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Technological Imagination in the Green and Digital Transition

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Chapter 39
From Nature to Architecture for Low Tech Solutions: Biomimetic Principles for Climate-Adaptive Building Envelope

Francesco Sommese and Gigliola Ausiello

Abstract Building envelopes represent the interface between indoor and outdoor environmental factors. In recent years, attention to climate adaptive building envelopes has increased. However, some types of adaptive envelopes don't always offer low-tech solutions, but require energy for their activation and high operating and maintenance costs. Nature has always proposed a large database of adaptation strategies that are often complex, multi-functional, and responsive. Transferring the functional principles of natural organisms and their associated adaptive modalities to technologies is the challenge of the biomimetic discipline (from Greek bios, life, and mimesis, imitation) applied to the field of architecture. In this article, various examples of biomimetic architecture that illustrate the relationships between biology, architecture, and technology, were considered. Various analyses of the operating principles of natural organisms are carried out, particularly with regard to self-adapting materials, in order to transfer them to the building envelope, and to propose technological solutions capable of passively adapting to external climatic conditions. Among all natural organisms, plants are prefereble to animals because, like buildings, they remain stationary in a specific location. Despite this, plants have developed different adaptation mechanisms to survive in certain environments. Buildings with biomimetic adaptive envelopes, characterized by passive and low-tech solutions inspired by plants, help limit energy consumption, and improve not only the indoor microclimate but also the outdoor environment. In line with the ecological transition, this work highlights the importance of biomimetic as a strategy to orient the new paradigms of built space design towards innovative and sustainable models of low-tech solutions.

Keywords Biomimetics · Adaptive building envelope · Responsiveness · Environment · Smart materials

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39.1 Introduction

The natural state of the climate is altered by accentuated anthropic factors (IPCC 2021).

Adaptation actions in all sectors are essential, especially in the building sector, which is held responsible for about 40% of energy consumption (IEA 2019). To ensure good indoor comfort while limiting the impact on the environment, traditional building envelope solutions are not particularly efficient due to their staticity. So, responsive solutions to changing external conditions are needed. The building envelope represents the interface between the indoor and outdoor space and plays an important role in the energy balance. In recent years, the building envelope has been the subject of studies and research to define solutions to improve energy efficiency, ensure optimal indoor comfort, and limit environmental impact. The latest technological solutions propose the adaptive envelope as an interface capable of responding and adapting to changing external environmental factors. Nature provides adaptive solutions because natural organisms have always used adaptive mechanisms to survive environmental stress. Transferring the adaptation strategies of natural organisms to building envelope technologies is the challenge of biomimetics, which is considered an emerging discipline in the field of engineering and architecture (Badarnah and Kadri 2015).

The combination of natural strategies with smart and self-activating materials make it possible to obtain low-tech solutions, that do not consume energy but are based on self-activating mechanisms (Sommese et al. 2022). In this way, the autonomous response to weather changes provides indoor comfort and, at the same time, the absence of energy consuption limits the impact on the environment, expecially the heat island in the city.

The focus of this work is on the use of self-activating smart materials for biomimetic adaptive envelopes. Some projects are analyzed and classified according to the type of material used and the response to a specific external environmental stimulus.

39.2 Environmental Challenges and Smart Materials

The most important external environmental factors to consider are solar radiation and high temperatures. Due to man-made pollution, the CO_2 content in the atmosphere is also particularly high. All these elements, and others that we do not consider in this article (such as chemical concentration or electrical voltage), are the environmental stimuli that allow materials, to activate and generate a response to such phenomena. In fact, smart materials represent a class of innovative materials that allow to develop architectural organisms capable of responding to environmental stimuli (Fiorito et al. 2016).

Table 39.1 Classification and characterization of smart and self-activating materials

Smart materials	External stimulus	Response	Adaptation mechanism	Visibility	Control mechanism
Photocatalytic	UV radiations	Chemical reaction	Static	No	Intrinsic
Wood	Humidity level	Shape change	Dynamic	Yes	Intrinsic
Shape memory	Temperature variation	Crystal structure change	Dynamic	Yes	Intrinsic

They are able to respond to stimuli in real time but some of them are also self-activating, meaning they have a reaction capacity inside the material and do not require external activation systems, such as sensors and actuators (Otsuka and Wayman 1999). In particular, they perceive the stimulus, respond to it, and return to their original state when the stimulus is removed (Tabadkani et al. 2020). In recent years, these materials have influenced the construction industry, in fact, various studies and experiments are present in the literature. Among the most widely used smart materials are shape memory alloys (SMA), shape memory polymers (SMP), electrochromic and piezoelectric materials, and others (Addington and Schodek 2005). The most common smart materials are based on an electrical stimulus (López et al. 2015). In this study, only materials that can act through an intrinsic change in properties and therefore without external implementation systems, were considered. The choice of self-activating smart materials orients the design towards low-tech and low-energy solutions, to limit consumption in line with the European goals of climate neutrality by 2050.

Table 39.1 shows the classification of some smart and self-activating materials used in the examples of biomimetic envelopes that are described in the following sections.

For each smart material, the environmental stimulus that triggers the reaction to the external environment was identified (Casini 2014). In addition, the type of response and the control and adaptation mechanisms are defined. The activation mechanism is classified as static when there is no visible movement and dynamic when there is no visible mechanism (Kuru et al. 2018). Intrinsic control is when the material response is due to the change in its properties; extrinsic control is when the change is due to external devices such as actuators or sensors that cause the material to move (Tabadkani et al.2020; Loonen et al. 2013).

Fig. 39.1 Lotus left and Italian Pavilion Expo 2015. *Credits* the author G. Ausiello

39.2.1 Biomimetic Solutions with UV Radiation Reactive Materials

Photocatalytic materials are widely used in the construction industry. Metal compounds such as titanium dioxide (TiO_2) react to UV radiation by oxidizing the material they come into contact with. The Italian pavilion at Expo 2015 is one of the latest examples of this solution. The interaction between concrete and titanium dioxide nanoparticles gives the surface the ability to self-clean and antipollution (Ausiello 2018). By absorbing light energy, nanometric crystals of titanium dioxide trigger photochemical reactions, and act as photoactive particles on the order of micrometres. The photochemical reactions, which take place in the nanometre range, and are therefore not visible to the naked eye, mimic natural processes that are reproduced and amplified by titanium dioxide becoming a conductor from semiconductor.

The ability to "self-clean" is called the "lotus effect", in relation to the natural behavior of the leaves of this plant which, immersed in muddy water, are always shiny and clean (Ausiello 2018). For several years these leaves have served as a model for experimenting with this property, which is reproduced by the photochemical effect induced by titanium dioxide, which leads to a nanometre scale change in the "roughness" of the surface. When exposed to sunlight, the surface becomes nanometrically hydrophobic and the water droplet remains in relief, resting only on the minute bristles of the lotus leaves, or on the nanoprotrusions of the surface of the concrete panels, then flows on the leaf or the surface of the panels, dragging dust and insects with it, which are thus naturally removed (Fig. 39.1).

39.2.2 Biomimetic Solutions with Humidity Reactive Materials

Wood is the natural material par excellence. It is not always classified among the intelligent materials, but it has the properties of hygroscopicity and anisotropy that allow it to be considered a self-activating material, that responds to the moisture content of the environment. An important example of this ability is the cones of conifers, which open and close the bracts depending on the humidity to protect the fruit (pine nuts) they contain. Inspired by the functioning of the pinecone is the project of the exhibition pavilion HygroSkin designed by the ITKE and ITC institutes of the University of Stuttgart. It is a meteorosensitive pavilion that uses the hygroscopic and anisotropic properties of wood to create an architectural skin that can open and close autonomously in response to climatic fluctuations (Krieg et al. 2014). In particular, the openings respond to changes in relative ambient humidity in the range of sunny to rainy climates in a mild environment (Correa et al. 2013). In this way, light penetration and the visual permeability of the interior spaces can be controlled.

39.2.3 Biomimetic Solutions with Temperature Variation Reactive Materials

In recent years, shape memory alloys (SMA) have gained notoriety in the architectural field. SMAs can return to their original shape or size when exposed to certain factors, including temperature. The material deforms due to an external force and contracts or resumes its original shape when heated above a certain temperature (Mohd Jani et al. 2014). SMA are considered intelligent materials in response to temperature variation due to its shape memory effect and pseudoelastic effect (Tamai and Kitagawa 2002). Air Flow(er) is a ventilation device designed to regulate air flow and internal temperature, without the use of electricity or mechanical equipment (LiftArchitects). It represents an interesting example of low-tech solutions.

The design principle of the Air Flower was based on the imitation of the thermonastic movement of plant organisms, in particular the yellow Crocus Chrysanthus, which responds to the increase and decrease in temperature that occurs in day-night passages (Rascio et al. 2017). Crocus flowers petals open when the temperature increases and closes when it decreases (Andrade et al. 2021). In the case of Air Flow(er), the kinetic reaction of the plant organism, due to the thermonastic movement, is provided by the shape memory alloy wire (Fig. 39.2).

When the alloy is exposed to low temperatures (martensite), it deforms more easily and then the four doors can open to allow the passage of air. However, when the alloy is exposed to higher temperatures, it returns to its original shape and the doors close, blocking the air flow.

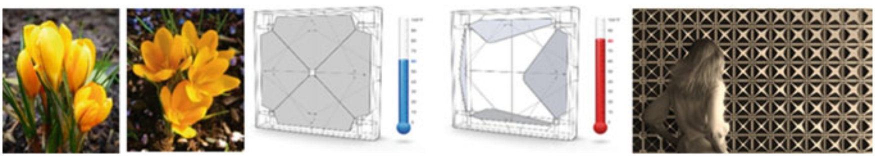

Fig. 39.2 Crocus chrysanthus and Air Flow(er) prototype

Fig. 39.3 Pho' Liage

A recent study of shape memory materials led to the definition of the prototype Pho' Liage, by ArtBuild studio (Fig. 39.3). It is a prototype of a kinetic device for shielding against natural light, which does not require human or mechanical action to activate. This system guarantees solar shielding through Thermo-reactive materials and the storage of thermal energy through photosensitive materials (ArtBuild). This solution is inspired by the opening and closing mechanism of the flowers, in response to variations in the intensity of solar radiation. In particular, the reference is to the troponastic (or thermonastic) mechanism, understood as the behavioral adaptation of some plant organisms, which has allowed to define of a solution capable of reacting autonomously by exploiting the chemical-physical and environmental interaction (Trelcat et al. 2022). This example, which does not require energy for activation, can also be classified as a low-tech solution.

Thermo-bimetals are among the materials that react to temperature difference.

They refer to a double layer conformation of the metal with different coefficients of thermal expansion, able to make it to fold in response to the increase in temperature (Al-obaidi et al. 2017). The use of laser-cut bimetal lining is illustrated by the Bloom system (Fig. 39.4), a self-supporting paraboloid-shaped shell structure. When the shell is heated at the surface, the structure curls autonomously. In this way the curling of the shape shades and allows air to pass through, thus ventilating certain areas. This solution emulates the mechanism of opening and closing of stomata in natural organisms. Moreover, this solution is configured as a passive system, as it opens and closes its slats according to the heat of the sun, without using artificial energy (Barozzi et al. 2016).

Fig. 39.4 Bloom system

39.3 Results

Table 39.2 summarises the examples analyzed in the previous section. They are classified according to various factors, including the required performance, controlled environmental factors, environmental stimuli (input), material, response, and organism inspiration.

The examples described above are all inspired by the plant world. Indeed, these have always inspired architects and designers (Ausiello et al. 2020). Nature provides a database of adaptation solutions to respond to changing environmental stimuli, and smart materials make it possible to transform these solutions into low technologies to be applied to the building scale.

The methodological approach of biomimetic design (Fig. 39.5) thus provides, as a starting point, the definition of the environmental challenge, then the identification of the biological organism to emulate (in this case plants), and finally the identification of the smart and self-activating material capable of reacting passively to environmental stimuli, as happens in nature. In this way, it's possible to move from biology to technology and define solutions, techniques, and materials that can emulate the functioning of the identified natural organism. Figure 39.5 shows the relationships between the different phases of the methodological approach, deriving from the analysis of the cases studied in this work.

39.4 Future Scenarios

In the panorama of urgent actions to limit environmental impacts, low-technology solutions are becoming increasingly necessary. This paper highlighted the combination of biomimicry and smart materials as an expression of a solution to be implemented in architecture to propose climate adaptive envelope solutions. Nature becomes a model and guide for the realization of new technological solutions and biomimetics is an essential tool in design, that facilitates the transition from the industrial to the ecological era. Biomimetic does not necessarily use natural resources, but reproduces the functioning of natural organisms in response to specific needs (Ausiello et al. 2020). The use of smart materials allows you to design buildings with advanced properties that can adapt to changing weather conditions while also saving energy and improving indoor comfort. Smart materials can completely revolutionize the construction industry to steer new building paradigms towards ecological transition and ensure sustainable solutions.

Table 39.2 Results and characteristics of case studio analysis

	Requirement	Environmental factor	Input	Inspiration organism	Material	Output
Italian Pavilion Expo 2015	CO_2 capture	CO_2	UV radiation	Lotus effect	Photo-catalytic	Inaudible
HygroSkin Pavilion	Modular light radiation and visual permeability	Water	Relative humidity	Pine cone	Wood	Elastic-flexural
Air Flow(er)	Regulate air flow and internal temperature	Air	Temperature variation	Flowers	Shape Memory Alloy Wire (SMA)	Kinetics
Pho' Liage	Solar shading	Light	Temperature variation	Flowers	Thermo-reactive materials (TBM) Photosensitive materials (PV)	Dilation
Bloom	Airflow shading	Air Light	Temperature variation	Pores/stomata	Thermo bimetal	Folding

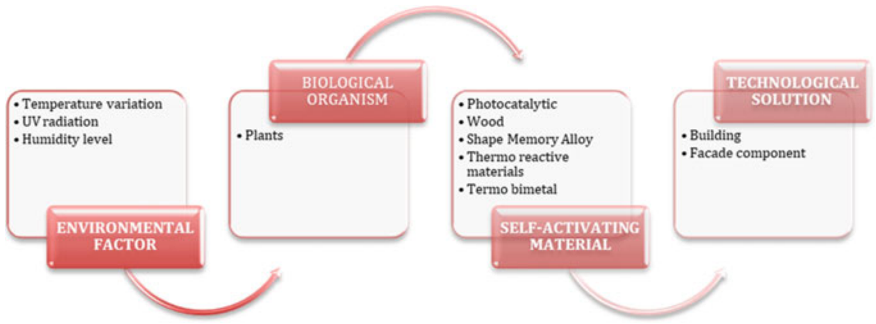

Fig. 39.5 Biomimetic approach from nature to technologies

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Author contributions Francesco Sommese: conceptualization, methodology, writing, editing and visualization. Gigliola Ausiello: Supervision.

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