Environmental Footprints and Eco-design of Products and Processes

Amilton José Vieira de Arruda
Felipe Luis Palombini *Editors*

Biology, Biomimetics and Natural Design

Innovative Technologies and Sustainable Materials

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Editors
Amilton José Vieira de Arruda
BioDesign Lab, Programa de
Pós-Graduação em Design (PPGDesign)
Universidade Federal de
Pernambuco [UFPE]
Recife, Brazil

Felipe Luis Palombini
Department of Industrial Design
Universidade Federal de Santa Maria
Santa Maria, Brazil

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Chapter 1
Adaptive Façades: A Comparative Analysis of Bimetal Solutions

Tarciana Andrade, José Beirão, and Amilton José Vieira de Arruda

Abstract The current knowledge demonstrates that the expansion of adaptive façades, which contribute to improving the energy performance of built spaces, can combine biomimetics research into advanced materials. The bimetal is a smart material that bends when heated. Designers use the bimetal to propose architectural solutions adapted to different climatic conditions, classifying them, for example, into the following typologies: self-shading [SH], self-ventilating, self-energizing, and self-structuring. This work seeks to demonstrate the potential of bimetal in architecture. We report on 20 solutions, including installations and proposals for façades, published between 2010 and 2022, then classify them among the typologies mentioned before. We identified five solutions by bioinspiration. Modules make up the solutions. Together, they provide complex structures and geometries that are lightweight and responsive. We selected four SH proposals for comparative analysis because these typologies correspond to the scope of this research. SH proposals are designs of smart systems that use solar energy to block the sun, avoiding excess heat gain. The projects selected are modular solutions that can have different characteristics, such as being a commercial solution, aiming to promote visual permeability, containing a photovoltaic cell, or using bimetal as an actuator. We conclude that bimetal façades have the potential to provide solutions that combine creativity with climate performance, with unique standard elements. By associating nature's strategies with development, it is possible to develop responsive solutions through the movement of modules. The elements adapt to different environmental conditions (that affect air temperature) and improve the energy performance of buildings.

T. Andrade (✉) · J. Beirão
CIAUD, Research Centre for Architecture, Urbanism and Design, Lisbon School of Architecture, Universidade de Lisboa, Lisboa, Portugal
e-mail: jnb@fa.ulisboa.pt

A. J. V. de. Arruda
BioDesign Lab, Programa de Pós-Graduação em Design (PPGDesign), Universidade Federal de Pernambuco [UFPE], Recife, Brazil
e-mail: amilton.arruda@ufpe.br

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Keywords Kinetic façade · Smart material · Bimetal · Thermobimetal · Biomimetic adaptive façade · Adaptive shading · Self-shading

1.1 Introduction

Biomimetics applied to architecture, in turn, presents transdisciplinary approaches that seek to connect biologists to designers and technologists [4, 19, 20]. It stands out for the research on new materials, their performance, and respective production processes [12, 19]. An attentive look at the solutions of nature, which has evolved over 3.85 billion years, can contribute to revolutionizing products, processes, and life [5].

To promote kinetic façades adaptable to different climatic conditions, extant research shows the intensification of solutions using smart materials [7, 12, 25] that aim to reduce system maintenance and achieve zero energy options. Solar shading and shutters can contribute to energy reduction during the different seasons and present a feasible reduction in CO_2 consumption rates [11].

Bimetal or thermobimetal is a smart material [24] that tends to bend when heated [22, 24]. The explanation for such behavior lies in the composition of the bimetal, which comprises at least two layers of metal, permanently bonded and with different thermal expansion coefficients [10, 19, 21, 22, 24] (Fig. 1.1). The temperature variation will cause the passive layer to expand less than the active one, causing the material to bend [10, 18, 21].

According to Sack-Nielsen [22], a bimetal exhibits isotropic properties (equal and predictable behavior for both the width and height of the material). The behavior of bimetal can be enhanced or even prevented depending on its shape [24]. There are several advantages to incorporating the inherent characteristics of bimetal in architectural projects, such as predictability, precision, power consumption reduction, and low maintenance [13]. The material also presents reversible behavior to promote solar protection of windows at times of high heat gain [1–3, 6–8, 13–17, 22–25].

Nowadays, there are countless applications, and we can find bimetals practically everywhere [10, 21]. We find it in products that regulate and control temperatures, such as electric stoves, irons, hair dryers, and systems for protecting electrical circuits.

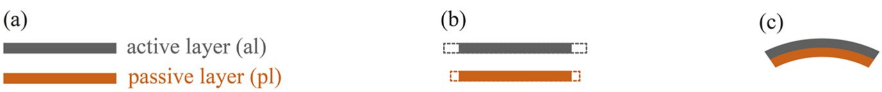


Fig. 1.1 Bimetal consists of two layers of metal with different rates of thermal expansion: (**a**) Layers that constitute the bimetal; (**b**) Each layer has different coefficients of thermal expansion; (**c**) Curvature of the material with the temperature rise: the active layer exerts compression, and the passive layer exerts tension. (Adapted from [2], License CC BY)

1.2 Bimetal in Architecture

In the last 20 years, thermobimetal has gained relevance in architecture [25]. Sung's work [9, 17, 24] is probably the most advanced example [24], relating form to performance [3, 24, 9]. She sought to develop solutions that are sensitive to environmental change, like human skin—without the use of energy and controls. Doris publishes the projects and experiments on the DOSU Studio Architects website [9] and classifies them into six typologies:

- ***Self-shading [SH]:*** Designs are smart systems that use solar energy to block the sun, avoiding excess heat gain, without the use of electromechanical devices.
- ***Self-ventilating [SV]:*** Projects that use the ambient air temperature to operate in order to release hot air. Once cooled, the system returns to its initial position.
- ***Self-structuring [ST]:*** Thicker versions of bimetal can be heated to higher temperatures (above 121 °C) to deform in the ideal condition for installation in tight spaces. Once cooled, the part can provide a pre-tensioned surface, resulting in a strong, light, and porous surface.
- ***Self-energizing [SE]:*** Uses solar energy in configuration to reflect, generate heat in a chimney, and provide air exchange, in order to ventilate the space.
- ***Self-assembling:*** Uses bimetal to facilitate toolless construction. In some cases, on non-reversible systems.
- ***Self-propelling:*** Experiments in the field of robotics to make things: spin, walk, roll, bounce, jump, slide, and shake. Such experiments use solar energy to drive movement and do not need computer controls or artificial intelligence to function.

Considering the first four typologies suggested by [9], we identified 20 bimetal proposals, published between 2010 and 2022, including installation [**IP**] and façade projects [**FA**] (Table 1.1). We also classified the proposals according to their inspiration in nature. We selected the first four typologies because of their relevance to this research, which aims to develop a self-shading solution for bio-inspired façades in the future. We classified the solutions as Complex Structures [**CS**] or Complex Movement [**CM**]. The classification process followed the definitions reported in the project descriptions.

We identified six projects inspired by nature. Tracheolis—ARS [**P5**] is bioinspired by the grasshopper's breathing system, which has a complex communication network between the vessels of the trachea. It is a proposal for self-ventilating. In turn, Urban Urchin [**P11**] emulates the morphology of the sea urchin. The aim of the project is to improve air quality through fluid dynamics. Air movement is associated with energy collection, a case of self-energizing. Solutions **P3**, **P18**, **P19**, and **P20** use the movement of plants as a reference. These proposals are examples of self-shading.

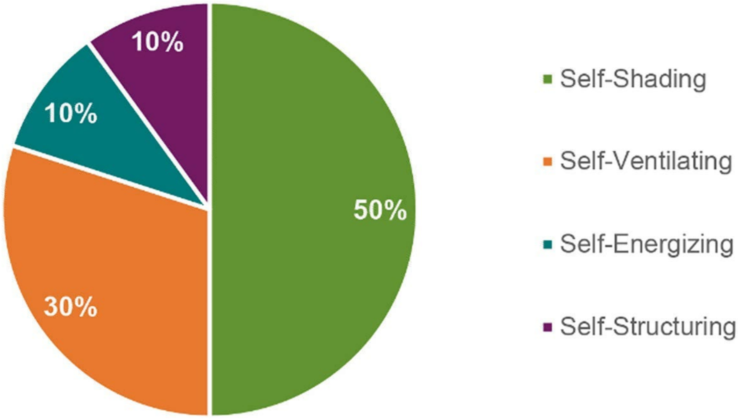
Ten solutions aimed to develop façade solutions [**FA**]. The other ten were installation proposals [**IP**]. *The self-shading typology corresponds to the classification with the highest incidence* (eleven proposals), followed by self-ventilating, self-energizing, and self-structuring (Graph 1.1).

Table 1.1 Twenty proposals with bimetal

Proposal	Year	FA or IP	B	SS or PM	C	Tipoloy				Refs.
						SH	SV	ST	SE	
P1—Waist Tigtennig (DeCours, AIA New Orleans, LA)	2010	IP	N	S	CS	–	•	–	–	[9]
P2—Armoured Corset (WuHo Gallery, Hollywood, CA)	2010	IP	N	D	CS	–	•	–	–	[9]
P3—Facade application of an arrangement of bimetallic strips as a responsive Building envelope	2010	FA	Y	S	CS	•	–	–	–	[13]
P4—Bloom (M&Gallery, Silver Lake, CA)	2011	IP	N	D	CS	–	•	–	–	[9, 14, 24, 3]
P5—Tracheolis – ARS (Electronica, Linz, Austria) and (Copernicus Science Center, Warsaw, Poland)	2012 and 2015	IP	Y	D	–	–	•	–	–	[9]
P6—Blink Exhibition, MOCA; Los Angeles, CA	2013	IP	N	D	CS	–	•	–	–	[9]
P7—Bimetal Facade System DARC-Digital Architecture Research Consortium (Texas—EUA)	2013 – 2014	FA	N	S	CM	•	–	–	–	[15, 6]
P8—Pivot Shade System	2014	FA	N	S	CM	•	–	–	–	[24]
P9—Dialectic Form Finding of Passive and Adaptive Shading Enclosures	2014	FA	N	S	CM	•	–	–	–	[1]
P10—eXo (Museum of Contemporary Art, Santa Barbara, CA)	2014	IP	N	D	CS	–	–	•	–	[9]
P11—Urban Urchin (New York, NY I Chicago, IL I Los Angeles, CA)	2014	FA	Y	D	CS	–	–	–	•	[9]
P12—Tw/rl (Chicago, IL)	2015	IP	N	D	CS	–	–	–	•	[9]
P13—Shading system relies on the toggling of the shapes as the temperature changes	2016	FA	N	S	CM	•	–	–	–	[24, 9]
P14—Drift (New York, NY I Chicago, IL I Los Angeles, CA)	2016	IP	N	S	–	•	–	–	–	[9]
P15—Oculus	2017	IP	N	S	CM	•	–	–	–	[9]
P16—Performance through thickfolds (Danish)	2017	FA	N	S	CM	–	•	–	–	[22]
P17—Fuller 2.0 (South Coast Botanical Garden)	2018	IP	N	S	CS	–	–	•	–	[9]
P18—Invert Auto-Shading Windows	2019	FA	Y	S	CM	•	–	–	–	[16, 9, 23, 3]
P19—Pho'liage 01 (Brussels, Paris, and Luxembourg)	2019	FA	Y	S	–	•	–	–	–	[7, 17]
P20—Pho'liage 02 (Brussels, Paris, and Luxembourg)	2022	FA	Y	S	CM	•	–	–	–	[7]

Source: Authors

B = bio-inspired projects; **Y** = yes, meets the requirement; **N** = No, without classification; **FA** = Façade solutions; **IP** = Installation proposals. "•" = identifying the classification; "-" = the criterion in question did not occur. **S** = Single standard; **D** = Different modules; **CS** = Complex structures; **CM** = Complex movement



Graph 1.1 Typologies of the twenty bimetal projects

In the analysis, we emphasize that the classification as to typology (SH, SV, ST, or SE) should follow the project descriptions. Figure 1.2 shows different types of projects. However, we confirm that a solution could be multifunctional (such as the Urban Urchin project [**P11**], which also has a scope for self-shading and self-ventilating).

An example of a self-structuring solution is the eXo [**P10**]. The development process for this project consisted of preheating constituent bimetallic pieces and fitting them together in a pre-tensioned way. When the pieces cool down, they form a strong and lightweight structure, like the exoskeleton of a lobster or crustacean. The tension on the surface is maintained afterward.

Of the **FA**, eight were self-shading. *The studies focus on the performance of material movement to promote shading* (of the ten proposals, **CM** = 8; **CS** = 2). Nine solutions presented studies with a *single version of the element* (**S** = 9; **D** = 1), which allows for tessellation on the façade.

We identified the opposite for studies of installations that explore complex volumetrics (**CS** = 7; **CM** = 3); (**D** = 6; **S** = 4). However, we would like to point out that the installations are smaller-scale experiments, which could have the potential for façades, such as the Drift installation (**P14**).

Sixteen projects used *bimetal as the primary raw material* (**P1** to **P4**, **P6** to **P8**, **P10** to **P15**, and **P17** to **P19**). While others combined different materials with the solution, they used the *bimetal as the system's sensor and actuator* (**P5**, **P9**, **P16**, and **P20**). Therefore, two different development approaches allow the potential use of the material to be extended by combining the performance requirements of the façade with creativity.

Finally, this first analysis shows that several *solutions used parametric algorithms for their design*. These allowed for *structural complexity* (nine occurrences)

Fig. 1.2 (**a**) Bloom [P4], self-shading project; (**b**) Fuller 2.0 [P17], self-structuring solution; (**c**) Invert auto-shading windows [P18], self-shading project. Source: (**a**) photo by Brandon Shigeta (2011), CC-BY-SA-4.0, via Wikimedia Commons. Available at: https://commons.wikimedia.org/wiki/File:Bloom_by_DOSU.jpg (Accessed 12 October 2023); (**b**) photo by Doris Sung (2019), CC-BY-SA-4.0, via Wikimedia Commons. Available at: https://commons.wikimedia.org/wiki/File:Fuller_by_DOSU.jpg (Accessed 12 October 2023); (**c**) photo by Pinkelephante (2018), CC-BY-SA-4.0, via Wikimedia Commons. Available at: https://commons.wikimedia.org/wiki/File:Invert_Shading_System.png (Accessed 12 October 2023)

and a study of the *kinetic properties of standardized modules in bimetal* (eleven solutions). Thus, we can confirm that even though bimetal has isotropic characteristics, it is possible to create complex volumes or elements that can be adapted to different climatic conditions.

1.3 Comparative Analysis of Self-Shading Projects

The self-shading typology corresponds to the scope of this research. To better understand projects related to the SH, we selected four of them for comparative analysis (Table 1.2). As a selection criterion we defined that the project should necessarily: (a) be classified as self-shading; and (b) have a physical prototype. Thus, the following were selected:

- *InVert Auto-Shading Windows*®: A patented, awarded, and commercial product solution [3, 9, 16, 23].
- *Bimetal Facade System*: A version that combines the function of shading with the promotion of visual permeability [6, 15].
- *Pho'liage*® version 1: A prototype that uses bimetal associated with photovoltaic cells to convert excess solar energy into renewable energy [7, 17].
- *Pho'liage*® version 2: The bimetal in this prototype plays the role of an actuator, acting with the biopolymer (material responsible for promoting shading [7].

In the following, we briefly detail each of the selected projects that presents a comparative and qualitative analysis of the designs.

InVert Auto-Shading Windows features patents, awards, and a commercial product that reduces the need for artificial air conditioning by up to 25% [16]. The movement of plants inspires the design of the InVert™ modules, such as flowers or leaves that rotate to face the sun as it moves across the sky [16]. The modules sit inside the

Table 1.2 Comparative and qualitative analysis between designs using bimetal

Features	(a) Invert auto-shading	(b) Bimetal facade system	(c1) Pho'liage®	(c2) Pho'liage®
Research group or architecture studio	DOSU studio architects and TBM-designs LLC (Texas—USA)	DARC—Digital architecture research consortium (Texas—EUA)	ArtBuild (Brussels, Paris, and Luxembourg—EU)	ArtBuild (Brussels, Paris, and Luxembourg—EU)
Year	2019	2013–2014	2019	2022
Bioinspiration	•••	–	•••	•••
Self-shading	•••	•••	•••	•••
Visual permeability	••	•••	••	••
Modular solution	•••	•••	•••	•••
Number of bimetal parts per module	1	2	3	1
Bimetal thickness	0.06858 mm	0.09 mm	–	–
Prototype sizes	–	99.06 × 99.06 × 15.24 cm wood frame 50 bimetal louvers 6 vertical aluminums 30 connection pieces	–	–
System between glasses	•••	•••	•••	•••
Presence of photovoltaic cells	–	–	•••	–
Patent	•••	–	••	–
Award	•••	••	–	–
Commercial product	•••	–	–	–
References	[16, 9, 23, 3]	[15, 6]	[7, 17]	[7]

Source: Authors
We assigned "•", "••" or "•••" for each criterion defining a hierarchy of interest. The higher number of points means that more attention was given to the highlighted criterion. A "-" means that the criterion in question did not occur

cavity of a standard insulated glass unit (IGU) [16]. It acts as an organic shutter system that reduces heat gain and energy consumption [9]. The modules rotate under the effect of temperature variation and solar radiation [3] (Fig. 1.3).

The *Bimetal Facade System* seeks to promote a balance between the contradictory performance parameters of the façade: visual permeability and solar performance throughout the day or year [6, 15] (Fig. 1.4).

A prototype version uses bimetallic fins, 0.09 mm thick, fixed between a 3D printed connection and vertical aluminum rods [15] (Fig. 1.4a). It positions the rotated modular elements (Fig. 1.4b) around the fixing axis and allocates them between triple-glazed window systems. The bimetallic fins remain parallel and straight at room temperature. When heated they curve into an "S" shape and tend to be positioned more horizontally. By containing the fins between panes of glass they amplify thermal factors to activate the system [15]. The solution features shutters to manage the air masses between panes using fluid dynamics.

The first version of the *Pho'liage*® is a bioinspired design by the opening and closing of the *Oxalis acetosella* leaves that respond to light and temperature variation throughout the day and night (Fig. 1.5a). The solution is composed of three bimetal elements (Fig. 1.5b) and photovoltaic cells [7, 17] (Fig. 1.5c).

During the winter it aims to reduce the energy required for heating. In summer, it protects the façade from overheating. Monocrystalline photovoltaic cells (integrated into the solution) transform surplus solar energy into renewable energy [7, 17] (Fig. 1.5c). They performed an anticorrosion test with a painted mock-up positioned outdoors for 36 months.

The second version also uses the curve-line fold found on the leaf of *Dionaea muscipula* and *Aldrovanda vesiculosa* as bioinspiration (Fig. 1.6a, b). The solution features a tiny bimetal piece as an actuator. This piece is centrally attached to the triangular module with a curve-line fold, made of biopolymer—thermoplastic elastomers [7]. The bimetallic alloys function as actuators in the sun, while the biopolymer provides shading.

The responsive modules are fixed on adaptable honeycomb support structures made of aluminum. This solution corresponds to an adaptive shading device developed through biomimetics and simulation processes to optimize thermal comfort and contribute to reducing energy consumption [7].

Fig. 1.3 Invert auto-shading windows [P18], self-shading project. (Source: photo by Pinkelephante (2018), CC-BY-SA-4.0, via Wikimedia Commons. Available at: https://commons.wikimedia.org/wiki/File:Invert_Shading_System.png (Accessed 12 October 2023))

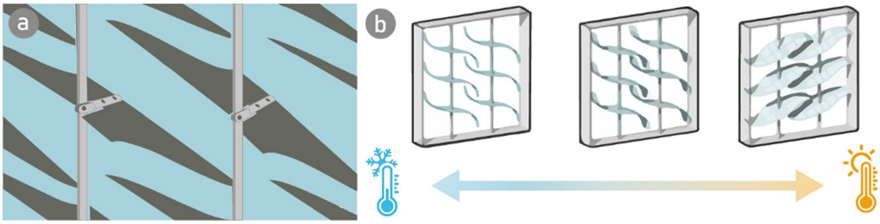


Fig. 1.4 Bimetal facade system. Authors based on the work of [6, 15]

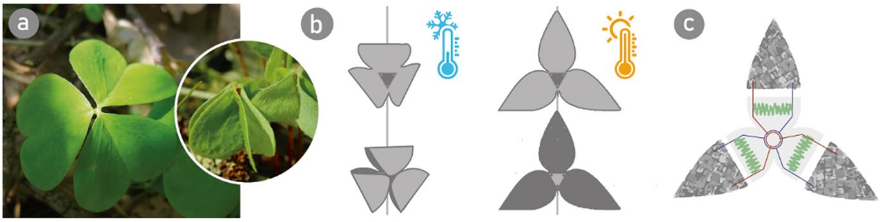


Fig. 1.5 (**a**) *Oxalis acetosella*; (**b**) three bimetal elements; (**c**) photovoltaic cells. (Source: (**a**) photo by Kristian Peters Fabelfroh (2005), CC-BY-SA-3.0, via Wikimedia Commons. Available at: https://commons.wikimedia.org/wiki/File:Oxalis_acetosella_blatt.jpeg (Accessed 12 October 2023); photo by Salicyna (2019), CC-BY-SA-4.0, via Wikimedia Commons. Available at: https://commons.wikimedia.org/wiki/File:Oxalis_acetosella_2019-04-04_8947.jpg (Accessed 12 October 2023); (**b**, **c**) Authors based on the work of [7, 17])

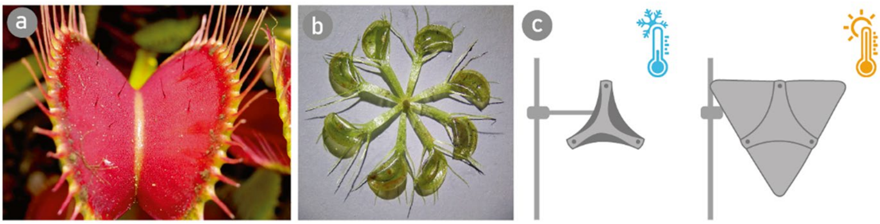


Fig. 1.6 Curve-line fold of: (**a**) *Dionaea muscipula*; (**b**) *Aldrovanda vesiculosa*; and (**c**) Module adaptable to different temperatures with the bimetal as an actuator. (Source: (**a**) photo by Noah Elhardt (2005), CC-BY-SA-2.5, via Wikimedia Commons. Available at: https://commons.wikimedia.org/wiki/File:Venus_Flytrap_showing_trigger_hairs.jpg (Accessed 12 October 2023); (**b**) photo by Stefan Lefnaer (2020), CC-BY-SA-4.0, via Wikimedia Commons. Available at: https://commons.wikimedia.org/wiki/File:Aldrovanda_vesiculosa_sl23.jpg (Accessed 12 October 2023); (**c**) Authors based on the work of [7])