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A Biomimetic Kinetic Facade Module to Enhance Building Thermoregulation: An Office Building

Módulo de fachada cinética biomimética para mejorar la termorregulación en edificios: un edificio de oficinas

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ABSTRACT

In recent times, with changing climate conditions, rising environmental awareness, and advancing technology, “environmentally friendly structures” have gained unprecedented importance. Technological progress enables a better understanding and application of nature’s principles in design, fostering eco-friendly strategies to address environmental challenges. Particularly in warm climates, thermoregulatory designs are vital for creating resilient urban environments. Rising temperatures affect the energy efficiency and comfort of buildings, prompting architects to explore solutions such as kinetic facades. These innovative systems, inspired by nature, adapt to external factors such as sunlight and temperature, enhancing the harmony between built environments and nature. This study presents a kinetic facade model designed for thermal balance and daylight optimization. Drawing inspiration from AskNature’s database, it mimics biological strategies, such as the Saharan silver ant’s micro-hair structure for effective heat reflection, the movement mechanism of Spanish moss, and the geometric form of the honeycomb. By integrating this feature, the proposed kinetic facade offers a sustainable solution for thermoregulation in modern architectural shells.

Keywords

biomimetics; kinetic facade; nature inspired design; responsive facade; thermoregulation

RESUMEN

En tiempos recientes, debido al cambio climático, al aumento de la conciencia ambiental y al avance tecnológico, las “estructuras ecológicas” han cobrado gran importancia. La tecnología facilita la comprensión y la aplicación de los principios de la naturaleza en el diseño mediante la promoción de estrategias sostenibles. En climas cálidos, la termorregulación es vital: el aumento de la temperatura afecta la eficiencia energética y el confort, lo que impulsa soluciones como las fachadas cinéticas. Estos sistemas, inspirados en la naturaleza, responden a factores externos, como la luz solar y la temperatura, y mejoran la armonía entre lo construido y el medio natural. Este estudio propone un modelo de fachada cinética para el equilibrio térmico y la optimización de la luz natural. Inspirado en la base de datos de AskNature, imita los micropelos de la hormiga plateada del Sahara para reflejar el calor, el mecanismo de movimiento del musgo español y la geometría del panal. Así, ofrece una solución sostenible de termorregulación para envolventes arquitectónicas modernas.

Palabras clave

biomimética; diseño inspirado en la naturaleza; fachada cinética; fachada receptiva; termorregulación

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INTRODUCTION

Climate change, acknowledged today as an inevitable and urgent global challenge with long-term repercussions, affects all countries worldwide (Barakat & Endalew, 2019). Significant issues such as environmental pollution and climate change, arising from the escalating global demand for energy and the use of fossil fuels, pose serious concerns for environmental sustainability. The indiscriminate consumption of natural resources and the resultant emission of greenhouse gases lead to irreversible ecological damage. The construction sector is among those that contribute substantially to global energy consumption (Energy, 2017). While the building sector consumes approximately 42% of the world's energy, it also accounts for 33% of carbon dioxide, a leading greenhouse gas associated with global climate change (Lemmet, 2013). According to analytical studies by energy organizations, buildings are responsible for 40% of direct and indirect CO2 emissions (IEA, 2021). Challenges arising from climate change include environmental degradation, an uneven distribution of resources, and unsustainable energy consumption patterns. Therefore, focusing on research aimed at mitigating and adapting to climate change is crucial (Ali et al., 2013).

In today's context, factors such as urbanization, population growth, global warming, and the climate crisis brought about by excessive heat have disrupted the internal thermoregulation of structures. This situation has paved the way for eco-friendly, alternative solutions that lighten the building load to address these issues. Consequently, architects and engineers view nature as a source of inspiration for solving design problems (Srisuwan, 2022). In nature, many organisms use behavioral and morphological features to support physiological strategies for environmental adaptation (Badarnah, 2017). Architects aim to discover sustainable and effective alternatives for heat regulation and to explore solutions inspired by nature (Abdullah et al., 2018). Thus, innovative facades and adaptable facade elements inspired by nature emerge as alternative building envelopes developed to meet increasing demands on user comfort, energy consumption, and cost efficiency (Ahmed et al., 2016). Also, Fraile-Narváez (2025) states that integrating biodigital design and artificial intelligence can support a "living architecture" approach, in which biological ways of thinking are used to create autonomous and sustainable systems.

Numerous facade studies in the literature draw inspiration from nature to achieve thermal balance within structures. One such study was conducted by Mazzoleni (2010) and Mazzoleni (2013), presenting a design concept inspired by the thick double-layered fur of a hippopotamus, which is resistant to heat transfer and optimizes daylight in the building envelope. Based on this characteristic of the animal, a facade was designed to regulate temperature in hot climates. This facade can be transformed into a double-walled structure with sliding panels. The panels in the structure respond to ground-level light sensors, adjusting their positions to meet the building's needs.

In the study developed by Globa et al. (2021), the concept of sustainability is explored through kinetic facades. They have designed and prototyped a sustainable green facade module that harnesses solar energy by cultivating plants on it. These modules can rotate to maximize sunlight utilization.

Faragalla and Asadi (2022) have presented a conceptual theoretical framework, based on a comprehensive literature review, to explore design approaches to enhance facades' performance in the early design stages. They have developed biomimetic methodology frameworks that emphasize selecting and implementing an appropriate strategy for planning adaptive facades in the early design stages. Similarly, Badarnah (2015) focused on biomimetic strategies for energy performance by developing a comprehensive model of thermoregulation that accounts for heat gain, retention, distribution, and prevention. The aim was to support designers in the early stages of concept development.

Arbabzadeh et al. (2020) conducted a comparative analysis of vernacular and biomimetic architectural examples in hot-climate regions, distinguishing their study from other examples. Comparative analyses were classified according to heat-regulation criteria in an analytical diagram, and similarities and differences were identified. The evaluation revealed that vernacular and biomimetic architecture adopt common strategies for heat regulation in different ways, and their knowledge in coping with environmental conditions is largely similar.

Based on their literature review, Imani and Vale (2022) argue for addressing the existing built environment and making structures less dependent on fossil fuels through biomimetic approaches. Otherwise, they argue that many models of nature provided by the ecosystem will disappear.

Approaching the relationship between thermo-bio-architecture differently, Imani and Vale (2020) discuss the limitations of sustainable building design in fully mimicking biological thermoregulation mechanisms. Considering that some biological thermoregulation strategies are independent of the limitations of existing sustainable building design methods, they conclude that energy consumption is a factor. As a result, building and organism thermoregulation may be incompatible in certain aspects.

In this study, distinguishing itself from previous research, a proposal for a kinetic facade is introduced to ensure thermal comfort in extreme weather conditions within an office building in Ankara. Drawing inspiration from desert-dwelling organisms and plants, the design aims to provide adequate daylight while reducing UV radiation intensity. The proposed kinetic facade model addresses the thermal balance within the structure, particularly during excessively hot summer days. The primary inquiries guiding the development of an adaptive and thermally balanced architectural shell/facade design are as follows:

- Can the thermoregulatory mechanisms of heat-resistant animals be translated into architectural knowledge to inform the design of an adaptive and thermally balanced architectural shell/facade?
- May the adaptation strategies developed by animals in hot-climate regions against extreme heat and UV radiation offer guidance to architects in creating adaptable, responsive facade designs?

The article provides general insights into the biomimetic approach in light of this information. Following this, examples of facade and building-shell designs inspired by nature are presented, along with information derived from research on thermoregulation strategies in animals inhabiting various climate regions. The study and analyses led to the selection of the Saharan silver ant and the Spanish moss plant as models for knowledge transfer. Biological insights from these phenomena are then translated into architectural principles for the design of a kinetic facade.

BACKGROUND

Biomimetic Approach

Approaches referred to as biomimicry, bio-inspired, biomimetic, and bio-informed have found their place in the literature as methods, tools, disciplines, or strategies to derive ideas from nature. The bio-informed approach is a broad methodology aimed at generating effective, innovative, and sustainable solutions to human problems (Kennedy et al., 2015). This approach not only influences design but also facilitates interactions among disciplines such as architecture, mathematics, art, biology, and engineering, catalyzing creative problem-solving and driving significant change (Arslan & Mutlu, 2021; Kennedy et al., 2015; Pohl & Nactigall, 2015). The term biomimicry was first used by Otto Herbert Schmitt in 1969 during the Biophysics Congress (Bensaude-Vincent, 2019). It signifies the examination and imitation of nature's methods, mechanisms, and processes (Schmitt, 1969). While the primary goal of biomimetics is to design multifunctional, high-performance materials, biomimicry emerged to reconnect design with nature, focusing more on developing sustainable technology than on innovation (Bensaude-Vincent, 2019).

According to Iouguina et al. (2014), bionics, biomimicry, and biomimetics encompass concepts of "innovation" and "inspired, imitated, copied, or learned from nature." Due to the lack of a fitting adjective for biomimicry, the term biomimetic design is used to refer to designs that align with its definition (Iouguina et al., 2014). Various approaches that consciously aim to mimic nature attempt to solve contemporary technical and ecological challenges by imitating biological models, including biomimicry (from the Greek bios, "life," and mimesis, "imitation"), bionics, permaculture, and environmental engineering. Among these terms, biomimicry, biomimetics, bionics, bioinspired design, permaculture, and ecological engineering are the most commonly used concepts (Gerola et al., 2023). According to Marshall (2007), the term bionics emerged in 1960, introduced by Jack Steele of the United States Air Force, to define a future field inspired by nature, encompassing processes of imitation and learning from nature. Research on the origins of these fields indicates similarities between bionics and biomimetics, but biomimicry is distinct. While bionics and biomimetics share roots in biophysics and cybernetics (control systems), biomimicry is associated with disciplines such as ecology and environmental sciences (Iouguina, 2013). The founder of the Biomimicry Institute, Benyus (2007), asserts that nature already has solutions to many of the problems humanity faces today. This is because nature has evolved forms, structures, materials, and processes that function across scales from macro to nano (Dicks, 2016).

In this context, nature is interpreted as a vast source of potential "design solutions" for designers, acting as an operational system similar to an inventory or catalog. Numerous online platforms, such as asknature.org, have been established to enhance perceptions of nature and biomimicry. Ongoing efforts in popular languages aim to increase interest in potential activities in this field (Mutlu & Arslan, 2020).

In architecture, Buckminster Fuller and Frei Otto are recognized as pioneers in biomimetic studies during the 1960s and 1970s, exploring how to incorporate morphological diversity from nature into design. In 1964, Otto established the Institute for Lightweight Structures at the University of Stuttgart, where he and his research team examined forms and structures such as soap bubbles and spider webs (Drew, 1976). The institute conducted interdisciplinary research and experiments, integrating biological principles into the design process to enhance structural efficiency. Otto's book *Finding Form* delves into construction-centric experiments, studying natural forms and phenomena like spider webs, soap bubbles, Earth movements, trees, rocks, wind erosion, lightning, clouds, birds, and bees (Pasic, 2014).

Institutions, including universities and laboratories, have widely employed bio-informed design concepts, methods, and tools to foster innovation in product development and educate students on design innovation through alternative inspirations. Organizations like the Biomimicry Institute and Biomimicry Switzerland provide resources for researchers, designers, and industry professionals on the principles and applications of biomimicry. These institutes' work guides the application of the natural world's unique strategies and design principles to human technology and projects. The Institute for Lightweight Structures in Stuttgart, led by Frei Otto, is recognized as one of the pioneering schools that observed nature and utilized its structural principles as building features (Nerdinger, 2005). To this day, biomimicry education is offered at institutions such as the University of Stuttgart, Arizona State University, and numerous others.

In the examinations conducted thus far, it has been observed that the process of acquiring information from nature is expressed through various concepts. In this context, the term "biomimetics" is used in this study to refer to the process of learning and transferring knowledge from nature.

Thermoregulation in Nature

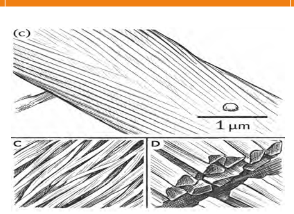
AskNature-based research highlights diverse thermoregulation and UV-reflection strategies across organisms. The Saharan silver ant reduces heat gain by reflecting light efficiently through grooved hairs, while desert snails use layered shells to create insulating airflow and reflect solar radiation. Emperor penguins support UV reflection with multi-layered beaks, and elephants cool themselves by directing blood flow toward the skin surface in hot conditions.

The silver ant (*Cataglyphis bombycine*), which inhabits the deserts of the Sahara, Sinai, and the Arabian Peninsula, is renowned for its remarkable ability to withstand extremely high temperatures, facilitated by its hairs (Willot et al., 2016). The specially shaped triangular hairs covering the upper and lateral parts of the ant's body keep its body cool. The hairs of the Sahara silver ant reflect sunlight and distribute heat across its entire body, minimizing heat absorption (AskNature Team, 2019a).

Desert snails, thanks to the reflectivity of the surface of their shells, provide 95 % reflectance in the infrared and 90 % reflectance in the visible spectrum (AskNature Team, 2019b). It is crucial for thermoregulation that, when retracted, the snail does not fully occupy the shell, leaving much of the largest spiral filled with air. The snail, when withdrawn into the upper portions of the shell, remains significantly cooler. Excess heat is transferred to the outside air through conduction (Schmidt-Nielsen et al., 1971), though the reflection of ultraviolet light by the edges of bird beaks has been discovered (Hunt et al., 2003). The first animal discovery of microstructures reflecting UV light in beak tissue was the Emperor penguin's beak (Dresp et al., 2005). With its multi-layered structure, the Emperor penguin's beak serves as a reflector, reflecting UV rays (AskNature Team, 2016a). Elephants can dissipate heat by dilating blood vessels beneath their 2.5 cm thick skin. Vasodilation allows the blood vessels to expand, bringing more blood to the skin's surface to cool the body. This process facilitates the dispersion of heat from the body to the air. Simultaneously, the heat accelerates the evaporation of water released through skin pores via sweat, further aiding in cooling (Lippsett, 2016).

In this section, the data obtained regarding animals is presented in Table 1. The thermoregulation characteristics of the investigated animals are analyzed in terms of the morphological, physiological, and behavioral adaptations they have developed in nature, accompanied by microscopic images of these features.

Table 1. Thermoregulation Methods of Animals in Nature

Animals	Developed thermoregulation method	Photomicrograph	Adaptation		
			Behavioral	Morphological	Physiological
SAHARAN SILVER ANT	Through the grooves on its triangle-sectioned feathers, it reflects sunlight and distributes heat across its entire body, minimizing heat absorption (AskNature Team, 2019a)			X	

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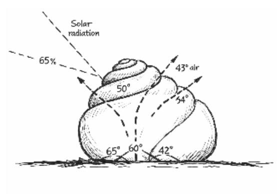
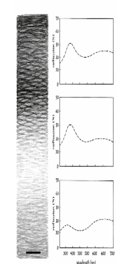
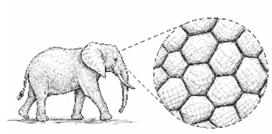
Animals	Developed thermoregulation method	Photomicrograph	Adaptation		
			Behavioral	Morphological	Physiological
DESERT SNAIL	Due to the reflectivity of the surface on their shells, they reflect 95% of infrared and 90% of visible light (AskNature Team, 2019b)			X	
EMPEROR PENGUIN	The multi-layered structure of the Emperor penguin's beak serves as a reflector, bouncing back UV rays (AskNature Team, 2016a)			X	
ELEPHANT	Elephants can dissipate heat by expanding the blood vessels beneath their skin. This allows the heat to be distributed in their skin and facilitates the release of warmth from the body into the surrounding air (Lippsett, 2016)		X	X	

Source: Own elaboration (2024)

Thermoregulation and Biomimetic Facade

Thermoregulation is the process by which an organism maintains its body temperature within a specific range regardless of environmental temperature (Farchi Nachman, 2009). In architecture, it is defined as maintaining indoor temperatures within a specific range, unaffected by external temperature fluctuations (Aydın et al., 2022). Examining nature and finding solutions are valuable endeavors for architects (Amer, 2019). Building modeling and energy performance prediction constitute an interdisciplinary field that requires collaboration for further advancement (Foucquier et al., 2013). The adaptive building envelope is expressed as the "morphogenetic evolution and real-time physical adaptation in the relationship of a design with its environmental context" (Al-Obaidi et al., 2017). Responsive buildings leverage various movements, such as kinetic motions/mechanisms and structural configurations (Lurie-Luke, 2014). Additionally, building facades employ biomimetic principles to achieve complex, flexible, and foldable forms (Hosseini et al., 2021).

In the facade study by El Ahmar and Fioravanti (2015), which employs a biomimetic approach, a folded surface self-shades, reducing heat gain from radiation. It aims to increase heat loss through convection by drawing inspiration from the porosity of termite mounds. This double-layered facade, inspired by termite mounds, serves as an example applicable to hot climate regions (El Ahmar & Fioravanti, 2015).

Sankaewthong et al. (2022) have designed a facade comprising movable modules. The inspiration for this facade module design was derived from the behavior of DNA sequences. In the design, the mimicry of DNA behavior has led to the proposal of a kinetic facade that filters sunlight into the structure's interior. The physical DNA, phototropism behavior, and Eshelby rotation movement facilitated the interpretation of ribbon forms, a key component of the kinetic facade, using a biomimicry approach. For the facade design, 10 patterns were created, each bending to various degrees (0°–100°) to provide suitable daylight for each space (Sankaewthong et al., 2022).

Al Bahr Towers, designed by Aedas Architects to ensure indoor comfort in the desert, features a kinetic facade inspired by cactus, pineapple, and flower forms. The facade design is based on adaptive flowers and a traditional wooden lattice element called “Mashrabiya” for shading concepts (Hopkins, n.d.). Additionally, inspiration is drawn from the airtight texture of cacti and the opening and closing features of flowers. The hexagonal envelope of the pineapple contributes to creating a double-sloped facade. Kinetic triangular shading elements open and close at various angles in harmony with the sun’s movement, optimizing the facade’s solar exposure. This situation reduces artificial lighting within the structure and associated energy costs (Karanouha & Kerber, 2015).

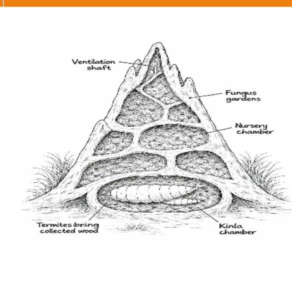
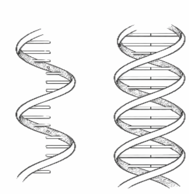
In another study conducted by Hosseini et al. (2021), a complex kinetic shading facade design was developed to enhance users’ daylight performance, drawing inspiration from plant movements. This research investigated the morphology of trees and leaves to extract daylight biomimetic principles and translate them into kinetic movements. The obtained forms and movements were translated into design solutions for the kinetic facade, resulting in an intersecting, multi-layered, and flexible form.

The glass facade of the Tricon Corporate Centre building is designed by mimicking the combination of the organism and behavioral levels of the *Oxalis oregana* plant. The photoreceptors of the *Oxalis oregana* plant enable it to track the intensity of sunlight. Its leaves can rotate from horizontal to vertical in 6 minutes (Elsakksa et al., 2022). The proposed facade design has been adapted for a 20-story office building in Pakistan with a hot, humid climate. This study presents an adaptive facade that reduces the building’s energy consumption while minimizing the compromise on users’ visual comfort. It exemplifies an adaptable biomimetic facade for high-glazed buildings in hot and humid regions (Sheikh & Asghar, 2019).

The kinetic facade developed by Sommese et al. (2024) draws inspiration from the movement of the Gazania flower. The crown petal of Gazania exhibits a tendency for expansion and contraction along the horizontal axis or, in any case, along the short axis of the element, induced by the bending and subsequent opening triggered by light. Direct observation of the Gazania flower’s movement enables articulating a facade design embodying two primary mechanisms: the curving along the longest axis of each petal’s tips and the curvature transition from vertical to horizontal. The movement of Gazania petals facilitates this design by summarizing bending and subsequent opening, allowing the three-dimensional triangular element to expand and contract in the horizontal plane or along the short axis of the component in all instances (Sommese et al., 2024).

The kinetic and thermoregulatory facade designs discussed thus far are presented in Table 2, analyzed in the design context, referencing living organisms and the targeted features.

Table 2. Biomimetic Thermoregulatory Facade Design Examples

Reference	Case study	Referred organism	Intended feature
El Ahmar and Fioravanti (2015)	*Biomimetic-Computational Design for Double Facades in Hot Climates: A Porous Folded Facade for Office Buildings*	 Termit mound	Inspired by termite structures, the design incorporates a double-shell structure to optimize heat and ventilation
Sankaewthong et al. (2022)	*Using a biomimicry approach in the design of a kinetic facade to regulate the amount of daylight entering a working space*	 DNA structure	Utilizing the movement of the DNA helix, a kinetic facade model is introduced for internal daylight control

(continued)

(continued)

Reference	Case study	Referred organism	Intended feature
Karanouha and Kerber (2015)	*Innovations in dynamic architecture*	 Mashrabiya	The opening and closing mechanism of the Al-Bahr Towers project is inspired by numerous plants, aiming to enhance the thermal balance within the structure
Hosseini et al. (2021)	*Biomimetic kinetic shading facade inspired by tree morphology for improving occupant's daylight performance*	 Leaf	The principle of reflecting sunlight, with its transmission and dispersion characteristics, found in trees, has been integrated into the design
Elsakksa et al. (2022)	*Biomimetic approach for thermal performance optimization in sustainable architecture: Case study: Office buildings in hot climate countries*	 *Oxalis oregana* plant	The plant's self-shading mechanism has inspired the facade design
Sommese et al. (2024)	*Light-responsive kinetic facade system inspired by the Gazania flower: A biomimetic approach in parametric design for daylighting*	 Gazania flower	The bending and flexing movement of the plant in response to solar radiation has defined the mechanism in the biomimetic facade

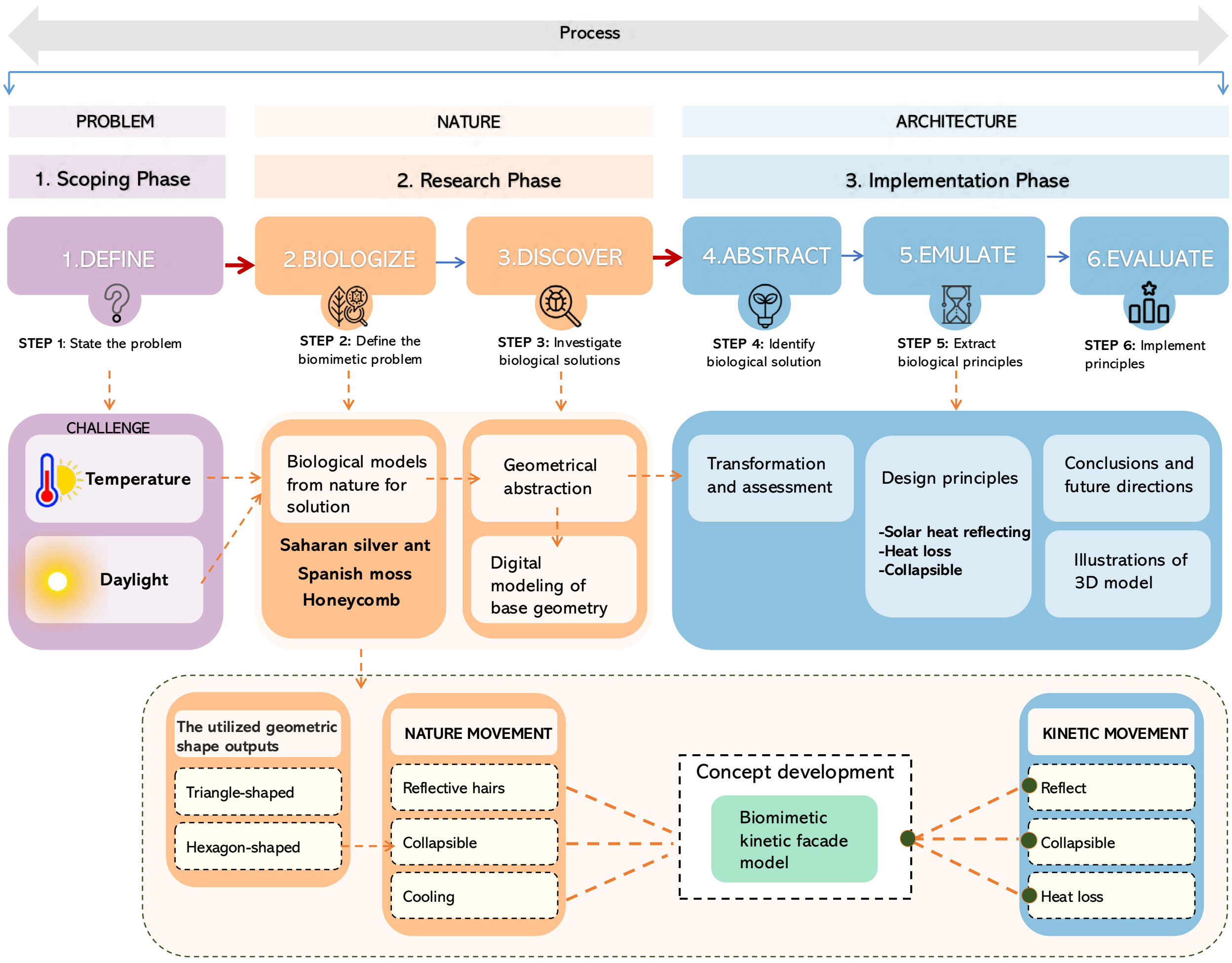
Source: Own elaboration (2024)

METHOD

In hot-climate regions, buildings often incur substantial energy costs to regulate indoor temperatures due to excessive exposure to sunlight. This situation leads to heating issues due to excessive sunlight and increased cooling needs (Laidback Gardener, 2022). To address this challenge, research on thermoregulation in nature was conducted on the AskNature website, examining data on the thermoregulation characteristics of animals. Based on this data, three notable organisms were selected. To implement this solution, a biomimetic approach was employed to investigate thermoregulation strategies in nature, resulting in the development of a kinetic facade design.

In the design of an office building with a chamfered facade, a "problem-focused" approach has been employed to explore natural solutions to reduce heat gain and improve thermal comfort within the structure. The initial phase of this process involved problem identification, followed by integrating the identified problem into a biological context. Subsequently, research was conducted to investigate biological solutions, and the acquired biological outcomes were thoroughly examined. Finally, based on the strategies derived from these biological solutions, the resulting principles were implemented as an architectural facade solution for the building. The steps of this biomimetic cyclical process, outlining the methodology, are shown in Figure 1.

Figure 1. Flow Chart of the Used Methodology



Source: Own elaboration (2024)

RESULTS

Case Study

In this section, the stages followed in this research, based on the problem-focused approach, one of the biomimetic processes, are elucidated.

Problem Statement

In regions with harsh climatic conditions, achieving thermal balance within structures is a critical concern, chiefly addressed through primary energy sources. Particularly in hot climate zones, there is an increasing demand for internal cooling to support thermoregulation during high temperatures, which significantly increases overall energy consumption. Therefore, optimizing the thermal balance within the structure through daylighting strategies implemented on the building envelope or facade emerges as necessary.

The motivation for selecting Ankara is that, when the city's temperature records are examined, the highest temperature is identified as 40.8 °C and the lowest temperature as −24.9 °C (T.C. Ankara Valiliği, 2025). In the climate classes produced for Ankara's urban core, the most prevalent class reported is "Moderate Warming" (18.76 %), whereas the least represented class is "Very Strong Warming" (0.05 %). This indicates that areas experiencing "extreme overheating" are spatially limited, while moderate warming is widespread across the urban fabric (Yıldız & Şahin, 2025).

In line with this approach, the present study is framed around the south facade of an office building located in Ankara. Under Ankara's continental climate, frequent sunny days and seasonally high solar irradiance intensify solar heat gain at the building envelope, thereby directly affecting indoor thermal comfort and cooling demand. Since the south facade is among the surfaces where overheating risk is most clearly observed due to sustained solar exposure throughout the day, regulating the thermal behavior of the building envelope/facade at critical locations is a crucial design consideration. Accordingly, the proposed kinetic module is designed for the south orientation to enable a clearer assessment of its thermoregulatory potential.

Defining the Biomimetic Problem

Similar to structures, living beings experience heat gain and loss through the interaction of their skin or shell surfaces with the external environment (Aydın et al., 2022). Providing an internal environment that ensures thermal comfort for living beings, which must adapt to varying thermal conditions, poses a significant challenge for architects (Mazzoleni, 2013).

From this standpoint, the problem statement identified in this section revolves around achieving in-building thermoregulation in regions with challenging weather conditions. The question posed in this context is: What biological strategies do animals employ in nature for thermoregulation, given the harsh climatic conditions and the intricate interplay of physical and physiological environmental factors?

Investigating Biological Solutions

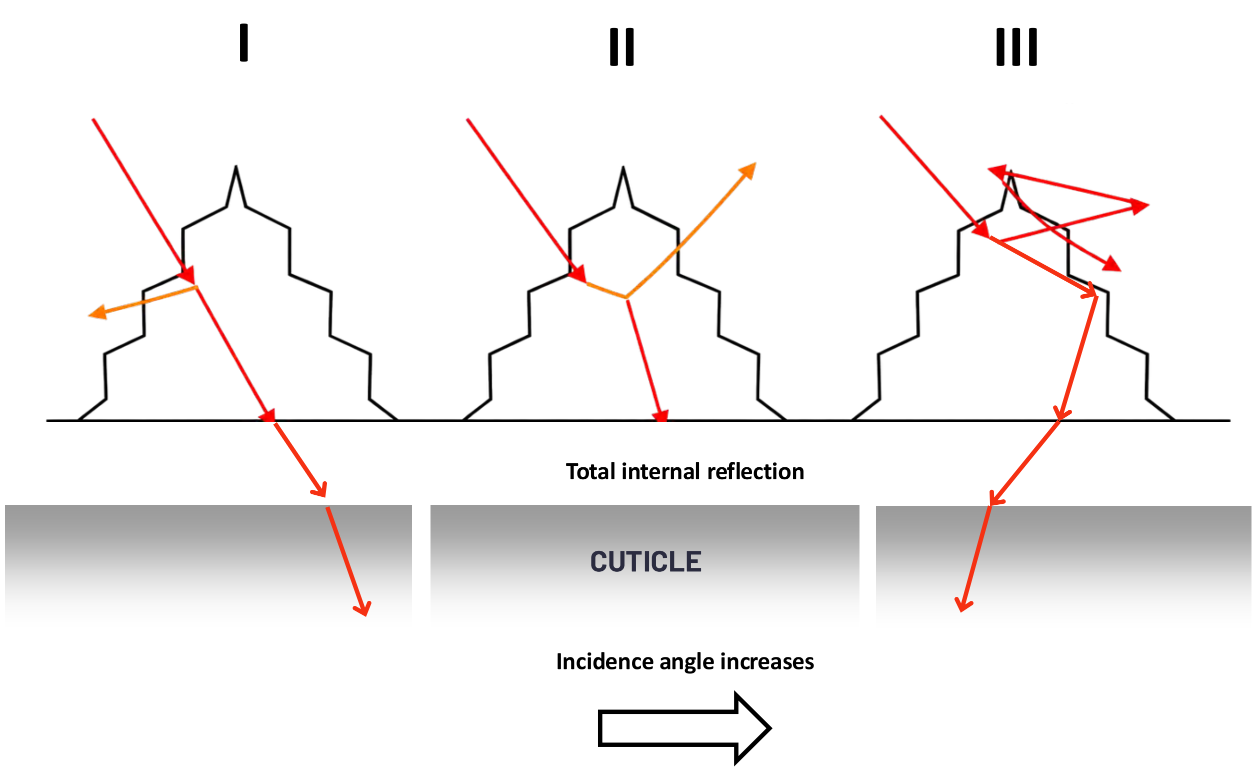
Biological references were selected using the AskNature database. The Saharan silver ant (*Cataglyphis bombycina*) was chosen for its reflective micro-hair (setae) structures, which provide a basis for improving solar reflectance. Spanish moss (*Tillandsia usneoides*) was selected for its ability to move, enabling dynamic shading. Honeycomb geometry was chosen for its lightweight, repeatable, hexagonal cellular structure, which supports modular panelization. These mechanisms were combined and translated into kinetic facade design parameters: reflectance, actuation potential, and modular cellular geometry.

Identifying Biological Solutions

Cataglyphis bombycina, chosen for the study, possesses a significant adaptation capability in the Sahara Desert, one of the hottest regions on the planet. Unlike many organisms that inhabit high-temperature environments and typically have flat skin, shells, or scales, these ants exhibit unique external defense mechanisms: hairs. These hairs can be considered distinctive adaptations that effectively cope with high temperatures (Ralevski, 2019).

The two upper surfaces with curved feathers enhance scattered reflection in the ultraviolet and visible spectra (Shi et al., 2015; Figure 2).

Figure 2. The Curved Surface of the Hair



Source: Own elaboration (2024)

The preeminent determinant in delineating the *Cataglyphis bombycina* phenomenon stems from its adaptive biological strategy in response to elevated temperatures. The ant, characterized by triangular feather cross-sections, is a source of inspiration for optimizing in-building thermoregulation through its corrugated and UV-reflective feather structure. The paramount attribute lies in its feathers, facilitating the reflection of incident sunlight and the dispersion of excess heat throughout the body, thereby contributing to the overall efficacy of thermoregulation.

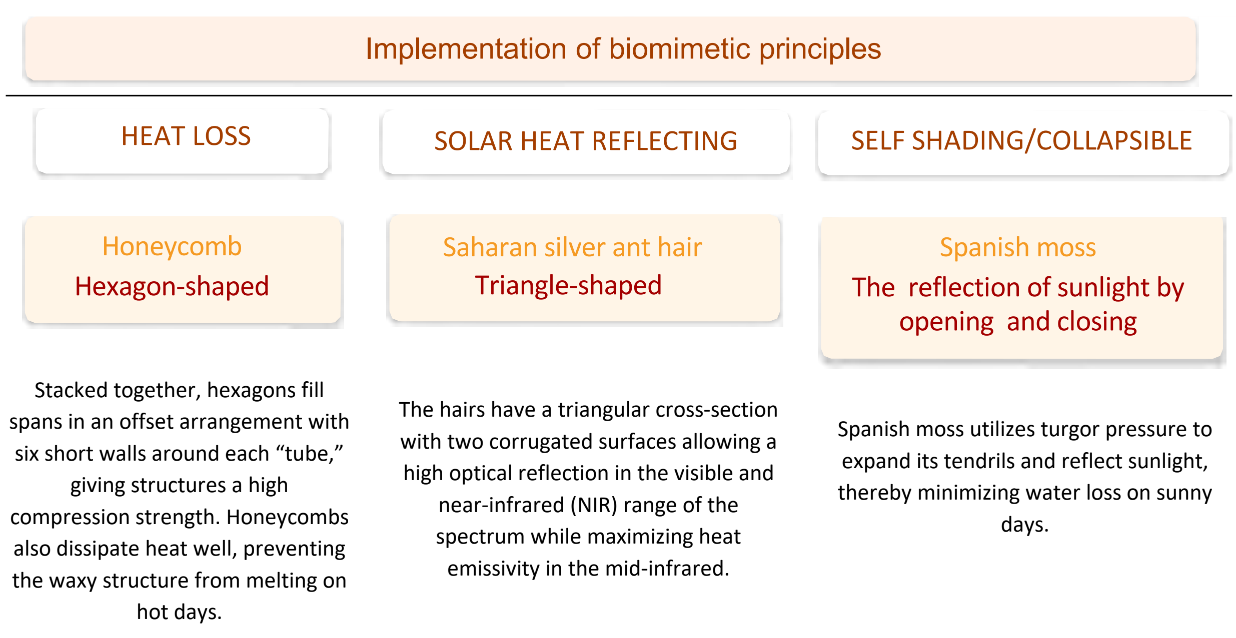
Another organism identified for the study, *Tillandsia usneoides* (Spanish moss), absorbs water through its densely covered leaves and, in situations of water scarcity, reflects sunlight through the movement of its scales (AskNature Team, 2016b). The primary distribution range of Spanish moss extends from the Southeastern United States to Argentina, where the climate is sufficiently warm, and relatively high average humidity prevails (Wikipedia contributors, n.d.). Virginia and Maryland are the northern limits of their natural distribution in the United States (Brown, 1984).

When the plant dries, its scales flex and move away from the surface. These scales readily absorb water upon rainfall, allowing for uniform absorption by remaining flat on the plant's surface. Dry scales play a significant role in reducing perspiration and reflecting solar radiation (Kew, n.d.).

Extracting Biological Principles/Information

The Saharan silver ant regulates its body temperature on hot summer days through reflective grooves on its hairs. Based on this characteristic of the organism, an adaptive kinetic facade module with adjustable features is proposed, inspired by the biological strategies of the other two organisms (Figure 3).

Figure 3. Biological Strategies of Selected Organisms against Temperature Challenges

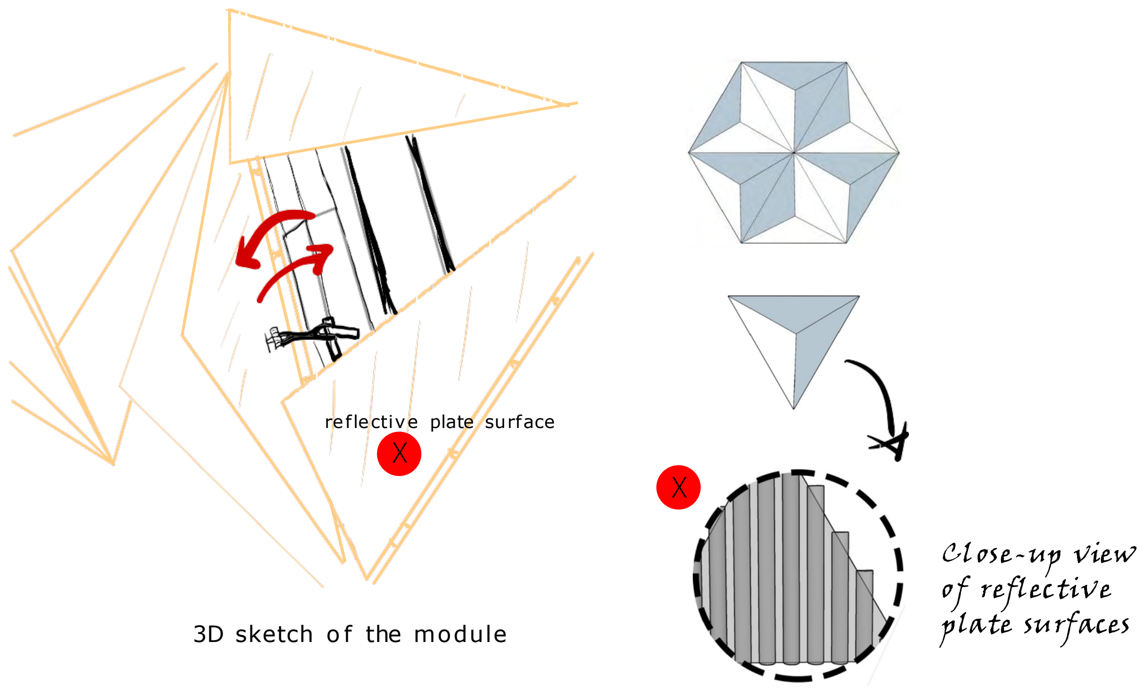


Source: Own elaboration (2024)

A kinetic facade has been designed by combining modules that mimic the behavior of Sahra desert ant Quedaría: Sahara desert ant ans Spanish moss. This kinetic facade features triangular pyramids with reflective surfaces that open and close in response to the sun's movement. These pyramids have corrugated curves on their triangular surfaces (Figure 4), allowing them to reflect UV rays.

Inspired by these three principles, the aim is to achieve infrastructural thermoregulation through the kinetic design on the southern facade of the structure at the angle of solar incidence. Consequently, it is anticipated that the reflective surfaces in the facade modules will reduce internal heating and lower energy consumption in the built environment, particularly during hot summer days.

Figure 4. Design Principle Sketch

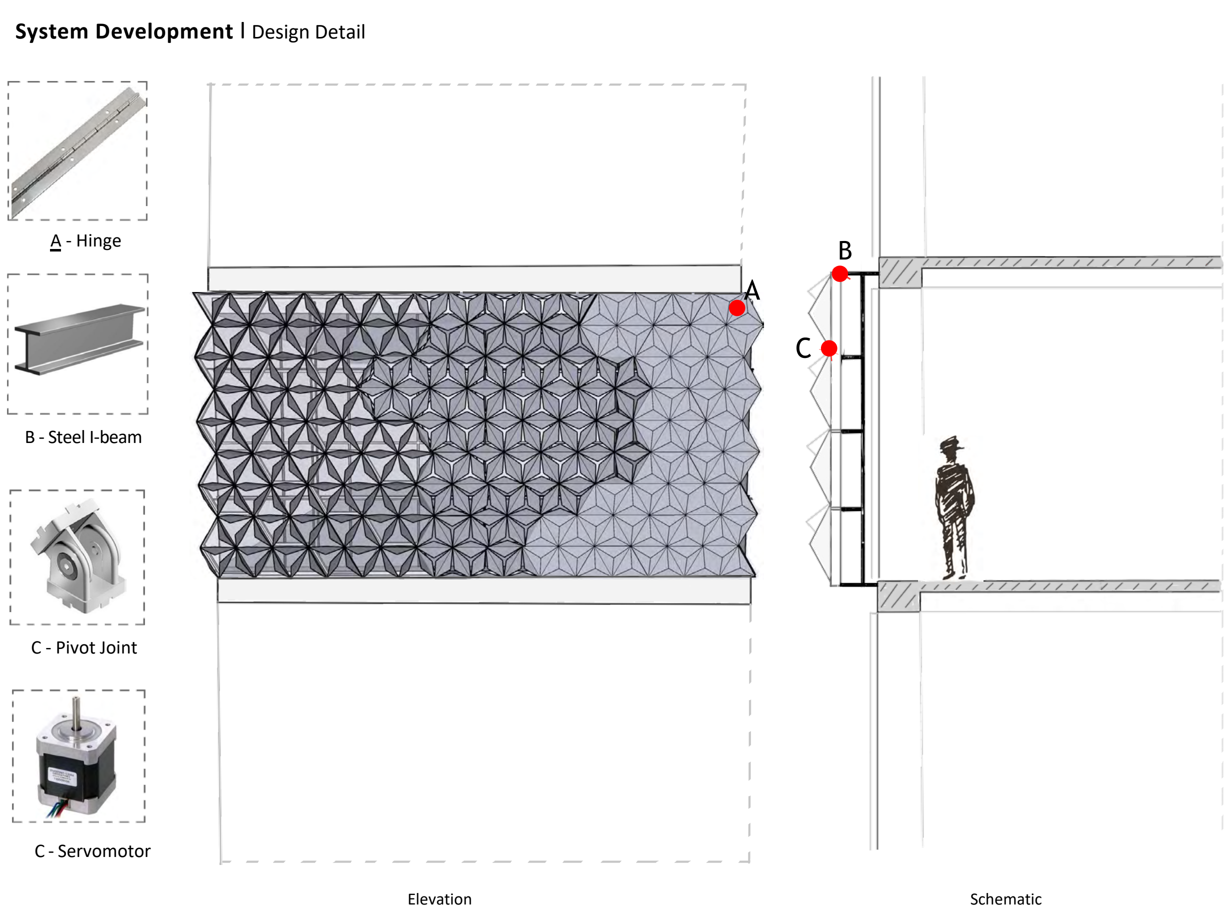


Source: Own elaboration (2024)

Implementing the Principles

The designed kinetic facade aims to facilitate infrastructural thermoregulation and reduce the cooling load and heat gain. The design concept is derived from the physiological characteristics of the triangle-sectioned feathers of the Saharan silver ant, which inhabits the Sahara Desert, and the movement strategy of Spanish moss during photosynthesis in response to sunlight (Figure 5).

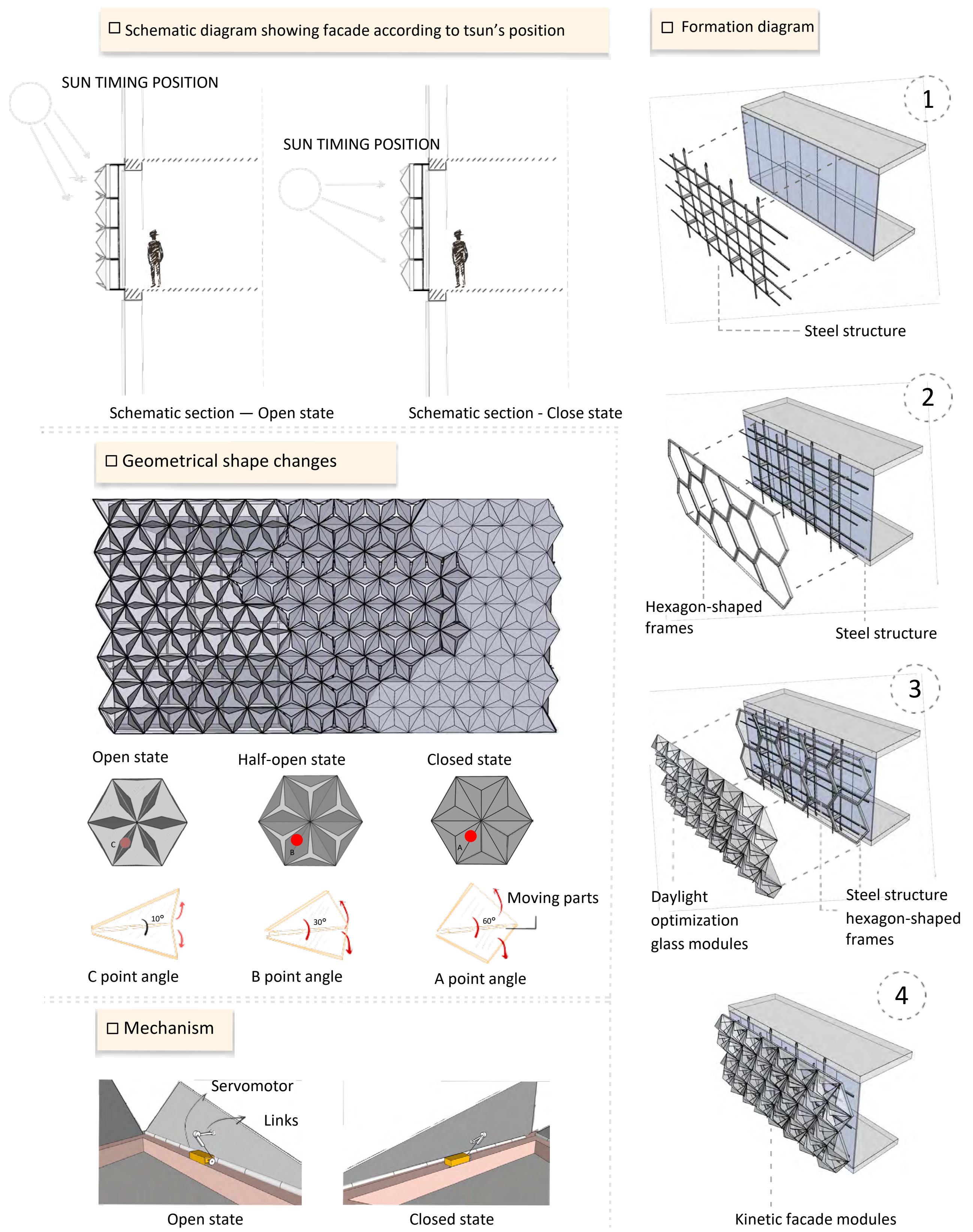
Figure 5. The Southern Facade and Cross-Section of the Designed Façade



Source: Own elaboration (2024)

Each module of the kinetic facade is controlled by a stepper motor, allowing it to open and close to three angles (60°, 30°, and 10°). Every unit in the design incorporates a mechanism that determines its angle based on the sun's position. In this context, Figure 6 illustrates the mechanism, along with a sectional representation of the facade at hours when the sun is directly overhead and at hours when it is directly opposite (60° to 10°).

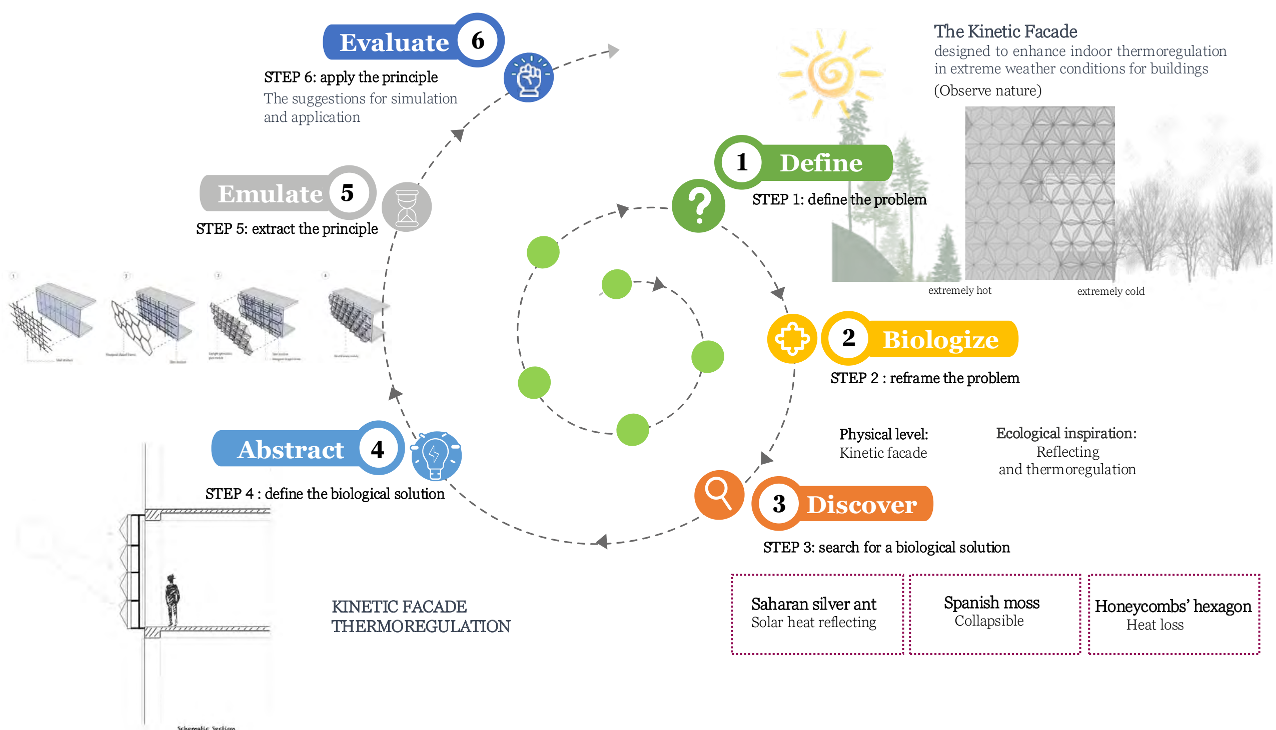
Figure 6. The Designed Module, Its Stages, and Its Operational Mechanism



Source: Own elaboration (2024)

This process initiates a meticulous delineation of the problem in its first phase. Moving on to the second stage, the functionality and context of the problem are analyzed using biological terminology, thereby being reframed within a novel framework. This prompts an inquiry into whether analogous solutions exist in nature to address the question of whether comparable solutions do. In the third step, an exploration into the biological solutions proffered by nature is undertaken, followed by the identification and definition of the biological solution in the fourth step. The fifth step involves determining which principles are to be transposed from the identified biological data. Lastly, in the sixth step, the solution to the problem is designed by applying the specified biological principles. Figure 7 illustrates the biomimetic cyclic process demonstrating the methodology of this study.

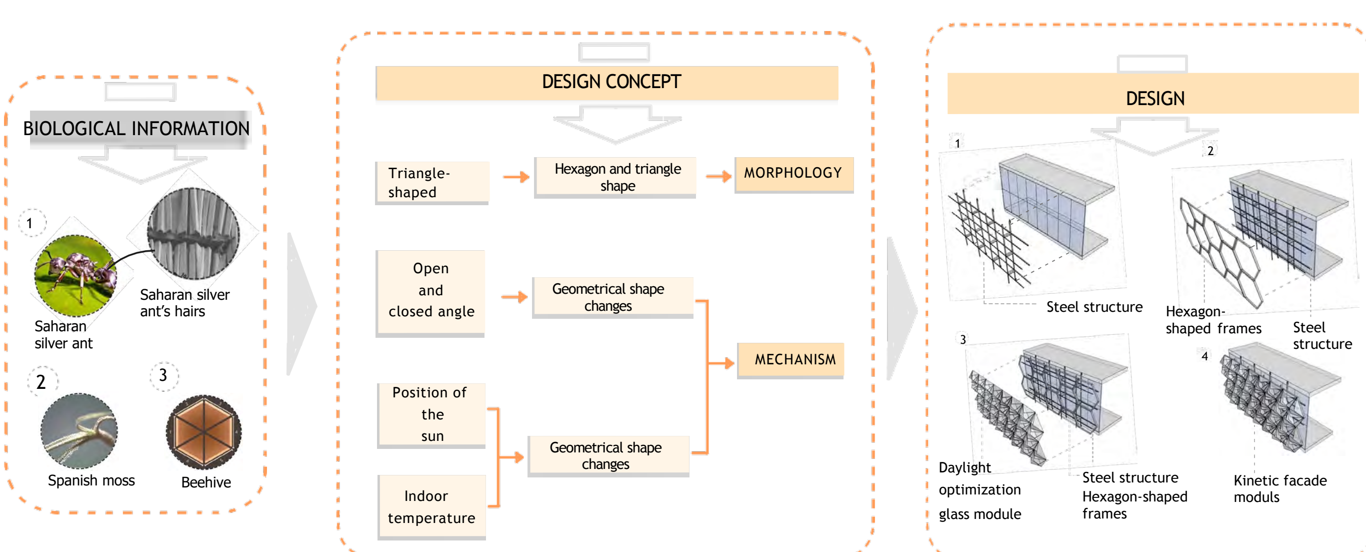
Figure 7. Biomimetic Design Spiral (The Biomimicry Institute) in Problem-to-Biology Transition: A Flowchart of the Implemented Design



Source: Own elaboration (2024)

In addressing the issue of excessive internal heating within the context of the article, a biomimetic approach has been employed as the solution. The research aimed to identify potential solutions to the heating problem by selecting organisms based on their inherent capabilities. The biological knowledge extracted from three prominent phenomena among the selected organisms was then translated into architectural information and adapted to a kinetic facade. Consequently, the architectural features derived from this biological information were integrated into operable modules for the building façade's glass surface. The intention was to facilitate internal thermoregulation within the structure. A graphical representation summarizing the entire process is depicted in Figure 8.

Figure 8. Design Process



Source: Own elaboration (2024)

DISCUSSION

This study evaluates a biomimetic kinetic facade approach to reduce energy consumption in buildings under high-temperature conditions. The micro-hair structure of the Saharan silver ant (*Cataglyphis bombycina*), which is associated with its capacity to reflect solar radiation, is considered a key design input and is translated into a module for the south facade of an office building in Ankara. The south orientation was preferred because sustained solar exposure throughout the day makes overheating risk easier to monitor on the south facade, enabling a clearer assessment of the module's thermoregulatory effect. However, such scenarios also require addressing additional design requirements, including waterproofing, wind loads, and maintenance access.

Biomimetic facade approaches in the literature vary according to their targeted performance goals. For instance, Sankaewthong et al. (2022) translate the DNA helix metaphor into a kinetic facade model for indoor daylight control, while Karanouha and Kerber (2015) reinterpret the opening and closing mashrabiya system of the Al-Bahr Towers, drawing on plant-based inspiration, to support solar-responsive shading and thermal balance. Similarly, Hosseini et al. (2021) integrate the transmission, dispersion, and reflection behavior of leaves into facade design; Elsakksa et al. (2022) adapt the self-shading behavior of *Oxalis oregana* as a facade logic; and Sommese et al. (2024) base their mechanism on plant bending and flexing responses to solar radiation. A common feature of these studies is that they manage solar exposure mainly through macro-scale geometry and kinematics. In contrast, El Ahmar and Fioravanti (2015) focus on heat and ventilation optimization by proposing a double-skin configuration inspired by termite mounds. Overall, the reviewed studies aim to reduce building energy consumption through nature-inspired facade strategies designed to control solar gains and cooling demand.

Building on this body of work, the present study differs by translating the Saharan silver ant's micro-scale optical and thermal principles into a controllable facade module, with the specific aim of reducing the risk of overheating on the south facade under Ankara's climatic conditions. Nevertheless, to demonstrate performance under real-use conditions, comprehensive simulations using a grasshopper-based ladybug and honeybee workflow (daylighting, solar irradiance, and energy loads) are required, and the results should be validated through field measurements. The broader applicability of the solution can be further tested by addressing practical constraints, such as integration into existing buildings, material selection, and cost. Accordingly, the module may be adapted to east and west facades by redefining the rotation axis and control thresholds to respond to low-angle solar exposure, and it may also be considered at the roof scale as a ventilated shading layer or a controlled skylight filter.

CONCLUSIONS

Biological strategies of organisms adapted to their environments have long inspired many fields, including architecture, and biomimetic studies offer the potential to reduce building energy demand while contributing to aesthetic quality. This study examines thermoregulation in animals adapted to extreme heat and translates the reflective principle of the Saharan silver ant's micro-hair structure into a kinetic facade module for an office building in Ankara. However, the impact of this reflectivity on cooling loads remains uncertain; therefore, climate-based simulations, prototyping, and validation through field measurements, together with material, daylighting, and cost analyses, are required. In this context, weather-responsive systems developed in Stuttgart and Freiburg that open and close autonomously without requiring operational energy input serve as an important reference. Future work may focus on scaling and deploying self-actuated, energy-saving adaptive facade solutions through university–industry collaboration.

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The authors of this work have made the following contributions: Öznur KARAKUŞ contributed to the design of the study, the organization, and the writing of the article; Güneş MUTLU AVINÇ contributed to the design of the study, the organization, and the writing of the article; Semra Arslan Selçuk contributed to the design of the study, the organization, and the writing of the article.

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