (2012), "Detailed simulation of structural color generation inspired by the Morpho butterfly", *Optics Express*, Vol. 20 No. 19, pp. 21485-21494, doi: 10.1364/OE.20.021485.

Tabadkani, A., Valinejad Shoubi, M., Soflaei, F. and Banihashemi, S. (2019), "Integrated parametric design of adaptive facades for user's visual comfort", *Automation in Construction*, Vol. 106, 102857, doi: 10.1016/j.autcon.2019.102857.

Tabadkani, A., Roetzel, A., Xian Li, H., Tsangrassoulis, A. and Attia, S. (2021), "Analysis of the impact of automatic shading control scenarios on occupant's comfort and energy load", *Applied Energy*, Vol. 294, 116904, doi: 10.1016/j.apenergy.2021.116904.

Taveres-Cachat, E., Favoino, F., Loonen, R. and Goia, F. (2021), "Ten questions concerning co-simulation for performance prediction of advanced building envelopes", *Building and Environment*, Vol. 191, 107570, doi: 10.1016/j.buildenv.2020.107570.

Thomé, M., Richalot, E. and Berthier, S. (2020), "Light guidance in photonic structures of Morpho butterfly wing scales", *Applied Physics A*, Vol. 126 No. 10, p. 778, doi: 10.1007/s00339-020-03948-x.

Tregenza, P.R. and Waters, I.M. (1983), "Daylight coefficients", *Lighting Research and Technology*, Vol. 15 No. 2, pp. 65-71, doi: 10.1177/096032718301500201.

Valitabar, M., GhaffarianHoseini, A., GhaffarianHoseini, A. and Attia, S. (2022), "Advanced control strategy to maximize view and control discomforting glare: a complex adaptive façade", *Architectural Engineering and Design Management*, Vol. 18 No. 6, pp. 829-849, doi: 10.1080/17452007.2022.2032576.

Vergauwen, A., Laet, L.D. and Temmerman, N.D. (2017), "Computational modelling methods for pliable structures based on curved-line folding", *Computer-Aided Design*, Vol. 83, pp. 51-63, doi: 10.1016/j.cad.2016.10.002.

Wang, Y., Han, Y., Wu, Y., Korkina, E., Zhou, Z. and Gagarin, V. (2022), "An occupant-centric adaptive façade based on real-time and contactless glare and thermal discomfort estimation using deep learning algorithm", *Building and Environment*, Vol. 214, 108907, doi: 10.1016/j.buildenv.2022.108907.

Wang, W., Zhang, W., Gu, J., Liu, Q., Deng, T., Zhang, D. and Lin, H.-Q. (2013), "Design of a structure with low incident and viewing angle dependence inspired by Morpho butterflies", *Scientific Reports*, Vol. 3 No. 1, 3427, doi: 10.1038/srep03427.

Wang, B., Zhang, X., Zhang, M., Cui, Y. and He, Y. (2024), "Development of novel variable building skin with solar concentrating technology for obtaining energy benefits and optimizing indoor daylighting", *Energy and Buildings*, Vol. 310, 114081, doi: 10.1016/j.enbuild.2024.114081.

Wienold, J. and Christoffersen, J. (2006), "Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras", *Energy and Buildings*, Vol. 38 No. 7, pp. 743-757, doi: 10.1016/j.enbuild.2006.03.017.

Yoshioka, S. (2013), "6 - structural color in nature: basic observations and analysis", in Kinoshita, S. (Ed.), *Pattern Formations and Oscillatory Phenomena*, Elsevier, Boston, pp. 199-251, doi: 10.1016/B978-0-12-397014-5.00006-7.

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