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Light-responsive kinetic façade system inspired by the *Gazania* flower: A biomimetic approach in parametric design for daylighting

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ABSTRACT

Through a multidisciplinary approach, this research proposes a design solution for a light-responsive kinetic biomimetic system, inspired by the functional principles of the *Gazania* flower. The adaptive movements of the *Gazania* flower were studied through a morphological-functional analysis and then used in the abstraction phase for the design of the biomimetic system, through parametric modelling. Climate-based daylight metrics and luminance metrics were evaluated for the different kinetic alternatives developed. The results of the parametric simulations, carried out for different occupant positions in an office building in a temperate Mediterranean climate show that the biomimetic kinetic system is well suited to provide the office space with variable natural daylight between 87,5 % and 100 %, promoting energy efficiency and user comfort. The results correspond to the optimal ranges of climate-related daylight metrics that prevent glare and overheating by shielding direct sunlight. The study also highlights the importance of further research, including material's prototyping, to validate and improve the proposed design and its translation into technology. Overall, this study demonstrates the potential of combining principles from biology, materials science and architecture to develop adaptable and sustainable design solutions that address sunlight and indoor comfort challenges.

1. Introduction

Ensuring optimal lighting conditions in buildings is an important aspect to consider in architectural design, as people spend most of their time indoors, where artificial light often replaces daylight [1]. The absence of daylight affects physiological functions, including the visual and well-being of users and indoor environment quality (IEQ) [2]. At the same time, the effective use of daylight is a way to reduce energy consumption of buildings [3–6]. The building envelope, designed as an interface to regulate the energy flows between inside and outside [7–10], does not always guarantee sufficient daylight conditions, which leads to problems such as glare, unwanted reflections and solar-induced overheating [11,12]. Envelopes or façade systems are designed with static solutions that are not able to interact with seasonal or daily weather-climate variations, such as the dynamic nature of the sky and the sun [3,5]. Given the AEC (Architecture, Engineering and Construction) sector's commitment to accelerate the transition to clean energy solutions [13] and achieve net zero emissions by 2050, dynamic solutions that interact with and respond to the environment are essential [3]. Dynamic systems continuously adapt the properties of the building envelope to environmental conditions (e.g. cloud cover) and seek to create optimal internal conditions while balancing energy targets and human factors [3,5].

Through parametric modelling and subsequent evaluation of daylighting simulations, this study proposes the design of an adaptive dynamic shading system inspired by the movement of the *Gazania* flower, in accordance with the principles of biomimetic design. The aim of this dynamic shading system is shading and minimise direct sunlight into spaces, as well as propose a potential solution for a smart material

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Abbreviations

AEC	Architecture, Engineering and Construction
AT	Attraction Point
bio-AM	biomimetic Adaptive Model
BSDF	Bidirectional Scattering Distribution Function
DGP	Daylight Glare Probability
EUDI	Exceeded Useful Daylight Illuminance
FRR	Focal Region Radius
PRD	Peripheral Region Domain
sDA	spatial Daylight Autonomy
SMPs	Shape Memory Polymers
UDI	Useful Daylight Illuminance

application to reduce energy consumption.

In recent years, attention to adaptive building envelopes has increased in the scientific literature, which proposes various definitions [14–19]; each of these underlines the strategic role of adaptive solutions, as they are able to interact with the external environment by changing their geometry and properties under the action of certain environmental triggers and depending on different reaction times. A recent study published by Borschewski et al., in 2023 [20] underlines the various advantages of adaptive façades (AF) compared to static ones, such as reduction of energy demand and building emissions, higher indoor and outdoor comfort, and aesthetic benefits. In recent years, the biomimetic discipline has emerged as a promosing alternative that aims to emulate the functional patterns and behaviours of nature [21,22]. For example, the living envelope is an adaptive building envelope solution inspired by nature that can adapt to the changes arising in the surrounding environment to maintain a comfortable state for its occupants [23]. The transfer of nature's behaviours and functional properties into technical solutions could be achieved through the use of smart materials, which, unlike conventional materials, are able to change their shape and behaviour under the influence of external stimuli [24].

The main innovation of this study is the integration of the biomimetic-adaptive model [25] (bio-AM), a methodological approach that defines the transition from nature to architecture, with the daylight simulation parametric workflow, to design a light-responsive biomimetic façade system inspired by the functional movement of the *Gazania* flower. The parallels between the nyctinastic movements of the *Gazania* in response to light, and the potential movements that can be achieved using smart materials enable to identify shape memory polymers as suitable candidates for the designed biomimetic system. The properties of these materials (e.g. reflectance) were taken into account during the parametric modelling. So, unlike existing examples in the literature [24,26], where adaptability is provided by an automated system of sensors or actuators, the adaptive response of the façade system, proposed in this work, could be delegated to the intrinsic property of photosensitive polymers, which provide an autonomous ability to change shape when exposed to light, but future prototypes and concrete physical tests will be necessary for thorough validation.

2. Theoretical background

2.1. Kinetic biomimetic adaptive façade

This study investigates both adaptive and biomimetic solutions that exist in the international scientific literature in order to identify gaps in terms of the use of materials as well as to define more precisely other features such as kinetic movements. Table 1 provides important information to identify the current gaps and propose a new solution through a multidisciplinary methodological approach. Adaptive and biomimetic façades were analysed considering climate (according to the Koppen-Geiger climate classification [27]), responsive functions [25], environmental triggers, kinetic movement and materials. Most of the examined study were mainly carried out for arid desert (Bw) and temperate steppe (Cs) climates. The predominant environmental trigger is the sun. These dynamic and interactive façades provide a double skin for the building conceived as a secondary element anchored to the main façade (generally made of glass), whose responsive functions are the control and the regulation of solar radiation to avoid glare and ensure optimal lighting conditions. In most of the cases studied, the design of adaptive façades with kinetic movements, which were used in test rooms intended mainly for offices, involved an evaluation of the quality of daylight based on various environmental criteria and parameters. Kinetic movements provide for changes in geometric configuration, two-dimensional and/or three-dimensional, such as bends, curvatures, expansions, contractions and translations.

The adaptive kinetic façade represents an innovative and interdisciplinary approach to building design that harmonises architecture, building physics and engineering. Some studies have limitations with regard to the movements. The adaptive façades with roller blinds presented by Le et al. [28] have the limitation that they were only analysed in their fully open or closed configuration, without considering intermediate positions. However, other recent studies have severely neglected the essential architectural contributions that lead to the definition of new architectural languages. They often consider particularly complex forms to be impossible to realise. For example, in 2022, Wang et al. [29], proposed an adaptive control system for the façade based on the movements of the occupants and the spatial position, through a particularly complex geometry and without reference to the architectural aspects and the use of intelligent materials to be used for future construction.

Kinetic façades interact with occupants and improve visual comfort [30]. They benefit from different geometries, two or three-dimensional, with dynamic and complex shapes. Different methodological approaches were used in the different studies analysed, including biomimetics [31–35], kinetic design strategies and origami [36–42], to define the best configurations to improve façade performance. Parametric simulations accompanied the design of a kinetic façade through generative design strategies capable of managing complex models and shapes. Most simulation workflows use a genetic algorithm [28,29] via a probabilistic procedure to obtain the results. Genetic algorithms can handle various parameters in complex linear and non-linear problems. However, they have some disadvantages, including the formulation of the fitness function, the use of population size, and the choice of important parameters such as the selection criteria of the new population. The use of architectural principles inspired by biomimicry simplifies the size of the problem and narrows the scope of exploration by eliminating extraneous parameters. It would be necessary to apply a brute force algorithm to evaluate all potential solutions and parameter combinations and ultimately obtain the most accurate and best results.

The materials used in biomimetic systems play a crucial role in their overall performance and effectiveness. Some studies do not specify the materials they use, while others rely on conventional materials like glass, metal, or plastic. However, a few studies (Kuru et al. [32] and Soliman et al. [31]) explore the use of smart materials, such as photochromic glass and shape memory alloys (SMA). Photochromic glass is a type of smart material that changes its optical properties in response to light. It can darken or change colour when exposed to sunlight. This makes it suitable for regulating light and solar radiation in biomimetic adaptive building envelopes. Shape memory alloys (SMA) are another type of smart material that can "remember" their original shape and return to it when heated. Thanks to this property, they can act as actuators and enable the opening and closing of photochromic glass flaps in the adaptive building envelope proposed by Kuru et al. [32] and Soliman et al. [31]. However, despite the promising results of these few studies with smart materials, there is still a gap in the scientific literature regarding the selection of suitable materials for biomimetic adaptive

Table 1
Analysis of kinetic biomimetic adaptive façade.
Climate [27]: BWh: hot desert; BSh: hot semi-arid; Cfb: Oceanic/subtropical highland; Csa: hot-summer Mediterranean; Dfb: humid-continental. **Responsive function** [25]: Regulate (Reg), Shield (Sh), Transfer (Tr), Reflect (R), Store (S), Transform (Tm). **Environmental trigger**: Sun (S), Light (L), Temperature (T). **Analysis**: Thermal comfort (T), Daylight quality (DL). **Building use**: Educational (E), Office (O), Hospital (H).

Object	Year	Building use	Country	Climate	Responsive function	Environmental trigger	Movement	Material	Analysis	Tools/Software	Dimension	Surface	Biomimetic
Multifunction biomimetic adaptive building envelope (MBio-ABE) [31]	2023	O	Egitto New Cairo	BWh	Reg	T	Folding and rotation	Shape Memory Alloy Photochromic glass	T	Energy Plus DesignBuilder	35 cm hexagon side	3D	Yes
Adaptive facade [39]	2023	O	Belgio Brussels	Cfb	Sh Reg	T	Open-closed	–	T DL	Energy Plus DesignBuilder Ladybug	–	2D	No
Climate responsive facade [49]	2023	H	Iran Teheran	Bsh	Sh Reg	S	Folding and basic rotation	–	DL	Rhinocheros Grasshopper Honeybee	Different	3D	No
Adaptive modular facade [38]	2023	O	Australia Melbourne	Cfb	Reg	S	Folding	–	DL	Rhinocheros Grasshopper Ladybug	1 mt × 1 mt	3D	No
Autonomous Climate-Adaptive Building Envelopes [50]	2022	–	Germany/ Spain	Cfb	Reg	T	Static	Shape Memory Polymer foam	T	WUFI Plus	–	3D	No
Dynamic solar shading system [33]	2022	O	–	–	Sh	S	Rotation	Coloured glass and transparent materials	DL	Rhinocheros Grasshopper Honeybee Ladybug Design Explorer	Depth: 0.25–1 m Scale change: 0.50–0.70 L	3D	Yes
Modular dynamic façade (MDF) [40]	2021	O	Iran Yazd	Bwh	Sh	S	Folding	–	DL	Rhinocheros Grasshopper Honeybee Ladybug EneegyPlus	–	3D	No
Biomimetic kinetic shading facade [34]	2021	O	Iran Yazd	Bwh	Sh Reg	S	Curling	–	DL	Rhinocheros Grasshopper DIVA	–	3D	Yes
Bio-inspired interactive kinetic facade [35]	2021	O	Iran Yazd	Bwh	Sh Reg	S	Elastic and deformable	–	DL	Rhinocheros Grasshopper DIVA	–	3D	Yes
Interactive kinetic facade [36]	2020	O	Iran Yazd	Bwh	Sh Reg	S	Rotation	Coloured glass	DL	Rhinocheros Grasshopper DIVA	–	2D/3D	No
Biomimetic building envelope (bio-ABS) [32]	2020	E	Australia Sydney	Dfb	Sh Reg	S T	Expansion contraction	Shape memory alloy (SMA) Photochromical	T	EnergyPlus	20 cm hexagon side	3D	Yes
Interactive kinetic facade [37]	2019	O	Iran Yazd	BWh	Sh Reg	S	Scaling and translating	–	DL	Rhinocheros Grasshopper DIVA	–	2D/3D	No
Adaptive solar facade (ASF) [42]	2019	O	Iran Teheran	Csa	Sh	—(users)	Folding	Traslucent	DL	Ladybug Daysim Radiance	–	3D	No
Sun-sensitive solar shading system [41]	2018	O	Iran Teheran	Csa	Sh Reg	S	Rotation	Metal Plastic	DL	Rhinocheros Grasshopper Ladybug DIVA	0.5 × 0.5 m rosette modules	2D	No

building envelopes. When selecting materials, factors such as movement, technical properties, performance, adaptability, indoor comfort, and durability over the lifetime of the building need to be considered. Mimicking nature's responsive and adaptive functions through the biomimetic discipline can be done precisely through the use of smart materials that can act as sensors and/or actuators thanks to the intrinsic properties of the material matrix itself, avoiding automated solutions that consume energy [43].

Therefore, this study proposes a design of a biomimetic kinetic façade system that interacts with the environment and is able to ensure kinetic movements in response to light by assuming the use of light-responsive polymers, the effects of which need to be accurately validated through physical prototypes, which is beyond the scope of this study, which instead focuses only on design and parametric modelling [24]. In contrast to existing studies in the literature, this study applies a brute force algorithm and combines aspects of building physics with engineering and architectural aspects.

2.2. Shape memory polymers

Shape memory polymers (SMPs) are a class of smart materials that combine the intrinsic properties of polymers, such as high deformability, processability, versatility, and light weight, with the ability to change reversibly shape in response to environmental stimuli [44]. To achieve an efficient response, it is necessary to apply an external treatment (a so-called programming process) that enables SMPs to transit from a stable original shape to one or more temporary ones, and to recover the original shape by exposing the material to a selected external stimulus. Structurally, SMPs demand a stable network and a reversible switching phase. The former is responsible for the recovery to the original shape and requires a stable crystalline phase, or of chemical or physical crosslinks. Within the stable network specific molecular segments are locked, which determine the reversible switching to the temporary shape. Their working principle is based on reversible transition that can be triggered by the external stimulus. Typical reversible segments are those based on photoisomerization, molecular rearrangements (e.g. Diels–Alder reaction), physical bondings (e.g. hydrogen bonding, coordination interactions, self-assembly processes), absorption/desorption phenomena. SMPs respond to stimuli such as heat, electric field, magnetic fields, pH variation to remote sources, such as light, magnetic, microwave and ultrasound fields. The combination of these modes, enables multi-stimuli and multi-level shape memory systems, enlarging applications for advanced materials and smart devices. To achieve the goals of this study, the property of light-responsive SMPs are investigated. Light-stimulated SMPs are shape memory polymers that undergo a reversible change in their molecular and electron structures upon photo-irradiation, which in turn is responsible for a macroscopic change in their shape [45–47]. In fact, light is a convenient source as it enables a remote, instantaneous and precise control of the shape change by acting on the source wavelength, intensity and location. Two types of photo-responsive mechanisms are known that can transform light into mechanical energy: photothermal and photochemical. Photothermal conversion is achieved by materials that are able to convert the light into thermal energy causing deformation temporary form transition [48]. This can be due to the presence of chromophores sensitive to light and can be enhanced through the incorporation of particles, such as gold and carbon-based nanoparticles, that are able to convert efficiently absorbed light energy into heat. Photochemical effect is based on specific transition/rearrangements of molecular switches introduced in the polymer skeleton. Depending on the specific chemical structure of the active molecular segments, transitions of photo-sensitive SMPs can be reversible (cinnamic, azobenzene, spiropyran, diarylethene) or irreversible (for example, o-nitrobenzyl, coumarinyl ester, pyrenylmethyl ester).

2.3. Adaptive movements of plants

Although apparently motionless, plants can move at different levels. From the roots moving into soil searching for nutrients and assuring plant stability, to the leaves and flowers that follow light direction and respond to tactile stimuli (tigmotropism), to the stomatic cells opening and closing to regulate the evapotranspiration [51]. Plants responds with movement to several stimuli such as light, humidity, temperature (Fig. 1), and to the presence of biochemicals as in the case of allelopathy [50].

Plants react to environmental changes by means of receptors. While some receptors, such as thermoreceptor [52,53], remain hypothetical, others, such as photoreceptors, including phytochromes, are known to detect variations in light quality [54] they can change shape under-different wavelengths and trigger biological response [55].

The movements can be categorized on the base of their behaviour, some indeed are very slow and can be observed only through time-lapse observations (e.g., *Helianthus annuus* L. rotation following the sun position), others are more sudden, as in the case of the *Mimosa pudica* L. leaves, that move quickly to discourage predators or reduce water loss due to evaporation; carnivorous plants, whose leaf rapid closure are used to capture prey (e.g., *Dionaea muscipula* Soland. Ex Ellis, 2000) [56–58]. The described movements in plants can be categorized as "induced" by external stimuli, like tropisms and nastic movements, or "spontaneous," such as stomata control and organ growth. These movements may be reversible, when repeated one or several time (e.g., as the case of the stomata opening/closure mechanism), or irreversible, when they occur only once (e.g., as the growth of a leaf) [59,60].

Plant movements depend on factors such as feeding and climbing. The tendrils of *Vitis vinifera* (L.), for examples, exhibit three types of movement: circumnutation, contact coiling and free coiling, to support the plant [61]. In other cases, the movements are determined by the presence/absence or the direction of light, as in the case of phototropism; some Leguminosae species, indeed, can open their leaflets during daytime and close at night to optimize light interception and avoid excessive loss of humidity. The opening and closing of certain organs, following the circadian rhythm, are movements controlled by endogenous rhythms of the plant which respond to the need to synchronize with the external environment. Synchronization with daily rhythms has important implications for plant survival and adaptive strategies, but also for reproductive success. Some flowers, indeed, regulate their opening during the night because they take advantage of nocturnal pollinators, this is the case of *Mirabilis jalapa* L., whose pollinating insect is a nocturnal moth [62]. Another example of synchronization with circadian rhythms comes from the nyctinastic movements of compound leaves. Most of these movements are dependent on the variations in the turgor of the thickening, called pulvinus, which is found at the base of the leaflets at their anchor point to the rachis [63,64]. Turgor pressure, the primary force that drives plant movement, allows plants to break through surfaces such as soil or asphalt to reach sunlight. This pressure results from the balance of water exchange between plant cells and the external environment, which is influenced by factors such as water potential, turgor pressure and cell wall properties [59,60].

Some evergreen plants employ photoprotective mechanisms to reduce the absorbation of solar radiation under cold conditions. These strategies vary, with some, such as reduced chlorophyll concentration [65], while others involve a movement known as thermonasty. *Rhododendron* species, for example, curl and roll their leaves in response to temperature fluctuations [66], which increases cold tolerance by reducing the risk of desiccation [67]. Similarly, some *Poaceae*, such as maize, uses leaf curling mediated by bulliform cells to conserve moisture during drought [68,69].

In other cases, as for the tulip and crocus, it has been hypothesised that the closing of flowers after temperature drop is related to the protection of the reproductive organs from being damaged by freezing or in general by unfavourable weather condition [70].

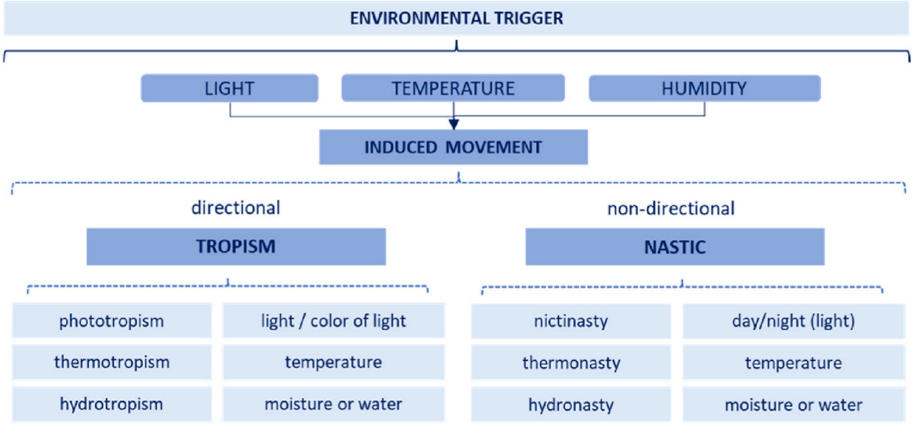

Fig. 1. Synthesis of the main adaptive movements of plants.

3. Methods: implementation of bio-adaptive model

Based on a preliminary analysis of the scientific literature, this study investigates the movements of plants as climate adaptation strategies and then transforms them into kinetic design solutions. The following research adopts a multidisciplinary approach that combines engineering-architectural skills with those of biology and materials chemistry to develop an environmentally adaptive biomimetic façade system, extracting the principles of the biological movement of *Gazania* flowers In particular, this study is structured according to the three main phases of the bio-AM (Fig. 2), proposed by Sommese et al., in 2022 [25]: scoping phase, research phase and implementation phase. It is integrated into the daylight simulation parametric workflow, which is useful for modelling and analysis of the proposed façade system.

The bio-AM is a problem-based approach which analyses the adaptation mechanisms of plants to translate them into architectural solutions and technologies assuming the use of smart materials. The first phase concerns the definition of the problem, which is the challenge that the resulting façade solution must address in terms of climate-related environmental issues. The second phase examines and selects the adaptation and behavioural strategies that plants use to meet environmental challenges and survive in their habitats. The third is about translating the principles gained from nature into adaptive solutions. Fig. 3 shows a specific framework for the implementation of bio-AM in the following study.

Phase 1: Scoping phase

As already mentioned in the introduction, the various challenges buildings face is certainly excessive solar radiation due to climate change, which often leads to glare, unwanted reflections and overheating problems for occupants. To address these issues, the first step of this study defines the development of a façade solution capable of limiting glare by adequately shielding, reflection or filtering solar radiation, while at the same time being able to illuminate the surroundings and provide adequate ventilation to limit overheating near the façade itself.

Phase 2: Research phase:

In this step it is necessary to answer the question, *"How does nature react?"* [25] in order to understand how natural organisms, especially plants, deal with the above challenges. Therefore, the study of the behaviours of plants under light stimuli is carried out, favouring nastic behaviours (undirected and not dependent on the direction of the environmental stimulus). Among the different biological species studied, the *Gazania* flower was chosen because it is characterised by nictinastic movement (it follows the day/night light cycle). The morphological and behavioural analysis of the *Gazania* flower is carried out to define the morphological and kinetic principles that will be translated into kinetic solutions of great architectural impact using a parametric model in the next phase.

Phase 3: Implementation phase

The third phase involves the transfer of light-responsive,

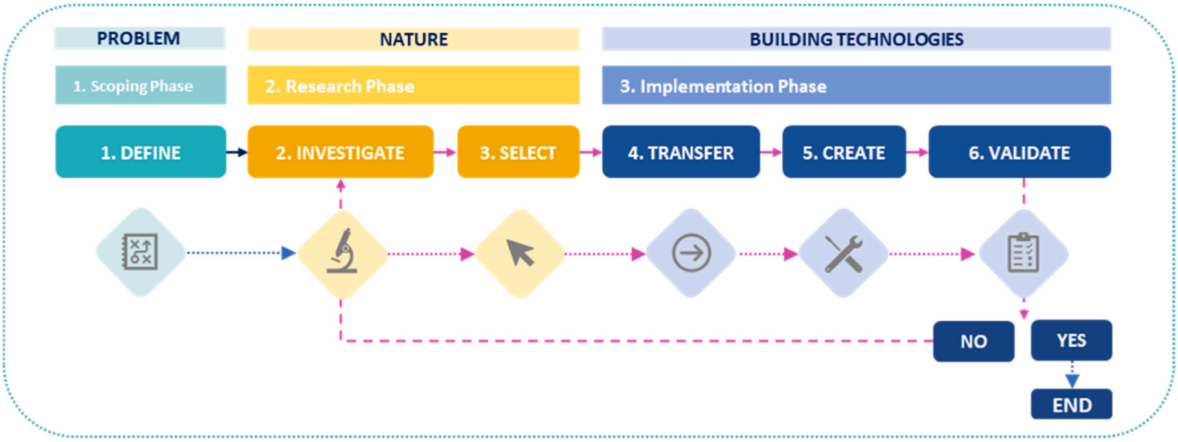

Fig. 2. General framework of bio-A M [25].

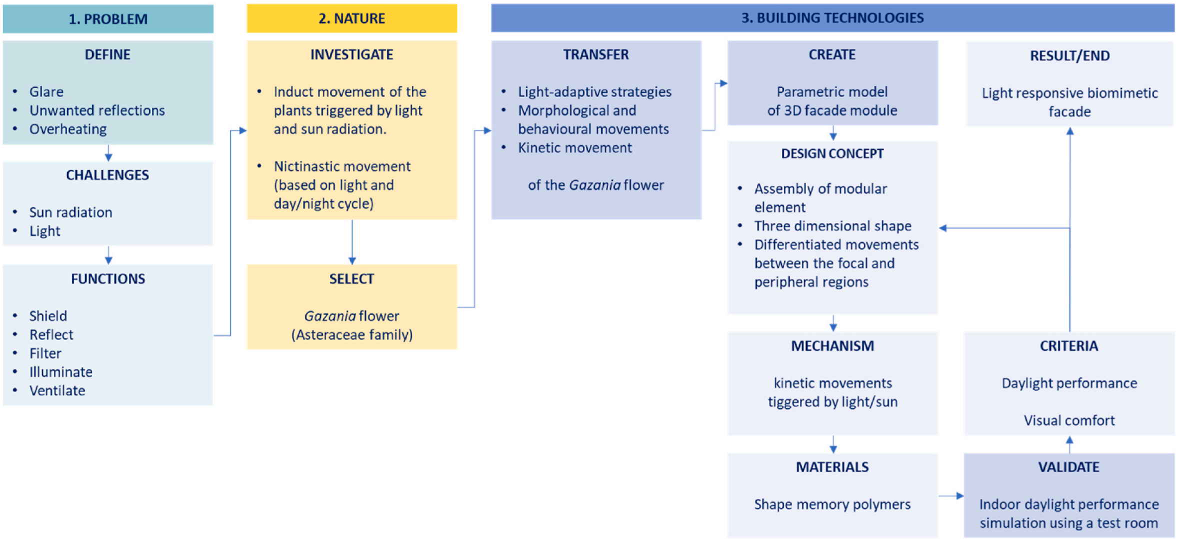

Fig. 3. Implementation of bio-A M for the following study.

morphological and behavioural strategies of *Gazania* flower identified in the previous step, into building solution to propose a biomimetic façade system. To do this, the starting point is the creation of a three-dimensional computational model through software that facilitate work and design in dynamic environments. Rhino 7 software is used for modelling and Grasshopper for the parametric interface. After the parametric model is defined, it is analysed through the evaluation of parameters based on daylight metric such us: sDA (spatial Daylight Autonomy), UDI (Useful Daylight Illuminance), EUDI (Exceeded Useful Daylight Illuminance), and DGP (Daylight Glare Probability).

The plug-in of Grasshopper, Honeybee and Ladybug, was used to enter climate information and evaluate daylight performance, respectively.

3.1. Design lesson by Gazania flower: light-responsive movement

Gazania is a light-responsive plant, belonging to the Asteraceae family. It follows nyctinastic-type induced movements. Fig. 4 shows the analysis of the morphological and behavioural characteristics of the *Gazania* flower. Morphologically, *Gazania* has an inflorescence characterised by tubular bundles in the central disc and ribbon-like ligulate petals in the outer radial part (Fig. 4a). From behaviour point of view, *Gazania* opens and closes the ligulate petals depending on the intensity of the light [71,72]; the petals open and close during the night-day cycle but can remain closed when the sky is cloudy (time varying from the minute-hour scale).

The sequence of the flower opening (Fig. 4a-g), obtained from direct observation of the flower and the creation of a time-lapse video, shows that the petals move from a vertical position to a curved horizontal position. In a cyclical and reversible process, the flowers assume a

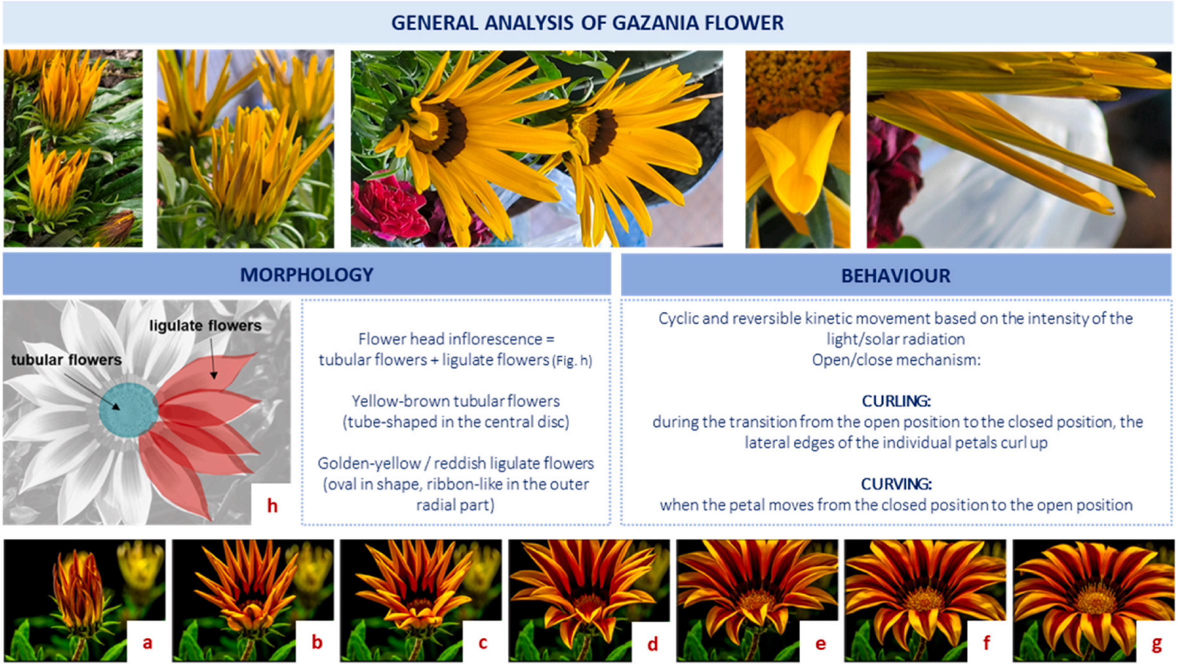

Fig. 4. Morphological and behavioural analysis of the *Gazania* flower.

vertical position when closing from the curved horizontal, with the ends of each petal curling. Direct observation of the movement of the *Gazania* flower has thus enabled us to summarise that the two main mechanisms involve the curling of the ends of each petal along the longest axis of the petal itself and the curving as it passes from the vertical to the horizontal.

3.2. Design process: abstraction and development of the biomimetic facade system

According to the principle of hierarchy [32], typical of biological structures, the behavioural mechanism is given by the single petal. The abstraction phase (Fig. 5) begins with the observation of a single petal which, when closed, assumes a three-dimensional conical shape (rolled), otherwise it assumes an extended configuration (unrolled) due to the impulse of light falling on it (Fig. 5c). Therefore, observing the single petal, it is possible to schematize its almost conical shape with an elementary geometric shape like the triangle. The petal of the *Gazania* keeps the extension along the vertical axis stable, while the dimensions of the horizontal axis vary according to the curvature of the edges. The curling of the petal and the subsequent unrolling by the light trigger leads to an expansion and contraction of the three-dimensional triangular element along the horizontal axis or, in any case, along the short axis of the element.

The design of the biomimetic kinetic façade system starts from the definition of a diamond triangular model that accommodates the kinetic movements and light-responsive behaviour of the flower identified as an abstraction model.

In this phase, the use of a light-responsive polymer based on azobenzene is assumed, which, after studying the literature, seems to be the best candidate for defining the kinetic movements described above, but, despite this, laboratory tests with real prototypes will be necessary to confirm its validity. In fact, among the various SMPs, the azobenzene-based systems are of particular interest for this specific study. Their photo-actuated effect is due to a reversible trans–to-cis isomerization upon radiation with UV light (λ = 366 nm UV). Trans (*E*) form is the most thermodynamically stable one. Heat sources, visible light (λ > 540 nm) or even storage in the dark can induce its recovery from the less stable cis (*Z*) form. During this reversible light-induced isomerization process, a variation of the geometry of N–N double bond occurs and, in turn, macroscopic properties, such as polarity, redox potential, and optical features change. When the azobenzene segments are attached to an opportunely engineered polymeric backbone, shape changes can be also observed. Therefore, functionalization of a material with azobenzenes is an effective way to amplify the light-induced nanoscopic movement to produce macroscopic structural modifications of the bulk system, thanks to a collective reorientation of azomolecules activated by light irradiation. In some cases, it could be much more convenient to use sunlight as a natural and unlimited activation source [73]. Visible light (λ = 390–700 nm) in the form of sunlight or indoor illumination, is the main energy sources on earth and it is unharmful for human beings. Recently, an increasing number of advanced systems and smart devices have been developed that rely on the use of visible light for the wavelength-selective control of shape memory behaviour in SMPs. By opportunely functionalizing azobenzene moieties one can tune and selectively activate the response to specific wavelength. In this way, it is possible to employ a wide range of artificial light sources, from IR to UV. Even though it is certainly more convenient to use sunlight as a natural and unlimited source of activation [73], natural light may not be able to ensure the complete movement and shape change of the material. To avoid indoor problems due to the lack of activation of the material, a dual activation approach can be used, by designing a material which is intrinsically sensitive to both natural light and other light sources attached to the facade. To this aim, the material must be modified by grafting the molecular chain with functional groups that make the material sensitive to a specific wavelength, or by dispersing photoactive

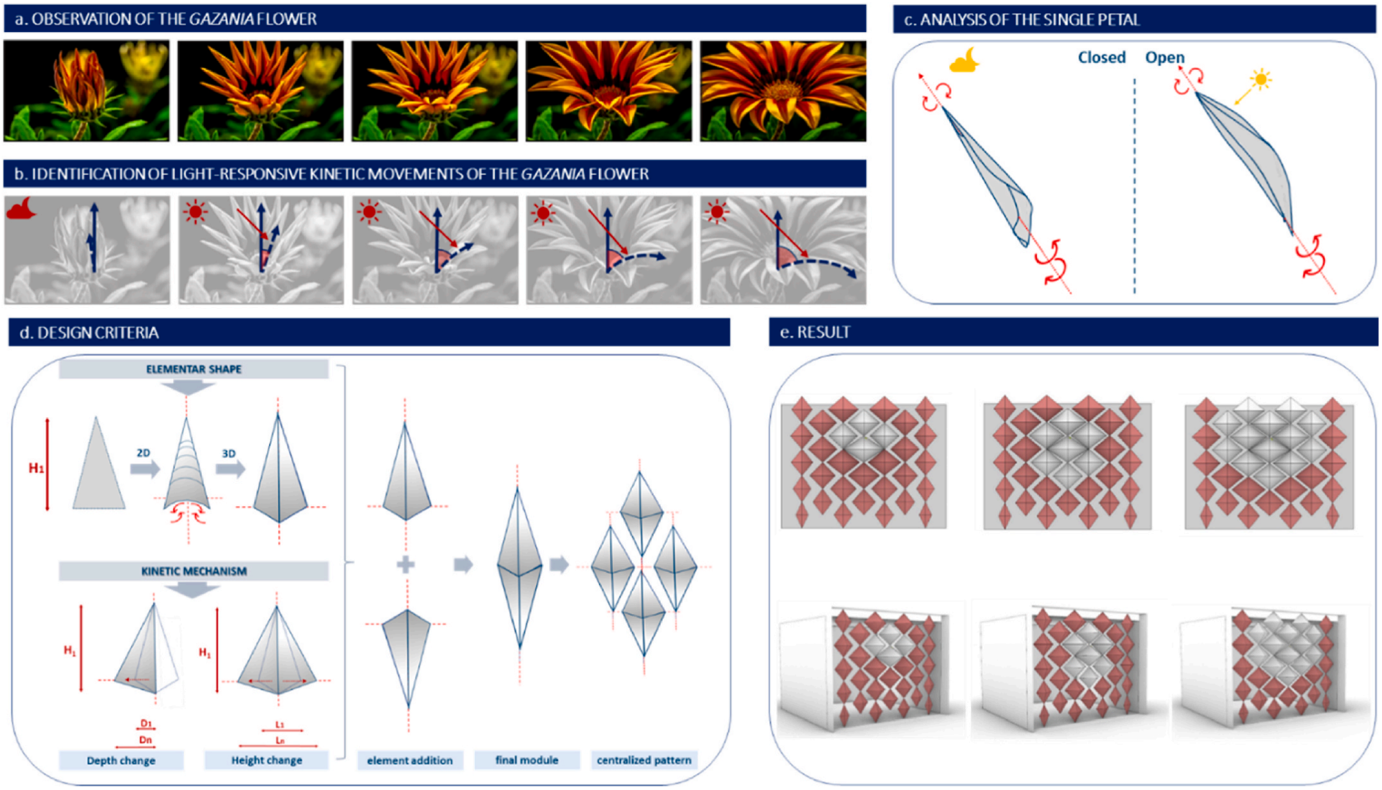

Fig. 5. Abstraction process. a-b) movement of *Gazania* flower: the incident solar radiation causes the opening of the flower by curling and curving movements which mark the transition from the vertical to the horizontal position. c) morphological and behavioural analysis of the single petal of the flower. d) design criteria of single facade modular element. e) Final results of biomimetic kinetic façade system.

nanostructures in the matrix. In their work Leeldhar et al. [74] fabricated a graphene oxide/polycarbonate bilayer structure photoactuator and demonstrated that it could be actuated by both natural sunlight and IR source, working as a smart curtain. The actuation was reversible, fast (response time lower than 1 s) and dependent on light intensity. The described photoactuor represents a valid approach for wireless-controlled shape change facade modules responsive to dynamic daylight.

3.3. Morphology and mechanism

Following the morphological structure of the *Gazania* flower, which has a fixed focal part and a radial part characterised by petals that move under the stimulus of light, the bio-inspired façade system is subject to periodic decentralised movements that depend on the distance of the modular element from the positioning of a sensor called the "point of attraction", which has dynamic properties determined by the dynamic sun time position and the position of the occupants. It is responsible for controlling actuation within in the focal region's center of gravity. The attraction point is understood as the intersection between the solar radiation (which varies during the day) and the position of the occupants along the vertical axis of the façade. This means that the elements placed in the central part, and thus in the focal point of the façade (Focal Region Radius – FRR (Fig. 6a–b)), are characterised by a low degree of movement necessary to block the intense light in the occupants' field of vision; otherwise, the modular elements of the peripheral areas (Peripheral Region Domain – PRD (Fig. 6a–b)) of the façade adopt more accentuated movements. The location of the focal point was determined using the intersection between the façade surface and a line formed by the dynamic sun positions and the occupants' positions. The days of the solstice and equinox, which occur at 9am, 12pm and 3pm, were selected as solar time positions to determine the point of attraction for implementing the kinetic configurations. Solstice and equinox days at 9, 12, 15 are assumed as representatives of sun-timing positions to create the attraction point for implementing kinetic configurations. Different hours and months make the positions of attraction point (AT) varied during the year. Based on the location of AT and radicues of focal and peropheral region, the kinetic elements get a hierarchy configuration based on depth and width changes. When exposed to light, each diamond element maintains its extension along the vertical axis, while its extension varies in width and depth along the horizontal axis.

3.4. Daylight performance simulation workflow

Following the study by Hosseini and Heidari [33], Fig. 7 shows an inverse design diagram [75] that highlights the utility of the parametric algorithm to combine the morphological, material and movement parameters that characterise the design of the façade model and implement the quality of the design.

As can be seen in Fig. 7, the development of the light-responsive biomimetic façade and the associated simulations are carried out through an algorithmic and parametric modelling process using Rhino 7 and Grasshopper as three-dimensional and parametric modelling tools, and Honeybee and Ladybug (Grasshopper plug-in) for climate information and daylight performance and visual comfort analysis. For the daylight analysis, the simulation guideline proposed by established studies such as (Reinhart 2018, 2019 [76]), (Brembilla E, Mardaljevic, 2019 [77]), (McNeil and Lee, 2013 [78]) was applied. The simulation is performed by applying the proposed solution to an office building in Naples, Italy. According to the Koppen-Geiger climate classification [27], the city of Naples is characterised by a temperate Mediterranean climate with dry summers (Csa). The meteorological data of Naples are imported into the software via Ladybug, deriving them from the epw-map database [79]. The simulation starts by applying the light-responsive biomimetic façade to the window on the south façade of the office space with dimensions 4.40 m (width) and 5.30 m (depth) and 3.40 m (height), as shown in Fig. 8. The building elements, floors and vertical walls, are modelled with a thickness of 0.30 m.

3.5. Daylight evaluation criteria

The study conducts both annual daylight simulation and point in time simulation for several forms of the proposed kinetic façade. Climate-based daylight modelling evaluations are typically conducted for a full year at a timestep of an hour or less to represent the daily and seasonal variations of daylight. In addition, point in time simulations using luminance-based metric at solstice and equinox days are performed to evaluate occupant's visual comfort satisfaction.

After analyzing the base case, and before proceeding to the analysis of the proposed biomimetic solutions, a parametric simulation is performed for a fixed shading to control the solar radiation in the room. The material properties of the fixed shading are listed in Table 2.

Considering the complex inherent of the developed biomimetic forms of the study, the three-phase method has been used to conduct daylight simulation with creation of databases using Bidirectional Scattering Distribution Function (BSDF) definition [78]. The method is a reasonable choice for evaluation and optimization of external shading designs [77]. We used a software Berkeley Lab WINDOW 7.6 and Radiance genBSDF command to create BSDF file which described the behaviour of light redirecting systems. The three-phase method break

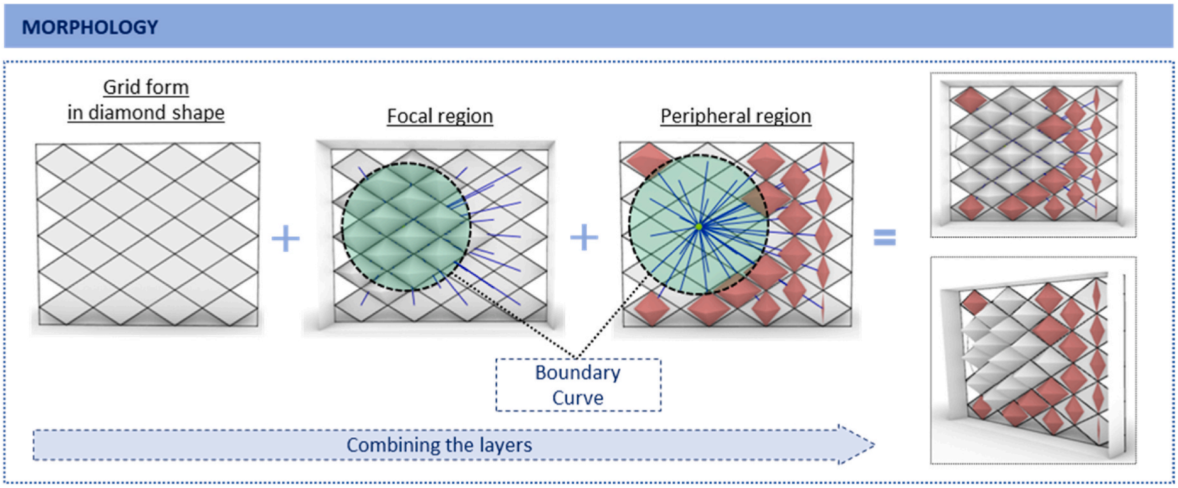

Fig. 6a. Biomimetic kinetic facade system development procedure: morphology.

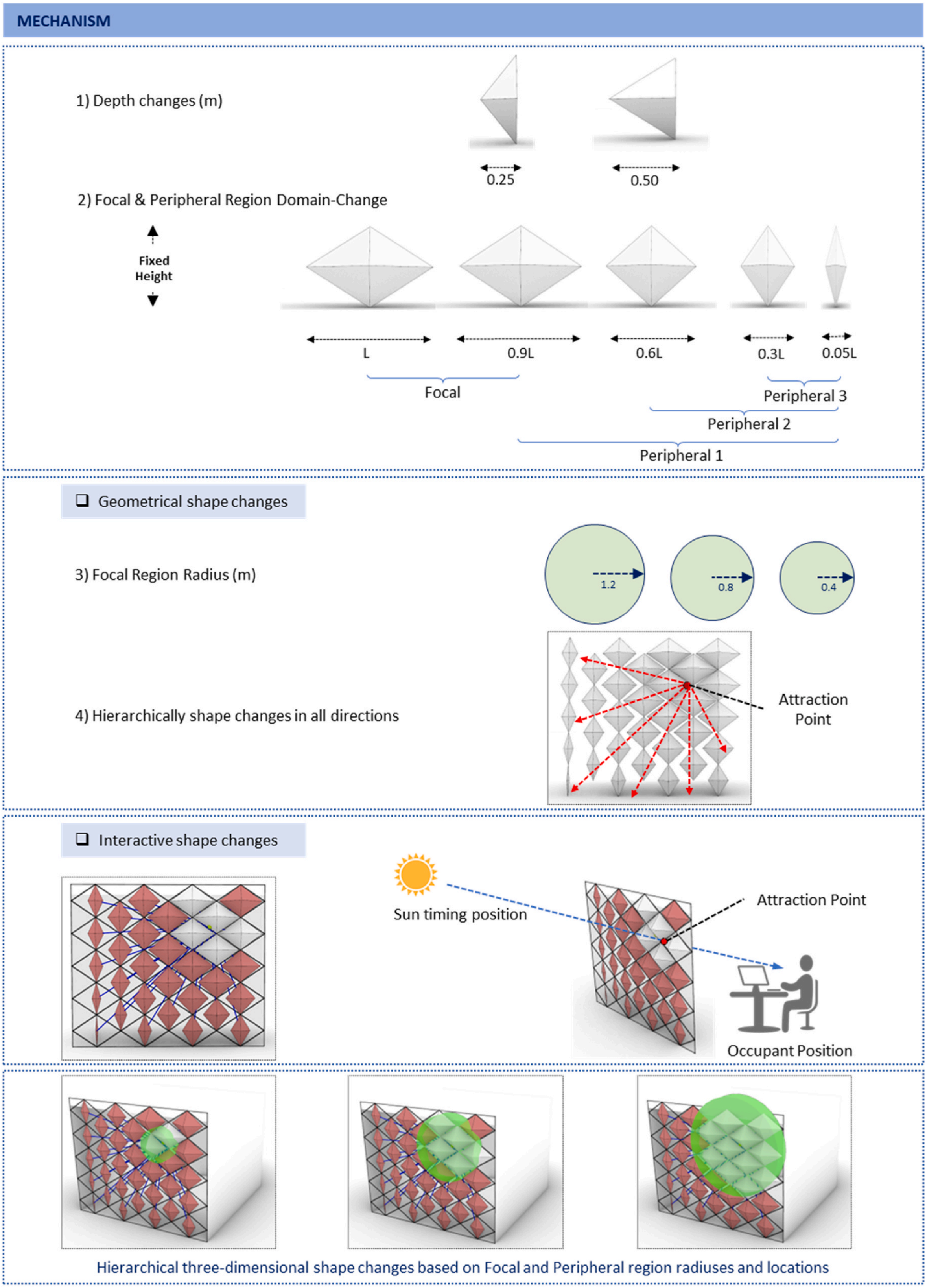

Fig. 6b. Biomimetic kinetic facade system development procedure: mechanism.

Flux transfer into three phases for independent simulation consisting of "sky to exterior of fenestration", "transmission through fenestration", and "interior of fenestration into the simulated space". The procedure can be described with equation (2):

$$E_{8760\times n} = V_{n\times 145} \times T_{145\times 145} \times D_{145\times 146} \times S_{146\times 8760} \tag{2}$$

Where $E8760 \times n$ is hourly simulation during a year recorded at n sensor points; $Vn \times 145$ is the outgoing light direction from the sensor points to

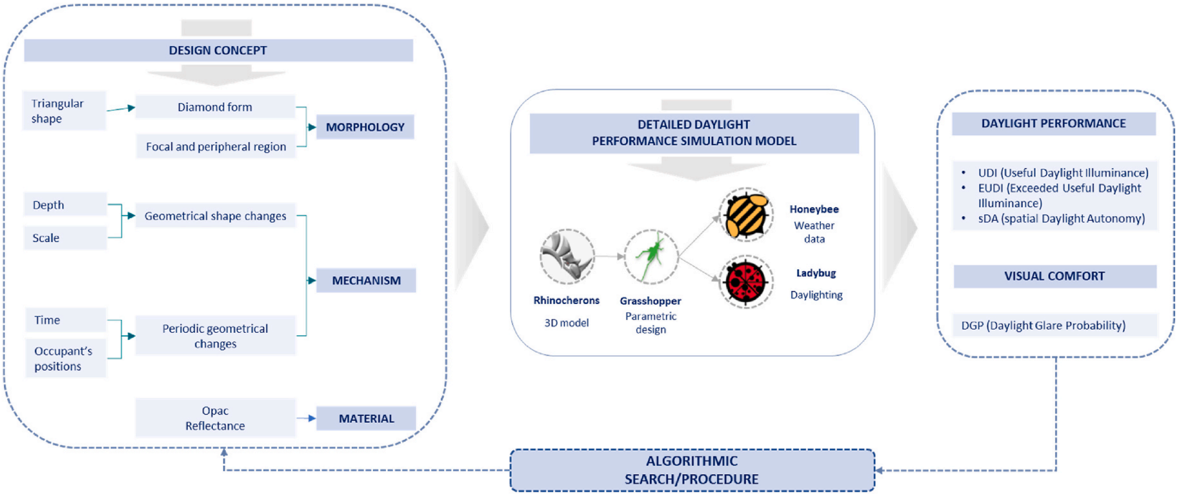

Fig. 7. Inverse design diagram of light-responsive biomimetic facade.

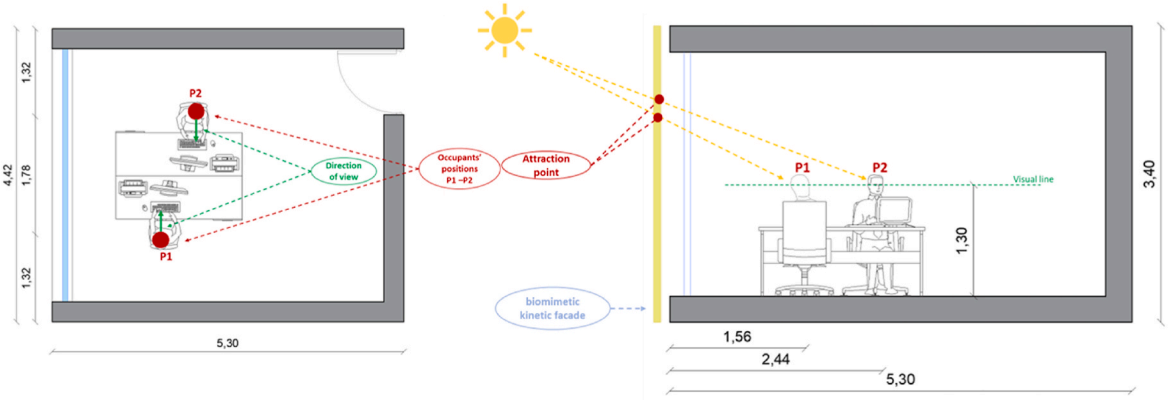

Fig. 8. Test room as an office building with occupant positions, direction of view, and attraction point. Left: floor plan; right: section.

Table 2
Properties of fixed shadings.

Properties	Input value
Blade material	Steel
Blade thickness	0.03 m
Number of blades	10
Vertical spacing	0.25 m
Blade angle	30
Distance from window	*0.2 m*
Blade depth	*0.2 m*
Reflectance	0.55

the fenestration system (View matrix); T145 × 145 is Transmission Matrix relating incident window directions to exiting directions (BSDF); D145 × 146 is Daylight Matrix relating sky patches to incident directions on window and S146 × 8760 refers to a collection of sky vectors for a whole year as Sky Matrix.

Regarding the Radiance ambient parameters, the study follows the suggested values by Ref. [77] including ambient bounces (-ab) of 5, (ambient divisions) -ad of 22,400, ambient super-samples (-as) of 0, ambient accuracy (-aa) of 0, ambient resolution (-ar) of 0, and light port width (-lx) of 5e-5.

To ensure efficient visual performance indoors it is necessary to balance daylight and avoid glare. Climate-based daylight metrics, including Spatial Daytime Autonomy (sDA), Useful Daylight Illuminance (UDI) and Exceeded Useful Daylight Illuminance (EUDI), and luminance metrics, Daylight Glare Probability (DGP), are evaluated for each specific façade configuration considering different Focal Region Radius (FRR) (1.2–0.8 - 0.4) and two different depths of the modular element on the solstice and equinox days: 21 December, 21 March and 21 June, during the different office working hours: 9.00–12.00 - 15.00. The two different depths indicate that each FRR region might have two configurations, one with a depth of 0.25 m and another with a depth of 0.50 m. The depth refers to how much the facade elements protrude or recede from the main building surface. Table 3 lists the performance criteria used for the simulation. Given that the validity of the material needs to be proven through laboratory studies using physical prototypes, the reflectance properties of the shape memory polymers were obtained from relevant scientific literature [80–82] in the simulation phase; therefore, the reflectance values were assumed to vary between 0.05 and 0.4 %.

Spatial Daylight Autonomy (sDA) is defined as "*the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone*" [83,84]; therefore, it is necessary to achieve at least 300 lux during 50 % of the hours when the building is occupied by users. When "*there is useful daylight in the back two-thirds of the space*" (UDI 100–3000 Lux) it's possible to define the UDI [84]. When UDI exceeds 3000 lux (UDI >3000 lux), light overload occurs near the façade, known as Exceeded Useful Daylight Illuminance (EUDI) [84]. Glare is the sensation that occurs when the luminance of the field of vision is higher than that to which the eyes are accustomed, causing discomfort in vision [85]. The most commonly used metric for assessing glare is the Daylight Glare Probability (DGP) empirical method proposed by Wienold and

Table 3
Performance criteria used in the parametric simulation.

Performance Criteria			
Parameters	Name	Unit	Range
Daylight Related Parameters	Useful daylight Illuminance (100–3000 lux)	Percentage	[0–100]
	Exceed Useful daylight Illuminance (>3000 lux)	Percentage	[0–100]
	Spatial daylight autonomy	Percentage	[0–100]
Visual comfort Relate Parameters	Daylight Glare Probability	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	Smart Material ID	Integer	[0-1-2][a]
	Module Depth	Floating point number	0.25, 0.5
	Peripheral Region Domain	Domain	(0.9–0.05), (0.6–0.05), (0.3–0.05)
	Focal Region Radius (FRR)	Floating point number	0.4, 0.8, 1.2
Model fixed Parameters	Glazing Ratio	Percentage	90
	Task Area Height	m	0.80
	Space Width	m	4.40
	Space Length	m	5.30
	Space High	m	3.4
	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	10
Time Parameters (daylight part)	Month	Integer	6-9-12
	Day	Integer	21
	Hour	Integer	9-12-15
Climate Parameters	Weather File for analysis	user-defined	temperate Mediterranean climate

a) 0 = 0.05, 1 = 0.2, 2 = 0.4.

Christoffersen [86], which gives the percentage of people disturbed by one or more sources of glare in daylit spaces [85], applying the CCD Camera based luminance mapping technology [33]. DGP (equation (1)) is a function of the vertical illuminance of the observer's eye (E_v), the luminance of the glare source ($L_{s,i}$), the solid angle ($\omega_{s,i}$) and the position index (P):

$$DGP = 5.87\times10^{-5}\times E_v + 9.18\times10^{-5}\log\left(1+\sum_i \frac{L_{s,i}^2}{E_v^{1.87}}\frac{\omega_{s,i}}{P_i^2}\right)+0.16 \qquad (1)$$

The GDP index is associated with four domains of glare comfort [41,42,84,87]: DGP <0.35 *imperceptible* glare; 0.35 < DGP <0.4 *perceptible* glare; 0.4 < DGP <0.45 disturbing glare; DGP >0.45 *intolerable* glare.

4. Results

The following subsections report the results of the parametric simulations for a base case (room without shading), a static case (room with a fixed shading) and the dynamic case of adaptive biomimetic shading for both occupant positions (Fig. 9). Since the biomimetic kinetic façade system is activated by the position of the sun and the position of the occupants near the attraction point, parametric studies of 486 alternatives are carried out for each position of the occupant (P1 and P2), totally 972 simulations, based on different values of FRR, PRD, depth and reflectance. By comparing the metrics' values across these different zones and depths, it's possible identify the most effective configuration for optimizing daylight performance, visual comfort, and users well-being in the building.

4.1. *Base case without shading*

The parametric simulation results for daylight performance for the base case (simple room with window) do not satisfy users comfort, due to an accentuated visual discomfort.

The sDA value of 100 % (Fig. 10) shows that the room is illuminated by a sufficient amount of daylight, but the index UDI (39.55 %) indicates that more than 60 % of the light introduced into the work room exceeds 3000 lux, resulting in visual and thermal discomfort for users, which is also evidenced by the EUDI index value of 59.54 %. Furthermore, the glare levels are considered *disturbing* (39.9 %) and *intolerable* (39.9 %) in most seasons, while they are considered *perceptible* (11 %) and *imperceptible* (11 %) only in a small range.

4.2. *Static case with fixed shading*

This subsection describes the results of the simulation for the case of static shielding whose material properties are listed in the previous Table 2. The room's sDA value of 100 % (Fig. 11) means ample daylight with no difference from the base case. However, the UDI value of 63.15 % shows that only 35 % of the light exceeds 3000 lux; it is higher than the base case without shielding, and this means a more pleasant result in terms of lighting. The EUDI value of 34.82 % confirms a reduction in discomfort compared to the base case without shielding (EUDI = 59.54). Furthermore, glare levels are lower than in the base case. They are always classified as *imperceptible* except in the winter season (9:00–21 December) where they are considered *perceptible* as they are above 0.35.

4.3. *Biomimetic kinetic facade with different combination of FRR for occupant 1*

Fig. 9 illustrates a general analysis for position 1 that shows the high potential of the biomimetic kinetic façade for daylight performance and occupant comfort.

The kinetic facade was designed with three areas of the focal region radius (FRR = 1.2–0.8 - 0.4), each of which can have two different

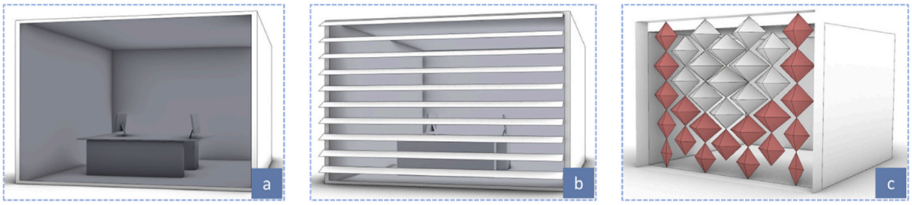

Fig. 9. Test room: a) base case without shading; b) static case with a fixed shading; c) dynamic case with biomimetic shading.

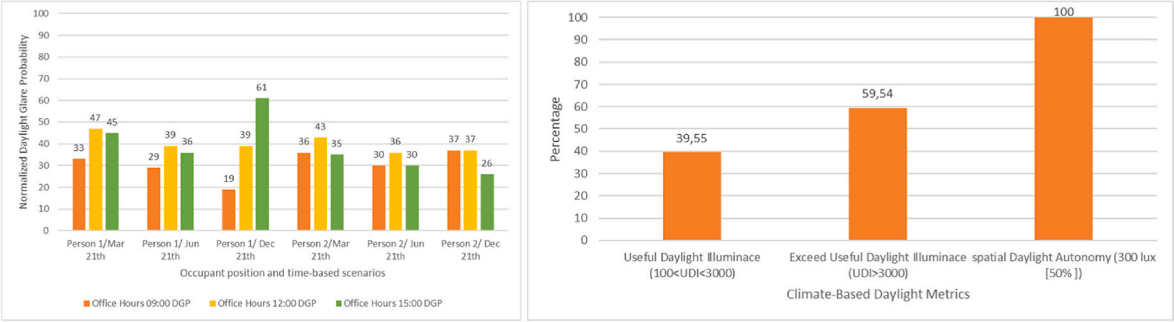

Fig. 10. Results of the parametric simulations related to the base case. Left: DGP values calculated on 21 March, 21 June and 21 December, at different office hours (9.00-12.00-15.00), occupant position and time-based scenarios. Right: Percentage mean of UDI, EUDI and sDA values.

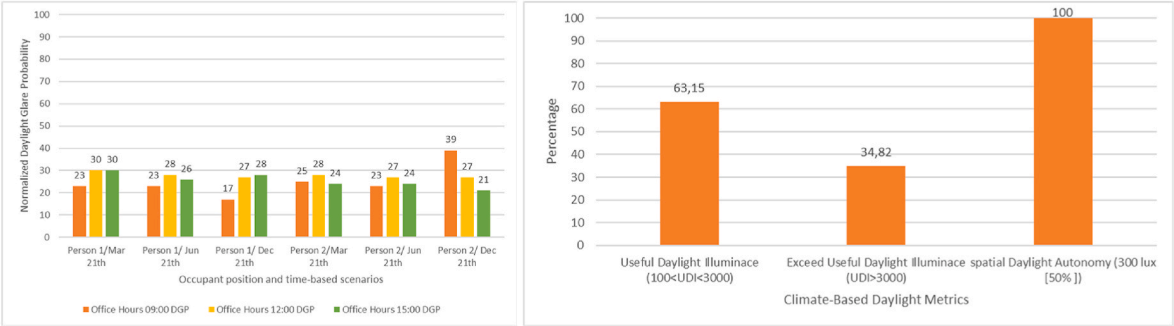

Fig. 11. Results of the parametric simulations related to the fixed shading case. Left: DGP values calculated on 21 March, 21 June and 21 December, at different office hours (9.00-12.00-15.00), occupant position and time-based scenarios. Right: Percentage mean of UDI, EUDI and sDA values.

Fig. 12. General analysis of daylight performance and visual comfort for position 1. Average of UDI, EUDI, sDA, WWR, DGP values for different Focal Region Radii (FRR) (1.2–0.8-0.4) and different depths (0.25–0.5).

depths (0.25 and 0.50). The bar charts (Fig. 12) show the average values of the analysed daylight metrics.

The sDA values show that the rooms are lit with a percentage of suitable daylight that ranges from 87.5 % to 100 %. The highest sDA values, close to 100 %, are provided by FRR = 4. In particular: for the configuration with a depth of the modular element of 0.25, the sDA values are equal to 100 % (in each month and hour analysed), while for the configuration with a depth of 0.50, the minimum value of sDA is equal to 98.44 % (month 12, h. 15). The lowest, but still optimal, value of sDA (87.5 %) is obtained by the configuration FRR = 1.2 with an element depth of 0.25 (month 9, h. 15). As far as sDA is concerned, the comparison with the base case and static one shows no significant differences. In summary, the study shows that various facade configurations achieve high sDA values, which means that all configurations effectively utilize daylight to illuminate the rooms.

The kinetic biomimetic facade has had a positive impact on the UDI percentages (83.42 %) compared to the base case (UDI = 39.55 %) and static case (UDI = 63,15 %), showing better comfort conditions. The values have increased, and the configuration with an FRR of 1.2 provides the highest UDI values, particularly for a depth of the element equal to 0.5. At this configuration and depth, the UDI value reaches 83.42 % at month 12 and hour 15. On the other hand, the minimum UDI value of 67.4 % is achieved by the FRR 0.4 configuration with a depth of 0.25 (month 12, h. 9).

As a result, the EUDI values decrease significantly compared to the base (EUDI = 59.94 %) and static case (EUDI = 34,82 %). The EUDI values vary from 30.91 % (month 12, h. 9, FRR 0.4, depth 0.25) to 12.4 % (month 12, h. 15, FRR 1.2, depht 0.5). Since the configuration FRR = 1.2 gives the highest UDI values, it is obvious that the same configuration gives the lowest EUDI values (12.46 %) for month 12 at 3 p.m. with an element depth of 0.5. The highest EUDI value (30.92 %), which in no way affects the comfort and well-being of users during working hours, is obtained for the configuration FRR = 0.4 with a depth of 0.25 (month 12, h. 9).

The glare values there are within the optimal ranges. Only in two cases does the DGP exceed 35 %, defining a *perceptible* glare condition: DGP = 36.6 % (month 9, h. 12, FRR 0.4, depht 0.25) and DGP = 35.5 % (month 9, h. 12, FRR 0.4, depht 0.5). The smallest DGP value is 18.82 % (month 9, h. 12, FRR 0.4, depht 0.5). Although in the base case only 39.9 % caused *intollerable* glare and 39.9 % caused *disturbing* glare, the presence of the biomimetic façade offers potential in terms of comfort, as glare can only be defined as *perceptible* under the above conditions, but in any case, has no negative impact on users.

The biomimetic solution offers the most favourable conditions, as it has high sDA values, low EUDI values and optimal glare values, indicating an improvement in user comfort and well-being. In summary, the biomimetic kinetic façade, analysed for position 1, is configured as the optimal solution to ensure adequate daylight in the workspace. It responds to the optimal ranges of climate-based daylight metrics and prevents glare and overheating by modulating direct sunlight.

Fig. 13 shows the parametric exploration of 486 biomimetic kinetic façade alternatives in the different FRR and PRD combinations, using different simulation parameters with several inputs and outputs. The graph shown in Fig. 13 selects only the best combinations by applying the criterion of considering only the values of sDA >80, UDI >80, DGP <0.35. Table 4 shows the climate-based light metrics and the luminance-based survey in the different FRR and PRD combinations for occupant 1 facing south.

Table 4 shows the optimum daylight performance of the different FFR and PRD configurations on solstice and equinox days with UDI, EUDI and sDA values varying in the ranges 80.03–83.48, 12.58–17.13 and 84.38–100, respectively, while benefiting from different window-to-wall ratios (WWR) between 0.46 and 0.53.

4.4. *Biomimetic kinetic facade with different combination of FRR for occupant 2*

Using the same approach as for position 1, in this section the results for position 2 are anlysing. Fig. 14 presents a general analysis for position 2 which demonstrate the high potential of the biomimetic kinetic façade for daylight performance and occupant comfort. The bar charts display the average values of the analysed daylight metrics for each of the FRR regions with their respective depths (0.25 and 0.50).

The sDA values fall within a range of 87.5 %–100 %. This indicates that the room is generally well-lit with natural daylight, which is considered suitable for visual comfort and reducing the need for artificial lighting during daylight hours. The highest sDA values close to 100 % are achieved with FRR = 4. The depth of the modular element plays a role in the sDA values. When the depth is 0.25, the sDA values are consistently at 100 % for all months and hours analysed. However, when the depth increases to 0.50, the sDA values drop slightly, with the minimum value being 98.96 % (month 12, h. 15). The decrease in sDA could be attributed to reduced daylight penetration due to the increased depth. The optimal configuration is given by an FRR of 1.2 and an element depth of 0.5 that achieves a still acceptable sDA value of 87.5 %. This indicates that even with a slightly reduced field of view fraction and deeper modular elements, the space still receives a considerable amount of suitable daylight.

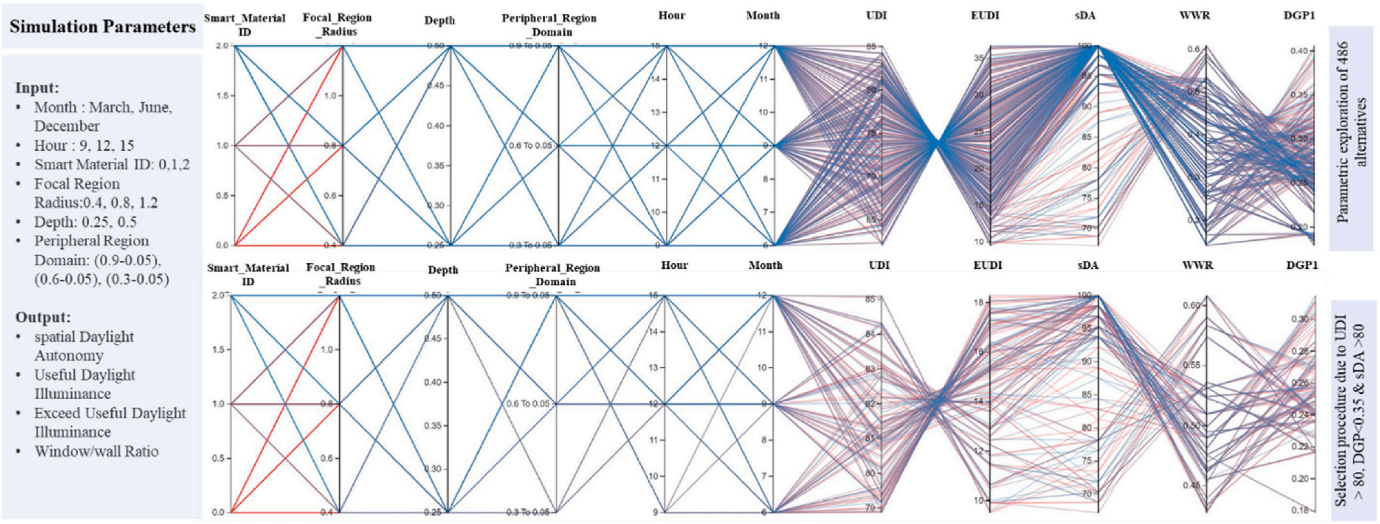

Fig. 13. Parametric exploration of 486 alternatives of biomimetic kinetic facade according to the occupant position 1.

Table 4
Climate-based daylight metrics and luminance-based investigation of the most optimum Biomimetic kinetic façades with different Focal Region Radiuses (FRR) and Peripheral Region Domain (PRD) for the South direction according to the occupant position 1.

Biomimetic Kinetic Façade Scenarios	Smart_ Material_ ID	Focal_ Region_ Radius	Depth	Peripheral_ Region_ Domain	WWR	UDI	EUDI	sDA	DGP1
March 21- Hour 9:00	1	1.2	0.5	0.9 To 0.05	0.47	80.17	16.76	100	0.25
March 21- Hour 12:00	1	0.8	0.5	0.9 To 0.05	0.50	82.19	13.88	98.44	0.29
March 21- Hour 15:00	2	0.4	0.5	0.9 To 0.05	0.46	81.29	15.43	98.44	0.26
June 21- Hour 9:00	1	1.2	0.5	0.9 To 0.05	0.49	81.09	15.44	100	0.23
June 21- Hour 12:00	1	0.8	0.5	0.9 To 0.05	0.49	81.45	14.65	95.31	0.28
June 21- Hour 15:00	2	0.8	0.5	0.9 To 0.05	0.50	81.64	14.30	84.38	0.24
December 21- Hour 9:00	1	1.2	0.5	0.9 To 0.05	0.479	80.03	17.13	100	0.17
December 21- Hour 12:00	1	0.8	0.5	0.9 To 0.05	0.52	83.14	12.94	95.31	0.25
December- Hour 15:00	1	1.2	0.5	0.6 To 0.05	0.53	83.48	12.58	95.31	0.21

Fig. 14. General analysis of daylight performance and visual comfort for position 2. Average of UDI, EUDI, sDA, WWR, DGP values for different Focal Region Radii (FRR) (1.2–0.8-0.4) and different depths (0.25–0.5).

The comparison with the base case and static case with fixed shading shows no significant differences in terms of sDA values.

The kinetic biomimetic facade has a positive impact on the UDI percentages compared to the base case (UDI = 39.55 %) and static case (UDI = 63,15 %). The UDI percentages increase with different configurations of the facade. The highest UDI value of 81.14 % is achieved with the facade having an FRR of 1.2 and a depth of the element equal to 0.5. This value is recorded at month 12 and hour 12. The lowest UDI value of 68.28 % is achieved by the configurations with FRR values of 0.4 and 0.8 and a depth of the element equal to 0.25. This value is recorded at month 12 and hour 15.

The studied facade variations resulted in a significant decrease in EUDI values compared to the base and static cases. The lowest EUDI value obtained was 14.91 %, and this occurred during month 12, hour 12, with FRR set to 1.2 and a depth of 0.5. This implies a higher level of occupant satisfaction and comfort during these conditions. The highest EUDI value obtained was 30.76 %, and it was recorded during month 6, hour 15, with FRR set to 0.4 and a depth of 0.25. Despite being the highest value achieved, it IS still considered acceptable as it does not affect the comfort and well-being of users during working hours.

The glare values there are within the optimal ranges. The DGP values does not exceed 35 % except in one case, where it reaches 35.32 % (month 9, h. 12, FRR 0.4, dephth 0.25). The smallest DGP value is 17.4 % (month 12, h. 9, FRR 0.4, depht 0.5). In the base case, almost 40 % of the time, glare caused intolerable and disturbing glareThis implies that the biomimetic façade helps significantly reduce glare-related discomfort.

Fig. 15 shows the parametric exploration of 486 biomimetic kinetic façade alternatives in the different FRR and PRD combinations, using different simulation parameters with inputs and outputs. The graph shown in Fig. 15 selects only the best combinations by applying the criterion of considering only the values of sDA >80, UDI >77, DGP <0.35. Table 5 shows the climate-based light metrics and the luminance-based survey in the different FRR and PRD combinations for occupant 2 facing south.

Table 5 provides information on the optimum daylight performance of various FFR and PRD configurations on solstice and equinox days. The performance metrics considered are UDI, EUDI, and sDA values that varying in the ranges 77.45–82.56, 13.92–20.37 and 92.19–100, respectively, while benefiting from different window-to-wall ratios (WWR) between 0.40 and 0.53.

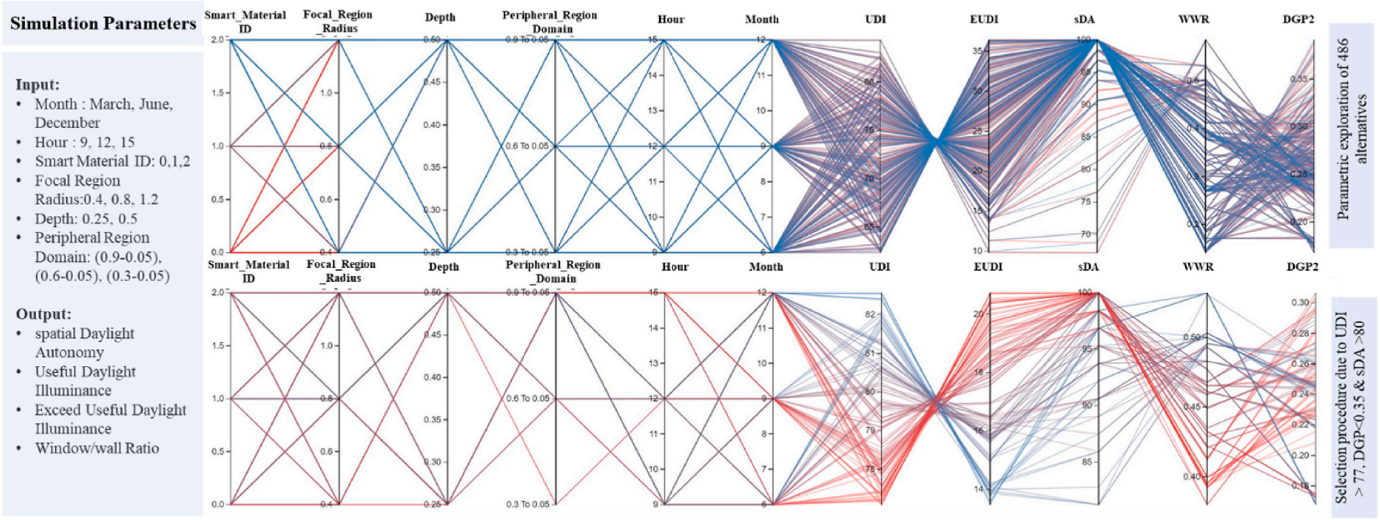

Fig. 15. Parametric exploration of 486 alternatives of biomimetic kinetic facade according to the occupant position 2.

Table 5
Climate-based daylight metrics and luminance-based investigation of the most optimum Biomimetic kinetic façades with different Focal Region Radiuses (FRR) and Peripheral Region Domain (PRD) for the South direction according to the occupant position 2.

Biomimetic Kinetic Façade Scenarios	Smart_ Material_ ID	Focal_ Region_ Radius	Depth	Peripheral_ Region_ Domain	WWR	UDI	EUDI	sDA	DGP2
March 21- Hour 9:00	0	1.2	0.5	0.9 To 0.05	0.50	82	13.92	92.19	0.24
March 21- Hour 12:00	0	0.8	0.5	0.9 To 0.05	0.47	80.90	15.60	96.88	0.28
March 21- Hour 15:00	1	1.2	0.5	0.9 To 0.05	0.42	78.38	19.19	100	0.23
June 21- Hour 9:00	0	0.8	0.5	0.9 To 0.05	0.46	80.9	15.61	98.44	0.22
June 21- Hour 12:00	0	0.8	0.5	0.9 To 0.05	0.46	80.67	15.81	93.75	0.26
June 21- Hour 15:00	1	1.2	0.5	0.9 To 0.05	0.53	82.56	13.48	98.44	0.16
December 21- Hour 9:00	0	0.8	0.5	0.9 To 0.05	0.48	81.04	15.67	100	0.17
December 21- Hour 12:00	1	0.4	0.5	0.9 To 0.05	0.45	80.41	16.45	100	0.26
December- Hour 15:00	1	1.2	0.5	0.9 To 0.05	0.40	77.45	20.37	100	0.23

5. Discussion

The integration of biological principles and their translation into a biomimetic design solution was enabled by the combination of the bio-AM [25] with the proposed daylight simulation parametric workflow, which represent the main novelty of this research. The morphological-behavioural analysis of the *Gazania* flower favoured the creation of modular elements that behave differently depending on their location in the focal or peripheral regions, like the radial distribution of petals around the central node of the flower. The modular elements, capable of periodic geometric movements, with different depths protruding from the plane of the façade, favour the achievement of daylight performance and visual comfort. In fact, some studies [37,42] have shown that the interactive modification of the shape of the façade modules improves visual comfort in relation to the position of the sun and that of the occupants, thanks to their high performance. The application of the biomimetic principles of the *Gazania* flower and the dynamism that emanates from the hypothesis of smart materials have covered the research gap regarding the lack of an architectural concept. These façades not only serve functional purposes by combining building physics and architectural technology, but they also provide added architectural value by transforming the static nature of buildings into a visually engaging experience. The interactive nature of kinetic-adaptive façades involves the user and becomes an iconic reference point for their visual impact, standing out in the urban context.

The results of the parametric simulations show that the light-responsive kinetic biomimetic façade system is able to ensure high values of daylight performance and visual comfort compared to the base case and static one. The setting of different material reflectance values (0.05–0.2-0.4) did not produce substantial results in the three reflectance combinations, therefore, only for safety reasons, the results were analysed considering the highest reflectance value equal to 0.4. The sDA values between the base case, the static case with fixed shading, and the kinetic biomimetic façade system do not show significant differences, while the UDI and EUDI values improve significantly and consequently also the DGP values.

The results for both positions (P1 and P2) showed improvements in UDI percentages with the kinetic biomimetic façade compared to the base case (UDI = 39.55 %) and static case (UDI = 63,15 %), with different configurations achieving different levels of UDI. The highest UDI values (83.42 %) were attained with an FRR of 1.2 and a depth of the element equal to 0.5, while the lowest values were associated with FRR values of 0.4 (67.4 %) and 0.8 (68.28 %) and a depth of 0.25. The EUDI values, which flag on overheating nearby the façade, decrease by about 50 % for both positions compared to the base case and static one.

The presence of the biomimetic façade system appears to significantly improve the glare conditions at both positions compared to the base case and static one. Most of the time, glare is non-perceptible or well below the threshold for discomfort, suggesting that the biomimetic façade contributes positively to user comfort. In both positions, the DGP values are generally within an acceptable range, and in position 1, the biomimetic façade significantly reduces intolerable and disturbing glare compared to the base case and static case.

However, it is important to be aware of the specific conditions and factors such as time of day, month and FRR that influence the occurrence of perceptible glare. Therfore, the comparison with the base case shows significant differences in terms of UDI, EUDI e DGP values, that increase more than 50 %. This suggests that the changes made to the facade configurations (e.g., different FRR and depth values) did have a substantial impact on the overall spatial daylight autonomy. In summary, the study demonstrates that adjusting the FRR and depth parameters can have a significant impact on occupant comfort at both positions, with some configurations providing higher UDI values and thus greater comfort and satisfaction. Overall, the results indicate that the biomimetic kinetic façade system is well-designed to put in the office room a high amount of natural daylight, promoting energy efficiency and occupant well-being. It responds to the optimal ranges of climate-based daylight metrics and prevents glare and overheating by blocking direct sunlight. The dynamic system can adapt to optimize its performance based on real-time conditions. Another advantage of the dynamic system is that it reduces artificial lighting during working hours, resulting in energy savings and better communication with the external environment. Overall, the dynamic solution, unlike the static one, offers adaptability, flexibility and the potential to improve comfort and energy efficiency. Modelling and parametric simulations have favoured the analysis of complex geometries by adjusting the shape and depth of each module element according to the position of the sun and the occupants. In this way, the façade's response can be analysed in real time in terms of filtering and modulating sunlight, whose dynamic nature leads to problems such as glare, excessive reflection, and overheating. Furthermore, the parametric study of the best façade combinations and configurations favours the future subsequent materialisation phase of the individual façade elements, which are created considering the results of the simulation itself. Indeed, the matrix of a photosensitive memory polymer varies from case to case according to need. Therefore, before its realisation, it must be defined taking into account various characteristics and conditions (e.g. modularity, cyclicity of the desired kinetic movement, depth of expansion, etc.) as well as the reaction function to be fulfilled. Modelling and parametric simulations therefore prove to be a preliminary stage for the future phases of material creation.

The selection of materials will be crucial in the creation of biomimetic kinetic façades, as the movement, engineering properties and performance of the materials significantly affect the adaptation and responsiveness of the façade. The integration of biomimetic and smart materials could represent an innovative approach to architecture that allows constructions to interact harmoniously with their surroundings. As mentioned earlier, concrete tests on physical prototypes are needed to test the validity of translating the biomimetic solution proposed in this study into biomimetic technologies.

The adaptive principles extracted from the flower provide a simple solution for the dynamic control of daylighting without a probabilistic approach, as used in existing works in the scientific literature, such as the use of dynamic roller blinds [28]. In this work, the brute force algorithm is configured as a valid approach to systematically evaluate all possible solutions and parameter combinations in order to arrive at the most accurate and optimal results. In biomimetic design, this method can help to explore a wide range of design possibilities and mimic the efficiency and effectiveness of natural systems. However, it is important to note that while the brute force algorithm allows for thorough exploration, it can also be computationally intensive and time consuming, especially for complex designs with numerous variables. However, when used effectively, it can lead to highly refined and efficient architectural solutions inspired by nature's ingenious designs.

In order to emphasise the novelty of this study in comparison with the architectural examples already existing in the literature or those already built, a comparative analysis is necessary.

However, most of the existing kinetic façades have a uniform movement of the façade modules, which leads to problems related to, for example, limiting the natural light entering the spaces, which could lead to the use of artificial lighting due to excessive screening.

In contrast to the kinetic façades of the Kolding Campus in Denmark, the Esplanade in Singapore and the Q1 building in the Thyssen Quarter in Germany, which are characterised by dynamic shielding systems with uniform movements of the individual modules activated by a sensor and actuation system, the kinetic biomimetic façade proposed in this study assumes to delegate the activation of its modules to the light-responsive polymer and shows an uneven distribution of the rhomboid elements depending on the point of attraction and thus on the position of the sun and the occupants.

In other examples, however, the modular shielding elements do not adopt uniform openings but vary according to their position on the façade and thus in relation to the orientation of the sun.

Although the shading solution of the Al-bahr towers has been proven to reduce solar radiation by 50 % [26] while improving visibility and having an uneven distribution of façade modules at the same depth, the rhomboidal modules of the façade, inspired by the *Gazania*, can adopt different depths and openings at the same level as the façade, which greatly improves indoor performance and meets real-time needs.

So, in contrast to these solutions, the following study also considers the position of the occupants and, above all, delegates the control of solar radiation to each system module, which, thanks to its intelligent characteristics, acts as a sensor and actuator, limiting energy consumption and automation systems.

The definition of the focal and peripheral areas brings an application-functional advantage, because in the FRR configurations, the light is shielded more according to the position of the sun and the location of the occupants, to avoid problems of excessive lighting and glare near the occupants, while in the peripheral areas, the expansion and contraction of each module is reduced compared to the focal areas, to ensure an optimal percentage of natural light in the rooms that does not disturb the occupants. In fact, the results of the simulations have shown that the solution with FRR significantly improves indoor performance compared to the base case without shielding. In particular, the EUDI and DGP values increase by 50 %. The introduction of the Focal Region Radius (FRR) is thus a key parameter that plays an important role in identifying areas of the façade that require more attention in terms of solar radiation modulation.

This advantage should also be emphasised in comparison with the studies available in the scientific literature. Recently, a study by Flor et al. [88] (2022) investigated the effects of daylighting in architectural spaces with adaptive ETFE façades and showed the possibility of a significant 59 % reduction in glare in the best configuration compared to the base case without double skin. A study by Norouziasas et al. [39] (2023) investigated the effect of automatically controlled blinds to evaluate the improvement in energy efficiency and lighting demand of an office building. Their results show that automatically controlled blinds improve the energy efficiency of an office by 19.47 % and reduce the lighting demand by 2.91 % compared to static shading, which also confirms the advantages of roller blinds over Venetian blinds. However, both studies lack reference to materials and configurations based on focal and peripheral areas.

The FRR concept proposed in this study is in line with previous studies by Hosseini, who introduced transient sensitive areas and periodic geometric changes. In 2020 [36], he presented a kinetic design integrating rotational motion with a coloured glass composition, while in 2022 [33] he integrated the coloured glass composition with the egg carton and hexagonal lattice (FEC-CCG) at different depths and demonstrated an improvement in UDI and EUDI compared to the 2020 solution and compared to the base case without shielding, proposing the optimal solution each time. The latest solution proposed by Hosseini [33] is inspired by the biomimetic lessons of the Morpho butterfly, which has enabled the integration of morphology with coloured glass, taking into account time, sun position and occupants. In the present case, however, the morphological-functional analysis of the *Gazania* flower has not only enabled the definition of parallelism with photosensitive polymers, but also the possibility of creating a dynamic and decentralised pattern of rhomboidal modular elements that parallel the individual petals of the flower. Therefore, the bio- AM is configured as an essential tool for biomimetic design, and the biological study is a fundamental phase as it allows abstracting from the principles of nature that provide ideas for the creation of high-performance kinetic facades. Indeed, in this study, starting from the analysis of the different adaptive behavioural strategies of plants, it was possible to identify the plant species that best implement light-responsive nyctinastic mechanisms in order to propose a solution capable of modulating, filtering and regulating solar radiation. BSDF definitions can also be derived from measurements of complex fenestration systems through goniophotometer testing, which necessitates the creation of a prototype and the execution of experimental measurements. However, this study was constrained to building performance simulations due to insufficient funding.

The integration of new intelligent materials could enhance the functionality of environmental systems. The shapes, colours, textures and translucency of the new materials create new relationships with the natural and/or the built environment to promote a more sustainable approach to designing environmentally responsive solutions in architecture.

6. Conclusion

The dynamic nature of daylight can cause discomfort for users due to glare, excessive reflection and overheating near the façade. Learning from the kinetic movements of the *Gazania* flower enables the development of a light-responsive biomimetic façade system capable of regulating and adapting to the dynamism of daylight to avoid the associated discomfort and reduce energy consumption from artificial lighting. Through a multidisciplinary approach, involving experts from different fields, this manuscript aims to translate the bio-AM to a computational design model and apply general lessons and logics learned from the *Gazania* flower to a kinetic mechanism that respond to user's visual comfort and daylight performance requirements.

The combination of bio-AM with the daylight simulation parametric workflow provides a method that can be followed by designers to define new responsive solutions inspired by nature. Unlike conventional adaptive solutions with uniform distribution, the modules of the biomimetic kinetic system have different dimensions and depths, depending on the radius of the focal region (FFR). This configuration not only ensures improved performance for user comfort through the principles of building physics, but also provides architectural value by transforming the conventional static character of buildings or the uniform homogeneous distribution of façade modules into a visually appealing experience for users and surrounding environment. Compared to the study presented by Le et al. [28] to evaluate the energy reduction and visual discomfort of adaptive façades with roller blinds that only provide the opening and closing mode without considering intermediate positions, the adaptive biomimetic façade proposed in this study emphasises the dynamic position of the façade modules based on the user's location and the introduction of the focal region radius. In contrast to some existing studies in the literature, such as the above-mentioned study by Wang et al. [29], which presents a complex geometry while neglecting the architectural and material aspects, the biomimetic solution presented in this study insists on these gaps and considers the depth and extension of the individual modules together with the material aspects, which cannot be neglected in the design phase.

The research demonstrated excellent performance improvement compared to the base case without shading and static case with fixed shading, when considering climate-based daylight metrics and glare values, particularly for UDI, EUDI, and DGP values.

Light-responsive polymers properties were analysed and chosen as the smart materials because they could guarantee the kinetic façade system to respond autonomously to light stimuli using the intrinsic properties of the material itself. This design solution, transformed into technology, would eliminate the need for external automatic devices, leading to reduced energy consumption, maintenance costs, and management expenses.

Although parametric modelling helped identify the best façade system configuration, including FRR and modular element depth, the physical response of the smart material, its cyclicity, and modularity need to be validated through real prototypes. Thus, creating physical prototypes represents a future research horizon resulting from this study to validate the real use of shape memory polymers.

The results of this study also highlight the need for further research to refine and validate the design of the proposed energy system, particularly under different solar angles, orientations and climates. It will be necessary to collect a large amount of data and analyse it using regression analysis as a new research study.

Although the proposed solution does not seem to require additional energy input due to the use of self-responsive smart materials, it could cause high costs during the production cycle and harm the environment during the life cycle due to the chemical nature of the materials. Therefore, Life Cycle Assessment (LCA) of the light-responsive biomimetic system is configured as a fundamental future step to quantify the environmental impact, including greenhouse gas emissions, to provide useful information on their performance over time in terms of reliability and longevity, but also to assess linearity with sustainability goals. Overall, this study presents a biomimetic approach in parametric design to develop novel façade systems, by combining biological principles, materials science and architecture for more adaptable and sustainable solutions to meet real-world challenges in daylighting and indoor comfort.

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CRediT authorship contribution statement

Francesco Sommese: Conceptualization, Methodology, Investigation, Resources, Formal analysis, Software, Data curation, Validation, Writing – original draft, Writing – review & editing, Visualization. **Seyed Morteza Hosseini:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Conceptualization. **Lidia Badarnah:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Fiore Capozzi:** Writing – review & editing, Investigation. **Simonetta Giordano:** Writing – review & editing, Investigation. **Veronica Ambrogi:** Writing – review & editing, Investigation. **Gigliola Ausiello:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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