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Adaptive façades bioinspired by the nastic movements of plants

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Abstract: The core concept of biomimetics is transferring biological principles to technology, which occurs under a transdisciplinary approach. Nastic movements correspond to plant movements regardless of the direction of the stimulus. The current state of knowledge demonstrates the emergence of bio-inspired solutions for façades based on nastic movements. This article highlights six solutions for adaptive façades that aim to promote reversible movements in response to environmental conditions, whether for shading or ventilating. The showcased projects include Air Flow(er), AlBahr Towers, Bimetal Biomodule, HygroSkin, Ocean Pavilion, and Pho'liage. These projects can use extrinsic control (artificial systems associated with sensors and actuators) or intrinsic control (self-adjusting systems without electricity or mechanical devices, using materials such as shape memory alloy, bimetal, or wood associated with synthetic composites and computer programming). These solutions also employ different material deformation strategies (such as geometric strategies, variation of material properties, and/or fluid incompressibility shrinking and swelling). Thus, we can assert that sophisticated nature-inspired strategies, like nastic movements, enable the abstraction of nature's intelligence into responsive human solutions that can contribute to the sustainability of buildings.

Keywords: Biomimetic - Bioinspiration - Movements of Plants - Nastic movements - Adaptative Façade - Kinetic Façade - Material deformation - Smart materials - Responsive material - Sustainability

[Resúmenes en castellano y en portugués en las páginas 77-78]

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1. Introduction

Transferring biological principles into technology is central to biomimetic approaches (ISO 18458:2015, 2015). Regarding bioinspiration for adaptive façades, three significant obstacles exist to the relationship between biology, biomimetics, and architecture (Oliveira, 2019). The first one involves establishing a systematic methodology of selective design to identify relevant biological systems (Badarnah & Kadri, 2014; Martín-Gómez *et al.*, 2019; Oliveira, 2019). The second concern is scale difficulty, as some functions only apply to specific scales (such as nano or micro scales) (Oliveira, 2019). The final obstacle is to integrate parts from different contexts into a single design concept, often involving conflicting parts (Oliveira, 2019; Royall, 2010).

The present study will focus on the development of projects that have used **nastic movement** in plants as a reference to develop bioinspired solutions. Nastic movement encompasses the **non-directional movements of plants in response to external stimuli**. The direction of movement is predominantly reversible and independent of the direction of the triggering stimulus (Fiorito *et al.*, 2016; Schleicher *et al.*, 2015). An example of nastic movement is the opening of flower petals at dawn and their closing at dusk, as observed in *Oxalis acetosella*, a plant species commonly known as wood sorrel (L. Charpentier *et al.*, 2022). This type of movement is classified as nyctinasty. According to a systematic review developed by Andrade *et al.* (2020), there are nine distinct types of nastic movement in response to stimuli such as temperature variation, light intensity, humidity, touch, vibration, chemical signal etc. Some leaves close in response to various stimuli. One of the types of responsive behaviour of *Mimosa pudica* leaves is folding in reaction to touch (López *et al*., 2017), classified as thigmonastic. The movement of *M. pudica* is one of the most investigated.

Several façades inspired by biological systems have an inherent responsiveness within the material, which can reduce the need for mechanical and electrical devices (Menges & Ahlquist, 2011). Next, we will outline concepts regarding **kinetic control stimuli** for the material (intrinsic and extrinsic control) (Andrade, Beirão, Arruda, & Eysen, 2021; Böke *et al*., 2022; Kuru *et al*., 2019; Loonen *et al*., 2013), as well as the different strategies for transforming of the material (Andrade, Beirão, Arruda, & Eysen, 2021; V. Charpentier *et al*., 2017; Schleicher *et al*., 2015; Vazquez *et al*., 2019). In addition to these classifications, we will describe the six case studies, highlighting the inspiration from the nastic movement and the reference plant.

2. Method

Through parameters such as nastic movements, reference organisms, adaptive façade control stimuli, and material deformation strategies, we selected six relevant projects to conduct case studies, namely: Air Flow(er), AlBahr Towers, Bimetal Biomodule, HygroSkin, Ocean Pavilion, and Pho'liage. We will demonstrate the most recent versions of the projects, whether prototypes or constructed façades. The development team has developed different project versions throughout the methodological process. However, before we present the case studies, we need to clarify the analysis parameters described below.

From a material classification standpoint, there are two approaches to establishing adaptability. The first one involves **Intrinsic Control (INT)**, which explores the material's inherent properties that alter behaviour (Böke *et al*., 2022; Kuru *et al*., 2019; Loonen *et al*., 2013), such as smart material and shape-changing materials (Andrade, Beirão, Arruda, & Eysen, 2021; Ritter, 2007; Sung, 2016; Vazquez *et al*., 2019). For example, bimetal and shape memory alloys are both materials that respond to temperature variation. As an advantage, intrinsic control presents a reduced vulnerability to technical errors (as mechanical systems do). However, it typically lacks user adjustability (Böke *et al*., 2022).

The second approach is classified as **Extrinsic Control** (EXT) as it requires an external impulse to activate the system (Böke *et al*., 2022; Kuru *et al*., 2019; Loonen *et al*., 2013). It extensively relies on digital control and automation technologies. Automated systems offer a high degree of flexibility and possibilities for intervention in digital control. However, it presents a series of disadvantages related to the lifespan of electro-technical components and their susceptibility to faults and maintenance (Böke *et al*., 2022). Additionally, it predominantly depends on the supply of electrical energy, despite reducing energy consumption (Böke *et al*., 2022; Loonen *et al*., 2013).

According to V. Charpentier *et al*. (2017), there are **different strategies to transform a small deformation into a large displacement in the material** through bioinspiration in plant movements, namely:

a. Geometric strategy (GS): produces geometries that react efficiently to demand, with the morphological structures 'ideal performance'.
b. Variation of Material Properties (VMP): works through three approaches:
- *Continuous variations of material properties* - single manufacturing material, however, containing variations in thickness or material stiffness depending on the location.
- *Discontinuous variations of material properties* - mainly observed in materials consisting of heterogeneous multilayers.
- -*Material anisotropy* - uneven distribution of material in different directions. Different directions can be combined with structural properties to provide different displacements, thus providing lightweight and efficient structures.
- Fluid Incompressibility Shrinking and Swelling (FSS) - use pneumatic or hydraulic structures to produce displacement.

c. Energy Storage (ES): Energy storage produces displacement or force that releases energy and provides movement.

The four strategies can coexist in the same solution. In other words, combining them to enhance the kinematic capability of materials is possible (V. Charpentier *et al.*, 2017). We will describe each project in the case studies section. In the discussions and results stage, we will present *Table 1*, synthesizing the main findings about the projects.

3. Case Studies

3.1 Air Flow(er)

The **Air Flow(er)** is a kinetic device that promotes environmental ventilation *(See Figure 1)*. By utilizing smart materials, such as Shape Memory Alloy [SMA], the device responds to environmental conditions without relying on electrical power (Lift Architects, n.d.). Its inspiration comes from the Crocus flower, an organism with nastic movement in response to temperature variation, namely thermonastic.

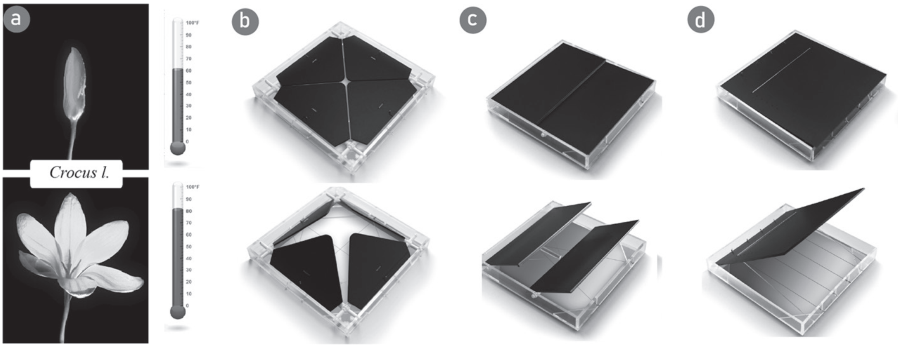

Figure 1. Air Flow(er) - a) Reference organism: Crocus flower, b-d) Different prototype versions, closed at low and open at high temperatures (Source: adapted from Lift Architects n.d.).

As the building warms beyond 27°C, the panel system opens to allow air mass exchange through the deformation of the SMA wire. When the indoor space cools below its lower temperature limit (approximately 16°C), the panels tend to close to maintain the temperature regulated at comfortable levels, and the wires return to their initial position. Lift Architects (n.d.) developed three prototypes for ceiling opening, traditional single-skin opening, and a naturally ventilated double-skin façade system. All prototypes were designed to provide natural ventilation in buildings and are energy independent (INT). The Air Flow(er) uses geometric strategy (GS) as material deformation strategy.

3.2 AlBahr Towers

The **Al-Bahr Towers** *(See Figure 2)*, built in 2012, exemplify kinetic architecture. They are internationally recognized and received the Best Innovation Award in 2012 from the Council for Tall Buildings and Urban Habitat (Karanouh & Kerber, 2015). Designed by AHR (formerly Aedas-UK) in collaboration with Arup, these 150-meter-tall buildings housed the Abu Dhabi Investment Council headquarters.

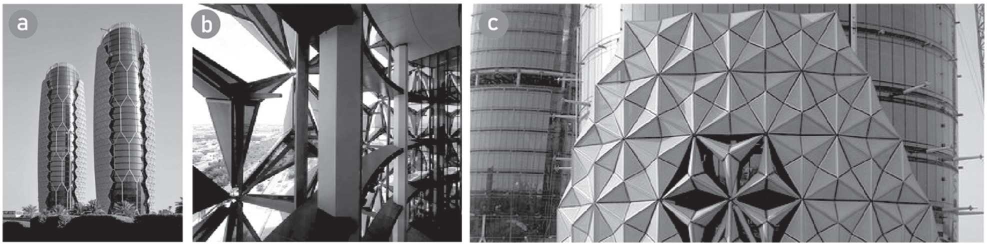

Figure 2. Al-Bahr Towers. a) towers; b) internal detail of the closed module within the building; c) detail with closed and open modules. Source: a; c) Cilento (2012); b) Karanouh & Kerber (2015, p. 217).

The towers employed performance-based design, and the dynamic façade operates following the sun's movement (Karanouh & Kerber, 2015), designed for Abu Dhabi's arid climatic context, where temperatures can reach 49˚C in the summer. The kinetic panels are placed where there is a higher incidence of solar radiation (Karanouh & Kerber, 2015). The authors stated that combining natural elements and cultural references inspired the project (such as Musharrabiya, a common geometric application in Islamic architecture). They drew inspiration from the opening and closing movement of flowers in response to changes in weather conditions. They also drew inspiration from the characteristics of cacti, which resemble umbrellas, to protect against the elements. Another reference used was the hexagonal envelope of the pineapple, which efficiently covers the surface.

Each tower features an envelope composed of 1,049 modules resembling origami folds (located two meters from the exterior of the building covered by an inner glass skin). This project presents a strategy of geometric deformation (GS) (V. Charpentier *et al.*, 2017). The kinetic elements are in aluminium with a fiberglass mesh coating (Karanouh & Kerber, 2015). The support structure around the perimeter of the building used stainless steel material. Each device is approximately 4.2 meters in height and can vary between 3.6 and 5.4 meters in width. Centrally positioned actuators and pistons control the mechanism. The largest unit weighs 625 kg. The project used a computerized dynamic façade through programming/scripting methods, parametric design, and advanced engineering analysis, including Finite Element Analysis and Computational Fluid Dynamics (Karanouh & Kerber, 2015). Energy analysis was conducted without the modules to evaluate the context for enhancing allocation, environmental performance, and visual permeability.

The façade management system allows for manual emergency, maintenance, or demonstration intervention (Karanouh & Kerber, 2015). According to the authors, the software includes sensors (light, wind, and rain) to monitor and manage risks related to wind speed, light intensity, rainfall levels, faulty units, and the folding positions of the modules. Each kinetic unit can be controlled separately. When the sun rises, the kinetic modules begin to close. Their opening and closing will change (vertically) with the solar path. The modules are folded at night to enhance visual permeability through the façade. Karanouh and Kerber (2015) stated that this screen **reduces the need for energy consumption by up to 50% in work environments in terms of lighting and cooling load requirements**.

3.3 Bimetal Biomodule

The **Bimetal Biomodule**, inspired by nastic movements observed in the grass *Ammophila arenaria*. This grass exhibits a remarkable mechanism wherein its leaves can reversibly open and close in response to water and salt stress fluctuations, a phenomenon known as hydronastic movement (Andrade, Beirão, Arruda, & Cruz, 2021). Drawing inspiration from the leaf morphology of this grass, Andrade *et al.* (2024) incorporated creases into the active layer of the bimetal material. This smart material responds to thermal variations by bending when heated (Sung, 2016). The creases, in turn, contribute to the opening of the material when the temperature rises and to its closing when it cools down (an opposite movement of the material without creasing). Andrade *et al.* (2024) developed prototypes of kinetic modules for self-shading façades, employing a stamping process (with 3D printed matrices) to create the creases - the Bimetal Biomodules *(See Figure 3)*.

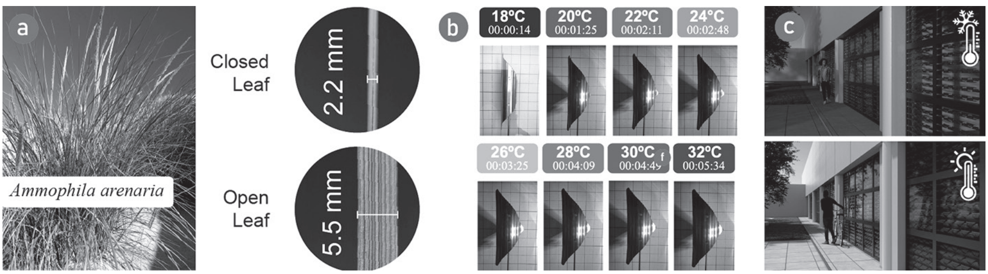

Figure 3. Bimetal Biomodule - a) Reference organism: *Ammophila arenaria*. b) thermal test between 18 and 32ºC. c) Biomodule behaviour in the face of low (between 13.6 and 13.8 ºC) and high temperatures (between 41.5 and 48.8 ºC) (Source: adapted from Andrade *et al.*, 2024).

The study suggests a kinetic module for adaptable building through bioinspired methods, material experimentation, and computational algorithm. The authors conducted experiments in an open environment (in summer, fall, and during a heat wave). Statistical treatment of the data identified equations explaining the behaviour of the biomodules, proving that they are adaptable to different climatic conditions. The computational algorithm integrates the equations, generates parametric variations, and simulates protection by solar incidence. The research's contribution lies in the creases' relevance to controlling the bimetal's behaviour enabling the biomodule's movement without needing electricity or mechanical devices (INT). Bimetal Biomodule uses b) variation of material properties (VMP) and geometric strategy (GS) as material deformation strategy.

3.4 HygroSkin - Meteorosensitive Pavilion

The **HygroSkin:** Meteorosensitive Pavilion project *(See Figure 4)* features hygroscopic properties to provide an autonomous structure that adapts to humidity conditions (Menges & Reichert, 2015; Reichert *et al*., 2014). The solution drew inspiration from the cone of conifers plants (Pinophyta) as the reference organism, which, in the presence of humidity, alters the behaviour of cone bracts (closing when in contact with water and opening as they dry). Wood utilizes material anisotropy through two layers of veneer that exhibit distinct expansion and shrinkage capabilities (VPM; FSS), allowing for reversible movement without any electromechanical actuation. The wood is also bound to a composite with epoxy resin and fibreglass.

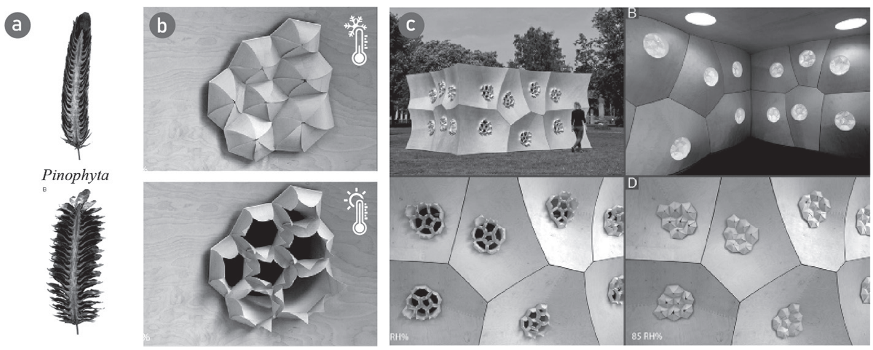

Figure 4. HygroSkin - a) Reference organism: Cone of conifers (Pinophyta), b) Responsive module: closed and open; c) Temporary exposure to air (Source: adapted from Reichert *et al.* (2014) and T. Andrade, Beirão, Arruda, e Eysen, 2021).

The material responds to humidity variation and uses computational design to program its responsive capacity, followed by execution via digital fabrication (Andrade, Beirão, Arruda, & Eysen, 2021; Menges & Reichert, 2015; Reichert *et al*., 2014). The result is a programmable wood veneer (Reichert *et al*., 2014). Altering fabrication parameters allows the calibration of the material to react to different relative humidity characteristics (Reichert *et al.*, 2014). The project utilizes a material deformation strategy through fluid incompressibility (FSS) and variation in material property by anisotropy (VPM).

3.5 Ocean Pavilion

The **Ocean Pavilion** *(See Figure 5)* comprises the permanent thematic pavilion for EXPO 2012 in Yeosu, South Korea, conceived by SOMA Architecture in Vienna (Knippers *et al.*, 2012). The project consists of a kinetic façade system inspired by the principles of flexible deformation found in plant movements (Knippers *et al.*, 2012). This pavilion used the studies of the Flectofin™ project as a reference, inspired by the elastic movement mechanism for the pollination of the *Strelitzia reginae* flower (Lienhard *et al.*, 2012), an example of thigmonastic. The Flectofin™ consists of a hingeless shutter system that operates through the elastic property of materials by appropriate arrangement in different directions of the fibers (Lienhard, 2014; Lienhard *et al.*, 2012).

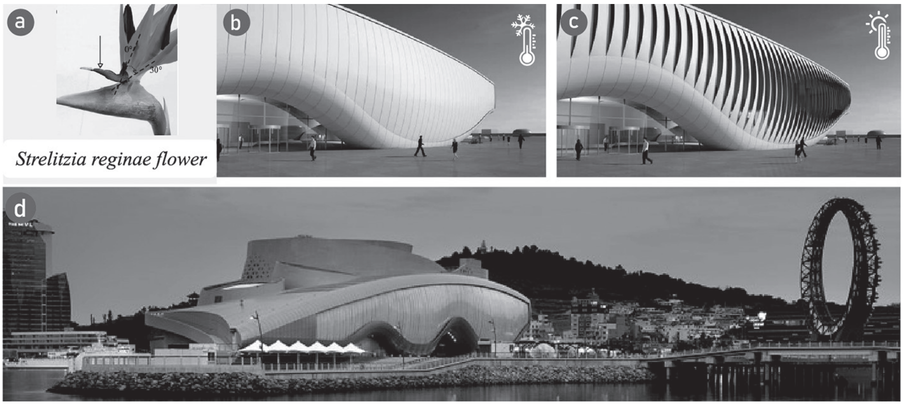

Figure 5. Ocean Pavilion. a) Reference organism: *Strelitzia reginae.* External rendering with b) closed shutters and c) open shutters; d) project executed in Yeosu, South Korea. (Source: a) Lienhard *et al.* (2012); b, c) Rendering: ©isochrom; c) photo by: ©Kim Yong-kwan).

During the development process of the operable shutters, the development team considered the climate of South Korea, which experiences intense typhoon occurrences. Fatigue and wind load studies provided aerodynamic stability, predicted lifespan, and enabled the façade's application to wind speeds of 35 m/s. The façade designed to close with winds ex-

ceeding 12 m/s automatically. SOMA Architecture designed the reversibly operable shutters using Glass Fiber Reinforced Polymer (GFRP) (Knippers *et al.*, 2012). The geometry and material of the shutters provide high tensile strength associated with low flexural rigidity, allowing for large elastic deformations (V. Charpentier *et al.*, 2017). Regarding the material deformation strategy (V. Charpentier *et al.*, 2017), the project used an association between VMP and SG.
The façade is 140 m long and has heights ranging from 3 to 13 m. It utilizes 108 kinetic shutters in GFRP. The shutters are moved by actuators located at the bottom and top ends, inducing compression forces, and creating complex elastic deformation capable of laterally rotating them (Knippers *et al.*, 2012) (EXT). Structural analyses examined the extremes of the shutters' geometries through finite element analysis of the longest (13.6m) and shortest (6.0m) ones *(See Figure 6)*. Opening a 13 m shutter requires a 450 mm movement for a 60° opening angle. The maximum actuator movement speed is approximately 3.80 m/minute. The development team conducted geometric analyses to avoid collisions between the shutters. According to the authors, the results allowed adjustments to the movement trajectories and bearing locations.

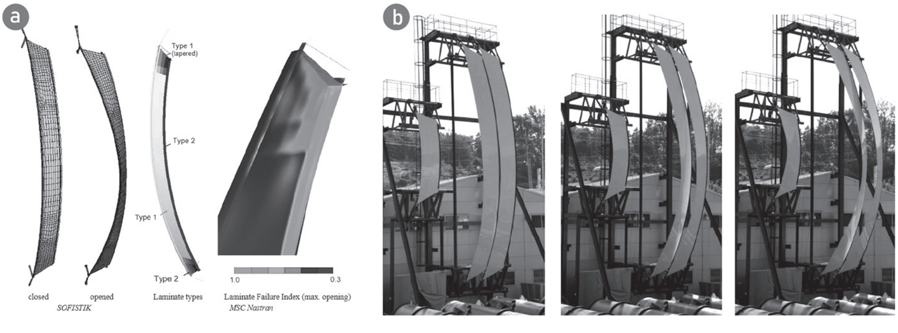

Figure 6. Operable blind of the Ocean Pavilion. a) Structural evaluation of the blind with maximum length; b) Full-scale performance model test of the smallest and largest blinds. (Source: Knippers *et al.*, 2012, pp. 6, 8).

Finally, the blinds allow different operating modes according to users' needs and fulfil a climatic function (Knippers *et al.*, 2012). They can be activated individually or synchronized to create different patterns along the façade, providing continuous shape change with smooth movements.

3.6 Pho'liage®

The **Pho'liage®** project is bioinspired by the curve-line folding of the *Dionaea muscipula* and *Aldrovanda vesiculosa*. Both organisms exhibit thigmonastic typology, which reacts to physical contact of prey with the plant. The kinetic module is a device to provide adaptive shading. In addition to biomimetic studies on the curves of the reference plants, the development team used climate simulation processes to optimize the thermal comfort of the building (L. Charpentier *et al*., 2022).

The bimetal acts as an actuator and is centrally fixed in the triangular module made of biopolymer (a thermoplastic elastomer) (L. Charpentier *et al*., 2022). The bimetal piece responds to temperature variation and solar incidence. The biopolymer, in turn, provides a shading function for façades. The responsive modules are fixed on hexagonal aluminium structures.

4. Results and Conclusions

The case studies present designs where bioinspiration by the nastic movements of plants have played a relevant role. These projects employed different organism strategies, such as the reversible opening and closing movement [P01 to P04, P06] and flexible mechanical deformation of the plant [P05]. Regarding the different typologies of nastic movements, we found two solutions inspired by thigmonastic movement, two by hydronastic movement, one by thermonastic, and another by nyctinastic movement. *Table 1* provides a comparative analysis of the six case studies.

Table 1. Analysis and classification of case studies – synthesis table. The signal "-" means that the criterion in question did not occur (Source: Authors).

	CARACT.	P01 **AIR FLOW(ER)**	P02 **ALBAHR TOWERS**	P03 **BIMETAL BIOMODULE**	P04 **HYGROSKIN METEORO-SENSITIVE PAVILION**	P05 **OCEAN PAVILION**	P06 **PHO'LIAGE®**
	YEAR	-	2012	2024	2012	2012	2022
NATURE	**Bioinspiration**	*Crocus flower*	Cactus, Pineapple, flower opening and closing	*Ammophila arenaria*	Cone of conifers *(Pinophyta)*	*Strelitzia reginae*	*Dionaea muscipula* and *Aldrovanda vesiculosa.*
	Organism's Strategy	Opening and closing of petals in response to temperature variation	Cactus morphology; opening and closing of petals	Opening and closing of leafs. Morphology full of veins and the existence of bulliform cells (motor cells).	Responsive behaviour of cone bracts (closing when in contact with water and opening as they dry)	Flexible mechanical deformation of the plant	Opening and closing of leafs. Curve-line folding of the organisms
	Typology of nastic movement	Thermonastic	Nyctinastic	Hidronastic	Hidronastic	Thigmonastic	Thigmonastic
DESIGN	**Responds to**	Temperature variation	Temperature variation	Temperature variation	Humidity Variation	Temperature variation	Temperature variation
	Stimulus for control	INT	EXT	INT	INT	EXT	INT
	Primary Environmental Function	Self-Ventilating	Shading	Self-shading	Self-Ventilating	Ventilating	Self-shading
	Different strategies for transforming	GS	GS	GS / VMP	FSS / VMP	GS / VMP	GS / VMP
	Material	Shape Memory Alloy	Aluminium structure coated with fiberglass mesh	Bimetal	Wood associated with synthetic composites and computer programming	Glass Fiber Reinforced Polymer	Bimetal
	Modular Solution	YES	YES	YES	YES	NO	YES
	The development stage	Pilot-scale prototype	Full-scale application	Pilot-scale prototype	Full-scale application	Full-scale application	Pilot-scale prototype
	REFERENCES	(Lift Architects, n.d.)	(Karanouh & Kerber, 2015)	(Andrade et al., 2024)	(Menges & Reichert, 2015; Reichert et al., 2014)	Knippers et al., 2012)	(L. Charpentier et al., 2022)

In terms of the design strategies, although the biomimetic references encompass four typologies of nastic movement, only two variations of environmental response are present: temperature [P01 to P03; P05; P06] and humidity [P04]. About 67% presented intrinsic material control, with adaptive responses inherent to the material properties [P01, P03, P04, P06], while 33% utilized electromechanical devices to operate the systems [P02, P05]. To address the main functions of environmental control, we distinguish self-shading from shading, and self-ventilation from ventilation. Classifications with the prefix "self" denote the lack of need for energy or mechanical systems to operate, meaning they are versions with intrinsic control. The others, consequently, denote extrinsic control by electricity with sensors and actuators. The projects adopted different materials, ranging from smart and shape-changing materials: SMA [P01]; Bimetal [P03; P06]) to computationally designed programmable materials [P04, P05]. The prevailing deformation strategies were geometric strategies inspired by plant morphology and variation in the material property (either by adopting materials already exhibiting the property, such as bimetal [P03; P06], or through material fabrication [P04; P05]).

Finally, we noticed that not necessarily the solutions present an analogy (ISO 18458:2015, 2015) in the cause of the triggering stimulus of the nastic movement. Only two projects demonstrated a direct functional correspondence between the type of movement and the response to environmental variation (P02 inspired by thermonastic movement and responds to temperature variation, while P04 by hydronastic movement and responded to humidity variation). The other solutions [P02, P03, P05, and P06] emulated the morphology of organisms in line with material deformation strategies (GS and/or VPM). Thus, they provided behaviour alteration through biomimetic processes by abstraction, which deals with inductive processes, where a general conclusion is obtained from observing something specific (ISO 18458:2015, 2015).

This practice highlighted several ways to draw inspiration from nature and showed that a direct correspondence between organisms' form, function, and behaviour is only sometimes necessary. The biomimetic process allows for the creative and innovative application of principles and strategies from organisms while maintaining responsiveness to different environmental conditions. Thus, it enables the resolution of human problems in various design contexts (in various Architecture contexts, namely in façade design). However, we emphasize that this article conducted a qualitative approach. We recommend a systematic literature review on façade designs with nastic movements followed by statistical data analysis for future studies.

We expect this research to demonstrate the different possibilities of configuring adaptive solutions for façades, which can adopt intrinsic or extrinsic control approaches and thus operate with or without electromechanical devices. The relevance of kinetic research that adapts depending on different climatic conditions. We believe that further exploration of this field of knowledge could increasingly enable more complex and more efficient solutions accessible to society contributing to reduce energy consumption and promoting thermal comfort in buildings. These themes are essential for fostering sustainable façade solutions and building sustainability.

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Resumen: El concepto central de la biomimética es la transferencia de principios biológicos a la tecnología, que se produce bajo un enfoque transdisciplinar. Los movimientos násticos corresponden a movimientos vegetales independientemente de la dirección del estímulo. El estado actual de los conocimientos demuestra la aparición de soluciones bioinspiradas para fachadas basadas en movimientos násticos. Este artículo destaca seis soluciones para fachadas adaptables que pretenden promover movimientos reversibles en respuesta a las condiciones ambientales, ya sea para sombrear o ventilar. Los proyectos presentados son Air Flow(er), AlBahr Towers, Bimetal Biomodule, HygroSkin, Ocean Pavilion y Pho'liage. Estos proyectos pueden utilizar control extrínseco (sistemas artificiales asociados a sensores y actuadores) o intrínseco (sistemas autoajustables sin electricidad ni dispositivos mecánicos, utilizando materiales como la aleación con memoria de forma, el bimetal o la madera asociados a compuestos sintéticos y programación informática). Estas soluciones también emplean diferentes estrategias de deformación del material (como estrategias geométricas, variación de las propiedades del material y/o contracción e hinchamiento por incompresibilidad de fluidos). Así pues, podemos afirmar que las estrategias sofisticadas inspiradas en la naturaleza, como los movimientos násticos, permiten abstraer la inteligencia de la naturaleza en soluciones humanas receptivas que pueden contribuir a la sostenibilidad de los edificios.

Palabras clave: Biomimética - Bioinspiración - Movimientos de las plantas - Movimientos násticos - Fachada adaptativa - Fachada cinética - Deformación del material - Materiales inteligentes - Material con capacidad de respuesta - Sostenibilidad

Resumo: O conceito central da biomimética é a transferência de princípios biológicos para a tecnologia, o que ocorre em uma abordagem transdisciplinar. Os movimentos nasais correspondem aos movimentos das plantas, independentemente da direção do estímulo. O estado atual do conhecimento demonstra o surgimento de soluções bioinspiradas para fachadas baseadas em movimentos násticos. Este artigo destaca seis soluções para fachadas adaptativas que visam a promover movimentos reversíveis em resposta às condições ambientais, seja para sombreamento ou ventilação. Os projetos apresentados incluem Air Flow(er), AlBahr Towers, Bimetal Biomodule, HygroSkin, Ocean Pavilion e Pho'liage. Esses projetos podem usar controle extrínseco (sistemas artificiais associados a sensores e atuadores) ou controle intrínseco (sistemas autoajustáveis sem eletricidade ou dispositivos mecânicos, usando materiais como liga com memória de forma, bimetal ou madeira associados a compostos sintéticos e programação de computador). Essas soluções também empregam diferentes estratégias de deformação do material (como estratégias geométricas, variação das propriedades do material e/ou contração e dilatação por incompressibilidade do fluido). Assim, podemos afirmar que estratégias sofisticadas inspiradas na natureza, como os movimentos násticos, permitem a abstração da inteligência da natureza em soluções humanas responsivas que podem contribuir para a sustentabilidade dos edifícios.

Palavras-chave: Biomimética - Bioinspiração - Movimentos de plantas - Movimentos násticos - Fachada adaptativa - Fachada cinética - Deformação de material - Materiais inteligentes - Material responsivo - Sustentabilidade

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