TOWARDS A BIOMIMETIC ENVELOPE

A case study of Rheum nobile: an investigation into building envelope design, inspired by Rheum nobile's adaptive solutions with a focus on light and heat control based on Vancouver climate

by

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Towards a Biomimetic Envelope

A case study of Rheum nobile: an investigation into building envelope design, inspired by Rheum nobile's adaptive solutions with a focus on light and heat control based on Vancouver climate

submitted by Shima Banaei in partial fulfillment of the requirements for

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in Architecture

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Abstract

Today, buildings with excessive energy consumption for heating, cooling, and lighting of indoor spaces have led to fundamental environmental problems, such as climate change, global warming, and air pollution. However, for more than billions of years, ecosystems and living organisms have adapted to environmental changes without disturbing the natural balance. Due to the perfect performance of nature's systems in adapting to environmental changes, the purpose of this research is to investigate a bio-inspired building envelope system based on Vancouver climate to reduce building energy consumption for indoor heat and light controls. According to the specific conditions of the project, after studying several organisms, the Rheum Nobile plant has been selected as the natural source of inspiration, which has been able to adapt to the freezing Himalayan climate with its unique features in controlling sunlight and temperature. In the proposed design approach, the natural adaptive solutions have been tested through a series of light simulations to ensure good light quality in the space.

The final design version is a dynamic system consisting of three postures, inflated, deflated, and partially inflated, in which the system is activated by temperature and light sensors. As a result of this design, the proposed biomimetic building envelope breathes like a living plant, which dynamically adapts to ambient temperature and sunlight to provide a comfort indoor condition for its occupants.

Lay summary

The primary purpose of this research is to investigate a new passive building envelope system inspired by nature, which decreases the destructive environmental impacts of current usable techniques for light and heat control of indoor spaces. It was done through biological analysis of a specific plant, Rheum Nobile, and tested in a series of light simulations. As the result of this envelope design, the building would breathe like a living organism, which adapts to the changing temperature and sunlight, dynamically.

Preface

The current research, including the proposed design project, is a result of the individual work of its author, Shima Banaei, which is inspired by successful precedent projects.

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Acknowledgments

I would first like to thank my thesis supervisor, Blair Satterfield, for all his support, guidance, feedback, and constructive criticism during my research. Without his support, this research would never have reached this stage today.

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1. Introduction

1.1 Background

Nature can be seen as a ‘mentor’ that has many lessons to teach humans, as a ‘measure’ to judge the sustainability of our designs and as a ‘model’ to solve human problems (Benyus, 1997). From my designer’s perspective, I ask myself: If nature performs perfectly for more than billions of years, why don’t we apply nature’s strategies to solve our design problems?

“Carbon dioxide causes global warming. Buildings emit almost half of the carbon dioxide in the U.S. That has to stop” (Cramer 2017).

Figure 1. Climate change[1]

[1] [Online]. Available at: https://www.architectmagazine.com/design/editorial/the-climate-is-changing-so-must-architecture_o [Accessed 22 April, 2021]

Climate change is the defining issue of our time. The destructive impacts of climate change, including global warming, land degradation, agricultural loss, sea-level rise, and general disturbances of the natural balance are undeniable. Buildings by consuming approximately 40 percent of annual energy in the U.S. are considered to be the biggest reason for climate change, even more than automobiles (Cramer, 2017). As referred by Maibritt Pedersen Zari, policies and actions must expand rapidly, particularly in the urban built environment and associated disciplines, to mitigate greenhouse gas emissions and mutually the impacts of climate change (Zari, 2010).

In this context, the building envelope as the first connecting layer between outdoor and indoor environments plays an important role in terms of controlling the energy usage of buildings. Building skin can be considered as a medium, which might maximize the interaction between human needs and the environment (Badarnah, 2017). However, in the most current design technics, the building envelope has been seen as a barrier or shield between inside and outside and is completely insulated to reduce the range of heat transfer (Badarnah, 2017). Also, in recent methods, ignoring the importance of natural light penetration through building façade and high dependency on artificial lighting has increased the electricity consumption of buildings. This approach to building envelope design limits the potential to passively control indoor temperature and lighting.

A new science called biomimicry attempts to mimic nature's solutions to solve analogous human problems. Biological organisms have evolved to perform without disturbing the natural balance. Adaptation abeles living organisms to better suit to their changing environment. (Badarnah, 2017). They regulate their body temperature without using fossil fuels or polluting the environment. Plants perform food processing by using natural sunlight without the use of electricity. Our skin, which is analogous to building skin, protects our body from the outside environment, receives Vitamin D through sunlight, and maintains core temperature steady by adapting itself to environmental conditions. To this end, this is the time to stop current destructive design methods and go towards sustainable strategies, inspired by nature.

1.2 Aims and Objectives

With all previous considerations, the purpose of this research is to investigate a bio-inspired building envelope system in terms of heat and light control, based on Vancouver climate, which is tested and modified through a series of light simulations to maximize its day-light performance. By considering the time limitation for this research and also the extent of this research topic, the focus of this paper has narrowed to focus on evaluating the light performance of the envelope through a series of simulations. For future research, the proposed building envelope can be tested in terms of heat control by energy modeling applications.

In general, the following objectives are set and will be addressed through this paper to achieve a bio-inspired building skin with proper heat and light adaptability.

Objective 1: Propose a living organism with good adaptability in the area of thermo-regulation and light control as our natural source of inspiration. Analyze the organism’s functional approach in terms of heat and light control and specific features that contribute to improving body performance.

Objective 2: Transform the extracted natural functional solutions and specific features into applicable strategies in architecture. Various design options need to be carefully analyzed to select the most suitable architectural strategy, which passes the design process to generate a conceptual idea.

Objective 3: Test and modify the generated concepts through a series of light simulations based on the climatic conditions of Vancouver. At this stage, computer simulations adjust and prove the functional performance of design concepts in terms of daylight efficiency.

By considering the above design hierarchy, the generated building envelope, as a computer-tested model, can be considered for further development and physical model testing in the future. Besides, this research may be considered a benchmark model for future studies that aim to generate bio-inspired designs, which determines major steps in the process of design and probable design challenges.

1.3 Research Justification

Although in previous years, some effective studies have been done in the field of biomimicry in architecture, the small number of successful built examples demonstrate that there is a lack of a practically defined design method to apply biomimicry in architectural design (Faludi, 2005, Zari, 2007). In recent years, the most successful examples of biomimicry in design tools were typically material productions or technical products instead of actual architectural buildings or systems (Zari, 2007).

In the area of building envelope design, some studies have been undertaken to generate design concepts inspired by nature. In some cases, the main concern of design was to mimic the form or aesthetic features of natural elements rather than their functionality. These examples cannot be identified as successful bio-inspired designs, because they are just photocopies of nature without any functional similarities. However, in some other studies, researchers focused on the performance of nature as an impactful imitation tool. I can refer to self-authored design proposals Mazzoleni in her book, 'Architecture Follows Nature' which mimic functional solutions of animal skin into building skin. Or, Bloom Pavilion by Doris Kim Sung, which is inspired by human skin to self-regulate indoor temperature.

Most of the previous cases of biomimetic envelopes are prototypes or at the design concept level that their performance in the real condition is under a layer of ambiguity. To this end, there is a need for evaluation tools to test and modify the performance of bio-inspired envelopes to maximize the envelope performance based on specific design conditions. It means, although imitation of natural solutions is valuable as a tool to improve our building performance, the implied strategy needs to be examined based on specific design conditions because a single natural solution can be translated into many architectural strategies. Therefore, the challenge is to investigate the best translation of natural solutions to architectural strategies, which is reachable through testing and analyzing different options.

1.4 Thesis Structure

The Paper is organized into two parts. Firs part is an introduction to Biomimicry, which introduces design principles that inspire from nature as well as different approaches to biomimicry, which offer a design framework for the next part. Also, in this part, precedent cases of biomimetic designs will be analyzed and the benefits and drawbacks of each example will be discussed. This part provides a background for further discussion and concept generation in the next part.

Part two focuses on design rationales and the methodology that has been applied to generate a bio-inspired building envelope, inspired by adaptive features and solutions of a specific plant in terms of heat and light control. At this stage, transformed biological solutions will be analyzed and tested by computer simulations based on Vancouver climatic features to modify and form the project concept.

2. Biomimicry

2.1 What is biomimicry?

“biomimicry – design inspired by the way functional challenges have been solved in biology – is one of the best sources of solutions that will allow us to create a positive future and make the shift from the industrial age to the ecological age of humankind” (Pawlyn, 2016).

Biomimicry is the process of applying solutions from nature to the human-made world to create a healthier and more sustainable life for people (The Biomimicry Institute, 2021). According to Janine Benyus, founder of biomimicry, biomimicry is a new science that analyses nature to mimic nature’s best solutions with the goal to solve human problems (Benyus, 1997). Also, biomimetic is identified as the abstraction of good design, inspired by nature (Vincent et al., 2006). It is a procedural approach containing three main steps: research, abstraction, and implementation (Pohl and Nachtigall, 2016). Research means searching for an answer or solution in nature according to the goals and concerns of design. Abstraction refers to transforming the extracted natural solutions into applicable strategies in architecture and implementation concerns the constructional techniques and proficiency to build the biomimetic design concept with high performance.

In the same way, biomimicry in architecture means imitating natural solutions and then translating these solutions to applicable strategies in architecture to solve design concerns. Biomimicry is a “powerful innovation tool” that can assist architects to transform from conventional design methods to new sustainable solutions, extracted from nature (Pawlyn, 2016). Previously, architects referred to nature as an inspiration source; however, the concern was mainly building forms, decoration, or aesthetic features of nature rather than its functional ability (Pawlyn, 2016). Biomimicry is searching for functional solutions and not necessarily aesthetic aspects (Pawlyn, 2016). It means that imitation of nature is valuable if considering its functional ability to solve design problems. In this context, the implementation of biological solutions in design projects leads to discovery, innovation, and novelty (Mazzoleni, 2013).

On the other hand, it is important to highlight although there are lots of benefits in applying nature's solution into architecture, all the strategies, processes, and solutions that exist in natural organisms and ecosystems are not perfect or appropriate for implementation in the human context (Zari, 2010). The main challenge in the process of biomimicry is to filter the extent of opportunities that nature provides (Badarnah, 2017). It means that due to the current technology limitations and complexity of the human context, all the natural solutions will not be adaptable and convertible to applicable architectural techniques. To this end, inspiration from nature needs depth analysis to find appropriate ideas according to the specific design concerns and transform the natural solutions to workable strategies in architecture, which lead to the same functional quality as the source of inspiration.

2.2 Challenges of applying biomimicry

Among the three mentioned steps of the biomimicry process, research, abstraction, and implementation, "Abstracting design strategies is one of the most difficult steps in biomimicry" (The Biomimicry Institute, 2021). As Michael Pawlyn mentioned in his book "Biomimicry in Architecture", the book intends to analyze ways to translate adaptations in nature into solutions in architectural design (Pawlyn, 2016). It emphasizes the importance of transforming from nature to architecture in the process of bio-inspired design. A single biological solution can be transferred into several architectural techniques and subsequently results in various deliveries and designs. The challenge is to translate the natural solution to an appropriate language, which is applicable in architecture with high performance. This translation does not need to have a similar form, shape, or apparent features as the natural source; however, the goal is to utilize the same functional concept and performance as the source of inspiration (Zari, 2010).

Although this transformation from nature to architecture is challenging, this goal is achievable by detailed analysis of the applicable techniques, the help of technology, and also by testing the translated architectural solutions through computer simulation modeling in a real context.

Another barrier against the employment of biomimicry in architecture is the lack of a defined design method of approach for architects to apply natural solutions into the design (Vincent et al., 2006, Zari, 2007). This is demonstrated by considering the small number of built bio-inspired case studies (Faludi, 2005, Zari, 2007). The successful examples of biomimicry in architecture are mostly products or material productions rather than designs on a bigger scale, buildings, or building systems (Zari, 2007). It emphasizes that biomimicry is a procedural approach and needs defining steps to pass the research, abstraction, and implementation stages. In this regard, there is a well-categorized model for applicable approaches to biomimicry in architecture by Maibrit Pedersen Zari and also a step by step design framework by The Biomimicry Institute, which will be analyzed in the following sections to form a background for the next part, biomimetic building envelope design.

Another challenging issue in applying biomimicry to design is the insufficient biological and ecological understanding and knowledge of designers. Translation of natural solutions to human design, without analyzing and understanding biological systems, may result in a design at a superficial level of biomimicry without a high performance (Zari, 2007). Usually, architects can mimic the form, material and aesthetic aspects of nature perfectly; however, implementation of natural functions in design is difficult by considering an architect's incomplete understanding of biological processes and systems (Zari, 2007). Nevertheless, designers can take advantage of applying nature's solutions to design by in-depth analysis of biological research and collaboration with biologists or ecologists to translate the extracted solutions to best strategies in human design.

Moreover, by considering that biomimicry in architecture is a new application, there is a limited motivation by building developers to invest in such risky research. It demonstrates one of the reasons why most of the precedent examples of biomimetic architectures are prototypes or at small scales rather than broad developments. By considering all the benefits of biomimicry implementation in architecture, especially in increasing sustainability, it seems worthy to overcome the mentioned challenges by expanding our research area in this field and computer testing of proposed models as an evaluation tool to gain developers' trust to investigate bio-inspired projects.

2.3 Approaches to biomimicry

According to the classification by M. Pedersen Zari, mainly, there are two types of approach to biomimicry: "design looking to biology" and "biology influencing design" (Zari, 2007).

2.3.1 Design looking to biology

In this approach, a human need or design problem leads us to look to nature to understand and analyze the way that other organisms or ecosystems address this concern (Zari, 2007). According to the investigations by The Biomimicry Institute, "Biomimicry Design Spiral" is a visual tool that helps to pass the stages of design in this approach, successfully. Considering the biomimicry spiral, generally, the biomimetic design consists of six main steps: define, biologize, abstract, discover, emulate and evaluate (The Biomimicry Institute, 2021) (fig.2).

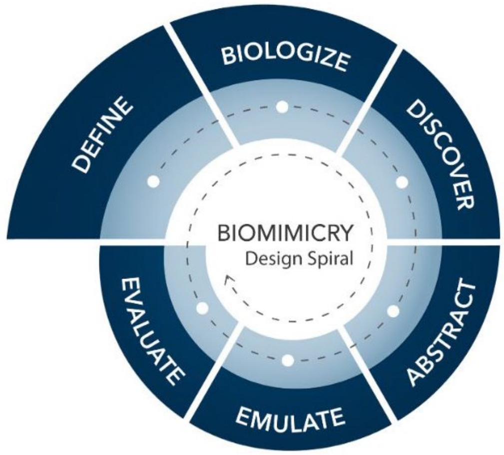


Figure 2: Biomimicry Design Spiral[2]

Define: This step contains a series of questioning, classification, and goal setting to define the challenge, problem, or opportunity that aims to be addressed in design (The Biomimicry Institute, 2021).

Biologize: It means to reframe the function and context that needs to be addressed in a biological term (The Biomimicry Institute, 2021). This step contains questions, such as how does nature…? In other words, in this step, we want to ask our design questions in a biologize language format, which eases the process of finding the solution in nature.

Discover: This step searches in nature to find natural models that address the same concern as the intended design problem (The Biomimicry Institute, 2021). It looks to find the main source of inspiration for starting design.

Abstract: Abstraction focuses on translating natural strategies into applicable design techniques in human design (The Biomimicry Institute, 2021). As referred previously, abstraction is the most challenging and a

[2] [Online]. Available at: toolbox.biomimicry.org/wp-content/uploads/2017/10/Design.Spiral-Diagram_10.17.pdf [Accessed 25 July, 2020]

difficult step in the process of biomimetic design, and therefore more time needs to be spent on this step to find, analyze and choose the best strategies that perfume the same as biological models.

Emulate: This step aims to develop appropriate design concepts based on the abstracted strategies of the previous step (The Biomimicry Institute, 2021). It is the main design part of the process that develops design ideas and results in project concepts or prototypes.

Evaluate: “This step is all about assessment” (The Biomimicry Institute, 2021). The potential design concepts can be tested through computer modeling, simulation, or physical modeling to select the one with more feasibility and efficiency. Also, this step might change and revise the results of the previous steps, which can improve and modify the final design concept.

By considering all the six steps of biomimicry spiral, it’s important to remember, although steps are listed in order, the process is a non-linear approach and new achievements in each step cause to rethink the previous steps in a spiral (The Biomimicry Institute, 2021).

According to M. Pedersen Zari, an example of design looking to the biology approach is the Daimler Chrysler bionic car, which is inspired by boxfish and the free form pattern of a tree (Zari, 2007). The bionic car mimics the aerodynamic shape of boxfish, which decreases fuel usage of the automobile (fig.3), and also the bio-inspired car inspires from the freeform skeletal frame of Dog-Strangling Vine, which reduces material consumption of its skeletal (fig.3) (Zari, 2007). This Daimler Chrysler bionic car is an improved version of ordinary cars, which is more efficient in terms of material and energy usage; however, this car is not an innovation and follows the same idea as using the automobile as a tool of transportation (Zari, 2007).

Figure 3: DaimlerChrysler bionic car inspired by the box fish and strangling vine pattern; Source: Pedersen Zari (2007)

2.3.2 Biology influencing design

In this approach, recognizing a specific feature, behavior, function, or opportunity that nature provides encourages us to translate it into human design (Zari, 2007). In other words, in this approach, first, nature attracts our attention and then leads us to mimic that specific feature or function to our human-made world.

One of the famous examples of biology influencing design is the invention of Velcro (The Biomimicry Institute, 2021). One day, when Swiss engineer George de Mestral was walking his dog in a field, he realized that burrs had stuck to his dog's fur. He took the burrs home and looked at their structure under a microscope, which led him to make an invention, Velcro, an innovative biomimetic fastener(The Biomimicry Institute, 2021) (fig.4). Velcro, the popular adhesive material, is a two-sided fastener in which the hooks mimic the burr while the loops mimic the fur (The Biomimicry Institute, 2021). According to this example, an advantage of the "biology influencing design" approach therefore is that biomimicry may lead human to an innovation beyond the ordinary systems (Zari, 2007).

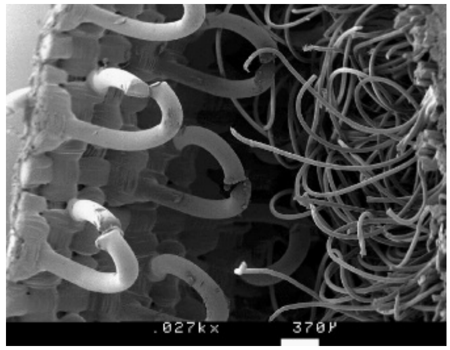


Figure 4: Invention of Velcro [3]

It should be highlighted that "there isn't one definitive way to practice biomimicry" (The Biomimicry Institute, 2021). Although basic steps are common in all methods of approach, each design process contains its challenges and subsequently results in slight differences in the process of approach. Regarding the two discussed approaches to biomimicry, in my opinion, "design looking to biology" is the more applicable method in architectural design. It starts with a design challenge, which is understandable by architects and leads them to look for a solution in nature. However, the "biology influencing design" approach should mostly start with biologists or ecologists whose profession is to analyze the biological and ecological world. In this way, biologists are not aware of design challenges that architects or other designers struggle with, and also architects don't know of discoveries by biologists to ask for further information. This separation of architecture and biology or in other words, architects and biologists demonstrates how difficult is the process of biomimicry in design, specifically in the "biology influencing design" approach.

2.4 Levels of biomimicry

According to the framework for understanding biomimicry application by M. Pedersen Zari, generally, there are three levels of biomimicry, organism, behavior, and ecosystem that each level can be

[3] [Online]. Available at: toolbox.biomimicry.org/methods/other/ [Accessed 25 July, 2020]

categorized in one of the five sub-levels: form, material, construction, process, and function (Zari, 2007) (table1).

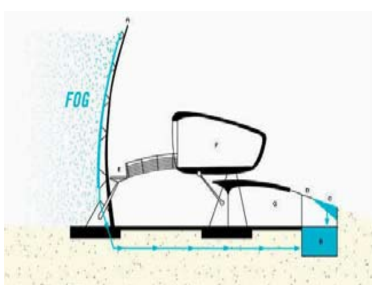
Levels of Biomimicry	Example : Building that mimics termites	
Organism level (Mimicry of a specific organism)	Form	The building looks like a termite.
	Material	The building is made from the same material as a termite; a material that mimics termite exoskeleton / skin for example.
	Construction	The building is made in the same way as a termite; it goes through various growth cycles for example.
	Process	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example.
	Function	The building functions like a termite in a larger context; it recycles cellulose waste and creates soil for example.
Behavior level (Mimicry of how an organism behaves or relates to its larger context)	Form	The building looks like it was made by a termite; a replica of a termite mound for example.
	Material	The building is made from the same materials that a termite builds with; using digested fine soil as the primary material for example.
	Construction	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example.
	Process	The building works in the same way as a termite mound would; by careful orientation, shape, materials selection and natural ventilation for example, or the building mimics how termites work together.
	Function	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable. It may also function in the same way that a termite mound does in a larger context.
Ecosystem level (Mimicry of an ecosystem)	Form	The building looks like an ecosystem (a termite would live in).
	Material	The building is made from the same kind of materials that (a termite) ecosystem is made of; it uses naturally occurring common compounds, and water as the primary chemical medium for example.
	Construction	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example.
	Process	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example.
	Function	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilizing the relationships between processes; it is able to participate in the hydrological, carbon, nitrogen cycles etc in a similar way to an ecosystem for example.

Table 1: Classification of biomimicry levels; Source: Maibritt Pedersen Zari (2007)

2.4.1 Organism level

The organism level focuses on a specific organism, to mimic a feature, part, or whole system of the organism biology into the design (Zari, 2007). Mimicking at this level has the potential to remain at the superficial layer of mimicry if the imitation is summarized in only a feature of an organism without considering its contribution to other parts and the whole ecosystem (Zari, 2007). In this context, the organism level of biomimicry can result in a broad spectrum of designs from innovations to very simple designs without any aim of reducing human environmental impacts. To that end, by considering the organism's participation in its ecosystem, the internal contribution of components, and understanding the whole biological system, we can achieve designs with high performance at the organism level of biomimicry.

As an example of this level, we can refer to the Hydrological Center for the University of Namibia by Matthew Parkes of KSS Architects, which is inspired by Namibian beetles (Zari, 2007). Namibian beetles live in the Namib Desert, one of the driest regions of the world with a high shortage of water (Zari, 2007). The beetle can catch moisture from dew and ocean fog by positioning its body right to wind direction and then condensing droplets with the help of bumps on the surface of its back and wings to direct water into its mouth (Zari, 2007). The proposed Hydrological Center positions itself in the direction of fog to produce water in the same process as a beetle (Zari, 2007) (fig.5&6).



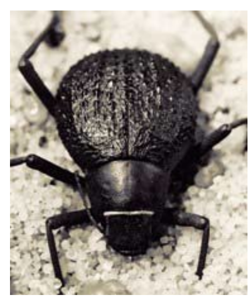


Figure 5 (left): Matthew Parkes' Hydrological Center for the University of Namibia ; Source: Zari, 2007;

Figure 6 (right): Stenocara beetle; Source: Zari, 2007

2.4.2 Behavior level

Mimicry at this level focuses on how an organism behaves to solve a problem, eliminate a special need, or connect to a larger context by translating that behavior into an appropriate language for human design (Zari, 2007). By considering the perfect performance of the natural cycle and how all organisms are integrated into this process, it can be realized that not only every organism adapts itself to its environment, but also adapts to other organisms and the whole ecosystem. Biomimicry at the behavior level contains the behavior of an organism in its self-activity and also with other species and elements of the ecosystem (Zari, 2007).

Buildings in Harare, Zimbabwe, and the CH2 Building in Melbourne, Australia, are examples of biomimicry at the behavior level, inspired by termite mounds (Zari, 2007) (fig.7&8). They thermo-regulate the indoor environment in a passive way with the assist of special techniques and natural ventilation, very similar to the process of thermo-regulation in termite mounds (Zari, 2007).

Figure 7 (left): Eastgate Building in Harare, Zimbabwe; Source: Zari (2007)

Figure 8 (right): CH2 Building in Melbourne, Australia; Source: Zari (2007)

2.4.3 Ecosystem level

Mimicry at the ecosystem level is more complete than the other two levels. It mimics the whole ecosystem and all its elements by considering their relations and effects on each other to manipulate successfully (Zari, 2007). According to Benyus (1997), the ecosystem level is an integral part of biomimicry. The ecosystem-level can be used in conjunction with organism and behavior levels (Zari, 2007). It means that organism and behavior levels are sublevels of the ecosystem.

A proposed example of this level is Lloyd Crossing Project in Portland, Oregon. This project analyzed the functional aspects of its ecosystem before development to design based on the estimated ecological situation of the site for a long-time period (Zari, 2007) (fig.9).

Figure 9: Lloyd Crossing Project, Portland, USA; Source: Zari, 2007

However, design at the ecosystem level has its complicity by considering the time required to understand the whole ecosystem and analyze all its elements and also their influence on each other. This might be the reason for the small number of projects, even proposals, at this level, although the ecosystem level is an integral part of biomimicry.

2.5 Precedent example of biomimetic envelope

The main goal of this section is to study a precedent example of the biomimetic envelope to analyze its advantages and disadvantages, gaps and potentials, and design methodology to build some ideas for starting the bio-inspired envelope design in the next part. Considering that biomimicry in architecture is a new science, particularly in envelope design, there is a lack of precedent examples, specifically built ones rather than proposed cases. In the following, Bloom Pavilion by Doris Kim Sung will be analyzed in terms of the type of approach to biomimicry, the level of biomimicry, and its potential and challenges.

2.5.1 Bloom Installation

"What I propose is that our building skin should be more similar to human skin and by doing so can be much more dynamic, responsive and differentiated, depending on where it is" (Sung, 2012).

Figure 10: Bloom Mesh[4]

[4] [Online]. Available at: www.archdaily.com/215280/bloom-dosu-studio-architecture [Accessed 25 July, 2020]

2.5.1.1 Project overview

Bloom is installed at the Materials and Application Gallery in Los Angeles. Bloom is a climate-controlled envelope that reacts according to surrounding temperature changes. It acts as a sun-tracking skin that senses time and temperature (Bengisu & Ferrara, 2018).

Bloom was designed by Doris Kim Sung. She is an architect with a biology background. Her architectural ideas integrate with biological knowledge, especially her specific vision of material (Furuto, 2012). According to her presentation at the TED conference in 2012, currently, our buildings by having floor-to-ceiling windows, high reliance on technology and fossil fuels for regulating indoor temperature, cause fundamental problems for the natural environment, such as the urban heat island effect (Sung, 2012). However, by looking into our body, the skin is a multifunctional organ. It cools the body through sweating, heats by inflating, and does so many other responsibilities in a sustainable format (Furuto, 2012). It means that all our skin components work together very dynamically and efficiently. Similarly, Sung believes that the building skin should act very similar to human skin without consuming excessive amounts of unnecessary energy for its operation (Sung, 2012).

In this regard, Sung in Bloom mesh displays a new type of smart material, thermo-bimetal, which is inspired by human skin to work dynamically based on temperature changes of the outdoor environment. As a result of the perfect performance of thermo-bimetal sheets in Bloom, this skin can self-shade, self-ventilate, and self-operate (Furuto, 2012).

2.5.1.2 Mechanism

Bloom is made up of around 14,000 pieces of laser-cut thermo-bimetal sheets (Furuto, 2012). Thermo-bimetal is not a newly invented material and it is commonly used as a thermostat in electrical devices to sense temperature (Bengisu & Ferrara, 2018).

However, using this material in the building envelope for temperature sensing is a new investigation. Thermo-bimetal is a lamination of two thin layers of metal with different coefficients of thermal expansion (Bengisu & Ferrara, 2018). Due to differences of expansion between the two metals, when the sheets become warmer according to the outdoor temperature, one side of the thermo-bimetal sheet expands faster than the other side and results in curling (Sung, 2012) (fig.11). In other words, by temperature rising, pores of the skin become open, and mutually by temperature dropping, pores start to be closed. This procedure provides a kind of passive automatic natural ventilation system. Therefore, by using thermo-bimetal sheets, buildings consume less amount of energy for air conditioning without requiring operational energy or manual handling (Bengisu & Ferrara, 2018). According to Sung's claim, the same system as Bloom pavilion with thermo-bimetal sheets can be applied to a single room and even skyscrapers to regulate indoor temperature, automatically (Sung, 2012).

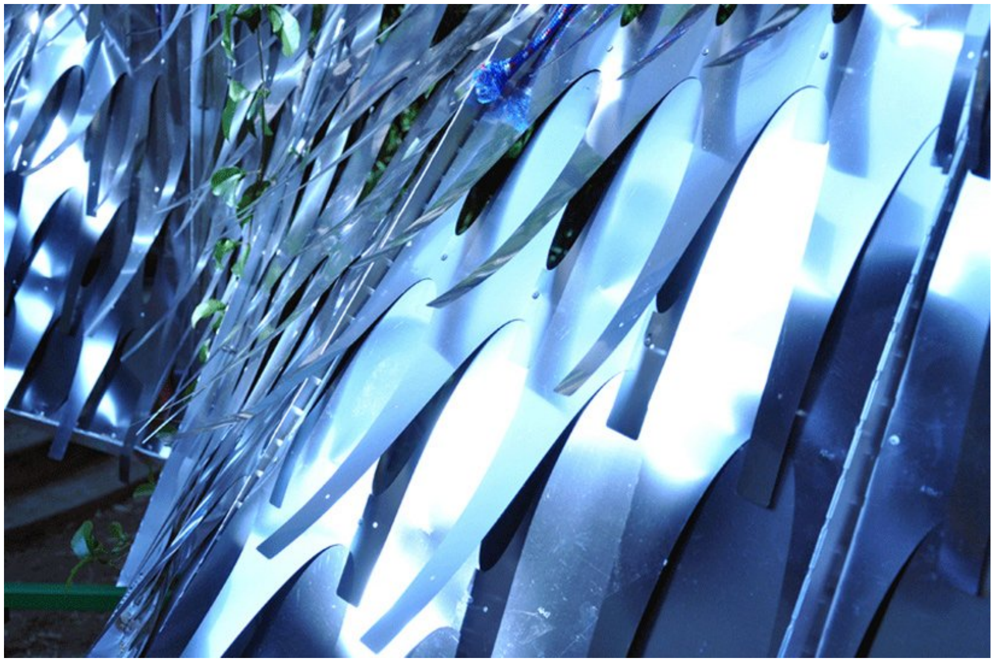


Fig.11: Thermo-bimetal sheets[5]

2.5.1.3 Analyze

Bloom thermo-regulates the indoor environment with the help of natural ventilation through its pores; however, human skin cools the body through sweating. As emphasized by Doris Kim Sung, the aim of mimicry in this project is to design an envelope similar to human skin to be more “dynamic, responsive and differentiated” (Sung, 2012). Nevertheless, there is no attempt to mimic the functional cooling process of human skin into the design. In this regard, it can be realized that Bloom mimics just a feature of human skin, self-operation in a dynamic way, rather than a deeper inspiration of the whole system.

[5] [Online]. Available at: https://www.designboom.com/architecture/doris-sung-bloom-at-materials-applications/ [Accessed 22 April, 2021]

2.5.1.4 Level of biomimicry

By regarding the discussed classification of biomimicry levels, Bloom is located at the organism level; because, it just mimics one of the features of human skin. However, it is not a complete mimicry of human skin and just focuses on an aspect of skin, self-operation, which seems a defective version of organism-level without considering the relation and influence of other factors.

2.5.1.5 Way of approach

As it is discussed, there are approaches to biomimicry, design looking to biology and biology influencing design. Regarding Bloom's approach, it can be a mix of both approaches as exemplified by Doris Kim Sung who is both a biologist and an architect. As she mentioned, her biological knowledge influences her design, although she referred to a design problem and the importance of an instant action to mitigate environmental impacts of buildings as the result of fossil fuel usage for indoor thermoregulation. In this regard, Bloom can be considered as an example of a mixed approach to biomimicry, although design looking to biology approach seems to be more outstanding by considering that the main concern of Boom design is to reduce the destructive environmental impacts of human design, which leads Doris Kim Sung to refer back to her biological knowledge to find a solution.

2.5.1.6 Advantages and disadvantages

The strength of Bloom is its self-operating system, without the use of any operational energy and with just the help of a smart material, thermo-bimetal sheet. It is also a responsive climate-control surface that reacts to temperature changes. It reduces the energy usage of the building, comparing to other smart envelopes that consume high amounts of energy to operate their movable system.

However, there are some disadvantages regarding this envelope that can be modified by conducting further research in this field. For instance, thermo-bimetal sheets are matt sheets that do not allow light penetration, which block the view and increase usage of artificial lighting during cold times, when the pores of the building skin are mostly closed. Also, Bloom does not follow any light control system, including shading elements, to reduce glare during sunny days.

Moreover, envelope maintenance is another challenge. The sensitive surface of Bloom is at risk of Bird damage or human intervention. Also, water penetration to inside spaces is problematic in the Bloom surface system. As a solution for these issues, Doris Kim Sung believes that the same system deployed in Bloom can be installed between two layers of glass and be used as a façade system for skyscrapers.

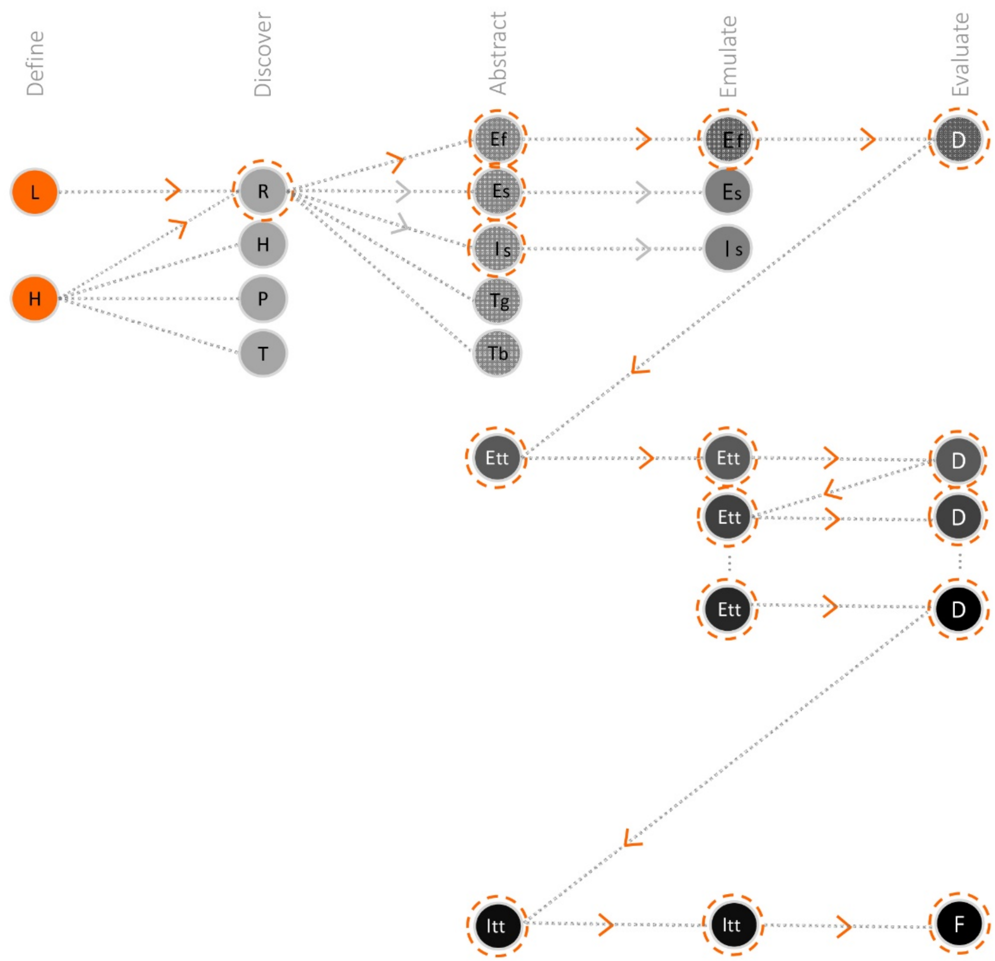
2.6 Conclusion

By considering all the discussed topics, it can be concluded although there are some challenges in the process of biomimetic design, the implementation of biomimetic approaches in architecture can considerably increase our design sustainability. However, it is crucial to understand the main principles and possible approaches in the field of biomimicry to select the appropriate ones according to the specific design conditions. Generally, there are two types of approaches to biomimicry, "design looking to biology" and "biology influencing design" that the first approach seems closer to the architectural design procedure.

3. Towards a biomimetic envelope design

3.1. Project Specific design approach

By considering the discussed possible approaches and our specific design goals, the selected biomimetic approach in this project is “design looking to biology”. As mentioned previously, the design looking to biology approach follows defined main steps in a spiral format, called biomimicry design spiral. The defined steps in the biomimicry design spiral might change, slightly, based on the specific conditions of each project. Generally, the biomimicry spiral contains five main phases: challenge, discovery, abstraction, emulation, and evaluation. According to our specific design goals in this project, the following design methodology is applied. In this approach, very similar to the biomimicry spiral, there are back and forces among different phases to finally achieve an acceptable design delivery (fig.12).



Define

L: Passive light control

H: Passive heat control

Discover

R: Rheum nobile

H: Human skin

P: Polar bear

T: Termite mound

Abstract

Ef: ETFE panel + fixed shadings

Es: ETFE panel + smart shadings

Is: Inflatable balloons + smart shadings

Tg: Thermochroic glass

Tb: Thermo-bimetal

Ett: ETFE panel (translucent and transparent foils)

Itt: Inflatable plastic bag (translucent and transparent)

Emulate

Ef : ETFE panel + fixed shadings

Es: ETFE panel + smart shadings

Is: Inflatable balloons + smart shadings

Ett: ETFE panel (translucent and transparent foils)

Itt: Inflatable plastic bag (translucent and transparent)

Evaluate

D : Daylight simulation: DIVA

PH: Physical model

Figure 12: Project specific design approach; source: Author

3.1.1 Define

Currently, our buildings consume an excessive amount of energy to control indoor light and temperature at a satisfactory level. It causes environmental problems, such as climate change, global warming, and air pollution. The purpose of this design project is to generate a bio-inspired envelope system, which decreases the energy usage of buildings in terms of indoor heat and light control.

3.1.2 Discover

The purpose of this step is to find natural sources of inspiration that contain adaptive solutions for heat and light control. Some organisms with good light and heat adaptability are addressed in our specific design process (fig.12). The main challenge of this step is to filter and select the most appropriate natural solution, which responses to the specific goals and conditions of the project.

Based on biological analysis of the selected organisms, Rheum Nobile seems the most suitable source of inspiration because it has adaptive solutions for both light and heat control. Rheum nobile is a native of the Himalayas. It performs very similarly to a greenhouse, which has enabled it to adapt to the freezing climate of Himalaya (Pawlyn, 2016) (fig.13).

Figure 13: Rheum nobile; source: Michael Pawlyn 2016

Rheum Nobile has two specific features that stand it out to adapt to Himalaya climatic conditions. First, its bracts have a variety of transparency. Bracts at the base of the plant are solid leaves with chlorophyll, while the bracts at the top of the plant are typically translucent to enter sunlight (Candeias, 2019).

Moreover, bracts all over the plant are overlapping to keep the air inside the plant and act as thermal insulators (Candeias, 2019). As a result of the Rheum Nobile's good adaptability, the temperature inside the flower column can be more than 10ºC warmer than outside (Candeias, 2019).

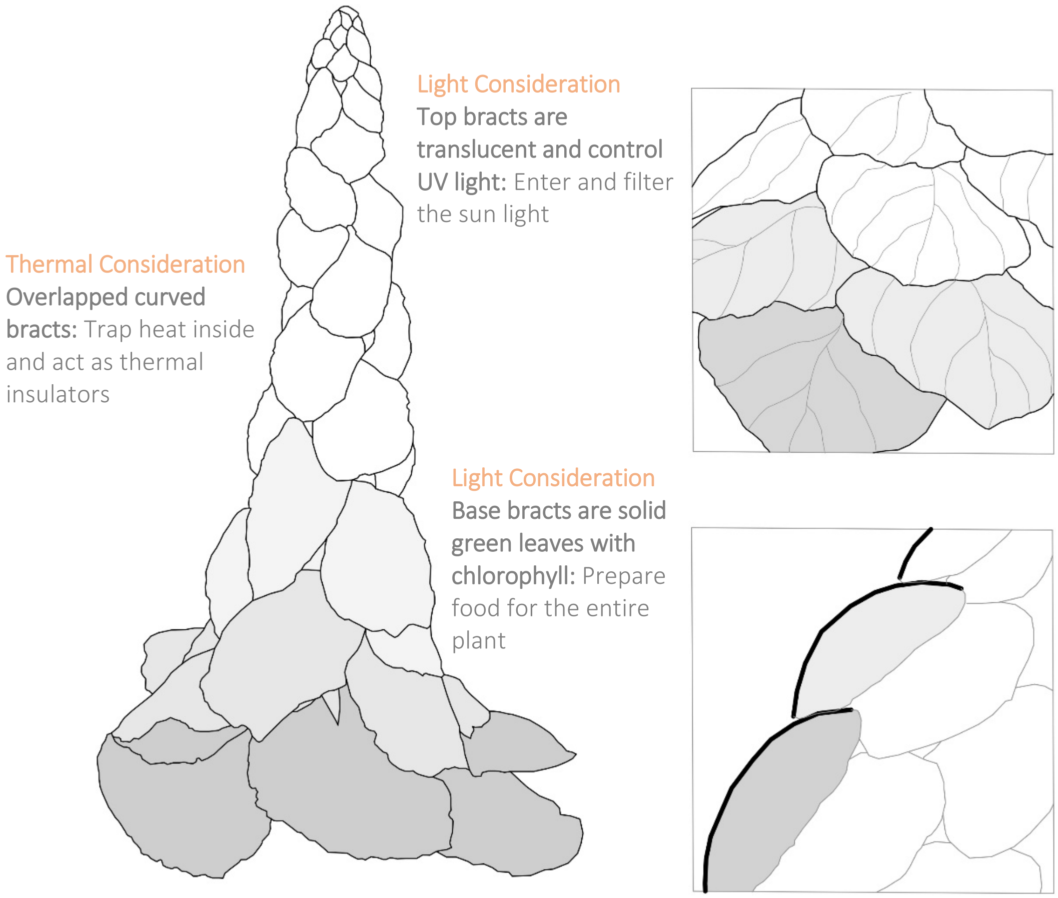


Figure 14: Rheum nobile biological analysis; source: Author

3.1.3 Design

This step aims to translate the natural solutions to appropriate strategies in architecture. After a series of back and forth iterations in the process of design, the overlapped bracts that work as thermal insulators in the plant are transformed into inflated plastic cushions that are filled by air. Plastic cushions act as thermal insulators and keep the interior warmer than outside (fig.15).

Also inspired by the plant, which has leaves with different translucency, including fully opaque, semi-opaque, and translucent, the proposed biomimetic envelope also has cushions with translucent and transparent materials to be able to control the amount of incoming sunlight. The aim is to determine the material of each panel based on a series of light simulations to ensure the light quality inside the space. The two inspiring projects are Water-Cube, Beijing, China, including fully opaque ETFE foils, and Eden Project, Cornwall, UK, with fully transparent ETFE foils (fig.16 & 17).

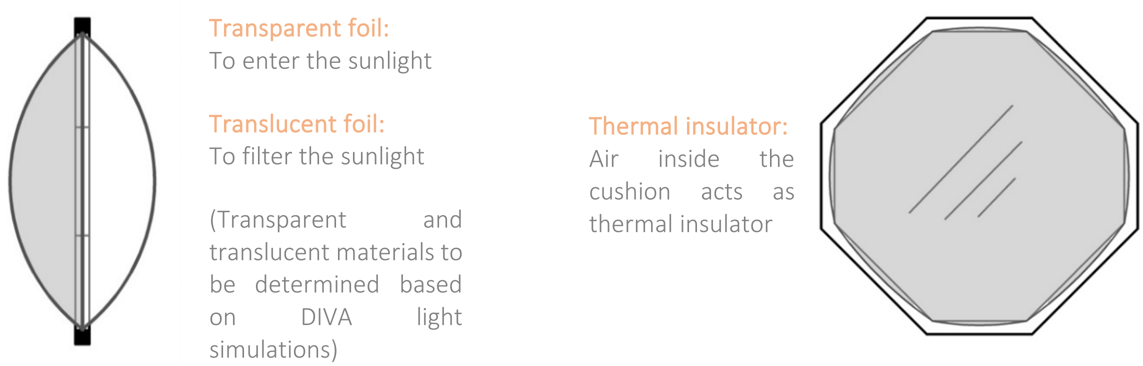


Figure 15: Concept idea; source: Author

Figure 16: Water Cube, China[6]

Figure 17: Eden project, UK[7]

[6] [Online]. Available at: https://inspiration.detail.de/watercube-national-swimming-centre-in-beijing-103313.html [Accessed 20 April, 2021]
[7] [Online]. Available at: https://www.archdaily.com/901136/grimshaws-next-eden-project-could-be-in-the-north-of-england/5b89237df197cc419300011c-grimshaws-next-eden-project-could-be-in-the-north-of-england-image [Accessed 20 April, 2021]

3.1.4 Emulate

In this phase of design, the idea of the inflated plastic cushion is extended to a module consisting of five components, which could be implemented independently in a facade system. The generated pattern is inspired by the shape of Rehum Nobile's bracts (fig.18). The proposed module can be expanded in different shapes and forms as shown in fig.19.

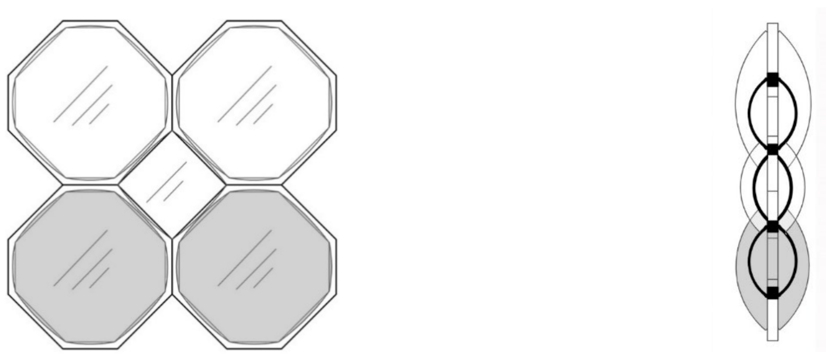


Figure 18: Emulation; source: Author

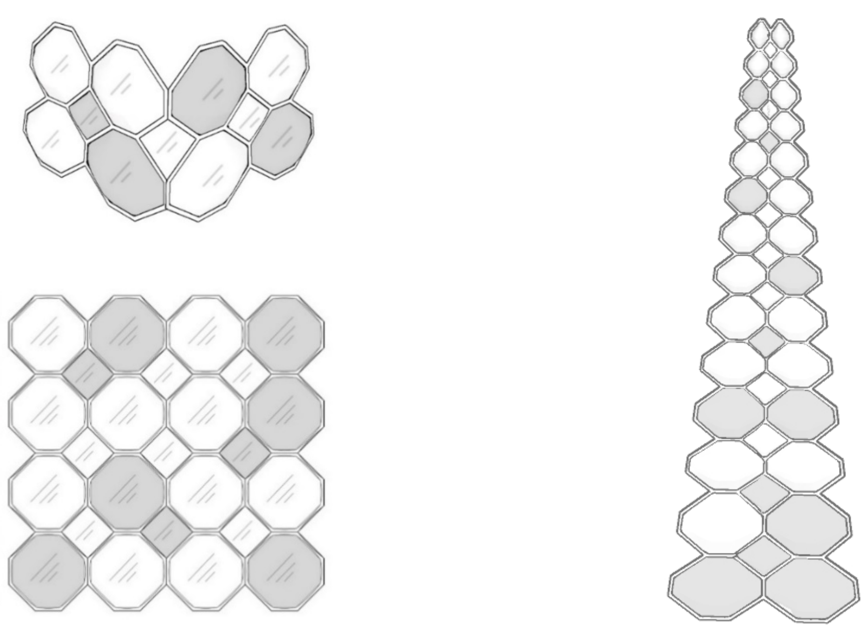


Figure 19: pattern development; source: Author

The study pavilion's form follows Rheum Nobile's form, which makes the project look similar to the source of inspiration. However, this system is not just limited to this form and function. In the following, we will discuss more opportunities for this envelope system regarding form and usage.

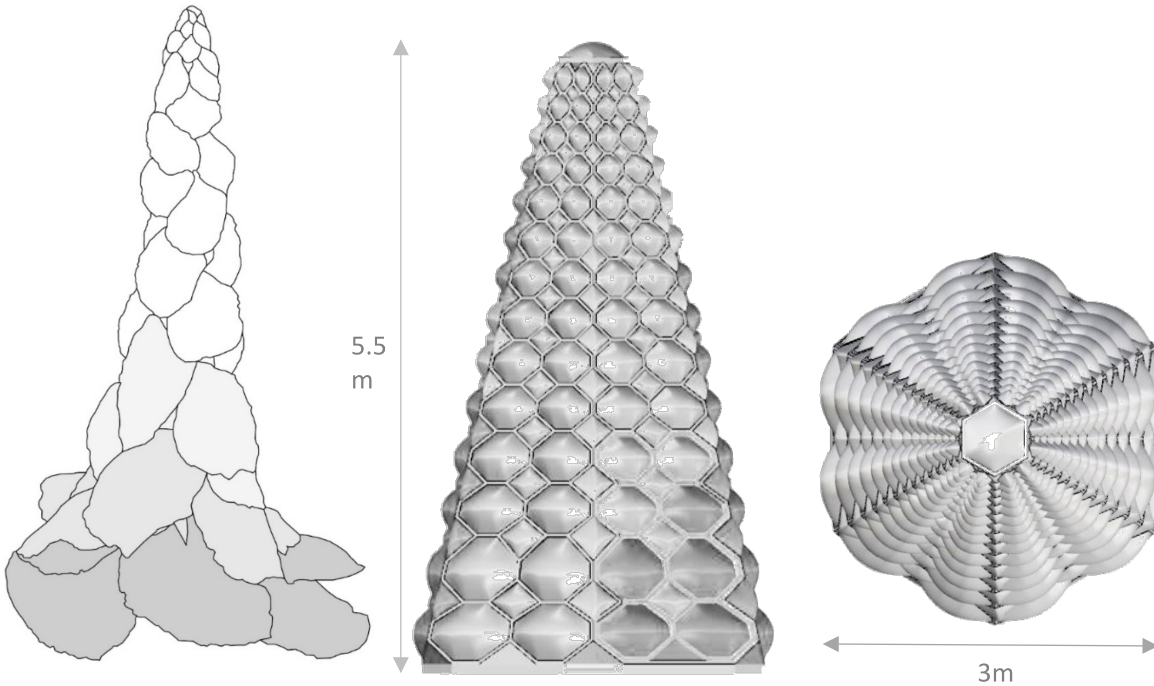


Figure 20: Form development; source: Author

3.1.5 Evaluate

This section aims to test the performance of the concept idea. Because the proposed biomimetic system contains both transparent and translucent plastic foils, the material of each panel needs to be determined through light simulations in DIVA. In the process of the simulations, the first step is to find a sense of light quality from each side of the pavilion. To do this, we tested each side separately by considering transparent material for the intended side and translucent material for the other sides of the envelope. As a result of the six simulations, the following chart is generated, which acts as a design guide for the next series of simulations.

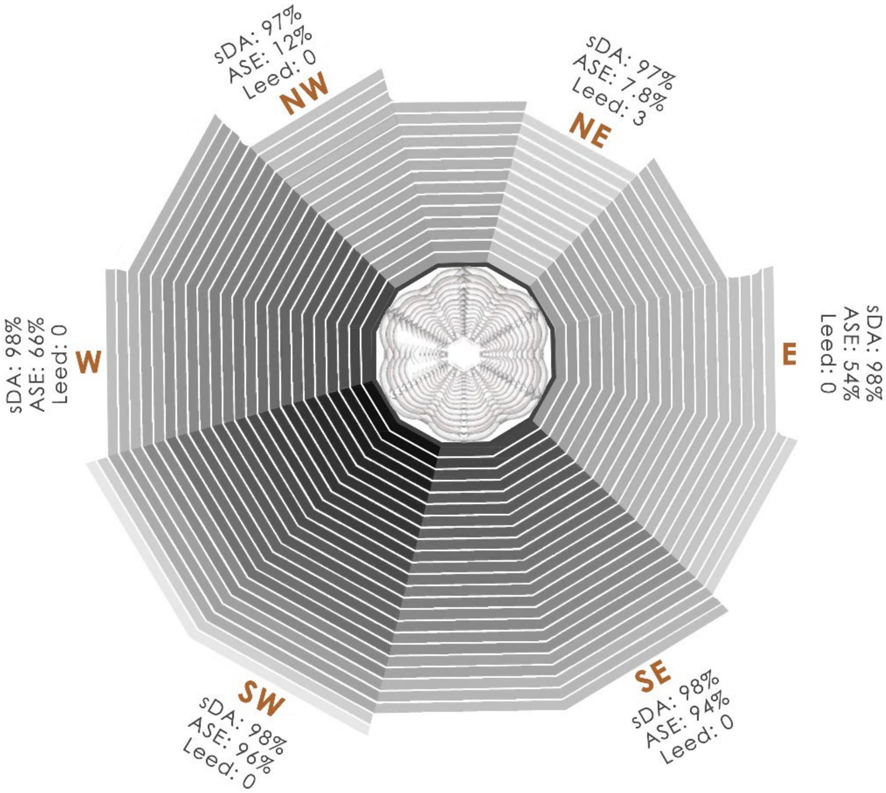
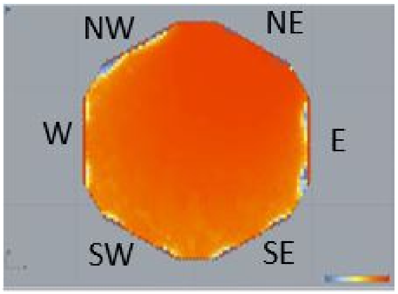
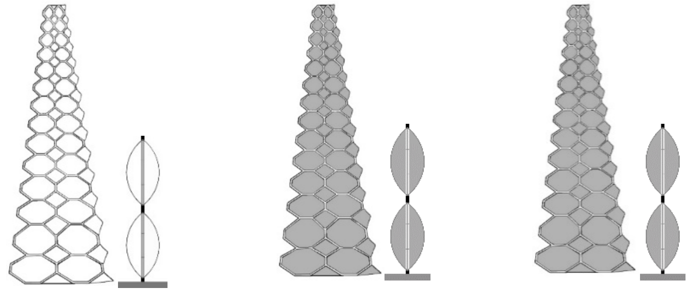


Figure 21: Light guide diagram; source: Author

According to the light analysis of each side, it can be figured out that sunlight from the south and west sides is more intense than the north and east sides. Therefore, it seems logical to have more transparent materials in the north and east comparing the south and west sides. The main aims in the following simulations are to ensure good light quality inside the space as well as maximizing visual connection to the outside by increasing the number of transparent materials.

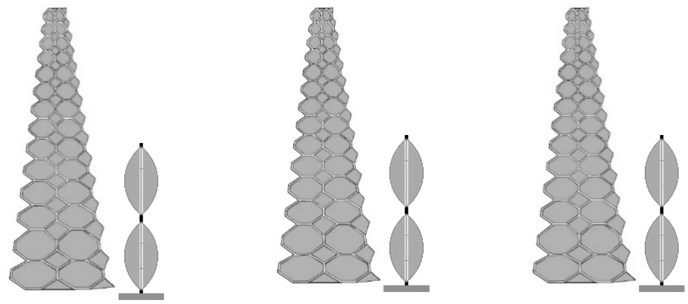
To this end, we start from the northeast side, which might have more transparent materials compared to the other sides. In the process of simulation, the aim is to try to contain as much transparent material as possible for the northeast side while the rest of the sides are covered with translucent materials. As a result of the DIVA simulations, the northeast side panels can be fully transparent (table 2).





Daylight Autonomy	(NE) Fully transparent	(E) No light entry	(SE) No light entry

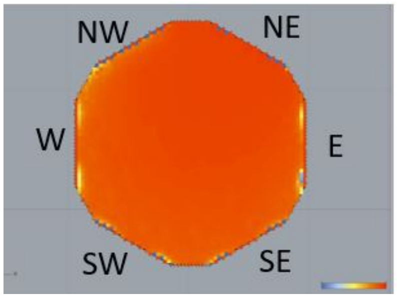
●	Generic translucent
○	Single glaze
sDA	97.4
ASE	7.8
Leed	**0 3**

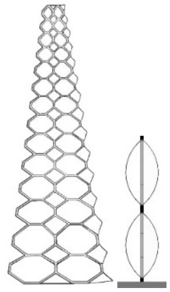


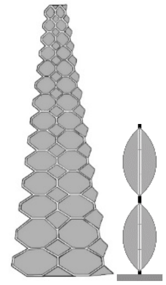
(SW) No light entry	(W) No light entry	(NW) No light entry

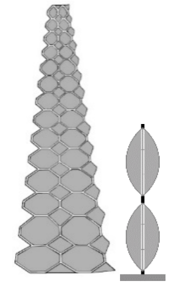
Table 2: Northeast light simulation; source: Author

Based on the design guide chart (fig.21), the next turn is for the northwest side to be tested through simulations. In this series of simulations, the northeast side is fixed with fully transparent materials, and the attempt is to contain as much transparent material as possible for the northwest side while the rest of the sides except the northeast are covered with translucent materials. As a result of the DIVA simulations, the following configuration is achieved (table 3).









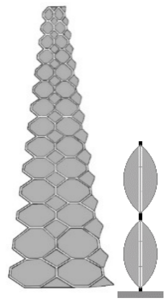
Daylight Autonomy

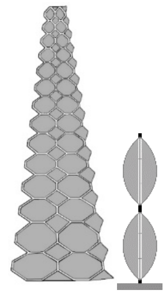
(NE) Fully transparent

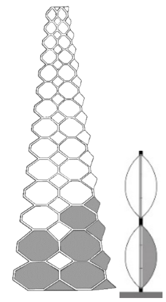
(E) No light entry

(SE) No light entry

●	Generic translucent
○	Single glaze
sDA	99.3
ASE	8.4
Leed	**03**







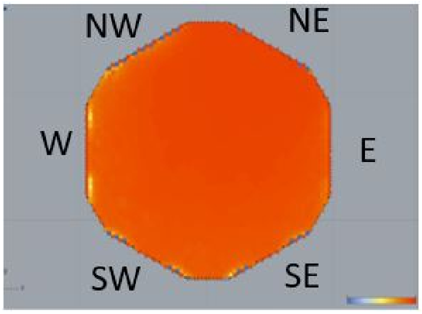
(SW) No light entry

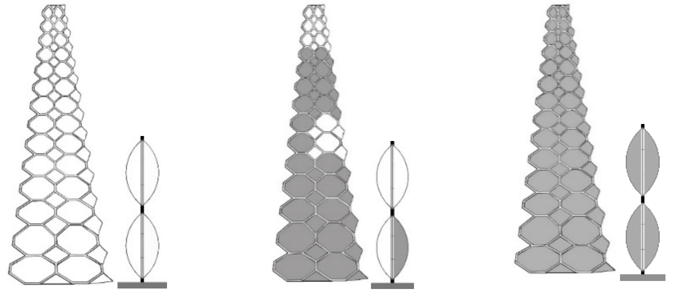
(W) No light entry

(NW) Partial transparent

Table 3: Northwest light simulation; source: Author

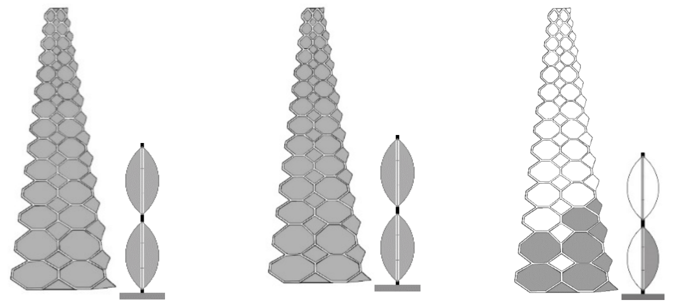
Based on the design guide chart (fig.21), the next turn is for the east side to be tested through simulations. In this series of simulations, the northeast and northwest sides are fixed, and the attempt is to contain as much transparent material as possible for the east side while the rest of the sides except the northeast and northwest are covered with translucent materials. As a result of the DIVA simulations, the following configuration is achieved (table 4).





Daylight Autonomy | (NE) Fully transparent | (E) Partial transparent | (SE) No light entry

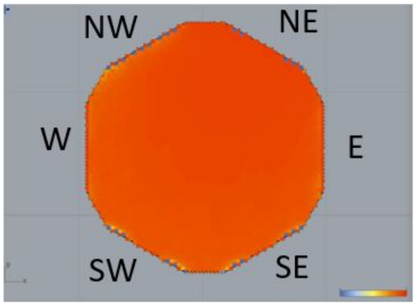
●	Generic translucent
○	Single glaze
sDA	99.3
ASE	9.5
Leed	**03**

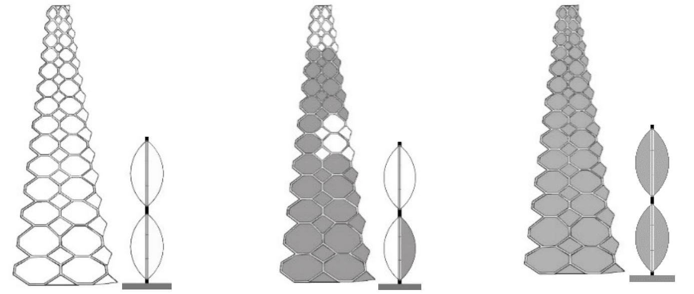


(SW) No light entry | (W) No light entry | (NW) Partial transparent

Table 4: East light simulation; source: Author

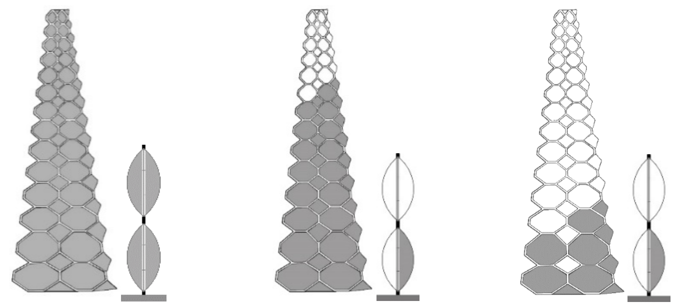
Based on the design guide chart (fig.21), the next turn is for the west side to be tested through simulations. In this series of simulations, the northeast and northwest and east sides are fixed, and the attempt is to contain as much transparent material as possible for the west side while the rest of the sides except the northeast and northwest and east are covered with translucent materials. As a result of the DIVA simulations, the following configuration is achieved (table 5).





Daylight Autonomy	(NE) Fully transparent	(E) Partial transparent	(SE) No light entry

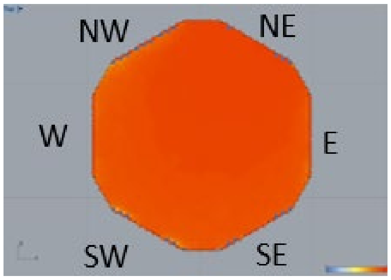
●	Generic translucent
○	Single glaze
sDA	99.3
ASE	9.6
Leed	**03**

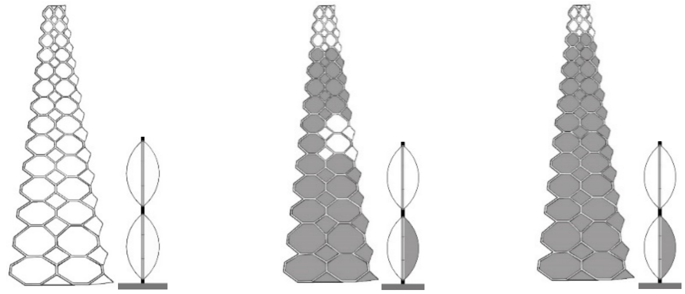


(SW) No light entry	(W) Partial transparent	(NW) Partial transparent

Table 5: West light simulation; source: Author

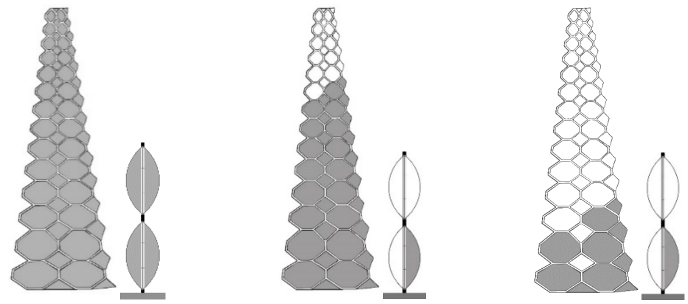
Based on the design guide chart (fig.21), the next turn is for the southeast side to be tested through simulations. In this series of simulations, the northeast, northwest, east and west sides are fixed, and the attempt is to contain as much transparent material as possible for the south east side while the rest of the sides except the northeast, northwest, east and west are covered with translucent materials. As a result of the DIVA simulations, the following configuration is achieved (table 6).





Daylight Autonomy	(NE) Fully transparent	(E) Partial transparent	(SE) Partial transparent

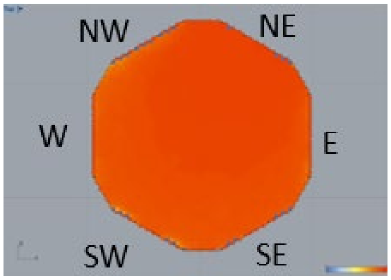
●	Generic translucent
○	Single glaze
sDA	99.3
ASE	9.6
Leed	**03**

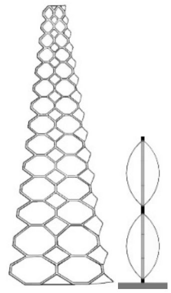


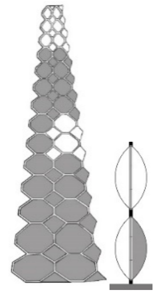
(SW) No light entry	(W) Partial transparent	(NW) Partial transparent

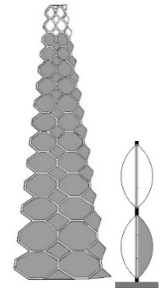
Table 6: Southeast light simulation; source: Author

Based on the design guide chart (fig.21), the next turn is for the southwest side to be tested through simulations. In this series of simulations, the northeast, northwest, east, west and southeast sides are fixed, and the attempt is to contain as much transparent material as possible for the southwest side while the rest of the sides except the northeast, northwest, east, west and southeast are covered with translucent materials. As a result of the DIVA simulations, the following configuration is achieved (table 7).









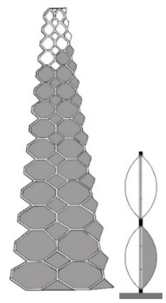
Daylight Autonomy

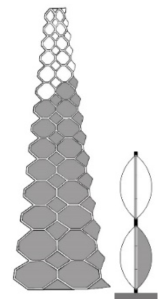
(NE) Fully transparent

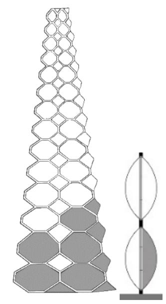
(E) Partial transparent

(SE) Partial transparent

●	Generic translucent
○	Single glaze
sDA	99.3
ASE	9.6
Leed	**03**







(SW) Partial transparent

(W) Partial transparent

(NW) Partial transparent

Table 7: Southwest light simulation; source: Author

The final material configuration from the simulations is the following pavilion:

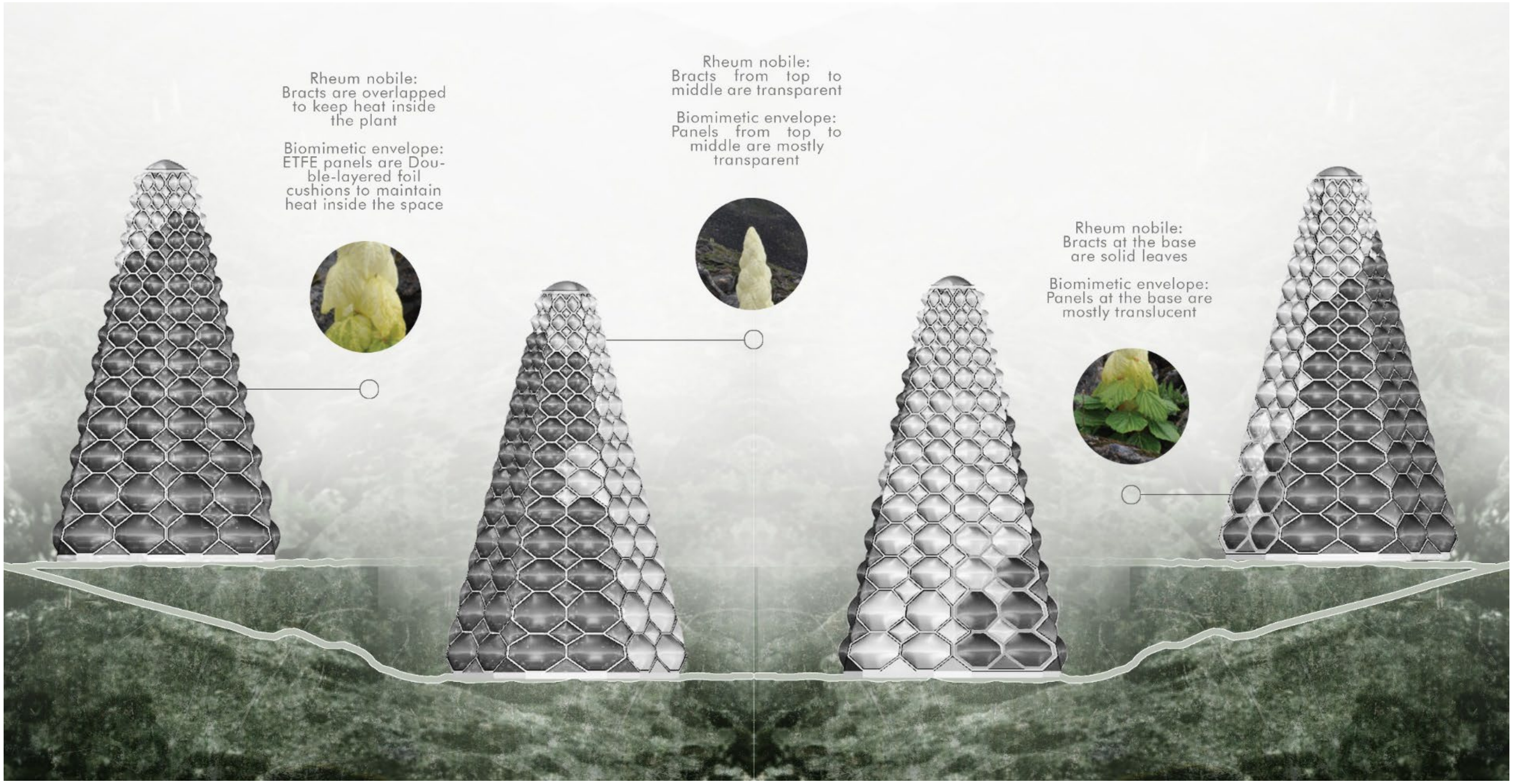


Figure 22: Material configuration; source: Author

3.2 Dynamic version

After reaching this stage, given that everything in nature operates dynamically, we tried to change the system from static to dynamic to increase the ability to adapt to the changing environment.

For this purpose, we analyzed the system in two modes: cold conditions and hot conditions. In hot conditions, there is a need for ventilation and shading system; however, in cold conditions, thermal insulation is required, and the need for a shading system decreases considerably. The following precedent examples were very inspiring in the design process (fig.23 & 24).

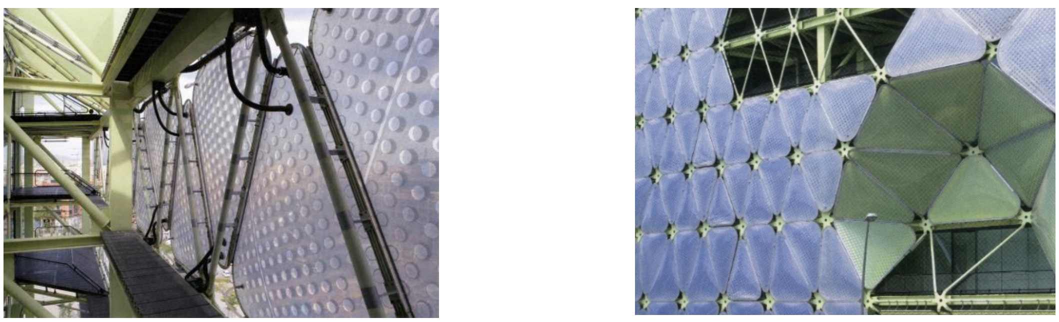


Figure 23: Media-ICT, Barcelona, Spain[8]

Figure 24: Nils voelker: 108 inflatable plastic bags[9]

[8] [Online]. Available at: https://safetythird.wordpress.com/2011/03/10/media-tic-office-building-in-22-barcelona-by-cloud-9/ [Accessed 20 April, 2021]

[9] [Online]. Available at: https://www.designboom.com/design/nils-voelker-108-inflatable-plastic-bags/ [Accessed 25 February, 2021]

After analyzing the previous examples, the proposed idea for the dynamic envelope system is to use inflatable translucent plastic bags that can switch between the inflated mood to the deflated mood depending on the temperature and sunlight changes. In hot weather conditions, the system switches to the deflated mood, which provides natural ventilation through the middle open vent, and the translucent plastic bags filter the incoming light. In cold weather conditions, plastic bags switch to an inflated mood, which creates thermal insulation. In other words, more air accumulates around the ventilation hole, which dramatically reduces ventilation and makes the indoor air warmer than outside. In terms of light, because the plastic bags have changed to inflated, they are somewhat stretched, which allows more light to pass through.

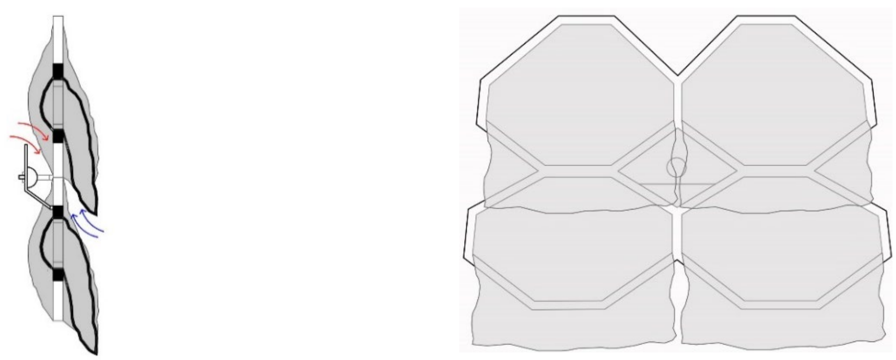


Figure 25: Deflated mood; source: Author

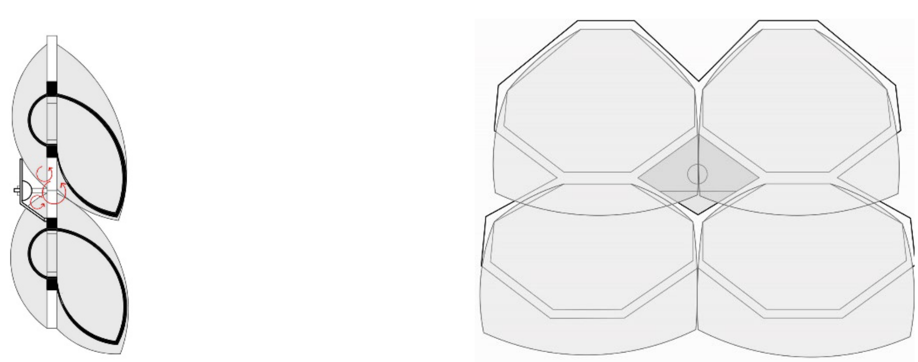


Figure 26: Inflated mood; source: Author

To operate this dynamic system passively, PV panels are assumed to generate the required electricity for the electrical pump to activate the inflation and deflation system. Also, by adding an air pump distributor and light and temperature sensors to each module, each series of panels can operate independently.

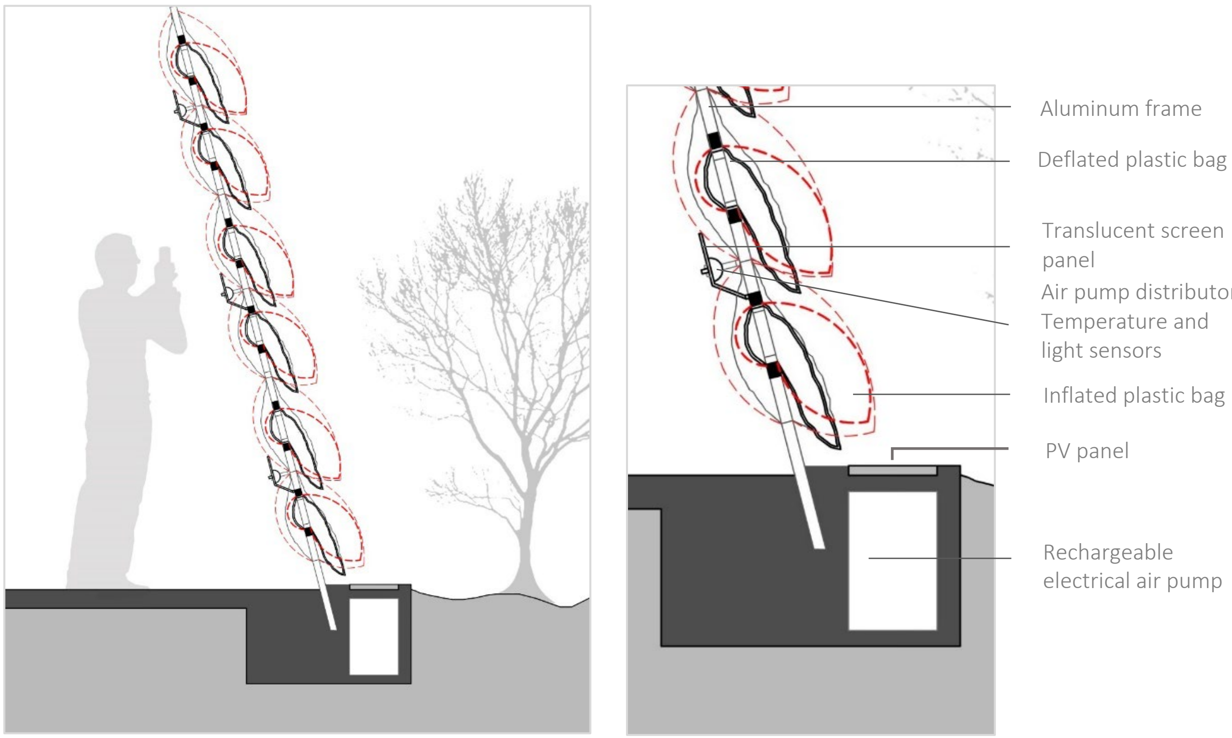


Figure 27: Controlling system; source: Author

As the result of this system, the envelope operates in three modes:

1. Temperatures above 30 ° C: In this condition, the thermal sensors activate the system to switch to deflation mood, which eases the process of natural ventilation. Also, translucent plastic bags can control sunlight and reduce the amount of light entry to provide good light quality inside the space.

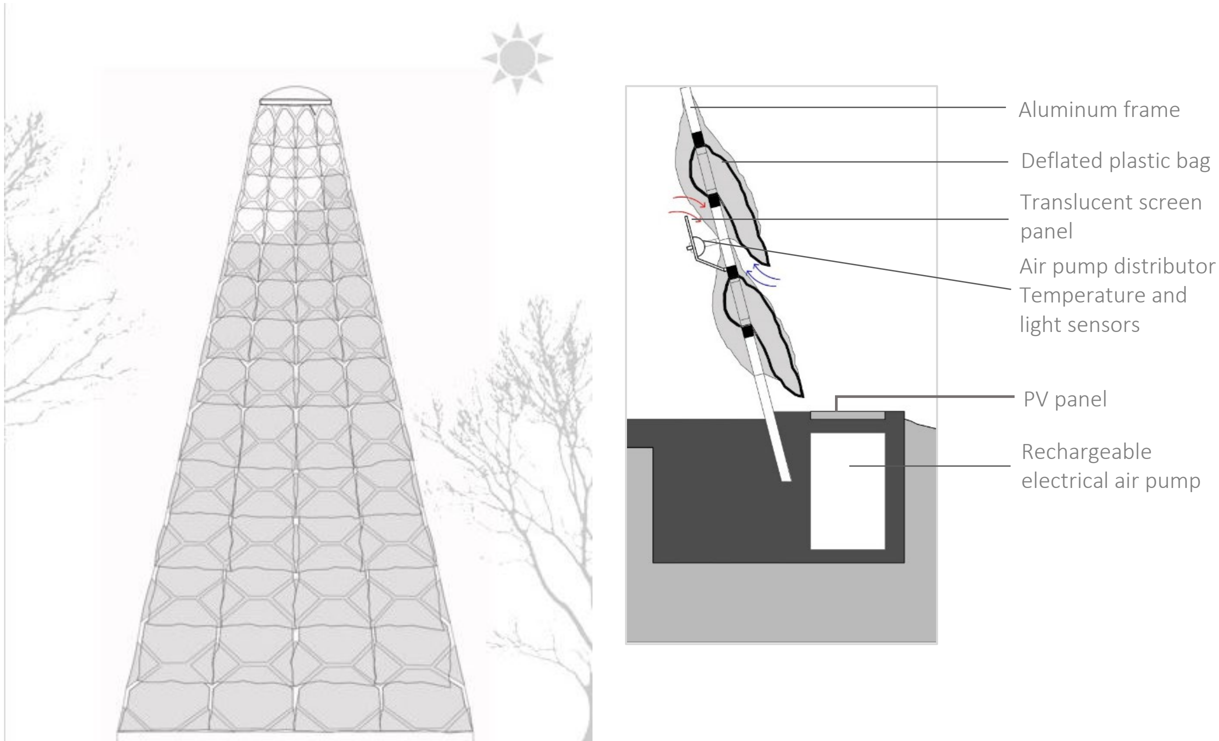


Figure 28: Temperatures above 30 ° C, deflated; source: Author

2. Temperatures under 10 ° C: In this situation, the thermal sensors activate the system to switch to inflation mood, which increases the thermal insulation and keeps the indoor warmer. Also, translucent plastic bags are stretched, which increases sunlight entry.

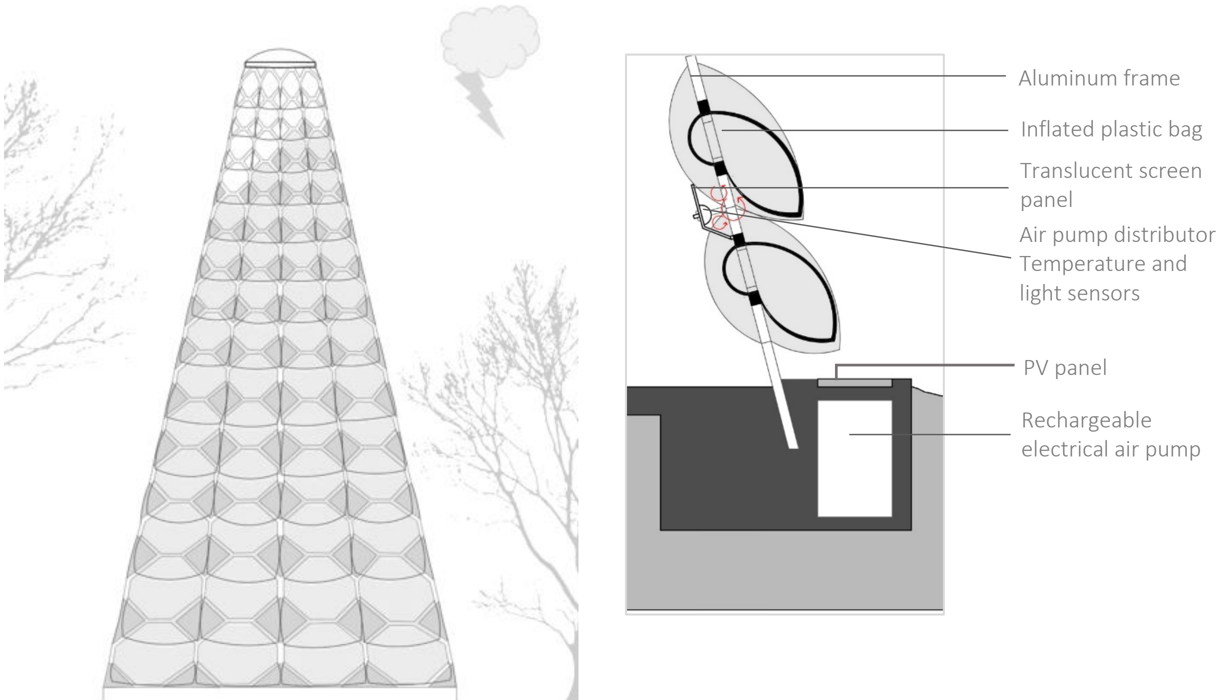


Figure 29: Temperatures under 10 ° C, inflated; source: author

3. Temperatures between 10 ° C - 30° C: In this condition, the light sensors activate the system to switch between inflated and deflated moods, which provides a shading system based on sun movement. Therefore, the panels that face the sun are in a deflated mood, while panels back to the sun are in an inflated mood.

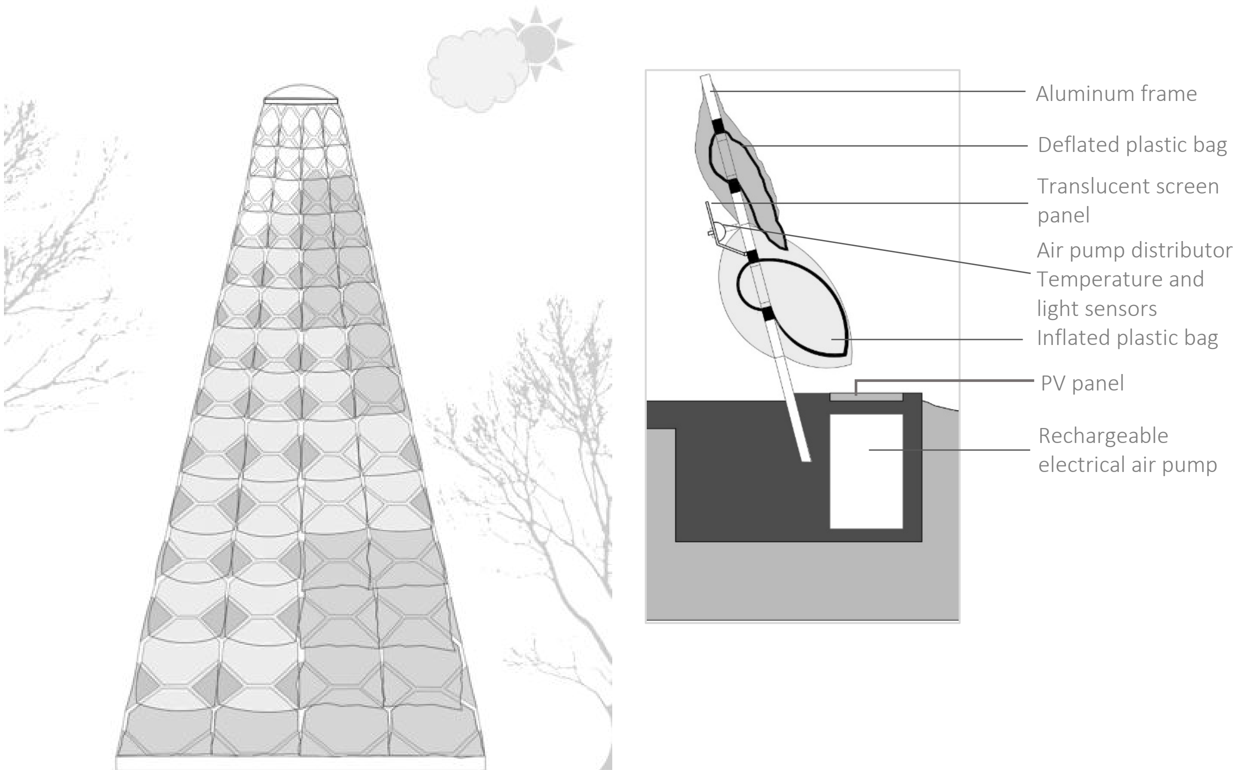


Figure 30: Temperatures between 10 ° C - 30 ° C, partial inflated; source: Author

Figure 31: Visual rendering1; source: Author

Figure 32: Visual rendering 2; source: Author

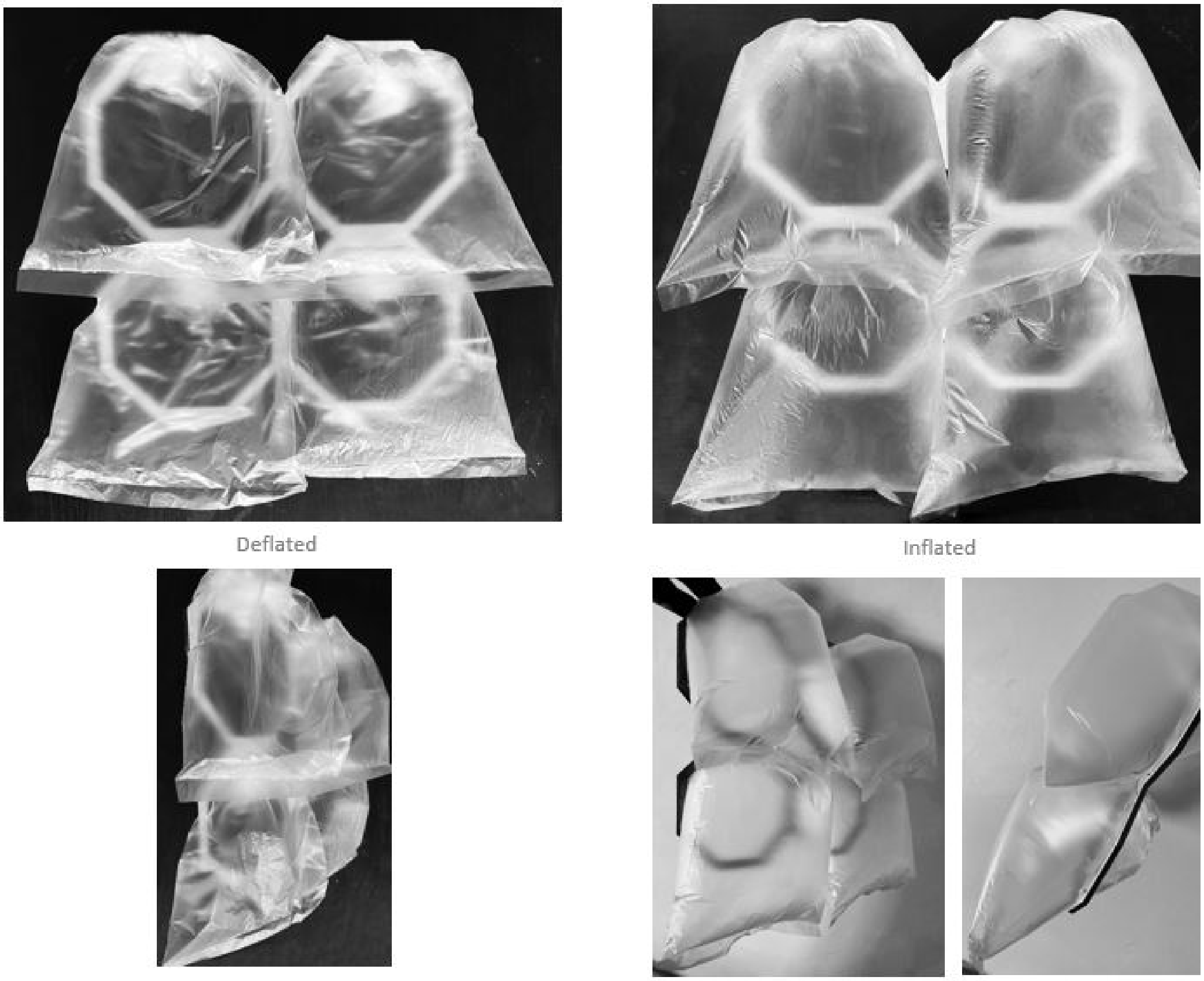


Figure 33: Physical model; source: Author

3.3 Further research development

The proposed envelope system is not limited to the discussed pavilion form or function and can be applied in various shapes and places, such as parking doors or building windows.

Figure 34: Parking door; source: Author

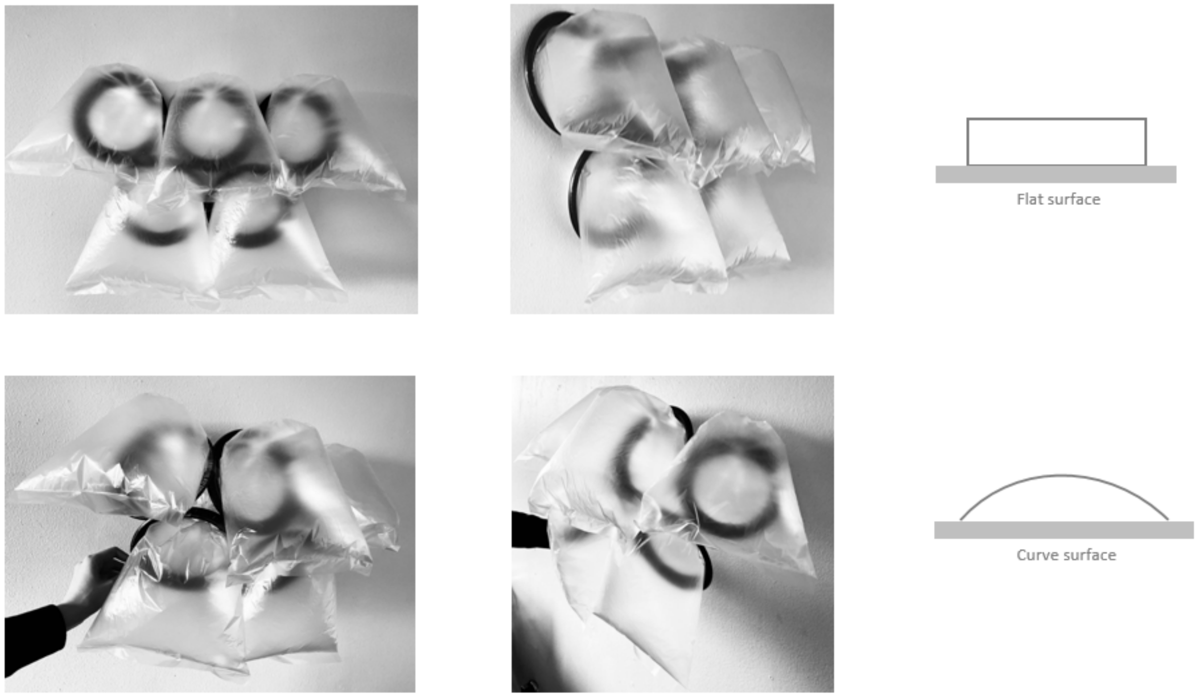


Figure 35: Different pattern; source: Author

Furthermore, there is an opportunity to test the envelope in different locations considering the surrounding buildings, elements, and specific variables, which may impact the form of the pavilion. It means that local context is another important factor that can dictate new ideas and considerations. Also, the idea of passive dynamism is the next spark to shift this envelope idea towards an alive system. The operating system can take advantage of smart materials to run the system without the need for an air pump system and sensors.

Figure 36: Different forms; source: Author

4. Conclusion

By regarding the discussed parts and the proposed biomimetic envelope, it can be concluded that the idea of this bio-inspired envelope is beneficial for reducing the energy consumption of buildings, especially for indoor heating, cooling, and lighting. However, there are significant challenges in the process of biomimetic design. First of all, the source of inspiration needs to be chosen properly from the vast expanse of nature, which requires careful and intelligent understanding both in the field of design and biology. Another challenging part in the process of bio-inspired design is to transform the natural solution to an appropriate solution in architecture that requires intelligent testing and study to achieve a suitable result. As we have seen in this design process, the evaluation step can modify and change the concept idea and move it forward for a better final product. Undoubtedly, the help of computer simulation software is not ineffective for speeding up the testing process. With all these explanations, it can be said that the presented envelope system has high potential to shift us towards more dynamic and responsive systems, which in turn can reduce the energy consumption of buildings for indoor heating, cooling, and lighting.

The proposed design idea can be extended to other forms and for a variety of applications, from the pavilion format to even implementation to a single window. However, the proposed project is not the end of the road, and there are more opportunities to expand this envelope system towards a passive dynamism system.

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