Review Article: Applications of Biomimetic Adaptive Façades for Enhancing Building Energy Efficiency

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Received: 3 Aug 2022; Revised from: 9 Dec 2022; Accepted: 19 Dec 2022
Print-ISSN: 2228-9135, Electronic-ISSN: 2258-9194, https://doi.org.10.56261/built.v20.247184

Abstract

The façade is the main component related to the design, occupation and performance of buildings. In the past, traditional facades were always constructed as load-bearing structural elements without flexibility, which made it impossible to deal with the changing environment, resulting in the consumption of large amounts of energy to maintain the internal comfort conditions. Biomimetic adaptive strategies have been proposed as an optimal solution for improving building façade performance. This paper aims to present biomimetic strategies that are translated into design solutions for dynamic façades at the early stage of design, resulting in adaptive, flexible and more efficient façade design. Then, the comparative analysis of several case studies are illustrated to show the high potential of biomimetic adaptive facades in reducing total energy consumption of building which is a promising new approach to energy-efficient and sustainable building solutions.

Keywords: Adaptive facade, Building envelope, Biomimetic, Energy efficiency, Flexible, Performance and Sustainable

1. Introduction

For centuries, architects and designers have taken nature as a source of inspiration in order to find solutions to solve design problems, called the 'biomimetic approach'. The word *biomimetic* (or biomimicry) derives from the Greek word: *biomimesis*, life-imitating. This term was coined by (Bhushan. 2009 quoted in Otto Schmitt. 1957) in his doctoral research and first appeared in Webster's dictionary in 1974 (Bhushan, 2009). In architecture, the main objective of *biomimetics* is to learn from and imitate the biological structures, processes and systems found in nature to deal with architectural problems. There are two distinct approaches in biomimetic processes: problem-based or top-down (moving from design to nature), which is the most commonly used by designers, and solution-based or bottom-up (moving from nature to design), which requires technicians with a background in biological knowledge. Due to the complexity and multidisciplinary nature of biomimetic design approaches, the principles of the biomimetic method were developed as shown in Figure 1.

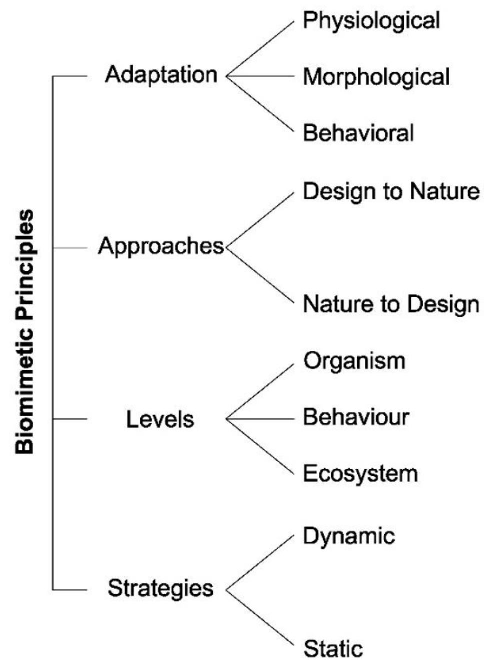
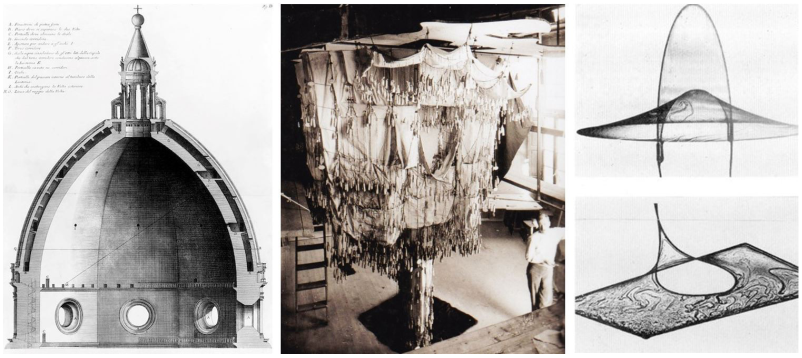


Figure 1. Biomimetic principles (Hafizi & Karimnezhad, 2022)

Over the 3.8 million years of evolution, all living creatures have learned to survive and adapted to the changing environment by using two major principles, high efficiency based on minimum energy consumption and recycling waste (Arbabzadeh et al., 2017). Therefore, imitating nature's strategies enables creatures to minimize the operational energy they use and enhance their sustainability. Several researches reveal that buildings worldwide are responsible for 36% of global energy consumption, mainly through heating and cooling building interiors, and 39% of global energy-related carbon dioxide emissions (Nalcaci et al., 2020). The building envelope is the most vital part affecting the energy consumption of a building (Schittich, 2006) due to its large surface area. Hence, to achieve energy-efficient solutions, the building's façade must achieve not only aesthetic attraction but also response to the changing environmental conditions. Biomimetic approaches by studying natural adaptation strategies should be applied to the building's façade design.

2. Biomimetic approaches for energy efficiency in architecture

Biomimetic approaches have been applied to architecture for a long time. In 1436, Fillippo Brunelleschi designed the dome of Florence Cathedral (Figure 2a) by using eggshells as a prototype (Hersey, 1999). Antoni Gaudi, a Spanish architect who was the leading representative of Catalan Art Nouveau, used the ideas of forces in nature to solve his design problems by carrying out experiments with suspended cables. The inverted forms of these cables are known as *catenary curves* (Figure 2b), which he used as his arch forms instead of using round arches with a circular shape (Huerta, 2006). Later architects and engineers in the 20th century, such as Frei Otto and Heinz Isler, conducted research from which many distinct methods using principles of form-finding developed (Figure 2c).



(a) (b) (c)

Figure 2. (a) Double-shell dome designed by Fillippo Brunelleschi (Mount, 2018),
(b) Suspended cables model by Antoni Gaudi (Burry, 2007),
(c) Form-finding experiments using soap film model (Otto et al., 2006).

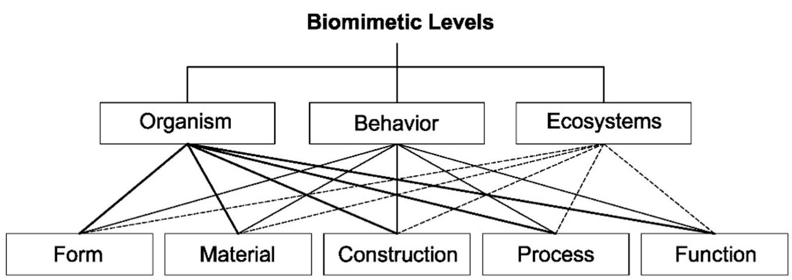
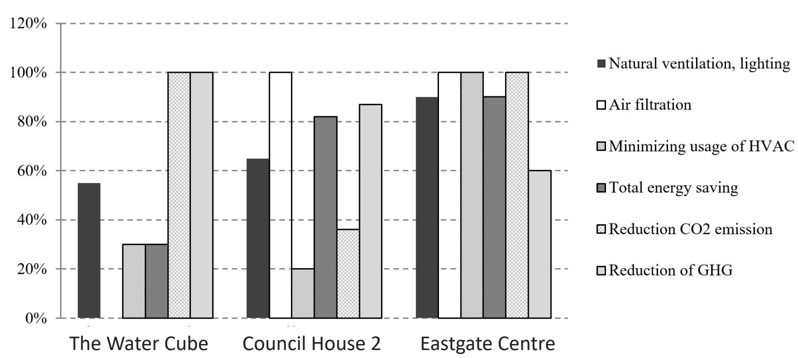


Figure 3. Biomimetic levels and dimensions (El-Rahman et al., 2020)



Building case study	The Water Cube	Council House 2	Eastgate Centre
Level of biomimetics	Organism	Organism & Behavior	Behavior
Natural ventilation, lighting	55%	65%	90%
Air filtration	0%	100%	100%
Minimizing usage of HVAC	30%	20%	100%
Total energy saving	30%	82%	90%
Reduction of CO2 emission	100%	36%	100%
Reduction of GHG	100%	87%	60%

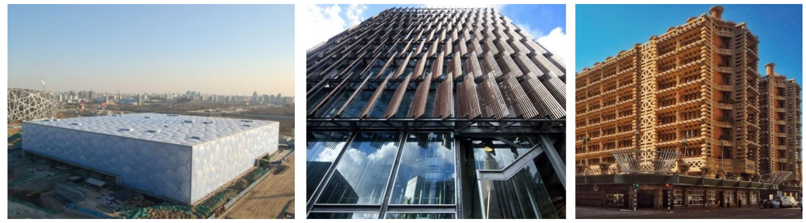
Figure 4. Comparison of total energy reduction in biomimetic building case studies (Mohamed, 2018).

Architecture incorporating biomimetic applications can be categorized into three levels: organism, behavior and ecosystem (Zari, 2007). Within each level, there are five different dimensions to imitate within design: form, material, construction, process and function (Figure 3).

Nowadays, biomimetics is considered one of the most important tools for enhancing energy-efficiency in architectural design. In the analytical study by Mohamed (Mohamed, 2018), three buildings from different continents were analysed in terms of their usage of biomimetic applications and the impact on energy reduction through the building skin. The results clearly showed that a biomimetic building skin contributes significantly to the total energy reduction in buildings (Figure 4).

As can been seen from Figure 4, The Water Cube in Beijing (Figure 5a), designed by imitating the form of soap bubble, can reduce the use of artificial lighting by 55% and provides a total energy saving of 30%. Council House 2 in Melbourne (Figure 5b) was inspired by the organism and behavior of tree bark. All the louvers on the building are made from recycled timber, and automatically pivot according to the sun's path. The adaptive shading of this façade provides a total energy saving of up to 82% and reduces the use of artificial lighting by 65%. The greatest energy saving is shown in the case of the Eastgate Centre in Zimbabwe (Figure 5c). The design is inspired by the ventilation of termite mounds, which circulate hot and cold air between the interior of the mound and the outside environment. This technique allows the Eastgate Centre to avoid the use of air conditioning and it consequently consumes 90% less energy than a building of the same size in the same regional conditions.

Since 2000, research on the application of biomimetics in the field of architectural design has been widely conducted. The fields of interest reflected in these research papers can be categorized into four topics: material, structure, system and biophilia. Examples of each subject can be addressed as follows: *Material* – bio-inspired building materials such as the use of mycelium[1] as the load-bearing structure in the design of MycoTree (Heisel et al., 2017); *Structure* – bio-inspired building structures such as cable-net structures which are drawn from the geometry of the spider's web in nature; *System* – an ecosystem level of biomimetics such as the Sahara Forest Project, a greenhouse which creates a new solution to produce food, water and energy in desert areas based on solar energy to obtain a zero waste system; and *Biophilia* – the theory that involves a process that offers a sustainable design strategy that incorporates people within the natural environment (Kellert, 2008). The trend of research on topics concerning *Structure* has been the most frequently investigated, followed by *Biophilia*, while the *Material* and *System* topics do not significantly differ in the number of published papers. The most frequently mentioned subjects addressed in the *Structure* topic are facades and building envelopes (Uchiyama et. al, 2020).



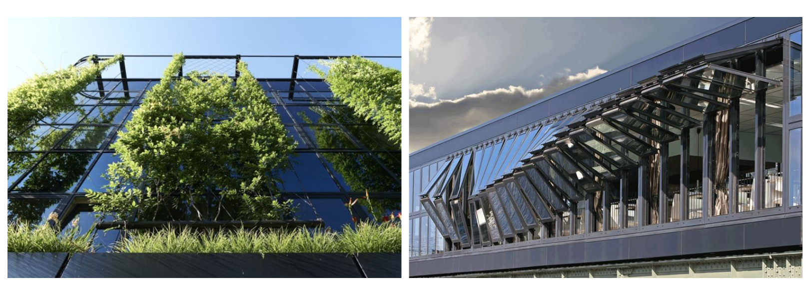
(a) (b) (c)

Figure 5. (a) The Water Cube (Tripblend, 2012), (b) Council House 2 (Dylanbragers, 2017), (c) The Eastgate Centre (u/Porkadi110, 2020)

3. Biomimetic approaches for adaptive façade applications

The façade of a building plays an important role in the building's performance. It performs as a buffer that defines the appearance of the building and isolates the indoor space from the outdoor environment. Throughout history, facades have been considered as a static structural element (Knaack et al., 2007), which has limited their functions and left them unable to adapt to the changing environment. Nowadays, driven by the global energy crisis, the façade is no longer only a barrier between the inside and outside of the building but is being considered as an important component in reducing the energy consumed for building operation (Wigginton & Harris, 2002). The energy efficiency of a building can be enhanced significantly by improving the design of its facades (Radhi, 2008; Mirrahimi et al., 2016). A building envelope that can be adapted to changes in its environment can reduce the total energy consumption and increase energy efficiency (Loonen et al., 2011). There fore, the design of a façade with integrated adaptive systems is becoming necessary for more sustainable building.

An 'adaptive' (alternative terms are active, dynamic, interactive, kinetic, responsive) facade is one that has the ability to adapt some of its functions, features and behavior in response to changing environmental conditions in order to improve the overall building performance while maintaining acceptable thermal and visual comfort conditions (Kirkegaard & Foged, 2011; Loonen et al., 2013). Adaptive facades belong to the category of '*dynamic interfaces*' (Premier, 2013) which can be subdivided into two types: green façades and adaptive facades (Figure 6).



(a) (b)

Figure 6. Dynamic interfaces classification: (a) green façades (Architonic, 2019), (b) adaptive facades (CT Today, 2022)

Green façades refer to the growing of climbing plants or a vegetative system that is developed across the façade of the building (Figure 6a) in order to create a natural sunscreen that can reduce the solar gain. Adaptive façades have a similar purpose to that of green façades, but make use of artificial materials operated by innovative technologies instead of plants (Figure 6b). However, it is at times difficult to make a distinction between these two types of dynamic interfaces because sometimes green facades can be characterized by an adaptive behavior (Marysse, 2016).

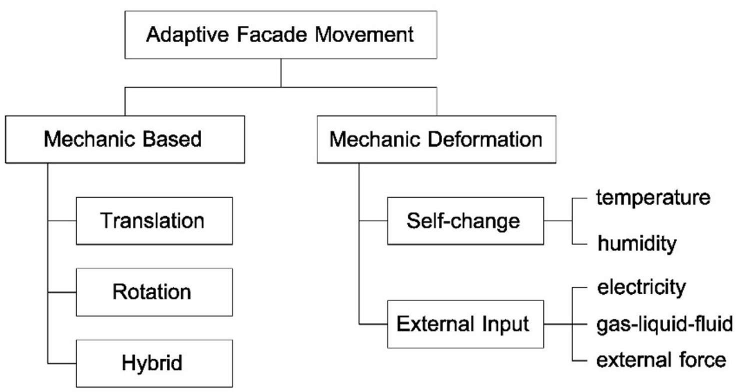
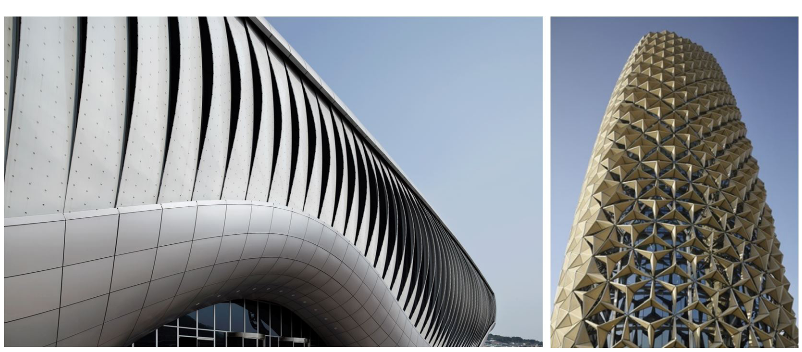


Figure 7. Classification of adaptive façade mechanics (adapted from Velasco et al., 2015).



(a) (b)

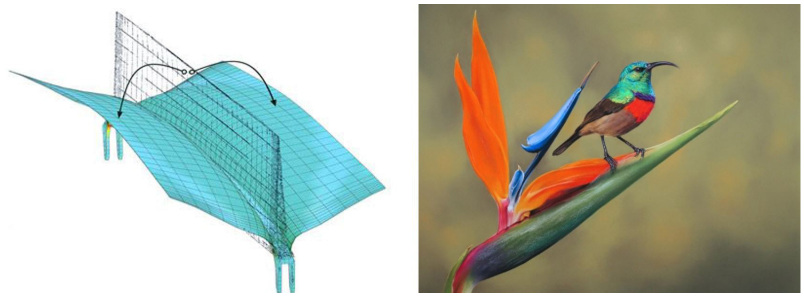
Figure 8. Mechanics-based adaptive facades: (a) Thematic Pavilion (Architizer, 2022), (b) Al-Bahr Towers (Richters, 2012).

The adaptive behavior of façades can be derived from biological motions, such as the movements of plants and animals which have provided the best type of adaptation for surviving in changing conditions over the years. The pattern of movements in adaptive facades can be subdivided into two main categories: mechanics-based and material deformation, as shown in Figure 7. The systems that move by transmitting motion via joint-connections are defined as *mechanics-based movement*, which can be classified into three different types of movement: rotation, translation and hybrid (a combination of rotation and translation). Examples of biomimetic adaptive facades made according to mechanics-based mechanisms are the kinematic façade of the Thematic Pavilion (Figure 8a) and the responsive façade of Al-Bahr Towers (Figure 8b).

The Thematic Pavilion 'One Ocean' was designed by SOMA Architecture for the World Expo 2012 in Yeosu, South-Korea. One of the outstanding features is its kinematic façade, which can respond to the changing natural light conditions during the day, resulting in an attractive dynamic pattern of the façade. The movement of the façade was inspired by the kinematic mechanisms of the *Flectofin* (Figure 9a). The Flectofin, the elastic structural innovation developed by the ITKE institute, was inspired by the compliant mechanism found in the bird of paradise flower (*Strelitzia reginae*). The movement of this flower is considered as a reversible deformation movement, which begins when a bird lands on the petal of the flower, when the perch will be bent downwards by the bird's weight (Figure 9b). This compressive force causes the same bending movement which is used in the kinematic façade of the Thematic Pavilion (Schleicher et al., 2015). When the bird flies away, the elastic mechanism resets to its initial closed state again.

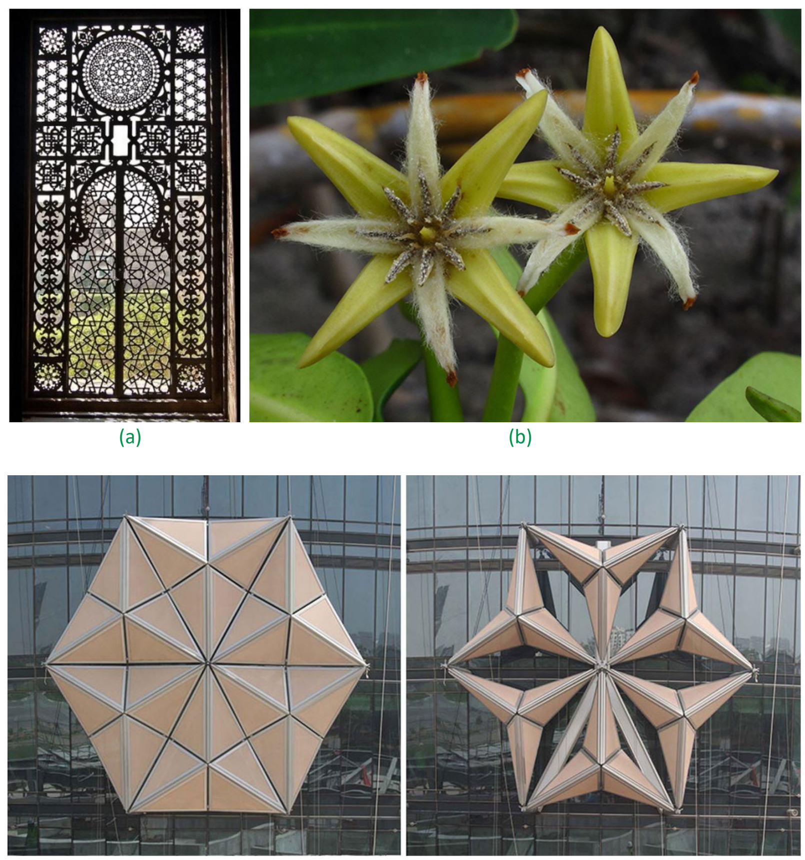
The responsive façade of Al-Bahr Towers in Abu Dhabi is another case of a mechanics-based mechanism. The concept of the folding motion of the façade system was inspired by the traditional shading screen of Islamic architecture, the 'Mashrabiya' (Figure 10a), and the folding of mangrove flowers in response to the movement of the sun (Figure 10b). The adaptive shading system consists of a series of transparent umbrella-like modules that open and close in response to the sun's path (Figure 10c). Each module comprises a series of PTFE[2] panels which is driven by a linear actuator that will progressively open and close to prevent direct solar gain, which is limited at the maximum of 400 watts per linear meter. This adaptive system improves the penetration of daylight, which results in a reduction by over 50% of solar gain and a reduction of CO_2 emissions by 1,750 tonnes per year (ARUP, 2012).

The façade movement caused by *mechanical deformation* employs the physical or mechanical properties of the façade's material components, such as elasticity, thermal expansion, reversibility etc., to create motion. This type of movement can be subdivided into two types based on stimuli: self-changing and external input. *Self-changing materials* are materials that can change their properties by folding, bending, contraction or expansion in reaction to the environment. An example of an adaptive façade using self-changing material is the Hygroskin Meteorosensitive Pavilion (Figure 11a). This pavilion was designed by Achim Menges, who took inspiration from the moisture-driven movement of pine cones which takes place in response to changes in humidity (Figure 11b). Menges used the intrinsic physical properties of wood to create a hygroscopic mechanism by combining the plywood sheets inside a semi-synthetic adaptive bilayer material (Charpentier et al., 2017). Due to the different swelling properties of these two layers, the structure of the Hygroskin can



(a) (b)

Figure 9. (a) FE-simulation of Double Flectofin (Lienhard et. al, 2011), (b) Bird of Paradise flower (Welcha, 2016).



(a) (b)

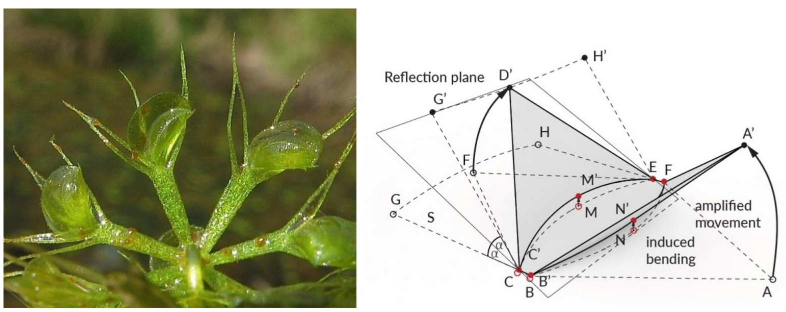
(c)

Figure 10. (a) The Mashrabiya pattern (Encinafemandez, 2016), (b) Red mangrove flower (Alan, 2018), (c) Adaptive shading system of Al-Bahr Towers façade (Aedas, 2012)

Wet condition
(a)

Dry condition
(b)

Figure 11. (a) Hygroskin Pavilion (Menges, 2013), (b) Pine cones in wet and dry condition (Bridgens, 2015)



(a) (b)

Figure 12. (a) Waterwheel plant (Aldrovanda vesiculosa) (Kameníček, 2019),
(b) Kinetic model for curved-line folding mechanism investigation (Körner et al., 2016)

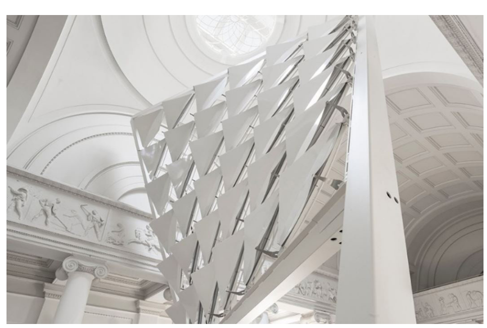


Figure 13. FlectoFold demonstrator at Natural History Museum (University of Stuttgart, 2018)

fully open in low-humidity conditions (around 45%) and close by itself when the relative humidity increases (around 75%) (Krieg et al., 2014).

The second type of mechanical deformation is external input, which involves utilizing external forces, such as electrical current or moving fluids, to cause material deformation. An exemplary biomimetic adaptive system of this type of movement is the FlectoFold, the façade-shading device inspired by the trapping movement of Aldrovanda vesiculosa (Droseraceae), commonly known as the waterwheel plant (Figure 12a). The trapping mechanism of this aquatic plant has five distinctive stages: open – shutting – narrowing – closed – reopening (Schleicher, 2016). The trap is composed of two sickle-shaped lobes which are connected by a stiff lens-shaped midrib. When a prey touches the sensory hairs, the trap-lobes close rapidly within 20–100 milliseconds and will reopen after half an hour. The trapping motion of *Aldrovanda vesiculosa* is considered as purely hydraulically driven (Körner et al., 2018), and is initiated by a rapid bending deformation of the midrib that results in a large movement of the lobes. This motion principle of the waterwheel plant has been abstracted to the kinetic model in order to investigate the curved-line folding mechanism (Figure 12b).

This study was developed with FlectoFold, a compliant shading system in which rigid-mechanical hinges have been replaced by a flexible curved-line folding. The kinetic model consists of elastomer glass fiber reinforced polymer (GFRP) driven by a pneumatic actuator. The experimental test showed that the system required a pressure less than 0.3 bars for actuation (Born et al., 2017). The large-scale prototype for application on the architectural façade was exhibited as part of the BauBionik Exhibition at the Natural History Museum in Stuttgart in 2018 (Figure 13). The anticlastic surface demonstrator consists of 36 FlectoFold

Project	Biological model	Adaptive level	Biomimetic strategy	Movement	Movement type	Application to façade	Performance
Flectofin	(Plant) *Strelitzia reginae*	M	Bending kinematics derived from valvular pollination mechanism.	MB	Fo	E	Reduction of local stress concentrations
Flectofold	(Plant) *Aldrovanda vesiculosa*	M	Flexible compliant mechanism	MD	Fo, PH	E	Reduction of mechanical complexity/requires less pressure to actuate system
Hygroskin Meteorosensitive Pavilion	(Plant) *Pine cones Pinophyta*	P	Weather-sensitive material	MD	EC	I	Requires no sensory equipment or electrical stimulus
Al-Bahr Towers	(Plant) *Mangroves flower*	M	Folding effect in response to the sun's path	MB	FO, EC	E	Reduction by 25% of cooling loads and over 50% of solar heat gain
Thematic Pavilion	(Plant) *Strelitzia reginae*	M	Hinge-less louver system developed from Flectofin	MB	FO	I	Increased shading efficiency and higher wind stability

Adaptive Level: (M) Morphological, (P) Physiological **Movement:** (MB) Mechanical based, (MD) Material deformation Movement Type: (Fo) Folding, (PH) Pneumatic or hydraulic, (EC) Expansion and contraction **Application to façade:** (E) Externally applied, (I) Integrated in the façade

Table 1. Overview of exemplary adaptive façades with comparative information.

modules, measuring 6m by 6m, each controlled by a pneumatic actuator which distributes pressure to the middle part of the panel. Table 1 shows the overview of the adaptive façades mentioned in this section, with comparative information based on the biological models, movement types, levels of adaptation, biomimetic strategies and performances.

4. Biomimetic adaptive façade for more sustainable buildings

Three strategies are often mentioned when discussing sustainability: efficiency, consistency and sufficiency. All of them are key to reaching the goal of sustainability. These guiding principles for reaching sustainability have been defined from the human perspective, whereas nature does not think and act, but is only characterized by biological evolution. Therefore, by definition, nature is not sustainable (Speck et al., 2019). However, nature provides the inspiration for the development of solutions to achieve the goals of sustainability. Thus, biomimicry, or learning from nature to create technical solutions, is considered a potential approach to contribute to more sustainable development.

To achieve sustainable architectural performance, buildings have to interact with the environment and adapt themselves to the climatic conditions. Adaptive façades using biomimetic approaches have been proposed as solutions for improving the energy performance of buildings, which is essential for sustainable design. In recent years, many studies have investigated the performance of buildings in which biomimetic adaptive facades have been applied. Many of the results reveal that the application of biomimetic adaptive facades can enhance the energy efficiency of buildings. An example is the proposed dynamic shading system, inspired by the cactus form and movement mechanisms of the Giant White Ipomoea (Figure 14), on a building skin in the hot climate of Cairo, Egypt, to obstruct direct solar radiation. This study used computational and simulation tools for modeling and analyzing biomimetic solutions. The simulation results indicated that the proposed system achieved over 50% reduction of solar gain, reduced cooling energy consumption by 39% across the year and increased the comfort hours by 2,873 hours per year (El-Rahman et al., 2020).

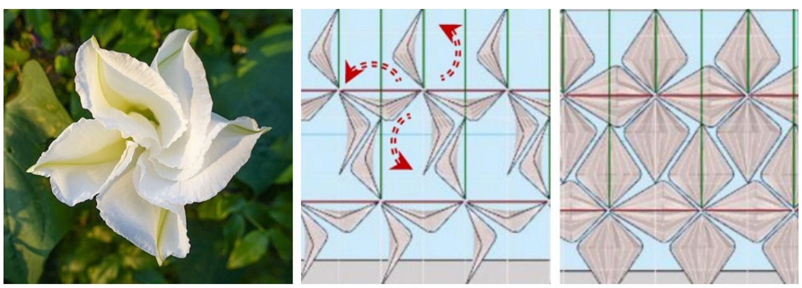


Figure 14. Proposed dynamic shading design inspired by rotation motion of the Giant White Ipomoea (El-Rahman et al., 2020)

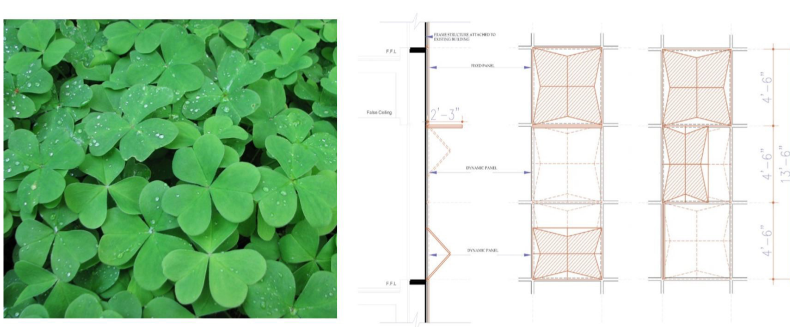


Figure 15. Proposed adaptive biomimetic façade inspired by the Oxalis oregana leaf mechanism (Sheikh and Asghar, 2019)

Similarly, the investigation of the proposed design of an adaptive biomimetic façade which imitated the physical and adaptation properties of an Oxalis oregana leaf (Figure 15) reveals a significant reduction in the energy consumption of highly glazed buildings in Pakistan. The numerical results indicated that the existing building with application of the proposed adaptive biomimetic façade can reduce the energy load by 32% while still maintaining a sufficient lighting level (500–750 lux) over 50% of the interior space (Sheikh, 2019).

It can be seen that biomimetics provide ideas to be discovered from nature's own adaptation processes into adaptive façade designs. Through the abovementioned examples of research, the integration of adaptability inspired by principles found in nature into building façades has great potential to improve energy efficiency in buildings, which is one of the key requirements of sustainable design.

5. Conclusion

The façade is the main component that influences a building's energy performance. Several reports have clearly indicated that building envelopes have an important role in relieving or worsening global climate conditions. One of the most important parameters used to evaluate the achievement of sustainable architecture is energy efficiency. The development of adaptive façade technology integrated with biomimetic approaches can achieve further energy reductions. The results of the prototypes and researches illustrated in this article indicate that biomimetic adaptive facades have the potential to reduce energy consumption for all building applications. Hence, the building envelope should no longer be a static load-bearing structure, but should act as a dynamic mediator between the internal and external environments, like the skin of a living organism.

Adaptive façades not only offer a barrier between the outside and inside environments or contribute to the aesthetic appearance of buildings, but also improve the visual comfort of occupants, leading to increasing satisfaction and productivity. Although not every biomimetic adaptive application is sustainable, the concept of biomimetics is in harmony with the concept of sustainability. Therefore, learning from natural organisms and imitating the adapting capabilities observed in plants and animals are important ways to achieve sustainable façade design solutions.

Note

[1] The root network of fungi, a fast-growing matrix that can act as a natural b

[2] polytetrafluoroethylene inder.

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