Bio-inspired Climate-responsive Wood Composite Architectural Façade Actuator

Architectural research based on the asclepias syriaca, mimosa pudica, and mandevilla plants as biological role models

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Passive designs, using smart and sustainable materials, are of great interest to the contemporary building industry as they can support a reduction in embodied carbon emissions and lower the operational energy consumption during a building's life cycle by adapting, replacing, or integrating with industry-standard and carbon-intensive mechanical systems. Shape-changing, programmable bilayer prototypes using wood can respond to the environmental changes of relative humidity. However, there is limited research in this field concerning the type of movement that these mechanisms can achieve and their potential integration into façade applications that are void of energy-dependent elements. Previous research has focused primarily on small single curvature deformations for apertures, complex wooden composite with double curvature for glue laminated structures, or large but very slow louvre mechanisms for shading.

A biomimetic approach was used to produce and develop a climate-responsive mechanism for façade applications built from prototypes of multilayered wood by looking at unique plant biomechanics of the Mimosa pudica, Mandevilla and Asclepias syriaca as biological role models. The research looks at the kinematic model, microscopic tissue structure, environmental adaptation strategies, structural growth pattern and functional performance of the three plant exemplars to develop a series of proposed bio-inspired mechanisms with the potential for upscaling into adaptive façade systems driven by passive actuation. We expect that this early-stage investigation can provide insights into the unique kinematic strategies of the selected plants while contributing toward a better understanding of a potential range of passive façade strategies that are achievable with climate responsive wood composite bilayers and the aspiration to support a more sustainable building industry.

Keywords: *Biomimicry, Climate Responsive Design, Passive Façade Systems, Wood Bilayers, Self-shaping Prototypes, Kinematic Model.*

INTRODUCTION

Passive actuation systems can improve building performance while reducing energy consumption (Dicks, H., *et al*., 2021, pp. 272-273; El-Dabaa and Abdelmohsen, 2023). A biomimetic approach to building passive actuated façade systems look at plants as biological role models due to their ability to respond to climatic changes through both active and passive strategies. (Benyus, 1997, pp. 1-10; Poppinga *et al*., 2018).

Previous research has identified wood bilayer composite mechanisms as an effective and relatively low cost strategy to achieve kinematic actuation in response to environmental changes of relative humidity; this includes thin veneer bilayers (Reichert, Menges and Correa, 2015), wooden laminate bilayers (Wood *et al*., 2016), large glue laminated structures (Grönquist *et al*., 2019) and wood bilayer coupling mechanisms for shading applications (Vailati *et al*., 2018).

This paper contributes towards a better understanding of the directional and multidirectional bending capacity of multi-restricted mechanism derived from plant biomechanics. The paper details the development of a series of kinematic mechanisms that can achieve controlled and reversible directional movement, as well as predictable multi-axis deformation. The investigation culminates in the development of a proof-of-concept architectural façade component.

The research started by studying three biological role models: the *Asclepias syriaca, Mimosa pudica* and *Mandevilla* (see figure 1). These plants were selected based on their distinct reversible and non-reversible physiological responses to external stimuli displayed throughout their life cycle.

The *Asclepias syriaca,* often known as the common milkweed, has a seed dispersal strategy that relies on the controlled drying of the follicle's tissue to release its seeds into the wind, also known as dehiscence (Borders and Lee-Mäder, 2014, p. 4; Jeffery and Robison, 1971). This is a climate adaptive mechanism uniquely tuned to respond to environmental conditions.

The *Mimosa pudica*, also known as the touch-me-not or sensitive plant, can move its leaves in response to tactile stimuli, the movement occurs rapidly enough to be perceptible to the naked eye (Volkov *et al*., 2010).

Lastly, the *Mandevilla,* often referred to as a rocktrumpet, has a unique anthesis where it displays a gaussian or double curvature bend in its petals during peak florescence. (Amar, Müller and Trejo, 2012; Woodson and Moore, 1938).

These characteristics of the selected plant models are driven by their natural functions, such as reproduction and self-protection, and response to changing external factors of physical stimulation, solar radiation exposure and fluctuating humidity.

Figure 1
Plant Models: *Asclepias syriaca* (A), *Mimosa Pudica* (B), and *Mandevilla* (C)

MATERIALS AND METHODS

The research consisted of two main components: First, the observational analysis of selected plants. Second, the design and testing of functional mechanisms based on the geometric and anatomical principles that drive the plants' stimulus-induced movements.

Asclepias syriaca follicles, native to Southwestern Ontario, were harvested locally and retained 4" of their stems. Samples of the *Mimosa pudica* and *Mandevilla* were acquired as potted plants. Detailed observation of the three plants were carried at different visual scales. Microscopic examination revealed the structural composition of the plants' tissue (see figure 2). The stimulus response of the plants was analyzed through climate-controlled experiments and documented using image registration in timelapse photography.

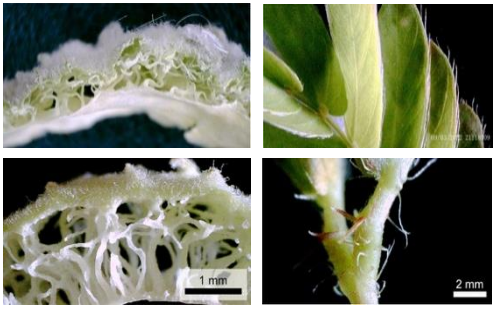

Figure 2
Microscopic images of *Asclepias syriaca* (left) and *Mimosa pudica* (right)

Plant Investigation: Asclepias Syriaca

Asclepias syriaca plants rely on the wind to spread their seeds, the botanical term for this process is anemochory (see figure 3). To be able to get the best weather conditions for aerial dispersal, the plant must plan for the follicle to open in dry sunny weather during late summer or early fall.

Figure 3
Asclepias syriaca anemochory ranging from 20°C (I) to 32°C (IV)

Similar to other seed dispersal strategies, the seed release mechanism relies on the tissue's passive pre-programmed structure to burst open under the right conditions. Both the shape of the follicle and the desiccation of its wall tissue must work closely together to facilitate the seed release; as a result, dry conditions create structural stress along the suture of the follicle. However, this process does not cause an abrupt opening of the follicle suture. Instead, it is a slow opening process that allows for the gradual release of seeds into the wind, which likely improves its chances of catching the right gust of wind (Sacchi, 1987).

For analysis, this process was accelerated through thermal induction, which increases air temperature and lowers relative humidity. With a reduction in moisture, the follicle's tissue shrinks causing tearing through the thinnest membrane along the suture (Borders and Lee-Mäder, 2014, pp. 61-69) (see figure 3).

Plant Investigation: Mimosa Pudica

The *Mimosa pudica* displays one of the fastest kinematic reactions to touch. This is an adaptive stimulus response whose kinematic range is innate in the tissue structure; the movement is active, requiring energy from the plant. It occurs in a specialized region of thickened tissue at the base of each leaflet and leaf stalk. Known as the pulvinus, this swollen structure consists of a group of motor cells that regulate leaf movement through changes in turgor pressure (Sen, 2023; Song, Yeom and Lee, 2015). The movement is quickly triggered by touch, but it also occurs in response to the daily cycles of light and darkness, a phenomenon called nyctinastic drooping (Hagihara and Masatsugu, 2020; Pischtschan and Claßen-Bockhoff, 2007).

The plant's response rate is proportional to the stimuli intensity (Sen, 2023). Detailed observations of the plant's movement in response to different stimulus (solar radiation, touch, and fluctuating humidity levels) were documented through image registration (see figure 4).

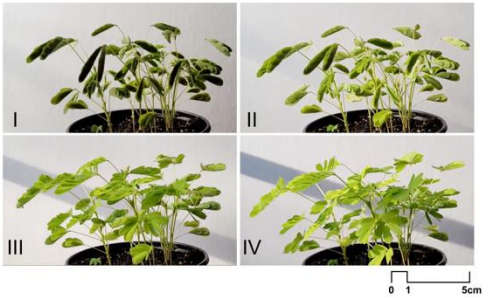

Figure 4
Mimosa pudica nyctinastic drooping

Plant Investigation: Mandevilla

The *Mandevilla's* flower has a distinctive double curvature bend in all five of its asymmetrical petals.

Gamopetalous, or trumpet-shaped, flowers consist of elastic tissues constituting a bilayer (Amar, Müller and Trejo, 2012). When the petals unfurl due to the elastic stress within its bud, by either genetic or environmental factors, the anthesis process begins (Amar, Müller and Trejo, 2012). Petals are fused at the corolla tube before separating, which along with its vein structure, determines the resultant shape of the gaussian curvature (Amar, Müller and Trejo, 2012). A gaussian curve bends in two directions. The first curve occurs in a diagonal direction causing the petal to turn in a clockwise fashion. Secondary to this, a curve in the petals' lengthwise direction promotes a 90-degree bend in relation to its corolla tube.

Observations of the *Mandevilla's* full anthesis were documented through image registration. In this investigation, the *Mandevilla* bloomed in a clockwise and twisted aestivation manner before it concluded at a 90-degree bend, perpendicular to its corolla tube (see figure 5).

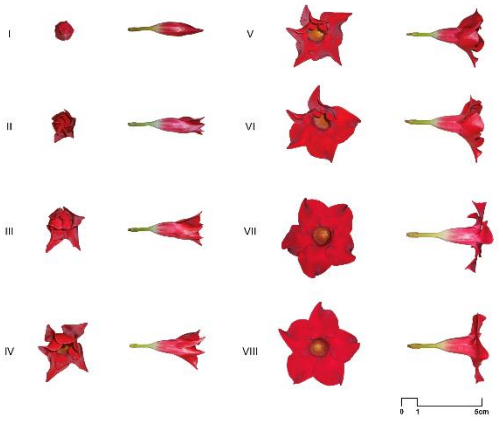

Figure 5
Mandevilla twisted aestivation growth pattern
I. Day 1 - 8:30
II. Day 1 - 19:30
III. Day 1 - 22:00
IV. Day 2 – 1:00
V. Day 2 – 5:00
VI. Day 2 – 8:30
VII. Day 2 – 13:30
VIII. Day 3 – 9:30

Material Investigation

For the passive actuator, 0.7mm wood veneer of maple, oak and beech hardwood was selected due to its well documented hygroscopic properties (El-Dabaa and Abdelmohsen, 2023), local availability, sustainable qualities, and variety of species. The actuators can be further fine-tuned through the selection of wood type and wood species. For example, bilayer actuators using hardwoods are known to achieve higher deflection value and a noticeably quicker response compared to softwoods (Abdelmohsen *et al.*, 2019). Previous literature has shown that quarter sawn veneer from maple, beech, and oak hardwood measuring between 0.2mm and 0.8mm in thickness provides the flexibility needed for small-scale bilayer actuators (Buchelt and Wagenführ, 2008; Wagenführ, Buchelt, and Pfriem, 2006). Veneer of the three wood species measuring between 0.5mm and 0.8mm were found to have a bending radius between 6mm and 12mm along its grain orientation and between 12mm and 16mm across its grain orientation (Buchelt and Wagenführ, 2008; Wagenführ, Buchelt, and Pfriem, 2006).

Wood expands due to a rise in moisture within its fibers causing them to swell, a phenomenon known as 'wood movement'. Due to its anisotropic properties, wood movement is higher along the radial and tangential axis and more limited along its longitudinal axis (Dinwoodie, 2000, p. 58).

To create bending, wood veneer is laminated to a non-hygroscopic passive layer that constrains the expansion of wood fibers and causes stress induced bending (Holstov, Bridgens and Farmer, 2015). Thin acetate and fibreglass sheets were used as constraint layers. They were adhered with a synthetic, non-water based, two-part resin product. The use of synthetic glue prevented moisture from initiating swelling during the lamination process, which is critical for setting the kinematic response of the actuator (Reichert, Menges and Correa, 2015). In a climate-controlled environment, this process of lamination at varying levels of relative humidity was used to program the kinematic state of the bilayer.

Construction of the wooden prototypes used quarter sawn wood as it displays the most consistent parallel grain and has the least number of knots – knots disrupt the direction of swelling so they must be avoided during sample selection (Holstov, Bridgens and Farmer, 2015). It is important to note

Figure 6
Structural dehiscence of the *Asclepias syriaca*

that the higher the moisture content of the wood, the easier it was to bend. Thus, the actuators have greater force when drying than during moisture absorption cycles.

RESULTS

Each biological role model served as inspiration for a distinct kinematic mechanism. Anatomical features and stimulus responsive behaviors were considered in the development of the bilayer architecture and functional kinematic response. Wood veneer and fibreglass composite bilayers were used for the models due to their ease of fabrication and multi-stimulus response to both moisture and temperature.

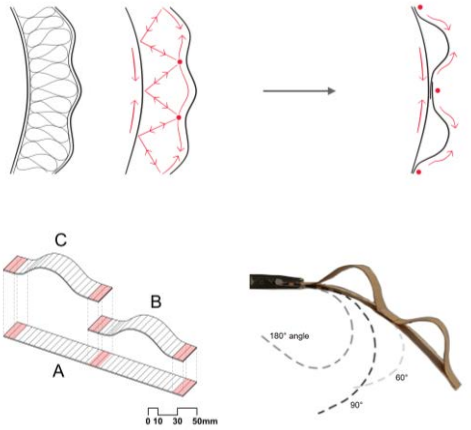

Figure 7
Asclepias syriaca prototype; component diagram (left), final prototype (right)

Asclepias Syriaca

To transfer the principles of the *Asclepias syriaca* follicle membrane into a working prototype, the pod's tissue anatomical structure was studied at the microscopic scale. Shown previously in figure 2, the tissue shrinkage during dehiscence is due to its multilayered truss-like structure. This material architecture was abstracted into a three-component truss-like module. It was understood from the plant investigation that the change in curvature from the cell wall contraction and shrinkage, was due to moisture loss, resulting in the decrease in turgor pressure. The goal was to test whether it was possible to abstract the tissue's anatomical features into a reversible module through responsive and constraint elements as well as integration of shape (see figure 6).

An actuator was fabricated by using three pieces of beech veneer of similar length; each piece was cut with cross-grain orientation lengthwise. Shown in figure 7, the pieces B and C created a truss-like configuration where strip A acted as the bottom chord in the mechanism. As the relative humidity increases, swelling of the wood fibres causes the prototype to curl in on itself. However, control points at its center and the ends of the 'truss' limit the extent of the movement before returning to its original shape when the humidity drops.

Mimosa Pudica

The kinematic principles of the *Mimosa pudica* are transferred through the abstraction of the leaflet's 90-degree folding. This response is driven by pulvinus-related nastic movements and is replicated through the simplification of the pulvinus as the actuator's control points (see figure 8).

Figure 8
Mimosa pudica nastic movement

This model resembles the highly directed hinge-like seismonastic movement without the implementation of tactile stimulation. Instead, the abstracted model responds to moisture as the driver of actuation. With the understanding of the anisotropic characteristics of wood, shown in figure 9, the primary component A of the model was cut lengthwise, perpendicular to the grain direction, allowing it to curve along its length. To expand the limit of the curl, central notches split component A into two 'leaflets' creating component B - a 'stem', to

imitate the tertiary pulvinus of the *Mimosa pudica.* To ensure single axis bending, thin rectangular pieces, component C of figure 9, were cut parallel to the grain and adhered to each 'leaflet' of the model to restrict curling. When the humidity increases the wood fibres expand, causing the leaflets to bend inwards at a 90-degree angle due to the cross-lamination of the secondary strips – highlighted in figure 9.

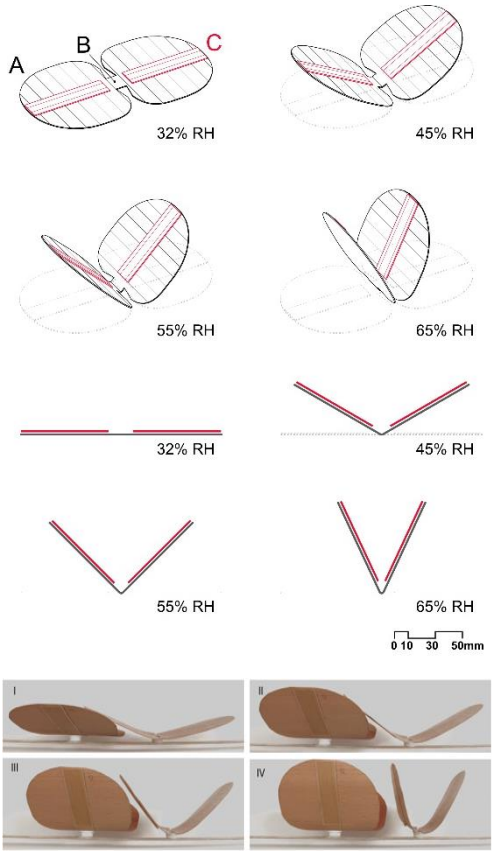

Figure 9
Mimosa pudica prototype; component diagram (top), final prototype ranging from 32%-65% RH (bottom)

Mandevilla

The unique characteristics of the *Mandevilla's* anthesis stage are transferred into a working prototype through the abstraction of the asymmetric petal's double curvature bend into a wood bilayer actuator. Considering the gaussian curvature and sequence in a clockwise and twisted aestivation manner, the goal was to test whether the properties found in the material investigation of wood veneer could reproduce these characteristics (see figure 10). This proof of concept reflects the components and assemblage that closely follow that of the *Mimosa pudica* model with further development into the form, shape and grain orientation.

Highlighted in figure 11, the primary component A is cut from wood veneer on a diagonal grain orientation to imitate the first curve of the *Mandevilla* in promoting the clockwise direction. To reflect the second curvature bend, the control layer B, with perpendicular cross-grain orientation, is overlaid to restrict the bendable extent of component A. The proportional difference of layer B's 90-degree bend to layer A's diagonal curl allows for a controlled double curvature bend. The passive fiberglass layer, located opposite of layer B, restricts moisture penetration and guarantees the induced stress to bend in a precise predetermined direction.

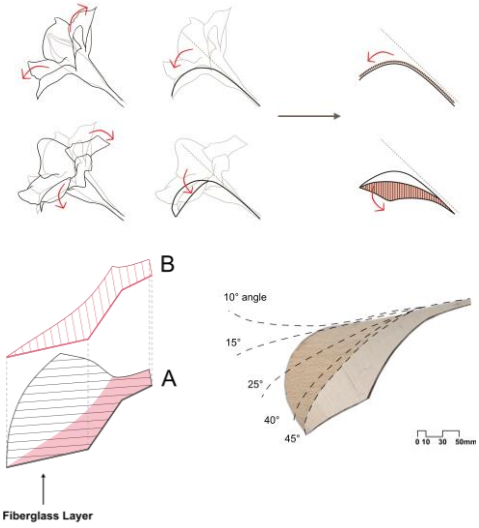

Figure 10
Gaussian curvature of the *Mandevilla*

Figure 11
Mandevilla single petal prototype; component diagram (left), final prototype (right)

To match the flower's distinct petal opening, five of these actuators were arrayed in a pentagonal shape. The aestivation flowering pattern of the *Mandevilla* is achieved by laminating each actuator at a consistent increase in relative humidity. This results in the effect of the actuators responding to the changes of humidity in a sequential order (see figure 12).

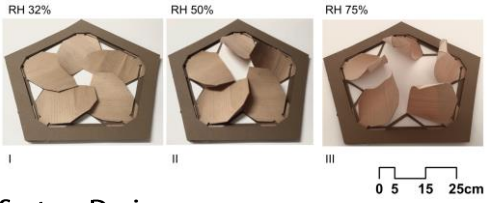

Figure 12
Twisted aestivation ranging from 32%-75% RH

System Design

To evaluate the integration of these components into a façade system, a new arrangement was developed using actuators reflecting the *Mimosa pudica.* The goal for this test was to consider a module with high kinematic range that is more suitable for replication. Further development on the cross laminated bilayer, constraint layers to control the direction, timescale, and bending radius were needed to produce this prototype.

The actuator producing a 90-degree bend from the *Mimosa pudica,* is arranged in a perpendicular and overlapping grid to produce an opaque screen. When exposed to higher levels of humidity, the actuators bend and increases the transparency through the screen. Due to a sequential lamination process, with humidity levels at ten percent increments, the actuators respond to the increase in humidity in a consecutive order from the largest of actuators to the smallest (see figure 13).

DISCUSSION

The façade system developed using the *Mimosa pudica's* actuator principles allow for an interactive humidity-dependent hygroscopic movement. Each unit responds to a localized change in humidity. This is in response to environmental factors such as an abrupt change in weather or programmatic elements such as a tea house, spa, pools or a gym. With the responsive changes of the façade, it regulates humidity levels to provide human comfort and an interactive feature as a passive design (see figure 14).

Limitations

The initial proof-of-concept research achieved prototypes inheriting the principles of the *Asclepias syriaca, Mimosa pudica* and *Mandevilla,* independent from active systems. However, further research should look at the scaling of materials and prototypes to validate its use in environments with long term humidity cycles. This may also involve the

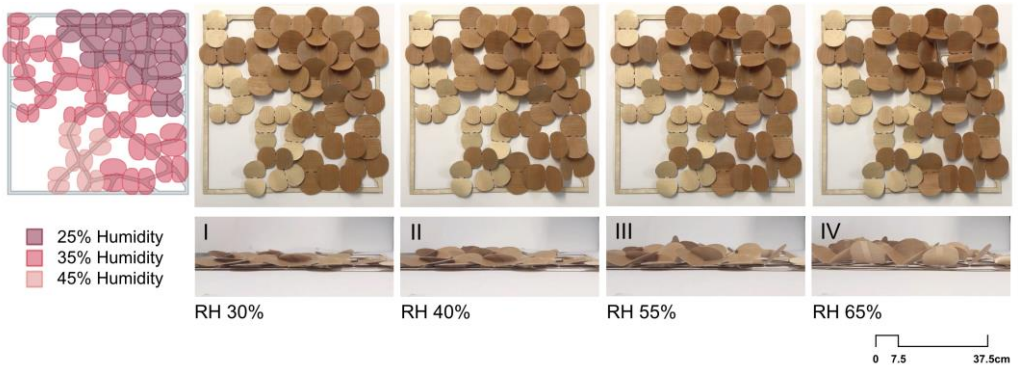

Figure 13
Mimosa pudica façade

further testing of material fatigue, specifically exploring the connection joints, as it could improve the prototypes longevity.

While this prototype is currently successful at an interior partition scale, the limited veneer thickness of the actuator proves difficult to withstand exterior environmental conditions. Continued research is needed for the possibility of producing an actuator that responds similarly to relative humidity at a larger scale.

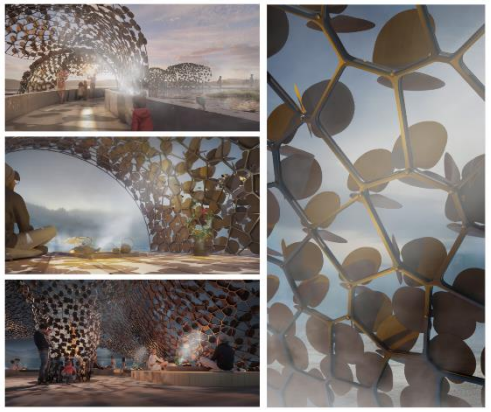

Figure 14
Final façade renderings

CONCLUSION

Asclepias syriaca, Mimosa pudica, and the *Mandevilla* served as valuable role models for the development of climate responsive actuators at the proof-of-concept scale. Each mechanism applies veneer bilayer actuators that can have reversible response cycles as a reaction to daily changes in climatic conditions, particularly localized moisture content as a reaction to relative humidity changes. As summarized in the kinematic mechanism matrix, the mechanisms demonstrate the ability to integrate shape-change directional restrictions, through the cross lamination of wood and constraint layers, which controls the direction, timescale and bending radius of each actuator (see figure 15).

Lastly, this investigation concluded by assessing the design potential and technical implementation of these principles into a repeatable module suitable for duplication at a façade scale. We hope that this early-stage investigation can provide insights into the unique kinematic strategies of the selected plants while contributing toward a better understanding of a potential range of passive façade strategies that are achievable with climate responsive wood composite bilayers and the aspiration to support a more sustainable building industry.

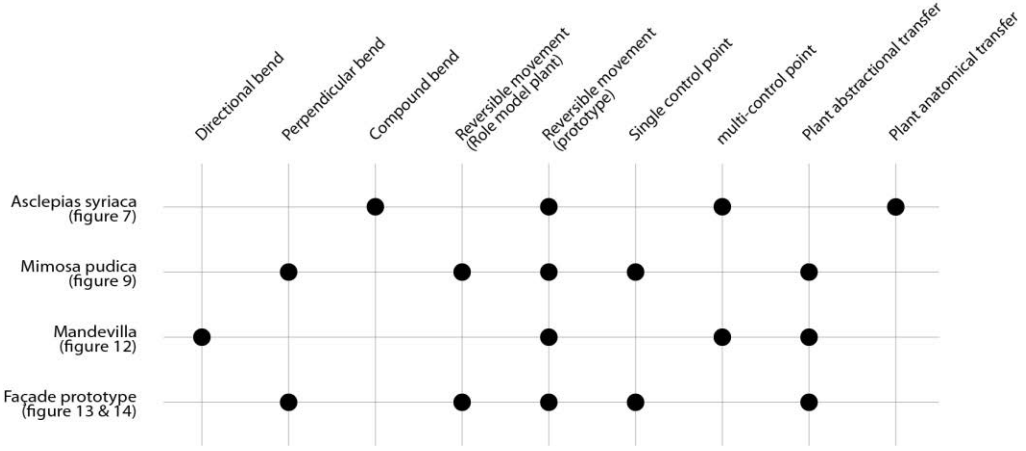

Figure 15
Kinematic mechanism matrix

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