Wing Coupling Pantographs: a Deployable Shading System Inspired by Insect Wings

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Abstract

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Saba Hor

This research investigates the design of a bio-inspired deployable shading system that addresses diverse user needs, including visual privacy, light control, and adaptability. Drawing inspiration from the morphology and mechanics of insect wings, the study translates natural principles, such as wing-to-wing coupling mechanisms and venation patterns, into architectural solutions.

The research employs an interdisciplinary methodology that integrates bio-inspired design approaches, parametric modeling, and iterative digital and physical prototyping. Through cycles of sketching, computational simulation, and prototype testing, the project examines how feedback between physical and digital models can enhance design outcomes, optimize tessellation configurations, and inform installation strategies. Two complementary bio-inspired design strategies, top-down technology-pull and bottom-up biology-push, were used to address both functional and aesthetic considerations, while parametric tools facilitated the translation of biological patterns into structural geometries.

The final prototype demonstrates a scalable, transformable shading system that merges traditional concepts, such as Orosi windows, with contemporary bio-inspired design thinking. Methodologically, the study contributes a hybrid workflow combining computational and hands-on experimentation; conceptually, it bridges cultural and natural frameworks; practically, it produces a functional, human-scale prototype with potential applications as interior partitions or adaptive façades. Limitations in time, funding, and fabrication scope suggest opportunities for further exploration of material strategies, structural behavior, and diverse wing-inspired patterns. The findings highlight the potential of insect-inspired transformable systems to inform responsive architectural design and offer a flexible platform for future research and innovation.

Acknowledgments

I am deeply grateful to my supervisor and mentor, Dr. Miranda Smitheram, whose patience, guidance, and steady belief in my work carried me through every stage of this research. Her support has shaped not only this thesis but also my growth as a designer and researcher.

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Finally, my heartfelt thanks go to my parents, my brother, and my friends, whose unwavering emotional support sustained me through every challenge and milestone of this journey.

Dedication

To my sister Zahra,

whose sacrifices, love, and unwavering support made this journey possible.

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Introduction

Shading has long been a central concern in architectural design, encompassing issues of sustainability, cultural expression, and visual experience. It manifests through window coverings of various forms, scales, and materials, which may be installed inside, outside, or within a building's envelope. These systems range from simple fabric curtains to intelligent, responsive façades on high-rise towers.

At the human scale, shading systems offer the advantage of direct interaction between the user and the device. In contrast, large-scale architectural shading systems are often automated to operate efficiently in response to environmental conditions and specific project requirements. Occupants' choices regarding shading devices are influenced not only by visual and thermal comfort but also by factors such as privacy, view quality, and social dynamics (Van Den Wymelenberg, 2012).

As an architect with a bio-inspired design approach based in Iran, visual privacy has always been one of my primary design concerns, alongside strategies for effective daylight distribution. My previous research involved the design of a "Superposition Reflective Louvre," a passive daylighting system inspired by the optical structure of lobster eyes. This system aimed to enhance daylight penetration into the central spaces of high-rise buildings. Through this research, I became deeply familiar with concepts of glare, light control through openings, and the extraction of natural principles for architectural light design.

After beginning my studies in Canada, I observed that sunlight is welcomed into buildings for most of the year. While overheating is less of a concern under these climatic conditions, there remains a significant gap in addressing visual comfort and visual privacy. This observation led me to propose the design of a bio-inspired shading system that responds more directly to these user needs.

Inkarojrit (2005) identifies four primary factors that influence the use of window coverings:

- Physical factors: ensuring visual and thermal comfort
- Physiological factors: sensitivity to glare
- Psychological factors: the need for visual privacy or access to views
- Social factors: organizational norms or a sense of ownership over blinds

To respond effectively to all these factors, shading systems at any scale need to provide adjustable control over coverage area or transparency. This need for adaptability led this research exploration of transformable structures as a foundation for designing shading systems. Developing deployable shading structures that can expand and contract, introduces opportunities for creating innovative solutions capable of accommodating users' changing needs.

The concept of transformation in response to environmental change is not unique to human design concerns; organisms in nature continually adapt to survive and thrive within their environments. Bio-inspired design, an emerging interdisciplinary approach, draws on these natural principles of adaptation to inform innovation in architecture and product design. Among various organisms, insect wings have served as the primary source of inspiration for this research project, both mechanically and visually.

Insect wings vary widely in shape, size, and cell pattern, reflecting functional adaptations for flight, defense, coloration, and thermoregulation (Celis & Diaz-Benjumea, 2003). They are particularly inspiring for deployable shading design because, like such systems, they must compact and expand efficiently for protection and performance. Structurally, they consist of delicate membranes supported by a lightweight framework—an analogy that strongly resonates with architectural shading design.

As transformable structures grow in complexity, predicting their behavior in tessellated configurations becomes increasingly challenging without computational assistance. This is where kinematic modeling and parametric design tools play a vital role in this design research. These digital methods not only facilitated simulation and optimization but also allowed the translation of biological geometries into design logic.

According to Frankel and Racine's (2010) classification of design research, this study falls under *research for design*, as it focuses on addressing a specific design problem rather than generating abstract theoretical knowledge. The problem at hand involves developing a bio-inspired deployable shading system capable of adapting to diverse user needs in an innovative way, particularly light control and visual privacy. All stages of the research, from conceptual exploration to computational modeling and physical prototyping, are directed toward resolving this central design challenge. The main research questions are as follows:

- How can iteration between digital and physical prototyping enhance the design process of a deployable shading structure?
- How can nature, through both Technology-Pull (top-down) and Biology-Push (bottom-up) approaches, contribute to the design of an effective deployable shading system?
- How can bio-inspired principles be translated into design using parametric design tools?

This research is inherently interdisciplinary, integrating perspectives from engineering, biology, and art. The morphology of insect wings serves as the central source of inspiration, forming the foundation of the bio-inspired design approach that informs both the conceptual and technical dimensions of the study. However, insights from the literature on scissor-like deployable structures and traditional architectural elements such as Orosi windows also influence the design development.

Accordingly, the methodological framework presented in Chapter 2 combines bio-inspired design methods with iterative hands-on and digital prototyping, where the parametric design process forms a key component. Chapter 3, the research creation chapter, documents the design process in detail, including the development of various scissor-structure prototypes, their kinematic models, and the translation of biological principles into design. This chapter also includes sketches produced throughout different stages of design. Finally, the conclusion chapter reflects on the overall design process, discusses the outcomes of this research, and identifies directions for future development and application of the bio-inspired deployable shading system.

CHAPTER 1

LITERATURE REVIEW

2.1 Introduction

Transformable shading systems can generally be classified into two main categories based on their method of structural transformation: deployable and demountable. Deployable structures incorporate kinematic mechanisms that allow them to transition from a compact configuration to an expanded state, enabling them to fulfill specific architectural functions (Fenci & Currie, 2017). Such structures are also referred to as foldable, reconfigurable, auxetic, extendible, or expandable systems (Rivas Adrover, 2015).

In this research, transformable shading systems are examined through both scales of application: human-scale window shading devices and architectural-scale kinetic shading systems. The literature review focuses on case studies that provide technical insights relevant to the design of deployable structures, particularly those integrating parametric design and bio-inspired design approaches. This review also includes selected design exemplars as contextual case studies, grounding the theoretical discussion in relevant design practice.

2.2 Human-Scale Transformable Shading Devices

Human-scale transformable window shading devices primarily address light control and privacy based on individual user needs. At this scale, human-in-the-loop configurations are essential, as the design often relies on user interaction and adaptability.

2.2.1 Facet: A Modular, Kinetic Partition System

A notable example of transformable structures at the human scale is the *Facet* Room Divider, developed by the Dutch studio Bloomming. As shown in Figure 1, *Facet* is a modular, manually adjustable partition composed of diamond-shaped units mounted on a fixed frame. Each module rotates independently along its central axis, allowing users to control light, transparency, and privacy in real time. This manual operation enables direct physical engagement without relying on mechanical or digital components.

Technically, *Facet* represents a low-tech kinetic design approach, achieving movement through simple geometric manipulation rather than automation (Bloomming, 2022). This system serves as a strong example of a multifunctional modular design, operating both as a shading device and as a spatial divider—an approach that similarly informs the development of my design.

Another key aspect of this project is its sustainable materiality. Made from lightweight, recyclable materials such as aluminum and ABS plastic, it serves as a flexible, non-load-bearing partition adaptable to diverse interior settings. Beyond functionality, *Facet* enhances spatial experience through dynamic light and shadow effects generated by user interaction (Bloomming, 2022). Its integration of manual control, modularity, and material efficiency makes it a practical example of sustainable and user-centered kinetic design, demonstrating how passive mechanisms can achieve adaptability while maintaining architectural simplicity.

Figure 1*.Facet partition system, (Bloomming, 2022). Reproduced with permission from Bas van Leeuwen, copyright holder.*

2.2.2 Magnetic Foldable Curtains: an Experimental Shading System

At the human scale, an exemplary case of a deployable shading structure is the Magnetic Curtain designed by Florian Kräutli (2008). This experimental system allows users to sculpt the fabric into various forms through embedded magnets arranged in a diamond-shaped grid. Figure 2 shows how the curtain operates manually—users can press the fabric to engage the magnets and hold a shape or pull it apart to release them. Made from a semi-transparent white textile, it admits diffused light while creating visually dynamic geometries when folded (Andreieva, 2014). This innovative folding mechanism presents potential benefits for apartment dwellers, offering a durable and adaptable alternative to conventional curtains by relying on magnetic manipulation rather than mechanical parts (Ahmed et al., 2020).

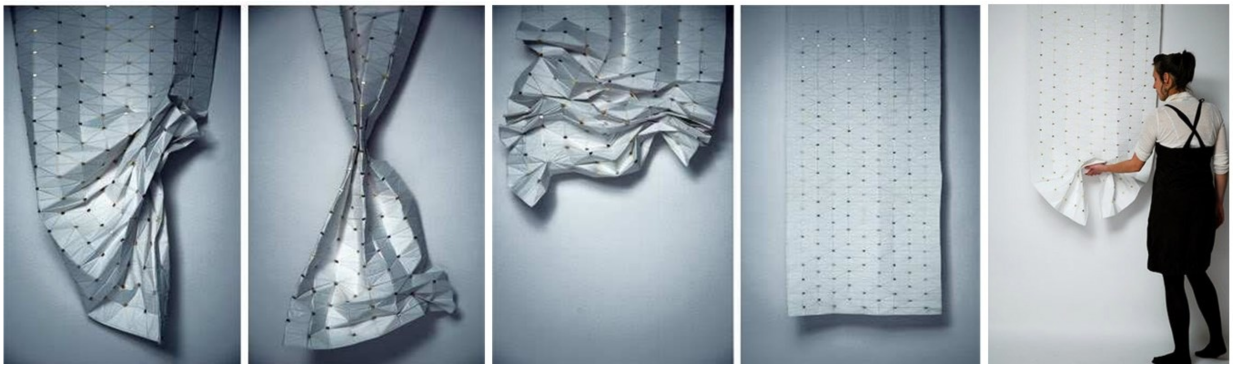


Figure 2. *The Magnetic Curtain. Source: Florian Kräutli, 200), Reproduced with permission.*

The *Magnetic Foldable Curtain* exemplifies a deployable structure grounded in origami principles. Rivas Adrover, in her book *Deployable Structures: Form and Technique*, categorizes deployable structures into six primary types, one of which—*generative techniques*—encompasses origami paper pleat. Origami is defined as the art of transforming a flat sheet into a three-dimensional form (Rivas Adrover, 2015).

As folding and unfolding represent some of the most prevalent strategies for achieving deployability, many deployable shading systems incorporate origami principles either as the main structural mechanism or as an auxiliary component integrated with other types of deployable. Similarly, this study investigates the potential of pleated paper membranes as part of the design exploration.

2.3 Deployable Shadings Based on Scissor Structures

Scissor structures and hinged plates fall under the category of rigid structural components. These deployable systems are composed of solid elements connected through joints, enabling stability and controlled motion throughout all stages of deployment. Due to their reliability and geometric versatility, scissor mechanisms are widely applied in architectural contexts for creating transformable, adaptable, and space-efficient designs (Rivas Adrover, 2015).

Scissor-like elements, also known as *pantographs*, consist of a pair of beams joined together by a pivot (revolute joints) so that free rotation of one beam relative to another about the axis of the pivot is allowed, and any other relative motion of the rods is prevented. According to You and Chen (2011), scissor-like elements are classified into two types based on the position of their hinges and pivots: conventional and angulated. In conventional elements, the pivot and end connectors are collinear, allowing the use of straight rods. In angulated elements, the hinges and pivot are non-collinear, requiring kinked beams or flat plates (You & Chen, 2011).

A notable precedent demonstrating the effective integration of origami with other types of deployable structures is the transformable shading system developed by Fan et al, students at Columbia University. This system incorporates scissor mechanisms as the primary structural framework, while a series of pleated paper membranes function as the shading elements. The scissor mechanism employed in this project corresponds to the same type of deployable structure utilized in my design.

The shading system designed by Fan et al. consists of two interconnected sets of scissor structures that operate in opposite directions—when one expands, the other contracts. One set is clad with pleated paper membranes, while the other remains uncovered. By pulling the scissor mechanism horizontally, the user can extend or compress the shaded area within the wooden frame, allowing control over light or privacy.

According to the described typology, the transformable shading system designed by Fan et al. is based on conventional scissor-like elements. As discussed in the Research Creation chapter, my study includes prototypes utilizing both conventional and angulated scissor mechanisms, while the final design is developed with the latter.

It is noteworthy that this and several other case studies were designed using Parametric design tools such as Grasshopper and Rhino 3D, a topic further elaborated in the next section. The reason is that as deployable structures grow in geometric complexity, predicting their behavior in tessellation becomes increasingly difficult, often impossible, without the aid of digital modeling and simulation tools.

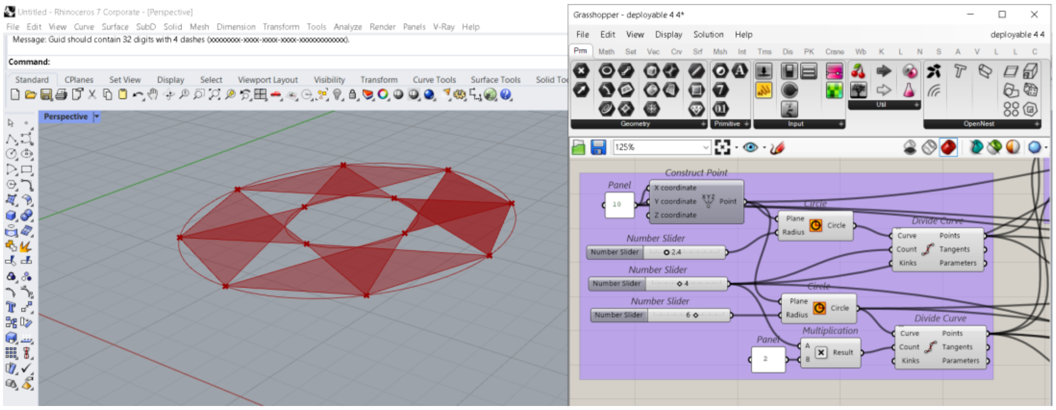
2.4 Parametric Kinetic Shading Systems

Deployable structures are applied not only at the human scale but also in large-scale architectural designs as kinematic façades. The rapid advancement of technology has revived interest in kinetic architecture, challenging conventional norms through the integration of manufacturing and digital innovations. These developments enable the creation of dynamic, responsive building envelopes that adapt to environmental conditions and enhance energy performance (Ahmed et al., 2016).

Parametric design tools are essential for kinetic façade development, as they enable rapid iteration, modification, and testing of design alternatives, allowing designers to refine both components and overall concepts efficiently. Parametric design empowers designers to explore countless variations of a concept through computational models that respond fluidly to change. These models are composed of geometric components defined by both fixed and adjustable parameters—so that when a parameter shifts, the entire system adapts and reconfigures itself seamlessly, eliminating the need to redraw or rebuild (Barrios Hernandez, 2006).

The creation of such models often relies on visual programming languages (VPLs), which replace lines of code with intuitive graphical interfaces. In these environments, designers build logic visually—through interconnected nodes that represent actions and relationships—translating complex algorithms into accessible, visual workflows. Among these tools, Grasshopper, integrated within Rhino3D, stands as one of the most powerful. It allows designers to script geometry visually, where parameters flow through networks of user-defined functions. Any adjustment to a parameter ripples through the entire algorithm, transforming the geometry in real time and making the design process both dynamic and deeply interactive (Cabrera-Revuelta et al., 2024).

The following figure shows the interface of Grasshopper and Rhino3D. Adjusting the slider values in Grasshopper instantly updates the geometry in Rhino, demonstrating the real-time link between parameters and form.



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Message: Guid should contain 32 digits with 4 dashes (xxxxxxxx-xxxx-xxxx-xxxx-xxxxxxxxxxxx).
Command:
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*Figure 3.**Rhino and Grasshopper interface (Hor, 2025)*

2.4.1 Al-Bahar tower: a parametric kinetic facade

The Al Bahar Towers in Abu Dhabi feature a kinetic façade composed of triangular modules inspired by origami umbrellas (hinged plates). These modules open and close in response to the sun's movement, each acting as an independent shading unit that adjusts to minimize solar heat gain. Extending 2.8 meters from the main structure, the cantilevered modules combine stainless-steel frames, aluminum arms, and fiberglass mesh, achieving both structural precision and elegant motion (Attia, 2018).

When deployed, the façade creates a continuous, veil-like surface that softens daylight; in motion, it transforms into a geometric lattice that animates the building envelope. The PTFE infill maintains interior transparency even when closed, while the hexagonal configuration of six folding panels allows adaptive control of light and thermal comfort (Yunitsyna & Lika, 2020). Each tower is enclosed by an independent glass curtain wall, separated by movement joints, enabling both layers to operate harmoniously yet autonomously (Attia, 2018).

The Al Bahar Tower is an outstanding example of how parametric design tools can be used to create a kinetic façade based on deployable structures. In this project, parametric design contributed to both the generation of the façade's geometry and the development of its kinematic behavior. It also served as a powerful tool for sustainable design, since the structure is designed to dynamically respond to heat and light conditions.

Another aspect of the Al Bahar Towers project that informed this research is how it transforms a traditional architectural concept into contemporary engineering. The design is rooted in the idea of the Mashrabiya (figure 4), intricate wooden screens historically used in Arab architecture to ensure visual privacy, reduce glare, and shield interiors from harsh sunlight. Traditionally, these screens played a crucial cultural role, particularly in women's quarters of courtyard houses, where maintaining privacy from the public realm was essential (Abdelwahab et al., 2023)

In this project, the Mashrabiya concept was reinterpreted as a kinetic façade system, translating its cultural and environmental logic into a modern language of dynamic panels. These panels move in response to sunlight, transforming a static ornamental screen into a living, adaptive structure (Alkhayyat, 2013).

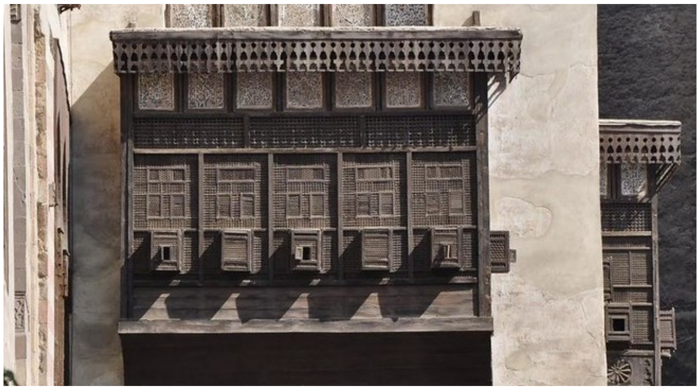


Figure 4. *Arabic Mashrabiya. Photograph by Sam Valadi (2015), Flickr. Licensed under Creative Commons Attribution 2.0 (CC BY 2.0).*

The design was also inspired by the biological movement of the mangrove flower, whose opening and closing behavior informed the pattern's logic, motion, and joinery mechanisms. (Alkhayyat, 2013). For this project, the designers established rule-based transformations to emulate the flower's responsive form, reflecting a bio-inspired design approach.

2.5 Bio-Inspired Shading Systems

Organisms in nature have always adapted to their environments by evolving multifunctional strategies that help them survive and thrive. After decades dominated by functionalism and post-modernism in architecture, designers are once again turning to the fluid, organic forms found in nature (Knippers & Speck, 2012).

Over the past few years, researchers have proposed various definitions for drawing inspiration from nature. The distinction between these terms lies in the depth and nature of their engagement with the natural world. (Pohl & Nachtigall, 2015) Although the terms are sometimes used interchangeably, their origins and emphases differ considerably (Dicks, 2016).

Biomimicry means "to imitate life," and focuses on directly replicating nature's forms, patterns, or behaviors in human-made designs (Pohl & Nachtigall, 2015). Benyus, (2009) defines biomimicry through three lenses: *nature as model*, studying and emulating nature's designs to solve human challenges; *nature as measure*, using ecological standards to judge the sustainability of innovations; and *nature as mentor*, shifting from exploiting nature to learning from it.

Biomimetics is less about copying and more about studying the underlying mechanisms of natural systems, applying those principles to create intelligent, efficient solutions in design and engineering. Rather than reproducing appearances, it seeks to translate nature's logic into functional innovation. (Pohl & Nachtigall, 2015)

Bio-inspired design or biologically inspired design (BID) is the application of knowledge of biological systems in research and development to solve technical problems and develop technical inventions and innovations. Bio-inspired design aims to mine biological knowledge to solve existing design problems systematically (Hashemi Farzaneh, 2020).

Bionics, coined in 1958 by Jack E. Steele, merges biology and technology, originally describing how observations of biological phenomena inspired technological advances (Pohl & Nachtigall, 2015) Bionics emerged from a background in engineering, cybernetics, neurophysiology, and early work on cyborgs. While its scope has since broadened, bionics remains closely associated with robotics and artificial intelligence. In bionics, the principle of "nature as a model" refers to imitating nature's processes for bringing things into being, rather than merely reproducing its external forms (Dicks, 2016).

The following figure maps the relationships between different nature-inspired design approaches, highlighting both their distinctions and areas of overlap.

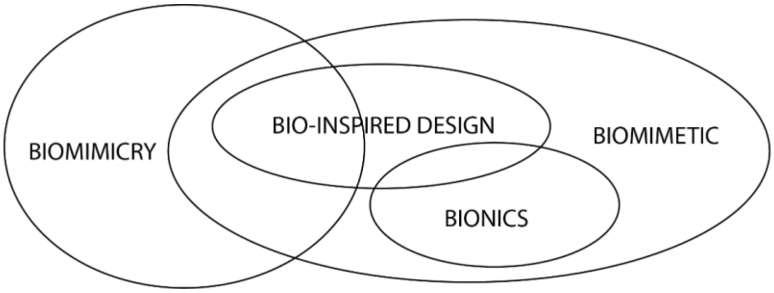


Figure 5. *Definitions for drawing inspiration from nature (Hor, 2025).*

In the following section, I will examine several examples of nature-inspired approaches used in designing transformable shading systems.

2.5.1 One Ocean Thematic Pavilion, EXPO 2012

The One Ocean Pavilion, part of the EXPO 2012 Thematic Pavilion in Yeosu, Korea, showcases a compelling example of a top-down biomimetic design approach. Inspired by the movement of the *Strelitzia reginae* flower (figure 6), researchers developed Flectofin, a hinge-less, adaptive shading system made of fiberglass-reinforced plastic (Lienhard et al., 2011).

The flower's mechanism—where a bird's weight causes petals to bend and expose reproductive parts—was translated into an engineering principle based on torsional buckling, a phenomenon typically regarded as structural failure, but here reimagined as a functional design feature. However, due to the structural limitations of scaling Flectofin for the pavilion's large and wind-exposed facade, a new kinetic system was created using curved plates with hinged corners, which buckle under compressive force to achieve controlled movement. The result is a wind-resistant, dynamic shading facade that fulfills both functional and aesthetic requirements of the architecture (Knippers & Speck, 2012).

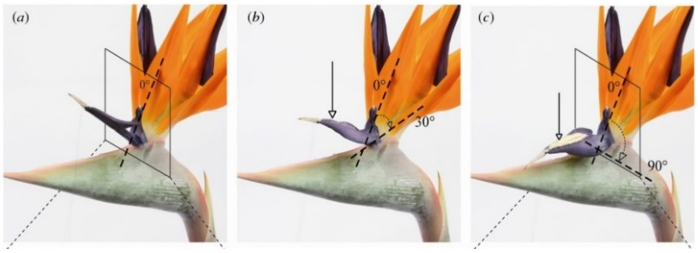


Figure 6. *Deformation sequences of the Strelitzia reginae flower. Source: Lienhard et al., "Flectofin: a hingeless flapping mechanism inspired by nature," Bioinspiration & Biomimetics, 2011. © IOP Publishing. Reproduced with permission. All rights reserved.*

Complementing this biomimetic logic, the pavilion's outer skin is constructed from thin sheets of glass-fiber-reinforced polymers, which enable a range of animated patterns. These responsive surfaces mimic fish fins, producing a rippling effect that allows the structure to "breathe" as the panels open and close rhythmically. This adds not only a biological elegance to the building's appearance but also enhances its environmental adaptability (Yunitsyna & Lika, 2020).

2.5.2 Helio Trace Center of Architecture

Engineering firm Buro Happold, in collaboration with deployable structures specialist Chuck Hoberman, founded the Adaptive Buildings Initiative (ABI) to explore intelligent kinetic surface systems. One of their major innovations is the *Strata* System, a modular, automated shading and cladding solution designed to retract into a compact, streamlined profile. This system served as the foundation for the Helio Trace Façade, developed in partnership with SOM and the Permasteelisa Group. The façade significantly improves building performance by reducing solar heat gain by up to 81%, while also enhancing daylight and glare control (Ahmed et al., 2016).

Each kinetic shading unit consists of twelve components, eight parallel and four perpendicular elements, made of perforated metal sheets that regulate airflow and light. These sheets expand and retract toward the center to form a pyramid-like shape, stabilized by small, welded beams. The system operates through one-dimensional motion along the X, Y, or Z axis, where the parallel elements move together while the perpendicular ones act semi-independently, providing dynamic, targeted side shading (Alkhayyat, 2013).

The design draws from both biological and linguistic generative systems. Morphologically, it is inspired by the sensitive plant, Mimosa pudica, which responds to touch by contracting—an analogy for responsive architectural behavior (figure 7). Simultaneously, the transformation of the shading pattern adheres to geometric rules that preserve parallel and perpendicular relationships, resembling a form of rule-based or linguistic system generation (Alkhayyat, 2013)

The importance of this project as a case study is the integration of biomimicry, geometric logic, and material innovation, which demonstrates how kinetic systems can enhance both performance and aesthetics through this integration.

Figure 7. *Left: Mimosa pudica plant, right: the shading system (Chehab et al., 2008), Source: Chehab et al., "Thigmomorphogenesis: a complex plant response to mechano-stimulation," Journal of Experimental Botany, vol. 60, no. 1, pp. 43-56, 2008. Reproduced by permission of Oxford University Press.*

2.5.3 Interactive Kinetic Façade Inspired by Orosi and Morpho Butterfly

The following case study examines a research project that explores the design of a deployable shading system inspired by the morphology of butterfly wings and informed by the traditional architectural concept of *Orosi*. This concept also underpins my current design, influencing both the lattice-like wooden supporting frames and the use of colored transparent materials as membranes within the deployable structure.

Orosi is a window featuring a wooden frame with a lattice design, filled with multicolored glass pieces (Hosseini & Heidari, 2022). As Figure 8 shows, this type of window slides vertically within a groove instead of rotating on hinges. In Persian, the prefix 'Or' refers to the action of moving upward (Mehrizi & Marasy, 2017). The Orosi, either movable or fixed, provides various functions, including aesthetic and decorative, daylight control, thermal performance (Hosseini et al., 2021), providing airflow, positive psychological effects, privacy, and even repelling insects (Ahmadi et al., 2023) (S. M. Hosseini et al., 2020).

Figure 8. *Orosi windows in Mashrutiat house located at Isfahan, Iran. Source:* S. N. Hosseini et al., 2020, *Licensed under CC BY 4.0.*

Several studies have explored the impact of Orosi windows on indoor daylight quality and visual comfort. In the study by Hosseini et al., (2018), the authors combined qualitative analysis with parametric simulations to assess how different colored glass options (red, blue, green, yellow, and multicolored) influence daylight conditions in interior spaces. Using Rhinoceros, Grasshopper, and the Diva plugin, they analyzed the performance of these configurations through climate-based metrics such as Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), and glare probability. The findings highlighted that colored glass can effectively balance natural light while enhancing visual comfort, with each color contributing differently to illuminance and glare control (Hosseini et al., 2018).

Building on the foundation of previous research conducted by Hosseini et al. (2018) on Orosi windows, he introduced an interactive kinetic façade design inspired by Orosi windows in 2020. This system features movable, colored panels, using the same traditional color palette, that rotate in response to sun angles and occupants' positions. By integrating passive cultural elements with active mechanical components, the design bridges traditional aesthetics with contemporary environmental performance needs. The team tested 72 façade scenarios using the same parametric tools, demonstrating that the kinetic system outperformed static façades by significantly improving daylight distribution and reducing discomfort from glare (S. M. Hosseini et al., 2020).

Further advancing this line of inquiry, Hosseini & Heidari, (2022) incorporated biomimicry principles inspired by the Morpho butterfly wing into their Orosi-based kinetic façade design (figure 9). Applying General Morphological Analysis (GMA), they developed a system of hexagonal colored modules that adapt dynamically to changing daylight conditions. Simulation results showed high levels of daylight performance, achieving up to 93.5% UDI and a significant reduction in glare and over-illumination. This study reinforces the potential of combining traditional architectural elements and biological analogies to create responsive, energy-efficient façade systems that enhance occupant comfort.

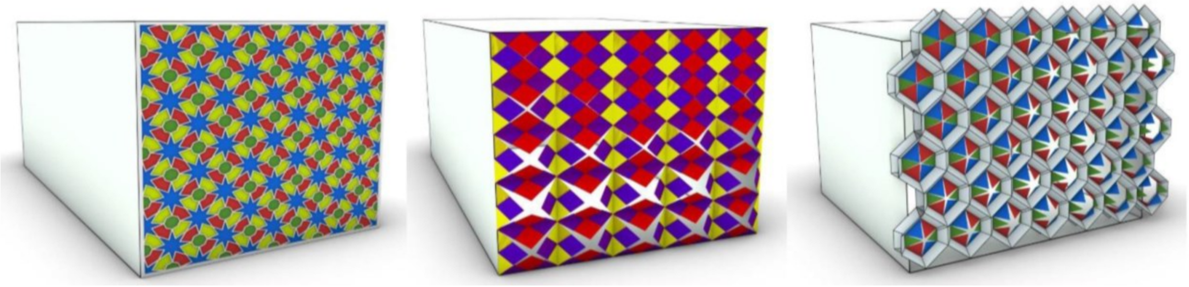


Figure 9. *Three distribution scenarios on the façade inspired by orosi windows. From left to right: Frame Islamic star pattern, interactive kinetic façade, inspired by the Morpho butterfly wing (Hosseini & Heidari, 2022). Reprinted from Journal of Building Engineering, Vol 59, Page 17, Copyright (2022), with permission from Elsevier.*

2.6 Summary of Literature Review

Through this literature review, each contextual case study, from human-scale to architectural-scale kinetic shading systems, has contributed valuable insights to my research.

The *Facet* system exemplifies how modular design can serve multiple purposes, functioning both as an interior partition and a shading device. Its user-centered kinetic approach enhances spatial experience through dynamic light and shadow interactions while emphasizing sustainable material use.

The deployable shading system developed by students at Columbia University demonstrates how conventional scissor mechanisms can be reimagined as adaptable shading structures. The incorporation of origami-inspired membranes and the use of kinematic modeling in Grasshopper underline the crucial role of parametric tools in designing responsive, transformable systems.

The Al Bahar Towers project informs my thesis by exemplifying how bio-inspired and kinetic design can merge with cultural heritage to create responsive shading systems. Its origami-like façade adapts to sunlight through modular movement, demonstrating how traditional aesthetics and advanced technology can integrate—an approach that parallels my design.

Both the One Ocean Pavilion and the Helio Trace Façade demonstrate how bio-inspired principles can lead to innovative kinetic shading systems. The One Ocean Pavilion translates the motion of the Strelitzia reginae flower into a hinge-less adaptive mechanism based on torsional buckling, while the Helio Trace Façade draws from the responsive behavior of the Mimosa pudica plant to create modular shading units that react dynamically to environmental changes. Together, they highlight how natural mechanisms can inform architectural adaptability, an approach that parallels my thesis, which takes inspiration from the insect wings to develop a transformable, responsive shading system.

Finally, the Interactive Kinetic Façade inspired by Orosi and the Morpho butterfly, informs my thesis by showing how traditional and biological references can be integrated to create responsive architectural systems. This project merges the optical and microstructural qualities of butterfly wings with the cultural and environmental logic of Orosi windows to enhance daylight and visual comfort. Similarly, I reinterpret biological principles; however, my design draws from Orosi differently, through its lattice wooden frames and colored transparent materials.

CHAPTER 2

METHODOLOGY

3.1 Introduction

The methodological framework of this research is primarily grounded in *bio-inspired design*. This approach provides both conceptual guidance and a systematic structure for transforming biological principles into practical design solutions and innovations. The following chapter discusses in detail the various levels of bio-inspired design and the specific methods applied in this project.

As a key objective of this study is to evaluate and compare digital and physical prototypes, the *parametric design* approach is particularly well-suited to this task, enabling rapid prototyping and iterative refinement between models. Beyond its practical application, parametric design is essential in bio-inspired design, as it allows the translation of biological patterns and geometric principles into functional design solutions. This computational approach ensures both precision and flexibility, supporting a dynamic workflow in which digital modeling and physical experimentation continuously inform one another.

In essence, the methodology adopts a hybrid approach, merging bio-inspiration, parametric modeling, and hands-on prototyping. Together, these methods aim to produce a shading system that is both aesthetically inspired by nature and functionally optimized through iterative design exploration.

3.2 Bio-inspired Design Approach

According to established definitions in the literature review, this research generally falls under *bio-inspired design*. The inspiration from the wing-coupling mechanism aligns primarily with the *biomimetic*, while the inspiration drawn from the venation patterns of insect wings corresponds more closely to the concept of *biomimicry* (Figure 11*)*. In the following sections, I will discuss the methods, dimensions, and levels of bio-inspired design in my project.

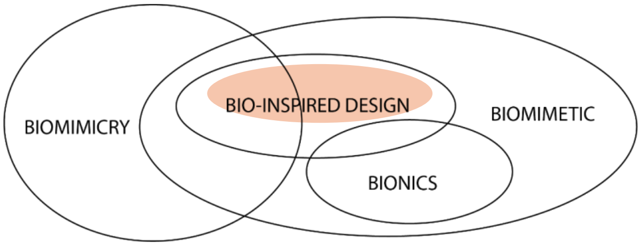


Figure 10. *The highlighted part in the diagram is where this research is situated (Hor, 2025).*

3.2.1 Methods of BID

Pohl & Nachtigall, (2015) , identified three main methods for bio-inspired design. The Biology Push or *bottom-up* approach begins with exploring biological systems to discover what can be extracted from them for technological application. The Technology Pull or *top-down* approach starts with a specific technological problem or product need and then investigates how nature can offer potential solutions. The third method, Pool Research, involves gathering and comparing information from both biology and technology to support the adaptation and innovation process in research. In this research, I used a hybrid approach following biology push and technology pull methods at two different stages of the design process.

First, while designing a deployable structure, I encountered a stability problem when the structure was fully expanded. I approached *nature as a solution* dataset, identifying efficient strategies to address technical challenges. Following the top-down bionic design framework by Knippers & Speck (2012), I began by defining the technical problem, then explored relevant biological concepts to identify suitable principles. The wing coupling mechanism in insects provided the solution through biomimetics. I abstracted these principles from their biological context, tested them through prototyping, and applied them to develop the final design. Figure 11 shows the steps of the top-down BID design for my project guided by the Knippers and Speck framework.

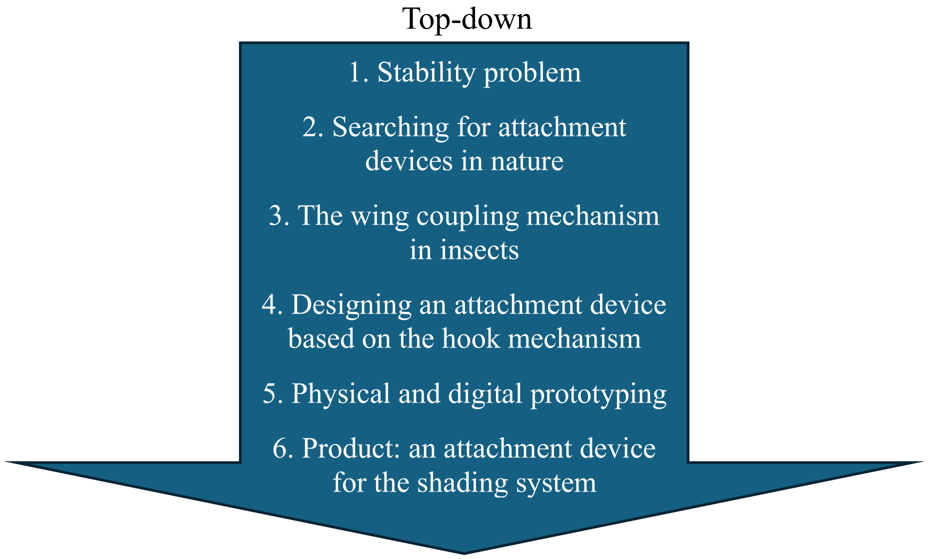


Figure 11. *BID steps for the top-down approach in my project (Hor, 2025) based on the framework introduced by Knippers and Speck (2012).*

Second, through further research on insect wings and their coupling mechanisms, I identified the venation patterns as a promising concept for developing my design. This led me to adopt a bottom–up approach for the next step. Guided by the biology of insect wings, I now view *nature as an inspiration* for designing the supporting frames for the membrane of the shading system (Figure 12).

Following the bottom-up approach of the *bionic design framework* proposed by Knippers & Speck, (2012) I began by exploring biological references related to insect wings. I then analyzed the morphology of wing venation to understand the underlying principles and geometric logic of these biological patterns. Subsequently, these geometric principles were translated into numerical constraints within *Grasshopper* to enable parametric exploration. Parametric design served as the main tool for developing and refining the concept through digital modeling. An iterative process between digital and physical prototyping facilitated the technical implementation of the bio-inspired patterns, culminating in the final product—a set of bio-inspired supporting frames for the shading membrane.

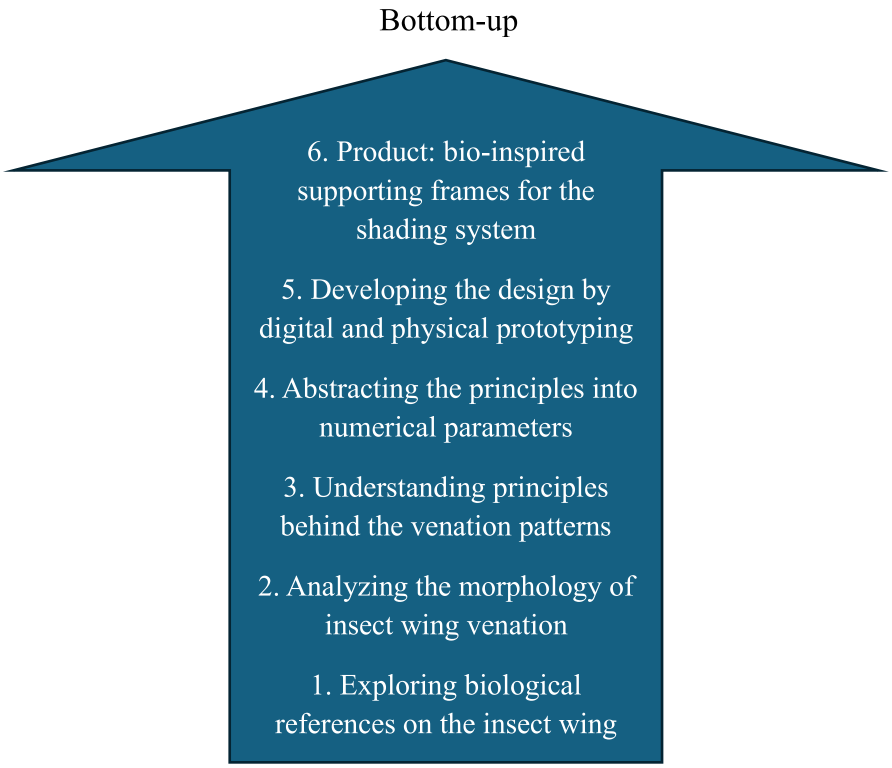


Figure 12. *BID steps for the bottom-up approach in my project (Hor,2025) based on the framework introduced by Knippers and Speck (2012).*

3.2.2 Levels and Dimensions of BID

Bio-inspired design can occur at three levels: the *organism* level, which involves mimicking all or part of a specific species; the *behavior* level, which focuses on replicating actions or interactions within a broader context; and the *ecosystem* level, which emulates the principles that govern entire ecological systems. Across these levels, five dimensions of mimicry can be identified: form, material, construction, process, and function. (Zari, 2007).

For the current study, the biological research operates at the *organism* level, focusing on the morphology and anatomy of insect wings. The bio-inspired design process engages with both the form and function dimensions. Inspiration was first drawn from the wing-coupling mechanism, addressing the functional dimension, while the second phase of bio-inspiration concentrated on the *form* dimension, exploring the shape and geometry of insect venation patterns.

3.3 Iterative Prototyping

One of the research questions in this study concerns the development of the design through iterative prototyping. The iterative process in this project unfolds in various forms, ranging from hand sketching to digital modeling and physical prototyping. The back-and-forth process between digital and physical models allows for ongoing exploration and refinement of the design solutions.

3.3.1 Physical Prototyping

For rapid physical prototyping of deployable structures, I used lightweight, sustainable, and readily available materials: wooden sticks for the main structure, brass paper fasteners for the pivots, and wax paper for the membranes (Figure 13). This approach enables quick experimentation without concerns about material waste or irreversible joints. As the project progressed, I experimented with different materials and fabrication methods to achieve a more solid structure and refined outcome. For example, I replaced paper fasteners with Chicago bolts to create more durable joints.

Figure 13. *Initial prototypes with wood sticks, paper fasteners, and wax paper (Hor,2024)*

Digital fabrication methods played a crucial role in enabling rapid physical prototyping. The fabrication of complex bio-inspired patterns for the supporting frames would not have been possible without laser-cutting technology. For producing the wing coupling attachment device, 3D printing the components proved to be the most effective option.

One challenge I encountered during the fabrication was coloring the wooden frames without contaminating the membranes, as the frames were also used as molds during membrane fabrication. To resolve this, I used a Cricut machine (Figure 14), to cut the frame shapes from white cardboard, which I later glued onto the wooden frames after the membranes had fully dried. This approach allowed for clean, precise coloring and assembly.

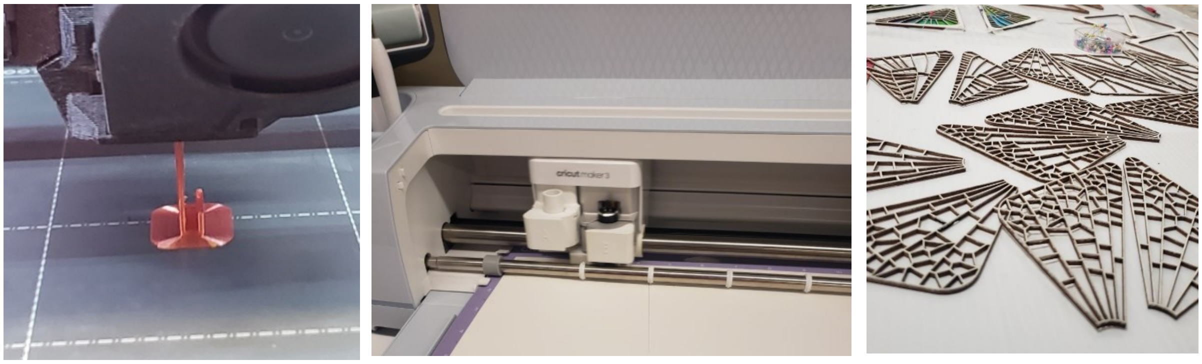


Figure 14. *Digital fabrication tools for rapid prototyping from left to right: 3D-printed attachment, Cricut-cut cardboard, and laser-cut supporting frames (Hor, 2025).*

In some stages, the process of physical prototyping has been extended into material exploration. I tested various options for the membrane, such as bioplastic and white glue (Figure 15), as well as plexiglass and wood sheets for the supporting frames. However, material exploration was not a central focus of this research. Therefore, I did not pursue iterative testing to perfect material compositions; instead, I explored readily available alternatives and selected the most suitable ones, as extensive material and fabrication studies were beyond the scope of this project.

Figure 15. *Prototypes with colored PVA glue (Hor 2025).*

3.3.2 Digital Prototyping

For iterative digital prototyping, the parametric design approach was essential, as generating design variations lies at the core of the process. I used Grasshopper for digital prototyping at two distinct stages of the project, each serving a different purpose.

In the first stage, I focused on prototyping the main deployable structure and its kinematics. Using Grasshopper at this level allowed me to explore the motion dynamics of scissor structures by applying external forces and observing how their geometry transformed during deployment. This process helped me investigate opportunities for design innovation, analyze the behavior of structures in tessellation, and identify the optimal points for securing the structure to a window.

The second stage involved applying digital prototyping to the bio-inspiration of insect wing venation. Here, parametric design enabled the translation of biological numerical principles into design geometry. As Asefi et al., 2019 note, parametric design can be applied not only during concept development but also in later stages, such as visualization. In this project, algorithmic design allowed me to compare different iterations of the final patterns and select the one that was visually most appealing for fabrication.

3.4 Design Process

The project began with a study of deployable structures and their mechanisms, drawing on both engineering literature and bio-inspired case studies, as well as traditional architectural solutions for shading systems. After producing initial sketches of shading systems based on various deployable structures, I narrowed my focus to scissor structures.

Following a detailed study of their mechanisms, I began physical prototyping various types and tessellation patterns of scissor structures, alongside new sketches and digital prototyping in Grasshopper. Physical prototyping at this stage helped me to understand the potential and limitations of different configurations, while kinematic modeling in the digital environment allowed me to predict their behavior, explore tessellation possibilities, and identify optimal installation options. The iterative process between digital and physical prototypes informed the design in multiple ways, providing a means for verification and refinement of the results.

Through these iterative experiments, one pattern emerged as the most promising for development into a functional shading system. However, during tessellation and technical exploration of window installation, I encountered a design issue: the structure lacked stability in its fully open configuration.

To address this problem, I adopted a top-down bio-inspired design approach, which involves searching biological databases for solutions to engineering challenges. Among various natural attachment mechanisms, the wing-to-wing coupling mechanism in insects proved to be an ideal analogy for stabilizing the deployable structure. Inspired by this biological model, I designed a hook-shaped attachment device, modeled in Rhino and 3D printed for integration into the final prototype.

The next phase focused on designing the membrane of the shading system. In the initial physical prototypes, I experimented with two types of membranes made from wax paper—one pleated and one flat. I decided to continue with the flat version as it performed better in terms of functionality.

Looking back at the core questions of this study, the design of the membrane aimed to achieve a balance between aesthetic innovation and functional shading performance—providing both visual comfort and a sense of privacy. Drawing inspiration from traditional Persian *Orosi* windows, where wooden lattices filled with colored glass create patterned light and privacy, I sought to reinterpret this concept in a contemporary context.

Focusing on a bio-inspired design approach, I turned to the microstructure of insect wings as another source of inspiration. This led me to revisit biological references this time through a bottom-up (biology-push) approach, which guided the development of the membrane’s form and structure. I began by sketching lattice-like support frames for the membrane, inspired by both the Orosi windows and the venation patterns of insect wings. From the biological study of four different insects, I extracted geometrical principles that informed the design. To recreate these geometries, I employed parametric design in Grasshopper, translating numerical principles from nature into deployable structures through visual programming. Laser cutting enabled the fabrication of precise physical prototypes of these support frames.

The final phase involved the development of materials and colors for the membrane. My initial choice was bioplastic, which was sustainable and easy to produce. However, I encountered issues with bioplastic, such as shrinkage during the drying process and deformation within the wooden frames. Additionally, it did not achieve the desired light effects reminiscent of the Orosi windows. Consequently, I decided to switch to using PVA glue, which excelled in terms of flexibility, transparency, and optical quality.

For coloring, I selected food dyes as a non-toxic and water-soluble alternative. Two coloring strategies were tested: (1) filling each frame domain with a distinct color, similar to Orosi windows, and (2) creating a color gradient inspired by insect wings. After prototyping both options, I chose the gradient approach for its natural and dynamic aesthetic.

The design process concluded with the assembly of all shading system components, resulting in a prototype that synthesizes biological inspiration, traditional architectural principles, and contemporary design methodologies. The following diagram (Figure 16) maps the design process, underscoring the central role of iteration between sketching, digital modeling, and physical prototyping.

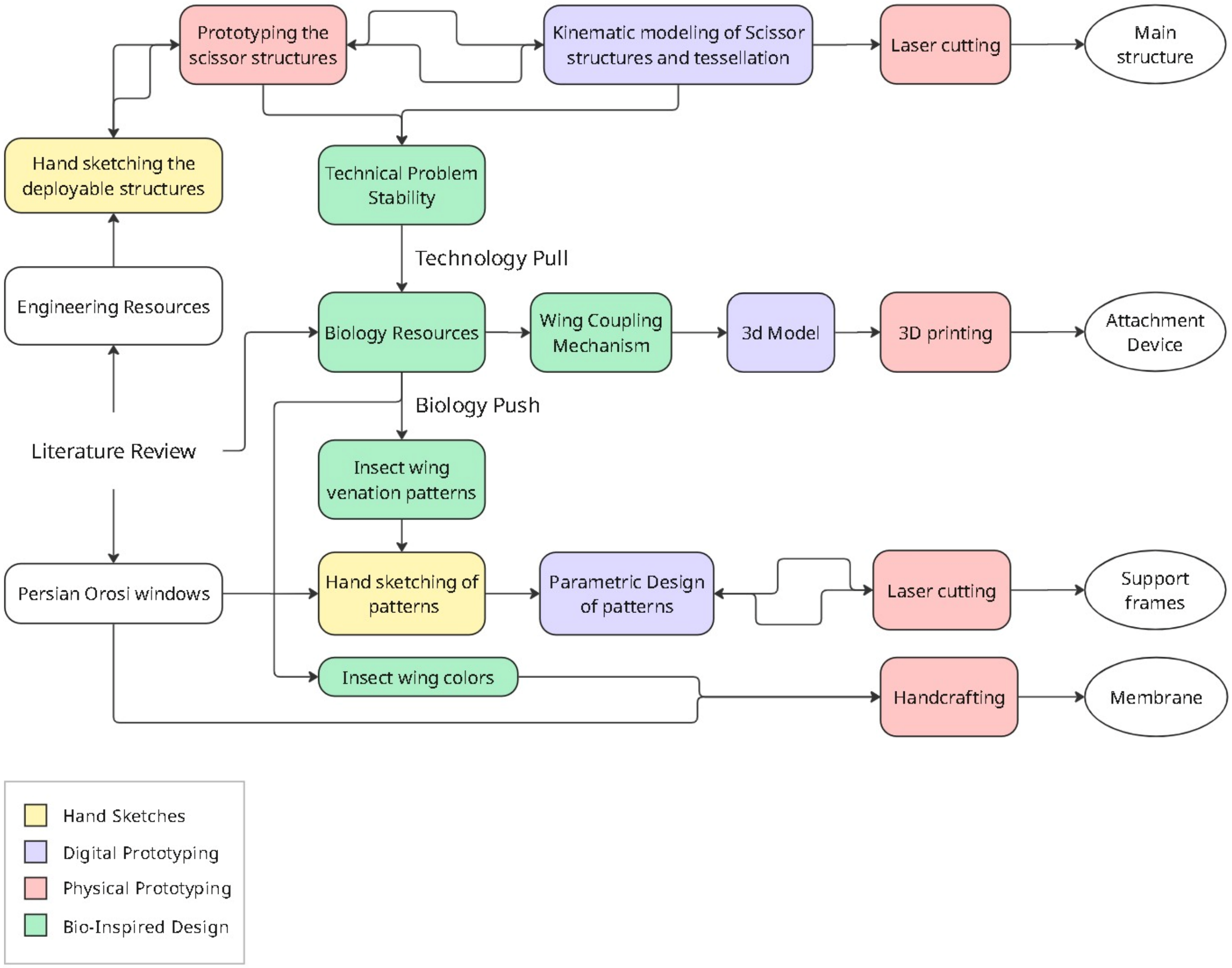


Figure 16. *Diagram: Process of design (Hor, 2025)*

CHAPTER 3

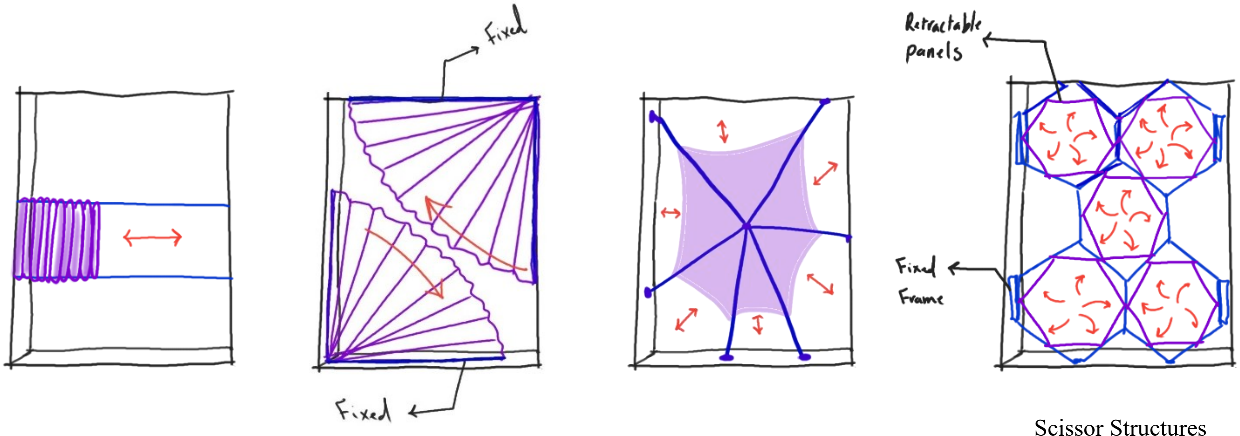
RESEARCH CREATION

4.1 Introduction

This chapter outlines the process of research creation through an iterative cycle of sketching, prototyping, and digital modeling. Grounded in a bio-inspired design approach, the project investigates scissor deployable structures as the basis for developing a kinetic shading system. Using Grasshopper algorithms as part of the parametric design process, I explored motion dynamics, design variations, and fabrication strategies. The chapter also presents the stages of material experimentation, fabrication, and the exhibition of the final prototype.

4.2 Designing the Main Structure

After reviewing various types of deployable structures, I identified scissor structures as the most suitable for this project, considering factors such as scale, form, and the feasibility of fabrication for a mobile shading system. Figure 17 presents a series of concept sketches exploring different deployable typologies for shading applications. The sketch on the right illustrates the concept based on scissor mechanisms, which I found the most promising and chose to develop further.



Foldable Membranes

Origami paper pleat

Deformable net structures

Scissor Structures and hinged plates

Figure 17. *Initial sketches of shading systems inspired by deployable structure typologies (Hor, 2024)*

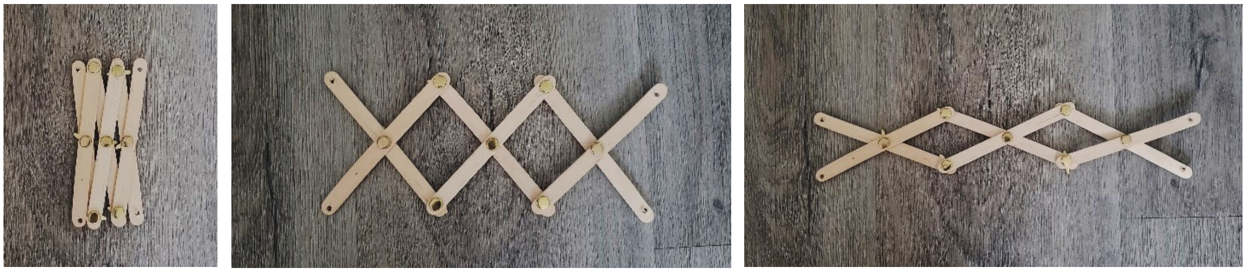
4.2.1 Physical Prototyping

As discussed earlier in the literature review, the form of the base elements, whether straight or kinked, and the location of the pivots determine different typologies of scissor structures, each capable of expanding in a distinct pattern. To explore their potential and limitations for design applications, I began developing a series of prototypes with varying geometric and mechanical properties.

4.2.1.1 Prototype 1: Straight scissor

This prototype consists of a simple chain made of conventional scissor-like elements. The base units are wooden sticks functioning as straight rods, with pivots positioned at the midpoint of each rod (Figure 18). The structure expands linearly, allowing smooth deployment along a straight axis. When additional elements are added, the overall scale of the structure increases without altering its fundamental morphology.

Base Element Pantograph



Expansion sequences

Figure 18. *Prototype 1 (Hor, 2024).*

4.2.1.2 Prototype 2: Curved scissor

This prototype is a simple chain composed of conventional scissor-like elements. The base unit consists of wooden sticks used as straight rods (Figure 19). In this version, the position of the pivot was changed from the middle to a quarter of the length of each stick. With this adjustment, the structure expands into a curved profile. A chain of three pantographs forms a three-pointed star when fully opened, while adding more pantographs—four, five, or six—results in four-, five-, or six-pointed star-shaped structures. The geometry of the internal shape varies through tessellation and does not follow a predictable pattern.

Base element

Pantograph

Expansion sequences
Chain of 3 pantographs

Expansion sequences
Chain of 4 pantographs

Expansion sequences
Chain of 5 pantographs

Expansion sequences
Chain of 6 pantographs

Figure 19. *Prototype 2 (Hor, 2024).*

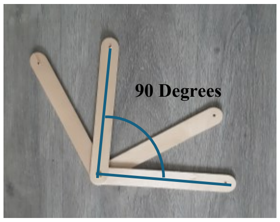
4.2.1.3 Prototype 3: Combined

For this prototype, I combined curved and straight scissor mechanisms. The pantographs were assembled in alternating pairs of each type. Experiments with this model showed that the structure tends to lock during expansion, and the colliding elements prevent it from fully opening or closing (Figure 20).

Figure 20. *Prototype 3 (Hor, 2024).*

4.2.1.4 Prototype 4: 90-degree Radial scissor

This prototype consists of a double chain made of angulated scissor-like elements. Each base element is formed by gluing two wooden sticks to create a kinked beam with a 90-degree angle (Figure 21). The pivot is positioned at the intersection point of the axes of the two sticks. When four pantographs are connected, they form a closed chain. By considering this closed chain as a single unit, tessellation becomes possible through repeating the unit along the x and y directions.



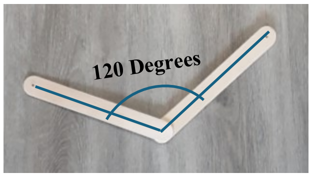
Pantograph

Expansion sequences

Figure 21. *Prototype 4 (Hor, 2024).*

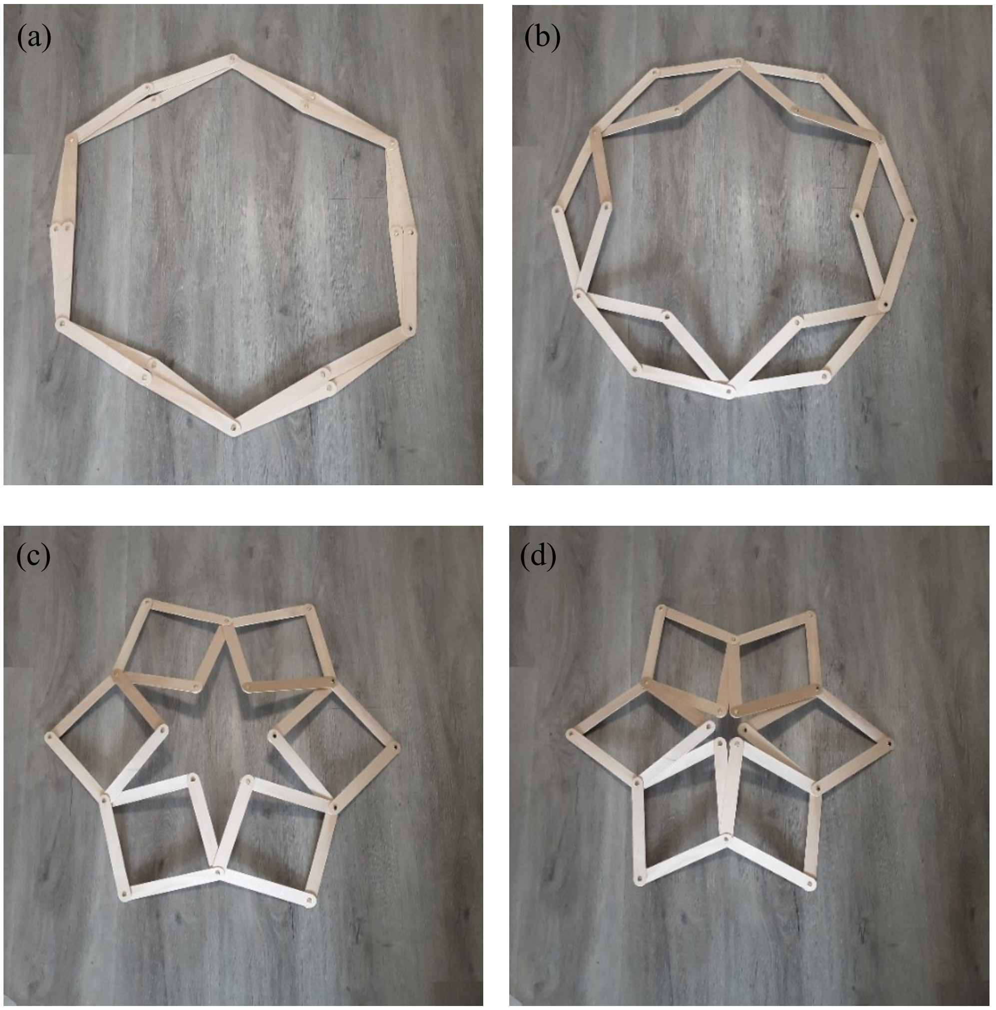
4.2.1.5 Prototype 5: 120-degree Radial scissor

This prototype consists of a double chain made of angulated scissor-like elements. Each base element is composed of two wooden sticks glued together to form a kinked beam with a 120-degree angle (Figure 22). The pivot is positioned at the intersection point of the axes of the two sticks. When six pantographs are connected, they form a closed chain. By treating this closed chain as a single unit, tessellation can be achieved by repeating the unit along both the x and y directions.



Base element

Pantograph



Expansion sequences

Figure 22. *Prototype 5 (Hor, 2024)*.

4.2.2 Developing design ideas

In the next step, I developed several design ideas through sketches, exploring the integration of scissor structures as components of a deployable shading system. These concepts involve attaching a membrane to the scissor framework to provide both shading and visual privacy.

4.2.2.1 Simple chains

Based on my prototyping experience, the scissor structures based on simple chains (Prototypes 1, 2, and 3) demonstrated the most potential for effectively folding and unfolding a membrane. The straight scissor structure enables the expansion of a pleated surface either vertically or horizontally (Figure 23), while the curved scissor structure facilitates a radial mode of expansion (Figure 24).

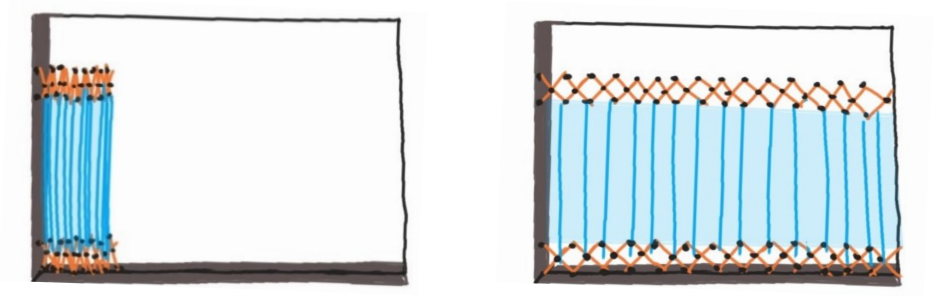


Figure 23. *Expansion sequence of a deployable shading system based on prototype 1 (Hor, 2024).*

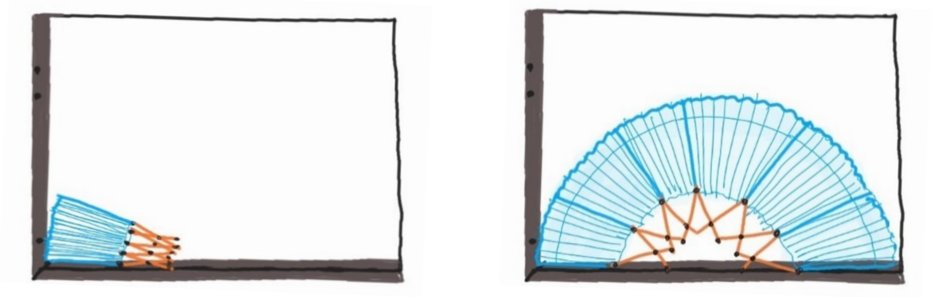


Figure 24. *Expansion sequence of a deployable shading system based on prototype 2 (Hor, 2024).*

4.2.2.2 Double chains

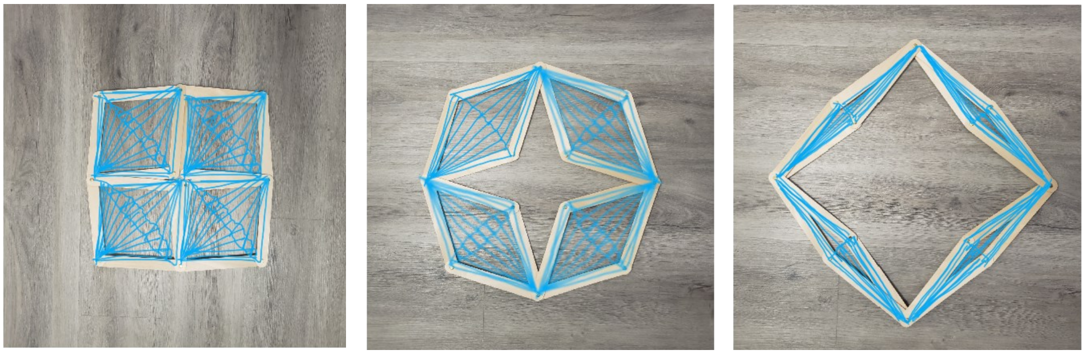
For the double-chain structures, I propose a different approach that responds to their unique expansion behavior. These deployable systems consist of an internal and an external chain, which together create positive and negative geometries during the expansion sequence. As figures 25 and 26 show, covering only one of the chains is sufficient to achieve both a fully closed shade and an open state when the structure is expanded or compacted. Through sketching and prototyping, I found that covering the external chain is the more practical solution for designing an effective shading system.

Figure 25. *Expansion sequences of negative and positive geometries for prototype 4 (Hor, 2024).*

Figure 26. *Expansion sequences of negative and positive geometries for prototype 5 (Hor, 2024).*

There are two approaches for covering the external chain of a double-chain scissor structure: using pleated fabrics or rigid plates. As shown in Figure 28, a set of pleated paper or fabric panels attached to the edges of the external chain can function effectively as part of a deployable shading system. Experience with physical prototypes revealed that flexibility or pleats in both directions within each unit of the external chain is essential. Otherwise, the material must be cut into two separate components that can overlap in certain configurations to accommodate the structure's movement (Figure 27).

Figure 27*. Expansion sequence of pleated covering for Prototype 4 -one unit (Hor, 2024).*



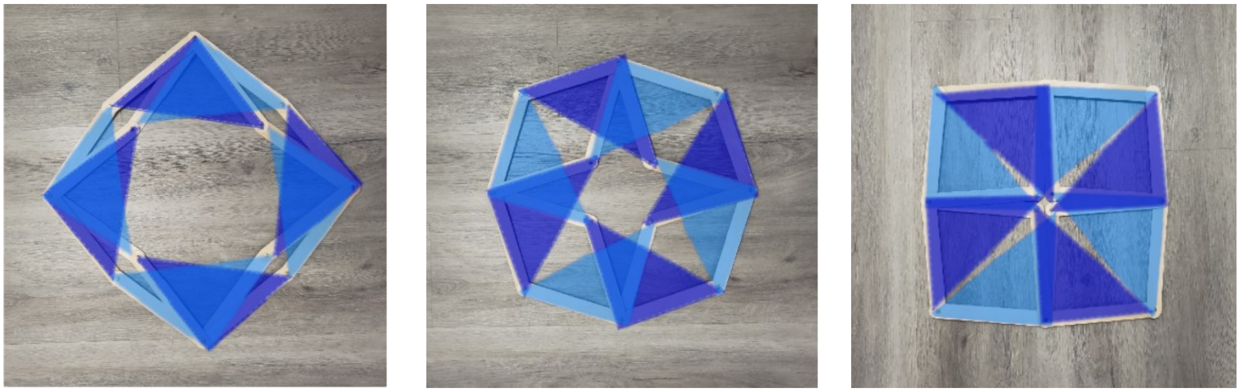
Prototype 4

Prototype 5

Figure 28. *Sketches of expansion sequences of pleating covering for prototype4 and 5 (Hor, 2024).*

As noted by You & Chen (2011), another method for covering the external chain involves replacing the angulated beams with rigid plates. Designs using retractable plates may incorporate overlapping elements, provided that the plates are positioned at different heights to prevent collision during movement. Figure 29 presents my experiment with covering Prototype 5 using rigid plates as the membrane. Figure 30 sketches this idea for covering the external chain of Prototypes 4 and 5.

Figure 29. *Expansion sequence— Attaching rigid plates to the two pantographs of prototype 5 (Hor, 2024).*



Prototypes 4

Prototypes 5

Figure 30. *Expansion sequence— Sketches of Prototypes 5 4 and 5 covered by rigid plates (Hor, 2024).*

4.2.3 Conclusion

Through iterative hand sketching and physical prototyping of various scissor structures, I found Prototypes 4 and 5 to exhibit the most promising patterns for further development. Among the different methods tested for attaching a membrane, covering the external chain of these two prototypes with rigid plates proved to be the most functional and practical approach—both easier to fabricate physically and simulate digitally in the next steps.

4.2.4 Digital Prototyping: Kinematic Modeling

At this stage, digital prototyping became necessary for three main reasons: (1) to explore alternative tessellation configurations, (2) to determine the most effective installation strategy in tessellated form, and (3) to verify the function and configuration of the structure through an iterative process between physical and digital models.

To simulate the behavior of a double-chain scissor structure in Grasshopper, it is first necessary to define its governing variables and constraints, as outlined below.

4.2.4.1 Geometrical Variables

The simulation process begins by generating two concentric circles, each serving as the base geometry for a chain. The inner circle is divided into *N* equal segments, while the outer circle is subdivided into *2N* segments. By systematically connecting the nodes of the two circles in a defined sequence, a series of triangular units is formed (Figure 31). Each triangle represents a kinked element, which in the physical model is covered by a rigid plate.

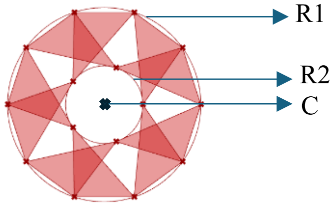


Figure 31. *Geometry variation of a double chain scissors structure (Hor, 2025).*

The primary parameters of the system include the center point *(C)* of the circles, the radii of the inner and outer circles (R_1 and R_2), and the number of divisions *(N)*, corresponding to the number of pantographs. The difference between the two radii $(R_2 - R_1)$ defines *(L)*, which in turn governs the length of the base elements. By modifying these parameters, a range of geometric variations of the scissor structure can be generated. Figure 32 illustrates the generated geometries of the scissor structure resulting from variations in the *N* parameter while *L* remains fixed, whereas Figure 33 shows the generated geometries produced by varying the *L* parameter while *N* is held constant.

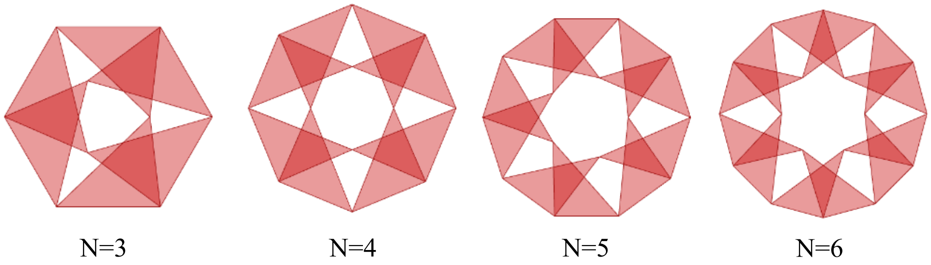

N=3 N=4 N=5 N=6

Figure 32. *Generated geometries of a scissor structure while L is fixed (Hor, 2025).*

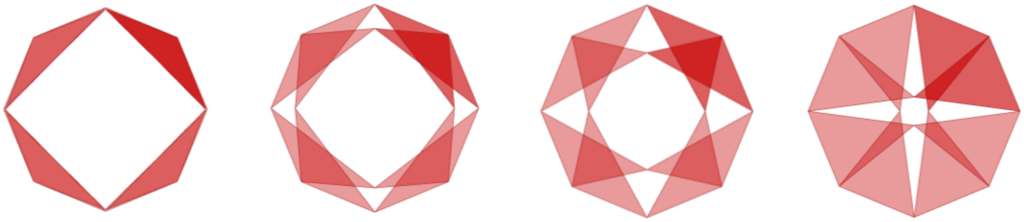


Figure 33. *Generated geometries of a scissor structure while N is fixed (Hor, 2025).*

4.2.4.2 Geometrical Constrains

At this stage, the algorithm generates a static parametric geometry. The next step involves introducing motion, allowing the structure to exhibit expansion and contraction configurations. To achieve this, a set of constraints was defined as goal objects for the Kangaroo solver in Grasshopper. In simple terms, constraints in kinematic modeling define which geometrical relationships remain fixed while others are free to move in response to external forces. The Kangaroo solver functions as a physics engine that maintains all defined constraints, enabling the geometry to behave as a coherent and responsive system when specific parameters are modified.

Figure 34 shows the grasshopper algorithm for simulating the scissor structures. The main constraints applied in this algorithm include:

- Rod: Ensures that each triangular element resists bending and stretching, maintaining complete rigidity.
- CoCircular: Keeps all nodes corresponding to R_1 and R_2 located on their respective circles.
- OnPlane: Restrains the nodes on R_1 and R_2 to remain on their respective planar surfaces.
- Floor: Prevents the structure from extending beyond the window plane.
- Grab: Enables manual interaction by allowing the user to drag the structure and observe its dynamic behavior in real time.

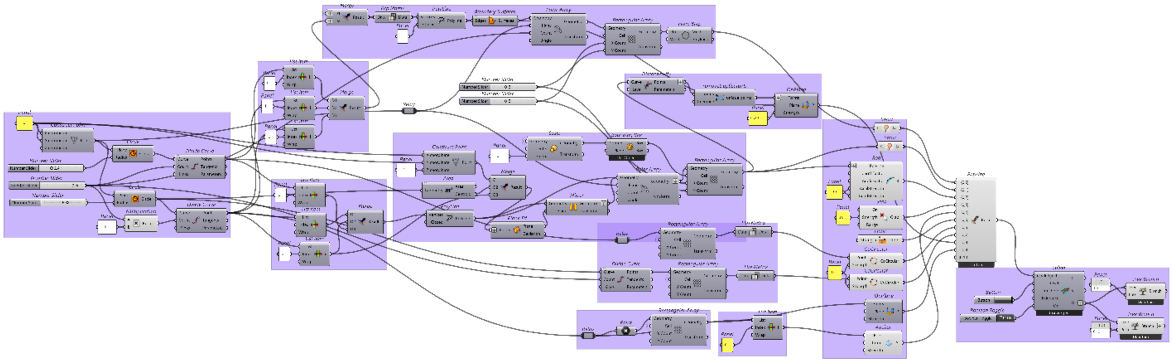


Figure 34. *The grasshopper algorithm for simulating the scissor structures (Hor, 2025).*

Finally, I introduced variations to define the number of units used for tessellation. It is important to note that each geometry requires the development of its own framework for tessellation, and a comprehensive exploration of all possible configurations lies beyond the scope of this study. The following figures illustrate the tessellation of Prototypes 4 and 5, which were arranged in rectangular and radial configurations, respectively.

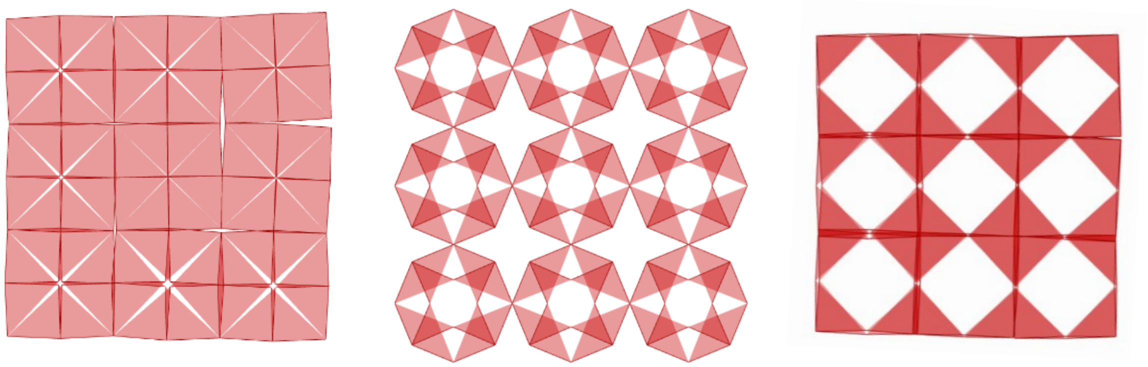


Figure 35. *Expansion sequence of Prototype 4 tessellation in Grasshopper (Hor, 2025).*

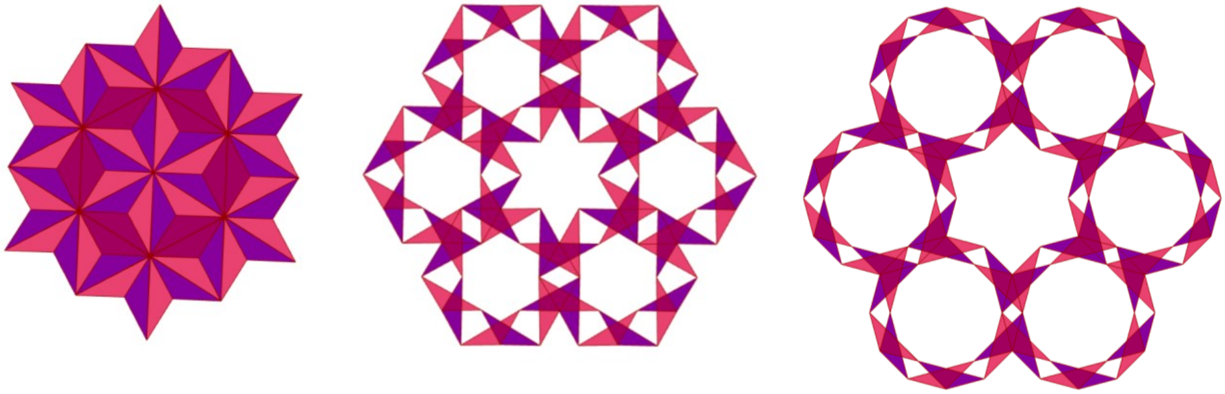


Figure 36. *Expansion sequence of Prototype 5 tessellation in Grasshopper (Hor, 2025).*

As illustrated in Figures 35 and 36, Prototype 5 in radial tessellation expands over a larger area when the shading is fully opened, whereas Prototype 4 encloses approximately the same area in both its fully open and fully closed configurations.

4.2.5 Installment Strategy

You & Chen (2011) proposed two attachment methods for double-chain structures: aligning and fixing them along symmetry lines using rails or connecting them to fixed rotational points that restrict translational movement, particularly evident in circular layouts. To explore these attachment methods and determine the most effective installation strategy, I incorporated additional constraints into the algorithm. The Anchor constraint was applied to simulate the first attachment method, in which one or more points of the structure are fixed. The OnCurve constraint was used to model the second method, allowing the structure to move along a predefined rail or track (Figure 37).

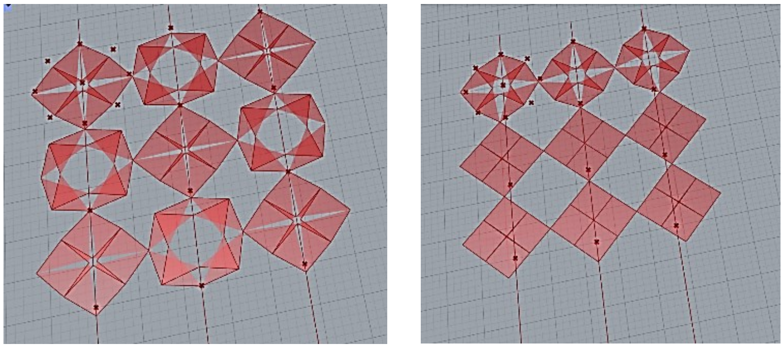


Figure 37. *Kinematic modeling of the railing installation method for prototype 4 (Hor, 2025).*

My experience with kinematic modeling of the Prototype 4 indicates that, fixed points strategy works better for this pattern. Although rail-based installation can generate innovative structural configurations, the presence of rails restricts the rotational movement of the units. This rotational behavior is a crucial aspect, as it enables the structure to achieve complete surface coverage when functioning as a shading system.

4.2.6 Insights from Comparing Physical and Digital Prototypes

While the physical prototypes provided valuable insights into the mechanisms of scissor structures, investigating their behavior across different tessellation configurations was nearly impossible without the computational capacities of parametric design—particularly within the limited timeframe of this study.

One of the key outcomes of the iterative process between physical and digital prototyping was the ability to refine the research focus and make informed design decisions. For instance, through this process, I observed that not all scissor structures remain planar during their expansion sequence. This observation was crucial in guiding the selection among different typologies of double-chain scissor structures. As illustrated in Figure 38, Prototype 5 gradually deviates from the XY plane during compaction, resulting in a spherical form that is unsuitable for the intended scale of this study.

Overall, by analyzing the behavior of Prototypes 4 and 5 across various tessellation and installation configurations, I concluded that Prototype 4 with the fixed-point installation method offers the most stable and applicable foundation for further design development.

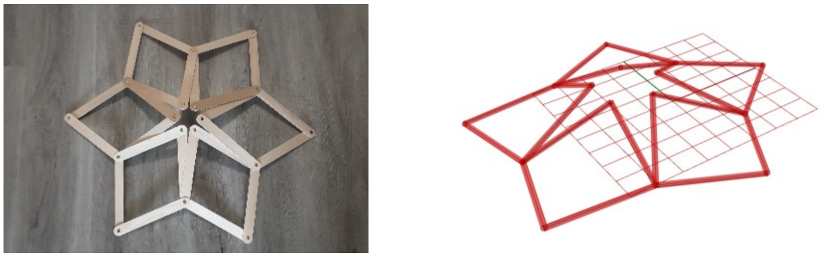


Figure 38. *Out-of-plane deformation of Prototype 5 in compacted mode (Hor, 2025).*

The comparison between the physical and digital models of Prototype 4 verified the accuracy of the kinematic modeling algorithm (Figure 40). With a focus on the technical aspects of installation, both prototypes exhibited that the tessellated structure, supported by a single fixed point, attains an appropriate configuration for shading applications. However, the system lacks intrinsic stability during the expansion sequence when installed vertically on a window surface. This observation indicates the necessity of incorporating a temporary attachment mechanism to ensure structural stability in the fully open position. Within the framework of bio-inspired design, this technical requirement could serve as a starting point for adopting a technology-push approach—that is, exploring biological databases to identify natural systems or mechanisms that offer potential solutions to this engineering challenge.

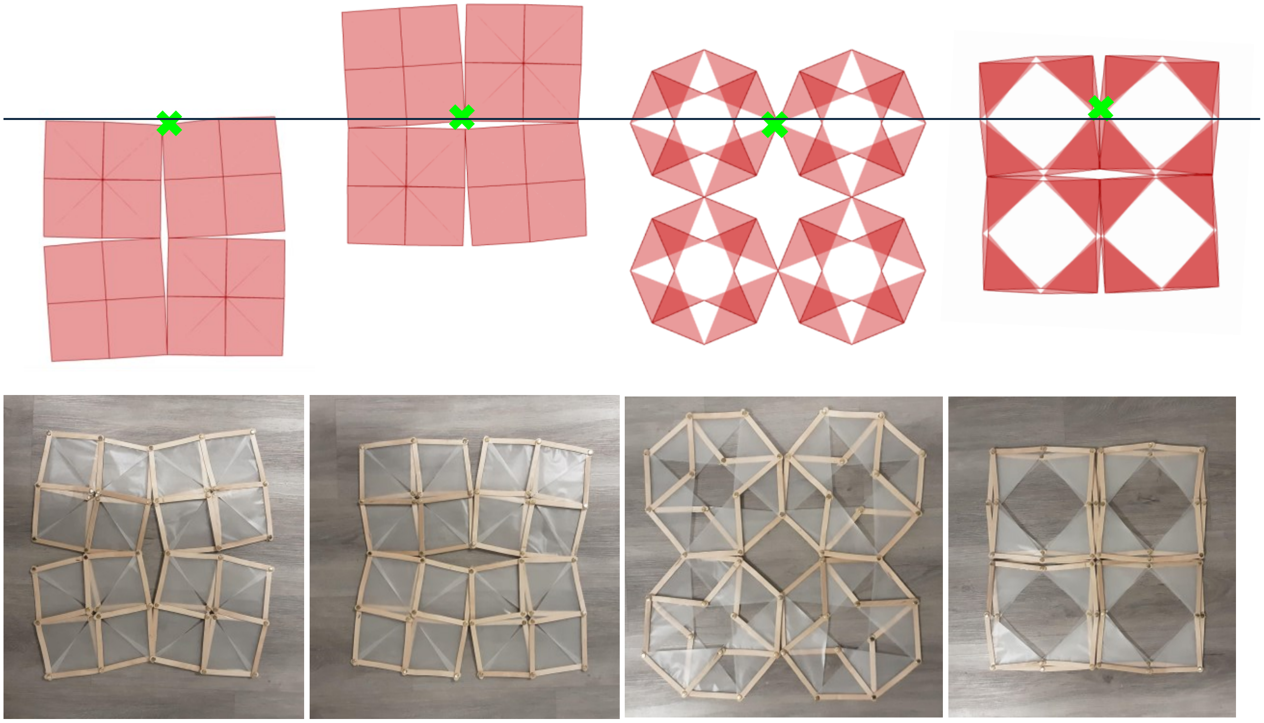


Figure 39. *Comparison between expansion sequences of digital and physical models for prototype 4. The green mark shows the fixed point on the structure during expansion (Hor, 2025).*

4.3 Bio-Inspired Design

As outlined in the methodology chapter, bio-inspired design can be approached through three primary methods: technology-push, biology-pull, and pool research. The selection of an appropriate method depends on the specific objectives of the project. In this phase, the study adopts a technology-push approach, beginning from an engineering challenge and seeking corresponding solutions in nature. Accordingly, the research focused on natural attachment mechanisms, examining their functional principles and exploring their potential translation into design applications. This stage views nature as a *source of solutions* for technical problems.

In the subsequent phase, the study shifts perspective to view nature not merely as a source of solutions but as a *source of inspiration*, informing the continued development of the design.

4.3.1 Wing Coupling Mechanism: Nature As A Solution

In nature, attachment devices are found everywhere, mainly serving to connect body parts either to a surface or to each other, whether temporarily or permanently. Figure 41 illustrates the 8 types of biological attachments, each of which is efficient for its function in nature (Eraghi et al., 2021).

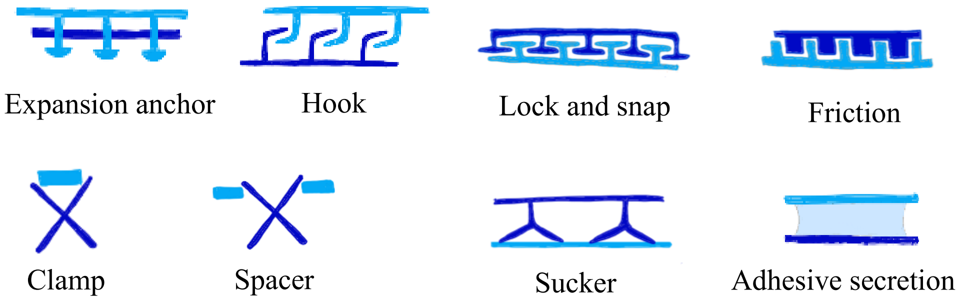


Figure 40. *Typology of biological attachment devices (Hor, 2025). Redrew with permission from Springer Nature (Gorb, 2001).*

Among all the nature's attachment systems, one offered a particularly fitting inspiration for achieving stability in the deployable structure when fully opened: Hamuli. The term Hamuli, meaning “tiny hooks” in Greek, describes the small hook-like elements found along the front edge of certain insect wings, such as those of honeybees and cicadas (Toofani et al., 2020). Generally, an insect could have one or two pairs of wings. In the case of having two pairs, they are called forewings and hindwings that are mechanically linked during flight (Persiani, 2018). Through this connection, the wings move together as a single aerodynamic surface, gaining balance, stability, and efficiency. This natural system, known as the “wing-to-wing coupling mechanism” (Saito et al., 2021).

Inspired by this mechanism, I designed a hook-shaped device to serve as a temporary attachment for the structure when it is fully opened. The device was fabricated using a 3D printer and then screwed onto the final prototype (Figures 41 and 42).

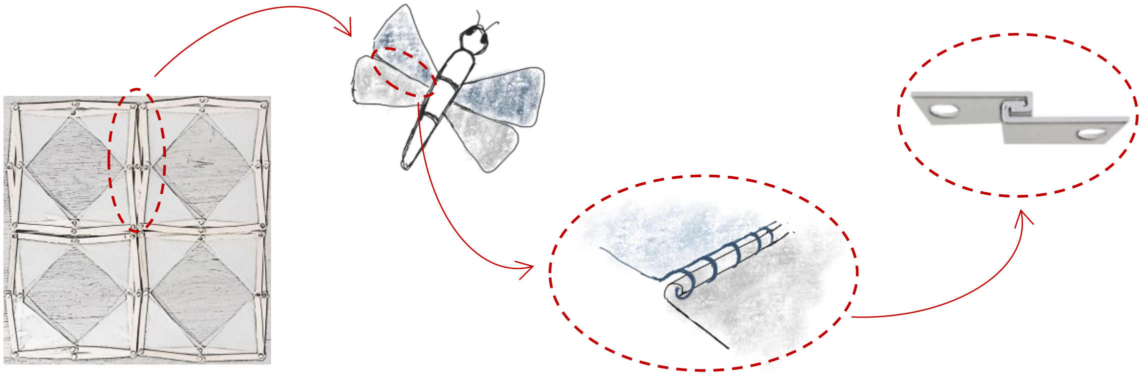


Figure 41. *Hamuli as an inspiration for designing a temporary attachment device for the shading system (Hor, 2025).*

Figure 42. *The 3d printed hook shape attachment (Hor, 2025).*

4.3.2 Insect Wing Venation: Nature As An Inspiration

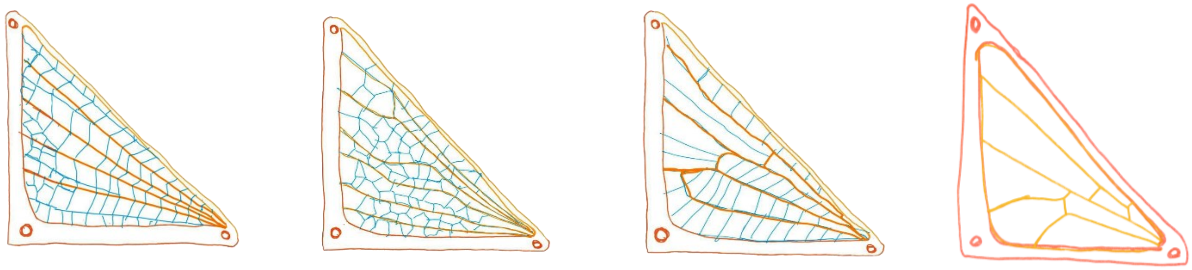
At this stage of the design process, while developing concepts for the shading membranes, I found insect wings to be a rich source of inspiration beyond their coupling mechanism. Composed of thin membranes supported by a vein network that extends from the exoskeleton, they function as lever systems generating thrust (Persiani, 2018). Their intricate structures can offer both aesthetic and functional potential—to enhance the visual quality of the membrane and provide a natural model for supporting the thin, transparent surface in the deployable system. For the biomimicry of insect venation patterns, it is essential to identify the underlying structural and geometrical principles.

Scientists classify insect wing veins into two main types: primary (longitudinal) veins and secondary veins (crossveins), each exhibiting distinct properties and patterns (Shimmi et al., 2014). The arrangement formed by these veins defines the vein domains, which describe the regions of the wing membrane enclosed by the veins (Salcedo et al., 2019) . Depending on the vein patterns, some wings are divided into only a few domains, while others are partitioned into thousands of closed polygonal shapes (Hoffmann et al., 2018).

Primary veins are more regular and informative of the wing structure (Hoffmann et al., 2018). In most insects, they extend from the wing base to the margin (Celis & Diaz-Benjumea, 2003). Secondary veins are less consistent and often unmatched between left and right wings(Hoffmann et al., 2018). The secondary veins run between the primary veins, connecting them and creating smaller enclosed domains (Celis & Diaz-Benjumea, 2003), providing rigid support to the two-layered wing membranes (Shimmi et al., 2014).

4.4 Parametric Design

At this stage of the design, my goal was to recreate insect wing vein patterns using parametric design, making them adaptable to any customized surface. For this purpose, I examined four types of insect wing venation patterns, each exhibiting distinct geometrical principles in the arrangement of their crossveins. Following the biological principles, I focused on the secondary (crossvein) patterns, since the primary veins are regular and their geometry is straightforward. For all species in this study, I drew the primary veins to match their natural appearance, forming the base framework for the crossveins, and then developed an algorithm to generate the crossveins between them. Figure 43 illustrates the conceptual sketches of structural frames inspired by the wing venation patterns of Orthoptera, Odonata, Plecoptera, and Diptera. The main structure is shown in red, the primary veins in orange, and the crossveins in blue.



Orthoptera Odonata Plecopteran Diptera

Figure 43. *Conceptual sketches of structural frames inspired by 4 different insect wings (Hor, 2025). The drawings are inspired by biological references by Salcedo et al. "Computational analysis of size, shape and structure of insect wings," Biology Open, 2019, licensed under CC BY 4.0.*

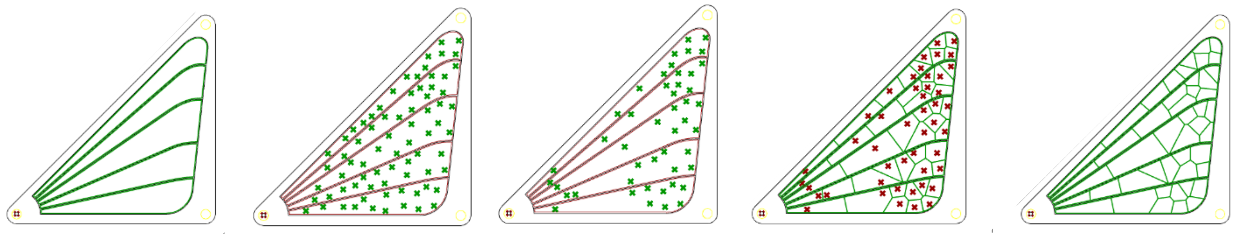
4.4.1.1 ODONATA (Anax Junius)

Odonata, commonly known as dragonflies, are an example of insects with wings featuring a dense network of crossveins(Shimmi et al., 2014). Like most insects, the vein domains of Odonata are smaller at the wing tip than at the base (Figure 44). The wing venation in Odonata stands out for its complex pattern, reminiscent of a Voronoi tessellation (Hoffmann et al., 2018).

A manual Voronoi diagram can be created by first selecting a set of generating points(seeds), connecting them with lines, finding the midpoints of these lines, and then drawing perpendicular lines from the midpoints. The intersections of these perpendiculars form the Voronoi network (Abdelhady et al., 2022).

Figure 44. *Green Darner Dragonfly. Source: Photograph by Dan Jackson (n.d.). Reproduced with permission of the photographer.*

The parametric design for the Odonata venation pattern was developed following five steps (Figure 46). First, the primary vein pattern was drawn to define the boundaries within the structural frame. Next, random points were generated inside these boundaries. A repeller point was then defined at the base of the wing (the left corner of the rectangular frame), and weights were assigned to regions based on their distance from this point. The points were subsequently filtered according to their distribution weights, and finally, the Voronoi pattern was generated using the remaining points.



1. Primary veins 2. Random points 3. Filtering the points 4. Voronoi pattern 5. Final simulation

Figure 45. *Steps of parametric design for Odanata venation pattern (Hor, 2025).*

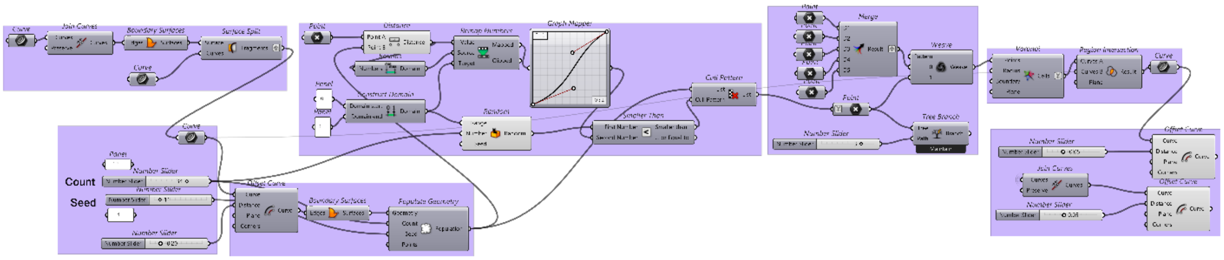


Figure 46. *Grasshopper algorithm for simulating the Odanata venation pattern (Hor, 2025).*

The input parameters for the algorithm include the boundary curves, represented by the primary vein pattern, the repeller point, the number of random points corresponding to the domain count, the random point seed value, and a domain distribution graph used to assign weights to different regions.

4.4.1.2 ORTHOPTERA (Schistocerca americana)

Grasshoppers, crickets, and locusts are among the most well-known species in the Orthoptera order (Hasan et al., 2019). Some Orthoptera have sound-producing forewings, where specialized venation patterns develop to support this function. In particular, the veins surrounding the mirror and harp regions are modified to amplify sound (Shimmi et al., 2014). A distinctive geometrical feature of Orthoptera wings is the distribution of vein domains (Figure 47): they are dense and small near both the wing base and tip, while larger and more widely spaced in the intermediate regions of the wing (Salcedo et al., 2019).

Figure 47. *American Grasshopper wing. Source: NPS (U.S. National Park Service), n.d. , Public domain image.*

For the parametric design of Orthoptera wings, I applied the same algorithm used for Odonata, with a modification in the third step: instead of a repeller point at the corner, I defined a Repeller Curve along the middle and filtered the points based on their distance from this curve (Figure 48). This approach results in denser points near the wing tip and base, and more sparsely distributed points in the central region.

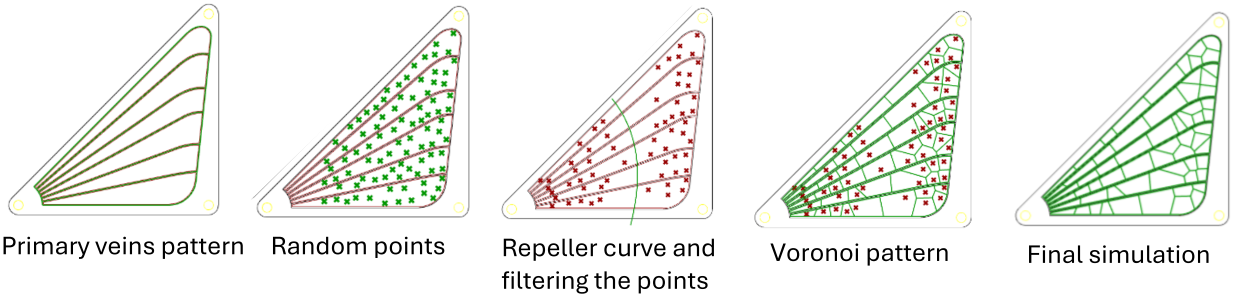


Figure 48. *Steps of parametric design for Orthoptera venation pattern (Hor, 2025).*

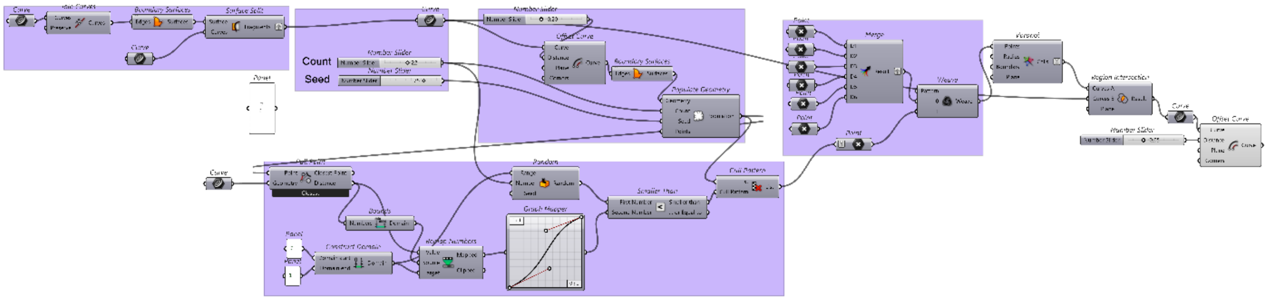


Figure 49. *Grasshopper algorithm for simulating the Orthoptera venation pattern (Hor, 2025).*

4.4.1.3 PLECOPTERA(Stoneflies)

Plecoptera wings show a domain distribution opposite to the typical pattern of insect venation, with larger domains located near the wing tips rather than the base (Figure 50). Another characteristic is the shape of the domains, which are predominantly rectangular (Salcedo et al., 2019).

Figure 50. *Stonefly wings. Source: Bernard Dupont, 2014, Licensed under Creative Commons Attribution–ShareAlike 2.0 (CC BY-SA 2.0).*

To simulate the venation pattern of stonefly wings, I took a different approach that was tailored to their specific properties. The design began by dividing the wing area into seven main boundaries based on the primary veins. To create the lattice pattern with rectangular domains, I generated random points along two sides of the four largest boundaries. The secondary vein pattern was then formed by connecting the points across each boundary (Figure 51).

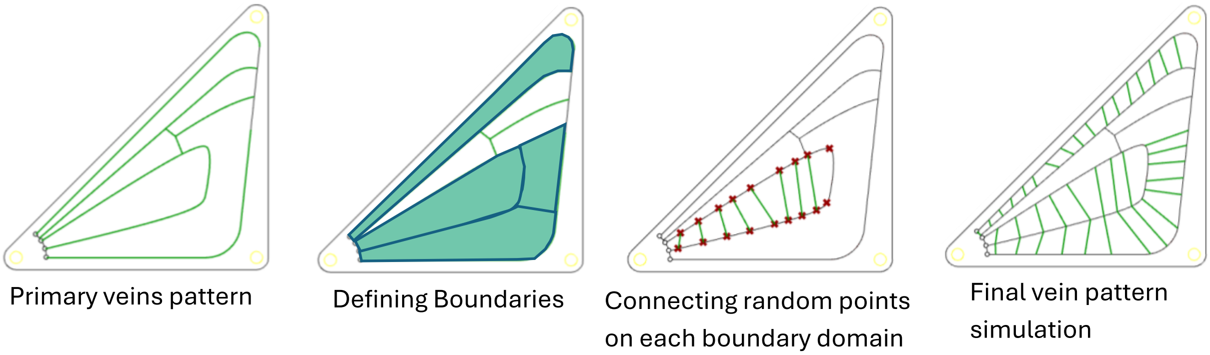


Figure 51. *Steps of parametric design for Plecoptera venation pattern (Hor, 2025).*

The parametric design variables include the primary vein patterns, the selected boundaries, the number of random points (corresponding to domain count), and the random point seed value. Figure 52 shows the Grasshopper algorithm for simulating the Plecoptera venation pattern.

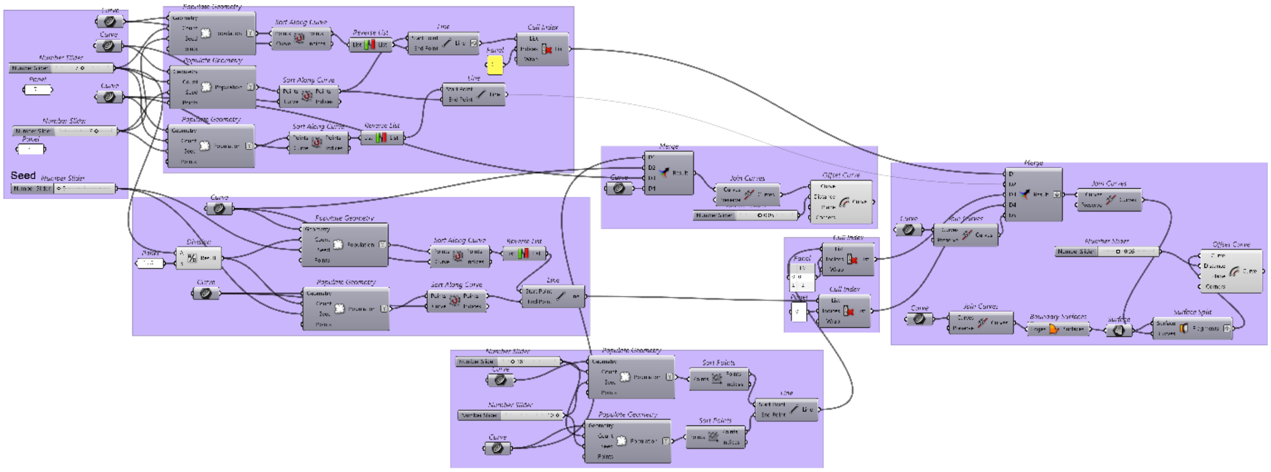


__Figure 52.__ Grasshopper algorithm for simulating the Plecoptera venation pattern (Hor, 2025).

4.4.1.4 Diptera (Drosophilida)

The most well-known species in the Drosophilidae family are fruit flies. The venation pattern of *Drosophila* is relatively simple compared to that of other insects. In Diptera, the anal veins are notably reduced in both number and extent, and the wings typically consist of four main longitudinal veins and two short transverse crossveins (Figure 53). In some Diptera species, the generalized primary vein pattern is further modified, with certain veins not reaching the wing margin and instead joining distally through transverse veins to form closed cells (Celis & Diaz-Benjumea, 2003).

Based on the straightforward biological principles of Diptera wing venation, there was no need to employ parametric design tools for pattern simulation; instead, the pattern was directly applied to the structure.

***Figure 53.** Right: the supporting frame design based on the wing pattern (Hor, 2025). Left: Fruit fly wings, Image by Elizabeth Beers. Reproduced with permission (Beers, 2010).*

4.5 Exploring Through Fabrication

The final stage of my design process focused on fabricating the structure, designing the membrane, and experimenting with different materials to achieve the best outcome for the final prototype. Several iterations of physical prototyping were carried out during this phase.

In addition to insect wings as the main inspiration for my design, another concept that continually influenced this part of my design was *Orosi*. As discussed earlier in the literature review, *Orosi* is a traditional Persian shading system composed of a wooden lattice filled with multicolored glass pieces.

4.5.1 Fabricating the Structure and Frames

I decided to fabricate the main structure and the inner patterns as separate pieces for two reasons. First, this approach allows the outer frames to serve as molds for casting the membrane material in its liquid phase. Second, using modular outer frames helps minimize material waste and simplifies replacement if any inner components are damaged during prototyping.

Same as Orosi windows, for both the main structure and the inner frames, I chose wood as the primary material. Wood is sustainable, lightweight, recyclable, and well-suited for laser cutting, especially for producing intricate patterns. Figure 54 shows Frames and supporting frames, which have been laser-cut from wood.

Figure 54. *Frames and supporting frames laser-cut from wood (Hor, 2025).*

4.5.2 Fabricating the Membrane

To design the membrane component, I focused on two key aspects: the color of the membrane and the interaction of the material with light and shadow. My intention was to reinterpret the concept of stained glass and evoke the colorful shadows of traditional Orosi windows within my design. To achieve this, I explored sustainable materials that could fill the supporting frames with multiple colors like those used in Orosi patterns.

4.5.2.1 Experiment with bioplastics

The first material I experimented with was bioplastic, a sustainable material derived from renewable biological sources. The recipe I followed was agar-based bioplastic, adapted from The Bioplastic Cookbook by Margaret Dunne (2018). For each batch, I dissolved 8 grams of agar-agar powder in 200 milliliters of water and added 13 grams of glycerin to a pot. The mixture was heated over medium temperature and stirred continuously until it reached a viscous consistency.

Once ready, I poured the liquid mixture into four beakers, coloring each batch with food dyes inspired by the traditional Orosi palette (Figure 55). The tinted mixtures were then cast into the supporting frames placed on a non-stick surface, filling each domain section with a different hue. The frames were left to air dry for 24 hours.

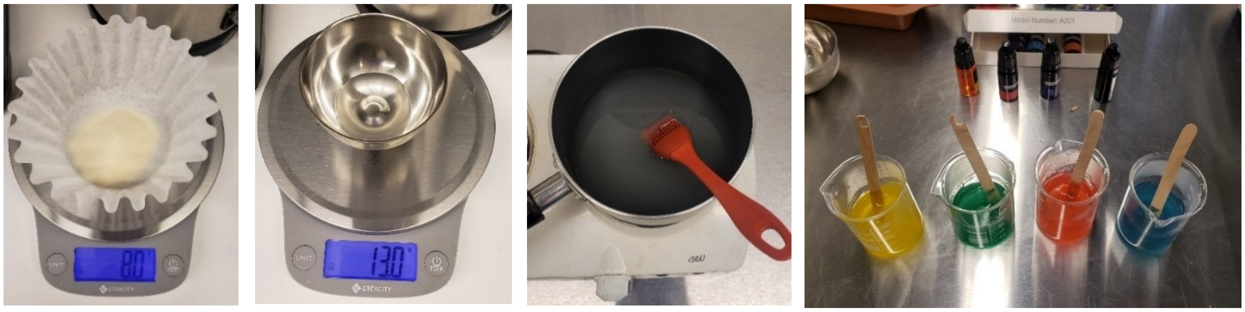


Figure 55. *The process of cooking and coloring the bioplastic (Hor, 2025).*

There are several observations from my experiments with bioplastic that ultimately led me the decision to transition toward alternative materials for the next stage of experimentation. Firstly, and most importantly, the bioplastic shrank significantly during the drying process (Figures 56 and 57), which made the fabrication method of pouring each domain in a different color unsuccessful. Secondly, although the bioplastic adhered well to the wooden support frames, the shrinkage caused the frames to deform. Lastly, contrary to my initial expectations, the material did not produce the vibrant colored shadows I had envisioned when exposed to light.

Figure 56. *Shrinkage of bioplastic prototypes — left: before drying; right: after drying (Hor, 2025).*

Although the issues encountered with this material could potentially be resolved through further material experimentation, several alternative approaches may be considered. For instance, instead of casting the bioplastic directly within the frames, it could first be produced in thin sheets and later assembled onto the structural supports. Additionally, modifying the thickness or improving the recipe formulation might enhance its optical performance for shading purposes. However, as material exploration was not the primary focus of this study and given the limited timeline of the project, this process was set aside to advance the fabrication of the membrane using an alternative material.

Figure 57. *Close-up of prototypes with bioplastic (Hor, 2025).*

4.5.2.2 Experiment with white glue (PVA)

The second material explored for the membrane was white glue, a water-based adhesive composed of polyvinyl acetate (PVA). This material was selected primarily for its accessibility, non-toxic nature, and strong adhesion to wooden support frames. Additionally, it could be easily tinted with food coloring and became transparent once dried. The resulting membrane demonstrated sufficient strength and flexibility, making it a practical option for the prototype at this stage of experimentation (Figure 58).

Figure 58. *The first experience with white glue (Hor, 2025).*

At the beginning of the experiments with white glue, another idea emerged—to shift the color palette from that of traditional Orosi windows to one inspired by insect wings, aligning more closely with the bio-inspired approach of the design. To explore this concept, two prototypes were fabricated: one with each domain filled using materials tinted in red, blue, green, and orange, reflecting the traditional colors of Orosi windows (Figure 59); and another featuring a gradient of blue, green, and purple, inspired by the iridescent hues found in insect wings (Figure 60).

Figure 59. *Prototype inspired by Orosi stained glass- left before drying, right after drying (Hor, 2025).*

Figure 60. *Prototype inspired by insect wing hues (Hor, 2025).*

By comparing these two alternatives, I decided to continue with the insect wing–inspired color palette. My decision was mainly influenced by the quality of the shadows, as the fabrication method naturally created light effects that resembled patterns found in nature (Figure 61). This spontaneous outcome highlighted and strengthened the bio-inspired direction of my design.

Figure 61. *Comparing shadow effects of two prototypes, left: insect wing–inspired; right: Orosi-inspired (Hor, 2025).*

Figures 62 and 63 show the final prototype components before and after assembly.

Figure 62. *The final prototype elements, inspired by insect wings (Hor, 2025).*

Figure 63. *Assembled pantographs functioning as one unit in the final deployable shading system prototype (Hor, 2025).*

4.6 Exhibition Practice

The following photos present the final bio-inspired prototype as displayed in a public exhibition featuring the work of MDes students. The exhibition provided a platform for disseminating the design process and outcomes to a broader, non-academic audience.

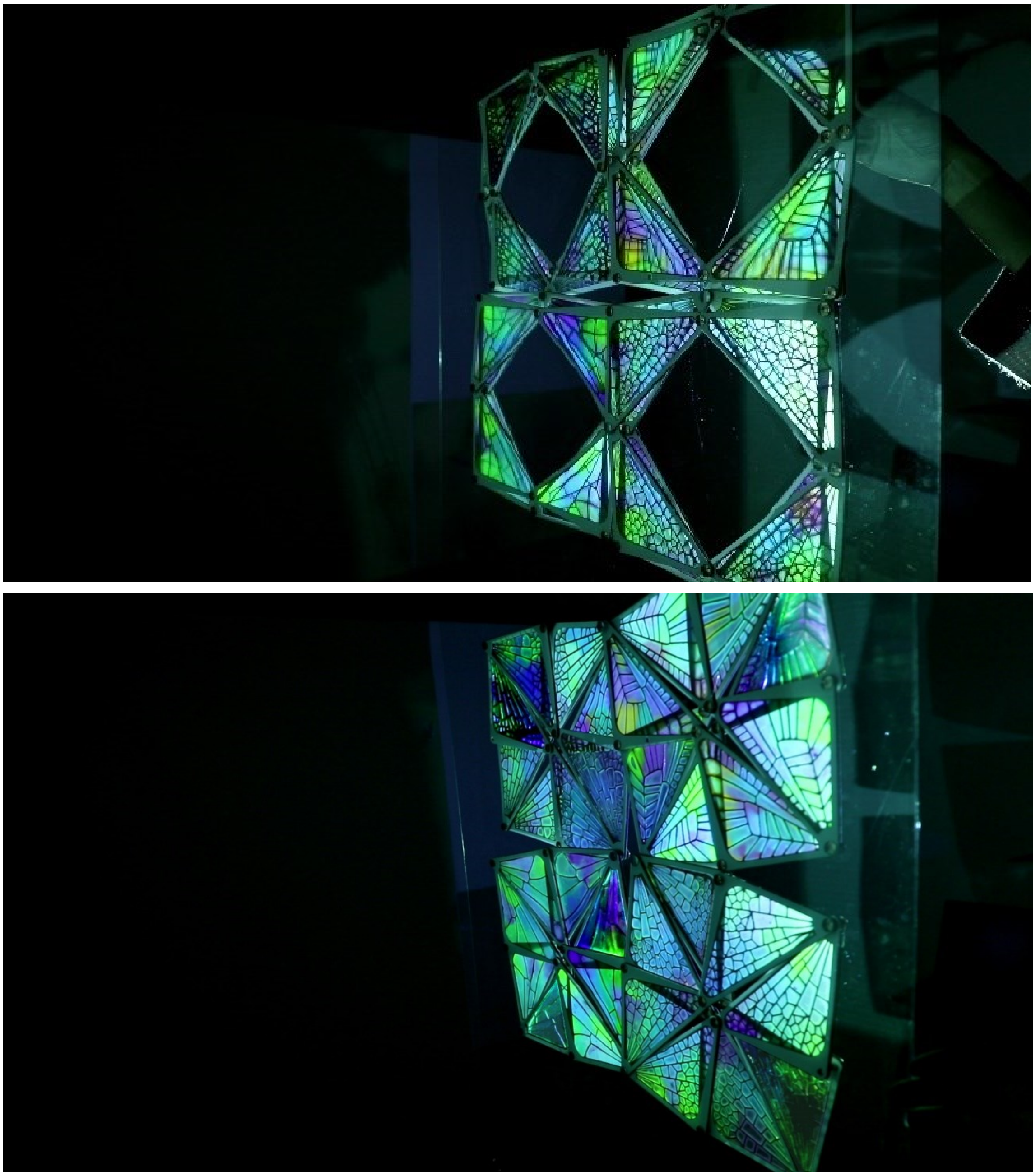


Figure 64. *Final prototype of the wing-coupling shading system shown in two states: fully open (top) and fully closed (bottom) (Hor, 2025).*

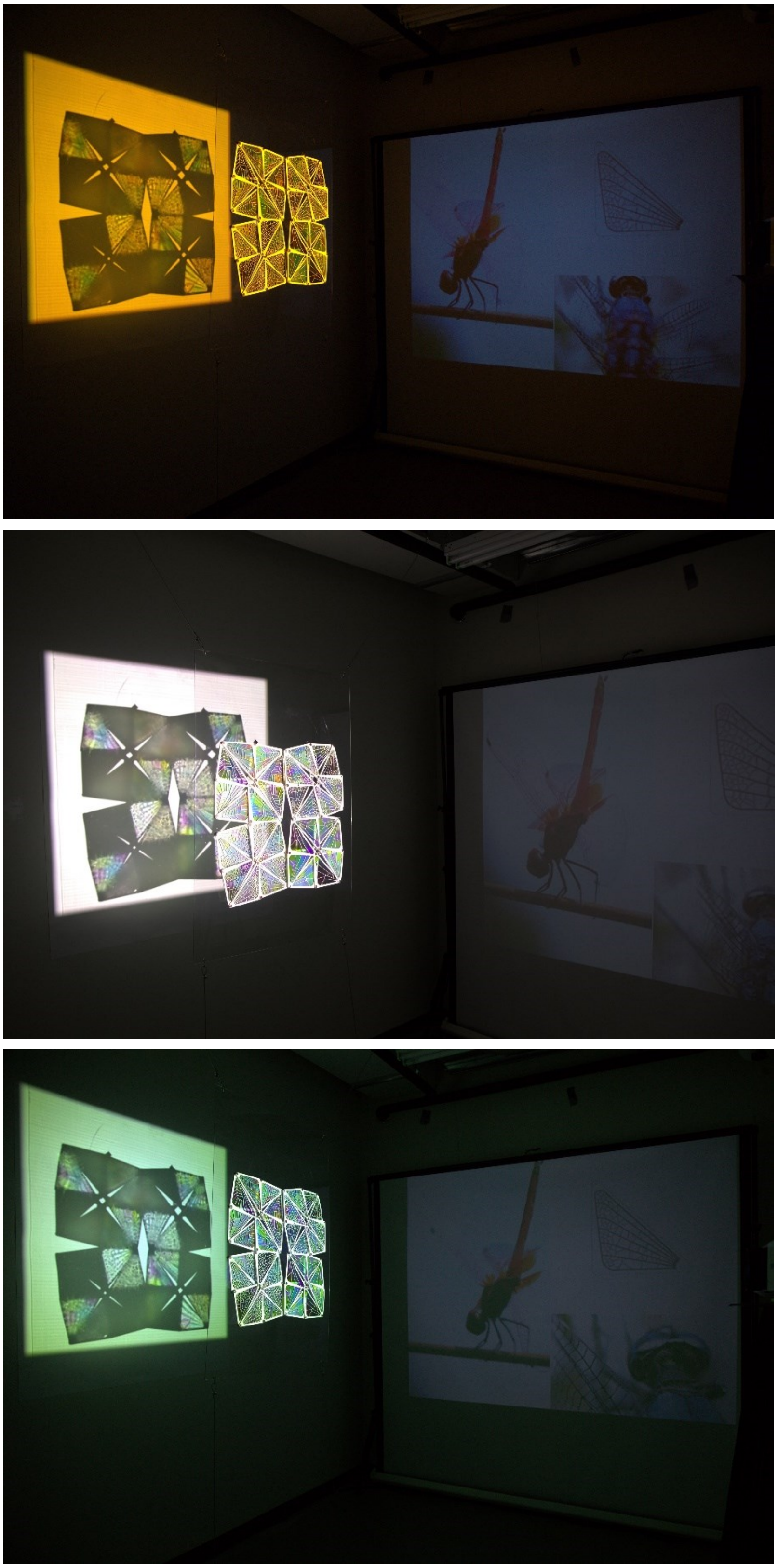


Figure 65. *General view of the wing coupling shading system at the exhibition (Hor, 2025).*

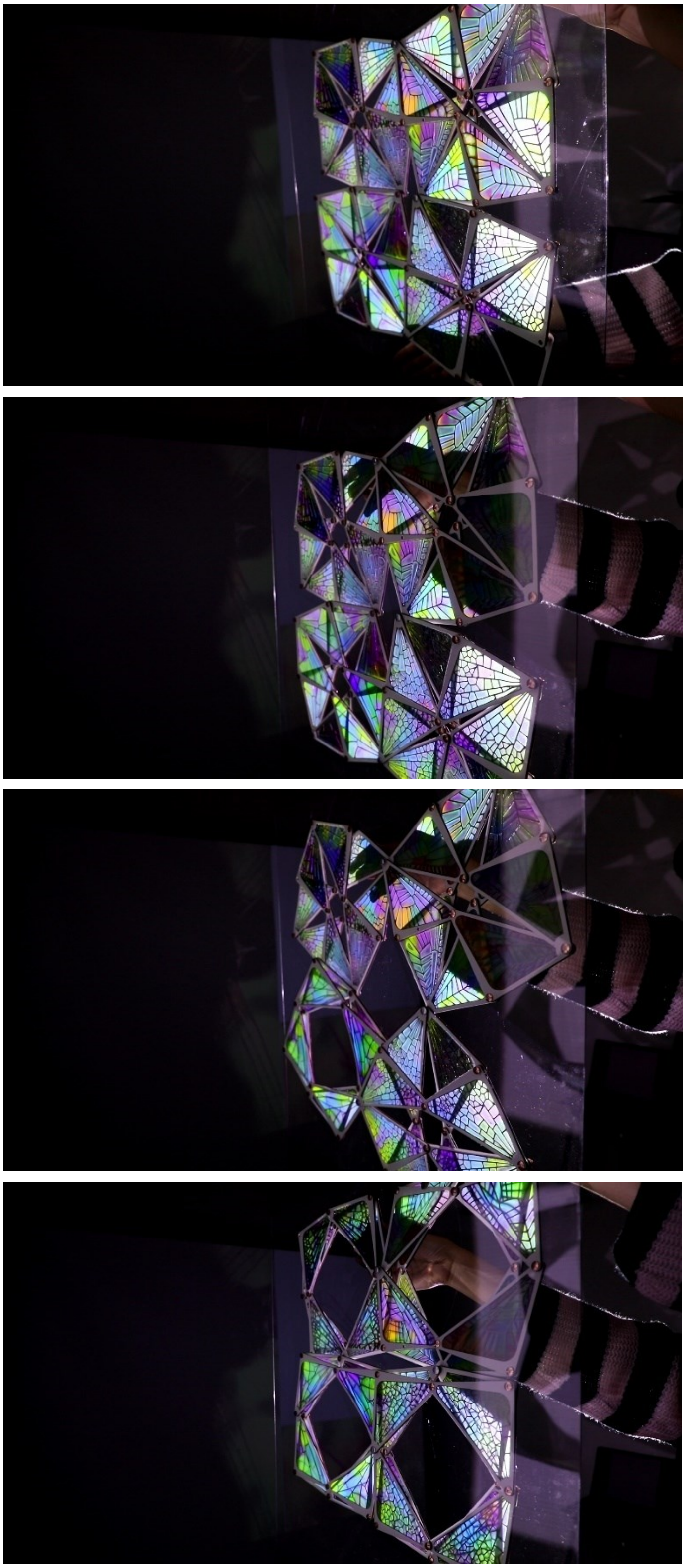


Figure 66. *Expansion sequences of the shading system (Hor, 2025).*

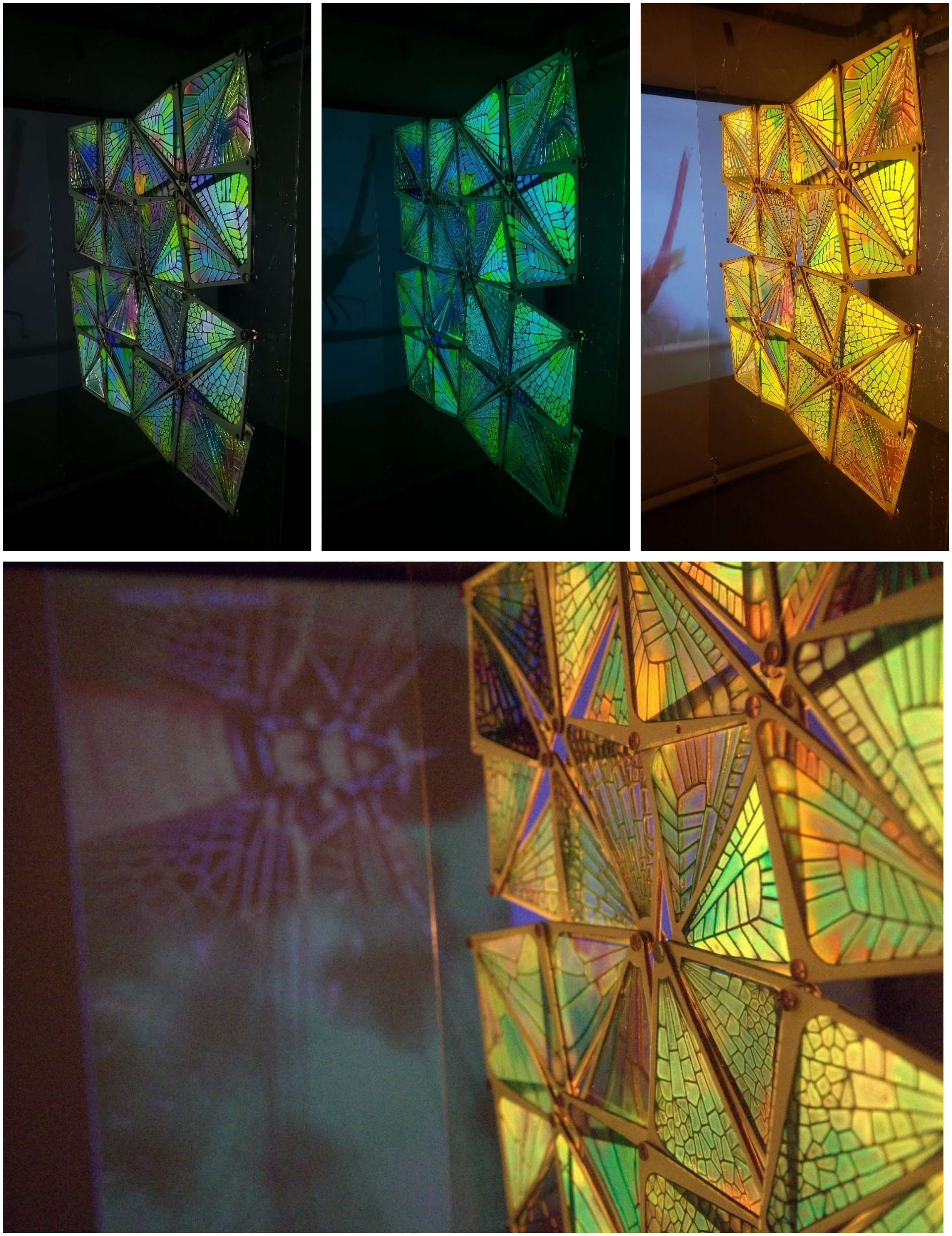


Figure 67. *Close-up shots (Hor, 2025).*

CHAPTER 4

DISCUSSION AND CONCLUSION

5.1 Conclusion

In this research, I aimed to design a bio-inspired deployable shading system that responds to diverse user needs, such as visual privacy and light control. Drawing on the morphology and mechanics of insect wings, the project sought to translate natural principles of the coupling mechanism and venation pattern of insect wings into an architectural context. The study addressed the design problem through an interdisciplinary methodology that combined bio-inspired design, parametric modeling, and iterative digital and physical prototyping. Through this approach, the research explored how biological mechanisms, particularly those observed in insect wing structures, can inform the development of transformable architectural systems.

5.1.1 Restate Research Questions

Guided by the central research questions, this study examined how iterative feedback between digital and physical prototyping can enhance the design process, how nature can serve simultaneously as inspiration and solution, and how bio-inspired principles can be effectively integrated into design through parametric tools.

To respond to the first research question, I developed several physical prototypes alongside digital simulations. Through this iterative process, I learned more about their potentials and limitations, which helped me narrow down my research focus and choose among different design ideas. Digital prototyping allowed me to explore alternative tessellation configurations and determine the most effective installation strategy in tessellated form. These iterations also enabled me to verify findings from one through the other across multiple stages of the design process.

To address the second research question, I first approached nature as a solution database through a top-down BID method, which provided answers to a specific design challenge, which was improving the stability of the deployable structure. The concept of the wing-to-wing coupling mechanism became the inspiration for designing the temporary hook shape attachment device of the shading system. As I continued working on other aspects of the design, particularly the membrane, I adopted a bottom-up BID method to extract principles from insect wing venation. This inspiration strongly influenced the artistic aspect of the design while also informing the structure of the supporting frame.

To respond to the third question, I used Grasshopper as a parametric design tool to translate the extracted biological principles of insect wing venation into design geometry. In this process, I was inspired by four different types of insect wing venation, which resulted in four distinct patterns for the supporting frames of the shading system.

5.1.2 Research Contribution

This research contributes to design knowledge at methodological, conceptual, and practical levels.

From a methodological perspective, it can be considered an interdisciplinary study that follows its own specific design process. The integration of two bio-inspired design approaches, technology pull and biology push, represents a key methodological contribution. In addition, the iterative framework developed through repeated cycles of sketching, digital modeling, and physical prototyping highlights a distinctive process that strengthens the research's creative and analytical dimensions.

From a conceptual perspective, merging cultural concepts such as *Orosi* windows with biological frameworks is noteworthy, as it bridges traditional architectural expression with contemporary bio-inspired design thinking.

From a practical perspective, the research culminated in the fabrication of a final prototype of a bio-inspired deployable shading system, which demonstrates the applicability of theoretical insights in a tangible, functional design outcome.

5.1.3 Limitations

The main limitations of this research were time and funding, which restricted the development of multiple prototype versions, deeper structural exploration through additional tessellation studies, and broader material and fabrication experimentation, particularly with sustainable alternatives. On the other hand, ideally, a research-creation project of this interdisciplinary nature would be carried out by a collaborative team of specialists working alongside the architectural designer, including biologists, industrial designers, mechanical engineers, and material scientists.

5.1.4 Future Work and Potential Applications

Insect wings remain a powerful source of inspiration with vast, unexplored potential. Future research building upon this study could investigate other structural or formal properties of insect wings beyond the coupling mechanism and venation patterns explored here. Since only a few types of venations were examined, many additional patterns could provide valuable insights and inspiration for architectural applications.

The final prototype was developed at a human scale as a shading system; however, the structure also has the potential to function as an interactive interior design element, such as a divider or partition. With further modifications, the system could also be adapted to an architectural scale, serving as part of responsive façades.

Another significant aspect of this research lies in the use of parametric design tools such as Grasshopper. The algorithms developed in this project are highly dynamic and adaptable, allowing them to be modified for other design explorations. This flexibility suggests that infinite variations of this design are embedded within the algorithm itself, waiting to be developed and expressed across different scales and contexts of design.

Throughout this project, the continual oscillation between physical prototyping and digital modeling became a defining aspect of the design process, enabling iterative refinement, immediate feedback, and a deeper understanding of the system's behavior. This hybrid workflow not only shaped the final outcomes but also affirmed the value of integrating hands-on experimentation with computational tools, an approach I intend to continue developing in future design research and practice.

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