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ENHANCING ENERGY EFFICIENCY IN GLASS FACADES THROUGH BIOMIMETIC DESIGN STRATEGIES

MEJORA DE LA EFICIENCIA ENERGÉTICA EN FACHADAS DE VIDRIO MEDIANTE ESTRATEGIAS DE DISEÑO BIOMIMÉTICO

MELHORANDO A EFICIÊNCIA ENERGÉTICA EM FACHADAS DE VIDRO POR MEIO DE ESTRATÉGIAS DE DESIGN BIOMIMÉTICO

Büşra Öztürk
Master in Architecture
Research Assistant, Department of Architecture
Selcuk University, Konya, Turkey
https://orcid.org/0000-0001-8177-0653
busra.ozturk@selcuk.edu.tr (Correspondence Author)

Güneş Mutlu-Avinç
Doctor in Architecture
Assistant Professor
Muş Alparslan University, Muş, Turkey
https://orcid.org/0000-0003-1049-2689
gunesavinc@gmail.com

Semra Arslan-Selçuk
Doctor in Architecture
Associate professor and researcher, Department of Architecture
Gazi University, Ankara, Turkey
https://orcid.org/0000-0002-2128-2858
semraselcuk@gazi.edu.tr

RESUMEN

La industria de la construcción, responsable de una gran proporción del consumo de energía, está buscando soluciones para reducir el consumo de energía. Este estudio propone fachadas biomiméticas para garantizar el confort térmico. En primer lugar, examinó los sistemas de fachadas biomiméticas en la literatura. Luego, analizó los métodos de termorregulación de la naturaleza, el nivel de biomimética y las estrategias desarrolladas por los seres vivos. Como resultado de los análisis, se amplió la información biológica relativa a los tres fenómenos seleccionados y se determinó cómo transferir el método de biomimética que podría estar en la envolvente del edificio. Se realizaron simulaciones de energía en la fachada de vidrio del baño Süleyman Pasha para evaluar la eficiencia energética de la envoltura. Se encontró que los métodos inspirados en la naturaleza contribuyeron significativamente al consumo de energía del edificio cuando se diseñaron los resultados de simulación de la fachada.

Palabras clave
biomímesis, diseño de fachadas, eficiencia energética, termorregulación.

ABSTRACT

The building industry, responsible for a large proportion of energy consumption, is looking for solutions to reduce energy consumption. This study proposes biomimetic facades to ensure thermal comfort. Firstly, it examined biomimetic façade systems in the literature. Then, it analyzed the thermoregulation methods of nature, the level of biomimicry, and the strategies used by living things. As a result of the analyses, biological information regarding the three selected phenomena was expanded upon, determining how to transfer the biomimicry method to a building envelope. Energy simulations were conducted on the glass façade of the Süleyman Pasha Bath to evaluate the envelope's energy efficiency. It was found that nature-inspired methods significantly contributed to the building's energy consumption when examining the simulation results of the façade designed.

Keywords
biomimicry, facade design, energy efficiency, thermoregulation.

RESUMO

A indústria da construção, responsável por grande parte do consumo de energia, procura soluções para reduzir o consumo de energia. Este estudo propõe fachadas biomiméticas para garantir conforto térmico. Primeiramente, examinou sistemas de fachadas biomiméticos na literatura. Em seguida, analisou os métodos de termorregulação da natureza, o nível de biomimética e as estratégias desenvolvidas pelos seres vivos. Como resultado das análises, a informação biológica sobre os três fenômenos selecionados foi ampliada e determinada como transferir o método de biomimética que poderia ser para a envolvente do edifício. Simulações energéticas foram realizadas na fachada de vidro do Süleyman Pasha Bath para avaliar a eficiência energética do envelope. Verificou-se que os métodos inspirados na natureza contribuíram significativamente para o consumo de energia do edifício quando os resultados da simulação da fachada projetada.

Palavras-chave:
biomimética, design de fachadas, eficiência energética, termorregulação.

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INTRODUCTION

Increasing global energy consumption and changing climate conditions have recently been on the agenda of many sectors, particularly the building sector. According to the International Energy Agency (IEA), the building sector accounts for one-third of total energy consumption (International Energy Agency, 2019), and most of the energy consumed in construction comes from heating, cooling, and ventilation (HVAC) systems (Engin, 2012). In particular, where large, glazed areas are used on facades, the cooling load increases during the day, and the heating load increases at night. This situation leads to high levels of energy consumption. For this reason, the construction sector is focusing on methods that use renewable energy sources to reduce energy consumption and harmful gas emissions and draw attention to energy-efficient building design. Along this line, energy-efficient building design aims to provide natural ventilation by directing daylight and reducing the required heating and cooling load (Pacheco ve diğ., 2012). Under this, thermal comfort in buildings is provided by increasing the efficiency obtained from natural resources such as heat, light, rain, and wind with passive energy-efficient methods and creating a climate-sensitive design (Kim ve Torres, 2021).

It can be said that nature also has much to offer in terms of developing energy-efficient proposals such as thermal regulation and climate-sensitive design to increase the efficiency of natural resources such as heat, light, rain, and wind. In this context, the thermal regulation methods used by living creatures in nature to ensure energy efficiency are being analyzed and applied to architecture. In nature, thermal regulation is referred to as thermoregulation, which protects an organism's body temperature from changing external factors and ensures it remains within an appropriate range (Farchi Nachman, 2009). In this context, biomimetic designs/materials are being developed by examining examples of thermoregulation, learning from nature, and benefiting by developing technology. By examining the physiology, morphology, and behavior of living creatures in nature, many methods have been developed, and solutions can be found to problems encountered in structures.

The fact that nature responds to the problems it encounters by finding the most appropriate solutions has led human beings to study nature throughout history. Practical solutions are offered to many daily life problems by learning from nature. This method, called bio-informed design/biomimicry/biomimetics/biodesign, focuses on assimilating the role of nature and producing functional solutions with the information obtained. This approach is on its way to becoming a branch of science that supports the process of learning from, adapting to, and applying the qualities of living or non-living organisms. Although this method is defined as 'emulating strategies' (Zari, 2007), it is developing as a field that produces innovative designs that contain solutions for humanity's problems by turning to biological solutions (Mutlu Avinç & Arslan Selçuk, 2019).

Facades are important energy-regulating components directly exposed to external factors and in contact with renewable energy sources (Tabadkani et al., 2021). For this reason, the literature has recently widely discussed energy-efficient building design proposals that can thermoregulate façade design with biomimetic approaches. For example, Badarnah et al. (2010) designed the stoma brick as a façade material by considering it as a thermal barrier to protect the heat of the façade and distribute it appropriately. This design proposes a building envelope with a cooling system for arid and hot climate regions. Kim et al. (2023) designed a kinetic façade using daylight-sensitive and innovative materials (shape memory alloys and actuators) in a pneumatic system. The biomimetic façade design, inspired by a hexagonal honeycomb module and a plant stoma feature, was analyzed by testing the simulation results and a prototype.

On the other hand, the façade study developed by Kalatha (2016) presents proposals for improving indoor comfort and ventilation. Sensitive panels that can change shape according to the temperature and physical factors have been proposed in the façade design, which is based on a working principle of stomata. In the study by Aly et al. (2021), a prototype façade was developed using water retention capacity with the capillary effect found in the skins of thorny devil lizards living in the desert climate. In a study by Lopez et al. (2017), a biomimetic approach is proposed for glass facades with high energy losses by considering the relationship between architecture and biology. By creating a dataset of plant adaptations, a methodology is proposed that reflects the adaptation of biological principles to architectural resources and new technologies. In their study, Sheikh and Asghar (2019) present a biomimetic adaptive facade design to improve the energy efficiency of high-rise glass facades in regions with hot and humid climates, reducing the energy load by 32%. In a study by Paar and Petutschnigg (2016), the issue of façade greening was addressed by considering the modular growth of prairie dog burrows and mussel colonies. To provide a solution to the urban heat island effect, the increased energy consumption due to global warming, and the increasing heating of cities, a façade design concept with natural ventilation and cooling functions has been developed based on biomimetic principles.

Another study by Faragalla and Asadi (2022) presents a methodology that includes different typologies, methods, and conceptual frameworks for adaptive facade design, focusing on biomimetic principles. This research highlights the importance of energy efficiency in the early stages of design. Meanwhile, Kuru et al. (2019) touched on the importance of biomimetic adaptive building envelopes for energy efficiency, and through characterization and strategies, they examined current technologies through a comparative analysis. In their study, Sommese et al. (2022) investigated sensitive and intelligent building envelopes. This study aims to draw attention to the potential of nature's vast database by critically examining current technology in terms of energy efficiency.

This study addressed in this article was based on the hypothesis that "a biomimetic solution to the problem of

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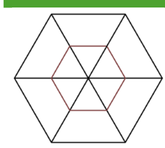
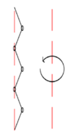
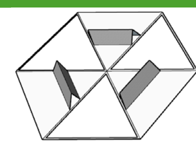
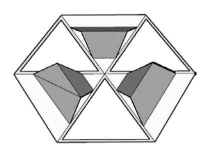
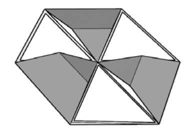
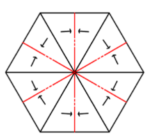
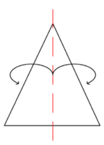
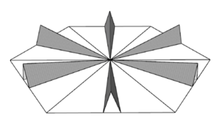
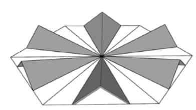
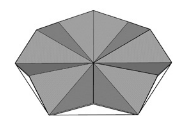
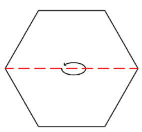
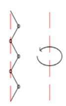
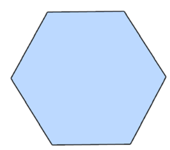
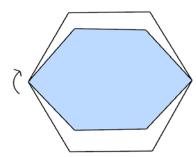
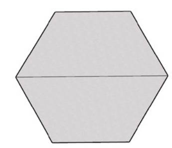
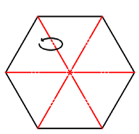
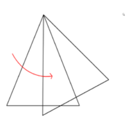
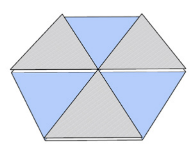
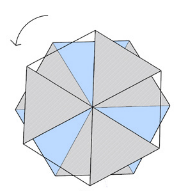
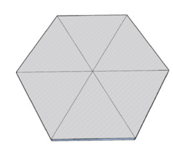
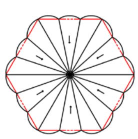
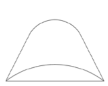
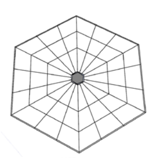
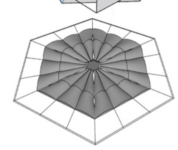
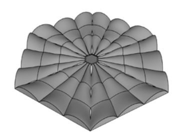
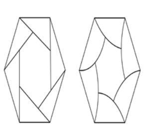
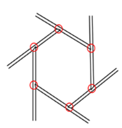
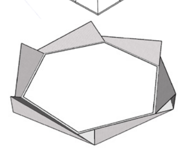
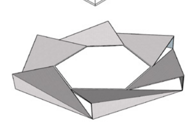
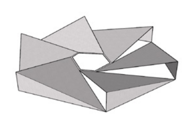
Table 1. Facade Module System Mechanisms - Alternatives. Source: Prepared by the authors

Module Form	Movement Axis	Movement Direction and Type	System Status - On	System Status - Half Open	System Status - Off	Structure Reference Sample
		Opening to the sides Folding system				CJ Blossom Park
		Folding along the axis Folding system				Kiefer Technic Showroom / Al-Bahr Towers
		Rotation around center Rotation				ThyssenKrupp Quartier Essen Q1
		Rotation around center Rotation				RMIT Design Hub
		Gathering Toward the Center Pneumatic System				Media-TIC Building
		Shift along axis Sliding System				Institut du Monde Arabe

indoor thermal comfort and excessive energy consumption caused by the use of glass facades can be proposed by plants and animals found in nature, and improvements in energy consumption can be achieved." For this purpose, the study looked at natural thermoregulation principles and strategies to prevent overheating (during the day) and overcooling (at night). Living things were reviewed using the keywords "reflection, heat prevention, absorb radiation, reduce irradiation, overheating, heat regulation" in the AskNature database, and principles have been derived by studying these living things' thermoregulatory methods and working mechanisms. Based on these principles, solutions have been sought to prevent overheating and overcooling caused by temperature changes in glass façade systems. For this purpose, five plants and five animals with thermoregulation methods for heat distribution and gain were discussed, and a double-façade glass system has been designed to be sustainable and energy-efficient, taking inspiration from living things. The study was analyzed using an energy simulation program, an innovative module in the glass facade system designed by learning from nature.

FACADE MODULE SYSTEM MECHANISMS - ALTERNATIVES

In today's evolving technological conditions, essential advances have been made in materials and techniques. Thanks to these developments, kinetic façade designs, which adapt to the façade and change according to the environmental conditions, are coming to the fore. Before deciding on the system design, this study studied the kinetic façade module using techniques developed on the regular hexagonal façade module, one of the Voronoi diagrams. Alternatives for daylight-sensitive opening and closing mechanisms were determined using the hexagonal façade module. In deciding these alternatives, kinetic façade designs in the literature and buildings with adaptive envelopes were examined. It can be seen that specific techniques such as sliding, folding, rotating, and pneumatic operation are widely used as opening and closing mechanisms in façade modules. These techniques model and express the fully closed, semi-open, and fully open states of façade modules designed for different systems. The kinetic façade, designed

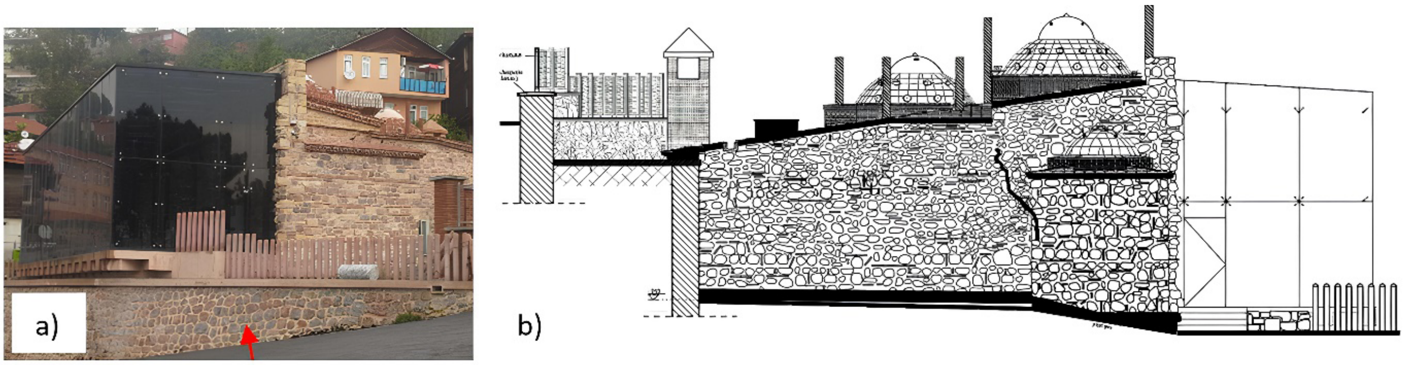


Figure 1. a) Süleyman Pasha Bath sections after repair b) Suleyman Pasha Bath Northwest Facade. Source: Güner Design - Architect Gülhan Dilaver.

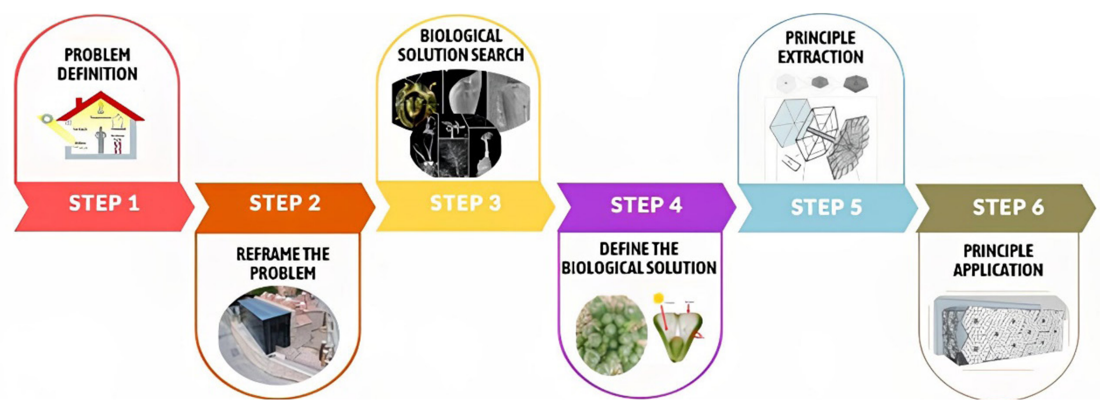


Figure 2. Problem-oriented approach used in biomimetic research. Source: Helms, Vattam, & Goel, 2009, edited by the Author.

according to biomimetic principles and using technically advanced materials, is expected to solve overheating and cooling problems by controlling daylight access to the interior (Table 1).

MATERIALS AND METHODS

The Suleyman Pasha Bath in the Akçaova district of Izmit, the case study, was built during the Ottoman period. The Suleyman Pasha Bath is the earliest surviving Ottoman structure in Izmit. Although part of the structure has been demolished recently, most of the baths have survived to the present day. The right to evaluate and use the bath for socio-cultural purposes has been transferred to the General Directorate of Foundations with the agreement of Kocaeli Metropolitan Municipality. Work has been carried out to ensure that the ruined bath, which was left unrestored for many years, regains its function and is used again (Polat et al., 2010). Built in the early Ottoman period, the bath has a traditional double bath designed separately for men and women. As an architectural feature, the bath comprises changing rooms, warm rooms, and hot rooms. However, since the changing room was demolished, this has been rebuilt and converted into a cafe (Kocaeli Cultural Envanteri, 2011) (Figure 1).

The glass façade of the cafe area at the Suleyman Pasha Bath, which has been given a contemporary addition as part of the restoration project, was evaluated as part of this study. The cafe is located on the south side and experiences overheating in summer and overcooling issues in winter, requiring high energy consumption to ensure indoor comfort. It has an essential problem that HVAC systems cause excessive energy consumption to provide the necessary comfort conditions for the space. This study proposes a biomimetic glass façade system that will reduce energy consumption while increasing indoor comfort conditions and can be applied as a secondary skin to the existing façade.

Within the scope of this study, biomimetic solutions were investigated to increase the comfort level of the café area's glass façade for the Süleyman Pasha Bath and reduce the energy consumed. As all living organisms can control energy losses and gains by thermoregulating their systems, a solution to the identified problem was sought using methods learned from nature. In this process, the problem-oriented approach method, one of the biomimicry approaches, was used. First, the process of identifying the problem was completed. Then, solutions to the identified problem were sought from nature, certain principles were derived, and a solution was proposed. In addition, the façade designed in the study was analyzed in an energy simulation program (Design Builder) to see the changes in heating and cooling load according to the material qualities. Finally, a solution was proposed for the problem, which was an architectural façade solution for

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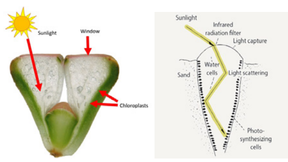
Table 2. Examination of the biomimetic solutions used in the design. Source: Prepared by the authors.

Reference	 Cactus Kingdom (n.d.)	 Asknature (n.d.)	 (Çağlar, 2020)
Method	Heat Prevention Heat Preservation Behavioral Adaptation	Heat Gain Heat Preservation Physical Adaptation	Heat gain Morphological Adaptation

the contemporary extension of the historical bath in Kocaeli (Figure 2).

CASE STUDY: BIOMIMETIC GLASS FACADE SYSTEM DESIGN

Thermoregulation methods for living things have been studied to address the overheating and overcooling problems in glass façade systems. Living things use three approaches to achieve thermoregulation: heat conservation, heat gain, and heat prevention. This study searched the AskNature database for keywords related to plants and animals. As a result of the research, creatures with a method for preventing overheating and heat gains were examined. Living beings in arid and desert climates have developed different strategies to avoid overheating. These strategies are generally seen in plants as adaptations that regulate heat loss by opening and closing stomata or morphological characteristics. On the other hand, in animals, thermoregulation has been observed by regulating color changes and surface area ratios according to skin characteristics. In the second part of the study, the thermoregulatory strategies of plants and animals were analyzed. Plants such as *Fenestraria aurantiaca,* English ivy, giant ground grass, alpine edelweiss, and the kukumakranka plant were found, as were animals such as turtle beetle, chameleon, morpho butterfly, bumblebee, and the hissing cockroach.

In the search for a biomimetic solution to the study's problem, adaptations for both heat gain and heat prevention were discussed. While a heat prevention function is required in glass façade systems in buildings during the day, a heat gain function is needed when the temperature drops at night. The aim is to design a double skin façade that reflects much of the daylight during the day and acts as an insulating layer at night. Fenestraria and giant marmot plants were considered as solutions among ten creatures whose thermoregulation methods were studied. The Fenestraria plant is thought to be a solution to the problem of excessive sunlight that the building is exposed to during the day, as it captures and cuts excess light in the desert climate and acts as a lens. It has also been suggested that the giant grass protects its inner leaves by closing when the temperature drops in the high parts of the mountains, acting as an insulating layer. The fact that this plant opens and closes depending on the temperature has led to a façade design that will act as insulation by closing a building's heat-sensitive facades. In addition, the modules to be designed are inspired by the Voronoi pattern seen on the shell and skin surfaces of creatures found morphologically in the mathematics of nature. Kahramanoğlu and Alp (2021), as a result of the daylight analysis of the façade systems designed in alternative shapes, showed in their study that when the Voronoi diagram is used, the light incidence on the façade is higher and can be controlled at the desired level by adjusting the thickness of the lines. For this reason, it was decided to use regular hexagons from the Voronoi diagrams in the glass façade module to be designed in the study (Table 2).

The design process examined mechanisms studied in nature and their methods applied to the façade. The method of directing and controlling excess light from the Fenestraria plant used in the façade design was used to solve the overheating problem in the façade module. In addition, the ability of the giant ground grass plant to close itself when the temperature drops and protect its system from the effects of frost was considered in the design. According to the principles learned from these two projects, it was decided to use electrochromic glass to direct excess daylight. In addition, the pneumatic system, made of ETFE material, which closes at low temperatures at night, is integrated as a double façade. Among the alternative façade modules shown in Table 1, a pneumatic system was designed with an actuator that closes at night at low temperatures and collects heat during the day (Figure 3).

As part of the study, a façade system that behaves like fenestraria and giant ground grasses was designed, adopting thermoregulatory principles. This system design aims to reduce the heating and cooling loads caused by glass façade systems. The pneumatic system, which is closed during the day, is activated at night and acts as a second façade covering the façade surface, protecting it from excessive cooling. In addition, the electrochromic glass used on the façade during the day will ensure that light above a specific wavelength is reflected, preventing overheating. The biomimetically designed double skin façade system was applied to the glass façade system in the contemporary annex ('cafe space') of the historic Suleyman Pasha Bath, and the energy simulation analyses were carried out (Figure 4). In the energy simulation calculations, the façade system information, consisting of

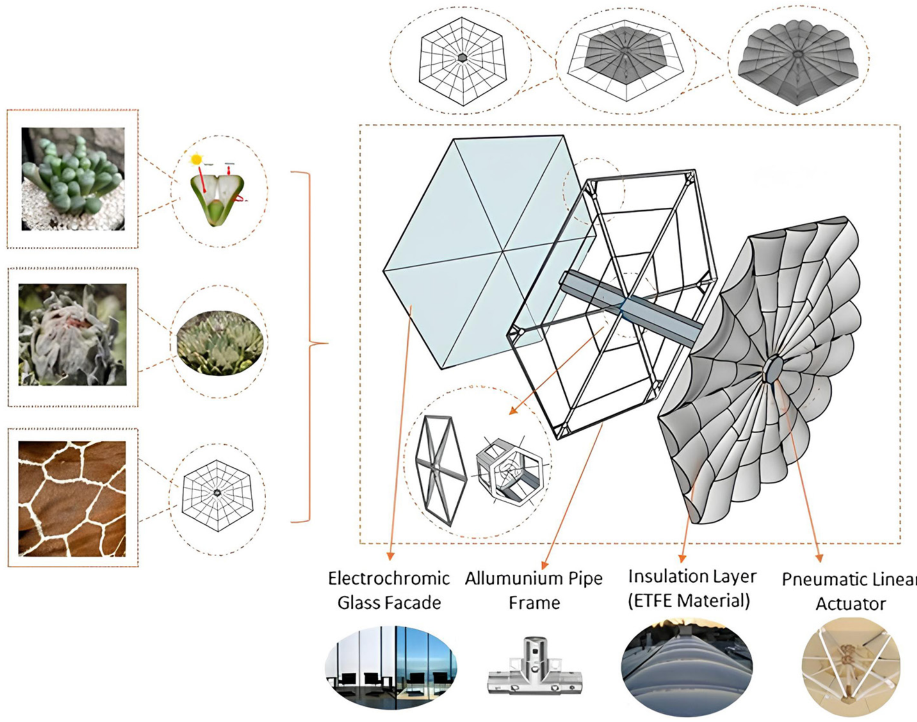


Figure 3. The double-skinned facade module was designed using a biomimetic approach. Source: Prepared by the authors.

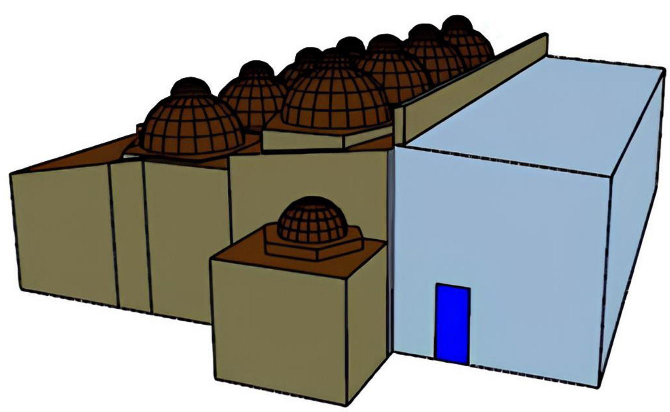


Figure 4. The Süleyman Pasha Bath model created in the Design-Builder program Source: Öztürk, 2023.

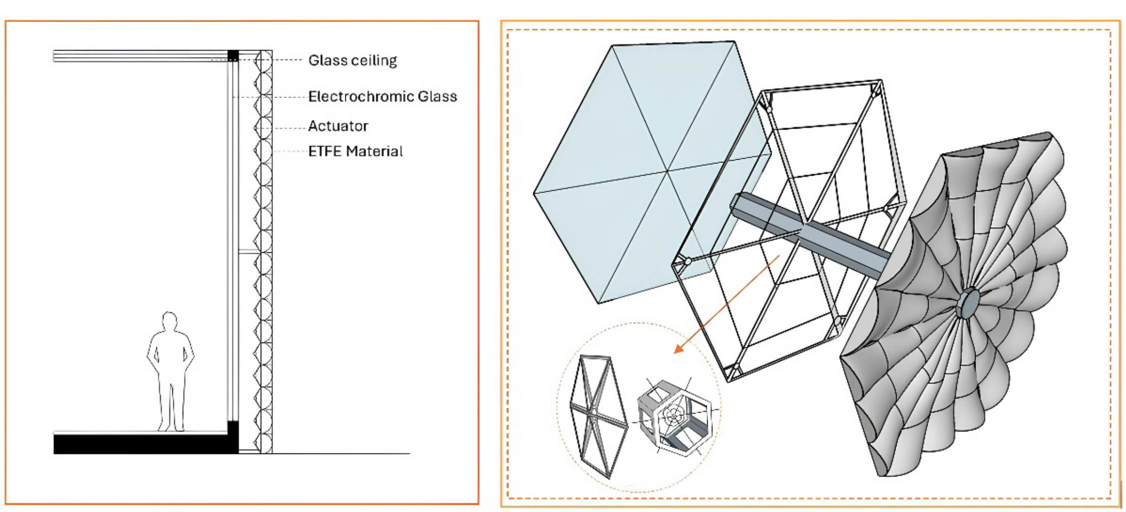


Figure 5. Application of the glass façade system to the Suleyman Pasha Bath Cafe space. Source: Prepared by the authors.

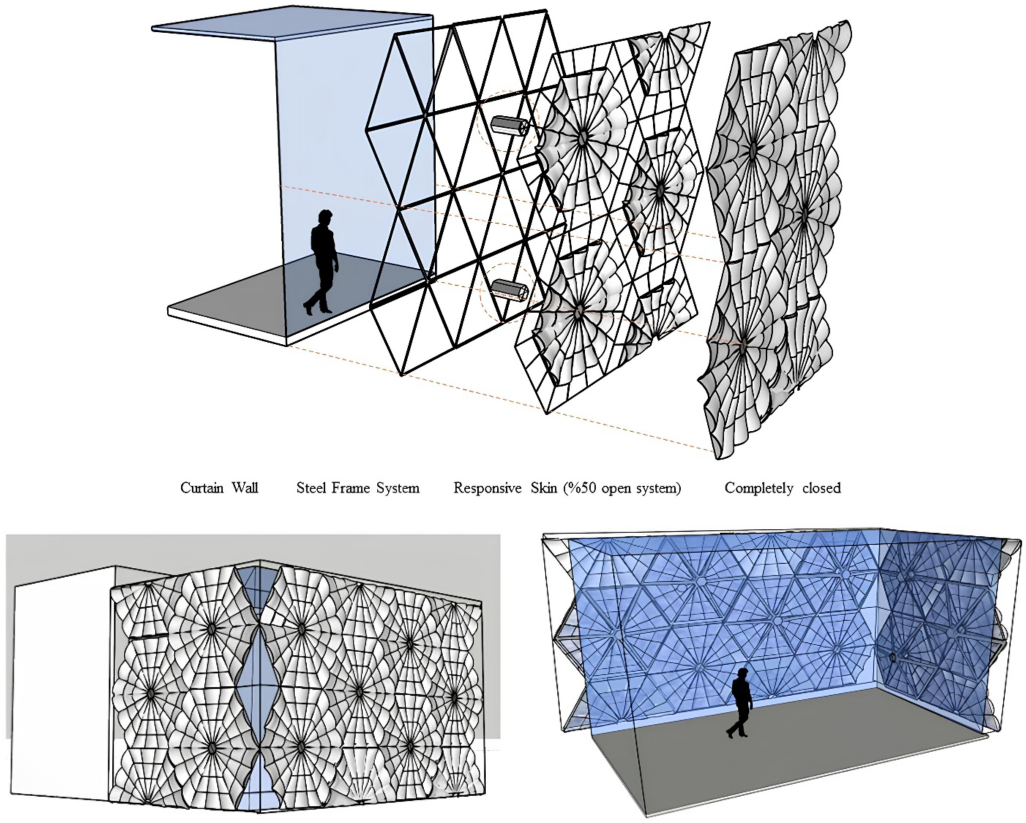


Figure 6. Application of the glass façade system to the cafe area of Süleyman Pasha Bath. Source: Prepared by the authors.

three different scenarios, was input into the program, and its effect on the heating and cooling load results was evaluated. The first scenario was calculated using the existing material properties of the building (Öztürk, 2023). The simulation results were obtained by incorporating the single-layer electrochromic glass system into the second and double-layer electrochromic glass façade material information in the third scenario (Figure 5 and Figure 6). The material properties of the electrochromic glass façade system were obtained from the Lee and Tavil (2007) study on electrochromic glass material performance and defined in the Design-Builder program. The total energy consumption values of the bath building were compared using the material properties determined and achieved in the Design-Builder program and by inputting the climate data of Kocaeli (Table 1 and Table 2).

The thermal properties of the materials used in the existing Suleyman Pasha Bath glass façade system and the thermal values of the proposed alternative single and double-story electrochromic glass façade system are shown in Table 3 below. Three different results were obtained by entering the climate data of Kocaeli province using three different materials in the Design-Builder program. Case 1 of these three scenarios is the heating, cooling, and total energy load analysis obtained by defining the existing material properties of the bath structure. In Case 2, the thermal properties of the single-layer electrochromic glass material in the glass material of the Cafe space of the building were defined in the program, and energy analyses were carried out. In Case 3, the simulation was run by defining the properties of the double-layered and reflective coated electrochromic glass material for the glass façade system. The electrochromic glass material types and thermal properties recommended in the study were taken from the study by Lee and Tavil (2007). They were defined in the program by adding the building's material properties and climate data (Table 3).

DISCUSSION

Increasing energy demand due to the construction sector and the energy of the systems used for occupant comfort significantly increase energy consumption. For this reason, attempts to reduce building energy consumption and ensure thermal comfort indoors are increasing. This study discusses the problem of overheating and cooling in glass façades.

The double-skin glass façade system proposed in the study was designed with a temperature-sensitive pneumatic system. The electrochromic glass was recommended to reduce the adverse effects of excessive light on the interior during the day. Simulation analyses were carried out on two types of electrochromic glass used in the design: single-layer and double-layer. It is expected that the designed biomimetic glass façade system will provide a solution to the daytime overheating problem of the café area of the Süleyman Pasha Bath. It is also expected that the pneumatic system, which forms the second layer of the façade system, will close at night and act as insulation for the glazing material, preventing

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Table 3. Thermal properties of glass facade systems and values defined in the program. Source: Prepared by the authors.

Buildings	Materials	Thickness (cm)	Thermal Conductivity λ (W/mK)	U value (W/m2K)
Cafe Space Wall analysis of the building (CASE 1) (Öztürk, 2023)	Tempered silver gray	0,8 cm	0,052	U: 1,70
	Air gap	0,05 cm	R: 0,11	
	Tempered laminated glass	0,8 cm	0,052	
Alternative Glazing System Wall Analysis (CASE 2)	Electrochromic Glass	1 cm	0,010	U: 1,07
	Single Layer Clear Glass	Solar Heat Gain Coefficient (SHGC): 0,69 Glass Transmittance (VT): 0,71 (Lee and Tavil, 2007)		
Recommended Glazing System Wall Analysis (CASE 3)	Electrochromic Glass Double Layer Reflective coating	2 cm	0,011 SHGC: 0,17 VT: 0,10 (Lee and Tavil, 2007)	U: 0,57

Table 4. Total heating and cooling load values according to energy simulation results

	CASE 1	CASE 2	CASE 3
Heating Load (kWh)	23,357.71	19,549.33	15,876.61
Cooling load (kWh)	13,849.10	12,347.49	9,476.18

excessive cooling in the interior. To see the effect of the facade system designed for this purpose on the total annual heating and cooling load of the bath structure, it was modeled in the Design-Builder program, and the material definitions and equipment used for space heating were processed in the program. The annual energy loads were obtained by creating three scenarios through the model. According to simulation results, the highest heating and cooling load is achieved in Case 1. In case 2, significant improvements were observed in both heating and cooling loads using single-layer electrochromic glass material. The total annual energy load of the space decreased by 16% compared to Case 1. When the simulation results are examined, a decrease in the total energy consumption of the building of approximately 32% is observed between Case 1 and Case 3 (Table 4).

CONCLUSION AND RECOMMENDATIONS

To reduce energy consumption in the building sector on a global scale, it is essential to focus on energy-efficient designs and to carry out interdisciplinary studies in this direction. Façade design studies, particularly those inspired by natural systems, have reached a critical point in the building envelope's energy efficiency. As the building envelope acts as a buffer between interior and exterior spaces, significant energy gains can be achieved by learning from nature and designing systems that respond sensitively to daylight. In this study, the hypothesis that biomimetic solutions could solve the problem of heating and cooling loads in glass façade systems in buildings has been confirmed as a result of investigations and simulation analyses. This study investigated plants and animals from nature to address the overheating and overcooling problems in glass façade systems in locations with high-temperature differences. An architectural façade solution was proposed based on the thermoregulatory principle of the two plants selected as the solution for the façade system. Studies have been carried out on designing the façade using plants that respond to excessive heating and cooling. The proposed façade system will be able to reflect excess light during high daytime temperatures. It will also reduce the cooling load demand by reducing the use of air conditioning in the interior. In addition, the system will switch off at night and act as an insulating layer on the façade during harsh weather conditions when the temperature drops. While electrochromic glass material is recommended to solve overheating in the double facade system, the pneumatic system design using ETFE material, which is activated at low temperatures, will form the insulating layer.

As part of the study, simulation analysis was carried out to test the designed façade system and to see the energy consumption rate. The designed façade was analyzed on a building located in the Kocaeli province, which gained a cafe space (contemporary addition) in the glass façade system on the south façade after restoration. Since the contemporary addition to the building is located on the south side, the indoor comfort in summer is negatively affected, resulting in overheating. When the simulation results were examined in three different situations based on the properties of the glass material, a 32% improvement in the total energy load was observed using a double-layer electrochromic glass façade. The search for solutions to architectural problems by analyzing nature leads, at this point, to the study of innovative biomimetic material designs. In this way, sustainable and energy-efficient solutions can be offered with an interdisciplinary approach.

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