

Review Article: Phyto-Inspired Design: Innovative Solutions for Architecture

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Abstract

For a long time, designers have mainly taken inspiration from nature as a solution, defined as bio-inspired, to overcome design problems. Phyto-inspired approaches, or phytomimetics, is a subdivision of bio-inspired approaches, which focus on inspiration taken from plants with regard to materials, structures, and movements, for example. Many well-known buildings and inventions in various time periods were designed by using phytomimetic approaches based on available technologies, such as the Gothic-style fan vault in medieval churches, many works with dendriform structures designed by Gaudi, coiled extension wires, and the development of monoplane aircraft in the twentieth century. This article intends to explore the use of plant-inspired problem-solving approaches in architectural design by subdividing them into three main types of inspirations: phytomorphism, dendriform structures, and phytomechanisms. Several case studies are presented to show how architects and designers can use inspiration from plants as a potential solution for sustainable and efficient design.

Keywords: Phytomimetic, Plant-inspired, Biomimetic, Sustainable, Compliant mechanism, Dendriform

1. Introduction

Living organisms have learned to adapt in the appropriate way to their environment through 3.8 billion years of evolution. Many architects and designers have mainly taken inspiration from nature to solve particular design problems. Numerous terms have appeared to describe the flow of ideas from nature to technical solutions, such as “bio-inspiration”, “bionics”, “biomimetics”, “biomimicry”, and so on. These terms are in common use and vary in their meaning and usage. “Bionics”¹ and “biomimetics”² are considered to be similar in definition; “bionics” is commonly used with regard to the application of construction principles in nature for the design of technological solutions, whereas “biomimetics” tends to be used for materials and systems (Barthlott, Rafiqpoor & Erdelen, 2016). For example, a building may be referred to as “bionic” but its surface as “biomimetic”. In contrast, the term “bio-inspiration” is more comprehensive, embracing everything from bionics and biomimetics to bioinspired design. The chemist Whitesides defined “bio-inspiration” as “using phenomena in biology to stimulate research in non-biological science and technology” (Whitesides, 2015).

Two different approaches are well established in biomimetics: the bottom-up approach (from nature to design or solution-based) and the top-down approach (from design to nature or problem-based). The initial approach to biomimetic design can follow either a bottom-up process or a top-down process; both result in “biomimetic development” (Speck, T. & Speck, O. 2008). Using biomimetic approaches as a design tool has specific potential to contribute to sustainable development, as indicated by the German biologist * while Michael Pawlyn, a pioneering architect who has applied biomimetic principles to architecture, defines biomimetic ideas as “mimicking the functional basis of biological forms, processes and systems to produce sustainable solutions” (Pawlyn, 2011).

Plants, in contrast to other living organisms, are tied to their specific location; they cannot hide or seek protection from drought, heat, or cold but are exposed to different environmental conditions. Hence, the survival of plants is dependent on their ability to adapt to the changing environmental conditions over a day or years. At present, the number of extant terrestrial (land) plants species, comprising flowering plants, gymnosperms, and ferns, is estimated to be approximately 370,000, of which more than 90% are known. This percentage is extremely

high compared with other taxonomic groups (Barthlott, Rafiqpoor, & Erdelen, 2016).

During their evolution, plants have developed excellent structures that are efficient with low density, high strength, and high energy absorption capacity (San & Lu, 2020). Throughout history, many architects and designers have used plants as a source of inspiration. In ancient Egypt, palm trees and bundles of papyrus plants were represented in floral capitals on stone columns (Portoghesi, 2000) (Figure 1a), while Acanthus plant features appeared in the capitals of the Corinthian and Composite order as ornaments in ancient Roman architecture (Rian & Sassone, 2014) (Figure 1b). The idea of mimicking tree-like shapes was also found in the Baroque period. The spiral columns of the Roman Basilica St. Peter (Baldacchino) were designed to represent the idea of the vine (Figure 1c) (Portoghesi, 2000)

The application of plant-inspired approaches to technological solutions emerged in the twentieth century. Ingo Etrich, the Austrian aviation pioneer, invented a monoplane-type aircraft, the Taube (Figure 2a). The Taube’s wing design is based on the concept of the seeds of the tropical plant *Zanonia macrocapa* (Figure 2b), which can be dispersed by wind over great distances. The Taube soon became known for its stability and safety. Plant-inspired designs are also found in the invention of barbed wire (Figure 2c) and extendable wire coil (Figure 2d), which imitate the thorny branches of the Osage orange *Maclura pomifera* and the tendrils of the climbing cucumber, respectively (Stahlberg, 2009)

The rapid increase of research publications on biomimetics indicated the significant potential impact on new innovations, especially in the field of sustainable architecture, which has become an important concern in recent years, since the building sector is responsible for 23% of global primary energy, 30% of global electricity, and approximately 25–33% of black carbon emissions (Ürge-Vorsatz, 2015). Consequently, this has led to growth in the integration of biomimetics and buildings, because biomimetics provides alternative solutions for structural efficiency, water efficiency, zero-waste systems, thermal environment, and energy supply, which are necessary for any sustainable building design (Singh, A. & Nayyar, N. 2015). This article aims to explore the potential of plant adaptation strategies in building design which might offer new approaches to sustainable solutions.

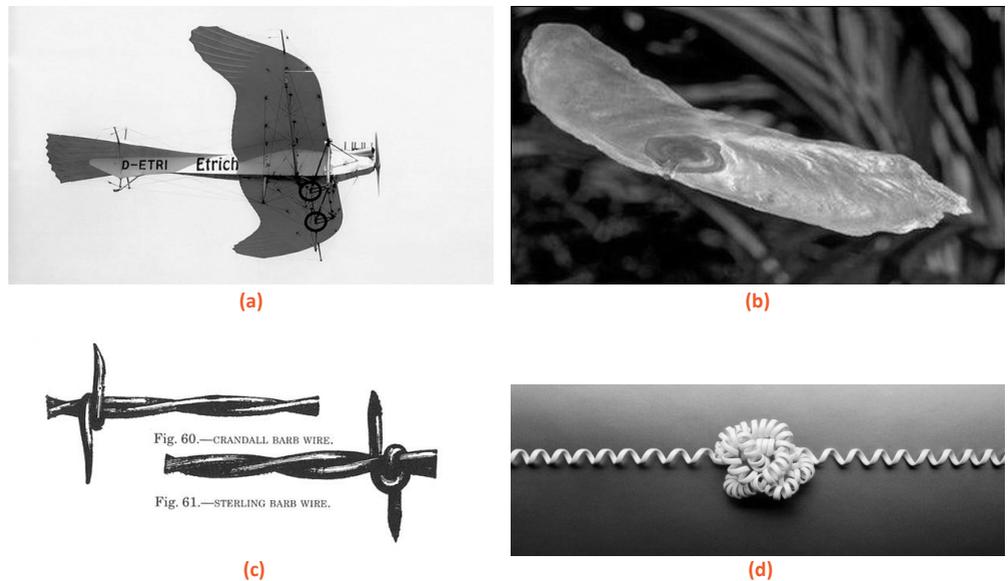
Figure 1.

(a) Ancient Egyptian column inspired by a bundle of papyrus plants. (Source: Distro, 2015)
(b) Capital of Corinthian order inspired by Acanthus plants in Classical architecture. (Source: Raingod, 1995)
(c) Baldacchino designed by Gian Lorenzo Bernini. (Source: Maltaly, 2011)



Figure 2. Examples of plant-inspired products.

(a) Taube monoplane aircraft type (Source: Bredow, 2019)
(b) Zonania seed (Source: Varma, 2018)
(c) Barbed wire, imitating thorny branches of the Osage orange. (Source: Martin, 2020)
(d) Extendable wire, imitating from the tendrils of the climbing cucumber (Source: StateTech, 2018)



2. Phytomimetic design – inspired by plants

Phytomimetics is a minor part of biomimetics. While the biomimetic approach attempts to imitate the function or structure of organisms in nature, phytomimetics deals only with botanical materials, structures, and movements (Stahlberg, 2009). In the past few decades, there are only a few well-known innovations which have served as successful phytomimetic designs, as shown in Table 1.

Biologically inspired design is not only defined as processes inspired by biotechnology, bionics, or biomimetics but also includes non-functional designs, called “biodecoration” (Barthlott, Rafiqpoor, & Erdelen, 2016). Therefore, the classifications of phytomimetic designs in this article comprise three main categories: phyto-inspired decoration, phyto-inspired structures, and phyto-inspired mechanisms.

3. Phyto-inspired decoration – Phytomorphism

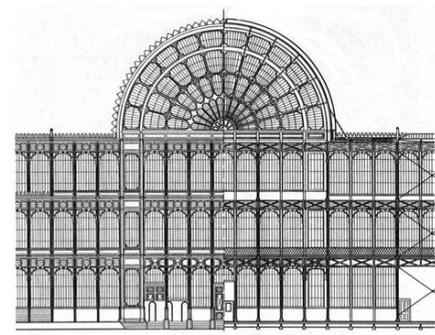
Phytodecoration or phytomorphism means mimicking an organism’s shape, pattern, or geometry without considering how it interacts with and contributes to the context (this approach is categorized in the organism level of biomimetics). Many design masterpieces have taken ideas from nature during architectural history. In the Classical period (500 BC to 400 AD), plants and floral shapes were the inspiration for designs for decorative purposes, such as decorative elements in orders (as mentioned before), which became essential ornaments in Classical style. During the Art Nouveau period in the late nineteenth century, plant-derived forms became the most popular features of architectural decoration, as can be seen from the famous design works such as the entrance gates of Paris subway metro stations (Figure 3a), designed by Hector Guimard, which were inspired by the curvilinear forms of vines and flowers (Rian & Sassone, 2014) and the Crystal Palace (Figure 3b), designed by James Paxton, which was inspired by the leaves of the giant waterlily (*Victoria amazonica*).

Innovations	Inspiration plants
Barbed wire	Osage orange thorny
Extendable wire	Tendrils of climbing plants
Velcro	Burdock plant
Taube monoplane	Zanonia seeds
Gyro-/helicopter	Maple seeds
Parachute	Dandelion seeds
StoColor® Lotusan®	Lotus leaves

Table 1. Examples of innovations based on phytomimetic approaches (Stahlberg, 2009)



(a)



(b)

Figure 3. Examples of plant-inspired decorations.

(a) Paris Métro entrances designed by Hector Guimard (Source: Paris Adèle, 2017)

(b) Crystal Palace, London, designed by Joseph Paxton (Source: Architonic, 2014)

4. Phyto-inspired structure – dendriforms

Concepts from nature, especially from plants, have been used for a long time by architects and engineers as inspiration to create structures with unique and efficient designs. Many builders have attempted to imitate the tree-like shapes, or dendriforms, in their designs to create large, long spans. During the Medieval age, dendriforms were constructed in the framework of the masonry construction of arches and vaults (Figure 4a). In the nineteenth century, when the “graphic statics” method was developed, it became an advanced tool for architects to visualize the stress equilibrium in structural design and allow them to create numerous dendriform structures (Rian, & Sassone, 2014). Antonio Gaudi, a pioneer of the bio-inspired architecture of the Art Nouveau period,



(a)



(b)

Figure 4. Examples of dendriform structures.

(a) Fan vault in King's College Chapel, England. (Source: Halling, 2013)

(b) Tree-like shape columns of Sagrada Família. (Source: Zander, 2012)



Figure 5.
(a) Mushroom-shaped columns designed by Frank Lloyd Wright. (Source: Tanzilo, 2018)
(b) Frei Otto's hanging models of branching systems. (Source: Nerdinger, 2005)

used a graphical method to design the tree-like columns in the Sagrada Familia Cathedral (Figure 4b), which collect the weights of the roof and take them to the ground (Huerta, 2006).

The development of reinforced concrete in the twentieth century allowed architects to develop the tree's complex forms into hyperbolic geometries known as "mushroom" or "umbrella" structures. A famous example is the tubular mushroom structure of the administrative offices of Johnson Wax designed by Frank Lloyd Wright (Figure 5a). Wright designed the interior columns in the form of a mushroom, inspired by the structural strength of the mushroom. According to a real-scale column load test, it was found that each mushroom column could carry an incredible load of 60 tons. Moreover, this design approach reportedly improved the company's office operations by 15–25% (Lipman & Wright, 2003).

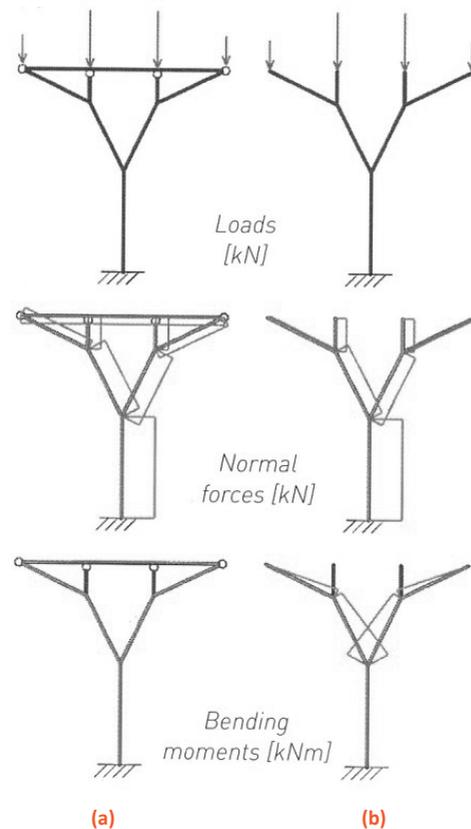


Figure 6.
(a) Internal forces of branched column with tension member.
(b) Example of internal forces in a tree. (Source: Jonas et al. 2019)

Dendriform structures perform force transfer with higher efficiency compared to regular structures because the tree-like branching system has short distances between the loading points and the supports (Ahmeti, 2007). Early experiments on branching structures using steel were done by the German architect Frei Otto. He carried out systematic researches and worked on the hanging models of branching structures (Figure 5b). Based on these models, Otto developed different branching structures in various designs, for example, structural support of footbridges, conference halls, and large grid domes.

Although branching structures are copied from plant ramifications, their load-bearing characteristics are quite different from those of natural trees. The loads are transferred as compression forces to the ends of the column heads, which are connected via horizontal load-bearing elements, whereas the branches of natural plants have free ends and are subjected to bending loads (Figure 6) (Jonas, F.A. et al. 2019).

Nowadays in advanced technology, determination of the form by physical model experimentation has been replaced by the use of computer simulation. A renowned example of the use of computational methods for the form-finding of a branching structure is the structural system of Stuttgart Airport Terminal 3 (Figure 7a). The tree-like steel columns, referred to as umbel systems (Figure 7b), are designed with multiple branching members which are distributed to carry the roof loads in compression with minimal bending moments. With this dendriform structure, the mass of structural materials is reduced while the load-bearing capacity is increased.

The development of algorithmic and parametric computer-aided design encourages more innovative and efficient dendriform structures. The Metropol Parasol (in Spanish: Las Setas de la Encarnación), designed by Jürgen Mayer-Hermann, is one of the largest wooden tree-like structures built in the world. The architect, who was inspired by the Cathedral of Seville and the ficus tree, expressed his idea by using the algorithmic and parametric technique as a form-finding process to create a complicated interlocking system of a massive timber structure (Figure 8a). Another example of the use of sophisticated computational design is MycoTree (Figure 8b). The geometry of MycoTree was designed by using 3D graphic statics, a novel method developed by Block Research Group at ETH Zürich (Akbarzadeh, 2015). The branching structure is made of load-bearing mycelium³ components which are designed to carry their self-weight plus the weight of the grid through compression. Although mycelium used as structural materials offers significant ecologic advantages, it is considered to be a low-strength material. Therefore, the appropriate structural geometry (using polyhedra in the form of branches like a tree) was designed to turn weak materials into load-bearing structures.



Figure 7.
 (a) Tree-like structure in Stuttgart Airport designed by Von Gerkan, Marg, and Partners (Source: Schlaich Bergermann Partner, 2019)
 (b) Umbel structural systems. (Source: Noll, P., 2017)

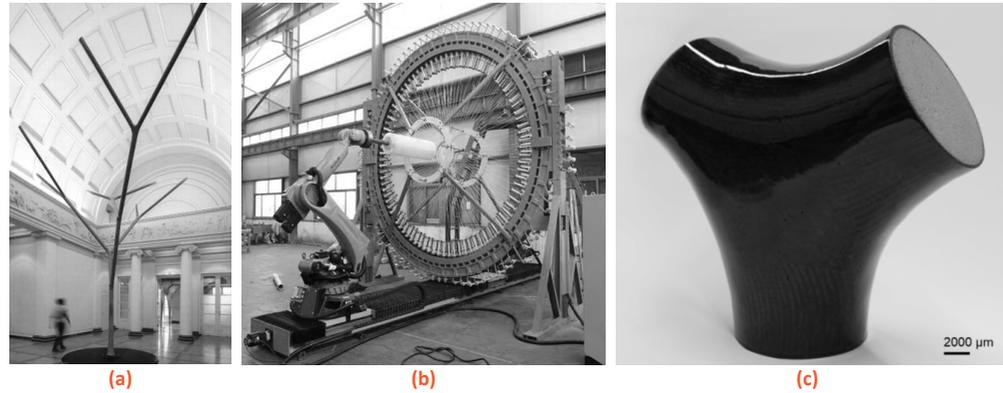


Figure 8.
 (a) Metropol Parasol, Spain, designed by Jürgen Mayer-Hermann (Source: Archello, 2011)
 (b) MycoTree developed by Block Research Group at ETH Zürich. (Source: Teteris, 2017)

Moreover, the compression-only branching geometry of MycoTree generates the minimal path under compression and significantly reduces the amount of internal stresses and subsequently reduces the amount of material required to carry the applied loads (Heisel et al. 2017).

Although there are many advantages of using branched columns compared to unbranched ones, such as being more slender and lightweight and giving more open space on the floor, they are very costly to construct. Hence, a solution for branched columns with cost-effective erection can be achieved by the development of bio-inspired branched structures based on lightweight fiber-reinforced composites. The function

Figure 9.
(a) Branched demonstration in Schloss Rosenstein. (Source: Jonas. et al. 2019)
(b) Radial braiding machine. (Source: Complex Industrial co.,Ltd, 2020)
(c) Concrete-filled branched node made of fiber-reinforced concrete composite plastic. (Source: ITKE, ITFT and PGB, 2018)



of fibers is to absorb the forces acting upon them, and the fibers should be oriented in accordance with the loads acting on them. This principle was adapted and transferred to a branched model, as demonstrated in the branched demonstration in Schloss Rosenstein at the Baubionik Exhibition in the Museum of Natural History in Stuttgart (Figure 9a). Fiber-reinforced plastics (FRP) are used in this project to produce ramified structures through a textile braiding process, which is done by Radial braiding machine (Figure 9b). However, the hollow structure suites for absorbing stresses resulting from tensioning, bending, or twisting but not compression. Therefore, concrete is then poured into the branched hollow structures in order to achieve the absorption of compressive stresses (Figure 9c) (Bunk et al. 2019).

According to the load tests, the results show that the three-armed node structures made of FRP and concrete with an arm diameter of 12.5 cm are able to resist compressive forces of up to 1706 kN (Jonas et al. 2018). This means that concrete-filled FRP branchings have sufficient load capacity for buildings of a few storeys.

5. Phyto-inspired mechanism – adaptive architecture

Plant movement mechanisms Plants, similarly to buildings, lack mobility, remain subject to a specific location, and have to cope with changing environmental conditions. Therefore, both plants and buildings have to be resilient and adaptable to the surrounding environment in order to achieve efficient performances.

Approaches to adaptive architecture can be learned from nature. Several mechanisms found in plants can be used as inspiration for adaptive building solutions. For instance, the air exchange solution in buildings by natural ventilation is analogous to the gas exchange process by stomatal apparatus which is found in plants (Sandak et al. 2019). Various examples of plants' adaptation to environmental conditions are illustrated in Figure 10.

As can be seen from Figure 10, plants are adapted to their environment in many different ways, which usually take place through two approaches: dynamic mechanisms and static strategies (López et al., 2017). These two approaches can be further divided into macro and micro scale, as presented in Table 2.

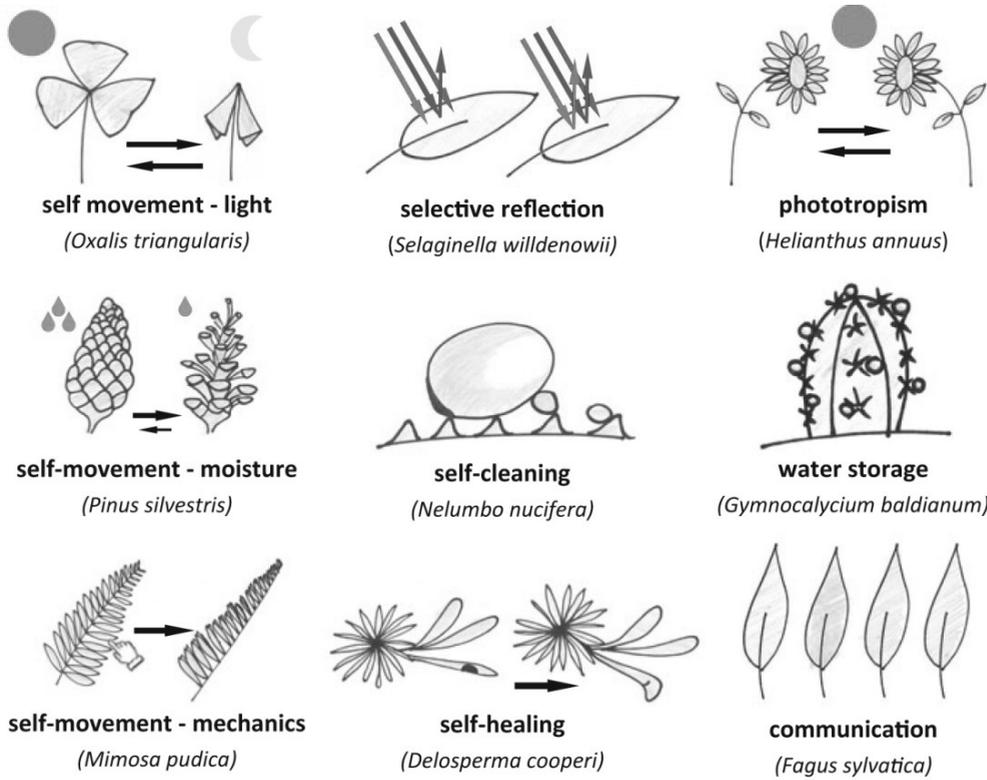
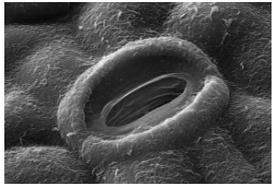


Figure 10. Adaptation of plants to environmental conditions. (Source: Sandak et al., 2019)

Table 2. Approaches of plant movements (adapted by author, 2020)

	Dynamic Mechanisms		Static Strategies	
	Macro scale	Micro scale	Macro scale	Micro scale
Plant example				
	Leaves of Rhododendron (Response to temperature)	Stomata in leaves (Response to water, light, CO ₂)	Cerastium tomentosum (Hairy surface)	Colocasia esculenta (Lotus effect)
Benefit	Prevent desiccation during cold periods	Control CO ₂ uptake and water loss	Protecting plant from direct sunlight	Self-cleaning

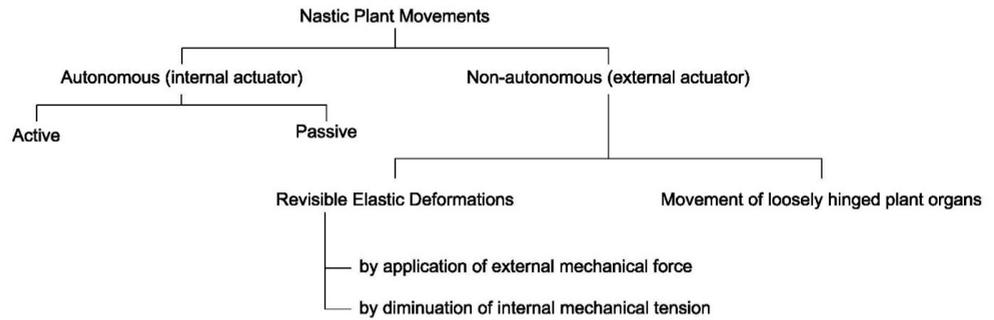


Figure 11. Classification of nastic plant movements (Source: Poppinga et al., 2010)

Dynamic mechanisms are the movements which result from plants' responses to external stimuli. Most plant movements typically involve tropisms (tropic movements) or nasties (nastic movements). Tropic movements refer to plant movements in response to external stimuli that have a certain directionality and are classified into five distinct categories: phototropism (light), geotropism (gravity), hydrotropism (water), chemotropism (chemicals), and thigmotropism (touching) (Guo et al., 2015). Nastic movements, unlike tropic movements, are reversible and repeatable movements and the direction of the response is not dependent on the direction of the stimulus, such as temperature or humidity. Nastic plant movements are classified into two types: autonomous movements which are driven by motor organs, for example the pulvinus, and non-autonomous movements caused by direct application of mechanical forces, which can be subdivided into reversible elastic deformations and movements of a hinged organ (Poppinga et al., 2010). Compared to tropic movements, nastic movements show a clearer structure–function relationship and have potential for biomimetic approaches (Burgert & Fratzl, 2009). The classification of nastic plant movements is presented in [Figure 11](#).

Unlike animals, plants convert hydraulic pressure into various types of movements of their organs (Stahlberg, 2009). For instance, they generate hydrostatic pressure through the process of osmosis in order to stiffen and stabilize their cells, tissues, or organs (Gibson, L.J. and Ashby, M.F. 1982). The hydrostatic pressure inside plant cells, known as turgor pressure, plays an important role in the processes of growth and organ movements. This principle of pressure-induced stability was used as a fundamental in the development of pneumatic and Tensairity structures (Luchsinger et al., 2004).

To avoid high stress and strain concentrations, the mobility of plants is based on the deflection of flexible members called “compliant mechanisms” (Howell, L.L. 2001). During motion, the mechanisms behave similarly to rigid-body mechanisms but use flexural joints instead of rigid hinges. This results in high elasticity, flexibility, and aesthetic movement patterns (Speck, T. 2015). One example of a flexural joint in plants is the pulvinus⁵, which facilitates the physical movement of the plant. When there is an unequal concentration of solutes, such as sodium or potassium ions, in pulvinus cells, it will lead to massive water flows, resulting in a sudden change of turgor pressure in the cells of the pulvinus (Kwan et al., 2013), leading to leaflet movements ([Figure 12](#)).

Plant movements can be divided into two categories based on distinct processes: active and passive movements (Westermeyer et al., 2019). They can be active when energy is used to regulate the internal pressure of their cells, such as turgor pressure. On the other hand, the movement could occur without consuming energy, such as swelling or shrinking processes caused by the uptake or removal of water (hygroscopic); this kind of movement is called passive movement. The general passive hygroscopic movement can be found in pine cones (*Pinus radiata*). The compliant structures of pine cones can move their scales as passive reactions to changes in environmental humidity: the whole pine cone opens when it is dry, enabling seed dispersion, and closes again when it is wet (Figure 13).

This natural behavior of pine cones inspired architect Achim Menges to create a climate-responsive skin which is used in the design of HygroSkin Meteorosensitive Pavilion (Figure 14). Menges combined the hygroscopic swelling properties of the plywood sheets into a semi-synthetic adaptive bilayer material (Charpentier et al., 2017). The different swelling properties in the texture of these two layers cause bending and curvature. The use of HygroSkin transforms the pavilion into a dynamic structure which closes at a level of relative humidity of around 85% and opens by curvature at a level of 45% (Menges, 2012).

Another example of an adaptive system derived from a plant mechanism is Flectofin. This innovation, developed by ITKE, is an elastic kinetic system inspired by the compliant mechanism found in the bird of paradise flower (*Strelitzia reginae*). The valvular pollination mechanism of this flower is considered as a non-autonomous, reversible deformation movement, which is driven by the application of external force (Poppinga et al., 2010). The perch of the plant is bent downward by the bird's weight (Figure 15a). It opens again when the bird flies away and transports the pollen to another flower.

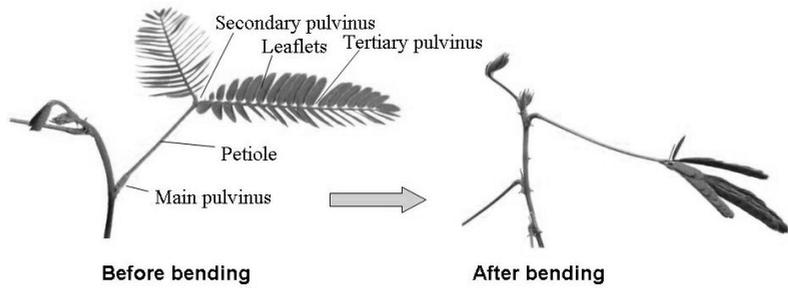


Figure 12. Autonomous, turgor-dependent leaflet movement in *Mimosa pudica* driven by the pulvinus. (Source: Yin, 2011)

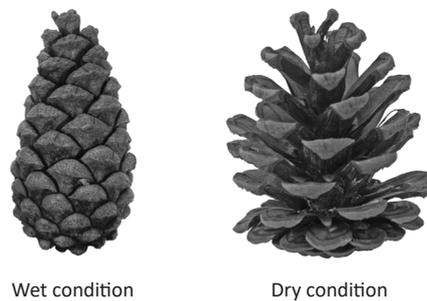


Figure 13. Pine cones in wet and dry conditions (Source: Bridgens, 2015)

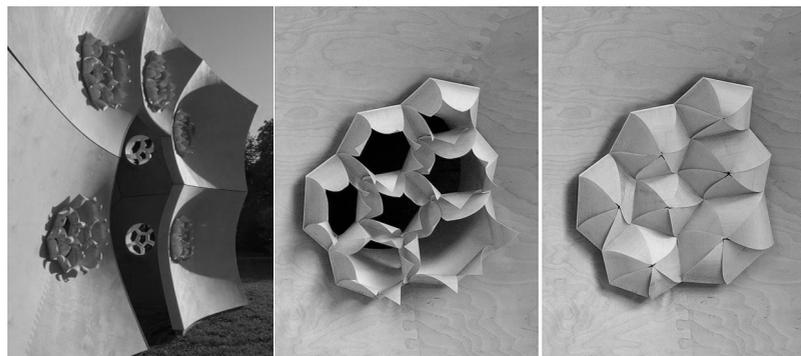


Figure 14. HygroSkin Meteorosensitive Pavilion designed by Achim Menges (Source: Menges, 2013)

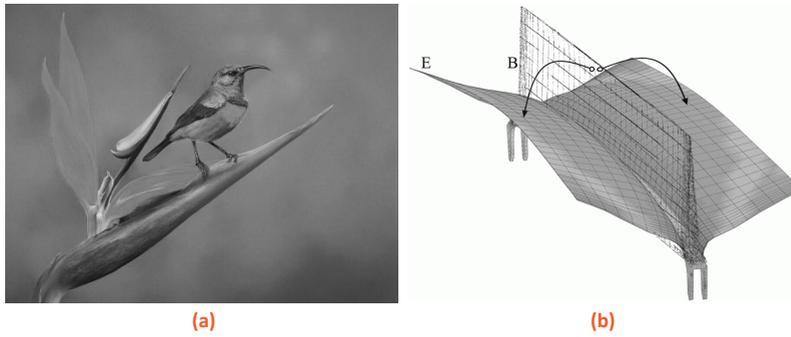


Figure 15.
(a) Bird sits on the perch of *Strelitzia reginae* flower. (Source: Desktop Nexus, 2016)
(b) FE-simulation of the Double Flectofin. (Source: ARCHmatic, 2014)

This reversible mechanical behavior was abstracted to the elastic structural innovation called Flectofin (Figure 15b), a hinge-less shading device system which is capable of shifting sideways-fins by up to 90 degrees by inducing bending stresses in the beam by displacement of a support or thermal expansion (López et al., 2017). The kinetic mechanism of Flectofin was applied in the façade of the One Ocean Pavilion, designed by SOMA Architecture, at the EXPO 2012 in Korea (Figure 16). The kinetic façade is made of slightly curved plates which can respond to the changing natural light conditions during the day by using energy captured by solar panels on the roof. The movement of the façade not only controls the lighting conditions of the interior spaces but also creates an attractive dynamic façade pattern.

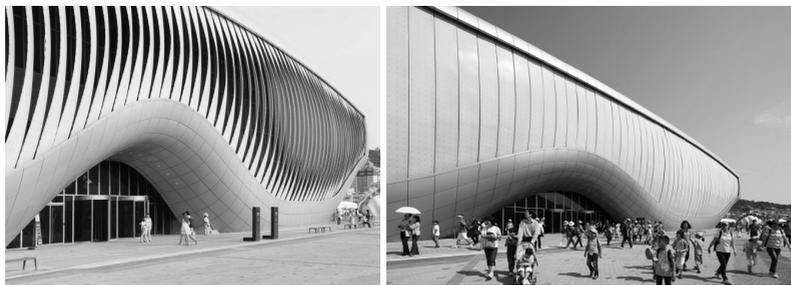


Figure 16. Adaptable kinematic façade of One Ocean Pavilion (Source: Transsolar Energietechnik GmbH, 2020)

Some recent innovative structures were inspired by the fast movements of carnivorous plants, which have the ability to react to mechanical stimuli within a few seconds despite a lack of muscles and nerves (Guo et al., 2015), such as *Dionaea muscipula* (Venus flytrap, Figure 17a) and *Aldrovanda vesiculosa* (waterwheel plant, Figure 17b). The trap of the *Dionaea* consists of two independent kinematic elements, whereas that of the *Aldrovanda* comprises only one kinematic element whose bending deformation is coupled with lobe movement (Poppinga, 2016). The next example focuses on the fascinating trapping movement of *Aldrovanda vesiculosa*, which became the role model for a biomimetic façade-shading device called Flectofold.

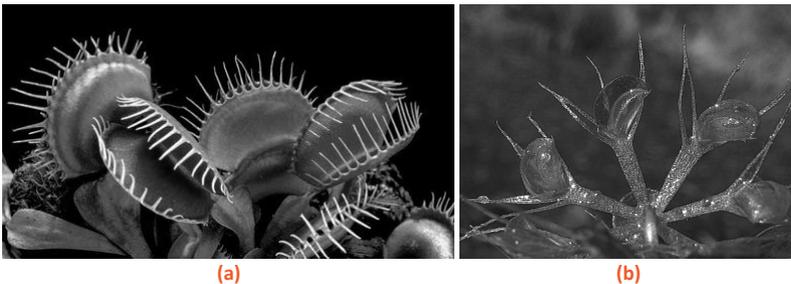


Figure 17.
(a) *Dionaea muscipula* (Venus Flytrap) (Source: Pennisi, 2020)
(b) *Aldrovanda vesiculosa* (Waterwheel plant) (Source: Kameníček, 2019)

Aldrovanda vesiculosa (known as the waterwheel plant) is an aquatic carnivorous plant and is considered as an example of a compliant mechanism. It has a trapping mechanism to catch prey. The trap has two sickle-shaped lobes which are connected by a lens-shaped midrib. The trap-lobes shut quickly, within a few milliseconds, when a prey stimulates their sensory hairs by touching. The lobes' movement is hydraulically driven by a bending

deformation of the midrib. In other words, a small strain in the midrib results in a large movement of the lobes (Charpentier, 2017).

The snap-shut mechanism of the waterwheel plant has been transferred to the concept of adaptive façade-shading in the Flectofold. A simplified finite element trap model was developed by Schleicher (2016) in order to verify the principle of motion of the plant. The trap geometry was transformed into curved-line folding mechanisms with given points A, B, C, and D to analyze the pattern's folding behavior, as shown in Figure 18.

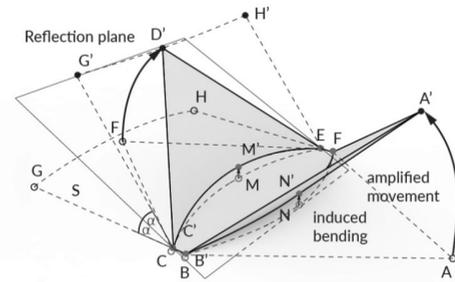
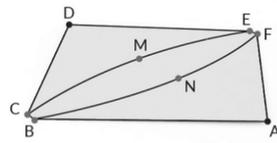


Figure 18. Basic concept geometry of Flectofold (Source: Itke/Körner, 2016)

The first prototype for the Flectofold was developed with the use of glass fiber reinforced polymers (GFRP) and pneumatic actuators. The use of GFRP allows for the precise articulation of mechanical properties in the midrib as well as the hinge zones (Körner et al., 2018). A large-scale demonstration of the Flectofold designed by the researcher Saman Saffarian was fabricated in the Baubionik Exhibition at the Rosenstein Natural History Museum, Stuttgart, in order to demonstrate the possibilities for application on an anticlastic surface façade (Figure 19).



Figure 19. Frontal and rear view of Flectofold demonstration (Source: Itke, 2018)

The anticlastic surface, measuring 6 m by 6 m, was covered with 36 Flectofold modules. Each module was controlled by a pneumatic actuator to apply distributed pressure to the air cushion behind the middle rib. When a uniform pressure is applied, the middle rib is elastically bent and then initiates the folding movement.

6. Conclusion

A variety of different systems found in the plant kingdom could serve as role models for concept generation and optimization in architectural design. Phytomimetic derived designs offer many possibilities for designing more esthetically innovative and highly efficient architectures and structures. The use of treelike

structures, referred to as dendrimors, from historical to modern times reflects the advancements in constructional and technological knowledge in different periods of time. The achievement of the novel braided concrete-filled fiber-reinforced plastic (FRP) construction method enhances the load-bearing capacity of dendriform structures and is suitable not only for new buildings but also for the extension of existing structures.

The passive response in plants can also be a source of inspiration for adaptive systems due to abilities such as elastic movement and actuating capability (Schumacher et al., 2010). Three examples of phyto-inspired mechanisms have been presented. Exemplary prototypes of

adaptive façade-shading systems, namely the Hygroskin, the Flectofin, and the Flectofold, show novel possibilities for adaptive exterior shading facades which are not necessarily restricted to traditional planar geometries but can be adapted to free-form curved surfaces. Furthermore, the use of elastic deformation which is derived from compliant mechanisms found in plant movements makes the kinetic facade more flexible and reduces the mechanical complexity (Poppinga et al., 2016), resulting in lower energy consumption and potential economy due to ease of assembly.

In summary, plants are recognized as adaptive systems which can contribute to more energy-efficient and sustainable structures. The adaptive building envelopes that can adjust themselves to the natural environment are growing interest in sustainability issue because of the highly positive effects of using natural resources and reaction to environmental conditions on reducing energy consumption (Asefi, 2010). Therefore, The use of Phytomimetic as a design approach not only offers novel innovative solutions for structural efficiency and thermal environments but also improving energy efficiency which are essential for sustainable building design.

Remark

- ¹ Bionics was introduced in 1958 by Jack E. Steele to refer to copying functions from nature.
- ² Biomimetics was coined by Otto H. Schmitt in 1957 as a biological approach to biology.
- ³ Mycelium is the root network of fungi, a fast-growing matrix that can act as a natural binder.
- ⁴ Osmosis refers to the movement of fluid across a membrane in response to different concentrations of solutes on the two sides of the membrane.
- ⁵ The pulvinus is a joint-like organ that connects the base of a plant leaf or flower head to a rigid plant body.

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