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Nature Pleated Surfaces

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Abstract. This paper presents a concept design methodology that intends to enable users to design a self-supporting structure based on the terrestrial plants' biological properties and on origami geometric principles that was tested on an eight-hour workshop at eCAADe/SiGraDi'2019 in Oporto. Focusing on rigid and flat-foldable origami surfaces the methodology invites its users to deal with several architectural aims, constraints and analysis based on the geometric rules of this origami type. These surfaces behave in a particular way through folding, they depart from a planar state and after the folding process they arrive to a new planar state (flat-foldable Origami). If the faces remain rigid and flat during the folding process, the only change happens at the creases that behave as revolute joints. This way the folding of the surface is directly related to rigid kinematics allowing for a geometry based digital simulation. After the aims, constraints and analysis definition, the methodology users are conducted through an abstraction process that explores the three fundamental forms of nature adaptation strategies – morphology, behavior and physiology, giving rise to a hybrid biological principle that will lead to the conceptual design process. The design process is conducted through analysis, experimentation with paper prototypes and the use of parametric design, enabling this way the emulation of the design process, where the functionality, geometry, robustness and aesthetics are tested and discussed.

Keywords: Biomimetics; Rigid Origami; Methodology; Emulation; Parametric processes.

1 Introduction

"At this point in our global ecological crisis, the survival of humanity will require a fundamental shift in our attitude toward nature: from finding out how we can dominate and manipulate nature to how we can learn from her." Fritjof Capra (1997)

It could not be wrong to say that Nature is probably the most efficient, reliable, and sustainable architect of the planet. Across the centuries the survey of Nature and the use of basic and local resources has inspired humans, leading to experiment and exceed formal, structural, and material boundaries, and also to the creation of new tools and methodologies (Oxman, 2010).

The present research intends to contribute to a sound relationship between humans and our planet flora by developing an architectural design methodology based on vascular plant events formalized through foldable origami surfaces. Architects are the great thinkers and builders of space. If, for hypothesis, architects could shape their constructions based on the “minimum inventory, maximum performance” motto, human constructions could not only improve human health, spatial conditions, and functional adaptation, but also improve a building’s life cycle by relating and integrating its environmental resources and the inhabitants’ needs while decreasing greenhouse gas emissions, energy consumption, resource usage, waste generation, among others.

The last two decades present several prominent experiences that cross nature and origami themes. On one hand the (re)rising of nature into the architectural panorama through the use of minimal resources and maximum performance from the utilization of the new digital tools, on the other hand the use of origami surfaces to potentiate the creation of exploratory geometries, material research and structural behavior. The combination of both vocabularies may generate a new and innovative architectural semantic.

In a very obvious way, of biomimetic design using origami surfaces, could be referred the series of Oribotic flowers designed by Gardiner from 2004 to 2011 (Gardiner, 2004) or Blumen Lumen flowers developed by Foldhaus in 2014 (Blumen Lumen, 2014). In both cases the designers used origami surfaces to create kinetic flowers that open and close in response to diverse stimuli.

In a non-so obvious way, there are examples of the utilization of origami surfaces to materialize concepts and buildings such as Vega, Gonzalez e Gutierrez that in 2009 developed an experimental shading canopy with their students at the Universidad Técnica Federico Santa Maria in Valparaíso, Chile (Britto, 2012). The developed self-supporting structure explored the deployment of catenary vaults created through the aggregation of modules with variable aperture which were designed and fabricated through techniques of folding and pinning – Botterfold. The parametric structure was designed based on the local solar trajectory in order to generate the most possible shadow at the hottest hours of the day. The canopy was composed of 1200 triangular aluminum modules, disposed in order to provide shading comfort to its potential inhabitants. Bathed in the late oceanic sunsets the optical characteristics of the structure create an ephemeral effect of sparkles which evokes its neighbor, the sea.

Later in 2016, at the Detmold University of Applied Sciences, Tal Friedman developed the Foldfinding- Origami Pavilion (Origami pavilion, 2016). Linking the self-supportive mechanism of the thin-shell of a flower to a self-supporting thin-shell folded structure, Friedman created a full-scale pavilion folded out of aluminum boards which were parametrically designed to fold into the flower-like shape inspired by the techniques of Origami. The final form is comprised of two "flower" modules connected together to form a gate structure resembling the outline of a Japanese Torii. Each flower is made of four sections which acquire a precise position when folded. Each folded piece contains around 12 to 20 interconnected flat faces. This technique saves fabrication time and building tolerance. This project is a proof-of-concept model to conclude that folded structures can be fabricated to full scale while maintaining their stiffness and self-supporting stability. By reducing the need for additional supporting structural systems, a new kind of thin shell lightweight structures made from just one material emerges.

In 2017, architects Cavada, Barcala and García drew inspiration from folded paper in Origami, to create a temporary installation for the architecture and design festival Concéntrico 03 in Logroño, Spain (Wang, 2017). The fundamental idea started with the statement that a paper sheet alone does not sustain itself, but when joined in a series of precisely folded sheets, they are capable of sustaining not only themselves but other forces. The installation was built from 39 wooden panels joined together with hinges and assembled without any other supporting structure or sub-structure. The gaps between the timber panels allow light to seep through, giving the structure the appearance of a glowing lantern at night.

Also, in 2017, Heather and Ivan Morison developed the Look! Look! Look! sculptural pavilion for the National Trust's historic Berrington Hall in Herefordshire (Look! Look! Look!/Studio Morison, 2017). Inspired by the eye-catchers buildings of the Georgian era and origami, the structure resembles a pineapple. The pavilion has a centralized plan and the folds depart from a radial crease pattern crossed all around twice by a v-line, which in the folded position leads to a progression in an accordion-like manner on the horizontal direction and two inversions of sense on the vertical direction. The structure is composed by 90 faces, erected through timber panels and coated with a translucent pink fabric, anchored to the ground through a metallic foundation frame. When seen from the outside the installation appears strong and sculptural and from the inside it has a translucent and delicate appearance allowing light to pass freely from the entrances and the open ceiling.

In the presence of such examples the authors of this paper have decided to make an experiment by joining two distinct PhD investigations, one on the field of the biomimetics and the creation of a biomimetic architectural process (Oliveira & Osório, 2017), and the other on the field of kinetic origami surfaces to be used in architecture and supported by the parametrization of origami crease patterns and their folding path (Osório, Paio & Oliveira, 2018).

The fundamental purpose of this project was to test if a biomimetic design process, that departs from the deep knowledge of terrestrial plants adaptation strategies, could use origami geometry and parametric design as a formalization of the goal of the biomimetic architectural process and produce foldable self-supporting structures.

Rigid origami surfaces can be achieved through tessellations that follow particular rules which leads to the generation of polygons constrained to rotate around their shared edges. These surfaces may follow rigid kinematics rules and may be able to fold from a planar state into another, collapsed planar state. This way the surfaces may undertake a range of configurations before collapsing into a bundle, thus occupying the least possible space and the use of only rigid faces simplifies the parametric simulation by allowing it to be purely geometric.

To test the feasibility of the combination of the two PhD researches was conducted the Nature Pleated Surfaces workshop for the eCAADe/SiGraDi'2019 in Oporto.

2 Nature Pleated Surfaces: The Workshop

2.1 Workshop Outline

This section presents the summary of the work developed at “Nature Pleated Surfaces Workshop”, held in September of 2019 during the eCAADe/SiGraDi’2019 in Oporto and the retrieved results.

The workshop had the participation of students and professionals from different fields, such as parametric design, biomimetic architecture, and origami design research, and also from different ages and countries – Chile, Bolivia, Brazil, Iran, Portugal and Turkey.

The workshop was conducted through eight hours and was divided in four distinct phases. The first was a theoretical phase where the students were introduced to the geometry of rigid and flat-foldable origami principles, its types, fundamental axioms and foldability rules. The second phase was also theoretical and concerned the presentation of plants’ biological principles, focusing on the specific case of the terrestrial vascular plants and its adaptation strategies as well as ways to interpret those strategies and bring them into the architectural practice.

The third phase was dedicated to the practical application of the theories. The students were divided in groups and started the development of their projects supported by online research, construction of diagrams, and concept definition. From the definition of the conceptual intention the groups started to experiment with paper folding and parametric design to achieve rigid and flat-foldable origami crease patterns. The fourth and final phase was entirely devoted to the design studio and to the materialization of the project of each group.

The main goal of this eight-hour experience was to develop a self-supporting structure, based on the biological adaptation principles of the terrestrial plants and on the geometry of rigid and flat-foldable origami. As final product, the groups should achieve: 1- an architectural challenge definition, by determining the function of the project and a corresponding four degree origami pattern for the self-supporting structure; 2- a meme event construction based on plants morphological adaptation (the conceptualization of an abstract idea of design) ; and 3- a parametric and physical model of the designed solution.

2.2 Rigid Origami Geometry

In what regards the origami geometry, the students were first introduced to some elementary concepts such as the basic type of folds and how to parametrize them using Grasshopper for Rhinoceros. The basic folds in origami are the mountain and valley folds and the parameterization of such folds corresponds to a simple rotation of each face of + or - 90° around the shared edge between the two faces (Fig. 1).

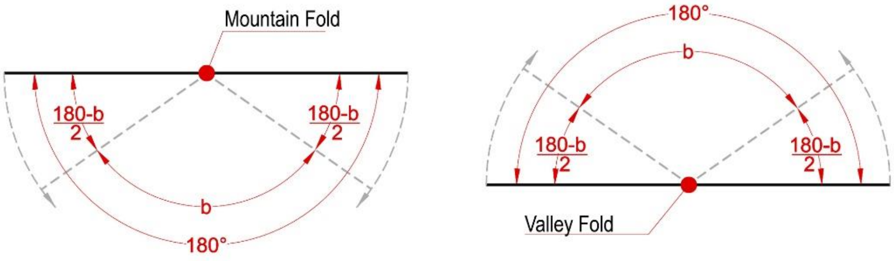


Fig. 1. Front view of the parameterization of Mountain and Valley folds.

Then were explained the seven Huzita-Justin Axioms for folding operations, which are very similar to the Euclidean axioms for constructions with straightedge and compass. These axioms allow to find creases and angles through folding. From these basic concepts the students were then introduced to the rules for rigid and flat foldability, such as the Maekawa-Justin and Kawasaki-Justin theorems and concepts such as the degree of a vertex.

In origami the degree of any vertex corresponds to the number of creases that depart from the vertex. It is the identity of the creases (Mountain or Valley), their assignment around the vertex and the angles between each crease that determines if the faces around a certain vertex can be rigid and flat folded. An origami tessellation can be described as a degree-n tessellation if all the interior vertices of the crease pattern have degree-n. So, the students were then introduced to some rigidly and flat folding tessellations of degree-2, degree-4 and degree-6 crease patterns (Fig. 2), as well as to the resulting folding of the tessellations at different stages.

Finally, were presented, and provided to the students, several parameterizations of rigidly folding patterns developed in Grasshopper for Rhinoceros, as demonstrated on Fig. 3. These parameterizations allowed the students to test and fold some crease patterns of degree 2, 4 and 6. Through the definitions the students were able to manipulate the geometry of the base crease pattern by changing the dimensions of the faces through sliders for the coordinates of the points that defined the faces. The definitions allowed also to determine the size of the tessellation to fold, that is the number of faces that composed it and were constructed in a way that obliges for the following of the rules for rigid and flat foldability. This way the students could manipulate the tessellations and make them fold through a folding slider which helped them to understand deeper the geometry relations of the folding of multiple faces.

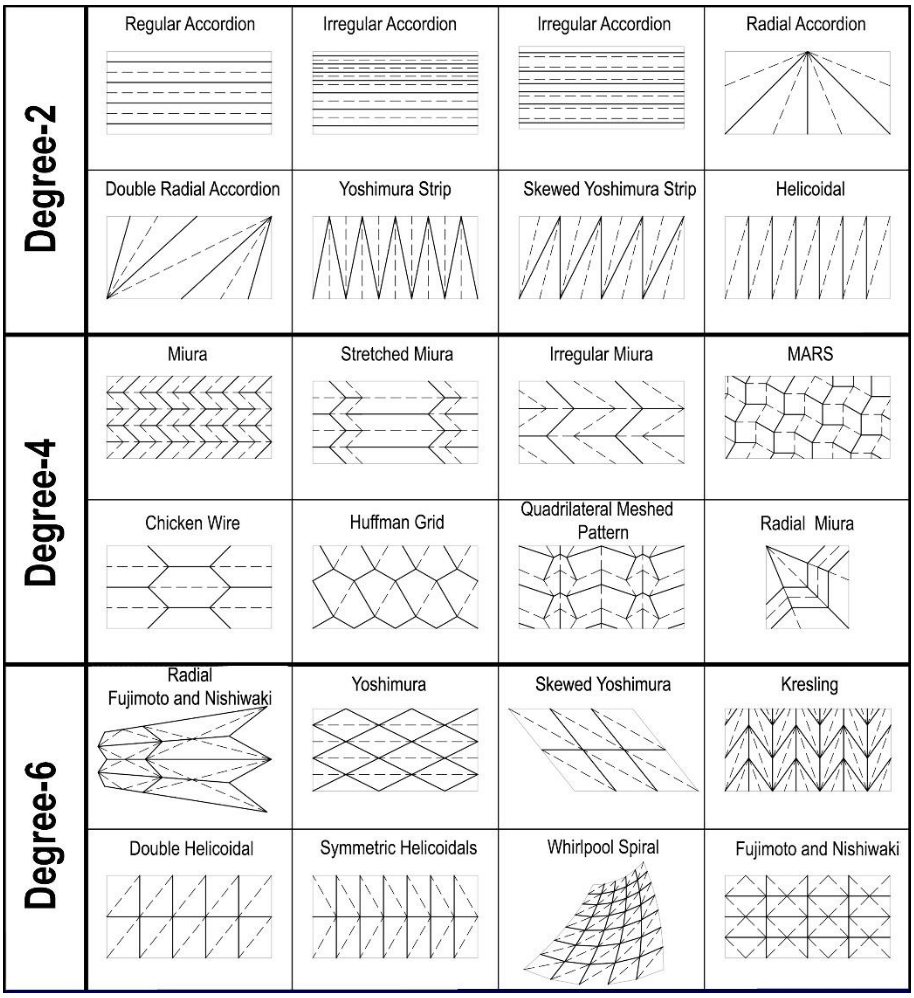


Fig. 2. Examples of rigidly folding origami tessellations of degree 2, 4 and 6.

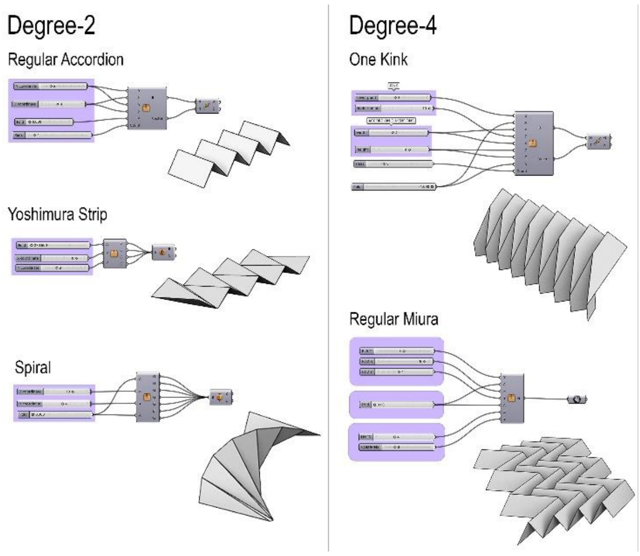


Fig. 3. Provided folding parameterizations.

2.3 Biomimetic Based Methodology

The second phase of the workshop concerned the predefined Biomimetic Design path Matrix (Fig. 4) composed by three main domains: The Architectural domain, Nature Domain and the construction of the Artifact domain.

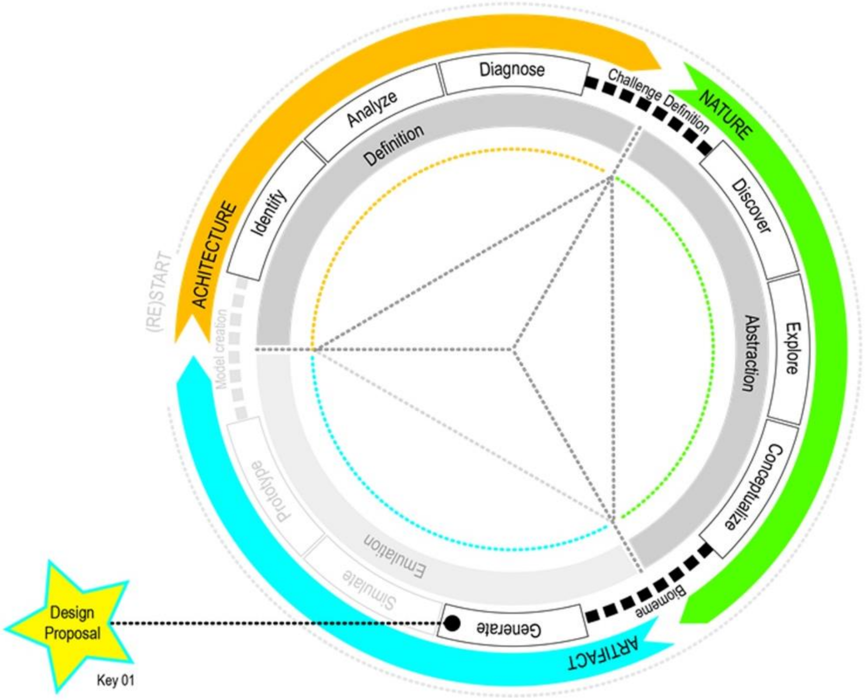


Fig. 4. Biomimetic Design Path Matrix.

Architecture domain – Identification, Analysis and Diagnose

The architectural domain aims to define the architectural main function.

Participants were free to choose their structure function as well as to choose their own rigid and flat-foldable origami crease pattern. These factors were a determinant mojo factor to engage participants into a design analysis and diagnose process essential to conceive an abstract idea of the structure that could be related with terrestrial vascular plants adaptation strategies events.

Nature domain – Discover, Exploration and Conceptualization

The Nature domain departs from the previous design solution intention focusing into the morphological adaptation strategies of terrestrial vascular plants discovery, by exploring its events and potential features translating it into a design conceptualization.

To the participants were given several online databases, and a synthetic list of the most well-known and documented morphological adaptation strategies of terrestrial vascular plants. Departing from the previous domain, where participants had diagnosed their self-supporting structure main function and defined possible origami rules and potential geometric solutions, at Nature domain, participants were then invited to enrich their structure functions and performative behaviour by linking morphological adaptation strategies to their design solutions. This is an abstract process, that begins with the identification of determine morphological strategies with which participants identify some of their initial potential ideas that could enable and potential their design structures. We called this process as the Biomimetic meme construction. The Biomimetic meme construction is composed by the extraction of strategies, patterns, material and performative features from the original morphological strategies, that combined give rise to a completely new and artificial Biomimetic meme. This biomimetic meme become the strategical model for the design project.

Artifact domain - Generate

From the design conceptualization, participants were engaged into the Artifact domain, by generating parametrically their design solutions, and confronting them with the inevitability of its materialization.

At this domain, participants were ready to engage the parametric design task. To generate their design solutions, participants used Rhino+Grasshopper software, as well as 80gr sheet paper. Origami theorems and axioms were determinant for the definition of the design form and foldability principle, as well as performative features.

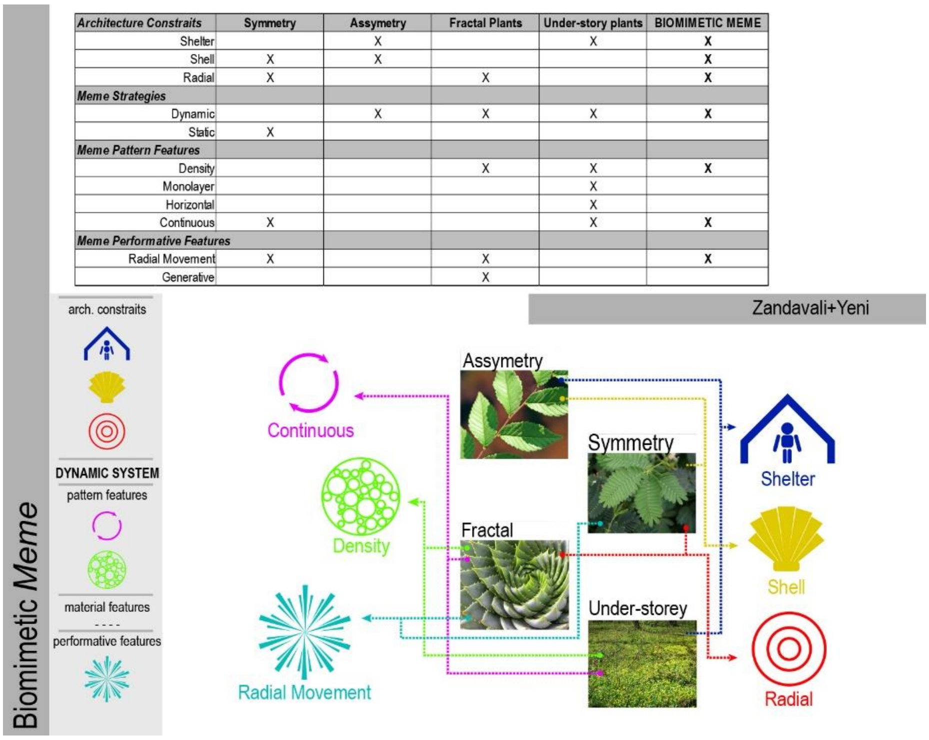
3 Projects

From the first two theoretical phases of the workshop the students developed five different design solutions. Each project was based on different natural systems and organisms and each arose different issues during the design process and the prototypes production. Regarding origami geometry one group used the Yoshimura pattern and the others used variations of degree four tessellations.

3.1 Project 01: Urban Furniture (Bárbara Zandavali + Yağmur Yeni)

The first project, developed by Bárbara Zandavali and Yagmur Yeni, was called Urban Furniture and the aimed function was to create an urban shelter with shading properties. Their biomimetic meme was essentially based on symmetry, fractal and under-storey plants as a way of radial spread in several directions. This morphological adaptation strategies conducted the group to a radial solution, with dynamic properties (Fig. 5).

The designed solution was a foldable self-supporting structure with three essential anchor points. They used a degree-4 crease pattern with several kinks to generate an ellipsoidal section shading canopy. The intention of the group was to use the same design to generate different structures by changing the positions of the anchor points. By having the same surface and placing differently the anchor points was possible to create structures with different radius, apertures and covered area, due to the geometry of the origami pattern (Fig. 6).



Architecture Constraits	Symmetry	Assymetry	Fractal Plants	Under-story plants	BIOMIMETIC MEME
Shelter		X		X	**X**
Shell	X	X			**X**
Radial	X		X		**X**
Meme Strategies					
Dynamic		X	X	X	**X**
Static	X				
Meme Pattern Features					
Density			X	X	**X**
Monolayer				X	
Horizontal				X	
Continuous	X			X	**X**
Meme Performative Features					
Radial Movement	X		X		**X**
Generative			X		

Fig. 5. Urban Furniture – Biomimetic Meme Construction.

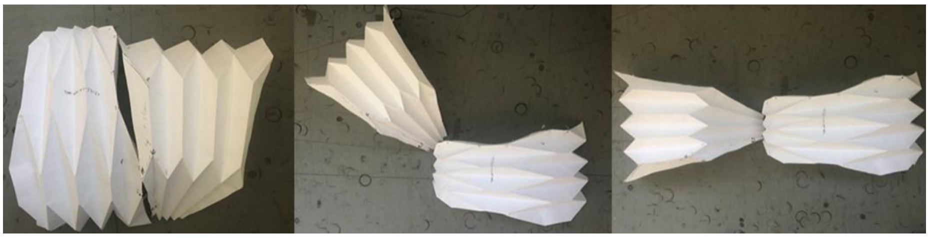
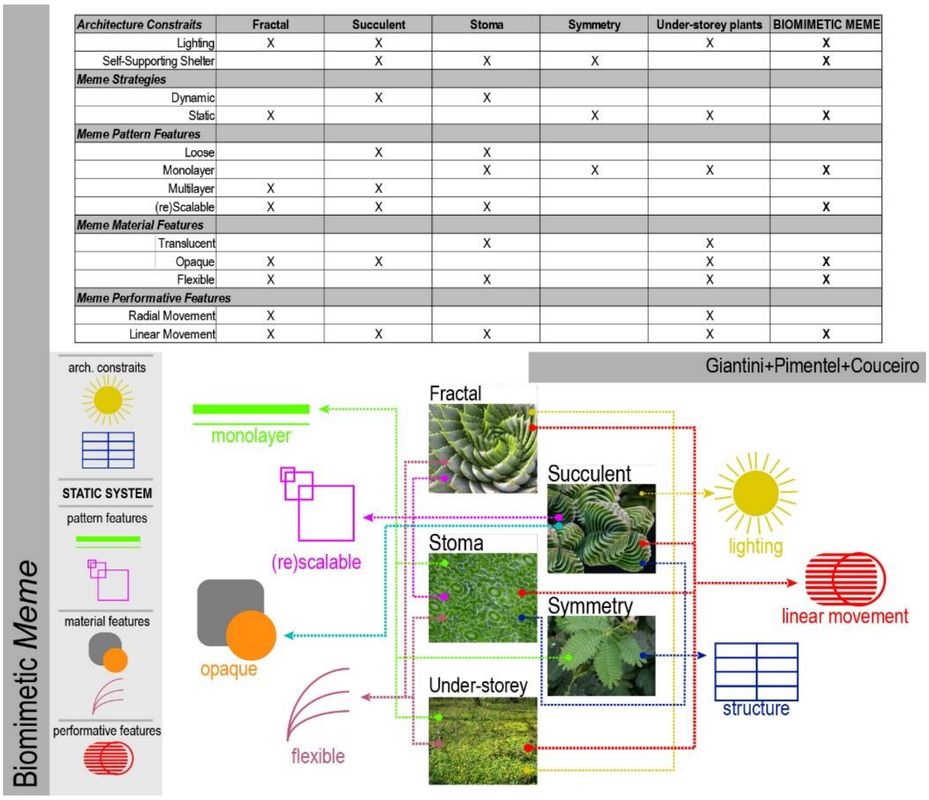


Fig. 6. Urban Furniture – Exploratory mockups.

3.2 Project 02: Foldable Hangar (Guilherme Giantini + Mateus Pimentel + Mauro Couceiro)

Foldable Hangar was the most ambitious project in terms of scale since the group intended to generate a structure to cover a long area. Their biomimetic meme was sustained on succulent and fractal morphological adaptation strategies, giving rise to a fractal and lighting pattern that could be static or dynamic, materialized through a monolayer structure that sustained translucent and opaque materials and that could be deployed through a linear movement (Fig. 7). Sustained by this initial premise, the origami selected pattern was the chicken wire with vertices so close that almost arrived to the Yoshimura pattern. The designed pattern was well achieved since its fractal type of repetition allows for good structural resistance, essential for the covering of large areas (Fig. 8).



Architecture Constraits	Fractal	Succulent	Stoma	Symmetry	Under-storey plants	BIOMIMETIC MEME
Lighting	X	X			X	X
Self-Supporting Shelter		X	X	X		X
Meme Strategies						
Dynamic		X	X			
Static	X			X	X	X
Meme Pattern Features						
Loose		X	X			
Monolayer			X	X	X	X
Multilayer	X	X				
(re)Scalable	X	X	X			X
Meme Material Features						
Translucent			X		X	
Opaque	X	X			X	X
Flexible	X		X		X	X
Meme Performative Features						
Radial Movement	X				X	
Linear Movement	X	X	X		X	X

Fig. 7. Foldable Hangar – Biomimetic Meme Construction.

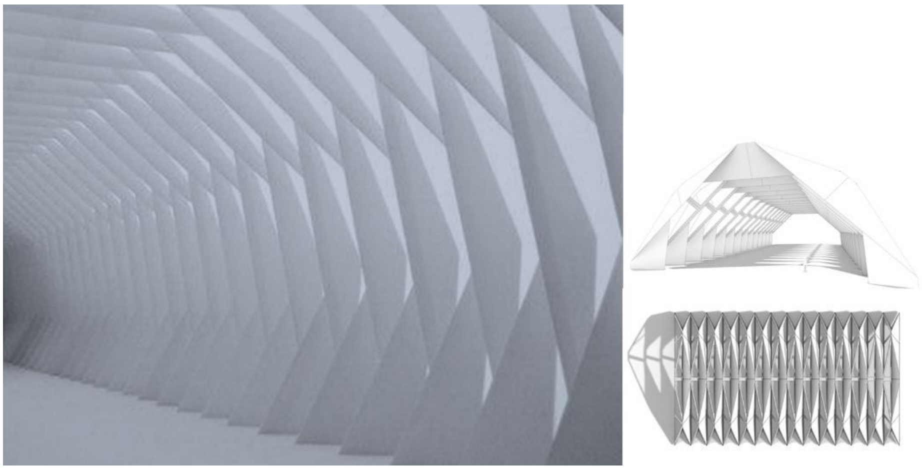


Fig. 8. Foldable Hangar – 3D simulation.

3.3 Project 03: Mini Orchid Yard (Débora Oliveira + Pedro Engel)

Mini Orchid Yard aimed at developing a water recycling flowerpot that could capture rainwater. The design project was based on canopy and carnivore plants adaptation strategies and their biomimetic meme was essentially sustained by the hygroscopic, packing structures, hydrophobic and symmetry morphological adaption strategies (Fig. 9). The design solution was intended to be constructed through a multi-layered, opaque and impermeable material. The water cycle would be defined by a convectional three-dimensional movement performative feature of the design strategy.

To formalize their intention, the group tried to develop the container based on an irregular degree 4 crease pattern that could have an organic form with continuous changing curvatures (Fig. 10). Unfortunately, they were not able to reach their intention neither in paper nor through the grasshopper definitions.

Architecture Constraits	Cannopy Plants	Carnivorous	Hygroscopic	Packing Structures	Symmetry	BIOMIMETIC MEME
Expandable	X		X	X		**X**
Storage		X		X	X	**X**
Meme Strategies						
Dynamic	X	X	X			**X**
Static				X	X	
Meme Pattern Features						
Loose	X					
Monolayer					X	
Multilayer	X	X	X	X		**X**
Compactability		X	X	X		
Meme Material Features						
Translucent	X				X	
Opaque		X	X	X	X	**X**
Impermeable	X	X		X	X	**X**
Permeable			X		X	
Meme Performative Features						
Convection		X	X			**X**
3D Movement		X		X		**X**
Radial Movement	X					
Linear Movement			X			

Fig. 9. Mini Orchid Yard – Biomimetic Meme Construction.

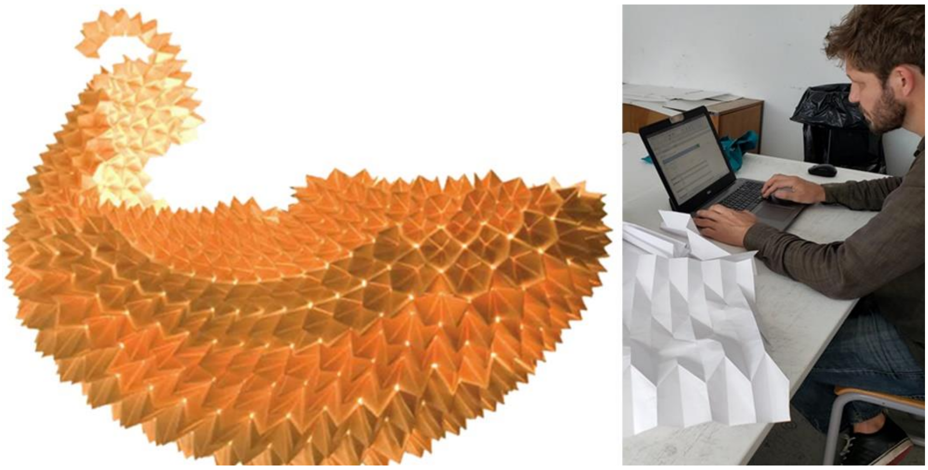
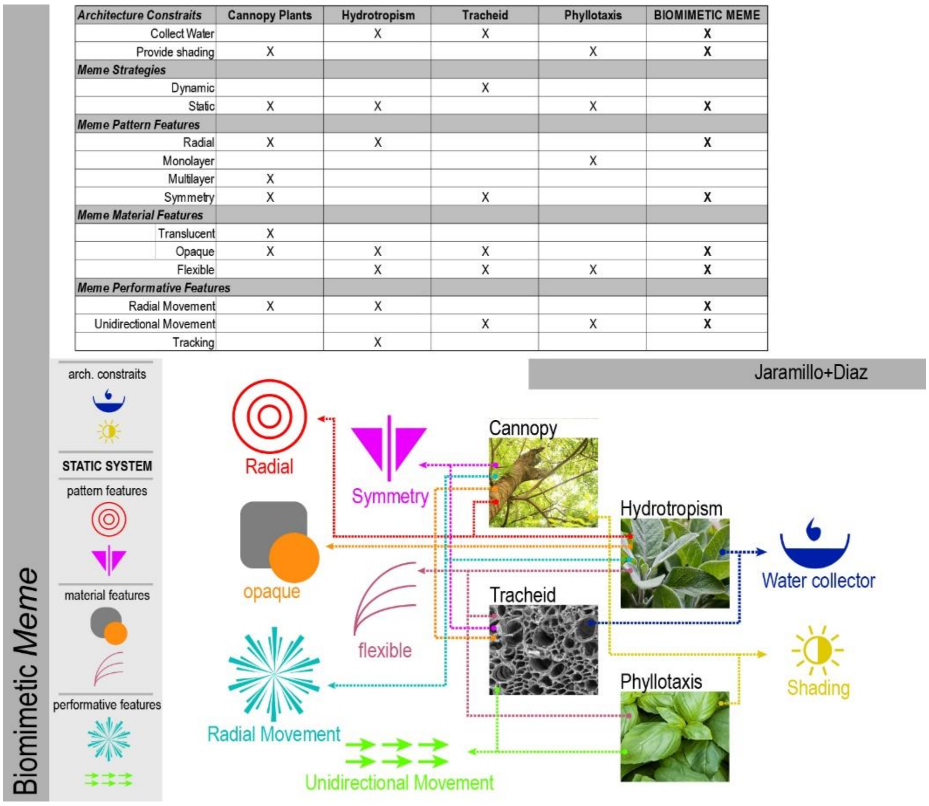


Fig. 10. Mini Orchid Yard – 3D simulation and exploratory mockups.

3.4 Project 04: Ibiscus Water Collector (Juliana Jaramillo + David Diaz)

Working at the installation scale, the Ibiscus Water Collector main function was to collect water for dry public spaces, at the same time that it could provide a shading shelter for the inhabitants. Sustained by vessels, canopy and hydrotropic morphological adaptation strategies, the biomimetic meme was a static, radial, monolayer event, with impermeable and rigid material features, that had the ability to storage and distribute water, in order to provide water to the surrounding living species (Fig. 11).

Since the project was based on the hibiscus flower the origami crease pattern was quite straight forward. It departed from a radial progression of folds with one kink that allowed for the closure of the structure and to the slight inflexion that would conduct water into the central part of the structure (Fig. 12).



Architecture Constraits	Cannopy Plants	Hydrotropism	Tracheid	Phyllotaxis	BIOMIMETIC MEME
Collect Water		X	X		X
Provide shading	X			X	X
Meme Strategies					
Dynamic			X		
Static	X	X		X	X
Meme Pattern Features					
Radial	X	X			X
Monolayer				X	
Multilayer	X				
Symmetry	X		X		X
Meme Material Features					
Translucent	X				
Opaque	X	X	X		X
Flexible		X	X	X	X
Meme Performative Features					
Radial Movement	X	X			X
Unidirectional Movement			X	X	X
Tracking		X			

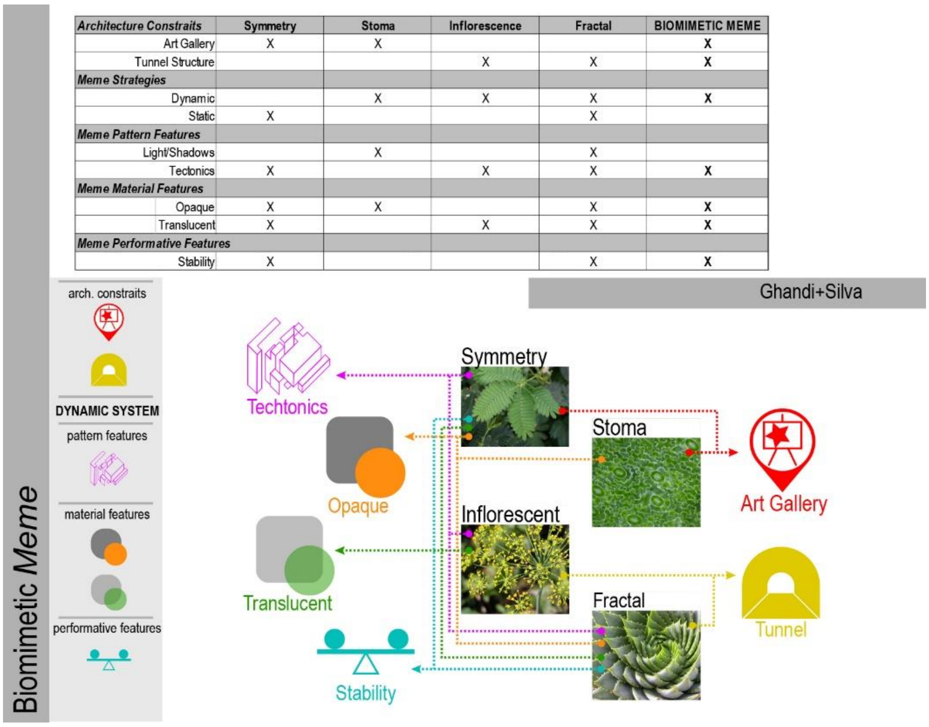
Fig. 11. Ibiscus Water Collector – Biomimetic Meme Construction.

Fig. 12. Ibiscus Water Collector – Exploratory mockup.

3.5 Project 05: FourToSix Walkway (Mona Ghandi + Victor Silva)

FourToSix Walkway was conceived as a movable and mutable structure. The primary main function for this self-supporting structure was to serve as an Art Gallery. Departing from the stoma and inflorescence as fundamental morphological adaptation strategies the biomimetic meme gave rise to a linear and dynamic structure, made of translucent and light materials in order to be (re)assembled and storage whenever needed (Fig. 13).

To materialize the linear and dynamic structure the group chose the Skewed Yoshimura pattern that could be locked when touching the ground through the use of triangular faces (Fig. 14).



Architecture Constraits	Symmetry	Stoma	Inflorescence	Fractal	BIOMIMETIC MEME
Art Gallery	X	X			X
Tunnel Structure			X	X	X
Meme Strategies					
Dynamic		X	X	X	X
Static	X			X	
Meme Pattern Features					
Light/Shadows		X		X	
Tectonics	X		X	X	X
Meme Material Features					
Opaque	X	X		X	X
Translucent	X		X	X	X
Meme Performative Features					
Stability	X			X	X

Fig. 13. FourToSix Walkway – Biomimetic Meme Construction.

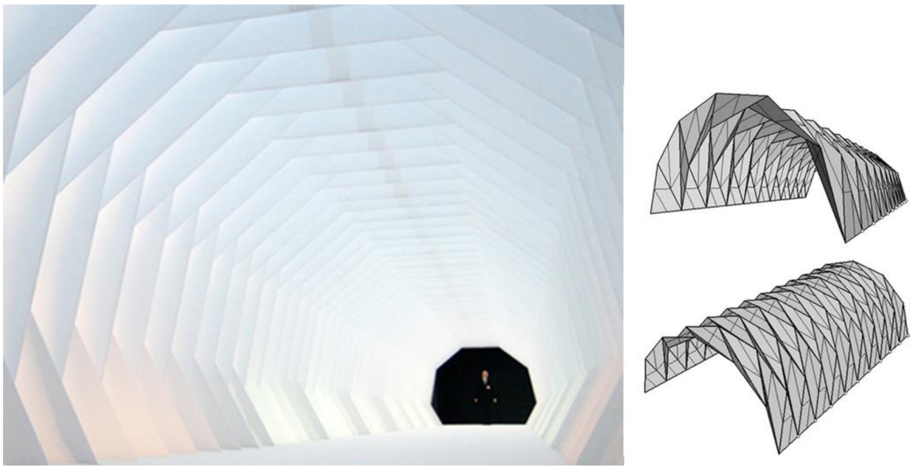


Fig. 14. FourToSix Walkway – 3D Simulation.

The five groups were able to present design proposals for structures based on rigid origami while exploring terrestrial vascular plants morphological strategies. From the study and abstraction of the meme pattern, material and performative features, all reached o global intention and some even considered the motion hypothesis and/or the mechanical implementation. Nevertheless, projects 02 and 03 are considered the less positive, based on the group's performance and work presentation.

Project 02 was not able to achieve the intended level of abstraction that could allow for the creation of a reliable biomimetic meme. And so, their design solution its technical and geometrical efficient, however lacks from biomimetic inspiration. In the case of project 03, the biomimetic meme was very strong but also very complex, and the students did not have enough time to conceive their parametric design solution.

On the overall, the final evaluation of the projects reflects a successful experience and a positive answer for the hypothesis of combining a biomimetic design process with a formalization through rigid origami geometry. At the end of the workshop the students were invited to share their ideas about the workshop, the most positive and negative points on their view, which will be extremely useful for the implementation of future similar workshops.

4 Conclusions

From the Nature Pleated Surfaces workshop was possible to retrieve valuable information, regarding the implemented biomimetic method, the ability of students to learn about origami geometry, but most of all regarding its application procedure.

During the *Architectural* domain, at the origami phase could be important to produce some practical exercises with the participants using paper and then implementing those same exercises on Grasshopper. Origami geometry is quite complex, and the exercises could help an origami beginner to engage easier on this type of geometry and understand in a tangible way the implications of the folds and their design. At the end almost every group was able to understand the basic principles of origami and how to manipulate the pattern in order to achieve a determined geometric concept, especially with the paper models, but this was only possible with direct aid from the tutors.

During *Nature* domain, the link elements between the origami geometry and the terrestrial vascular plants that enable the search and exploration through the terrestrial plant's adaptation strategies, should be rooted and extracted from the architectural function definition, and not from the origami geometry. In fact, all the five groups rooted they *Biomeme* on the architectural functions. This was one of the most relevant discoveries during this process.

At the final *Artifact* domain, when conceiving the parametric design solution, some of the participants anchored their design solutions on the biomimetic material features. This revealed to be an essential factor for the parametric design construction, elevating the projects to a more realistic and concrete state.

However, the generation of the parametric grasshopper definitions was not so well achieved. The groups were not able to create their definitions from scratch, most used the given definitions and altered them to reach their intended geometry. It was clearly too ambitious to expect that the students would be able to learn and produce so much work on their own in only eight hours.

The workshop could be much more successful if it had at least three days (twenty-four hours) for the development of the four phases. For forward experiences, the first day should concern the first phase, that is origami geometry experimentation with paper and parameterization, engaging the participants into origami theorems and geometric rules. The second day should concern phase two, getting familiar with the biomimetic process, exploring terrestrial vascular plants morphological and even other adaptations strategies. And finally, the third day would be used for phases three and four, by devoting their time to the parametric and simulation design studio. This way is believed that the students could go deeper on every presented subject and develop the ability of being autonomous while using the presented concepts and thus reach more interesting and complete project proposals.

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