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BIONIC ADAPTIVE FACADE DESIGN

Evaluation of adaptive façade design for bionic envelope system inspired by ladybug wings and its implementation

MASTER THESIS

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ABSTRACT

The current development trend of building exterior enclosure is to achieve a more efficient, smarter and more environmentally friendly and responsive dynamic enclosure system. When the external climate changes and internal user needs change, the dynamic enclosure will change its arrangement and structure to respond to and meet the needs. When exploring the principles and innovations of supporting enclosure systems, bionics is an excellent source of inspiration. Many biological characteristics can complete the ability to respond to external stimuli to transform or resist climate change.

Based on this background, this research aims to study the design process from biometrics to enclosure systems. The research briefly describes the current research progress and the corresponding dynamic enclosure and bionic cases to determine the building's requirements for the enclosure system, the possible form of the enclosure system, and how to realize the design to the demand. Based on these conclusions, we will further explore the appropriate way to transform from inspiration to design, as well as how to select, evaluate, and implement methods.

After completing the theoretical research, complete a specific design to verify the feasibility of the theory. The preliminary design of structure and geometry is completed by the inspiration obtained from the ladybug wing elytra, and the simulation calculation is carried out according to the parametric software to evaluate and select the appropriate enclosure plan. And for the final plan, practical mechanical details and actual model verification are proposed.

CHAPTER 1 Introduction

1.1 Forward

The global climate is warming, and in addition to the carbon emissions caused by industry, transportation, and manufacturing, the use of buildings without proper design can easily lead to excessive use of electricity, which will undoubtedly create higher carbon emissions. As architects and engineers, we are concerned with maximizing natural ventilation, improving the rate of natural lighting, and avoiding the hazards of glare, in addition to making good spatial designs to bring maximum comfort to users. One of the most important legislative instruments aimed at improving the energy efficiency of buildings in Europe is the Directive 2010/31 / EU[1.1]. The key element of this directive is its requirement for nearly-zero energy buildings(nZEB).

In order to achieve energy efficiency, we study roughly two related theories: 1. the development and overview of dynamic building skin 2. the bionic design of buildings. Regarding the dynamic skin of a building, if we compare the interior space of a building, the part that differs from the boundary between the interior and exterior space is called the façade, and it provide various functions in order to give protection and comfort to the interior of the building. The advancement of science and technology has made it possible to realize more and more ideas about building facades, and its multifunctional, interactive and dynamic nature has opened many possibilities for the development of this subject. BIO-Design, as a design method and process of learning from existing biological patterns, behaviors, and ecosystems and applying the results to buildings, has great potential for aesthetics, dynamic orbit, and climate adaptability.

This thesis focuses on the learning of the two related disciplines involved above, specifically, to understand the existing forms and development process of adaptive facade and bionic architecture through papers and case studies, to learn the best design methods and materials used in them, to classify and summarize them, and to experimentally compare the control variables of existing cases to come up with a relatively optimized direction. Based on experimental design, advanced parametric tools are applied to simulate and process the results to obtain more comprehensive experimental results and explore their sustainability and prospects.

It should be noted that the final conclusions reached in this thesis are relatively unique, since it is difficult to follow a uniform empirical and standard rule for defining experimental results and evaluating performance, as experimental designs are usually based on a comparison of control variables for specific geometry, materials and especially for different climates.

1.2 Goal and scope

The above descriptions roughly establish the purpose to be explored in this paper, the disciplines involved, and the general structural framework of the article. After the introduction of the proposed research purpose, we need to briefly define the concept of the object of the paper and its significance.

Building façade is a relatively broad scope, including walls, windows, doors, roofs, etc. As part of the separation of users defining the internal and external space, the design of the building façade is of great significance: from an intuitive point of view, the design of a building façade directly affects the appearance of the building, and its aesthetic influence ranges from small users to large urban planning and design; from a functional point of view, the design of the building façade also has great significance. A good building façade design will bring comfort to the user by providing sufficient natural light, avoiding glare, reducing energy use by improving ventilation, and so on.

In fact, it is difficult to always provide the most efficient care for a building with a fixed skin, because the climate is dynamic, and as the angle of sunlight and temperature changes, dynamic skin is more efficient. Adaptive facades are both multi-functional and highly adaptive systems derived from this need, which can change its function, properties, behavior or change the boundary state to enhance the overall building performance with the diversity climate [1.2]. The object of this thesis is to study the performance of the building skin and to compare the response of the building façade to different climatic changes over the period of a year, based on meteorological data, with respect to the energy savings and user comfort of the building in a given geographical climate.

Up to now, there have been many studies on adaptive façade and bionic architecture. Especially in recent years, as the climate warms up, countries around the world are paying more attention to green buildings, and sustainability of projects is gradually being implemented, but the term "green building" and "bionic design" is too broad, so in this thesis we are going to explore bionic adaptive façade design for energy saving purposes in more depth with the existing knowledge system.

Along with the history of architecture, we can find that buildings in different climates have their own characteristics, but their common goal is to bring the best living and using experience to the occupants and users in a specific environment. Modern buildings are equipped with air conditioning, heating and other technologies that blurred the seasonal patterns in the interior of the building and allow the indoor temperature and relative humidity to reach the most comfortable values for the human body. This leads to the energy burden and environmental demands mentioned at the beginning of this thesis, forcing us to do a sustainable search in this field.

Architects and engineers are exploring effective solutions in their field and as students in building and architectural engineering we hope to use our knowledge to give our thought to this issue.

1.3 Outline

The thesis is divided into eight chapters, including literature reading part, geometric design part, experimental inspection part and mechanical design part.

Chapters 1-3 are the introduction and literature theory part. In the literature theory part, we will describe it from three aspects: adaptive facade, bionic design and inspection and evaluation of sunshade skin.

Chapters 4-5 are the design part from inspiration to geometric design. We got preliminary inspiration from ladybug's wings. After in-depth understanding and research on related structures, materials and motion principles, we designed three potential geometric schemes and the materials and motion mechanisms that can be used in these three scenarios are common.

Chapter 6 is the simulation calculation part, used to verify and confirm the design from Chapter 6. We set up three plans on the selected reference room, and then use the plug-ins ladybug and honeybee in Grasshopper to perform simulation calculations on daylight and energy. And based on this, compare and choose a better plan.

Chapters 7-8 are the introduction to the mechanical principle and the solid model. These two chapters transform the motion mechanism and materials we studied in Chapters 4-5 into a practical mechanical structure and complete the entity that can more closely express the real motion structure. The model serves as a display.

1.4 Statement of working division

In this teamwork, we each played different roles and were able to communicate effectively, which was the main reason for the successful completion of this thesis. Each of us has our own specialties, and we learned from each other in this collaboration so that we could make progress together; Fu is good at literature collection and organization, Lin is good at energy simulation, and Wang is good at the design of mechanical components, and all the chapters in the collaboration are the conclusions we came up with after collaborative discussion.

The literature review and the bionic-inspired section were done together, and the three of us each completed a geometry design of the adaptive façade based on the inspiration to facilitate comparison in the form of data. Fu and Lin are mainly responsible for the Simulation and calculation part, Wang is mainly responsible for the implementation part, and we are jointly complete the solid model.

CHAPTER 2 ADAPTIVE FACADE

Abstract: In this chapter, we will briefly introduce the development and application of the current global adaptive facade, and pay attention to the important parameters of the adaptive facade that affect the building's indoor environment. At the same time, we will conduct research on geometry and movement based on real case analysis. According to the results of collection and learning, a universal design framework for the adaptive facade is summarized and a complete and comprehensive design + inspection process is proposed.

2.1 Introduction of adaptive façade

In this chapter, we start with the introduction of adaptive façades, describe their development and the current level of application of adaptive façades around the world, investigate and analyze the most important factors that affect the energy efficiency of buildings, and learn practical cases based on the results of the analysis, to come up with a comprehensive framework of adaptive façades for this innovative technology.

2.1.1 What is adaptive façade

Nowadays when we talk about adaptive façade, there are few kinds of literature corresponding with: kinetic, interactive, advanced, foldable, While the meaning should be more precise: adaptive façades consists of multifunctional highly adaptive systems, where the physical separator between the interior and exterior environment (i.e. the building envelope) can change its functions, features or behavior over time in response to transient performance requirements and boundary conditions, to improve the overall building performance. [1.2]

Fig. 2.1. Adaptive concept in the literature.

The concept of architectural 'skin' was first proposed in 1981 by architect Mike Davies [2.1], who speculated on the potential of adaptive skin as a kind of polyvalent wall, and in 2006 by Professor Hasselar of the University of Delft in the Netherlands, who first suggested that it could be used as an adaptive wall. A dynamic skin that adapts to the environment, modifying internal and external environments through skin changes; Professor Loonen of the Technische Universiteit Eindhoven (TU/e) introduced the concept of CABS(Climate adaptive building shells) in 2010, i.e. "repeatedly and reversibly altering its functional characteristics or behavior to influence changing performance requirements. In 2013 Prof. Loonen summarized the organization of the adaptive façade system, which is composed of three important elements: sensors, controllers and processors.

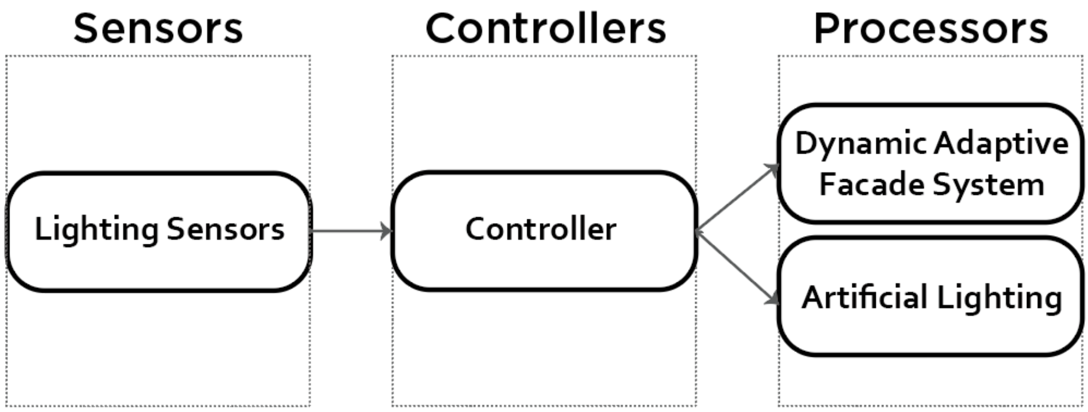


Fig. 2.2. The adaptive façade system composed.

In 2011 Prof. Lienhard J carried out research on smart materials using linear component design and thermal shape memory smart materials; in 2014 Prof. Steffen Reichert of the University of Keplerstraße illustrated the potential of adaptive smart materials by controlling the opening and closing of the skin by moisture absorption of beech wood, but its It is expensive and there are problems with stability and accuracy so smart materials are still far from marketable applications.

However, the development of adaptive façades does not stop there, even before the concept was fully developed, there were attempts by architects, engineers and researchers, such as the Trombe Wall [2.2], a passive solar building design strategy that uses the concept of indirect gain, in which sunlight first hits a solar collector surface that covers the surface of the building at the thermal mass between the sun and the space. Sunlight that is absorbed by matter is transformed into thermal energy (heat) and then transferred to the living space to provide the building with the heat it needs. This shows that building maintenance structures, or building skins, can naturally provide a degree of energy to the interior space of a building if the building skin is properly designed, and has led to a consideration of climate-resilient building components.

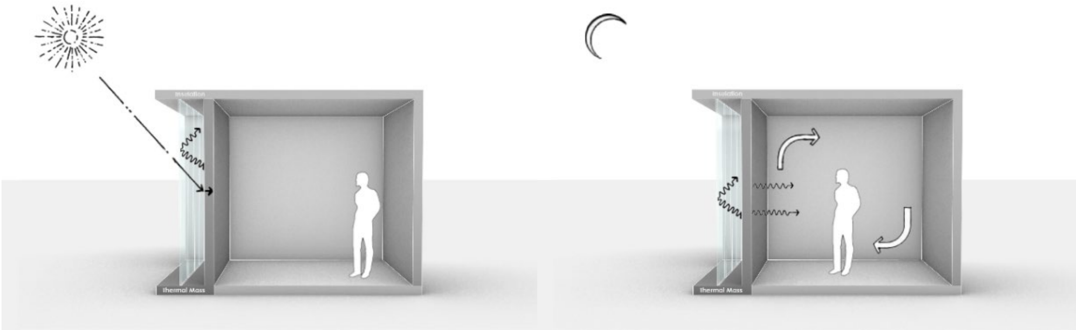


Fig. 2.3. Principle of The Trombe wall. Image credits to https://en.wikipedia.org/wiki/Trombe_wall.

2.1.2 The development of adaptive façade

At the beginning of the 20th century, the famous architect Le Corbusier explored and tested the basic concept of the double-skin façade, which he called mur neutralisant [2.3] (neutralizing wall) and which he used in his Villa Schwob. The concept was developed and refined in later years and is characterized by " The cavity between the two building skins can be in the form of natural ventilation or mechanical ventilation. The solar gain within the cavity can be circulated to offset the heating demand close to the occupants. The well-designed double skin setup improves the energy performance of the building, both in cold and warm climates." [2.4]

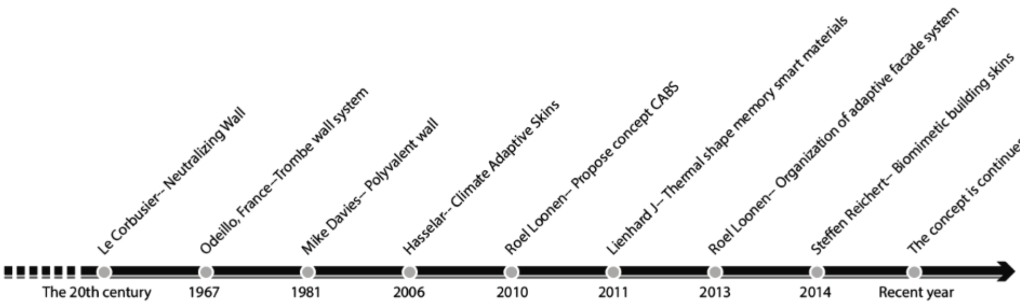


Fig. 2.4. Timeline of the adaptive façade concept.

The development of building skins has been driven by the ability of practitioners to learn from their knowledge base and experience and apply it to the construction industry, and in fact, similar environmental treatments have already been applied to buildings in specific regions. For example, "solar chimney" and "induction vents wall" use simple physical principles to solve the harsh environment of the hot and arid Middle East, providing a more comfortable experience for users. Likewise, in recent years, some bold architects have been able to take help from other disciplines to implement their ideas as technology advances, such as bionics, mechanics, electronics, etc. The interaction of these disciplines has facilitated the development of this field, which is described in the following sections.

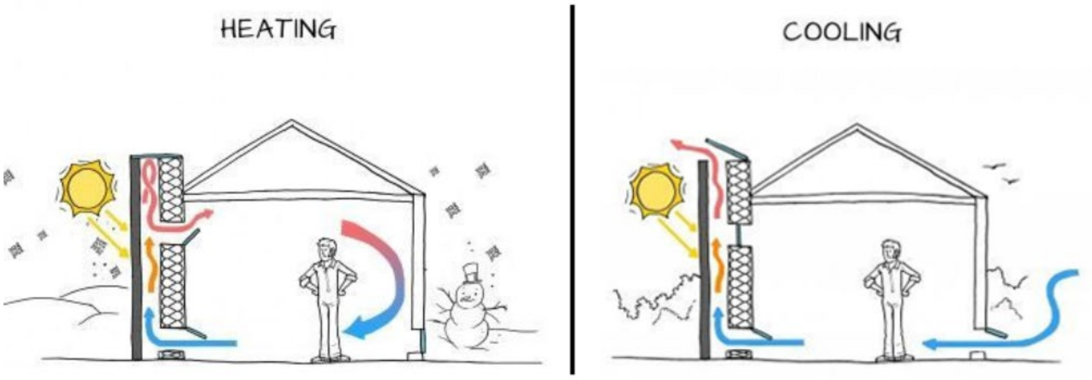


Fig. 2.5. Principle of "solar chimney". Image credits to http://ae390-systemsvariety-group6.weebly.com/solarthermal-chimney.html.

In general, an adaptive façade is a device that changes in response to ambient stimuli in order to ensure optimal comfort inside a building, from the point of view of ventilation, lighting, relative humidity, etc. As many advanced methods have been proposed and referenced, we have been able to see the continued development of adaptive façade in architectural applications, and the following timeline chart provides a brief overview of the history of adaptive façade's elevation.

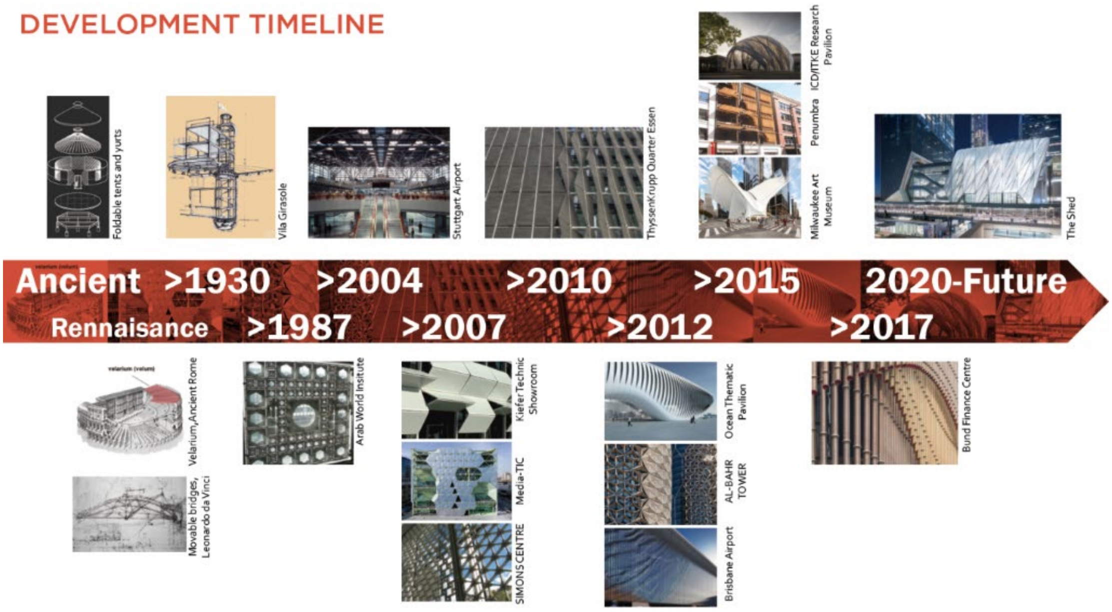


Fig. 2.6. Development timeline of façade from movable to adaptive.

2.2 Classification of adaptive façade

2.2.1 Overview of classification

Since the concept of adaptive facade was proposed, there have been many studies devoted to dividing different concepts of adaptive skin into subsets with the same characteristics. Many existing papers have pointed out this point. After these overview papers, their various classification methods basically revolve around three stages:

1.Stage of environmental information collection(sensor)

2.Stage of environmental information processing(control)

3.Stage of movement controlled by information(deformation)

（R.C.G.M. Loonen [2.12], J.M. Rico-Martinez, F. Favoino, M. Brzezicki, C. Menezo, G. La Ferla, L. Aelenei， 2015）（Design for façade adaptability – Towards a unified and systematic characterization）

The purpose of our research of classification is to assist the skin design and determine a reliable and effective evaluation standard. Therefore, after weighing, we summarized two simplified versions of the classification to organize the classifications proposed in these papers:

1. according to mechanism （movement and driven force）

2. according to response （Information in response to deformation, how to achieve the response (ie. control method), driving force）

2.2.2 ACCORDING TO MECHANISM

Addington and schodek, 2005

Kinetic architecture: buildings, or building components, with variable location or mobility and/or variable geometry or movement

Movement	folding	sliding	expanding	transforming		
Driven force	pneumatic	chemical	magnetic	natural	mechanical	
Control type	internal	direct	in-direct	responsive in-direct	ubiquitous in-direct	heuristic in-direct

Addington and schodek's research on the mechanism of adaptive skin starts from three aspects, namely the change mode, driving force and control mode. [2.5] Their summary of the driving force is sufficiently objective, and other paper authors also have different opinions and further research on the way of change and control.

OTHER CLASSIFICATION OF MOVEMENT

Gianluca Rodonò, 2016 *Kinetic Architecture and Foldable Surface*						
Movement	folding	sliding	expanding	rolling	transforming	

Schumacher, Schaeffer and Vogt, 2010 *MOVE*						
Movement	**Plastic/rigid deformation:** folding; sliding; rotation	**Elastic deformation:** expansion; bending; rolling				

Compared to addington and shcodek's classification on movement schumacher,Schaeffer and Vogt subdivide movement into plastic and elastic deformation.[2.6][2.7] Plastic deformation directly responds to sunlight and reduces radiation through shading. This is what addington and shcodek mentioned in 'driven force' as mechanical deformation. And mechanical deformations are based on the axis of movements and the degrees of freedom. In addition, elastic deformation is a deformation driven by elastic force, like pneumatic force and magnetic force, ETFE is a common facade material that carries elastic deformation.

Maria Anishchenk, 2018 *WOODEN LACE: SMART MEMORY MATERIALS IN DYNAMIC FACADE SYSTEMS*						
Movement	spatial deformation folding; sliding; rotation; reaction	elastic deformation pneumatic; bending; rolling; expansion	non-spatial deformation adaptive material			

Maria Anishchenk, 2018 further increases the classification of materials. [2.8] The driving force can be considered as natural force, that is, the properties and properties of the material itself.

Fox and Yeh, 1999 *M.A. Fox, B.P. Yeh, Intelligent kinetic systems in architecture*						
Property changing	Internal or external stimuli affect the nature of the material	example	color changing materials	phase changing		
Energy changing	Response can be controlled, strength can be adjusted	example	Light-emitting materials, photovoltaic materials	thermo-electric materials	shape memory materials	

Fox and Yeh subdivided variable materials, dividing variable materials into two types: property change and energy change. [2.9] From the perspective of controllability, energy change materials have greater advantages.

2.2.3 ACCORDING TO RESPONSE

INFORMATION FOR RESPONSE

J. Wang, L. Beltrán, J. Kim, 2012 *From Static to Kinetic: A Review of Acclimated Kinetic Building Envelopes*						
Solar responsive	solar heat	solar light and heat	solar electricity			
Air-flow responsive	natural ventilation	wind electricity				

Wang focused on external stimuli. It is believed that the kinetic envelope is similar to the stimulated response of living organisms, responding and moving when receiving changes or stimuli in external conditions. [2.10] The general response sources are solar and airflow, and the sensor transmits deformation instructions to the deformation unit to adjust the envelope when it senses the corresponding conditions.

Ochoa and Capeluto, 2008 *Strategic decision-making for intelligent buildings: Comparative impact of passive design strategies and active features in a hot climate*						
sensor/input elements	**sensors**	light	temperature	glare	solar radiation	
	user interfaces	switches	thermostats			
control elements	**individual control**	light control	shading control	thermal confort	ventilation control	energy control
	schedules	Collect separate controls and form a schedule				
actuating elements	**daylighting system**	shading system				
	fenestration	glazing system				
	ventilation system	window system				

Ochoa and Capeluto's cognition of response includes internal and external stimuli and pays more attention to the response to the internal environment of the building. [2.11] The main sensors should be placed indoors to collect indoor information. This information is used as the basis for response behavior. For indoor information, a series of data needs to be collected including light, temperature, glare, solar radiation, and user feedback should also be taken into consideration. At the same time, for the control method, it is more economical and more efficient to use schedule for overall control than to process each data separately.

CONTROL TYPE

Loonen, R. C. G. M. 2010 *Overview of 100 climate adaptive building shells*						
Relevant	physics	Thermal	Optical	Air flow	Electrical	
Time scales	Seconds	Minutes	Hours	Diurnal	Seasons	
Scale of adaptation	Macro	Micro				
Control type	Extrinsic	Intrinsic				

Loonen's opinion can be used to supplement the control type, and raise the issue of heat, light, wind, electricity, physical driving methods, and the frequency and interval of the sensor/generator. [2.12] Summary: The classification of the response part can be used by us in the testing and evaluation process after the structural design is completed.

2.2.4 FOR DESIGN PURPOSE

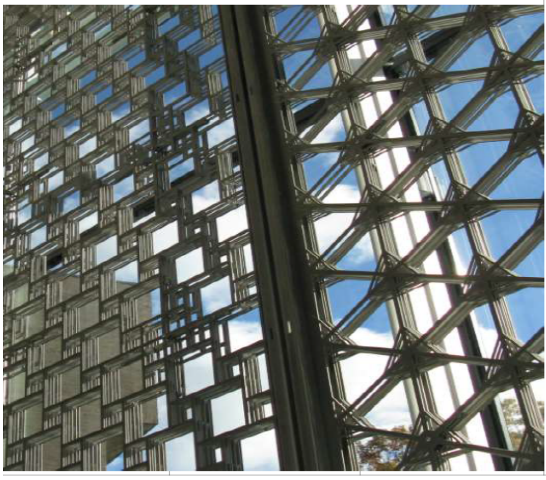
For the purpose of assisting design, we summarized the previous classification methods and carried out adaptive skin classification from the perspective of deformation. The purpose is to use the appropriate classification as the starting point, combined with real architectural skin cases, to establish prototypes with different deformation mechanisms, and to guide us to combine with bionic for the next step of the design. In our classification, all deformations can be divided into two categories:

physical deformation	**plastic deformation**	sliding	
		folding	
		rotating	
		reaction	
	elastic deformation	rolling	
		expansion(pneumatic)	
		bending	
non physical deformation	**adaptive materials**	property change	color/phase···
		energy change	light/thermal/shape memory···

2.3 Cases and Reference

CASE1： SIMONS CENTRE AT STONY BROOK UNIVERSITY

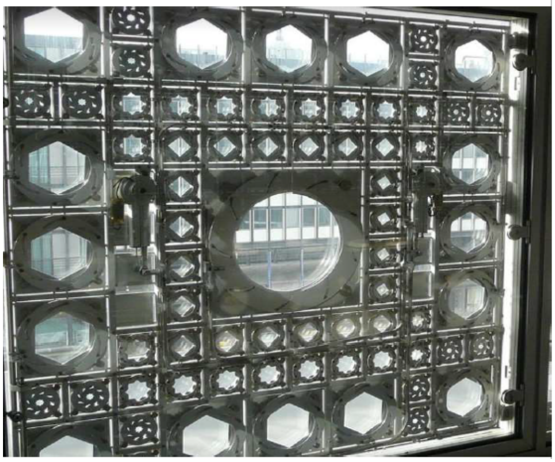
KEYWORDS: sliding, shape combination



Several patterns are featured on the interior of the new Stony Brook Facility, serving as both the building's artistic centerpiece as well as a functional shading system. The floor-to-ceiling metal surface is made by layering four panels manufactured in perforated stainless steel. Three of the layers are motorized to open and close based on temperature requirements. Each of the motorized panels revolve around one another on an engineered track defined by the designed components. The visual effect is like that of a flower, blossoming into a burst of patterns – hexagons, circles, squares and triangles. At one point in the cycle, the perforated patterns all are aligned, allowing the maximum open space. At the other end of the cycle, the pattern becomes an opaque mesh.

CASE2： ARAB WORLD INSTITUTE

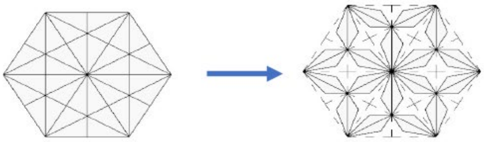
KEYWORDS: reaction



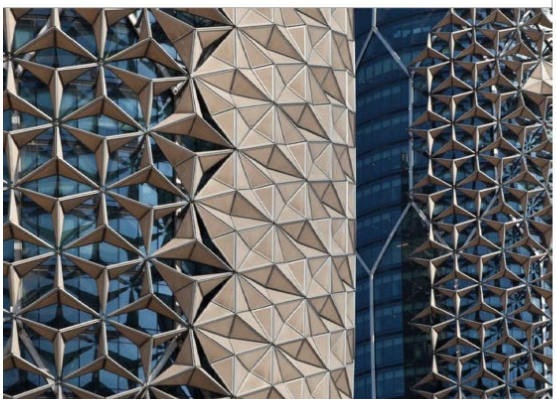
The system incorporates several hundred light sensitive diaphragms that regulate the amount of light that is allowed to enter the building. During the various phases of the lens, a shifting geometric pattern is formed and showcased as both light and void. Squares, circles, and octagonal shapes are produced in a fluid motion as light is modulated in parallel. Interior spaces are dramatically modified, along with the exterior appearance.

While these ocular devices create an incredible aesthetic, they are functional from an environmental controls standpoint as well. Solar gain is easily mitigated by closing or reducing the aperture sizes.

CASE3： AL-BAHR TOWER

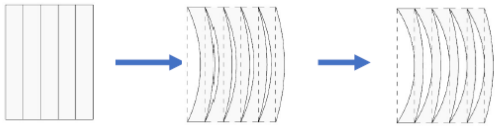


KEYWORDS: folding, parametric, traditional pattern



The distinguishing feature of the towers is their protective skin of 2,000 umbrella-like glass elements that automatically open and close depending on the intensity of sunlight. Inspired by the 'mashrabiya', geometrically-designed wooden lattice screens that have been used to fill windows of traditional Arabic architecture since the 14th century, the 'intelligent' façade of the Al Bahr Towers is dynamically controlled by a building management system. The adjustable shades help reduce interior heat gains caused by sunlight by around 50 percent.

CASE4： OCEAN THEMATIC PAVILION

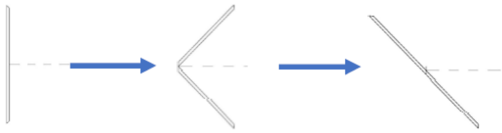


KEYWORDS: bionic, bending

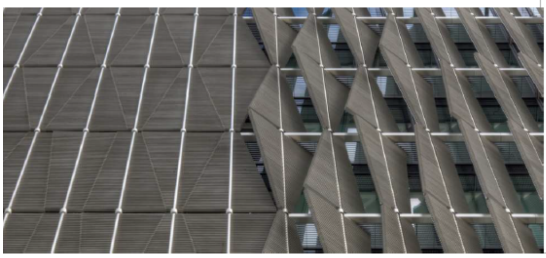
By day, the moveable lamellas of the kinetic facade control the entry of light into the foyer and the Best Practice Area. Individually controlled, opening and closing these in succession allows choreography of wave-like patterns to be created along the entire length of the building.

After sunset, the visual effect of the opening movements is enhanced by LEDs fitted into the inner side of the lamellas. In the opened position, the LEDs illuminate the adjacent lamella. In this way, the bionic principle creates a consistent effect: geometry, material properties, opening angle and light integrate seamlessly into one another; the longer the lamella, the wider the opening angle, the larger the illuminated surface.

CASE5： Q1, ThyssenKrupp Quarter Essen / JSWD Architekten + Chaix & Morel et Associés



KEYWORDS: Metal grille, rotation, folding



The new, highly efficient sun protection system has a key role in the overall appearance of Q1. The circa 400,000 stainless steel lamellas are oriented in response to the location of the sun and enable light redirection without blocking the view.

The two grids of each unit are controlled by a shaft, and the two grids can rotate at the same angle at the same time or at different angles respectively.

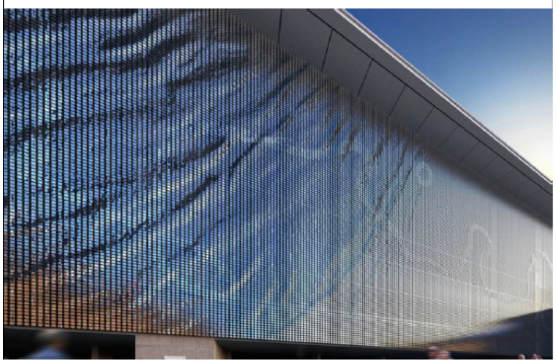
CASE6： Media-TIC / Enric Ruiz Geli

KEYWORDS: ETFE, expansion, pneumatic

Other buildings using ETFE such as Grimshaw's Eden, a microclimate space, or the illuminated Allianz Stadium in Munich by Herzog & de Meuron are iconic statements, but the Media-TIC has a system of distributed intelligence with 300 sensors. 104 of these are connected to the façade to enable the ETFE cushions to respond in diaphragm or fog mode, adapting the building to light changes and for energy saving.

CASE7： UAP + Ned Kahn to create kinetic artwork for Brisbane Airport

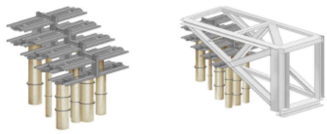
KEYWORDS: natural/wind reaction, free moving



Artist Ned Kahn has designed an aluminium façade which fluctuates with the movement of wind while masking the side of a car park in Brisbane, Australia.

The new façade is swathed with 117,000 suspended aluminum panels. Bolted to a steel substructure, the panels hang eight storeys and cover an area of 5000-sq-m. Hinged at one side only, the individual panels are encouraged to shift in accordance with the air current to reveal complex patterns of wind turbulence.

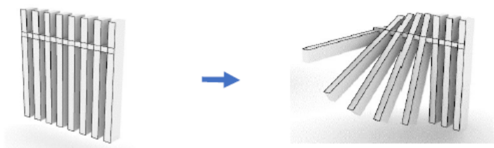
CASE8：Bund Finance Centre / Foster + Partners + Heatherwick Studio



KEYWORDS: traditional pattern, sliding

The building is encircled by a moving veil, which adapts to the changing use of the building and reveals the stage on the balcony and views towards Pudong. Developed in collaboration with local engineers Tongji University, the façade is a veil organised along three tracks and made up of layers of 675 individual magnesium alloy 'tassels' – a reference to the traditional Chinese bridal headdress. The tassels range in length from around 2 metres to 16 metres so that as each track independently moves, the veil rotates with the tassels overlapping and producing different visual effects and levels of opacity.

CASE9：Penumbra – A Kinetic Daylighting and Shading System



KEYWORDS: louvers, rotation

This project was designed to offer a kinetic and mechanical solution to a problem that would otherwise be nearly impossible to solve with static architectural components: providing shading across a building facade for both low evening sun and high afternoon sun conditions. The solution was a series of vertical shading louvers, that can independently pivot to maximize solar protection, and when the sun reaches an altitude in which vertical louvers would be ineffective, completely rotate upwards to act as a horizontal shading element and light shelf. All of the mechanical components and gear ratios were fully resolved, and the result is a hand or computer-operated system that creates a beautiful undulating

CASE10: Kiefer Technic Showroom / Ernst Giselbrecht + Partner

KEYWORDS: folding, aluminum panel

The shell construction of the facade consists of solid brick walls, reinforced concrete ceilings and floors, and steel encased concrete columns. The facade consist of aluminums posts and transoms with protruding bridges for maintenance, with an EIFS-facade in white plaster. The sun screen operates on electronic shutters of performated aluminum panels.

2.4 Typology study of the geometry (folding focused)

After studing previous references and cases, we tried to build a typological model of adaptive façade through summarizing, collating, analyzing and extending research. This typological study includes plastic deformation and elastic deformation, and the change of materials is not within the scope.We believe that for each type of deformation, there is the same internal transformation logic and combination. We hope to explore the shape, structure and possibility of our future design through this method. In our research, each type of deformation corresponds to a core shape that guides the change. At the same time, due to the functional limitations and control accuracy requirements of the façade, the unit skin can be considered as the optimal or even the only solution. Any transformation must also consist of several basic graphics as units or constituent units to form the entire skin.

For basic shapes, we think there are four types that need to be discussed:

1. Square

2. Parallelogram (diamond)

3. Triangle (Equilateral triangle, right-angled triangle mainly)

4. Hexagon

For the guiding shape, each kind of deformation corresponds to one:

1. Folding: symmetrical folding Folding axis: symmetrical deformation on both sides of the axis, there are two ways of change: 1 degree of freedom, 2 degrees of freedom; single axis, double axis, three axis. Asymmetric folding: asymmetric folding on both sides of the shaft

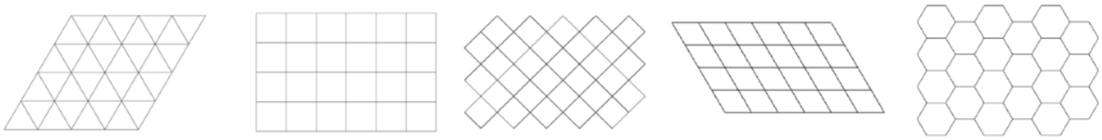
2. Rotation: Rotation point or axis: point: horizontal rotation, axis: vertical rotation

3.sliding: sliding axis: same direction, different direction

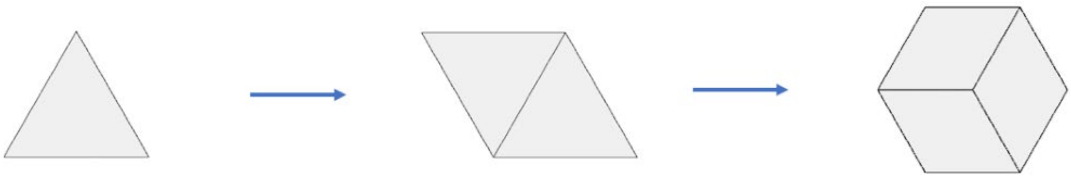
4.reaction: center point (circular)

Among them, since the deformation mechanism of folding is changeable, including different deformation and combination methods such as rotation and reaction, we will focus on the exploration of folding and sliding. Since the part of rotation and reaction is also involved in folding, only a brief description is given.

2.4.1 Basic Unit Shape



When designing a variable skin, the division of units is an important part. Only by dividing the facade into multiple small units can it be possible to carry out precise and appropriate control. The shape and size of the divided units are what we need to study. When we differentiate a rectangle (that is, ignoring boundary errors), there are generally four basic element graphics that may be used: square, triangle, parallelogram (rectangle, rhombus, etc.), and hexagon. Similarly, for the division of the skin facade, it is also reasonable and feasible to study these five shapes as the basic graphics. As shown in the figure above, under the condition of the same size of each unit, there are the above five division methods (these five only represent the basics, and there are also the possibility and demand for heterogeneous and mixed use)



At the same time, among the four basic types, triangles, parallelograms and hexagons still have this cumulative and progressive relationship. Therefore, just using the same basic type can also form a variety of different facade compositions. At the same time, the grouped combination unit has certain advantages in terms of control, which can effectively save the number of sensors and the complexity of the control device.

2.4.2 Folding Study

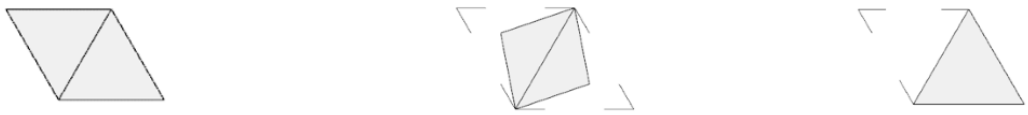
After case analysis and actual origami exercises, we have made a series of conclusions on the principles and methods of folding: The folding motion mode is based on the folding axis as the core, and there can be many folding motions starting from the axis. We used the parametric modeling method of Grasshopper to sort out the different forms of, and obtained two classifications of folding modes:

1. Symmetrical folding

2. Asymmetric folding

Symmetrical folding: Symmetrical folding means that the objects on both sides of the axis are of the same shape and the axis is mirrored at the same time. Take the simple folding of a parallelogram as an example, as shown in Figure 1, the triangles on both sides of the axis are folded toward the axis at the same time. Symmetrical behaviour also produces symmetrical shapes.

Asymmetric folding: Asymmetric folding is the opposite of symmetric folding. The folding behaviour of the objects on both sides of the axis is not mirrored, and the shape of the object can be different. As shown in Figure 2 below, only the triangle on the left side of the axis performs the folding behaviour and folds to the right half.



SYMMETRICAL FOLDING

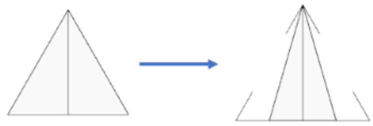
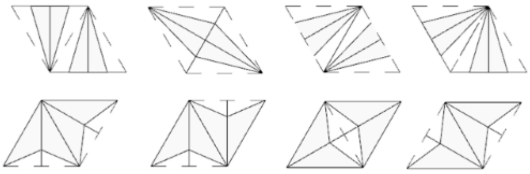
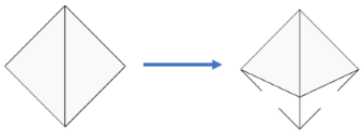
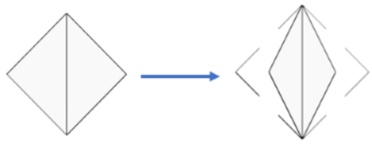
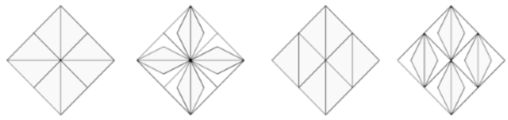
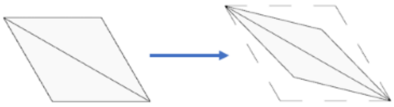
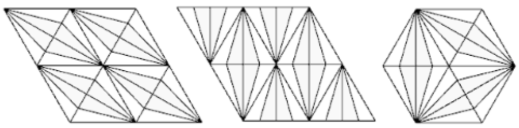
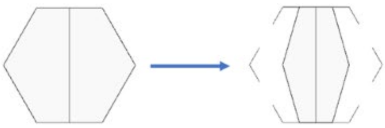
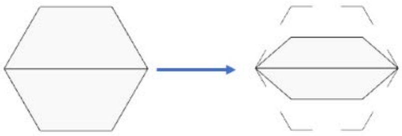
For symmetrical folding, since both sides of the shaft have the same shape and the same movement mode, it is a simple and easy-to-operate system that can well match the needs of adaptive skins. Most folding skins fall into this category. In symmetric folding, we need to study and focus on two points: 1. Axis 2. Movement mode

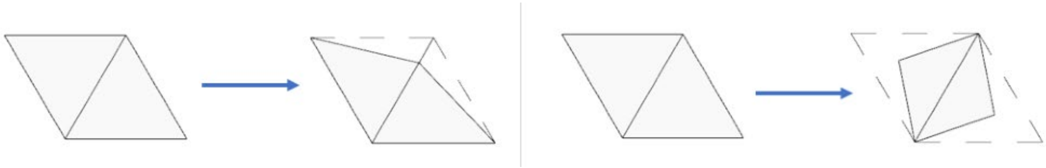
First, the research on the folding motion mode starts from a basic square, and the folding axis is the diagonal of the square. From the figure below, you can find that there are two different folding modes:

1. Folding with movement of folding axis 2. Folding with fixed folding axis

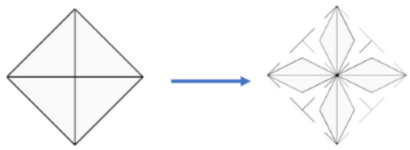
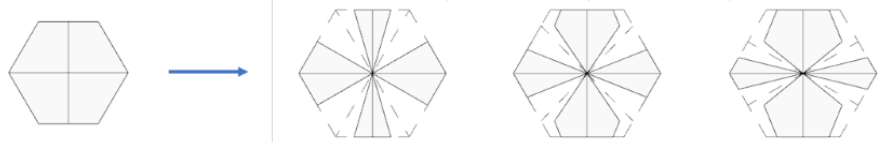
If we analyze these two different motion modes from the principle, we can think that the folding deformation of the movement of the folding axis, in which two sides of the single-sided figure need to be fixed to the connection (one side and the folding axis), and for the folding deformation whose folding axis is fixed, only one side of the single-sided graphics needs to be fixed (folding axis), and the other two sides can move freely. Therefore, we are more inclined to distinguish these two kinds of deformations according to degrees of freedom. Folding with a moving folding axis is a single degree of freedom folding and folding with a fixed folding axis is a folding with two degrees of freedom. According to this standard, we further carried out typological research on the shaft. According to the number of shafts and the connection method, the situation can be roughly divided into the following:

First, we pay attention to the internal changes of a unit, assuming there is only one folding axis inside the unit (the folding axis currently is generally the axis of symmetry)

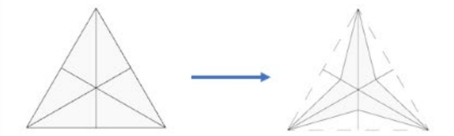
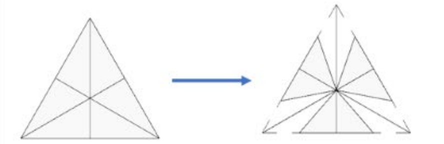
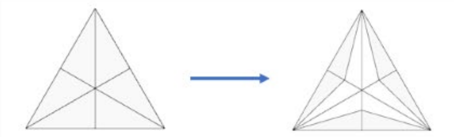
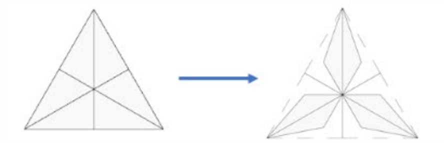
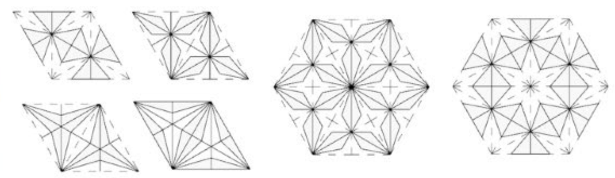
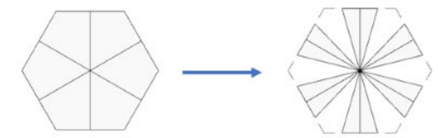
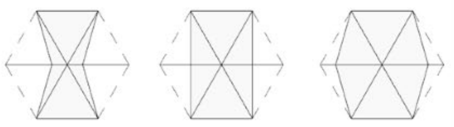
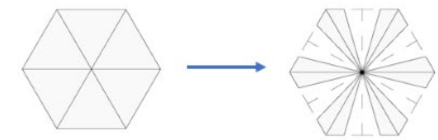
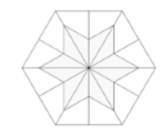
Single axis	Single degree of freedom	Double degrees of freedom
Triangle		
	Taking triangles as the basic unit can form a variety of different combined folding systems. Here, taking the upper-level system diamond of triangles as an example, two identical triangular units can form a group. If different triangular units are used to combine, It can form more diverse diamond folding systems	
Square	/	
	Single-degree-of-freedom folding is only applicable to the folding pattern of the triangle pattern (the other odd-numbered side patterns are also possible, but considering the overly complicated pattern and the effect on the skin is small, so it is not considered)	
		
	Similarly, the square as the basic type can also form a variety of higher-level systems, here only the simplest combination system is shown	
Parallelogram		
		
	As the superior system of triangles, parallelograms can also be used as units to form higher systems: larger parallelograms and hexagons	
Hexagon	/	
	/	



These folding changes in the uniaxial case can be considered as the basis of all folding changes, and the remaining changes can be a combination of a single basic change or a combination of multiple basic changes. In addition, when the number of folding axes changes in a unit, different folding shapes will also occur. Below we will list the folding shapes when the number of axes in a unit change:

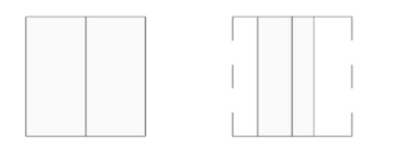
Dual axis	Single degree of freedom	Double degrees of freedom
Triangle	For triangles, there is no situation that symmetrical folding can still be satisfied in two axes. Only in the case of asymmetrical folding can there be two folding axes in a triangular unit.	
Square		
		
		Two-axis folding can be regarded as a simple combination of basic shapes, and different combinations will produce different shape results. The above pattern is the case of folding from the outside to the inside, and the figure on the left is the case of folding from the inside to the outside. .
Hexagon	The shape that a hexagon can be folded under the condition of two axes is not a conventional basic shape. Therefore, we use this as a simple example of unconventional shape folding. The figure below is a case of folding a hexagon. From left to right, the folded graphic changes with the position of the dividing line. The position of the dividing line can also be used as a starting point to study the influence of the shape on the skin performance.	
		

The nature of multi-axis can be considered as the folding change caused by the logical combination of multiple basic transformations (controlled by the axis). Under the classification of the two-axis, we can already see this commonality. In the next three-axis and in the multi-axis enumeration, this point will be clearer.

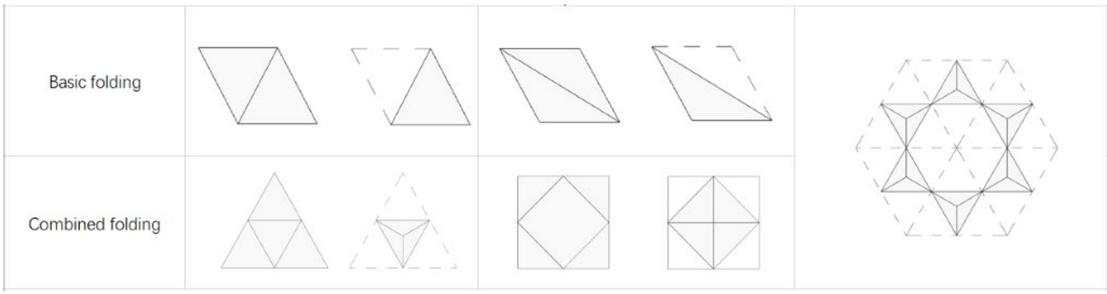
Three-axis	Single degree of freedom	Double degrees of freedom
Triangle		
		
	For triangles, the three-axis form is the most morphologically reasonable folding method. The form of the combined unit using this as the basic unit continues the order and beauty of the triangular unit, and from the perspective of the aesthetics of the facade, this form is an excellent alternative.	
Square/Parallelogram	Just like the two-axis of a triangle, for a quadrilateral, the three-axis is non-ordered, so it is difficult to have a reasonably applicable folding shape	
Hexagon	/	
		
Multi-axis	With the increase in the number of axes, the folding form must develop in a more complex direction. The previous folding principle will still be followed, but the generated graphics may be too complicated for us to design the skin, so we will not continue the discussion. However, there are also ordered patterns like the picture on the right when the number of axes is high, but this pattern is usually composed of simple basic units, so we need to focus on the combination of basic graphics.	

ASYMMETRIC FOLDING

The folding modes of the two sides of the asymmetric folding axis are different, and even the shape can be different. Therefore, there are two classifications of asymmetric folding. One is the folding axis, which is the axis of symmetry. And based on symmetric folding, the folding angles of the two sides are different. The second is that the shapes on both sides of the shaft are also different. In the actual facade design process, the second type is difficult to use due to irregular shapes. Generally, it is not a systematic use, but a special design based on actual conditions, so we will not discuss it. The first type of folding angle is the mainstream folding method.

	Left: The folding axis is the axis of symmetry Right: The folding axis is not a symmetry axis	

Since this folding method can also be regarded as an extension of symmetrical folding, the combination and foundation discussed in symmetric folding can also be applied to asymmetric folding. We will not expand the discussion, but only show several basic deformation methods. As an example:



In summary, asymmetric folding can be regarded as an upgraded version of symmetric folding, which may increase the difficulty of control, but it is a very good choice under the requirements of control accuracy and special needs. In the design process, we can start with symmetrical folding, and then make special adjustments to special functional requirements by changing the folding angle and changing the folding shape.

2.4.3 Conclusion

After conducting typological research on deformation, we have obtained the above-mentioned series of possible situations. In actual design, we can draw inspiration to these movements and shapes, and combine reality to obtain a better design plan. In addition to the mechanical movement plastic deformation, we discussed above, the use of wind, pneumatic, and thermal elastic deformation is also a good way of movement.

When designing, the ideal design process should be: get the general motion mechanism or shape according to the inspiration, translate the motion mechanism and shape into basic motion units or basic shapes, and combine and change these basic motion units or shapes. After obtaining a reasonable basic façade unit, consider the overall and unification. After completing the above-mentioned structural design process, the next step of analysis and simulation experiments can be carried out.

2.5 How to Evaluate Adaptive Facade

As stated, adaptive façade is a functional building skin and its evaluation criteria are influenced by a variety of factors, so it is important to understand the specific environmental factors to which adaptive façade is influenced, and the ways in which adaptive façade can enhance the performance of a building compared to a standard building skin. The first and most basic requirements are the same as for any other building component, such as: stability and mechanical strength, health and safety of occupants, pollutants' emission and fire resistance of materials etc. Moreover, in many urban areas, the building skin often has the greatest potential for integrating renewable energy components such as solar PV, thermal, piezo-electric, etc. From the user's point of view, building window views, proper sound levels, thermal comfort and air humidity, ventilation and glare issues all need to be evaluated appropriately. From the user's point of view, issues such as building window views, appropriate sound levels, thermal comfort and air humidity, ventilation and glare need to be assessed appropriately.

The key element of the Directive is the requirement for nearly zero energy buildings (nZEBs)[1.1], which utilize very little energy from renewable sources. Performance of Buildings Directive (consolidated version) requires all new buildings to be nearly zero-energy by the end of 2020. All new public buildings must be nearly zero-energy by 2018. Moreover, in the context of nZEB[1.1], where the buildings must be interactive in zero energy and smart city context to provide the operational flexibility needed to avoid or minimize the Given the complexity of the topic and multiple variables affecting the performance of these systems, the collaborative COST Action TU1403 [2.13] was organized in four Working Groups.

Given the complexity of the topic and multiple variables affecting the performance of these systems, the collaborative COST Action TU1403 [2.13] was organized in four Working Groups:

WG1: Adaptive technologies and products.

WG2: Component performance and characterization methods.

WG3: Whole building integration and whole-life evaluation methods of adaptive façades.

WG4: Dissemination and future research.

The present study is part of the work developed within WG1 - Adaptive technologies and products - of which the major objective is the development of novel adaptive façade technologies, materials and systems.

According to the scientific program COST TU1403 [2.13], in order to evaluate adaptive façade, it is necessary to define the technology and its purpose prior to testing. As shown in the figure 2.7, the following are listed horizontally: purpose, responsive function, operation, components, response time, spatial scale, visibility, degree of adaptability. The bubbles under each column list what is covered in each column and the hierarchy, and this table allows us to think more visually about the characterization parameters of the adaptive skin.

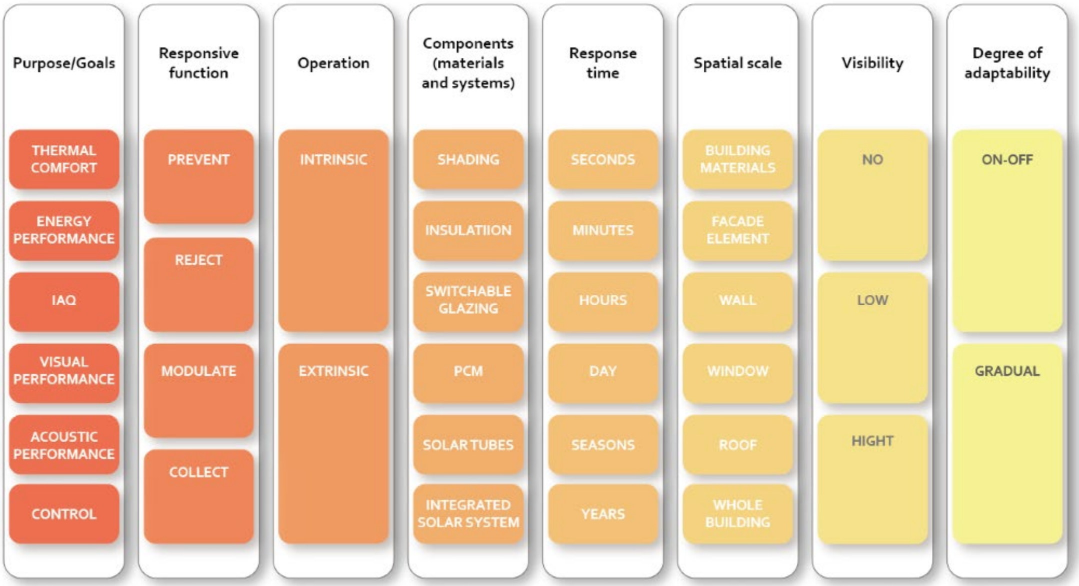


Fig. 2.7. Overview of characterization concepts for envelope adaptivity. Image referenced from Daniel Aelenei, Adaptive Façade: Concept, Applications, Research Questions.

To further investigate the specific effects of external factors on the building facade, Daniel Aelenei et al. introduced a representative sample of 130 buildings distributed under different climatic characteristics according to the Köppen Climate Classification. The internal environment is judged according to thermal comfort, energy performance, IAQ (indoor air quality), temperature, temperature, humidity, humidity, precipitation and noise. air quality), acoustic performance, visual performance and durability.

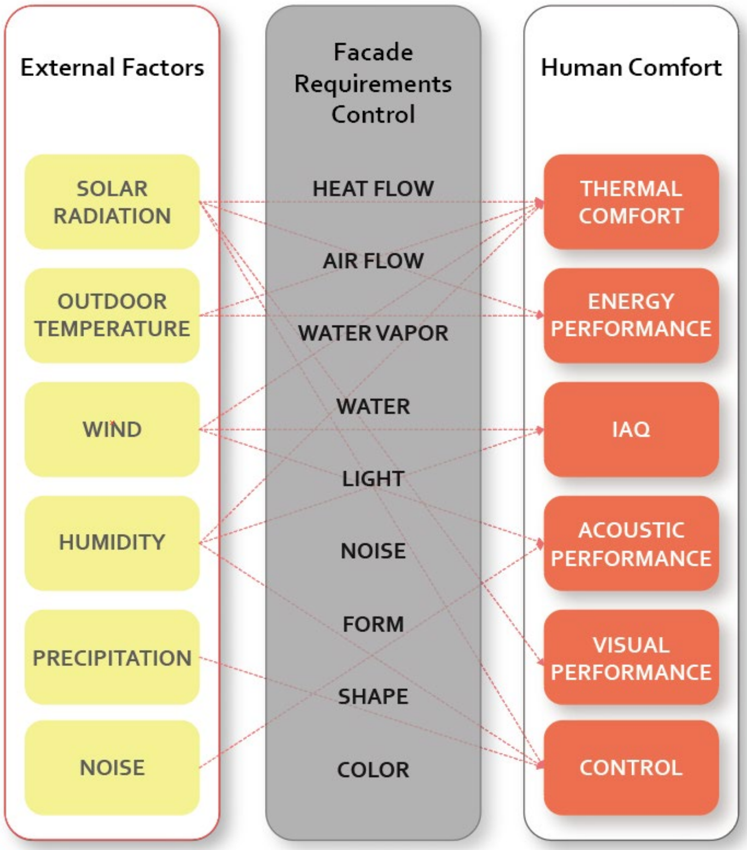


Fig. 2.8. Schematic role of adaptive facade. Image referenced from Daniel Aelenei, Adaptive Façade: Concept, Applications, Research Questions.

2.5.1 DAYLIGHT FACTOR

About 50 years ago, the daylight factor (DF) was proposed as the metric that would better define the daylight assessment of buildings, and right now it is the required metric to calculate by many codes: the daylight factor is defined as the ratio between the illuminance measured at a certain point inside a room and the illuminance measured outside without presence of any obstruction, evaluated under overcast sky conditions and assuming a constant distribution of the sky brightness. It can be formed as:

$$DF = (E_i / E_o) \times 100\%$$

where, E_i = illuminance due to daylight at a point on the indoors working plane, E_o = simultaneous outdoor illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky.

DF is best considered as an indicator of room performance when the sky is overcast. But it is very sensitive to some assumed parameters such as windows' visual transmittance.

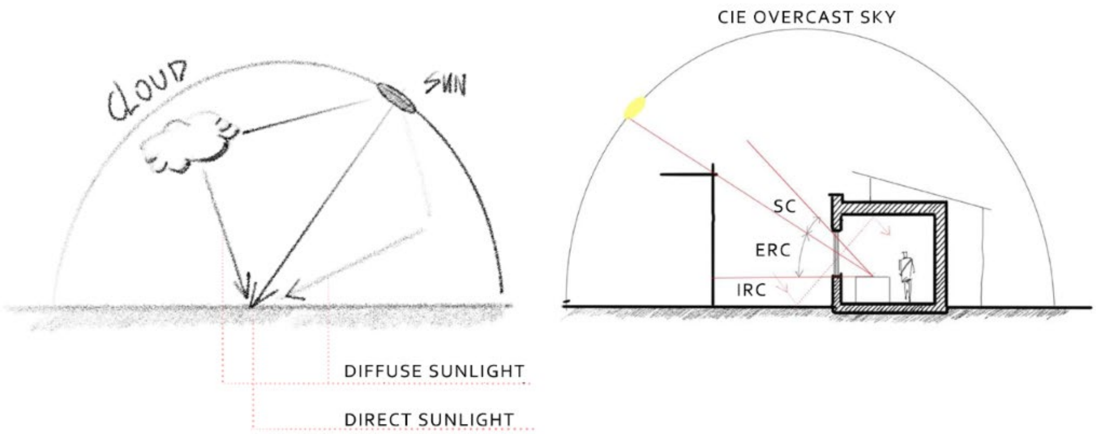


Fig. 2.9. Daylight factor (DF).

In recent years, a new climate-based analysis method has been proposed as an alternative to the DF method: climate-based daylight modelling (CBDM) is effective because it relies on realistic sun and sky conditions defined by typically registered values incorporated in weather files, allowing to generate and analyze new metrics such as the daylight autonomy (DA), the useful daylight illuminances (UDI), the spatial daylight autonomy (sDA), etc.... And this evaluation brings to very similar final results.

The Spatial Daylight Autonomy (sDA) uses an hourly illuminance grid on a horizontal working plane to check if the space receives enough daylight per year during standard working hours (8:00 a.m. to 6:00 p.m.). Instead of collecting one year's data in the field, sDA is calculated through a computational simulation with precise parameters.

Floor areas or grid points in the building model that reached 300 lux for at least half of the analysis time were considered to meet the daylighting threshold. As a result, the sDA value can range from 0% to 100% of the floor area under discussion. 75% of the sDA value indicates a space where the user "likes" the lighting. An sDA value between 55% and 74% indicates a space where the user is "nominally receptive" to daylight. Therefore, lighting designers should aim to achieve sDA values of 75% or higher in frequently used spaces (such as open-plan offices or classrooms), and at least 55% sDA in certain areas where daylight is important.

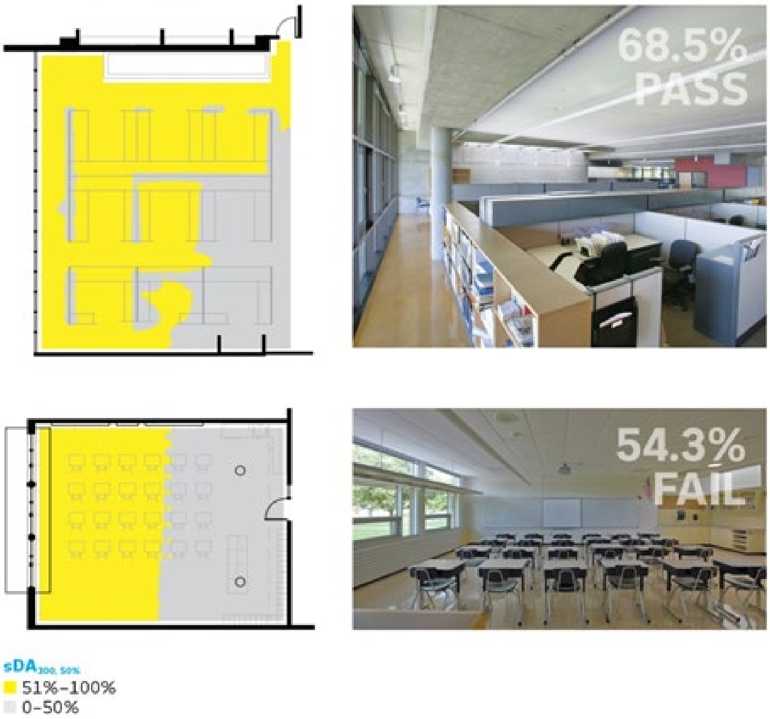


Fig. 2.10. Spatial daylight autonomy evaluation. Image credits to: https://www.architectmagazine.com/technology/lighting/annual-daylighting-performance-metrics-explained_o

2.5.2 UDI Useful Daylight Illuminance

It is a modified form of DA, a metric that classifies hourly time values subject to three lighting ranges (0-100 lux, 100-2000 lux, and 2000 lux and above), providing full credit only for values between 100 lux and 2000 lux, which indicates that horizontal lighting values outside of this range will be useless.

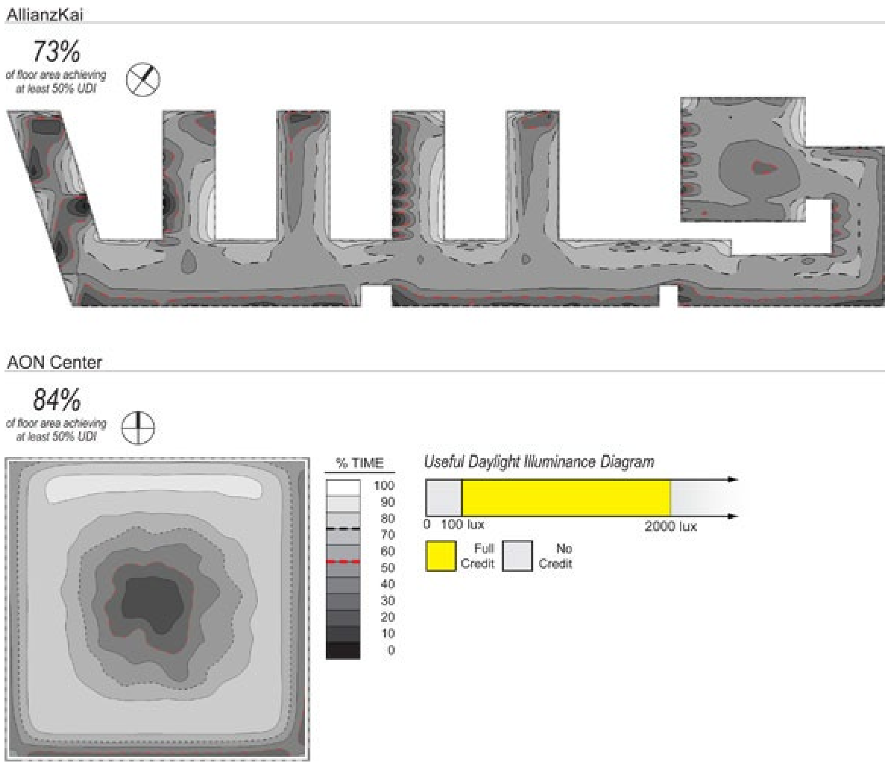


Fig. 2.11. UDI. Image credits: https://patternguide.advancedbuildings.net/using-this-guide/analysis-methods/useful-daylight-illuminance

2.5.3 DGP

DGP is a metric to estimate the appearance of discomfort glare in daylit spaces proposed in 2005 by Jan Wienold and Jens Christoffersen (original paper).

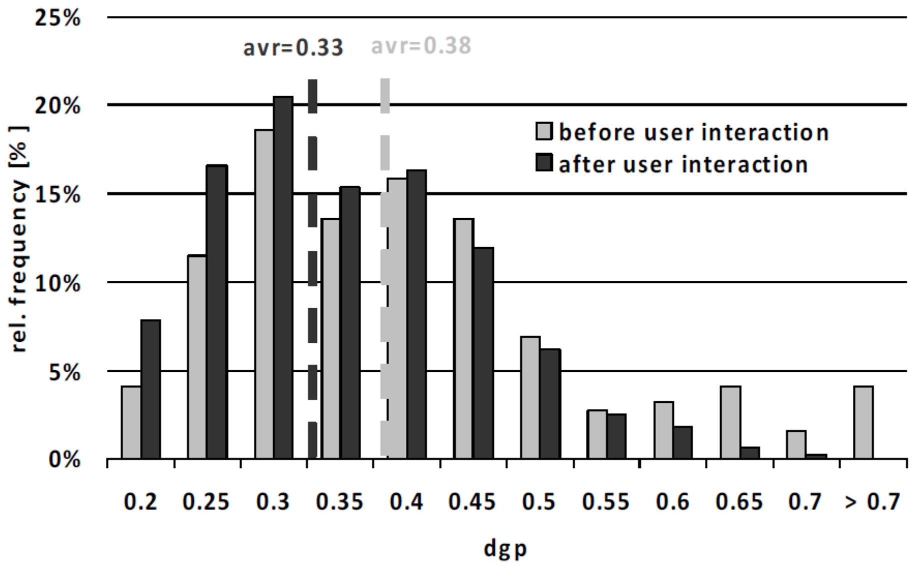


Fig. 2.12. Acceptance of glare. Image credits: https://www.radiance-online.org/community/workshops/2014-london/presentations/day1/Wienold_glare_rad.pdf

Thanks to grasshopper's plugins ladybug and honeybee for providing us with accurate computer simulations, the following are the definitions and general ranges of values for the above parameters in the plug-in manual.

DLA (DA)

Daylight Autonomy > Percentage of the time during the active occupancy hours that the test point receives more daylight than the illuminance threshold.

UDLI_Less_100

Useful Daylight illuminance > Percentage of time during the active occupancy hours that the test point receives less than 100 lux.

UDLI_100_2000

Useful Daylight illuminance > Percentage of time during the active occupancy hours that the test point receives between 100 and 2000 lux.

UDLI_More_2000

Useful Daylight illuminance > Percentage of time during the active occupancy hours that the test point receives more than 2000 lux.

CDA

Continuous Daylight Autonomy > Similar to Daylight Autonomy except that the point receives illuminaceLevel/illuminance threshold for hours that illuminance level is less than the threshold.

sDA

Spatial Daylight Autonomy > sDA is the percent of analysis points across the analysis area that meet or exceed _DLAIllumThresholds value (set to 300 lux for LEED) for at least 50% of the analysis period. Honeybee doesn't consider the effect of dynamic blinds in calculating sDA.

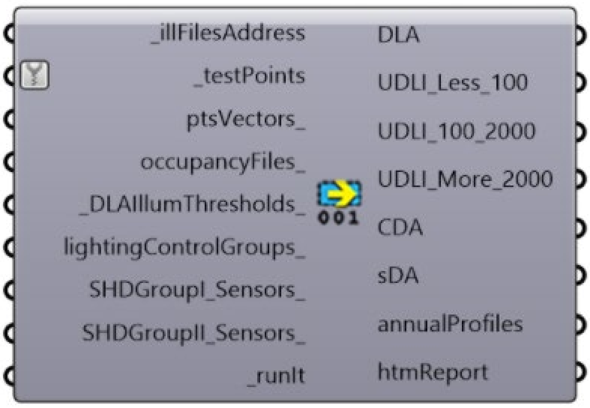


Fig. 2.13. Read Annual Daylight Results tools panel from honeybee.

2.5.4 Glare Comfort Range

Comfort Ranges. Imperceptible Glare [0.35 > DGP], Perceptible Glare [0.4 > DGP >= 0.35], Disturbing Glare [0.45 > DGP >= 0.4], Intolerable Glare [DGP >= 0.45]

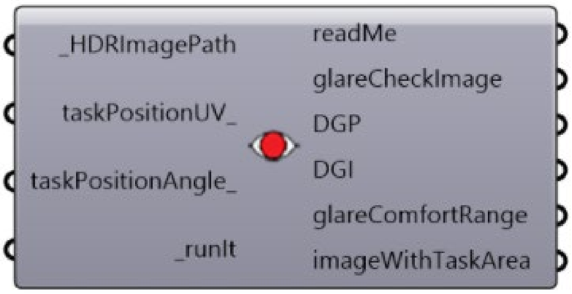


Fig. 2.14. Glare analysis tools panel from honeybee.

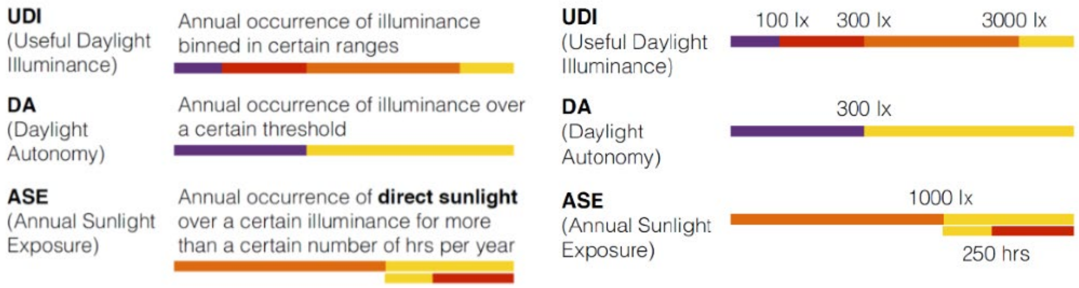


Fig. 2.15. The certain threshold of each parameter. Image credits to Elenora Brembilla& John Mardalijevic. Climate based daylight modelling the what the why and the how.

In addition to this, we also need to consider the heat exchange that takes place inside the building in order to simulate the cooling, heating and electrical energy consumption of the building more accurately. These analyses need to be implemented in specific use cases, depending on the type of building, the climate conditions of the region, and the entry of a schedule to get a more accurate assessment of energy use.

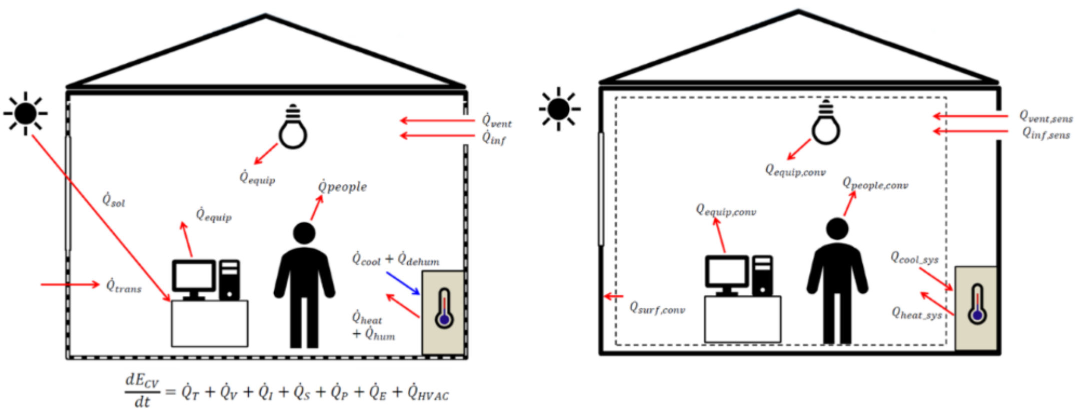


Fig. 2.16. General energy rate balance for a room/ Sensible convective energy rate balance for a thermal zone

Grasshopper can also be linked to EnergyPlus to obtain our required electricity consumption (Kwh).

Total Thermal Load

The total thermal energy used by each zone in kWh. This includes cooling and heating.

Thermal Load Balance

The thermal energy used by each zone in kWh. Heating values are positive while cooling values are negative. This is useful for computing balance points.

Cooling

The cooling energy needed in kWh. For Ideal Air loads, this output is the sum of sensible and latent heat that must be removed from each zone. For detailed HVAC systems (other than ideal air), this output will be electric energy needed to power each chiller/cooling coil.

Heating

The heating energy needed in kWh. For Ideal Air loads, this is the heat that must be added to each zone. For detailed HVAC systems (other than ideal air), this will be fuel energy or electric energy needed for each boiler/heating element.

Electric Light

The electric lighting energy needed for each zone in kWh.

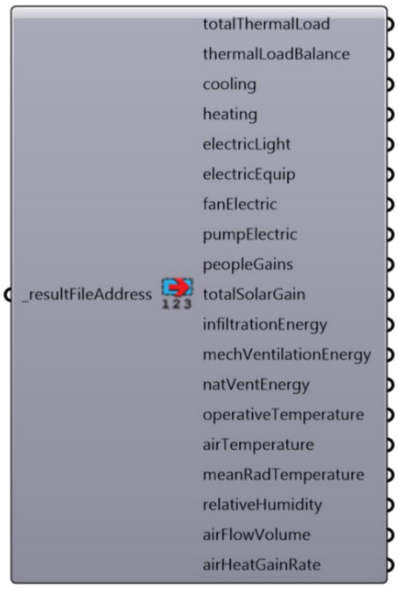


Fig. 2.17. honeybee tools on grasshopper

Based on the evaluation criteria described above, it is sufficient to perform a simulation of the geometry in the computer software for different climates and adaptive facade. In the following sections, we will describe the procedures and results of the analysis in detail.

2.6 DESIGN PROCESS

So far, we have completed the classification of adaptive skins and the definition of evaluation criteria. The next step in the research is to determine the adaptive skin design process. In this part, we mainly refer to Amir Tabadkania, Masoud Valinejad Shoubib's research on AL-BAHR TOWER. They studied the development process of adaptive skin based on parametric design tools, and they focused their evaluation on the impact of skin on the visual comfort index. They used the Grasshopper plug-in based on Rhino for parametric simulation. The honeybee and Ladybug plugins for Grasshopper are used to explore the influence of shapes, opening methods and angles on the light environment.

In their research, the design process is broken down into five phases:

1.inspiration and structure design: design the basic kinetic structure according to inspiration

2. make hypothesis: assume ideal space and ideal parameter for simulation

3. Parametric modelling and analysis: use parametric tools to build models and adjust and analyse based on assumed parameters

4.simulation: Perform simulation analysis, analyse the data obtained, and find the optimal solution or adjustment method or new structural logic

5. practical facade and assessment: zoom in to the entire building and re-evaluate

We believe that their design process is reasonable, credible and repeatable. We adopt such a five-stage design process segmentation and make some detailed adjustments in each part according to our needs. For example: In the second part of the hypothesis stage, according to the evaluation parameters and standards determined in the previous chapter, the following fixed parameter table is given to determine the analysis basis of the third, fourth, and fifth stages.

In the design process, the core steps are the second, third, and fourth phase. These three phases are used to determine the epidermal shape through parameterization. If we make a detailed description of this part, the debugging and design flow of these three phases is as follows. In phase 2, two important parameters need to be given: one is the relevant parameters of the tested room, environment, and surface material properties (plus specific parameter names), and the other is about the evaluation parameters (plus specific parameter names afterwards) And its threshold (ie standard). In phase 3, we input these parameters into the model to obtain the corresponding evaluation parameters. After the simulation in phase 4, we return the feedback to the phase 3 and adjust the skin model to obtain better results.

FLOW CHART

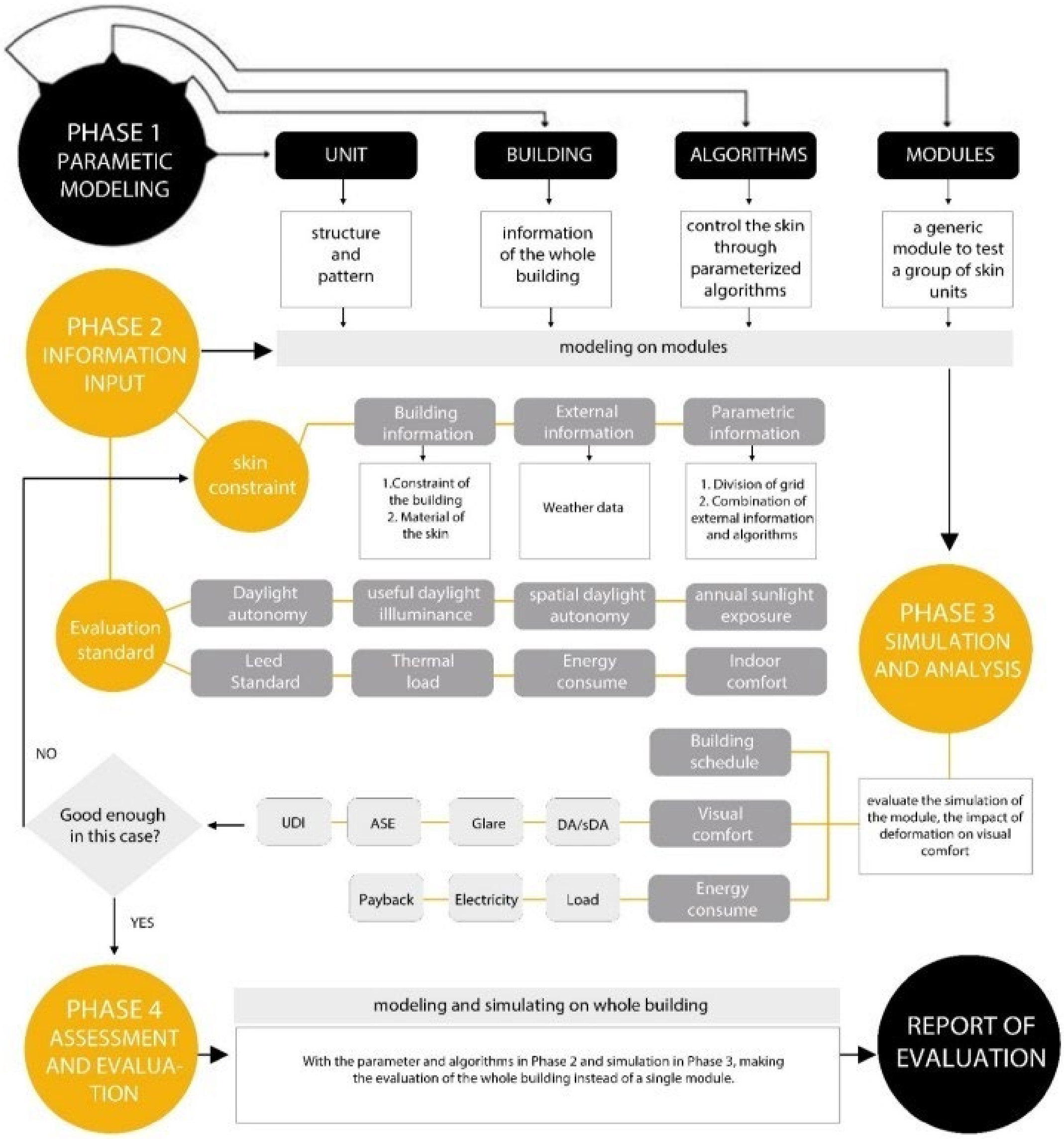


Fig. 2.18. Design and evaluation flow chart

2.7 Explanation of Flow Chart

2.7.1 Phase 1 Parametric modeling

Phase1 is the modelling phase. In this phase, the modelling of the facade unit, building, and module needs to be completed. Among them, the modelling of the facade unit needs to use parametric modelling ideas and use grasshopper to use parametric algorithms to Control the shape change of the unit. Since the purpose of modelling is for analysis, it is necessary to pay attention to the structure of the unit and the pattern composed of multiple units in the modelling.

In addition to modelling the unit, the building model and the module model are for analysis and evaluation. Start with a standardized small space (module), such as a 7m*5m*3.5m room and attach the skin to it. Facade, and then analyse the room to perform a simple analysis and optimize the result. The model of the building is an overall evaluation after the optimization is completed, and it is a step to test the effect and efficiency of the design results.

2.7.2 Phase 2 Information input

Phase 2 is the information input phase. The information input in this phase can be divided into two parts:

1. Construction and skin constraint information input

2. Evaluation standard input

Construction and skin constraint information input

Information about restriction conditions can be divided into three parts. One is building information, including the material of the skin and the restriction conditions of the building itself (orientation, special function requirements, etc.); the other is external information, such as climate data, etc., which can be used. For analysing shading, thermal load, building schedule, etc.; the third is parameterized information. To combine the parameterized algorithm determined in phase 1 with the above two parts of information, a series of prototype parameters need to be found and determined to supplement the algorithm. In addition, in terms of parameterized information, we also need to divide the module into the grid. The grid is the subdivision of the module to visualize the data results and simplify the analysis process.

Evaluation standard input

In the previous chapters, we conducted some simple analysis and description of the evaluation criteria. In the actual analysis, we are more concerned about visual comfort and energy saving. At the same time, in the plugins honeybee and ladybug of Grasshopper, these data are available: Daylight autonomy, useful daylight illuminance, spatial daylight autonomy, annual sunlight exposure, glare. Therefore, we will evaluate the criteria in this part, namely Threshold input of these parameters to make a reasonable evaluation of the simulation results.

2.7.3 Phase 3 Simulation and analysis

Phase3 is to evaluate the simulation of the module and study the impact of deformation on visual comfort. In the process of simulation analysis, in addition to the threshold parameters input by phase2 (DA, SDA, ASE, UDI, Glare), another important conclusion needs to be obtained is the building schedule led by visual comfort, which plays an important role in the annual assessment. In addition, the energy and load conditions can also be simulated through the schedule. After performing these analyses, the effectiveness of the epidermis can be judged by the effectiveness, and the first part of phase2 can be returned to modify the epidermal data to find a better solution.

2.7.4 Phase 4 Assessment and Evaluation

phase4 is the phase of testing the design results. In this stage, the simulation and analysis steps performed in phase 3 will be repeated, but the object is replaced by a single module to the entire building, so as to conduct a reasonable analysis and evaluation of the entire building's skin.

CHAPTER 3: Adaptive facade and bionics

Abstract: In this chapter, we first introduce the advantages and necessity of bionics, and briefly summarize the development status of bionics and the current popular bionics research methodology. We use these methodologies to study and learn some classic architectural bionic cases and analyze their design ideas and processes as much as possible. According to the process and conclusion of the case analysis, we concluded our bionic design process for the adaptive facade.

3.1 Introduction of bionic

3.1.1 Why we need bionic.

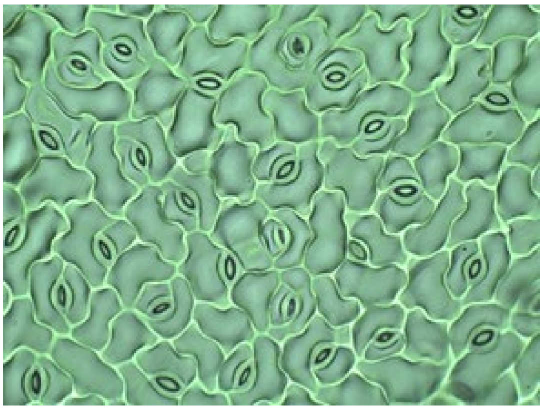
Today in the 21st century, the population is growing rapidly, and the proportion of cities is also rapidly increasing. The huge consumption and waste and pollution of the earth's energy in urban areas are huge and cannot be ignored. For these problems, can there be ways to improve them from the perspective of an architect? David Pearson said in the new organic architecture [3.1], Any living organisms, their external form and internal structure provide endless ideas for design. Bionic technology may become our new way of solving problems. Before that, we first need to understand what bionics is, how it is used in architectural history, and how can bionics be sustainable? And how can bionics contribute to the development of the city. And later we will introduce the classification of the application of bionics in architecture, what efforts have been made in existing bionic buildings, and how we should apply bionics in design, and how to use software to optimize our design.

3.1.2 Definition of Bionics

What is bionics? In the process of evolution, many organisms have also faced various environmental problems, and have evolved effective methods to use and adapt to the environment. The living creatures that exist today are the products of successfully adapting to their environment, and they are successful models in the process of evolution. In the result and process of their evolution, there are many adaptive methods that can be learned by us, whether in art, industrial science or architecture. Therefore, these disciplines that obtain inspiration and create new results by understanding the structure and function of organisms are called bionics. In the sense of modern science, bionics is defined as a science that studies the structure and function of biological systems and applies these special structures and functions to technical systems to create new crafts, buildings, and installations. [3.2]

3.2 The research value of bionics

So why can bionics become our new idea? We can see that in the process of evolution, each life is constantly adapting to the new environment. They gradually evolve in biological form, structure and function, evolving into a biological world full of life diversity and complexity, in order to give us bionics Academic revelation. In other words, organisms are all adaptable. Acclimatization of organisms is the process by which organisms adapt to changes in external climate and environmental conditions, such as temperature, humidity, and light intensity. They change their organ morphology, behavior, and physical or biochemical characteristics. To respond to changes in the external environment and adapt to the new climate and environmental conditions. In this adaptation process, the biological homeostasis mechanism or regulation mechanism can keep its internal environment under stable conditions within a specific range. [3.3] For example, biological thermoregulation can keep organisms within a certain range when the external temperature changes.



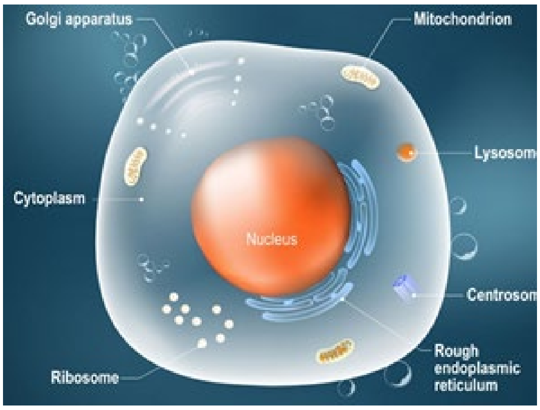


Fig. 3.1. Microscopic diagram of plant stomata

http://cell.bio1000.com/molecular-cell/201908/2230131.html

Fig. 3.2. Schematic diagram of animal cell structure   by colematt / iStock / Getty Images Plus https://www.thoughtco.com/all-about-animal-cells-373379

Secondly, a very important stage in the process of biological adaptation to the environment is the formation of biological separation, that is, the biological structure is relatively separated from the external environment through the biological appearance, forming a stable biological internal environment, creating a life and evolution. [3.4] A basic material condition. With the evolution, life has evolved from low-level to high-level, and the composition of organisms has become more complex. In addition to plant epidermis and animal skin, various biological epidermis can filter and secrete substances that are not needed for body functions or that are unfavorable to the body. Allow beneficial substances or pheromones to selectively permeate, such as cell membranes (Figure 1) that separate living substances from the inorganic natural environment, forming a biological internal environment opposed to the outside world, and cell membranes are selective and permeable. Through the exchange of materials and energy with the outside world, the living body and the outside environment are unified: there are usually many stomata on the epidermis of plants (Figure 2), which are the gateways for gas to enter the plant body. The guard cells surrounding the stomata can control the opening and closing of the stomata by changing their shape, thereby effectively regulating the gas in and out and water transpiration. Animal skin not only protects the body from trauma and prevents water loss in the body, the sensory nerve endings of the skin also make the skin a huge receptor. Make a stressful response to another external stimulus. It can also be said that the surface structure of the organism affects the adaptation relationship between the organism and the environment. The existence of the building also isolates a relatively stable environment through the building, allowing people to have a suitable environment, separating people from the natural environment, and allowing external gases and radiation to enter selectively. To protect the objects and people inside the building, it can be said that the enclosure of the building and the separation of living things have a certain similarity. Therefore, some of the adaptation and self-regulation of the biological skin can also bring us inspiration for architectural enclosure.

In addition to individual organisms, the response mode of biological groups to the environment is worthy of reference. Simulating the response mode of biological adaptation to the environment can enable buildings to acquire certain life-like characteristics, and autonomously adjust their own existence and operation according to environmental changes. The model is conducive to making full use of environmental resources and forming an adaptive relationship that is in harmony with nature; drawing on the symbiotic relationship between species and the relationship between organisms and the environment to form a symbiotic architectural philosophy system, analyzing the hierarchical relationship within the community of animals and summarizing them It is helpful to understand the hierarchical relationship between the building group and the internal space of the building. [3.5] It is inspired by the internal synergy of the natural biological community to produce the design ideas of various modern building clusters: imitating the internal adjustment mechanism of biological adaptation to the environment, and the building can be in the external natural climate and Realize the active material and energy flow regulation and control between the internal artificial climate, and achieve a healthy and comfortable building environment with the highest climate utilization efficiency and the lowest environmental load. In the course of long-term development, architecture has slowly evolved a life-like adaptive operation and adjustment mode. [3.6] In the face of changes in external conditions, architecture can actively make self-adjustment and adaptability, gaining more flexibility and adaptability: As a complex social space system, architecture and city, multiple functions and constituent elements form an interdependent and interactive whole within a certain area, and have self-organization performance similar to life system and synergy between each other.

3.3 Bionics and architectural design

Bionics is not only a branch of applied biology, but also intersects with mathematics and engineering sciences. In the field of architectural science, the concept of bionics has been involved earlier, and the research object of bionics is the pattern or function of a certain creature in the biological world. [3.2] It promotes the efficient and orderly function layout and physical structure of the architectural design by applying the most common and reasonable scientific laws in the nature explored by the science in architectural design. The bionic structure derived from this concept takes into account both mechanical properties and material properties, and the derived bionic design takes into account both natural aesthetics and functional rationality.

3.3.1 The history of the development of bionic architecture

As early as the period of ignorance, people began to imitate birds to build nests on trees. (figure 3) In order to avoid the harm of animals, insects and snakes, some primitive tribes in Africa still retain the habit of nesting in trees. In China, there are many types of cave dwellings in plateau areas. (figure 4) It may be a dwelling model built by the ancestors imitating animals such as rats, ants and rabbits by digging underground. The cave dwellings are easy to construct, warm in winter and cool in summer, and are widely used due to their good environmental adaptability. These dwelling forms are direct imitations of nature and cannot be mentioned as bionics in the modern sense. As humans further understand the laws of nature, architectural forms with more complex architectural functions and more environmentally adaptable gradually appear to satisfy the gradual improved life needs. During the ancient Greek period, various natural totems were widely used in architectural decorations, such as the Greek column capitals, internal reliefs and sculptures. The prototype of bionic architecture has long been in the history of modern architecture, which can be traced back to the works of natural plasticity by the talented Spanish architect Gaudi. Contemporary architectural design has broken through the early modernism's pursuit of a single architectural form and a pure collection. Free form and bionic form have become an important trend in the development of modern architecture. At the same time, the research of bionic architecture is not only limited to the simulation of biological forms, but also focuses on studying the functions and life patterns of various animals, exploring how organisms adapt to the environment, how to cooperate and react independently, and consciously imitate in architectural design. Later, some modern famous architects or structural engineers such as Buckminster Fuller, Nervi, Frei Otto, Santiago Calatrava [3.7], seem to be inspired by natural biological structures and connect their creations with natural biological structures.

Fig. 3.3. cave dwellings in China plateau areas
https://www.sohu.com/a/210027782_128340.

Fig. 3.4. Tree house in Korowai tribe
https://www.flickr.com/photos/50773627@N00/386045390/

In recent years, architects and structural engineers have systematically explored the functional structure and form of living organisms under the guidance of bionics theory and developed many sub-disciplines of architectural bionics based on this, such as bionic materials and bionic technology, Urban Bionics, Building Waterproof Cytology and Building Bionic Ecology, etc., enrich the theoretical system of architecture. [3.5]

Bionics has its reference value for all aspects of architecture, in terms of building structure technology. All the laws of nature can also be used as a reference for us to use modern technology to create a bionic structural system. From a drop of water and a shell, we can see the tension of the free parabolic surface and the high strength of the thin wall: a spider web can reflect its cross-web-like support weaving texture. These are very useful inspirations for the innovative design of building structures. The giant vault of the Turin Exhibition Hall in Turin, Italy, designed by the Italian structural engineer Nervi, was constructed by imitating the vein texture; the German pavilion built by the German structural engineer Frei Otto at the Montreal International Fair in Canada in 1967 was the first The web-cable structure that imitates the spider-web-like membrane is used, like a group of tent-like buildings, which is not only novel in space, but also developed into a tension structure system and widely used all over the world. [3.7] The bionics of these structural technologies fully illustrates the tremendous progress made in the application of bionics principles in construction technology.

In contemporary times, the modern architectural system has begun to differentiate and transform after years of development. The use of modern new technologies and materials, respect for the environment and history, and changes in the aesthetic concept of the system have made the pure geometric modeling system more and more diverse. In terms of architectural design, it is not only limited to the concrete imitation of biological forms, but also uses computer technology to design various streamlined buildings, and new materials and new structures are used to construct abstract bionic forms. At the same time, the building is regarded as a living organism, which has the characteristics of growth, evolution, movement, self-organization, self-regulation, and metabolism over time, and can dynamically adjust itself to adapt to changes in new functions. The building is no longer regarded as a fixed structure and can adjust itself to adapt to the climate as the environment where the building is located, such as pressure, wind, temperature, humidity and other natural elements. In form bionics, the imitation of biological nonlinear forms is possible with the support of digital technology. In functional bionics, the requirements of ecological energy conservation for practical problems and our learning of biological strategies to cope with environmental changes make the building functional organization and energy-saving technology bionic design have more choices; in the field of computer-aided design, with the decryption of biological characteristics, various algorithmic buildings and generative buildings based on digital technology have also appeared one after another. The changes in design methods have naturally brought new architectural forms. [3.8]

3.3.2 Theories and cases of bionic architecture

As we know, bionics covers all fields, and bionic architecture is only a branch of bionics.

Architectural bionics is not only a technical means, but also a way of thinking. It uses the perspective of biological systems to Internal function and external form, action form and construction technology, existence mode and natural environment are considered as a whole, in order to achieve mutual coordination between each other and become a part of the overall adaptation.

Architectural bionics is in the performance of complex non under the combined effect of linear science, digital technology, biology, and cognitive concepts, it has evolved from a simple morphological simulation of organisms to a simulation of more biological problems such as streamline morphology, physiological functions, and laws of life generation. The comprehensive disciplines.

1983 J. S. Lebedew wrote a book (Architecture and Bionic) [3.9], which systematically clarified the meaning of architectural bionics, the method of applying bionic theory in architecture, the relationship between architectural bionics and ecology, and the relationship between architectural bionics and aesthetics. Before and after, many creative architects also carried out the practice of architectural bionics, making architectural bionics gradually become a new idea that has attracted much attention. The Italian architect Paolo Portoghesi published Nature and Architecture in 1997 [3.10], and wrote about the natural world. A lot of research has been done on the colorful forms, comparing them with human architectural forms from the overall form to the partial components. At the same time, the author shows a strong tendency of bionics in many designs.

Gunther Feuerstein understood architecture as a living human body in Biomorphic ahrchitecture [3.11] and used this as a starting point to make a more detailed case study on the form and function of architecture in bionics. In addition, the author made a detailed analysis of many animal forms. And summed up a number of design languages used in architectural design.

David Pearson traced the origin of organic architecture in New Organic Architecture [1], and performed a geometric analysis of natural forms, and finally listed a long list of architects and works with organic architecture tendencies.

In< Zoomorphic: New Animal Architecture > [3.12], Hugh Aldersey Williams divided the bionic design of buildings into symbolic bionics, static functional bionics, dynamic functional bionics, non-subjective bionics, and biological mimicry , and a lot of cases of bionic architecture were listed in his research.

Frei Otto's <Finding Form> [3.13] has made a detailed analysis and research on the numerous structural forms of living things and non-living things in nature, and applied them to the design of building structures, especially making outstanding contributions to the light structure of buildings. The author proposed a form-finding method the concept of structural design, that is, the role and transmission method of imitating force in the natural structure, find the most economical and reasonable structural form according to the actual role of the structure.

Level of Biomimicry	Example-A building that mimics termites	
Organism level (Mimicry of a specific organism)	form	The building looks like a termite
	material	The building looks 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 termites;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.
Behaviour 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 it 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 for example.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 ecosysytem(a termite would live in)
	material	The building is made from the same 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 works in the same way as a (termite) ecosystem ; principle 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,anf 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 utilising 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. A Framework for the Application of Biomimicry (adapted from Pedersen Zari, 2007)

Although the classification methods are slightly different, we can see that architects mainly start from the three aspects of architectural form, architectural structure and functional form. Through the study of biological species, ecological environment, biological and architectural relations, they create biological models and Technical model. First, the researcher selects research objects from nature, and then builds various physical or virtual models based on the objects, uses various technical means to study them, and obtains a quantitative mathematical basis; through qualitative and quantitative analysis of organisms and models Analyze, transform the form and structure of organisms into abstract functions that can be used in the technical field, and consider using different material materials and technological means to create new forms and structures. And conduct feasibility analysis and research, so that the architectural works can not only adapt to the natural laws of the environment, but also meet the needs of human continuous development.

Therefore, we use two different classification angles of bionic prototypes and imitation products, from the micro to the macro order to classify the bionic architectural design: from the perspective of architectural design, it can be divided into building material bionics, building component bionics, Building structure bionics, spatial organization bionics, building construction bionics, urban design bionics.[3.14] From the perspective of inspiration source, it can be divided into cell bionics, biological structure bionics, biological function bionics, biological behavior and product bionics, biomorphic bionics, and ecosystem bionics. It is worth noting that these classifications are not absolute, and there is overlap between the angles of these two classifications.

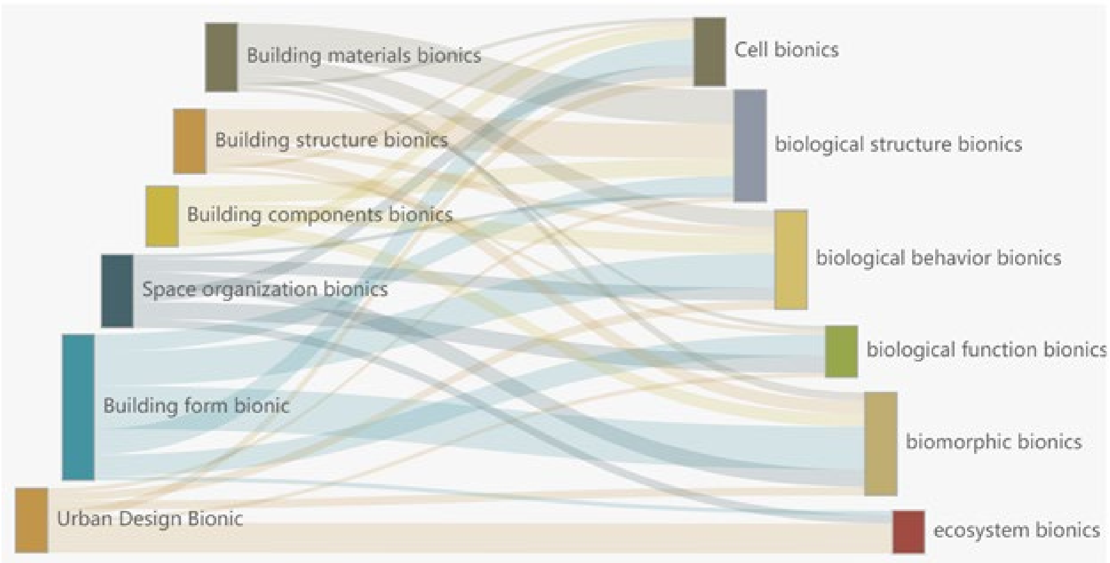


Fig. 3.5 The relationship between the design of different levels of the building and the bionics

Among them, cell bionics refers to the morphology and function of single-celled algae animals and plants or animal and plant cells. Biological bionics refers to biological components such as muscle fibers, the surface structure of fur tissues and lotus leaves. Biomechanical bionics refers to the digestion system of animals, the respiratory system, such as the filtration of soil by fish gills and earthworms, also includes the photosynthesis of plants and the purification of air. Biological behavior and product bionics are the activities and products of biological activities such as spider weaving, bird nesting, termite nesting, etc. Biomorphic bionics refers to the shape of a creature or the shape of a certain part of a creature, such as bird wings, shell shapes. Ecosystem bionics refers to the distribution of natural colonies, fish schools and ocean currents, for example.

Most biological materials in nature have a micro-composite and macro-perfect structure. By studying the structure and principles of biological bodies, building materials similar to the structure of biological bodies can be constructed, and similar functions can be achieved through similar structures. For example, honeycomb structure materials can be developed by imitating honeycomb structures [3.15]. It has the advantages of light weight, high strength, good insulation and sound insulation performance; research and imitate the chemical composition and formation mechanism of living organisms, and use similar constituent materials and mechanisms to produce new building materials, such as imitating shell components and structures to develop natural ceramic materials and even Imitate the environmental perception, self-regulation and repair functions of biological materials to develop intelligent building materials.

The following are examples of some cases.

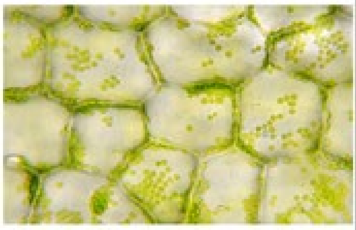
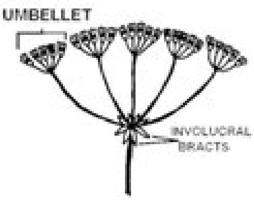
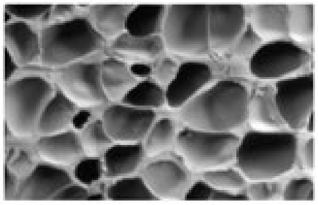
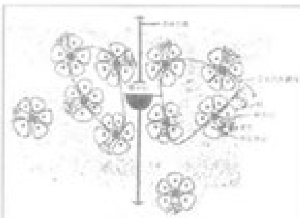
	BIONIC PROTOTYPE	BIONIC DESIGN	
BUILDING-MATERIALS	 Butterfly wings	 tunable structural color coating	Cypris coatings are designed to replicate the naturally-occurring periodic dielectric nanostructures that produce the brilliant colors observed in butterfly wings,.Their technology can improve building and automobile energy efficiency by reflecting UV, visible, & infrared light.
BUIDING STRUCTURE		 Beijing Olympic swimming center	The 2008 Olympic swimming pool looks like a huge blue box with irregular bubbles on the wall. The size and arrangement of this layer of bubbles are designed with reference to the precise geometric structure of nature such as cell and molecular structure. And help to achieve the perfect lighting
BUILDING COMPONENTS	 COMPOUND UMBEL	 Stuttgart Airport Terminal	The terminal building of Stuttgart Airport designed by Otto is a classic tree-like structure supporting work. It not only has a beautiful appearance, but also has structural advantages in terms of force dispersion.
SPACE ORGANIZATION			The Taichung Opera House designed by Toyo Ito uses a curve as a structure, and the internal space is like a porous sponge structure, which is not only unique in shape and space, but also has superior acoustic effects.
BUILDING FORM		 milwaukee-art-museum-	The Milwaukee Art Museum is a moving building. Calatrava uses a mechanical transmission device to slowly open the two steel wings on the top of the building that spread like wings in the sun. Endows the building with vitality.
URBAN DESIGN			The Columbia New Town planned in 1961 consisting of 10 petal-shaped clusters. Each group has a population of about 10,000 to 15,000. With the town center as the service center, buses and intercity highways are connected in series with each 'petal'

Table 2. Bionic prototype and design case, table: self-drawing, picture from https://www.google.it.

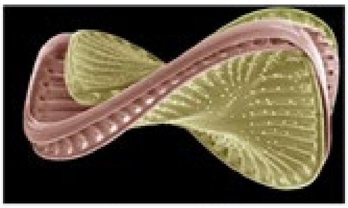
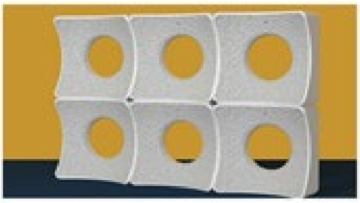
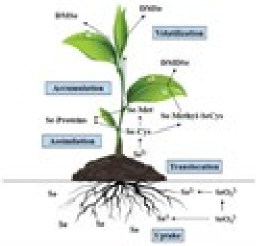
	BIONIC PROTOTYPE	BIONIC DESIGN	
CELL BIONICS	 A type of Diatom	 2022 Winter Olympics Speed Skating Hall	Take the speed skating hall of the 2022 Winter Olympics as an example, there are many sports buildings shaped like a saddle line. At the same time, the shape of other algae is also a good reference.
BIOLOGICAL STRUCTURE BIONICS	 Texas Horned Lizard	 Moist Brick (concept)	Moist Brick was created as a building material that would condense water from nighttime air and collect it on the surface as an evaporative cooling system for buildings. Inspired by the Texas Horned Lizard, which uses capillary action to move water from anywhere on its skin to its mouth.
BIOLOGICAL BEHAVIOR BIONICS	 Agyroneda Aquatica	 ICD/ITKE RESEARCH PAVILLON 2014-15	The ICD/ITKE Research Pavilion was inspired by the underwater nest construction of the water spider. The resulting lightweight fiber composite shell forms a pavilion with unique architectural qualities, while at the same time being a highly material-efficient structure.
BIOLOGICAL FUNCTION BIONICS		 Yamanashi Culture Hall	The cultural hall built by Kenzo Tange in Yamanashi Prefecture, Japan, is a famous work of the Metabolism . Its plane composition is to imitate the function of plant metabolism and can be expanded or reduced as needed.
BIOMORPHIC BIONICS	 Lotus	 Mother Temple, Delhi, India	The Mother Temple in Delhi, India. After its completion in 1986, its architectural shape resembled a huge blooming lotus flower, which attracted many tourists from home and abroad. It expresses the image of holiness and beauty.

Table 3. Bionic prototype and design case, table: self-drawing, picture from https://www.google.it

What needs to be realized is that we can make many classifications according to the different functions and properties of living beings, but it must be noted that classification is only a method of understanding things, which is helpful for more in-depth research on things, but we cannot divide the original connection between class and class.

The topics of bionics in modern architecture have changed endlessly, and the system of architectural bionics has not matured enough to be systematically stated. On the one hand, the research content of architectural bionics is very extensive, ranging from molecular bionics in the microscopic world to cosmic bionics in the macroscopic world. Human beings summarize the nonlinear fractal geometry from the self-similarity of natural forms in thousands of poses. From the cytoskeleton we can find the network-like curved structure intertwined with microtubules and microfilaments, from the physiological structure of biological epidermis we can learn the principle of selection and permeability of various environmental factors, and from animal nests in various environments to natural architecture we can learn the ecological adjustment mechanism of the city. These all provide very useful inspiration for the innovation of architectural design. On the other hand, the application range of architectural bionics also covers almost all aspects of the architectural field from architectural form to architectural structure, from building materials to architectural structure, from existence to mediation mode, from human settlements to urban planning. All of these determine that the research system and theoretical system of this thesis are open, and it is a preliminary study of various bionic designs in the current architectural field.

3.3.3 How to design a bionic building

How to design bionic buildings, the existing views can be divided into two categories, that is two methods (figure 3.6), one is top-down design, we call it a design based on biological system inspiration which refers to the type and process of designing some characteristics, behaviors and functions of the biological model that are obtained through research and summary. The other is bottom-up design, which we call problem-based heuristic design direction, which refers to the type of design that starts with existing design needs or existing design problems and drives researchers to explore natural biological models to find solutions and process. [16]

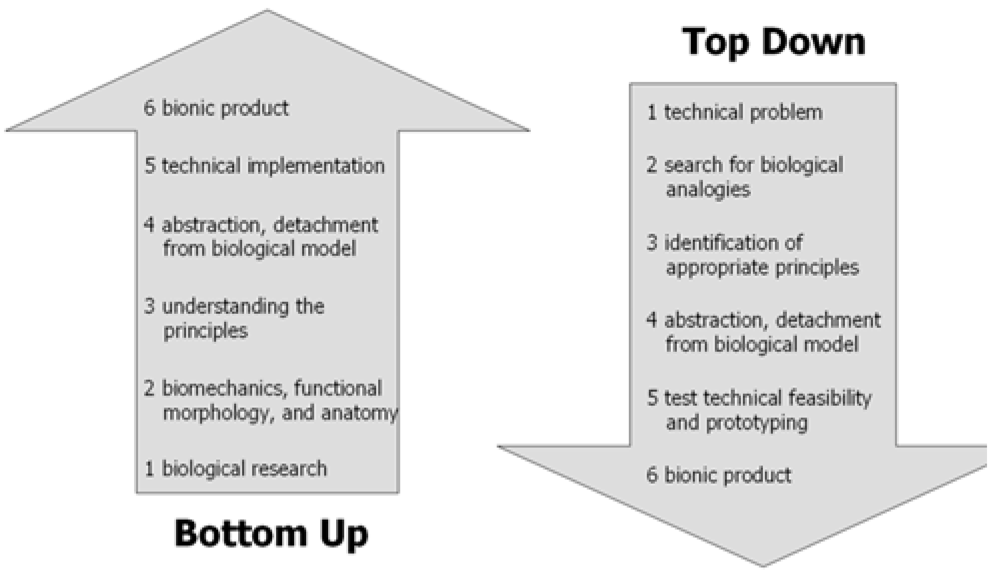


Fig. 3.6 Process sequences in biomimetic research. Left:Bottom-up process of biomimetics (biology push). Right: Top-down process of biomimetic research (technology pull)

From: Design and construction principles in nature and architecture Article in Bioinspiration & Biomimetics · March 2012

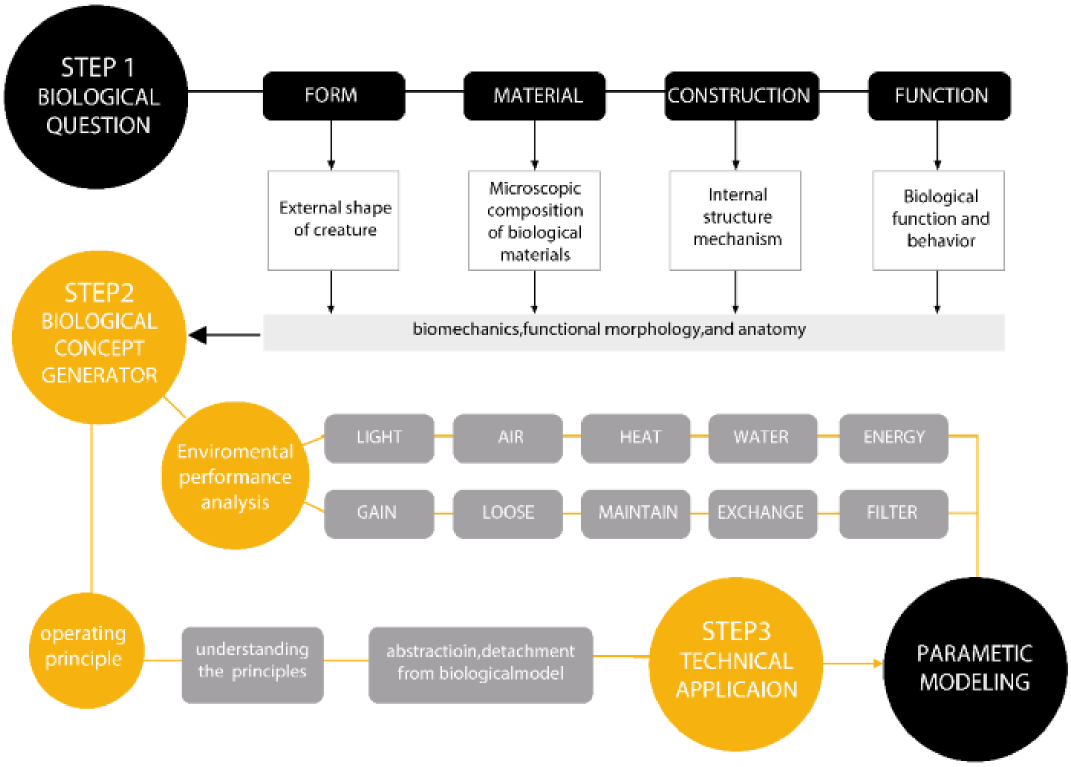


Fig. 3.7 bionic design flow

The general procedure of bionic research on ecological architecture is: searching for biological prototypes, analyzing the mechanism of prototypes, and building model experiments. After summing up, we came up with the design flow chart in the figure 3.7. In-depth bionics research often regards the organism as a system and draws on the method of systematic research; and the architectural strategy for a specific ecological problem is often proposed through the method of building model experiments. Biology in the natural world has many enlightenments to ecological architecture. Based on the systematic theoretical research of bionics, several bionic methods of ecological architecture can be proposed, such as intensive, adaptable, multifunctional, and evolutionary.

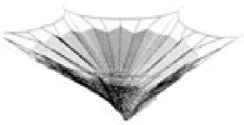
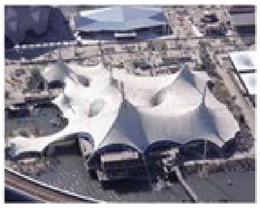
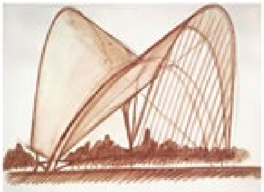
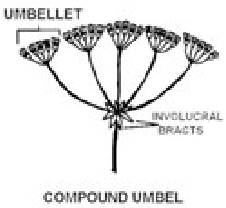
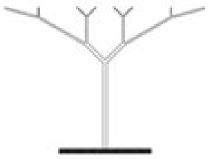
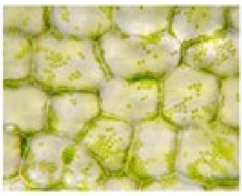
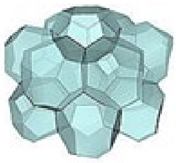
Biological archetypes	Structural principles	Building reconstruction
		 The German Pavilion - Montreal World Expo
		 World Trade Center transportation hub
		
		
		

Table 4. Case from biological archetypes to structure to design, table: self-drawing, picture from https://www.google.it

Specifically for the bionic building skin, the authors from UNSW Sydney summarized the influencing factors of the building skin and the reference for evaluation. He divided the skin factors into light, heat, air, water, and energy, and respectively compared and referenced with the activity of the epidermis of the plant. This is of reference value for our design of bionic adaptive skin.

3.3.4 From idea to design

In order to make the whole experiment more objective and accurate, we set up a set of design process before we started. The figure below can clearly show our design ideas. First of all, we hope to draw inspiration from the biological world. The inspiration comes from the moving posture and microstructure of creatures. The observation objects are mainly birds and coleoptera insect wings. We use origami to test whether the inspiration from the biological world can be completed by origami.

In the second step, we start to build data on the computer. The software we mainly use is Rhinoceros, Grasshopper and some of the plug-ins. In this step, we will select a site, select the weather data of the city, and set a standard room for test and enter the geometric design of our several feasible solutions. In the third step, we will use the software mentioned above to simulate the data and introduce the mechanical components suitable for our design such as actuation and sensors.

In the last step, we will compare the results of several designs in accordance with the evaluation criteria mentioned in the previous chapters and select the best solution for in-depth design and inspection.

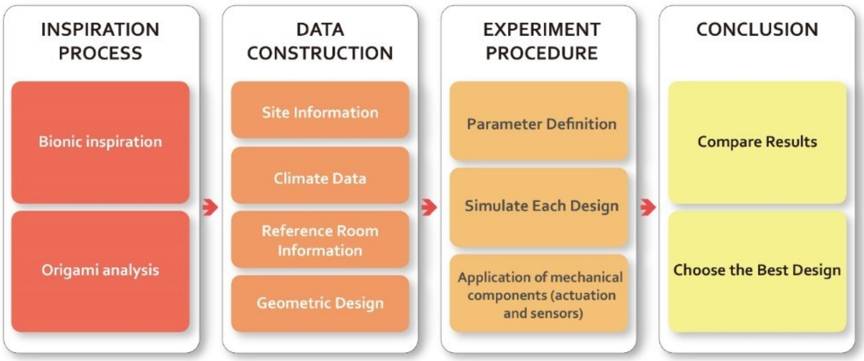


Fig. 3.8. Specific steps of digital analysis

CHAPTER 4: INSPIRATIONS

Abstract: The content in this chapter is the first step for us to transform theory into actual design. In this chapter, we have completed the steps of transforming inspiration into design guidance based on the design theory of the previous chapter.

We first take the wings that are more related to the adaptive facade as inspiration, and list several biological characteristics that are related but have different characteristics. Among these biological characteristics, we were inspired by the double-layered wings of ladybug, and analyzed the skin design with the goal of light and durable façade. In terms of movement mechanism and material structure, we got inspiration from the layered structure of ladybug's wing veins and wings.

After getting inspiration from ladybug and determining the design direction, in order to determine the geometric shape, we studied the folding of insect wings and used origami as a medium to explore the geometric possibilities of the scheme.

4.1 Ladybug's wings study

In the part of bionic architecture in the previous chapter, we cited a lot of bionic content related to architecture. In fact, from the development of human civilization, there are countless designs and principles inspired by nature. From the draft of the wing bone design of Da Vinci, to the nano-structured self-cleaning product (Self-cleaning paint Lotusan ®) developed by modern humans inspired by lotus. Therefore, as the "answer given by nature", bionics is a database that can provide us with sources of inspiration. The following creatures give us great inspiration in the direction of our research on architectural façade. The skin design of modern buildings needs to consider many factors: adapt to changes in the environment, have a specific shading effect, have the ability to resist wind loads, and so on. Considering the above factors, we are curious about which creatures in nature can achieve a balance among these problems.

4.1.1 Introduction

At the beginning we focused our attention on the wings of creatures, because wings not only provide the ability to fly many times the weight of wings, but also have a variety of storage methods, so we think that wings are the best reference for a good balance of solidity and foldability in the biological world. Ladybug, also known as Coccinellidae, is a very common insect in our daily life, belongs to the order Coleoptera, its wings are very different from those of other creatures, it is a double structure of wings, the outer wings are called "forewings", which are hard and heavy, while the inner wings are called "hindwings", which are light and thin. The ladybug is a highly mobile insect that can roam vast areas by switching between walking and flying modes, and its wings are small in size compared to its body but can help it accomplish long-distance flight, a combination that arouses our curiosity.

Fig. 4.1. Fore wing and hind wing of ladybug. Photo credits to http://photography.leavesnbloom.com.

To learn more about the uniqueness of ladybug wings we read Prof. Kazuya Saito's paper "Investigation of hindwing folding in ladybird beetles by artificial elytron transplantation and microcomputed tomography" [4.1], in which he transplanted artificial transparent material to live ladybugs to observe in detail the specific folding process of ladybird internal wings as shown in Fig. 4.2, and demonstrated this folding process by the method of origami, which is expected to contribute to the understanding of this remarkable expandable structure. The paper is expected to promote the understanding of this remarkable naturally optimized system in the unfolding structure and also to give us great inspiration.

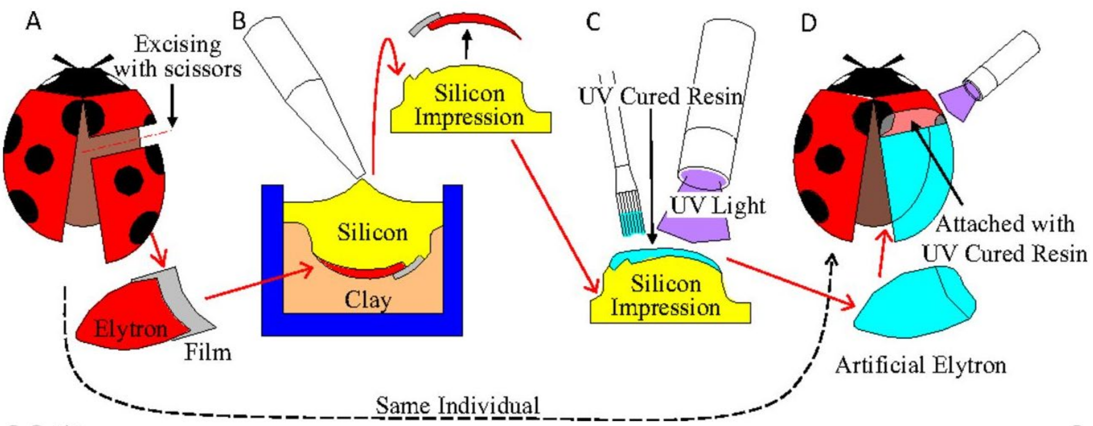


Fig. 4.2. Schematic representation of the transplant operation. Photo credits to Kazuya Saito, https://www.pnas.org/content/114/22/5624

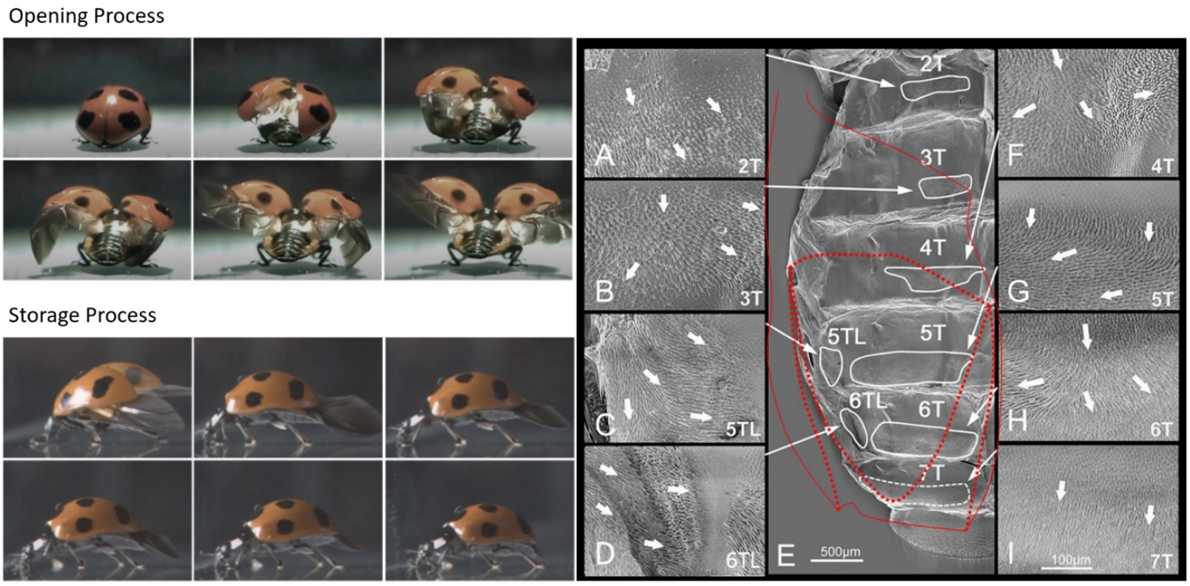


Fig. 4.3, left, opening and closing process of ladybug's wings, right, Abdominal tergites and wing-folding spicule patches in C. septempunctata, Photo credits to Kazuya Saito, https://www.pnas.org/content/114/22/5624

As shown in Fig. 4.3, the process of opening and closing of the ladybug's wings can be seen as a clear division of labor, with the forewings needing to open earlier in the process of opening, and the hindwings spreading from multiple folds to full opening like a spring when the forewings are half-open. In contrast, the closing of the wings takes a longer period. First, the hind wings need to be simply folded, and then the forewings cover the hind wings but are not completely recovered. The microscopic structure of the abdomen of the ladybug is shown in Fig. 4.3 with a fine granular structure, which aids the hind wings to storage by peristaltic movement until they are fully recovered.

Scientists use high-speed digital video to record the folding and unfolding of the wings of coleopteran insects. We were inspired by this, hoping to use a hard material to shield the relatively fragile material in order to protect the relatively fragile material from natural damage, such as cutting, corrosion, and abrasion. And this combination of hard and fragile materials can also allow the two different materials to maximize their value. The hard part can provide strong support for the structure and provide 100% shading effect and resist solar radiation. The fragile part can adopt a translucent structure similar to that of insect wings. Its biggest feature is lightness and easy folding, so it can save the electric energy required to move the heavy skin during the movement of the adaptive skin. In addition, the combination of the two materials will also provide us with more possibilities in the next design from the perspective of architectural aesthetics.

4.1.2 Characteristics of ladybug's wings

Through our study, we summarized two characteristics of ladybug wings: protective and foldability. Protective refers to the different hardness of the double-layered wing structure of the ladybug. The forewing is a hard and bulky shell-like structure, which does not play a helpful role in the flight of the ladybug, but the wrapping of the forewing can play a role in protecting the hindwing and even the body of the ladybug when it is in non-flight mode. As the figure 4.4, shows the structure of the forewing of the ladybug [4.2] under the electron microscope, we can see that it has an irregular shape and a multi-layered shell structure with uneven thickness.

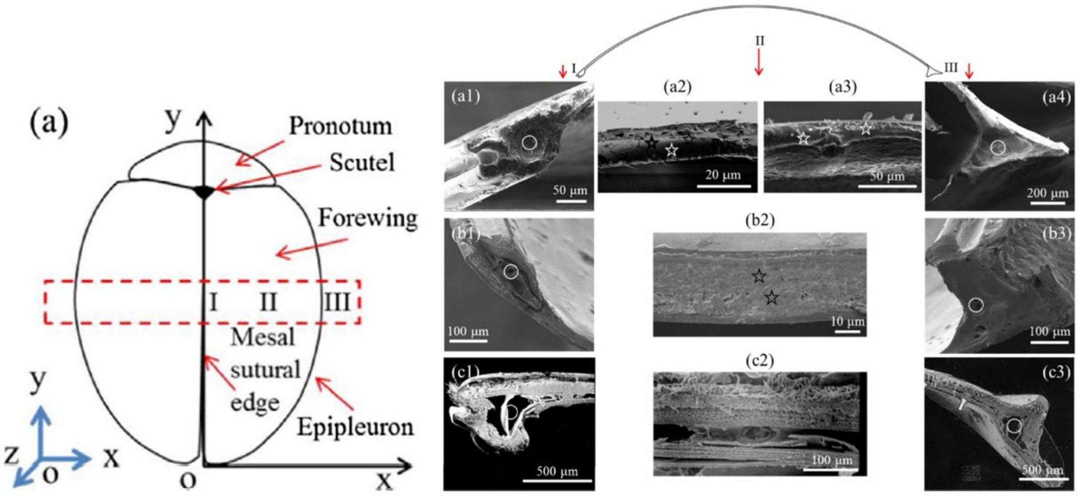


Fig. 4.4, the structure of the forewing of the ladybug under the electron microscope. Image credits to Jinxiang Chen. https://www.sciencedirect.com/science/article/abs/pii/S0968432817302184?via%3Dihub

This double-wing structure is a great inspiration for us, specifically in the combination of two different materials, i.e. hard and light materials. As we mentioned in the previous chapter, the adaptive façade is characterized by the ability to change its configuration according to the external environment to maintain that the internal environment is in the best condition, and the change is accompanied by the movement of the components, which inevitably concerns the weight and stiffness of the material and other properties. We know that most of the more common materials in the market, stiffness, and weight are proportional to the density of the material, light plus stiff materials are often more expensive, so balancing the weight, stiffness, and price of the material is also relevant for the design of adaptive façade. The inspiration from the ladybug wings is that we can use soft materials and hard materials to match, the hard materials protect the soft materials from being damaged, while the overall structural mass can be reduced, making the adjustment process more energy-efficient and thus reducing the waste of electricity.

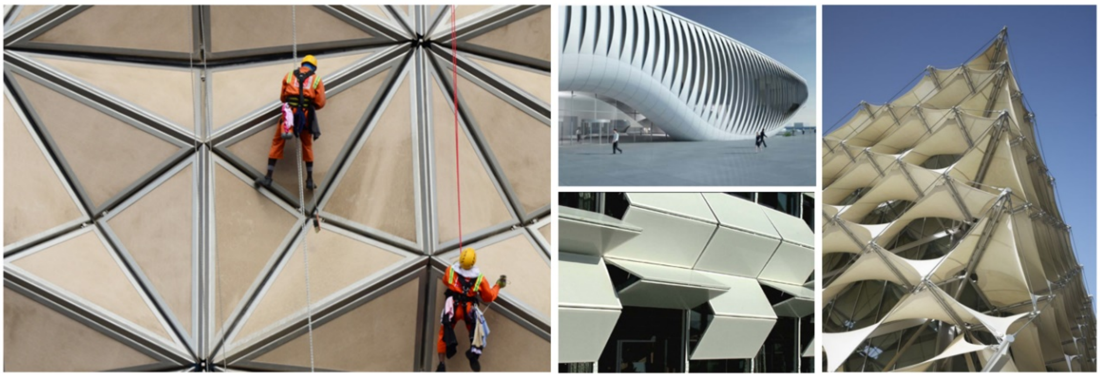


Fig. 4.5, left, Shading divices of Al bahar tower, middle top, Expo 2012 Yeosu Pavilion: Landmark Building Korea, middle bottom, DYNAMIC FACADE (KIEFER TECHNIC SHOWROOM) Bad Gleichenberg, Austria, right, King Fahad National Library, Riyadh / Saudi Arabia / 2013

The second characteristic of the ladybug wings is their foldability, which is complex but ensures the required stiffness for flight, and this is exactly the characteristic we want our design to achieve by opening and closing them in a folded way, thus controlling the shading of the building facade.

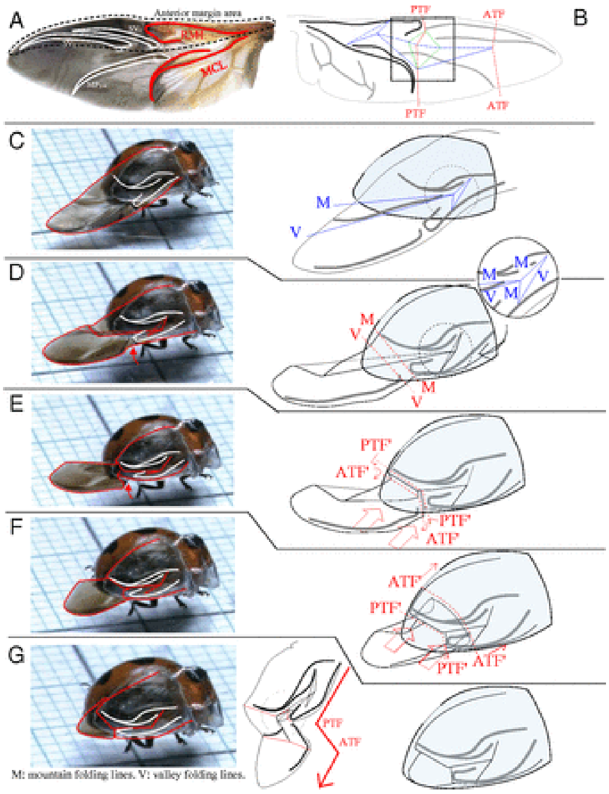


Fig. 4.6. Closing process of ladybug's wings.

Prof. Kazuya Saito's experiment well demonstrates the specific folding steps of the hind wings of the ladybug, as shown in Figure 4.6, A, B are the distribution of veins and folds of the ladybug wings, and from C to G are the specific steps of the ladybug wing stowage and the folding method. The most representative one is the diamond-shaped crease pattern shown in the box in Figure B. The four creases intersect at a point, where the ratio of crease mountain to crease valley is 1:3 or 3:1 (the crease mountain and valley represent the crease facing the observer whether it is convex or concave for naming.), through the study we found that this type of folding is commonly found in insect wings, as shown in Figure 4.7 or even in origami techniques.

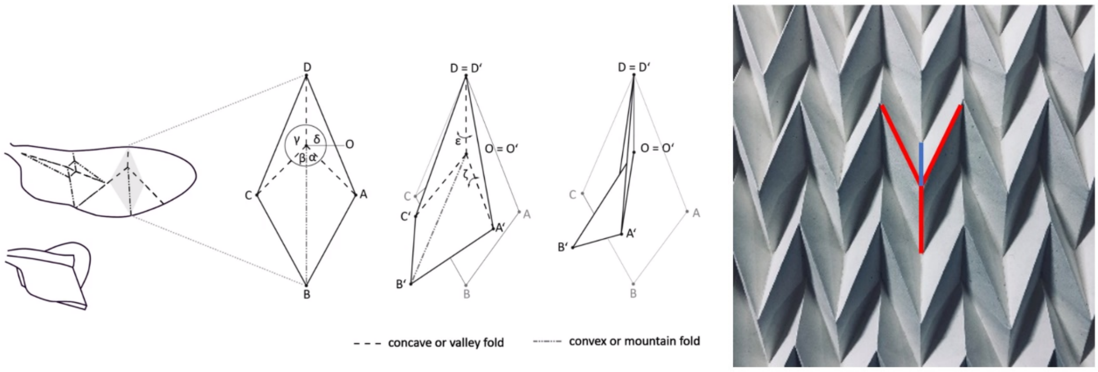


Fig. 4.7. left, folding method found in insect wings,. Photo credits to Prof. Dr.-Ing. Jan Knippers, Gundula Schieber, Anja Mader, Axel Körner, ITKE. https://vimeo.com/295534361. right, origami techniques.

This is an efficient way of folding and can easily reduce the orthographic projection area of the shading system. Changing the size of the angle between the creases can also change the overall folding configuration. In the next sub-section, we will describe this folding method and its verification.

4.1.3 Inspiration of balancing foldability and stiffness

The ladybug's hind wings are folded and stored under its front wings at the end of its flight, so the hind wings have been folded and unfolded numerous times throughout its life cycle. What unique way it can balance the folding of the wings and the stiffness of the flight triggered our thoughts and were equally inspiring for our design. Because we wanted to use a combination of two different materials to achieve the folding of the shade component, but the accumulated folding of the material also faces the problem of balancing durability and stiffness considerations, we hope to learn from the ladybug's wings and try to find a solution.

4.1.3.1 Bearing structure: wing veins

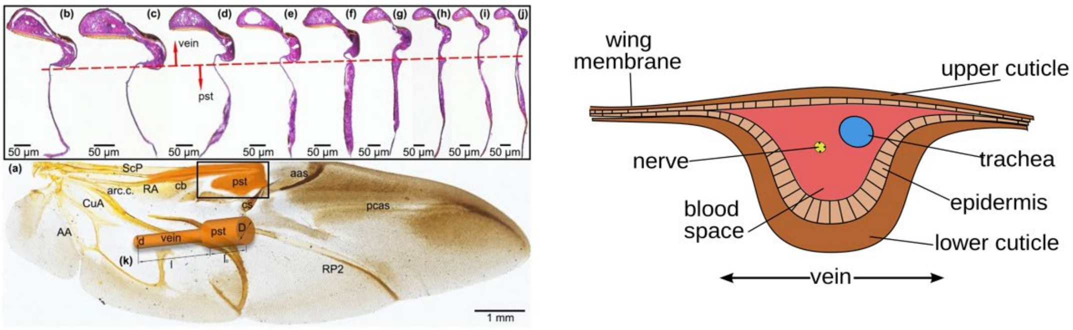


Fig. 4.8. left, insect's veins distribution, right, section of veins. Image credits to https://www.nature.com/articles/s41598-020-68384-6, https://es.wikipedia.org/wiki/Ala_(insectos)#/media/Archivo:Crossecion_of_insect_wing_vein.svg

Each wing is supported by a venous system, wrapped by a membrane, which is formed by two layers of integument closely apposed, which are distributed as shown in the figure 4.8. As the wing develops, the dorsal and ventral sides are closely apposed by the membrane layer and the remaining areas form channels, the future veins. The cuticle surrounding the veins thickens and is more heavily sclerotized to provide strength and rigidity to the wing, which is the reason why it can undergo multiple folding but still have stiffness.

When it comes to folding, we must mention the load-bearing structure on insect wings: wing veins [4.3] [4.4]. The structure of insect wings is very important to ensure that the wings are strong. Take the oldest insect dragonfly as an example. The long and transparent wings of the dragonfly are not smooth and translucent but are covered with interlaced wing veins. These veins are densely divided on the wings of insects, dividing the wings into small grids one after another, and it is these tiny grids that increase the toughness of insect wings by a full 50%. However, the more veins on insect wings are not the better. Because too many wing veins increase the weight of the wings, making insects more strenuous to fly. Therefore, nature has found an optimal point for the wing vein distribution on insect wings, that is, when a part of the wings is damaged, the wing vein distribution can just prevent the crack from extending, and there will be no more wing veins produced.

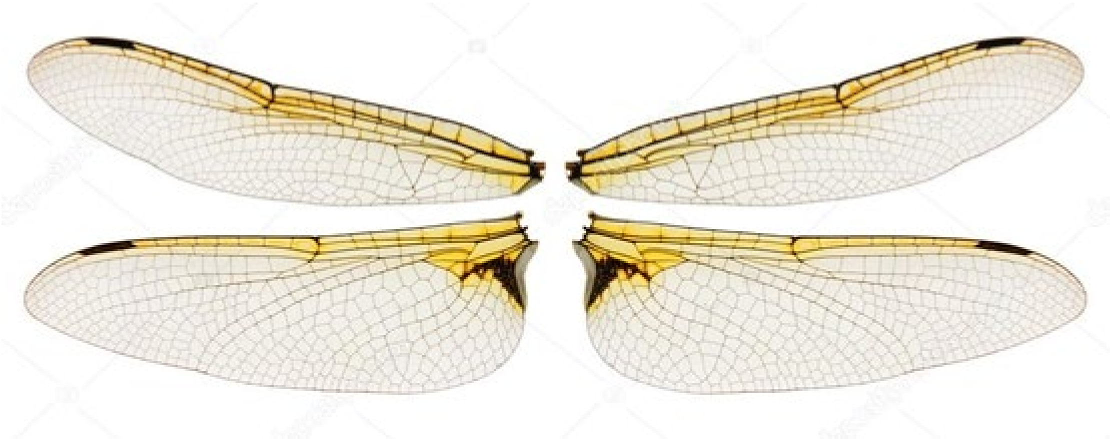


Fig. 4.9, Dragonfly wings structure,https://stock.adobe.com/

4.1.3.2 Folding buffer structure: elastin

The wing vein structure similar to insects has been widely used in the formation of membranes, but there is still another very useful structure on insect wings: elastin. The researchers found that the crease pattern of insect wings corresponds to the distribution of elastin along the insect's wings. Resilin is a rubber-like protein that stores elastic energy along the crease to promote the folding and unfolding mechanism. Therefore, the distribution of elastin is often used as a tool to analyze the folding patterns of insect wings. Elastin is distributed on both sides of the folded wing veins. When the insect wings are folded, the wing veins and wing membrane are protected by elastic materials, which act as a buffer zone.

Fig. 4.10. Creases of insect wings,. Photo credits to Prof. Dr.-Ing. Jan Knippers, Gundula Schieber, Anja Mader, Axel Körner, ITKE. https://vimeo.com/295534361.

For us, elastin is an excellent folding structure for membrane structure. The membrane structure has poor tolerance when facing folding. We can consider incorporating this structure into our design to extend the life of the membrane folding structure. The specific research and design will be described in detail in the structural design chapter.

4.1.3.3 Special folding pattern

Some insect wings have impressive horizontal folding patterns to increase storage capacity. These lateral folds are actuated remotely by other parts of the folding pattern. Therefore, these creases can be used to unfold complex patterns with a limited number of actuators. Dermpaptera and Blattodea have studied the wing folding patterns of various insects. The most typical pattern is shown in the figure below. They abstracted them into configurations that can be folded in two different ways. This configuration has a vertex and four creases intersect to form four slices or sectors. None of the creases are aligned with each other on the other side of the vertex. Due to this characteristic, the pattern can be folded and unfolded in two different ways by rotating the two sheets of paper along their common crease line.

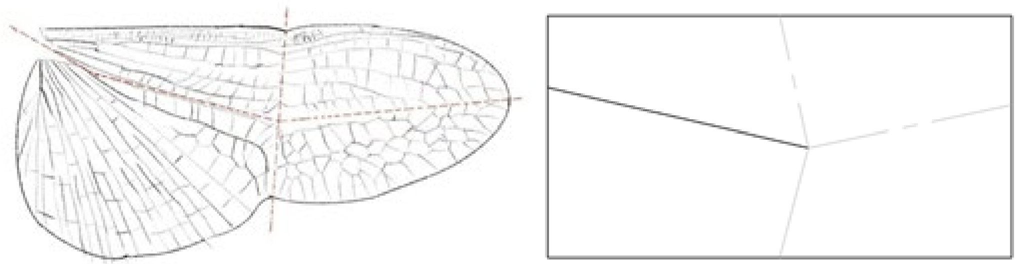


Fig. 4.11, Wing folding zone

4.2 From wings folding to origami

Professor Kazuya Saito demonstrates the exact process of folding the wings of a ladybug using origami, as shown in the figure 4.12, which is a very good way to realize the translation from biology to design, to visually verify the feasibility of folding, and to easily record the creases and change them easily. In this subsection, we learn more insect wings and classify them according to the folding method and verify their feasibility with the origami method.

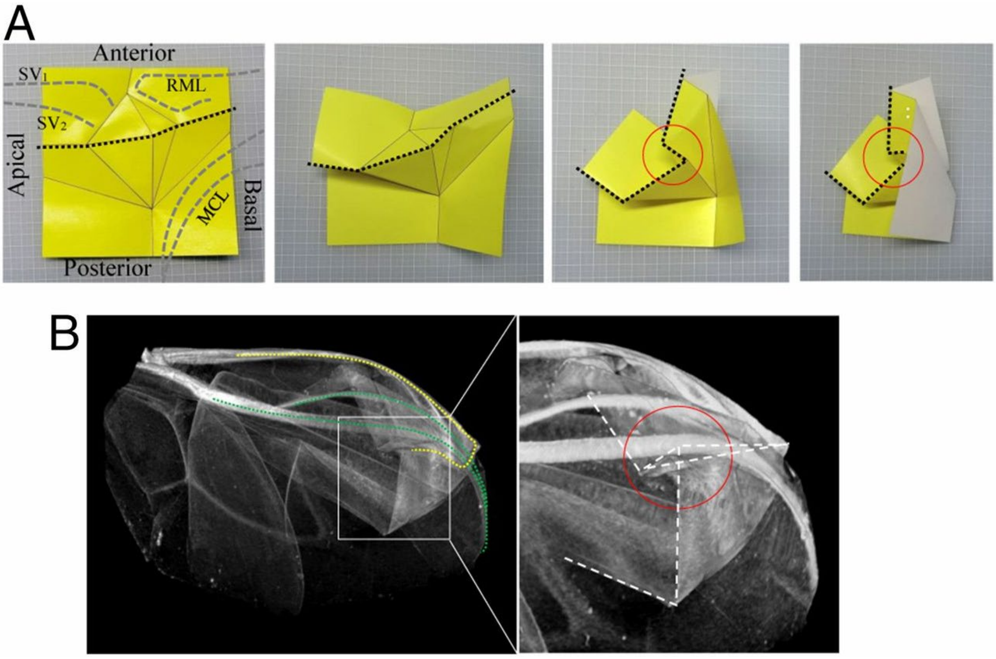


Fig. 4.12, Using origami to show the steps of storing the ladybug's hind wings, Photo credits to Kazuya Saito, https://www.pnas.org/content/114/22/5624

4.2.1 Classification of Folding Types of Insect Wings

In addition to the above-mentioned inspiration from the structure and graphics, we still hope to get more inspiration from the folding method of insect wings, so we have made some explorations and conclusions about the folding of various insect wings.

First, we need to clarify the type of insect we want to focus on:

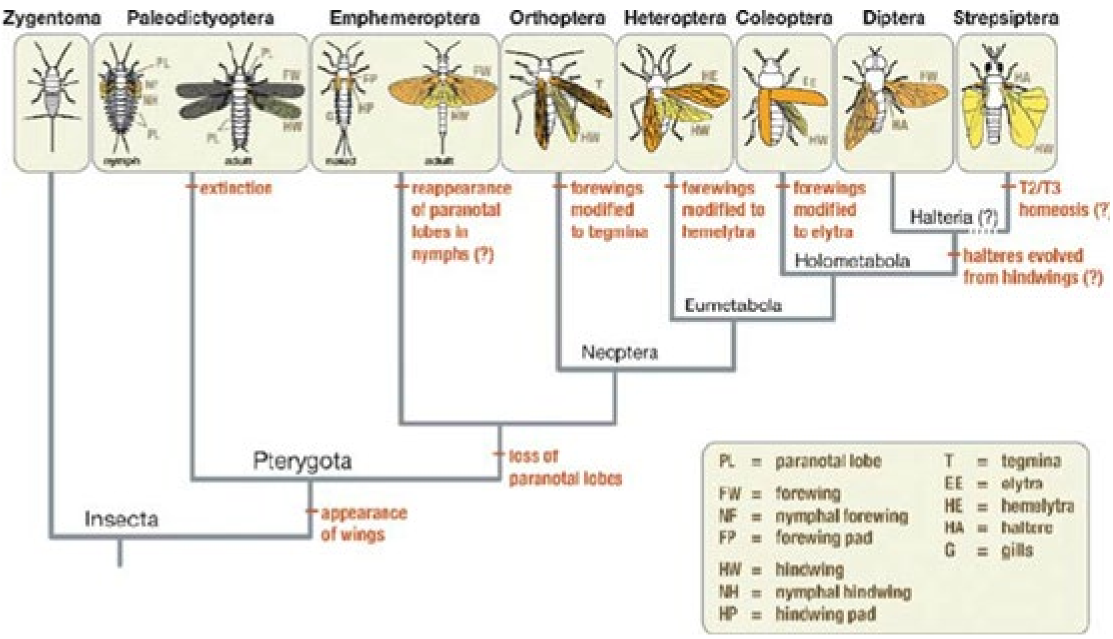


Fig. 4.13, Insect wings and insect classification

Stark contrasts between the wings distinguish the four largest orders of insects (and, in fact, the wings are the principal distinguishing factor in the hierarchy of insects and are the reason for the 'ptera' ending of order names).

4.2.1.1 Coleoptera

In addition to a pair of membranous wings, the Coleoptera have converted the front pair of wings into thick, hard shields which protect both the hind (flying) wings and the beetle's body as demonstrated by the Tortoise beetle (photo).

4.2.1.2 Hymenoptera

Wasps and bees, in the order Hymenoptera, keep their two pairs of wings together with a zipper-like structure to allow the wings to act as a single pair, as a single flight surface provides greater stability and flexibility during flapping flight.

4.2.1.3 Epidoptera

The large wings of the Lepidoptera are covered with countless tiny scales of the same material as the wings themselves. These scales are colored or just refract the light to produce the beautiful patterns that we see every summer and obscure the wings which are as transparent as a housefly's.

4.2.1.4 Diptera

The Diptera, one of the most recently evolved insect orders, are the Red Barons of the insect world. The common housefly (photo) has converted its hind wings into stumps which act as a gyroscope to stabilize it. This is the reason why flies are able to dart about as they do, changing direction suddenly, turning right angles, even flying backwards.

4.2.1.5 Exopterygota

They are distinguished from the Endopterygota (or Holometabola) by the way in which their wings develop. Endopterygota develop wings inside the body and undergo an elaborate metamorphosis involving a pupal stage. Exopterygota ("external winged forms") develop wings on the outside of their bodies without going through a true pupal stage, though a few have something resembling a pupa (e.g., Aleyrodidae).

Among these classifications, our main research objects are insects of the order Coleoptera whose forewings receive their hind wings, and those insects of the order Hymenoptera that have folding behavior.

4.2.2 Summary of the folding types of insect wings

Among the many insect species, not all insect wings fold. Most of the folding phenomenon occurs in Coleoptera. Of course, other kinds of insects also have wings folding phenomenon, such as Hymenoptera wasps.

We divide the wing movement into 4 different basic movements, including the rotation of the overall wing and three types of folding, namely fan folding, horizontal folding and vertical folding. These basic deformations can be combined to form complex deformations of wings. In other words, we can say that all the movement of insect wings can be divided into a combination of simple folding and simple rotation.

4.2.2.1 The first type: simple rotation

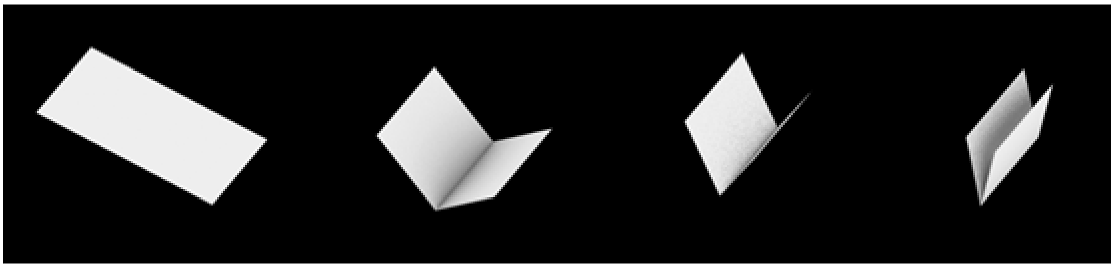


Fig. 4.14, simple rotation model of wing in rhino

The most common case of rotating wings is the Lepidoptera butterfly.

Fig. 4.15, butterfly wing movement from http://www.google.it

If the butterfly is a simple two-dimensional rotation, then when the rotations of different dimensions are combined, there is a multi-axis rotation of the wings:

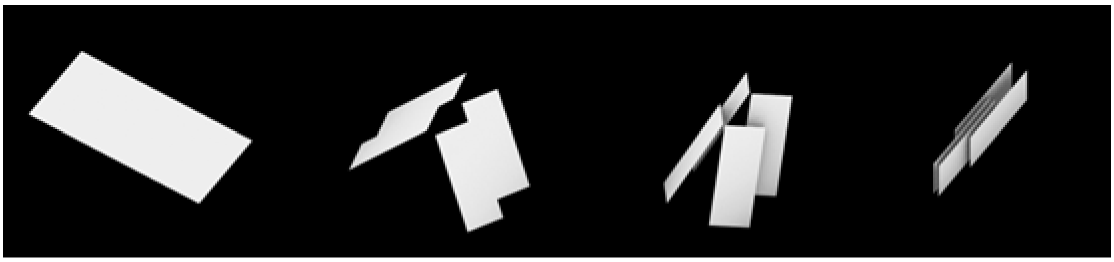


Fig. 4.16, multi-axis rotation model of wing in rhino

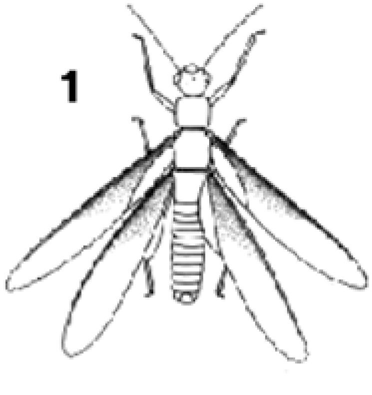


Fig. 4.17, insect wing movement from http://www.google.it

4.2.2.2 The second type: fan folding

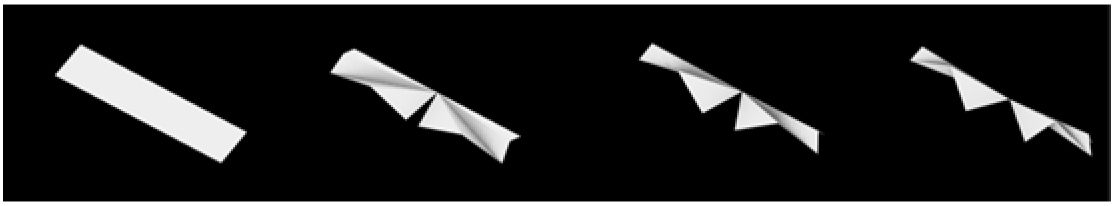


Fig. 4.18, fanl folding model of wing in rhino

Representative insect：stick insect

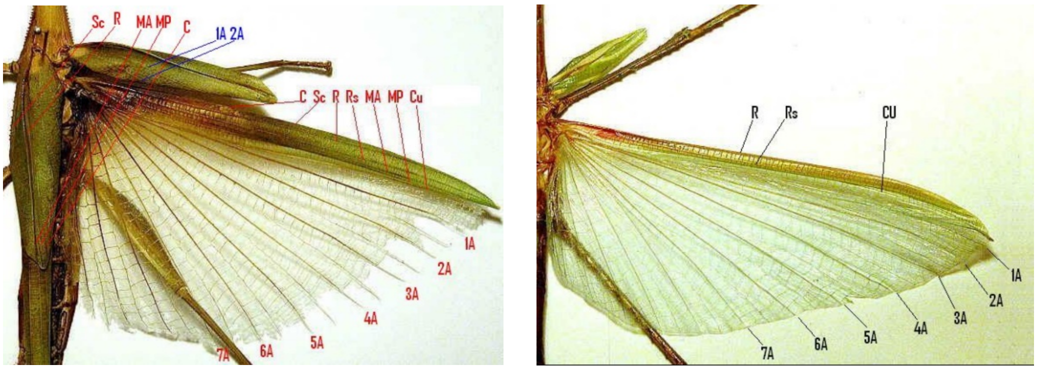


Fig. 4.19, stick insect wing folding from
https://www.oocities.org/brisbane_insects/InsectWings.htm

4.2.2.3 The third type: horizontal folding

Fig. 4.20, horizontal folding model of wing in rhino

Representative insects: Pachnoda marginate

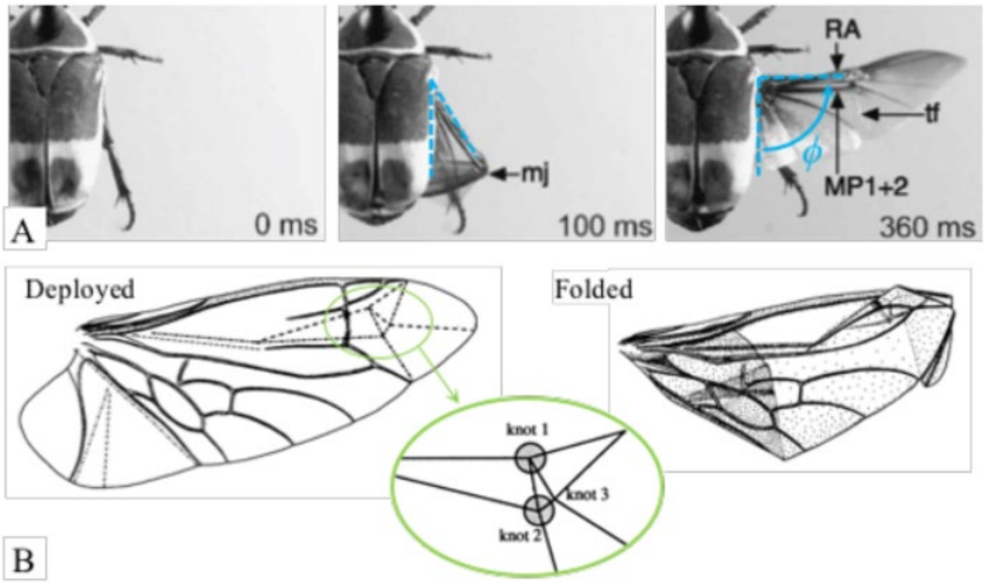


Fig. 4.21, Pachnoda marginate wing folding from Published in 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2016 A drone with insect-inspired folding wings

4.2.2.4 The fourth type: long direction folding

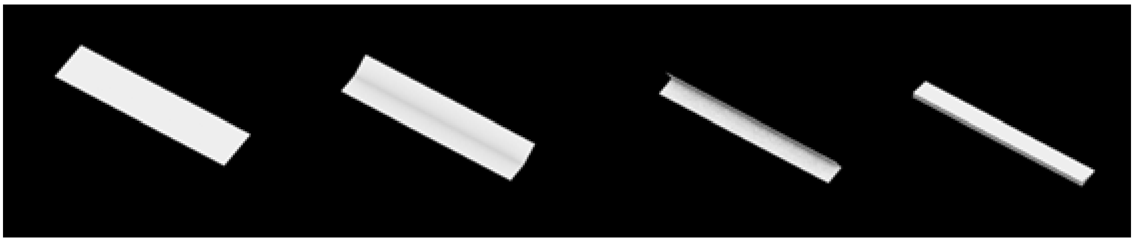


Fig. 4.22, long direction folding model of wing in rhino

Representative insects: Wasp

Fig. 4.23, Wasp wing folding https://commons.wikimedia.org/wiki/File:Waspwings_folded.JPG

In practice, more of the folded wings of coleopteran insects are folds that are a complex combination of horizontal and horizontal folds, such as paederans. The special feature of the paederus is that the same wing has two different folding methods. The left side is mainly vertical folding, and the right side is mainly horizontal folding.

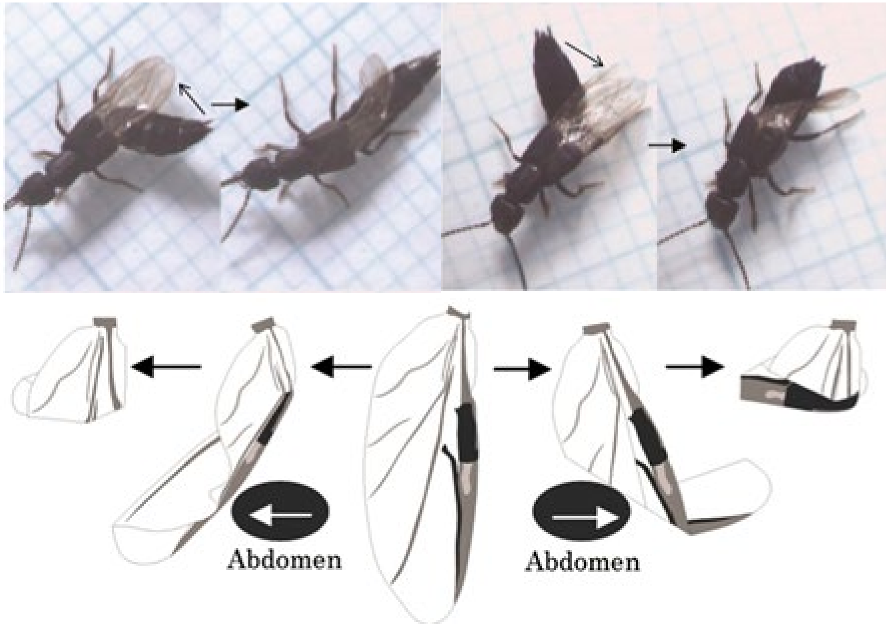


Fig. 4.24, Rove beetle wing folding process

from: Asymmetric hindwing foldings in rove beetles by Kazuya Saito, Shuhei Yamamoto, Munetoshi Maruyama, and Yoji Okabe

4.2.2.5 The fifth type: Center folding

In the same way, when insects add the other two folding methods to the fan-shaped folding, and combine them with horizontal and horizontal folding repeatedly, there will be the folding of earwig wings:

Fig. 4.25, Earwig wings' folding process. Image credits to https://ethz.ch/en/news-and-events/eth-news/news/2018/03/earwigs-and-the-art-of-origami.html

The picture above is a model simulation of earwig wings from ETH. It can be seen that the folding of earwig wings is not a single method of folding, but a complex folding composed of simple folding, first center folding, then horizontal folding (same process with the third type).

Fig. 4.26, Center folding demonstrated in origami.

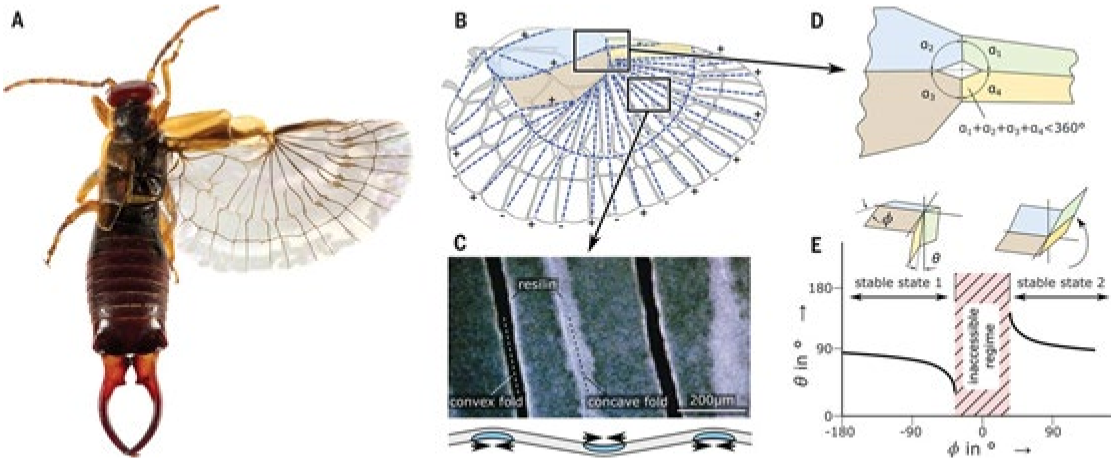


Fig. 4.27, Earwig wings' resilin distribution. Image credits to https://science.sciencemag.org/content/359/6382/1386/tab-figures-data

4.2.3 The most feasible method of folding

4.2.3.1 Basic horizontal folding

We exploded the rectangle into two figures along the structural axis, and we can find that the original figure is obtained by superimposing two folding figures with similar principles. In these two graphs, the peak and valley fold lines appear alternately and can be folded and extended indefinitely according to this principle, so we have the following basic folding method:

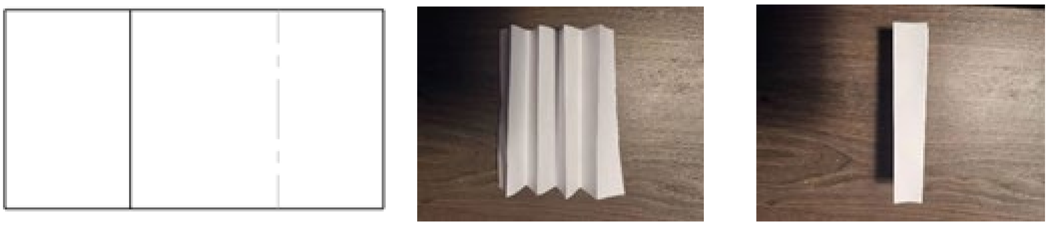


Fig. 4.28, Horizontal folding.

4.2.3.2 Miura folding (point-to-point folding, collinear folding)

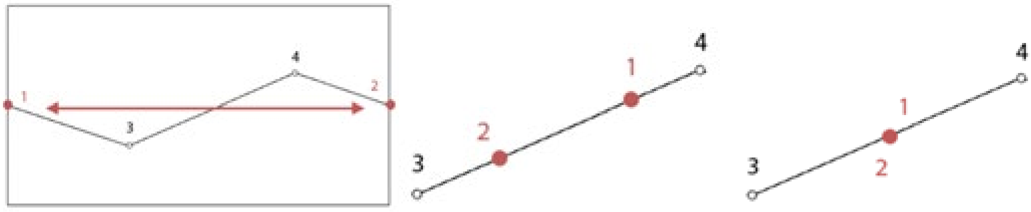


Fig. 4.29, Section of Miura folding

When we focus on the structural axis, folding graphics can be simplified as point-to-point folding or can be called collinear folding. The principle is to store each segment of the polyline on the shaft on the same straight line, or it can also be interpreted as: the two end points of the shaft approach each other, which is a point-to-point folding method. This folding method reminds us of Miura folding.

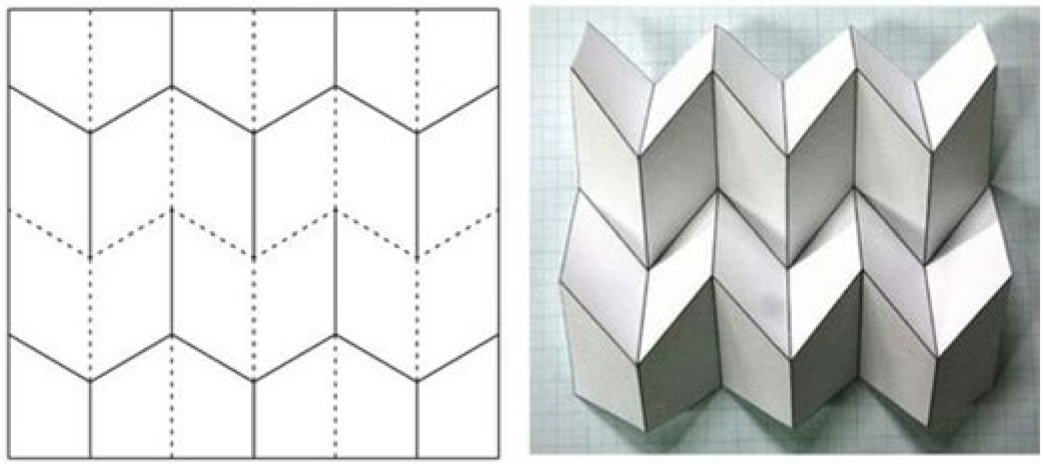


Fig. 4.30, Miura folding

4.2.3.3 Center folding variation

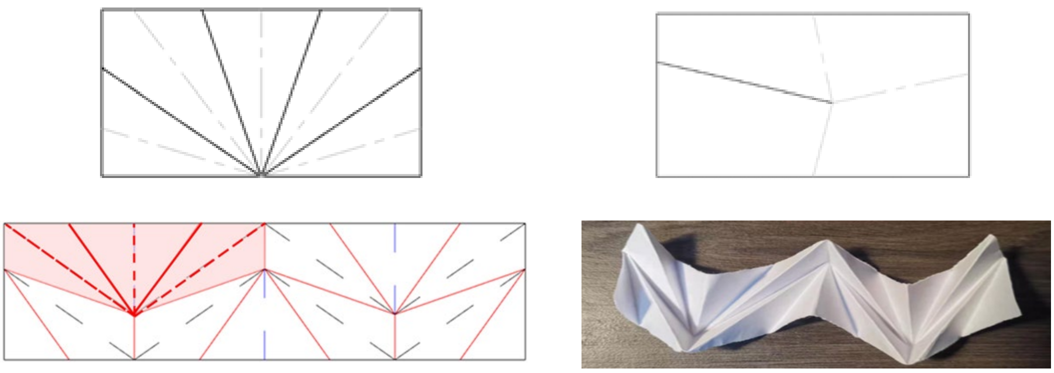


Fig. 4.31, Center folding variation

The central folding increases the precision of the unfolding, allowing more intermediate forms of folding and unfolding. This fold combines the Miura fold and the center- folding in a way that has clear bionic traces. To verify its folding effect, we describe in the next section how one of the designs uses this folding method.

4.2.3.4 Further folding principle: the study of several special Coleoptera insects

After completing the folding analysis of the wings of birds and insects, we explored the changes, progress and differences of insects in these two ways based on the three-fold and two-point folding.

Our main research object is insects of the order Coleoptera, therefore, here we have selected several representative insects:

The most classic coleopteran insects with folded wings:

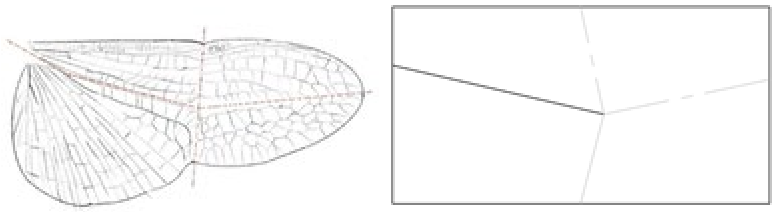


Fig. 4.32, Creases of insects' wings.

This folding method is the most common folding method for coleoptera insects.

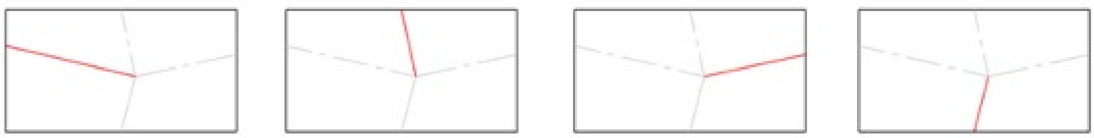
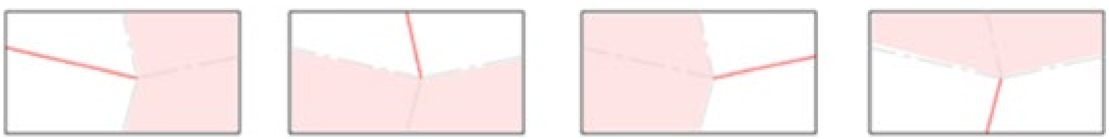
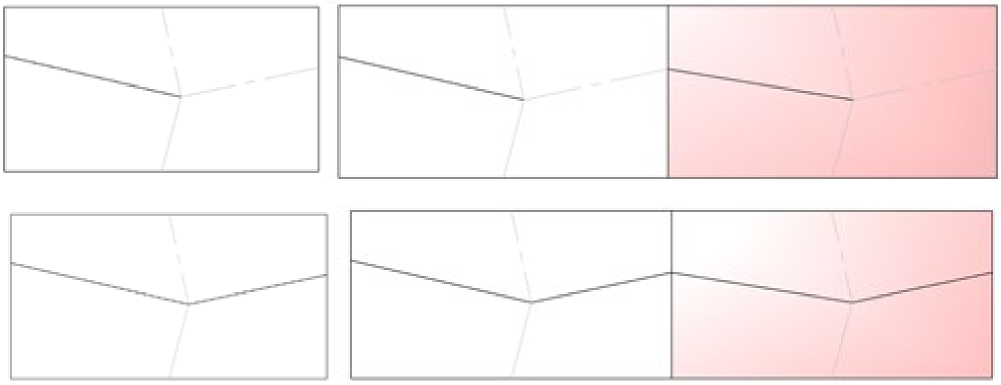


Fig. 4.33, Mountain creases distribution of insects' wings.

This folding method can be regarded as a two-step folding. The wings are divided into two parts for folding. The internal structure of the two parts of the wings is different. Corresponding to the skin design, it can correspond to two different skin materials which have different light transmission, weights, hardness, etc.



We can first call this kind of fold as a three-one-fold: as the name implies, a fold composed of three peak fold lines and a valley fold line at one point. Since the peak and fold lines of this folding are not continuous, there is no continuity in the pattern (the continuity here refers to whether the folding can be continued in a similar folding pattern or way). On the basis of considering the continuity, we can further extend its variant folding, that is, the folding of two peak fold lines and two valley fold lines alternately, which also returns to the fold we analyzed from bird wings.



Paederus: There are two different folding possibilities on the same wing

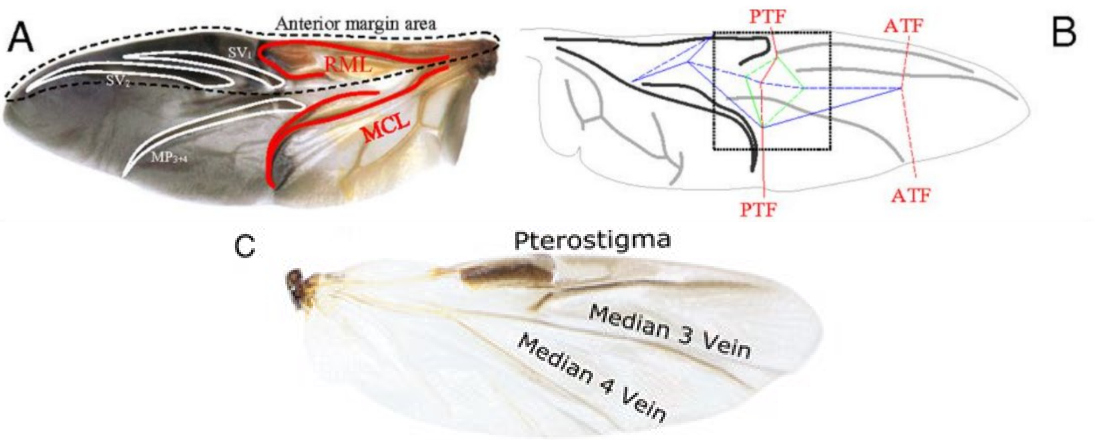


Fig. 4.34, Hindwings of ladybugs and beetles, Photo credits to Kazuya Saito, https://www.pnas.org/content/114/22/5624

https://www.pnas.org/content/pnas/111/46/16349.full.pdf

This insect's wings provide two different folding methods. For insects, these two folding methods represent different folding times to meet different needs. For us, setting two different folding methods on the same folding skin may become a new design possibility. Different folding methods of the same skin are likely to help us achieve wider applicability, and through a suitable design, it is also possible to merge two sets of folded creases to solve the problem of overly complex structure.

4.3 Conclusion

In this chapter, we are inspired by the special wing structure of the ladybug and summarize its characteristics. The biggest features that can be applied to the architectural field are: 1. the collocation of light and hard materials; 2. The foldability of the hind wings can be applied to the opening and closing of shading devices. These two features provided the original inspiration for our design. We also found that the hind wings of ladybugs are light, rigid and durable. After studying them in depth, we found that their vein structure provides rigidity for the wings and elastin provides buffering for the folding structure to make the wings more durable, and these findings provided us with great help in the selection of materials to be used and the design of material cross-sections later. After classifying the insect wings according to the folding method, we selected the most feasible folding solutions and extracted their folding patterns: Basic horizontal folding, Miura folding and Center folding.

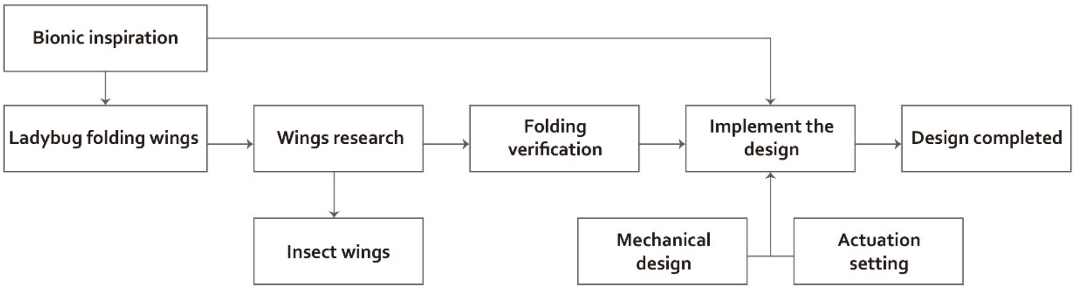


Fig. 4.35, Bionic design process

As shown in figure 4.35 is the flowchart of our design. First, we were inspired by the biological world, specifically the wing system of ladybugs reminding us of the relevance to the adaptive façade, and then we studied the wings in-depth, specifically the wings of insects. After categorizing them we verified their feasibility by using origami, achieving a formal transformation from biology to design. In order to realize each design, we still need to consider some practical issues such as mechanism, material selection, and actuation, and how they can be applied to the actual construction.

In the following chapters, we describe in detail how we applied these biological inspirations to our designs, and what technical challenges the bionic inspiration solved for our application steps.

CHAPTER 5： Design part

Abstract： This chapter is divided into two parts. The first part is the determination of design information. We will display building information, local climate information, and simple analysis of shading and wind to help us with specific shading design.

The second part is the geometry design of the facade. According to the design guidance in the previous chapter, we have completed the design of three schemes. We will introduce our design logic and ideas in detail. In the next chapter, we will evaluate and select these three options through specific simulation analysis.

5.1 Design information

We started to develop our design part after getting inspiration from the biological world and we verify the feasibility of some experiments in the way of origami. This chapter highlights some of the adaptive façade designs that emerged from our study of biomimicry, which were applied to selected testing rooms for analysis.

MADRID was selected as the test city, and a standard office building were used as the test building, because offices consume the most energy and have the highest requirements for indoor lighting effects and glare phenomena, also the density of people in ordinary office buildings is relatively high, which is the ideal building with the most critical issue to analysis.

The main direction of the experiment is divided into two parts: architecture and engineering. For the architectural part, we mainly consider the geometry of the adaptive façade, which will directly affect the aesthetics of the building facade, the shading effect of the geometric changes, and the eyesight effect of the users looking out of the windows. On the other hand, engineering needs to consider how to implement a specific solution design, including how the shading panels move, the material properties, and the actuation of the adaptive façade.

In addition, we also need to use software to simulate the scheme experimentally, through grasshopper's plug-in named ladybug and honeybee to experimentally simulate the effect of the project, so that we can more intuitively get the advantages and disadvantages of the scheme, each scheme is divided into three modes, respectively: OPEN-SEMI OPEN- CLOSED, several cases of dynamic shading test environment analysis results were compared with the same room without shading equipment. In addition, in order to ensure the accuracy of the experiment, we will also test the rooms with different orientations (South-East-West) in the same building to ensure the accuracy of the simulation results.

5.1.1 Site and Building information

For the installation of the adaptive façade, we chose an existing project with architectural drawings from an office building called FUX Center designed by Birk Heilmeyer und Frenzel Architekten. In order to adapt the project to our climate choice, we placed it in Madrid, Spain, to test the impact of the adaptive facade on the building.

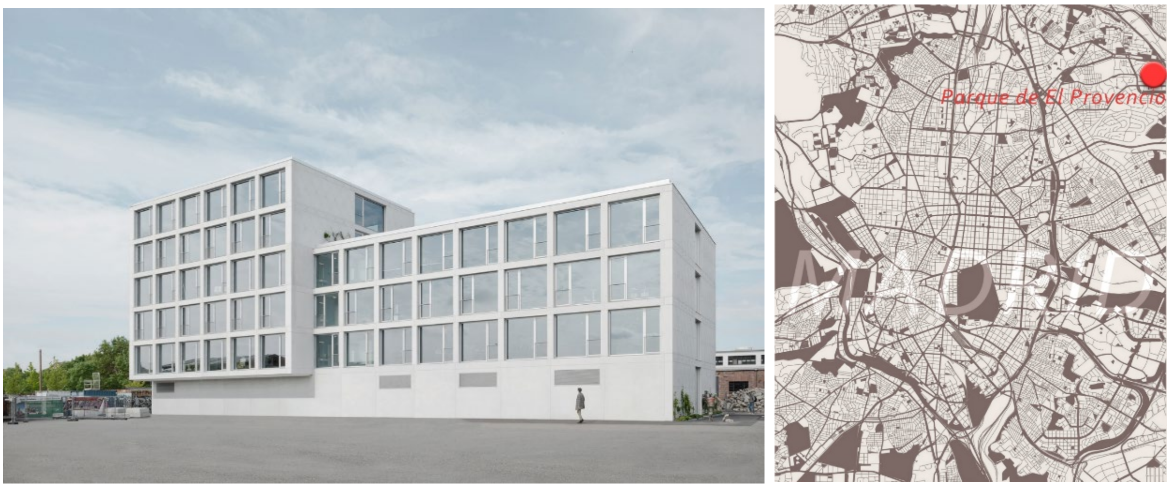


Fig. 5.1. left, Selected building photos, right, site location. Photo credits to Brigida González, https://www.archdaily.com/921355/fux-center-birk-heilmeyer-und-frenzel-architekten?ad_source=myarchdaily&ad_medium=bookmark-show&ad_content=current-user, The base layout from: raenordico.com

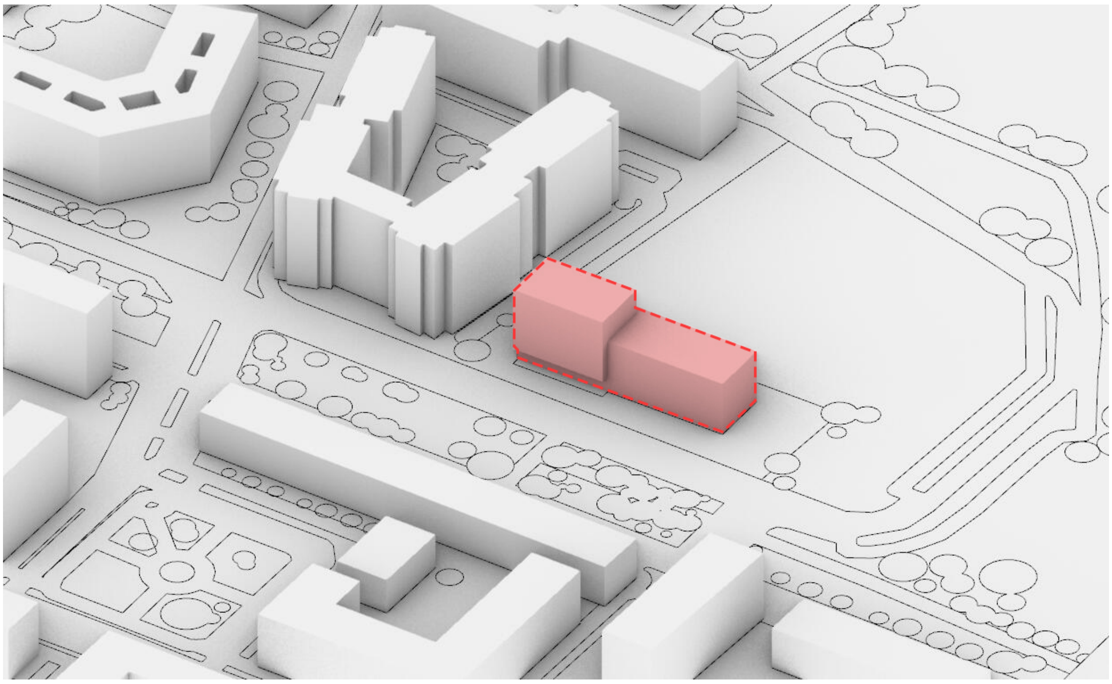


Fig. 5.2. Selected building

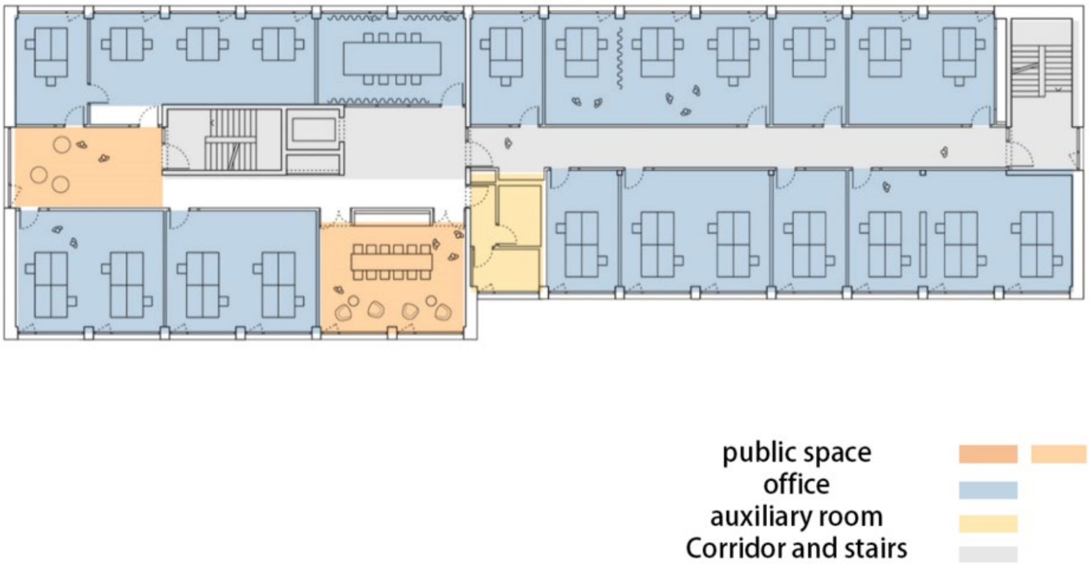


Fig. 5.3. Standard floor plan

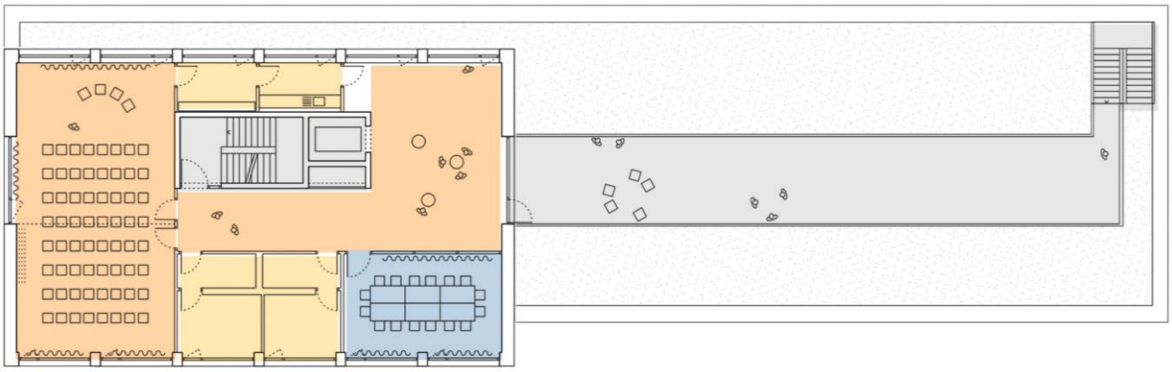


Fig. 5.4. 4th Floor Plan

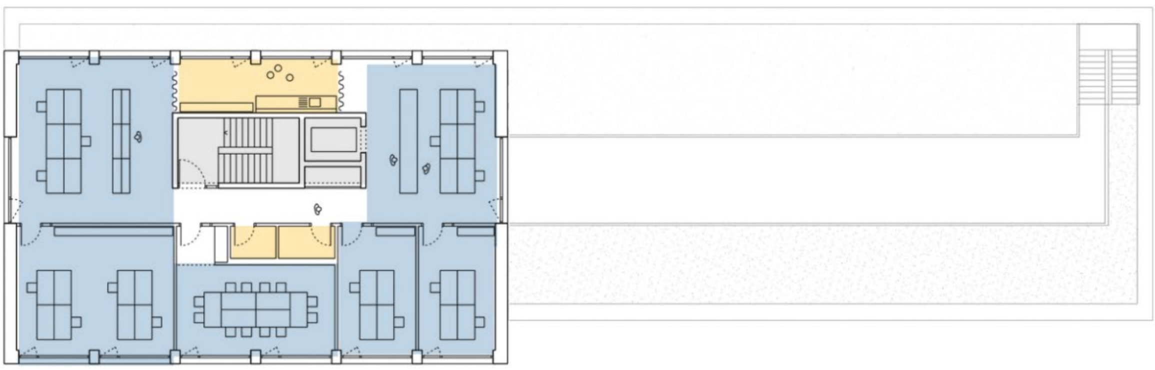


Fig. 5.5. 5th FLOOR PLAN

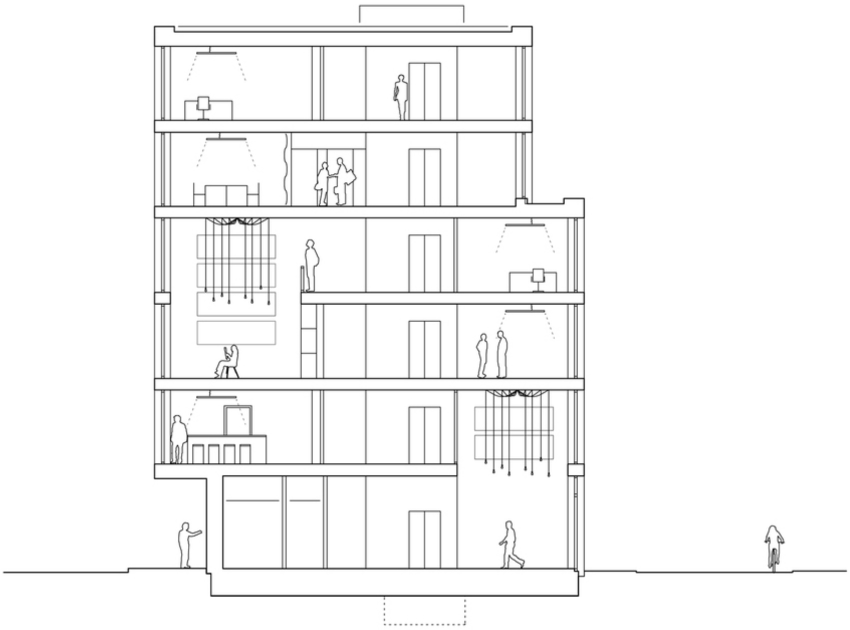


Fig. 5.6. View from east to west

5.1.2 Madrid climate information

The hourly weather data come from the Madrid International Weather for Energy Calculations (IWEC) file as collected from the US Department of Energy (DOE) database (ASHRAE 2001).

The building is located in Madrid, Spain which is the capital and most popular city of Spain. The city has almost 3.3 million inhabitants and a metropolitan area population of approximately 6.5 million. It is the second-largest city in the European Union (EU): the municipality covers 604.3 km2.

Fig. 5.7. Location of Madrid.

It lies on the southern Meseta Central, south of the Guadarrama mountain range and straddling the Jarama and Manzanares Rivers. Over a quarter of the Madrid municipal area is covered by the largely forested protected area of El Pardo.

According to the Koopper Climate Clasification, Madrid has a Mediterranean climate (Csa), which traditions to a semi-arid climate, with hot and dry summers and very or partly cold winters. over the course of the year, the temperatures typically veries from 0°C to 33°C and is rarely below -5°C or above 37°C.

Temperatures in Madrid strictly depend on seasons. Summer is characterized by quite high temperatures, most of all during July, whereas winter can fall to freezing point temperatures, especially in the months from November to February. This climate analysis will bring the design of the envelope towards the regulation of the incoming heat intake in the summer case, thus shielding the interior spaces to encourage less use of thermal machines. By the way the climate during the year is tempered, with a frequency of 70% of the temperatures above and around 18°C.

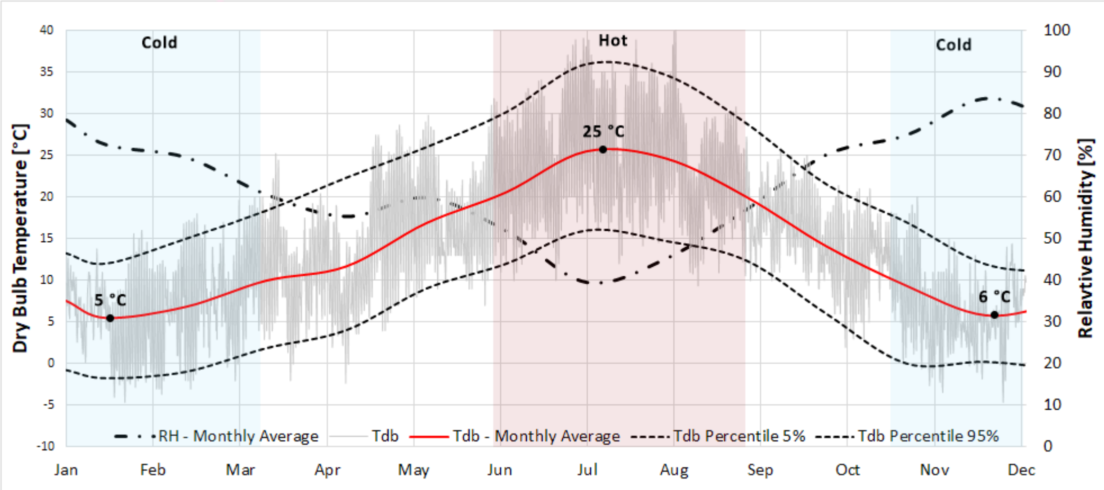


Fig. 5.8. Yearly dry-bulb t & rh distribution of madrid

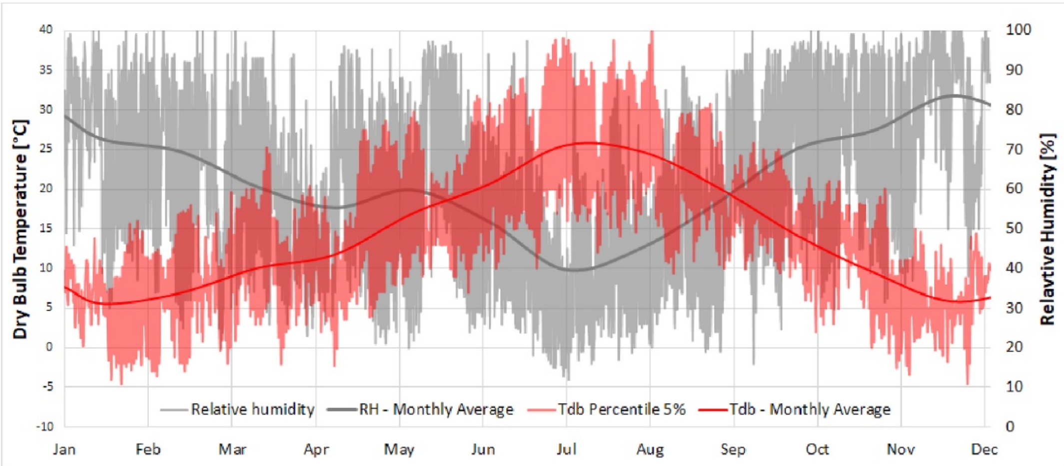


Fig. 5.9. Relation between temperature and relative humidity

The curve relationship between relative humidity and temperature is in opposite. In winter, the temperature is lower, about 5℃ to 8℃, and the relative humidity is higher, about 70%-85%; in summer, the temperature is higher, about 20℃ to 26℃, and the relative humidity is 40%-50%. These two factors will directly affect the comfort of users, if relative humidity is too high it will lead to the growth of mold in the winter, and if it is too low it will cause changes of the materials inside the building such as paper will become brittle. A good adaptive facade with maintenance structure will help the building better control temperature and humidity by providing shading and the use of reflective building envelope will also assist in reducing the impacts of exterior conditions on interior environments.

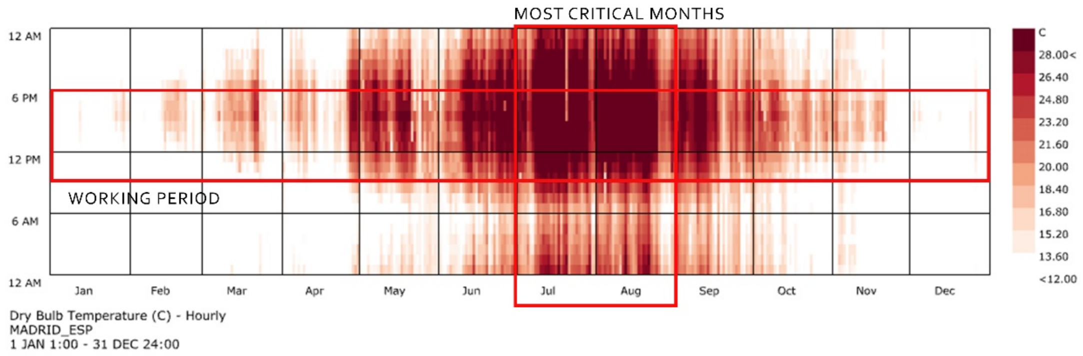
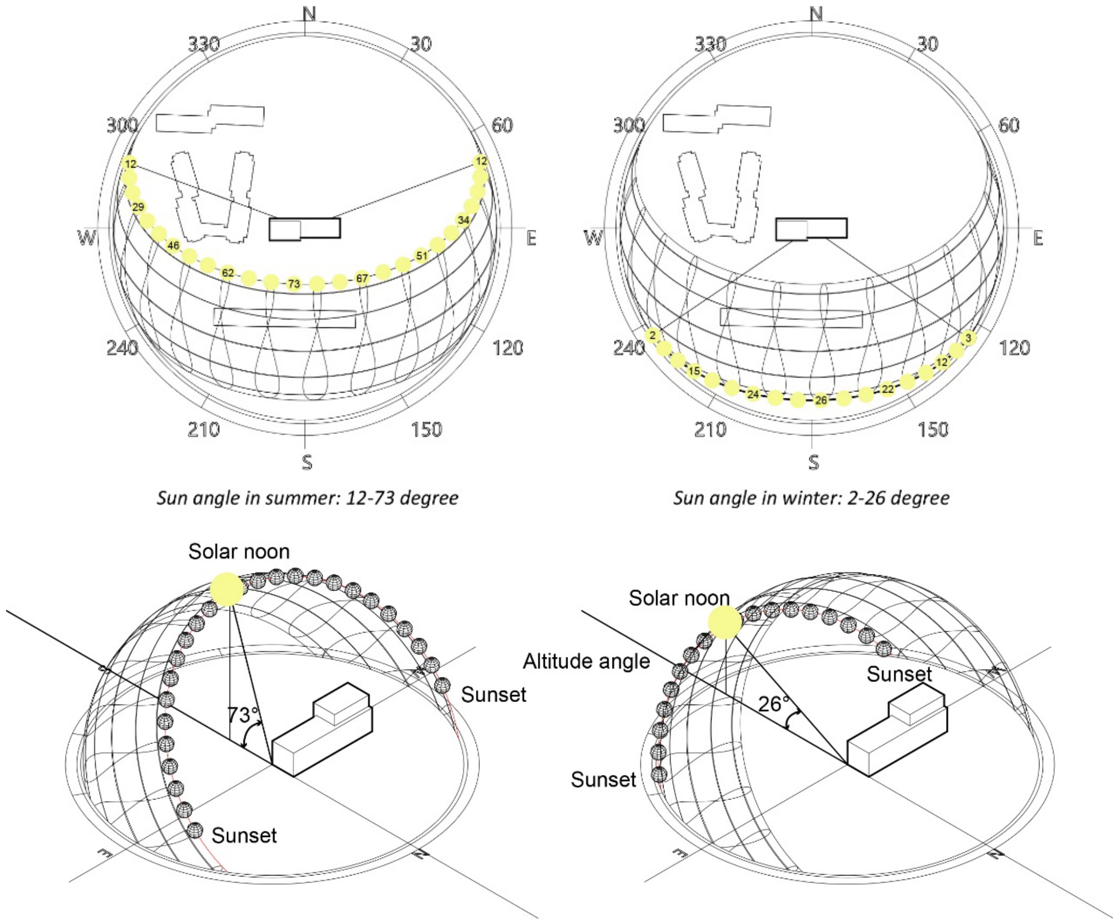


Fig. 5.10. Yearly dry-bulb temperature distribution

This picture shows the distribution of dry-bulb temperature throughout the whole year. The red line frame represents the use time of this building which is from 9 a.m. to 6 p.m. It can also be clearly seen from the picture that the month from early May to mid-October, the dry-bulb temperature in Madrid the dry-bulb temperature is relatively high, it is higher than 28℃ in the afternoon. The most severe months are July and August. The proportion of dark red in these two months is significantly higher than that of other months. Therefore, we need to note that these two months are the months when the adaptive facade needs to solve the temperature problem.



Sun angle in summer: 12-73 degree

Sun angle in winter: 2-26 degree

Sunpath on summer solstice at southern latitude

Sunpath on winter solstice at southern latitude

Fig. 5.11. Sun angle and sun path of Madrid during summer and winter.

Figure 5.11 shows the variation of the sun angle in summer and winter. For example, in summer the sun angle is high and the amount of light shining into the room is fewer than in winter, while at noon the sun angle is higher than at other times of the day. The sun angle range in Madrid is 12-73 degrees in the summer and 2-26 degrees in the winter. We will use these values when we do the analysis of daylight in the section of the test room.

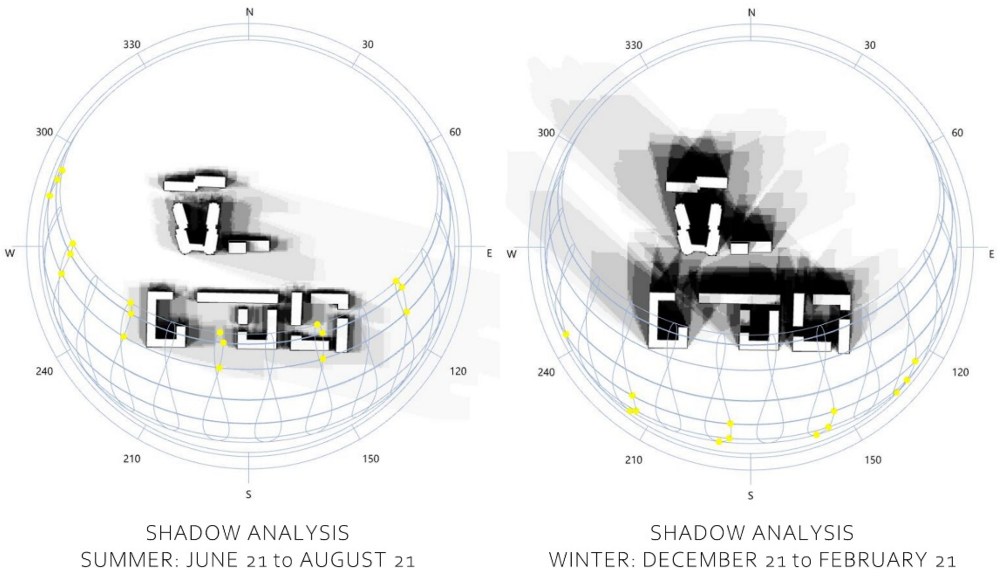


Fig. 5.12. Shadow analysis of Madrid during summer and winter.

Shadow analysis is also essential, it is an analysis of the relationship between the building and the surrounding buildings, as shown in Figure 5.12, there are two buildings on the south and west side of the building, and the building on the south side does not constitute an obstacle relationship to the building because it is farther apart. While the building located on the west side is closer to the test building, which will cause a shading relationship, and the specific thermal radiation values are shown in the simulation results in Fig. 5.13.

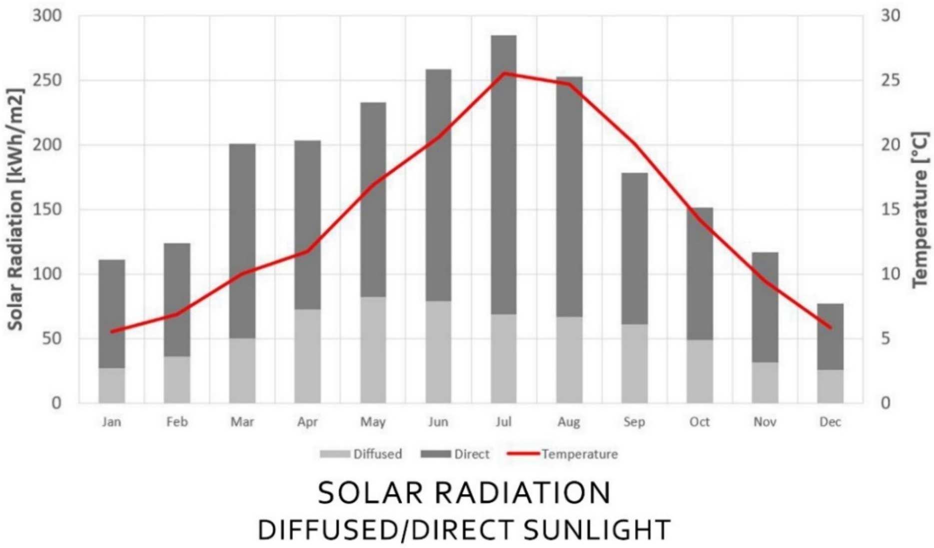


Fig. 5.13. Diffused & direct solar radiation of Madrid during the whole year.

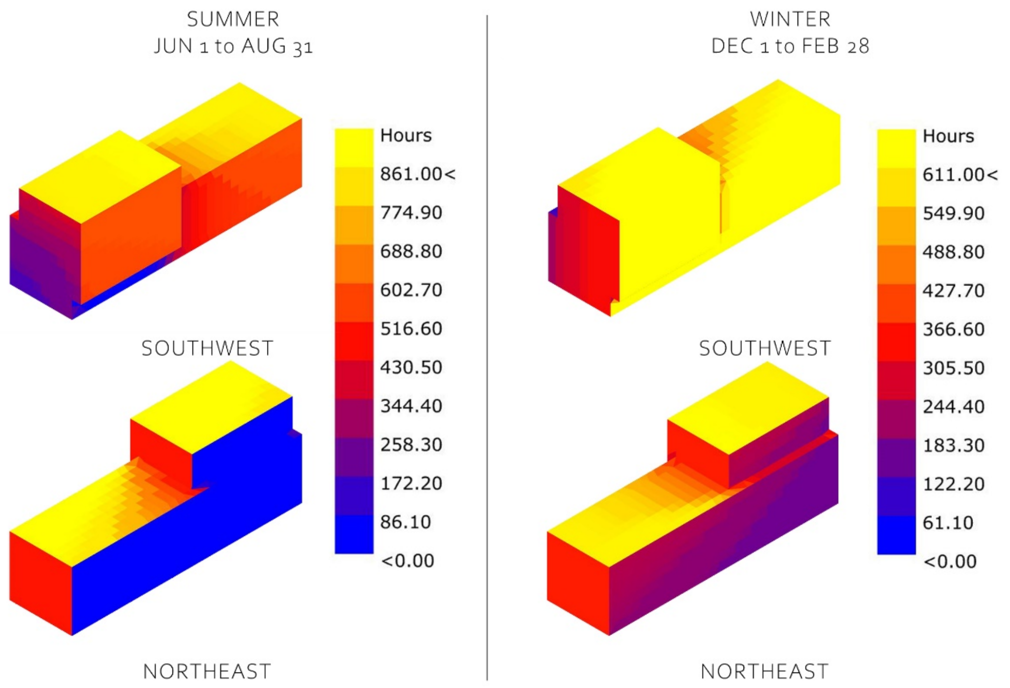


Fig. 5.14. Solar radiation analysis for each elevation of selected building during the whole year.

After the analysis, we can get the results as shown in Fig. 5.14, the analysis units are in hours. The east-west and south directions of the building are affected by thermal radiation, and the north side is slightly affected in winter. In the three directions of east, west, south, the south side is affected the most, followed by the east side. The west side is less exposed to sunlight in winter and summer because it is shaded by another building. Since the building appearance has Partially protruding, the shape provides a certain amount of shading in summer, so this shaded part has the least affected by thermal radiation in summer.

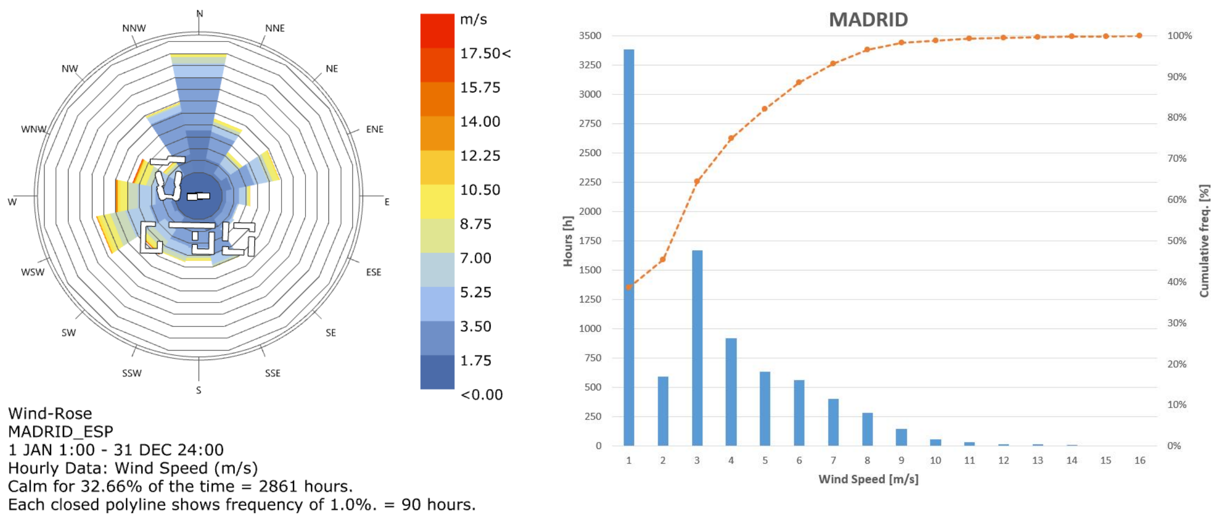


Fig. 5.15. Wind analysis of Madrid.

Wind analysis has a great impact on the building façade, mainly in terms of structural stability and adjusting the interior and exterior wind pressure, an excellent design can make good use of wind for heat exchange, improve indoor air quality through wind flow, etc. The figure 5.15 shows the wind rose of the city, we can easily read the distribution of wind speed in each direction and the frequency throughout the whole year. From the figure 5.16, we can see that the frequency of wind blowing from the south is the highest during the year, the wind speed from this direction is comparatively low, while the higher wind speed is mostly from the west side, with a wind speed of about 12-15 m/s.

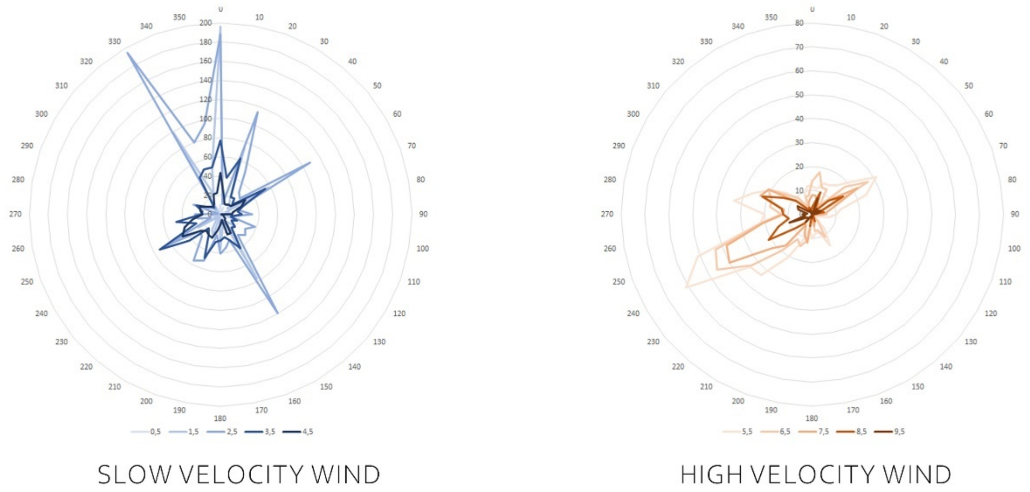


Fig. 5.16. Wind analysis of Madrid by velocity.

5.2 Design principles

Through previous literature studies on bionic architecture, insects and bird wings, we concluded that in the subsequent designs, our designs should meet the following common principles.

1. The scheme is collapsible and when the geometry is fully open the area is as minimal as possible. And the folded part should be as continuous and integral as possible, rather than separate.

2. The materials of the design are selected to be a combination of lightweight and normal facade materials, and there is a covered relationship between the materials when it folded. Just like the hard elytra of insects can protect the weak and soft membrane wings. At the same time, we hope that the “elytra” part is as small as possible, so as to reduce the load on the skin as much as possible.

3. Our design should meet the basic requirements of the building site code for indoor lighting.

4. When all the conditions are met, we hope that the skin is as lightweight, energy-efficient and beautiful as possible.

5.3 Geometry design

5.3.1 Design 1

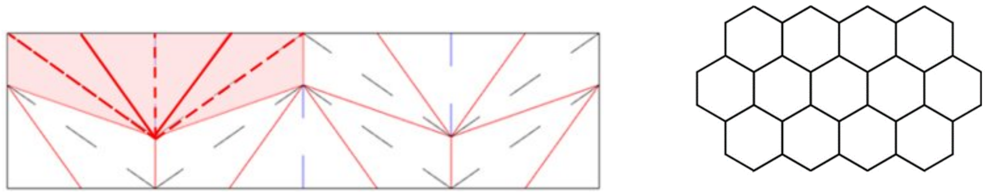


Fig. 5.17. Creases inspiration from insect wings.

From origami study, we create several useful patterns that can be used to fold a strip area. These folding methods can fold a continuous area into the smallest possible area

We chose hexagon as the shape of the basic unit and start to design from the simplest division: triangle. Inner triangle is the panel to protect the film, as the step 1 we show below. The inadequacy of the shape of step 1 is that the area of the membrane is relatively small and discontinuous. Which can't reflect our design principles well. So in step 2, we focus on improving the discontinuity problem, and try to expand the proportion of the membrane to the total area. If we want to expand the area of the membrane while ensuring that the membrane is a continuous whole. A single folding of the membrane cannot meet this demand. In order to meet the problem of continuity, we consider double folding the membrane. After trying this version, we found that the problem is that the folding angle of the membrane is too sharp and the trajectory is complicated. Therefore, we tried to use the research on the origami part to improve this problem, hoping to simplify the folding trajectory and further increase the percentage of membrane area.

From origami study, we create several useful patterns that can be used to fold a strip area. On the basis of step 2, we convert the pattern on the rectangle to the pattern on the hexagon. As showed in step 3.

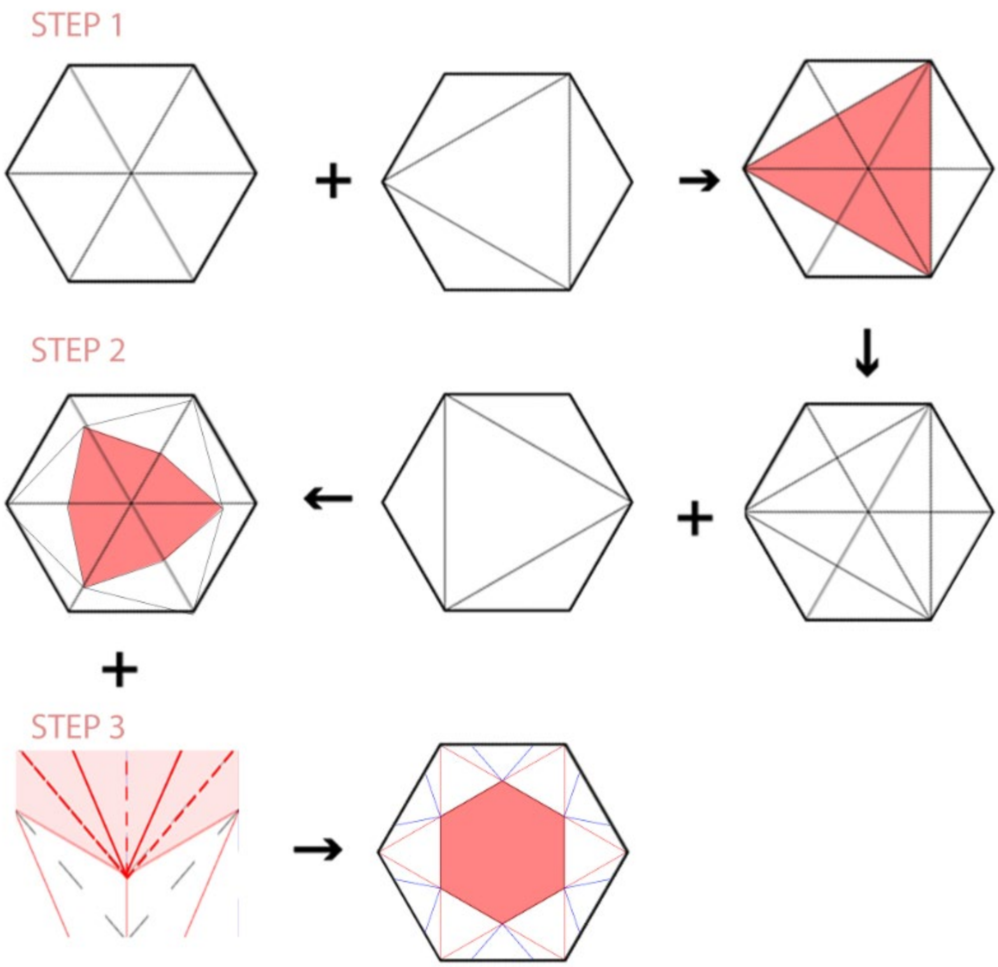


Fig. 5.18, Design geometry generation.

After the final superposition, we get the final version of Scheme 1. The last step of the step diagram shows the peak and valley lines of the membrane folding, blue is the folded valley line, and red is the peak line. Finally, the outer continuous membrane material can be completely hidden under the inner hexagonal hard material after two folds.

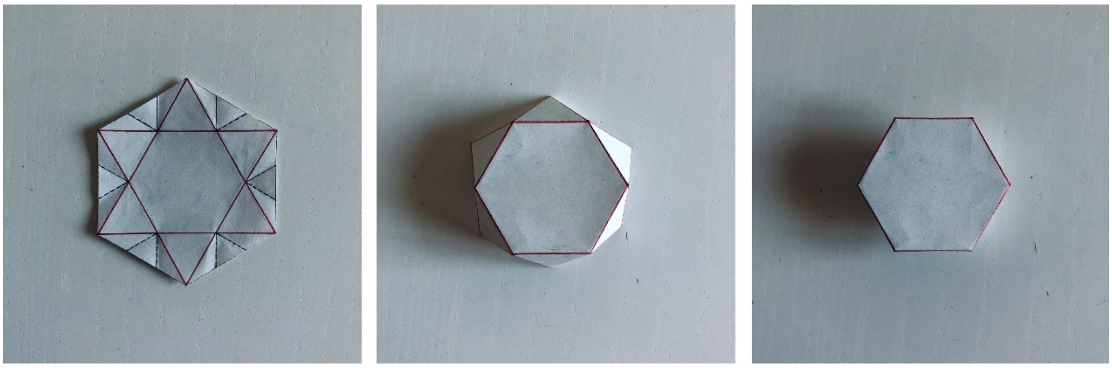


Fig. 5.19. Verification in origami method, mountain creases in red, valley creases in blue.

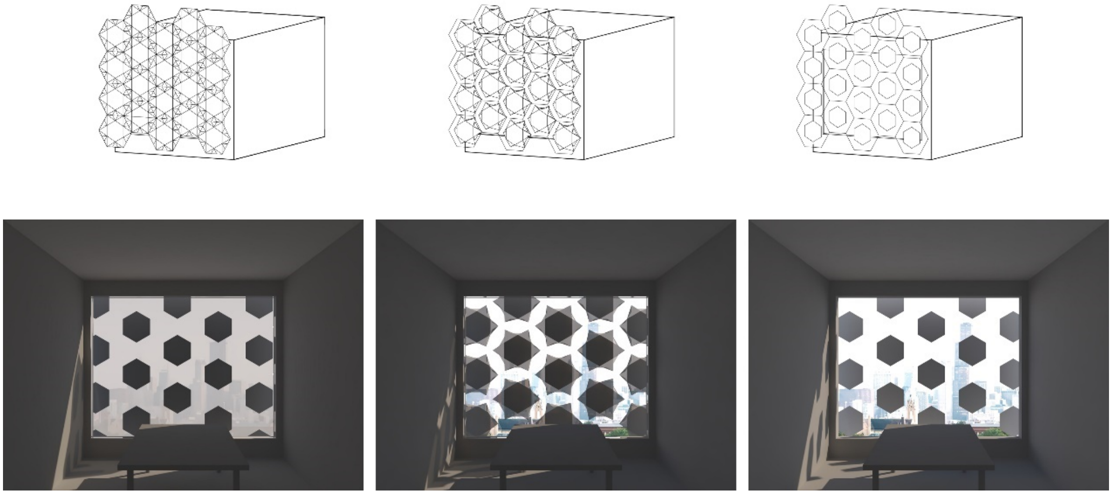


Fig. 5.20. The effect of covering in front of the test room.

5.3.2 Design 2

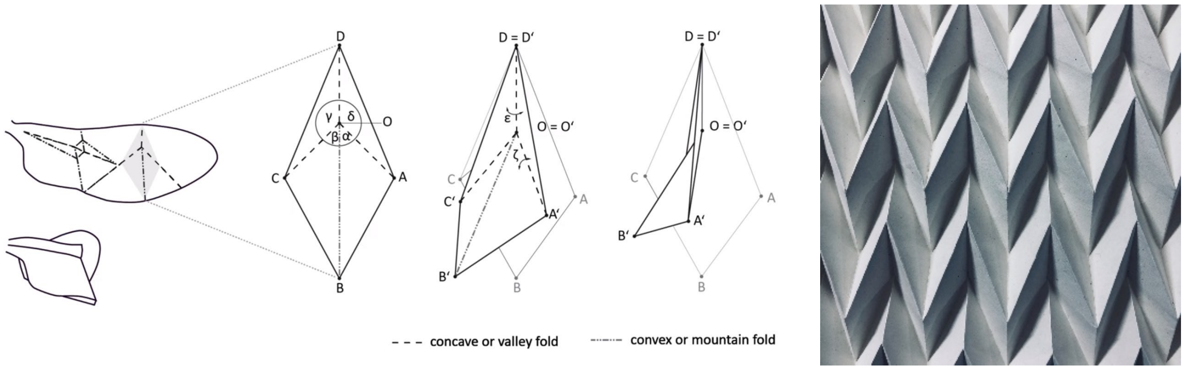


Fig. 5.21, left, folding method found in insect wings,. Photo credits to Prof. Dr.-Ing. Jan Knippers, Gundula Schieber, Anja Mader, Axel Körner, ITKE. https://vimeo.com/295534361. right, origami techniques.

The fig. 5.21 shows one of the more common folds in the process of storing insect wings, which is summarized in this technique as "Miura Fold", which is manifested by the ratio of Mountain Fold to Valley Fold at the folding point is 1:3 or 3:1. This folding method can better compress the area so that the folded object has a smaller space volume.

As in figure 5.22, the folding process requires a crease, we first need to present the crease we want in the basic geometry. In order to ensure that the geometry is as symmetrical and regular as possible, we try to connect the corner points or the midpoints of the edges as the endpoints of the folds when defining creases. This gives us the initial creases in the following figure, the first one is the figure with the corner points connected to each other, In the second figure, we only connect non-adjacent corners, this is not the only way, but by rotating we get practically the same geometry.

By superimposing the first and the second graph we can obtain the crease present in third graph, which is as regular and symmetrical as we predicted. So we set the mountain and valleys folds using the way called "Miura fold" that stated above, where the red lines are the peaks and the blue lines are the valleys to obtain the results in the fourth graph. Similarly, graph 4 is not the only possibility, as the red and blue lines can be switched to give the result of folding in the opposite direction, but in this design, we chose graph 4 as the solution. The result of this method can be divided into two parts, the red part in graph 5 is the part that faces outward during the open state, and graph 6 is the part that faces inward during the open state, this form of area division is in accordance with our initial idea, so these two different areas can be divided into different materials.

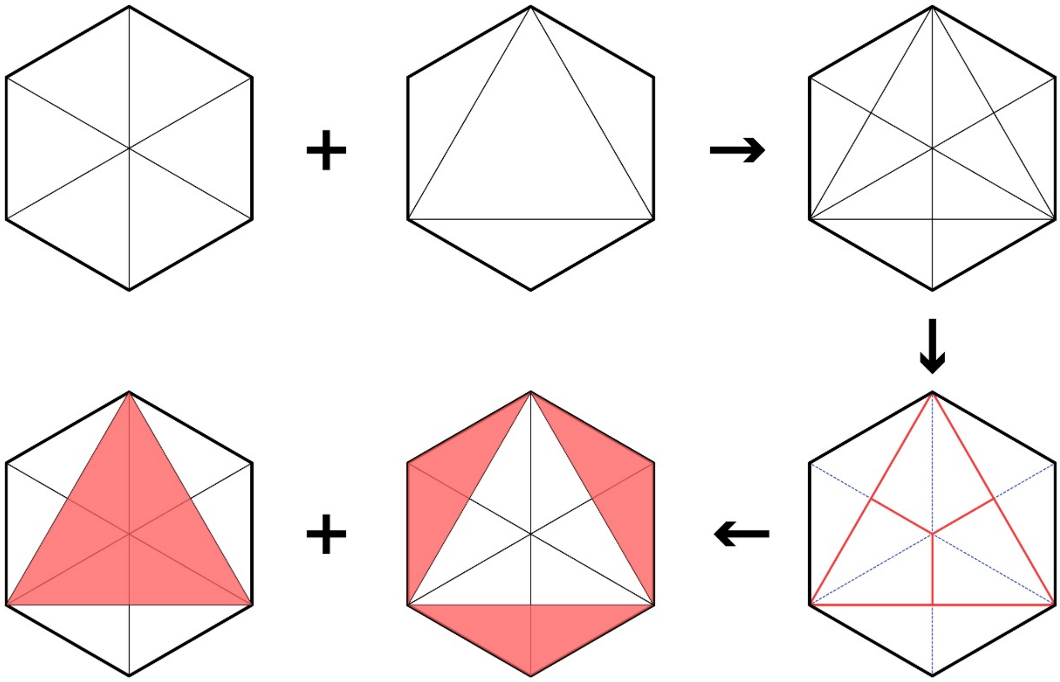


Fig. 5.22, Design geometry generation.

Before making a specific material selection, we simply divided the materials of the scheme into heavy material panels and lightweight materials, to pre-determine the characteristics of the materials and also to see the effect of the design scheme. Inspired by the wings of coleopteran insects, we wanted to use a combination of a hard panel and a soft material, with a relationship between cover and protection in the process of folding and unfolding. Folding is a way of decreasing the area in space, by folding the skin of the building, to accomplish an increase or decrease of the shading area.

In this scheme, we set the outer unit to be an opaque panel and the central part to be lightweight material, so that the outer heavy material will cover the inner lightweight material when the building skin folded, thus extending the lifespan of the building facade.

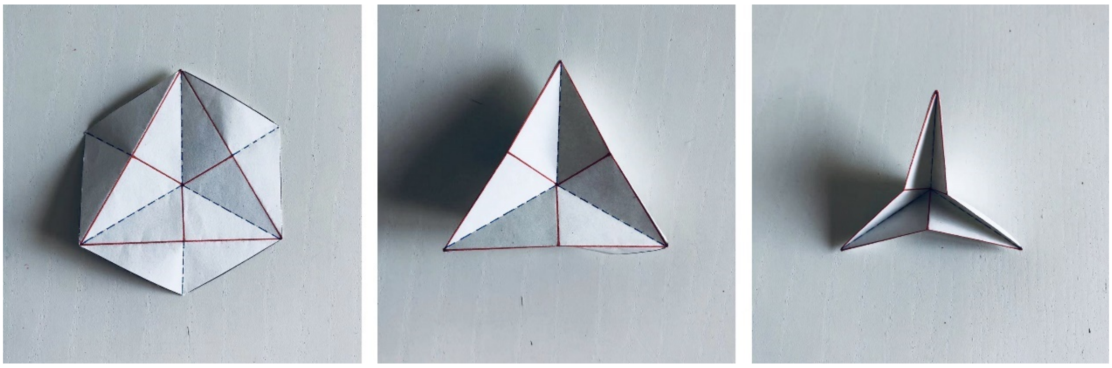


Fig. 5.23. Verification in origami method, mountain creases in red, valley creases in blue.

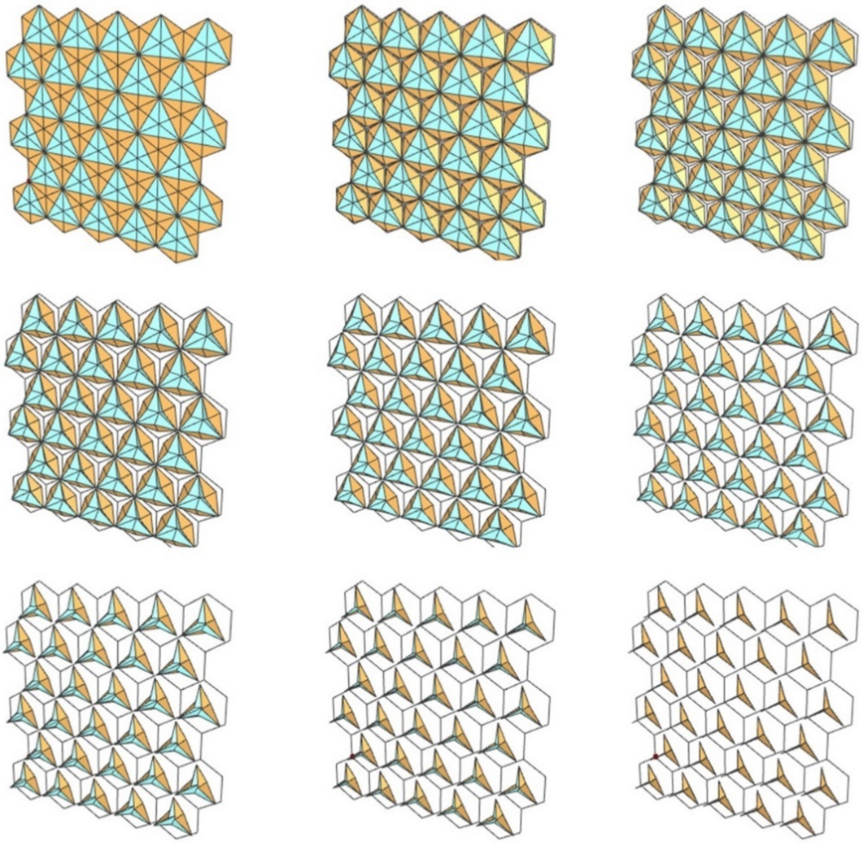


Fig. 5.24. The effect after the combination. Made by grasshopper.

The solution was positioned in front of the testing room. To observe the effect, we first proposed a small-scale design, with each hexagonal unit having a radius of 0.6 m and no gaps between the units spliced until the testing room could be completely shaded.

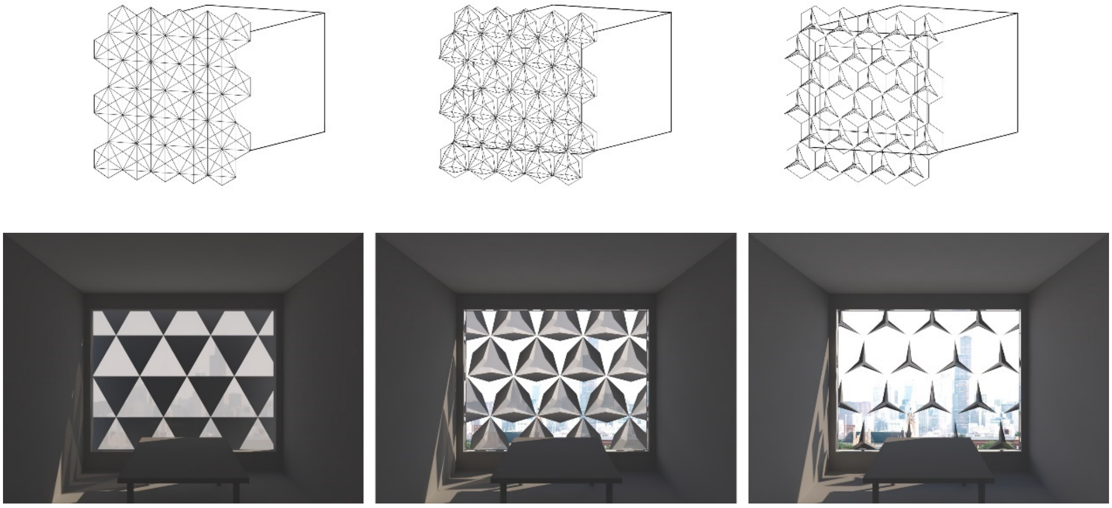


Fig. 5.25. The effect of covering in front of the test room.

5.3.3 Design 3

The way bird's wings are folded is simpler compared to insects, and it can be simplified into three segments, analyzed from a planar perspective (2-D), where one end of the bone is fixed and the other two joints are bent in opposite directions, but since the length of the three segments is fixed, the joints away from the trunk part are respectively constrained by the length to do local circular motion, which is the cause of the end bones to move inward during wing' contraction process. This simplified form is similar to the "Linear Divisions into sixteenths" mentioned by PAUL JACKSON in his book "FOLDING TECHNIQUES FOR DESIGNERS FROM SHEET TO FORM "This jagged form of paper folding compresses the visible area of space in a single direction.

To apply it to our design, we want to achieve the control of a single component to drive the movement of other components, specifically as shown in Figure 5.26, the side view of this structure can be seen, the ends of the structure are "Fixed point" and " Moving point", the two nodes in the middle are equipped with a device to limit the rotation angle or a pre-defined crease respectively, the details of which will be developed in the part of mechanical components. When the "moving point" is close to the "Fixed point", the whole will be spontaneously rotated and folded with the moving point, which is placed in space (3-D) by simply arranging a simple linear track on both sides of the device.

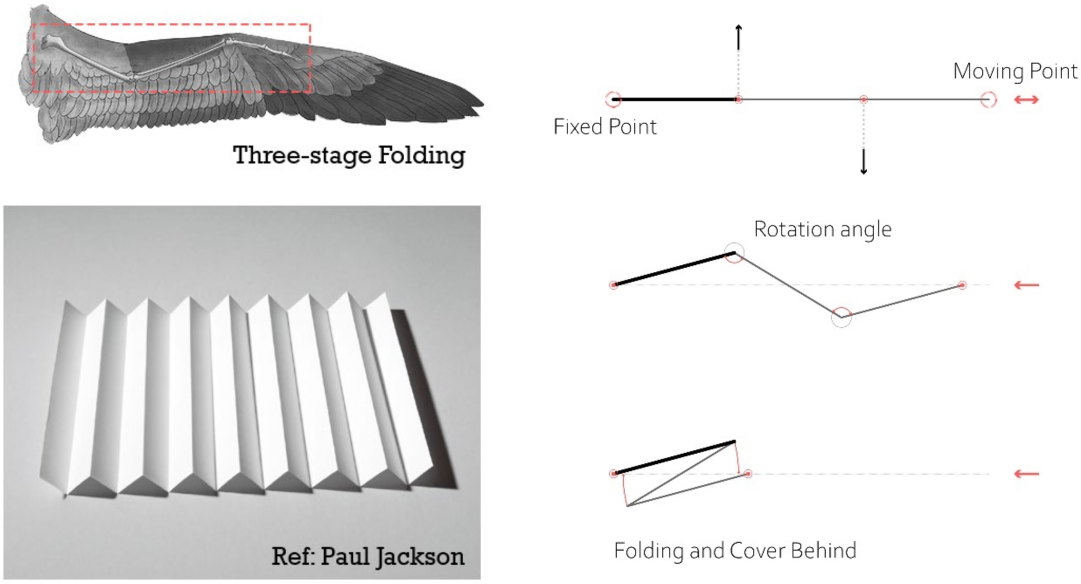


Fig.5.26. Design geometry generation. Left top, image credits to https://www.pinterest.com/pin/438538082463805303/, left bottom, image credits to Paul Jackson, folding techniques for designers from sheet to form.

The design also takes advantage of the characteristics of the coleopteran insects and distinguishes the material of the three parts of the folding unit, so that the external hard material protects the internal fragile material, so we set the panel near the fixed end as a hard material, and the rest as a light material. At the same time, the lightweight material has the characteristics of easy folding, small thickness, etc. When the device is in the open state, the lightweight material will not have the problem of overlapping.

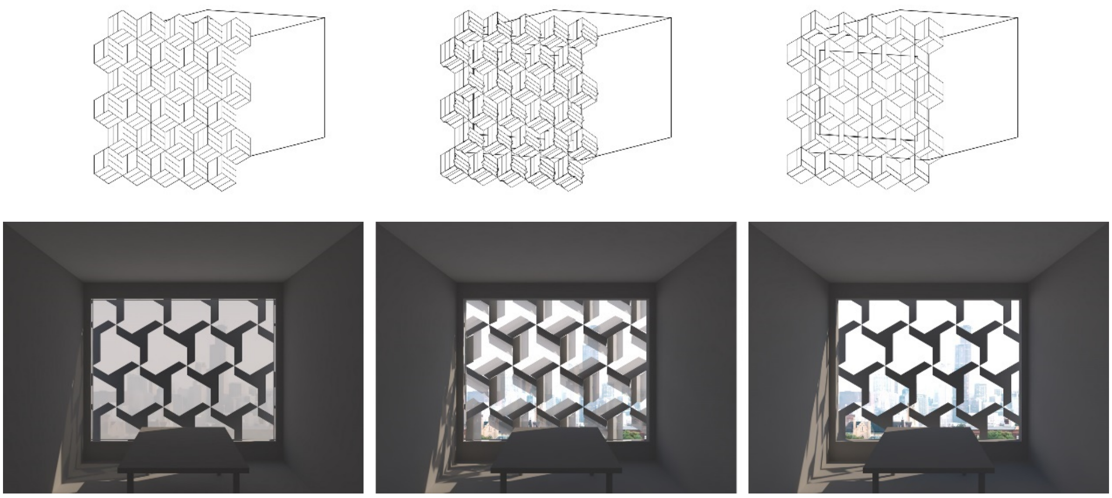


Fig. 5.27. The effect of covering in front of the test room.

CHAPTER 6： Simulation and Calculation

Abstract： The content of this chapter is the simulation calculation of the three schemes. We will calculate the three schemes in the rhino plug-in grasshopper according to the indoor lighting quality and energy consumption. After obtaining the calculation results, we will evaluate and compare the three aspects of geometry, sunshine, and energy to select the most suitable plan.

6.1 Data construction before simulation

In this part, we hope to test the shading and energy-saving effects of these three design schemes through simulation. We chose a standard office room as the test space in the building.

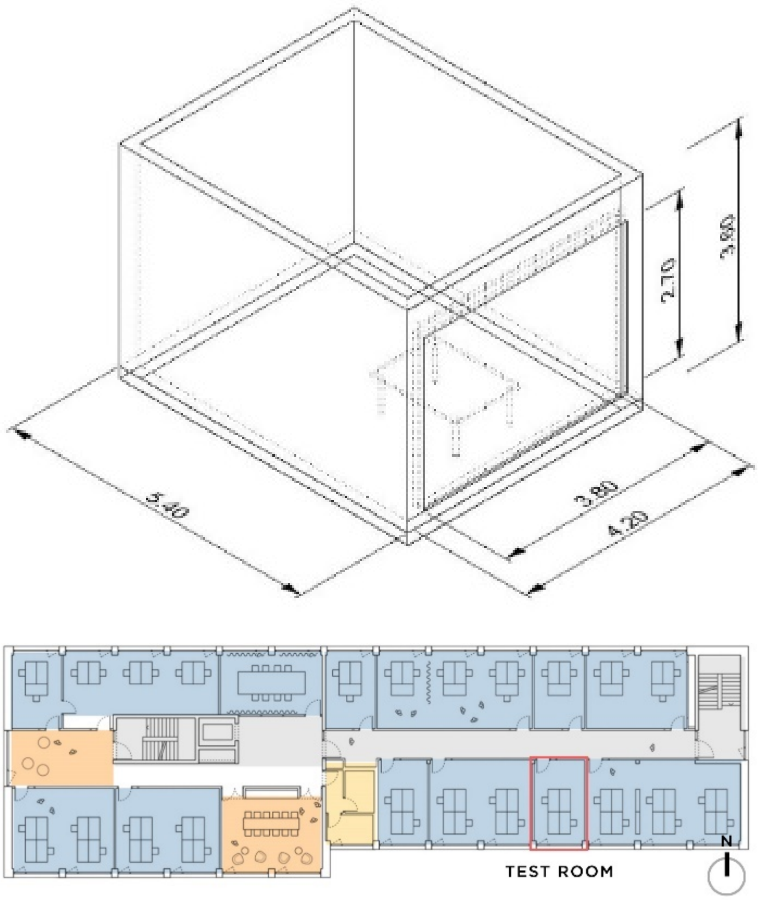
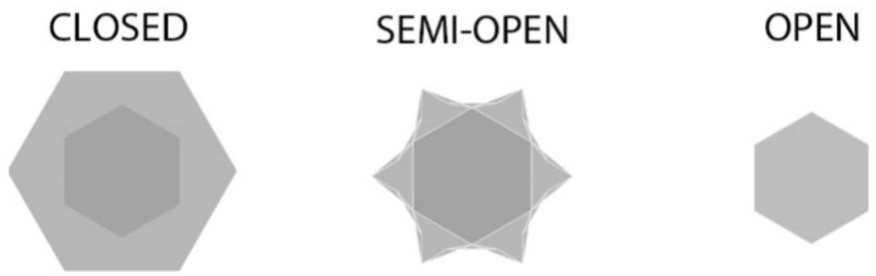


Fig. 6.1. Geometry of testing room and the position is in the third floor of the building.

A test room was selected from this building, which faces south and has an east-west opening axis distance of 3.6 m and a depth axis distance of 5.4 m. The net height of the room, excluding the ceiling, is 2.85 m. The window length is 3 m and the height is 2.3 m. The bottom of the window is 0.55 m from the floor. The room is positioned on the third floor of the building, with an elevation of 8.1 m. This testing room is a small standard office. Only the south elevation of this room is exposed to the external boundary conditions, while the rest of the surfaces are almost adiabatic.

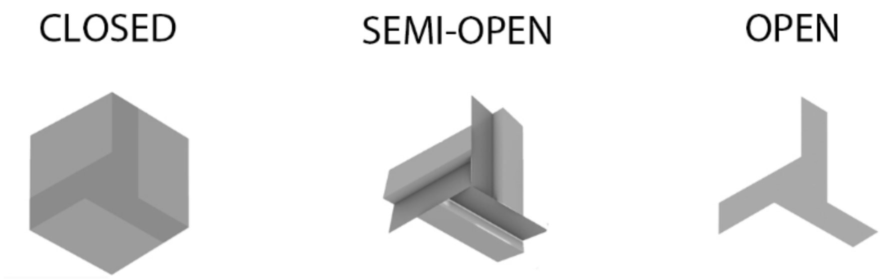
For the three schemes, they are simulated in three states: open, semi-open, and close. Since we have selected two materials with different light transmittance as the sunshzz+ade, the difference between open and close of these three solutions also needs to be recorded and compared in the simulation.

Case 1:



Case 2:

Case 3:



According to the evaluation criteria listed in the literature review and the grasshopper parameter settings in similar papers, we list the following table as the basic settings for the simulation parameters:

ANALYSIS CARD

Site Location
Madrid, Spain

Function of the room
sibgle office room, 5.4m x 4.2m x 3.6m

REQUIREMENTS

Design Objectives
1. Maximizing Hourly Useful Daylight illumianance
2. Decreasing Daylight Glare Probability
3. Meet other Visual comfort requirements
4. Balancing the energy cost

Analysis Objectives
1. Hourly daylight factors
2. Annual daylight factors
3. Daylight Glare Probability
4. Radiation and energy factors

Visual Comfort Design Threshold
UDI: 300 Lux
Acceptable DGP: Lower than 0.35
Acceptable Glare Comfort: Imperceptible Glare

ANALYSIS CRITERIA

	Name	Unit	Range & Value
Daylight Parameters	UDI - min	Lux	[0-300]
	UDI - normal	Lux	[300-2000]
	UDI - max	Lux	[>2000]
Glare Parameters	Daylight Glare Probability	Decimal Number	[0-1]
	Glare Comfort	Level	[Impercebtible, Perceptible, Disturbing, Intolerable]
Energy Parameters	Solar Radiation	kWh/m2	[0-100]
	Heating/Cooling load	kWh/m2	[0-100]
Model Parameters	Schedule Pattern	Stage	[Open, Semi open, Close]
	Shading Material	Type	[Translucent, Opaque]
	Indoor view for DGP	Degree	[Towards Outdoor, 45 Degrees towards Outdoor]
Geometry Parameters	Glazing Ratio	Percentage	80
	Task Area Height	mm	850
	Space Width	mm	4200
	Space Length	mm	5400
	Space Height	mm	3600
	Wall Reflectance	Percentage	50
	Celling Reflectance	Percentage	80
	Floor Reflectance	Percentage	20
	Frame Reflectance	Percentage	10

Fig. 6.2, Data construction before simulation

6.2 Experiment procedure

The starting point of the basic parameter setting is to solve the glare problem as much as possible while ensuring sufficient sunshine. Therefore, we analyzed the sunshine conditions of the three schemes, selected June to December for detailed analysis of hourly sunshine and radiation, and then conducted annual sunshine analysis and load analysis throughout the year to confirm whether it can meet the requirements of indoor sunlight demand and energy consumption. At the same time, according to climate analysis, October and November are the months when the direct sunlight is relatively large, which is the period when glare is high. We selected the glare analysis in these two months and selected two indoor fisheye perspectives for analysis.

6.2.1 Calculation flow

Performing simulation calculations for the three configurations of the three cases. The calculated target values are UDI, DA, DGP, Load (as a comparison with the base case and each other), and the hourly illuminance (As a reference to determine the working schedule of each case). After determining the schedule, we will integrate the calculation results of the three configurations in each case according to the schedule, and compare them with the base case respectively. Based on the base case, a reasonable score is evaluated for each calculation item of each case as a basis for mutual comparison.

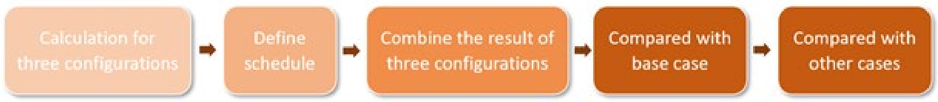


Fig. 6.3, Calculation flow chart

Due to limited space, it is not possible to display all the data, only the graphs and data of the comparison part will be displayed

6.2.2 Determination of schedule

For the selected test points (coordinates are 2m, 2m, 0.9m), after obtaining the hourly illuminance and hourly DGP values, we set the schedule based on these two values. We hope to reduce the glare problem while ensuring sufficient light. Therefore, we use illuminance as the first reference value, and select a configuration with a value between 300lux and 3000lux as the current hour's working status. When there are multiple configurations in this range When in, choose the one with lower DGP and higher illuminance. When all values are less than 300lux (usually early morning and night), set to open state. When the illuminance value is too large, it is set to the close state.

6.2.3 Comparison with base case:UDI,DLA,DGP

UDI:

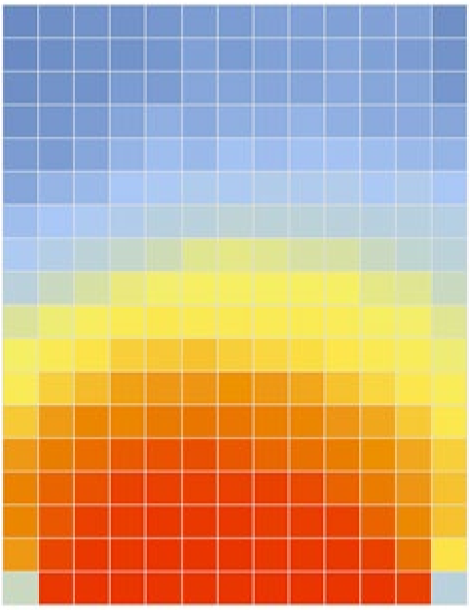


Fig. 6.4, UDI over 2000 Lux - base case

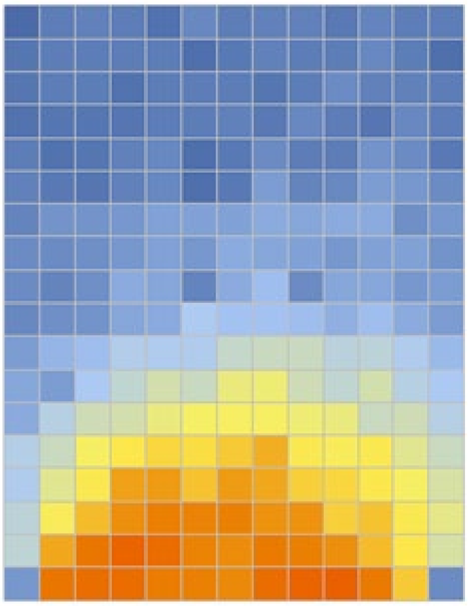


Fig. 6.5, UDI over 2000 Lux – case 1

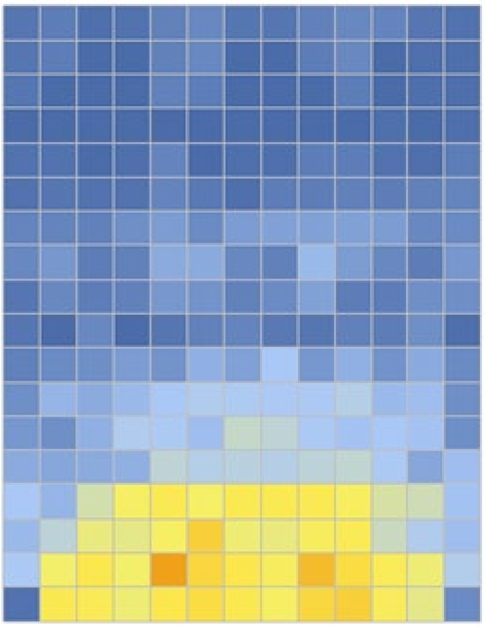


Fig. 6.6, UDI over 2000 Lux - case 2

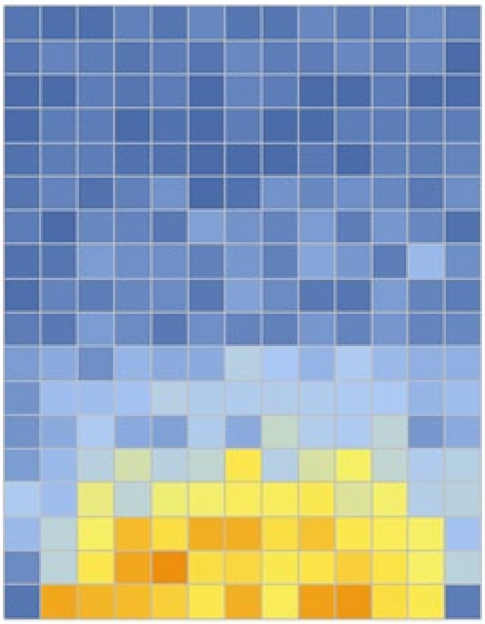


Fig. 6.7, UDI over 2000 Lux – case 3

From the UDI image of more than 2000 Lux, we can find that case2 has better shading performance, with a shading efficiency of more than 60%, and case1 has the worst shading effect.

DLA:

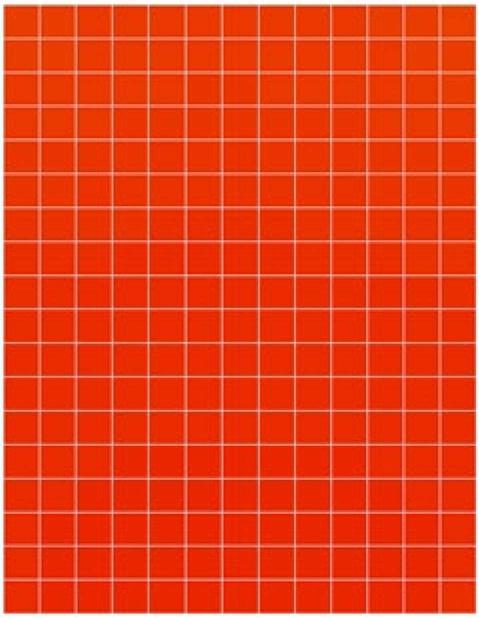


Fig. 6.8, DLA(%) – base case

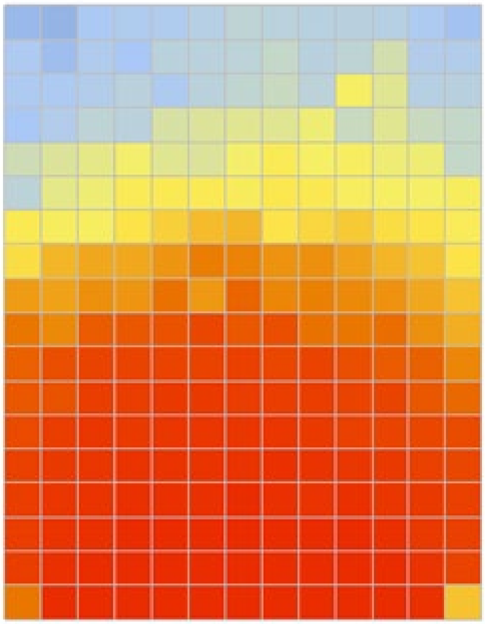


Fig. 6.9, DLA(%) — case 1

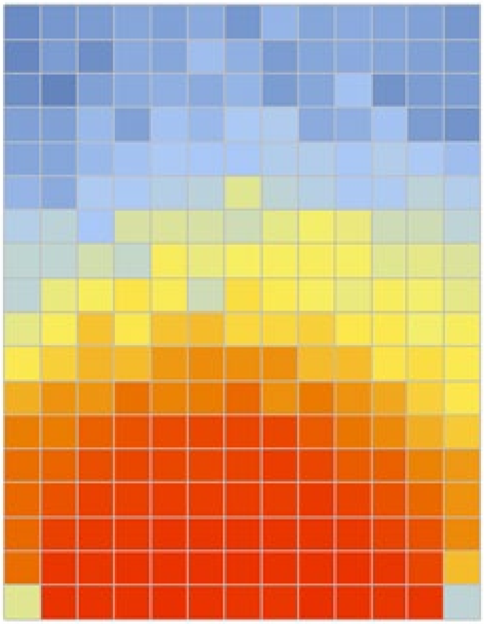


Fig. 6.10, DLA(%) –case 2

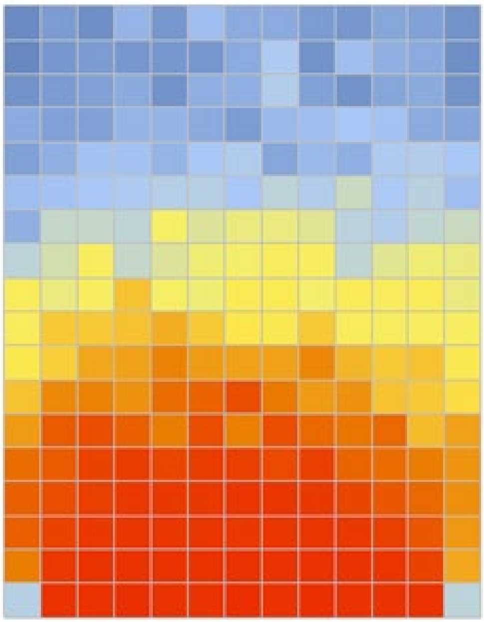


Fig. 6.11, DLA(%) — case 3

Here shows the DLA of all the cases, the indoor lighting ratios of these three cases are all within an acceptable range.

DGP:

Before the analysis of DGP, we first need to set the perspective of analysis. We have selected the following two views as the object of glare analysis:

View1：45 degree **View2：90 degree**

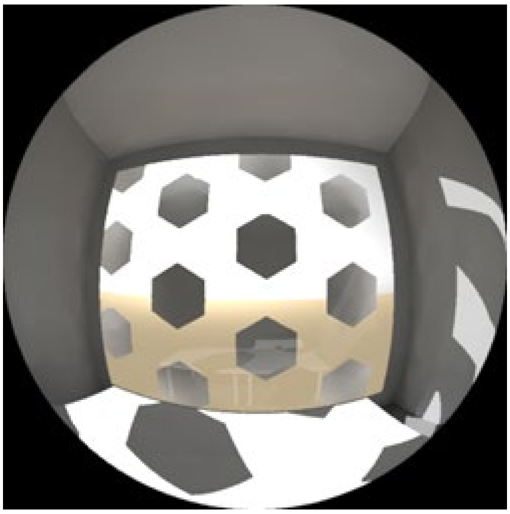


Fig.6.12, Case1 in View1 as example   *Fig. 6.13, Case1 in View2 as example*

We selected view1 as the main analysis perspective of DGP, and view2 as the auxiliary analysis perspective. The figure below shows the distribution comparison of the annual DGP value of the base case and the other three design cases.

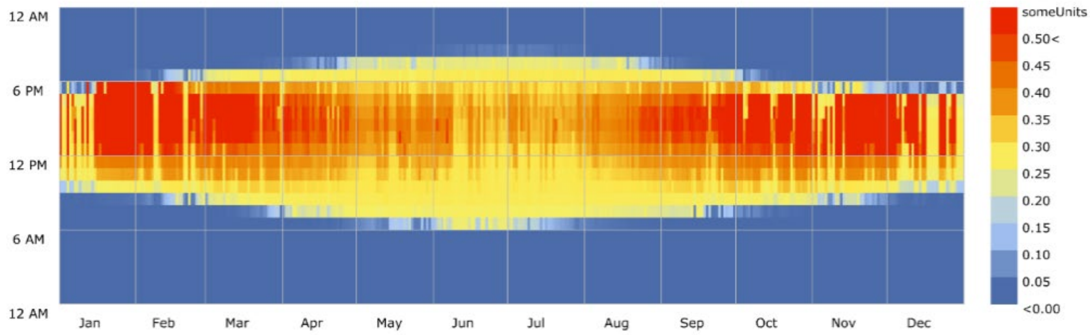


Fig. 6.14, Annual DGP Base case

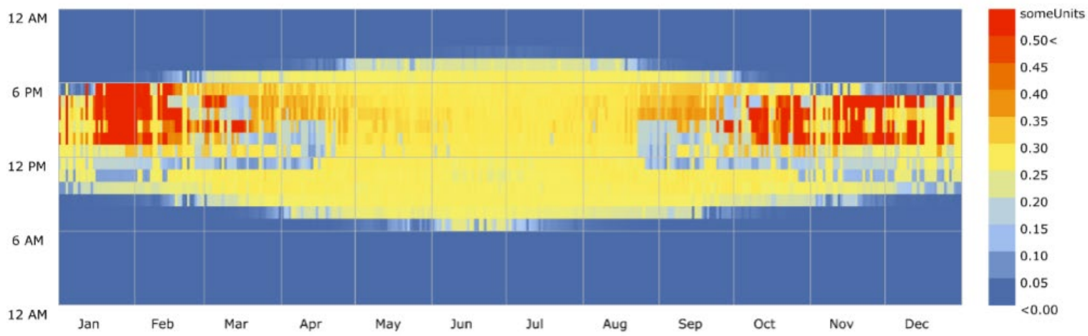


Fig. 6.15, Annual DGP Case1

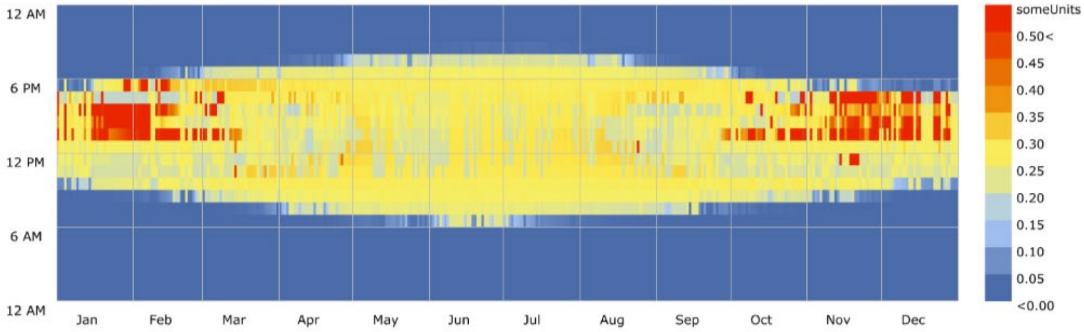


Fig. 6.16, Annual DGP Case2

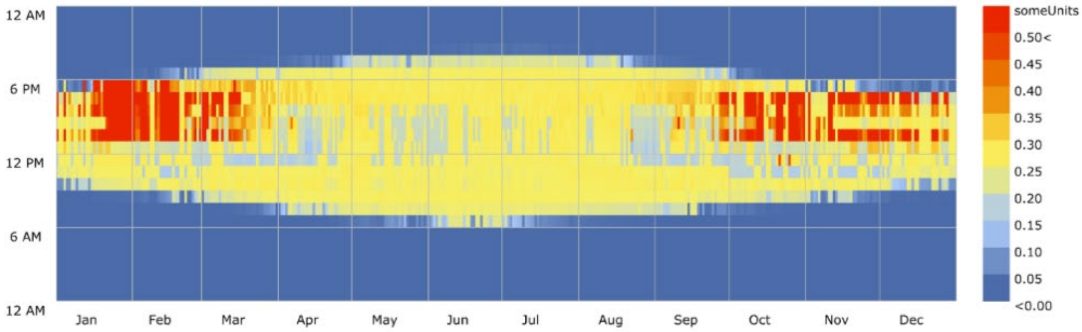


Fig. 6.17, Annual DGP Case3

Glare Hours/year	base	case1	case2	case3
intolerable glare	1539h	396h	302h	433h
percentage	100%	74%	80%	72%

Fig. 6.18, Annual intolerable glare hours for each case

The conclusion can be drawn from the image and table: case2 has the best shading performance, and the number of hours with glare problems has been reduced by 80%, while case3 and case1 have similar capabilities in solving glare problems and can effectively reduce glare problems in summer. However, these two programs performed poorly in winter.

Check: In order to make the calculation more accurate, we have selected a few severe times to check for each case: 12 o'clock and 15:00 in October and November.

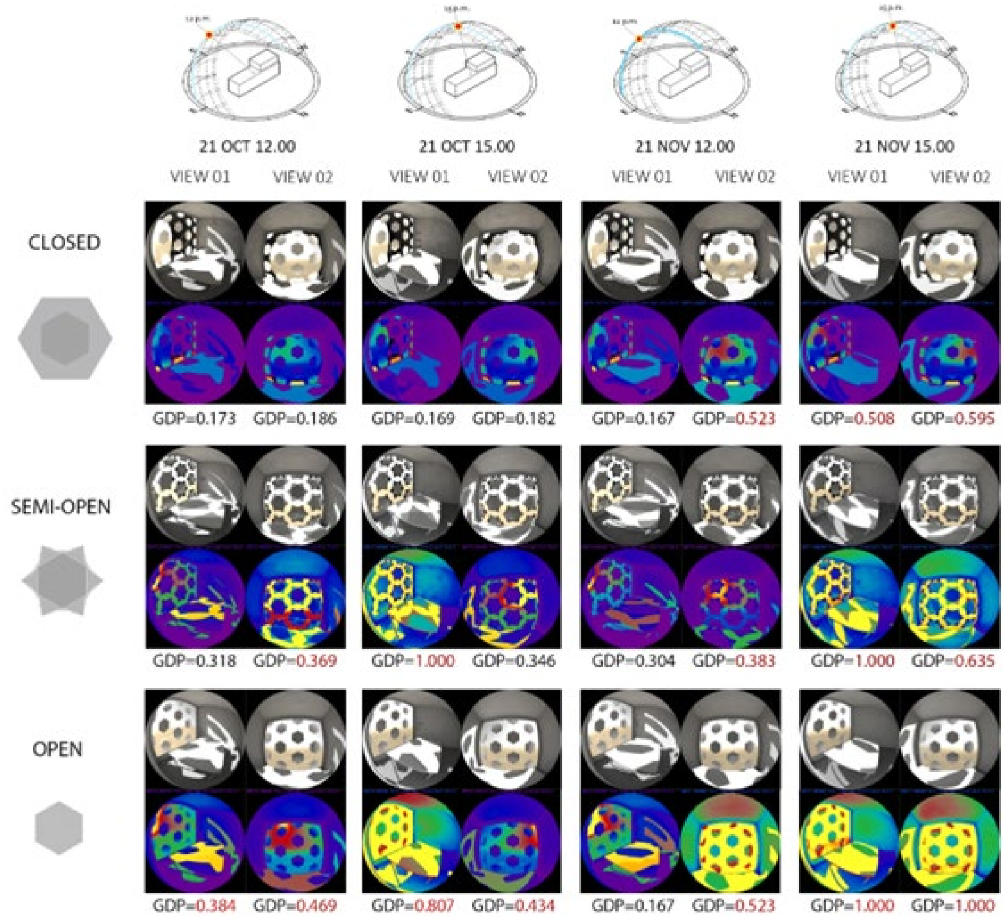


Fig. 6.19, image based glare analysis for case 1

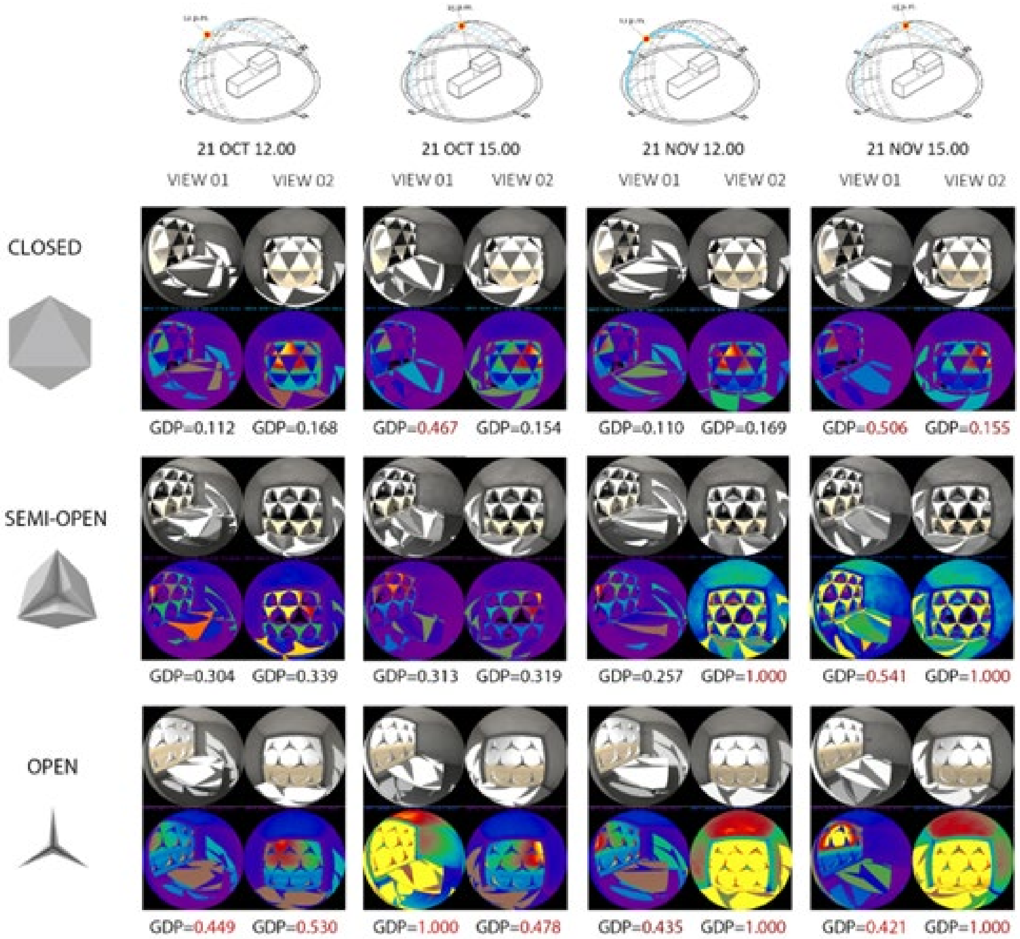


Fig. 6.20, image based glare analysis for case 2

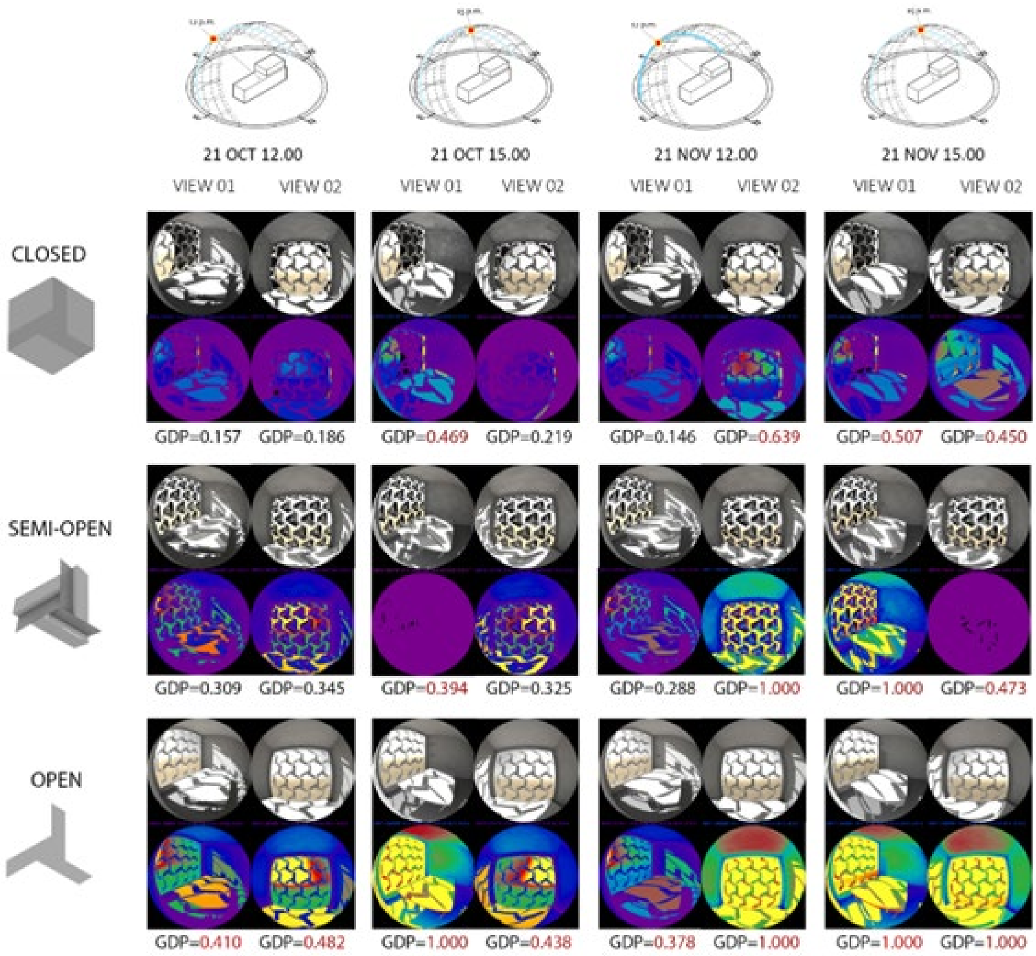


Fig. 6.21, image based glare analysis for case 3

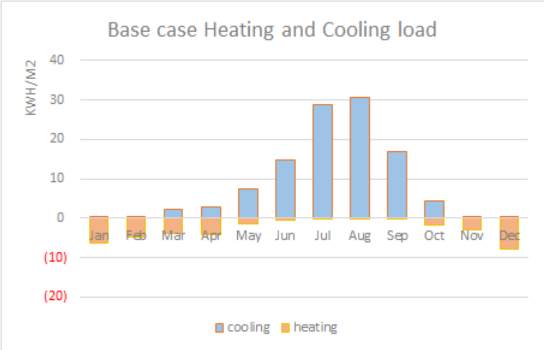
When checking the glare problem, our main focus is on the close and semi open situations.

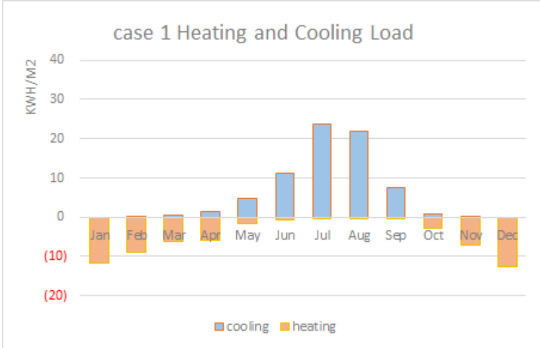
Close: When the epidermis is closed, we found that in the afternoon of November, when the solar altitude angle is relatively low, the DGP value will reach about 0.5, which is not a very ideal situation considering it is closed which means people have to endure the glare. The reason for this is that because the intensity of sunlight is too high, the film material with light transmittance will still put the light intensity that can cause glare into the room. Therefore, we decided to use an opaque film material as the final material choice to solve this problem.

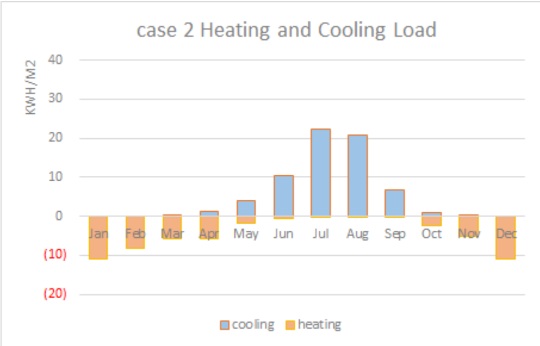
Semi open: When the skin is semi open, the glare is mainly determined by the shape of the folded aperture. In this regard, case2 and case3 have certain advantages. At the same time, the shape advantage of case2 is that it can block the glare on the side, while the shape of case3 The advantage lies in the frontal shielding of glare, case2 is more suitable for actual use needs.

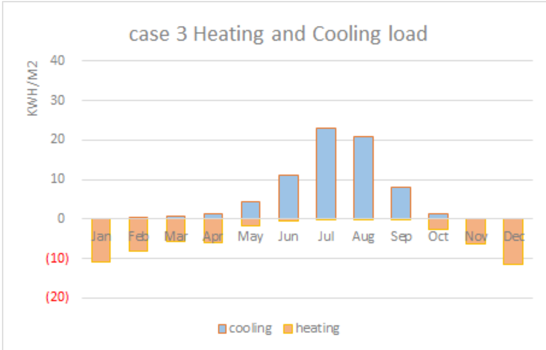
6.2.4 Comparison with base case: Energy part(Cooling load and Heating load)

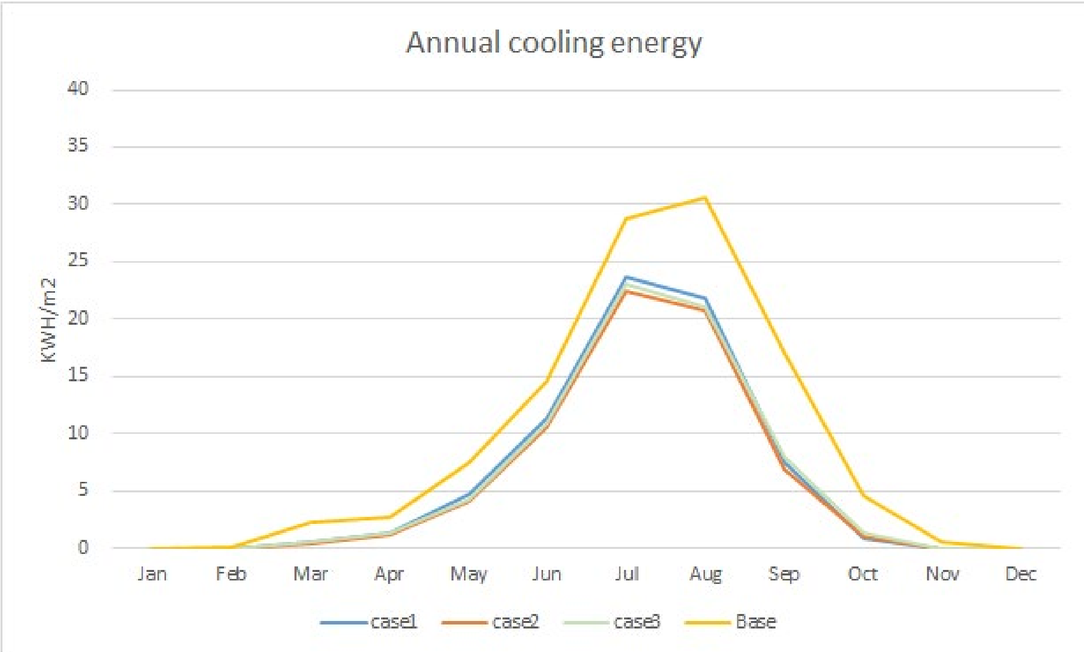
In this part, we use the honeybee plug-in in Grasshopper to simulate the energy load through energy plus. Our main focus is on the changes in heating and cooling load and the changes in solar gain. The unit of data is kWh/m2. The time range of the simulation is from 9 o'clock to 17 o'clock during working hours.


Base case Heating and Cooling load
KWH/M2
cooling
heating

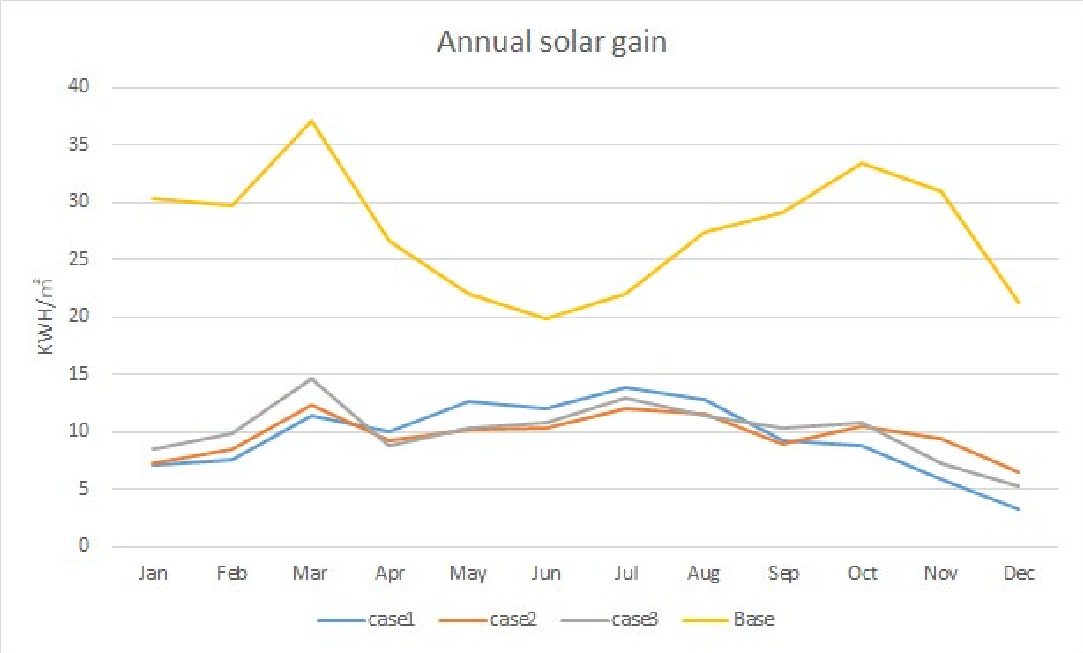

case 1 Heating and Cooling Load
KWH/M2
cooling
heating


case 2 Heating and Cooling Load
KWH/M2
cooling
heating


case 3 Heating and Cooling load
KWH/M2
cooling
heating


Annual cooling energy
KWH/m2
case1
case2
case3
Base

We can find that case1, case2, and case3 have effectively reduced the cooling load, but at the same time, the value of the heating load has also increased to a certain extent.



From the perspective of the annual solar gain, for the base case, the solar gain in winter is higher than the solar gain in summer. This is because the depth of the room is relatively large, while the solar elevation angle in summer is small. Although the value of solar radiation is higher in summer, However, the indoor solar gain in summer will be smaller than that in winter when the solar altitude angle is smaller. For the other three solutions, they all reduced solar gain by more than half.

6.3 Comparison and conclusion

6.3.1 Comparison

For the comparison of these three cases, we conducted six evaluations for the three categories of geometry, sunshine, and energy, and designed a percentage score standard based on the base case for each evaluation to compare:

For geometry, we are more concerned about the opening and closing ability of the epidermis and the problem of visual occlusion. The opening and closing ability of the epidermis is expressed by the ratio of the area of the open state of the epidermis to the area of the closed state. The visual occlusion score of the epidermis depends on the working schedule of the epidermis, the area of each state, and the material of the epidermis (translucent materials are equivalent to 0.7 opaque materials in terms of visual occlusion).

For sunlight, we pay attention to whether the indoor light is sufficient and the shading ability of the skin. The assessment of adequate indoor lighting is the ratio of the lighting of each case to the base case. The smaller the ratio, the less the sunshine. We use DGP to evaluate the shading ability, but the image analysis of glare needs to be taken into account when evaluating.

For energy, we pay attention to the increase of heating load and the decrease of cooling load. The addition of sunshade components reduces the cooling load while also increasing the heating load to a certain extent. We use the increase and decrease of each case compared with the total amount of base case to evaluate. It should be noted that the total amount of heating load in Madrid is much smaller than cooling load, so the reduction of cooling load is a more important factor.

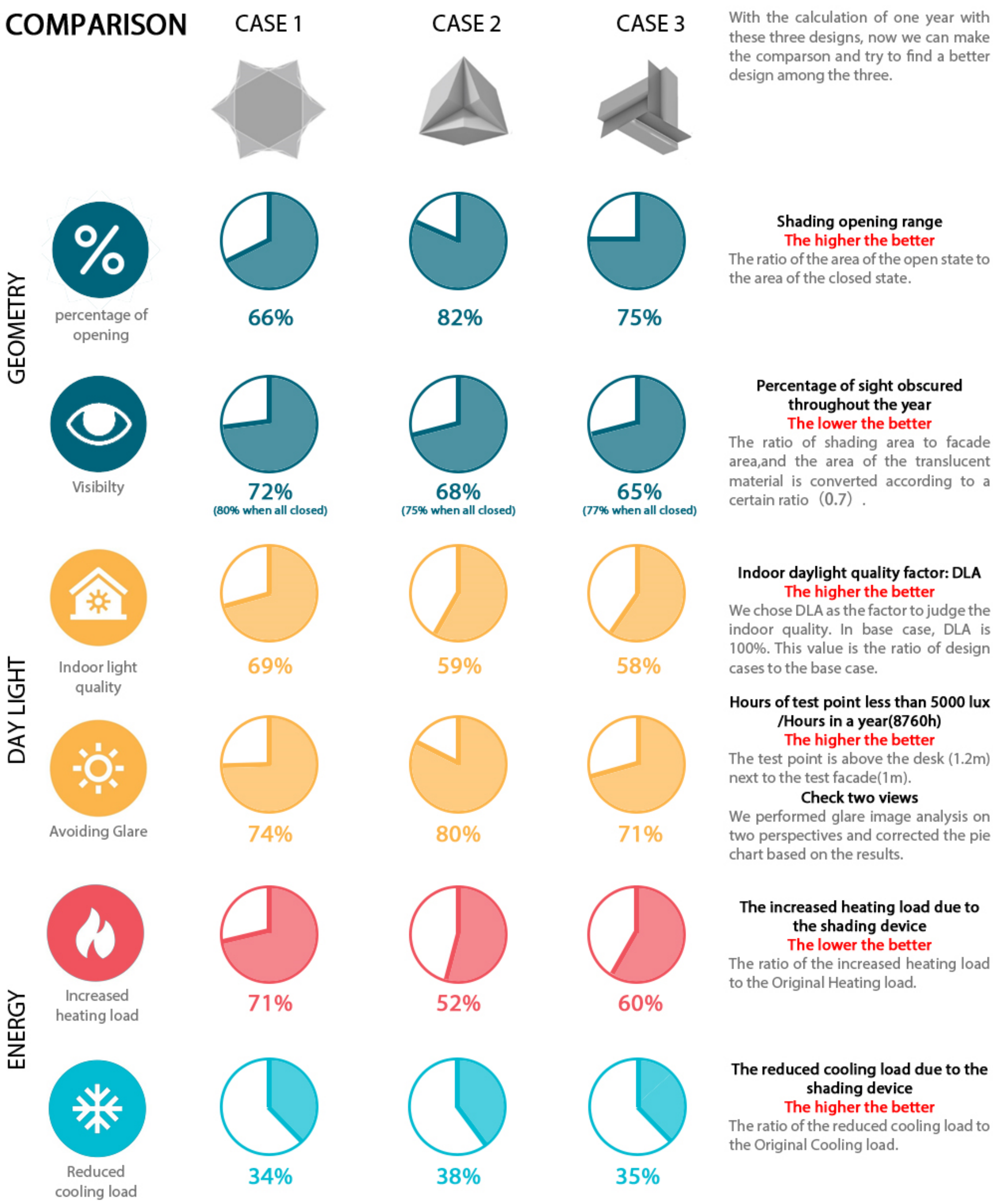


Fig. 6.22, comparison pie chart of case 1,2,3

6.3.2 Conclusion

Among the three solutions, case one is a relatively undesirable solution. It has the shortcomings of small opening and closing and affecting the line of sight. At the same time, the effect of preventing glare is weaker than the other two cases. We can exclude it first.

For case2 and case3, comprehensively considering the shade effect and considerations based on mechanical and maintenance difficulty, we believe that CASE2 is a more reasonable and appropriate solution. In the next step, we will make further improvements to CASE2 to solve the glare problem without reducing sunlight as much as possible.

Since our previous glare analysis, we found that even in the case of close, no matter which scheme will produce intolerable glare problems during working hours, opaque materials must be used instead. Therefore, in the following program, we will change the membrane material for case2 and perform another analysis. Just in case case3 has better performance after changing the material, we also analyze case3 to compare and test case2.

In addition to changing the material, there is another way to improve the shading performance of case2: **changing the Pattern**

We can change the shape and pattern according to the angle of sunlight. In semi-open, in the hours when the glare of each program is the most serious, the determining factor for determining whether there will be a glare problem is the relationship between the shape of the opaque part and the direct angle of the sun. In the current plan, the pattern combination shown in the left side of the figure below is adopted. According to the angle of the direct sun angle, it can be found that direct sunlight is mostly from directly above. Therefore, the glare problem can be effectively improved by rotating the graphic and changing the pattern combination.

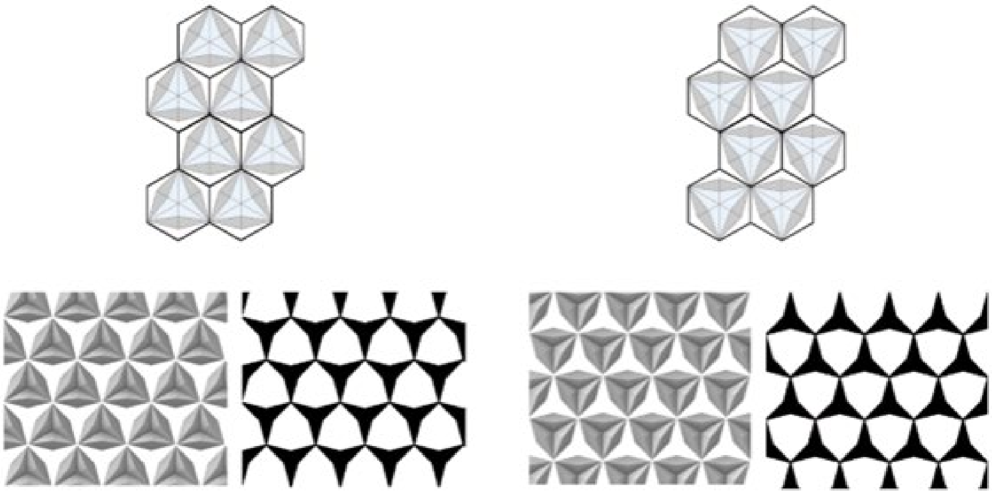


Fig. 6.23, different pattern of case2

6.4 Improved simulation

The gap between these three solutions in terms of DLA and UDI is relatively small, so we only use DGP and Glare analysis for image comparison, and data comparison for energy .

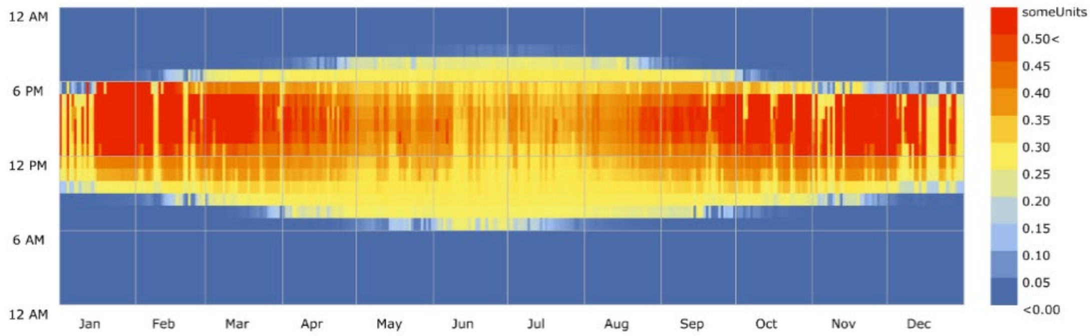


Fig. 6.24, Annual DGP Base case

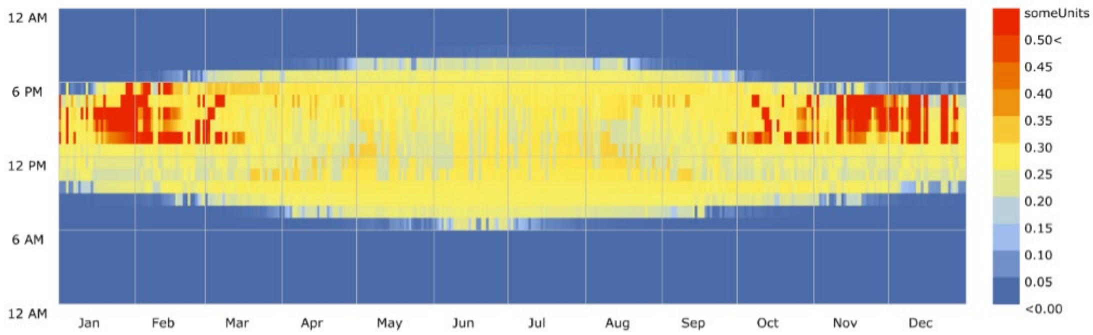


Fig. 6.25, Annual DGP Case2 opaque

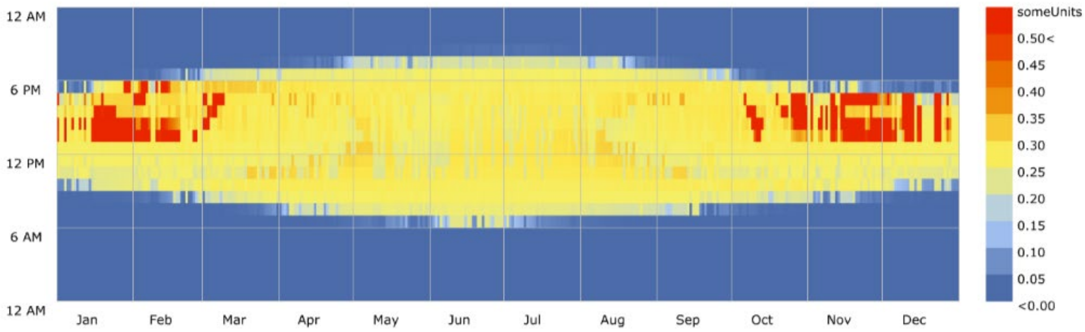


Fig. 6.26, Annual DGP Case2' opaque

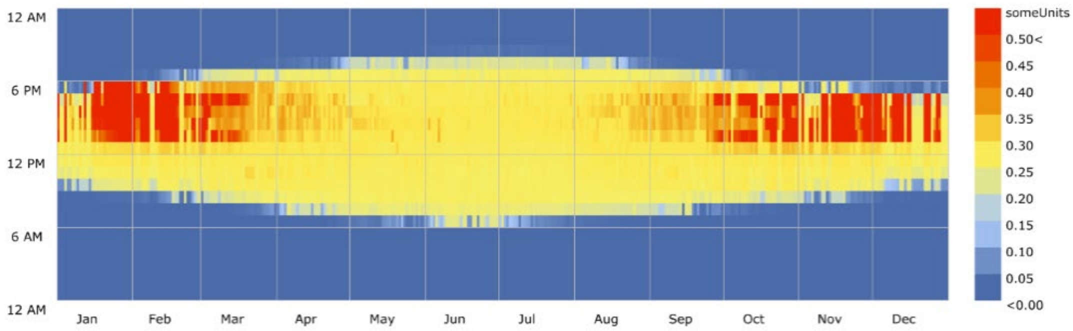


Fig. 6.27, Annual DGP Case3 opaque

Glare Hours/year	base	case2 opa	case2' opa	case3 opa
intolerable glare	1539h	313h	282h	506h
percentage	100%	80%	82%	67%

Fig. 6.28, Annual intolerable glare hours for each case

It can be seen from the image and table that the performance of case3 opaque is somewhat different from the other two cases. Therefore, for more detailed glare image analysis and comparison, we will perform case2 opaque and case2' opaque. Similarly, we chose 12:00 and 15:00 on November 21 and December 21 as the time for glare analysis.

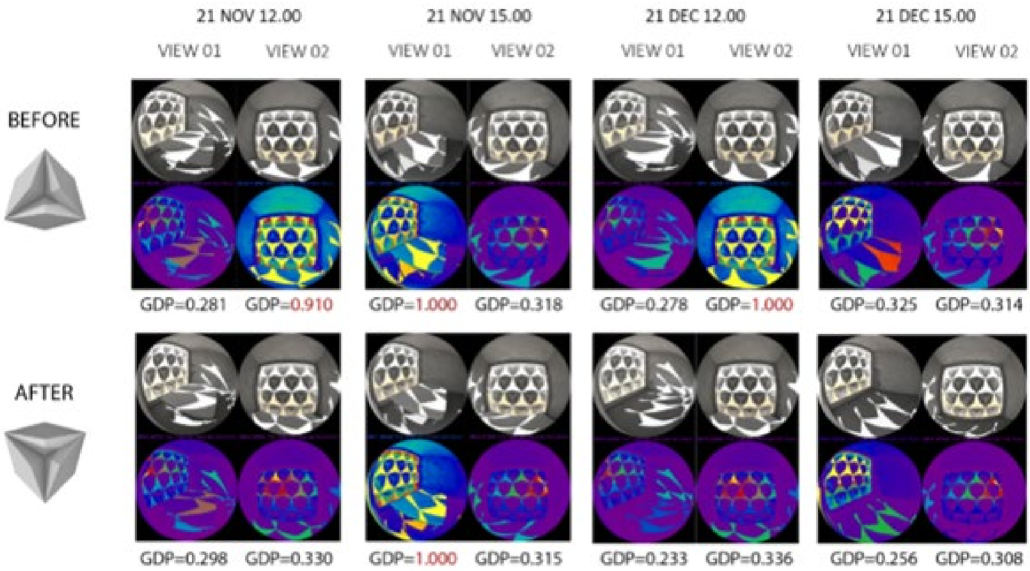


Fig. 6.29, image based glare analysis for case 2 and 2' in semi open state

In view2 at noon in November and December, pattern 2 shows obvious shape advantages, which can effectively reduce the glare problem.

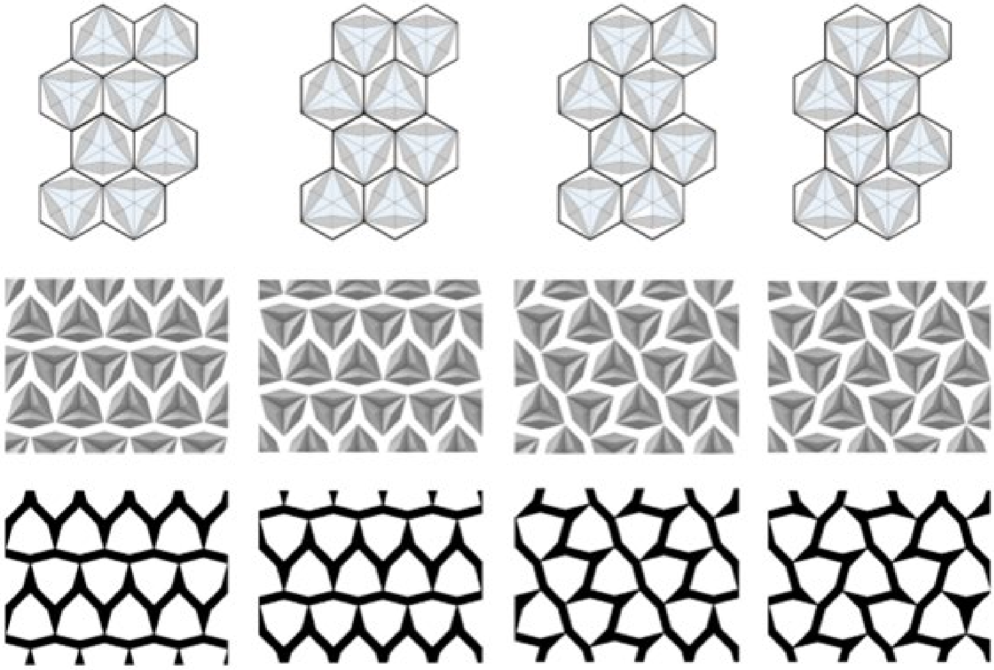


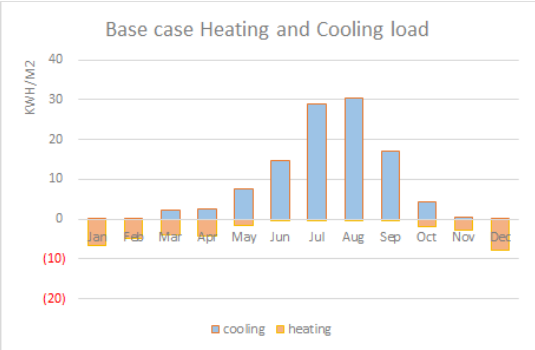
Fig. 6.30, different pattern of case2

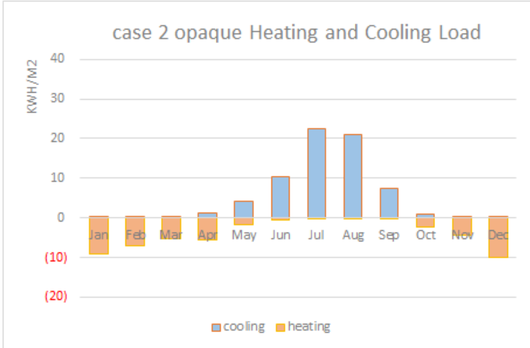
As we can find that pattern2 has better glare protection and has similar daylight factors, thes pattern change makes sense. Beside these two patterns, other patterns maybe can provide better indoor light quality. So we experimented with the following different pattern combinations to determine the final scheme pattern.

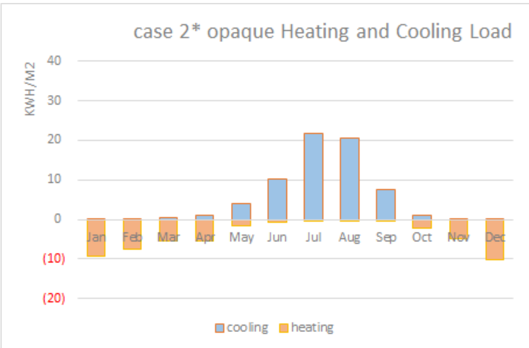
However, these four patterns still meet the glare problems as pattern1, so for the room faced other orientation, pattern2 may be the better solution to solve the glare problem.

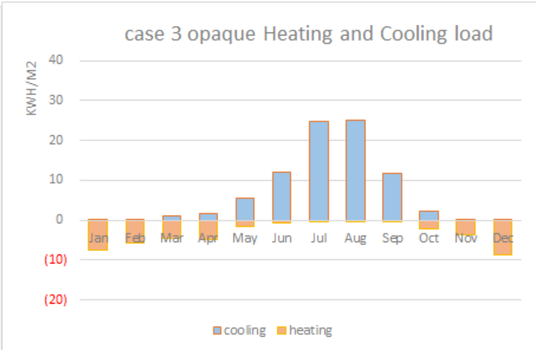
Energy simulation

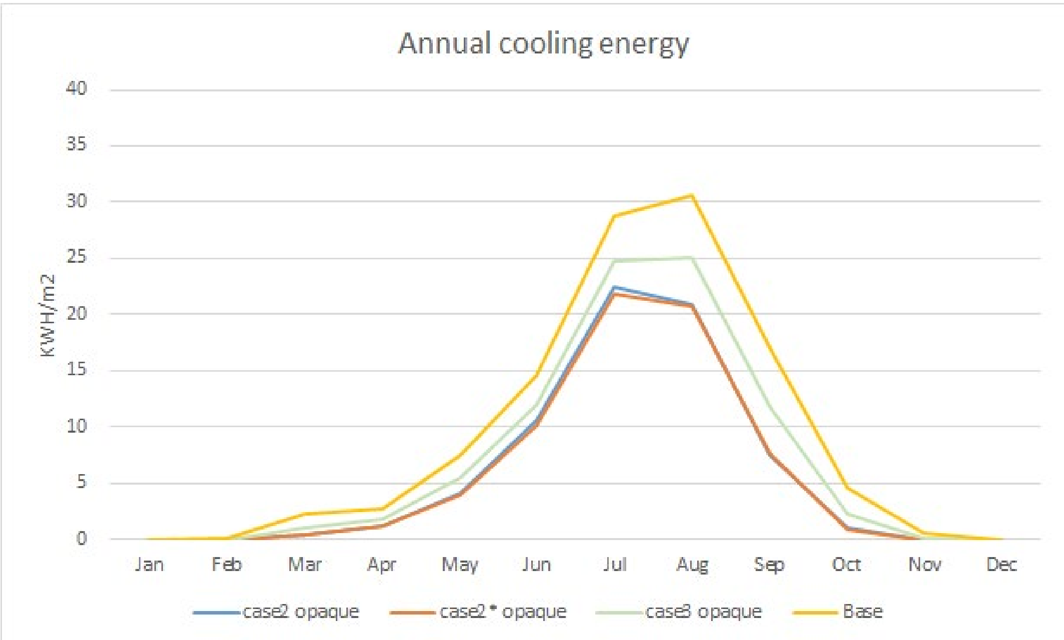
We repeat the previous energy calculations, and compare heating and cooling load for base case, case2 opaque, case2' opaque, and case 3 opaque.

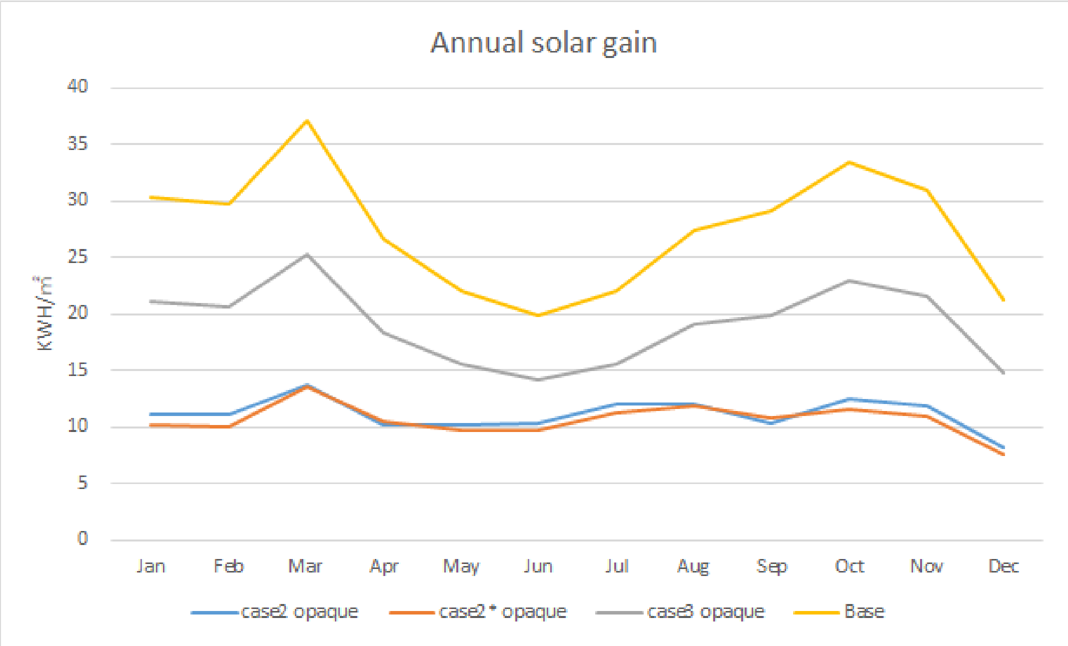












From the figure, we can find that, compared to case2 opaque and case2’ opaque, case3 opaque is slightly worse in terms of shading performance.

6.5 Final comparison

For the new changes, we repeated the previous comparison process and decided our final case.

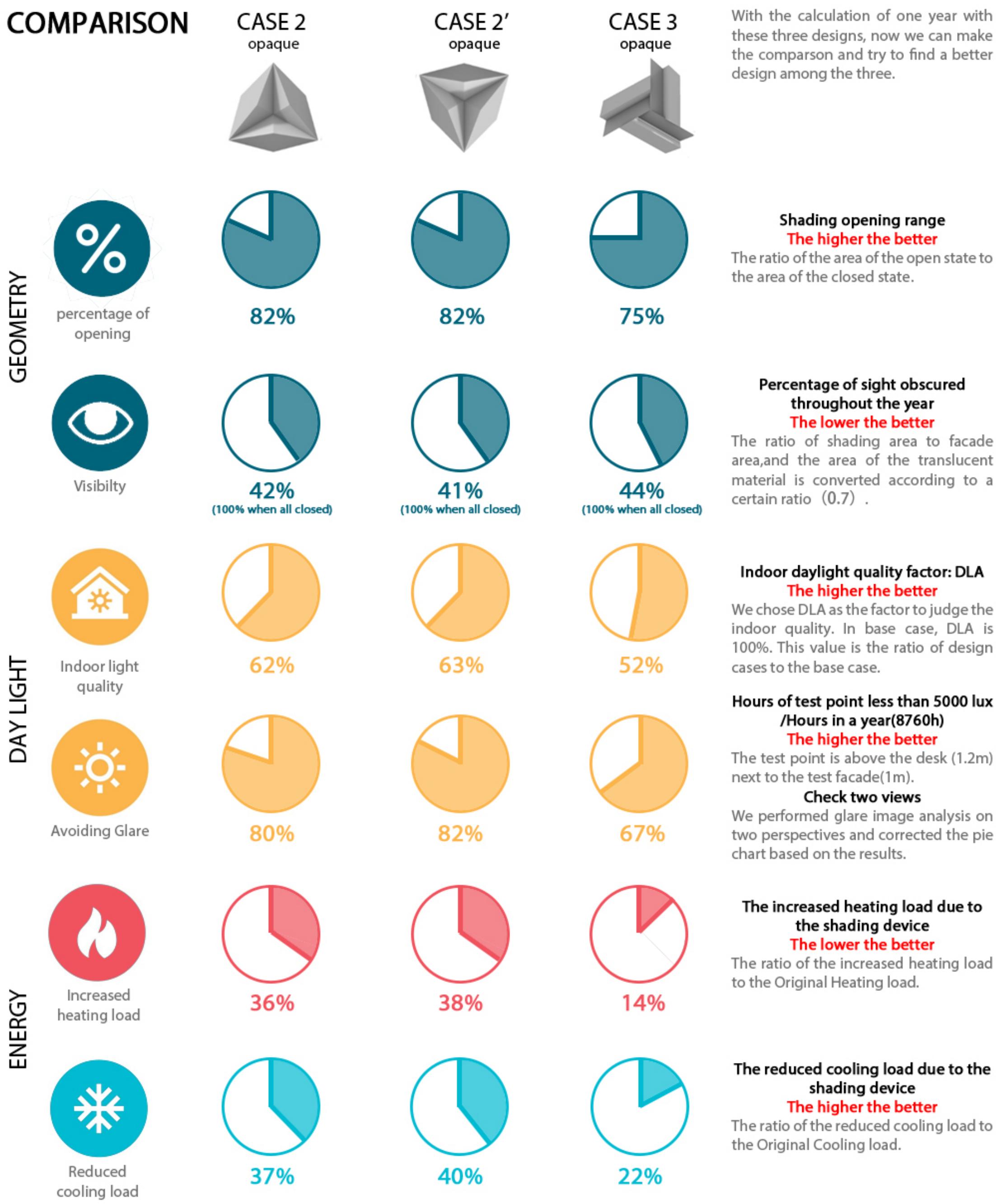


Fig. 6.31, comparison pie chart of case2 opaque,2' opaque,3 opaque

After comparison, we found that compared with the other two solutions, case3 has some shortcomings in daylight and energy, so it was excluded. Case2 and case2' are very similar in all aspects. This is related to the way we choose schedule. Since the working schedule of the epidermis is controlled by indoor illuminance, whether there is a specific glare problem cannot be clearly shown. From the previous glare image analysis, we know the advantages of the pattern of case2' in preventing glare, and considering that case2' is not inferior to case2 in other aspects, we have reason to think that case2' is a more suitable solution for us.

CHAPTER 7: IMPLEMENTATION

Abstract: In this chapter, we will introduce in detail the various content about the realization of the scheme, including the selection of sensors, the realization of the principle of motion in real machinery, the form of actuators and the selection of materials. The detailed drawings related to it will be attached in the relevant part. In addition, in order to ensure that the theory is true and reliable, we have completed the realistic model according to a certain proportion and displayed it.

7.1 Sensor technologies

In this project we choose an extrinsic (active) system sensor, the advantage of this sensor is that it can automatically adjust the degree of opening and closing of the facade, which minimize the human operation steps, and the sensor real-time monitoring of outdoor solar radiation index is often more accurate, to ensure that the indoor environment is always in the optimal condition. When the solar radiation exceeds the value we set, the shading device will tend to close to create more shading to the interiors, on the contrary, below the set value, the shading device tends to open, plus we can set a gradient for the solar radiation value interval so that the shading device can present different degrees of folding under the specific solar radiation condition so that the indoor environment is always in the most comfortable condition.

The technology of sensors has been developed, and there are more abundant choices in the market. Its essence is a mathematical calculation, comparing the difference of the input value and the set value to get the result of "YES" or "NO", this kind of calculus makes multiple judgments to get the results we want, then we can define those various results as "CLOSED", "SEMI-OPEN", "OPEN", etc. The specific logic diagram is shown in figure 7.1.

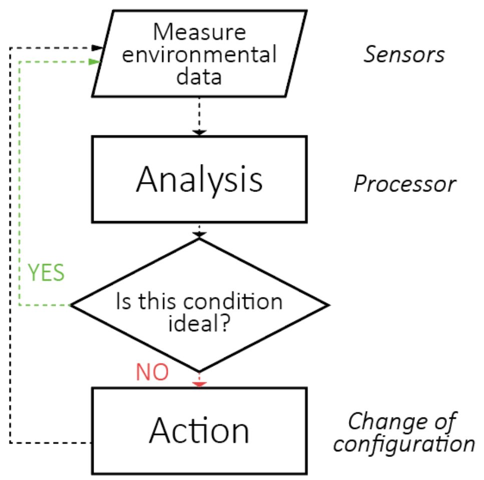


Fig. 7.1. Logic diagram of the sensor.

The logic diagram applies to the monitoring of many parameters, and today in our daily life the types of sensors cover a wide range. These can include air temperature, relative humidity, air quality, light intensity, window and door contacts, movement sensors, fire alarms, burglar alarms, buttons and switches for manual control, solar irradiation, pressure, force, power consumption, energy consumption and multiple others. (Schumacher et al., 2010)。

According to Schumacher, Schaeffer, and Vogt (2010), "measurements should be as imprecise and as precise as possible". This means that it is not required to use the best equipment available all the time, but the best equipment that can provide the necessary information. The most suitable sensor for this project is the solar radiation sensor, and we need to observe the time point beyond the target to determine the degree of opening and closing of the adaptive façade.

Fig. 7.2. *Common solar radiation sensors, wind sensors, rain sensors on the market.*
Photo credits to https://www.campbellsci.com/cmp10-l,
https://www.omniinstruments.co.uk/weather-stations-and-instruments/wind-

speed-and-direction-sensors/gmx200-weather-station.html,
https://rainsensors.com/products/model-comparison/.

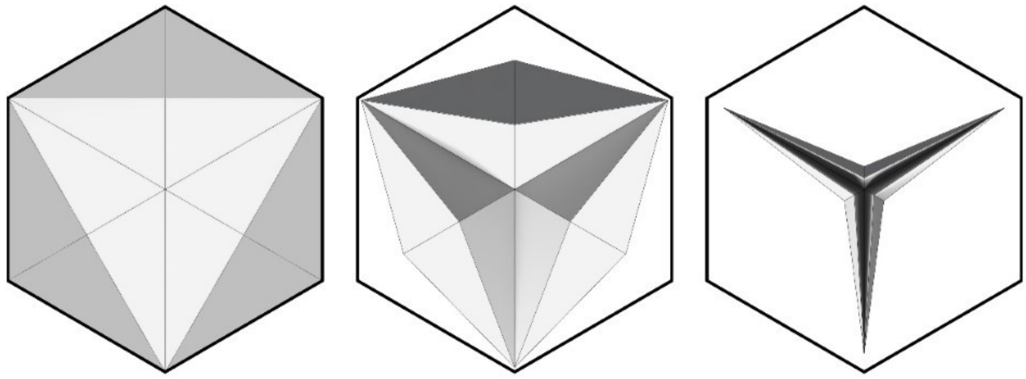
As shown in figure 7.2 are some common types of sensors on the market, the multiple types of sensors can be programmed in series to work together on the building facade.

For example, when the signal of rain is received from the optical rain sensor, the command can be directly conveyed to the processor to make the adaptive façade close, and similarly when the wind speed is not conducive to the comfort of indoor users, the data output from the sensors can also directly change the configuration of the façade to open or closed. The combination of multiple sensors is promising and the monitoring of multiple parameters will create a more comfortable environment in the interior of the building, reducing the overuse of ventilation, heating and cooling air conditioning, and lighting systems.

7.2 Mechanism

We have compared the data of each of these design schemes and have chosen the most optimal one. In the project presentation, we have verified the collapsibility of this geometric unit using the origami method, which shows that it is practically feasible. Considering the actual construction of the adaptive facade, it is not enough to just fold the paper sheet, because in the actual space the parts have a thickness, which involves a series of problems such as how to fix the whole device and let the movable parts move in the predetermined direction, and the parts cannot collide with each other, etc. Also, in order to let the adaptive façade can move base on the outdoor ambient temperature changes and thermal radiation changes, we also need to set up the sensors. These mechanical components are not complicated, some of them are simple and can be found on the market, while others are in the experimental stage but still have great market potential. In this chapter, we will deepen the optimal solution we have chosen, presenting the mechanical components needed to be able to realize the adaptive facade movement in practice, the arrangement of the sensors and the conditions that trigger them, the actuation forces that make the device move, and the mechanical feasibility of the structure.

7.2.1 Detailed introduction of mechanical parts



Closed Semi- open Open

Fig. 7.3. The geometry of unit adaptive facade.

The design is a hexagon that can be divided into 12 triangles of the same area and shape, which, if duplicates are removed, are essentially quadrilaterals made up of 4 triangles, replicated by rotating 120° and 240° around the center point. The installation is composed of two materials: light laminated membrane structure and rigid panel material, which account for about 50 percent of the overall area, respectively, with the distribution rules shown in the closed state above, with the dark gray part being the rigid panel and the light gray part being the light laminated membrane structure.

The moving process of these geometries could be seen as the movement of points. Since the panel is an entity, the length between each point of the connecting triangle is constant, so we only need to consider the moving track of special points and specify special tracks for them, and then we can use the computer to accurately imitate the movement of the geometry. This can help us build a movable model in Grasshopper, and can help us understand the real track of mechanical components in space.

Because the panel has a certain stiffness, so we only need to apply a certain force to the "active point" of the triangle unit, the rest of the points will move with the movement of the "active point", as shown in Figure 7.4, point A moves between the orbit A'B', if the we assume this 2-D graph is imagined as x-axis and y-axis, then point C will move towards the z-axis of the arc orbit, point D is moving with the two panels.

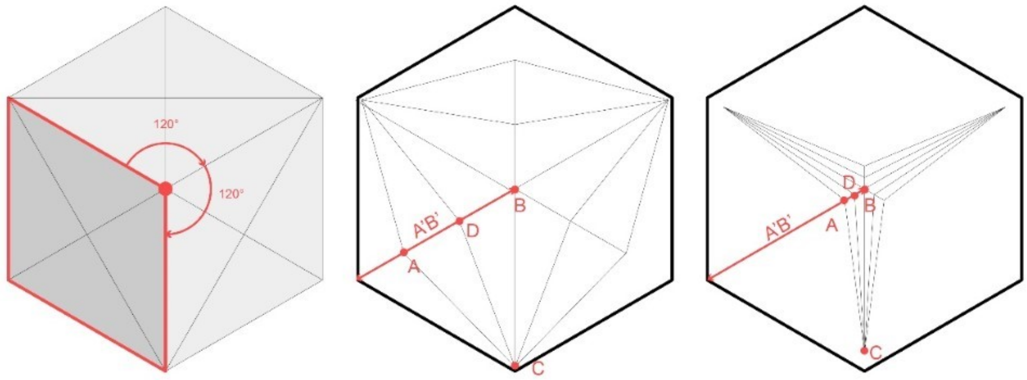


Fig. 7.4. Rename each point.

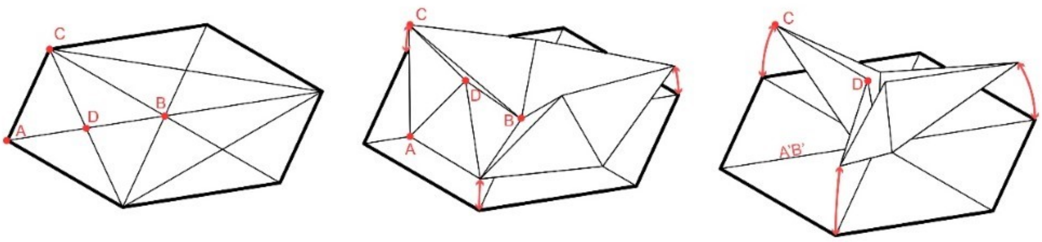


Fig.7.5. Movement of each node in space

To avoid problems such as collision and extrusion of each part during the actual movement, we next specify the actual mechanical components needed at each point to meet their space requirements. To facilitate the introduction, the names of the following parts will be replaced by the four points ABCD and the triangle formed by ACD, BCD.

7.2.2 Point A：

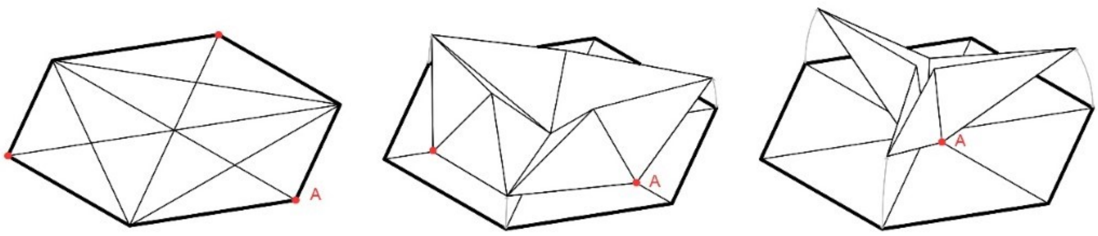


Fig. 7.6. Movement of point A in space

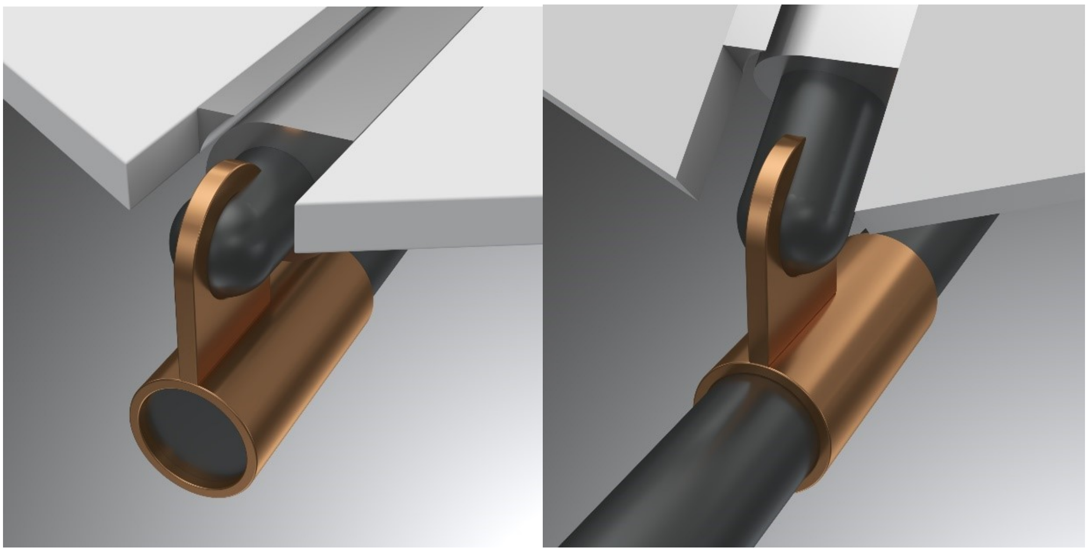


Fig. 7.7. Construction details of point ***A***

Point A is the "active point" we defined, and its trajectory is to move along the rod A'B', so we set up an adjustable sliding bar for this part, and when the device is opened, the mechanical part slides inward, which drives the panels and other points to move. Also, the rod coupling the two rigid panels between them is able to rotate around the circular piece welded on the slide bar. The actuation of the part is electric, at the bottom of the part a mechanical gear rotates to drive the track, which enables the lateral movement of the slide bar on the rod, and the engine is placed centrally on the steel structural part behind the adaptive facade panel.

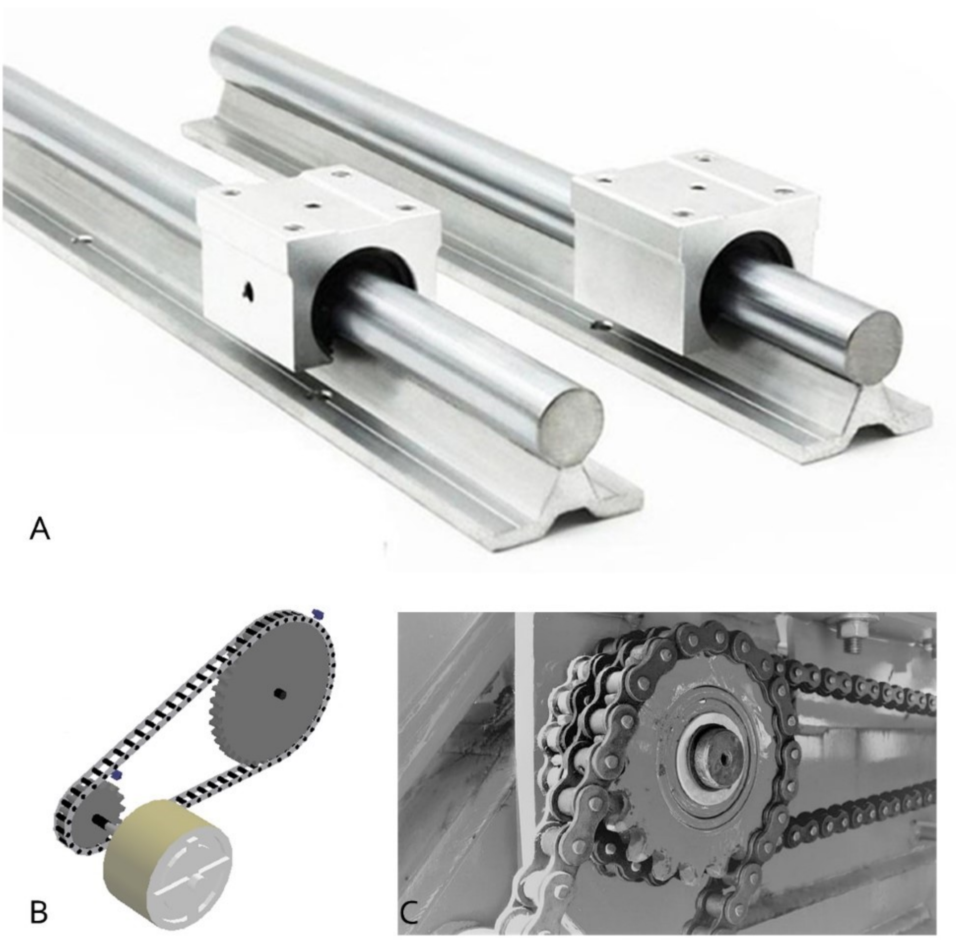


Fig. 7.8. Possible commercial solutions for rail systems

7.2.3 Point C：

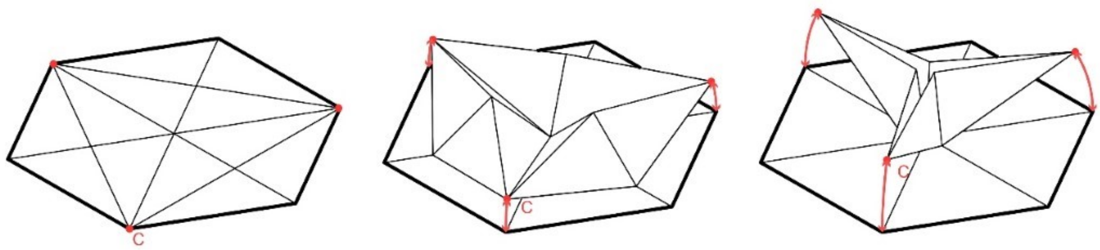


Fig. 7.9. Movement of point C in ***space***

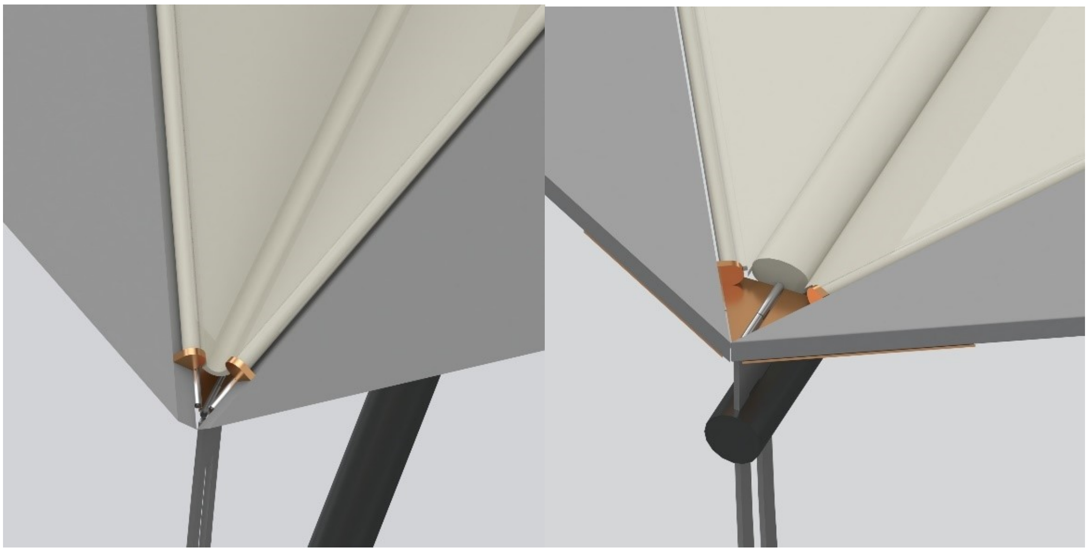


*Fig. 7.10. Construction details of point **C***

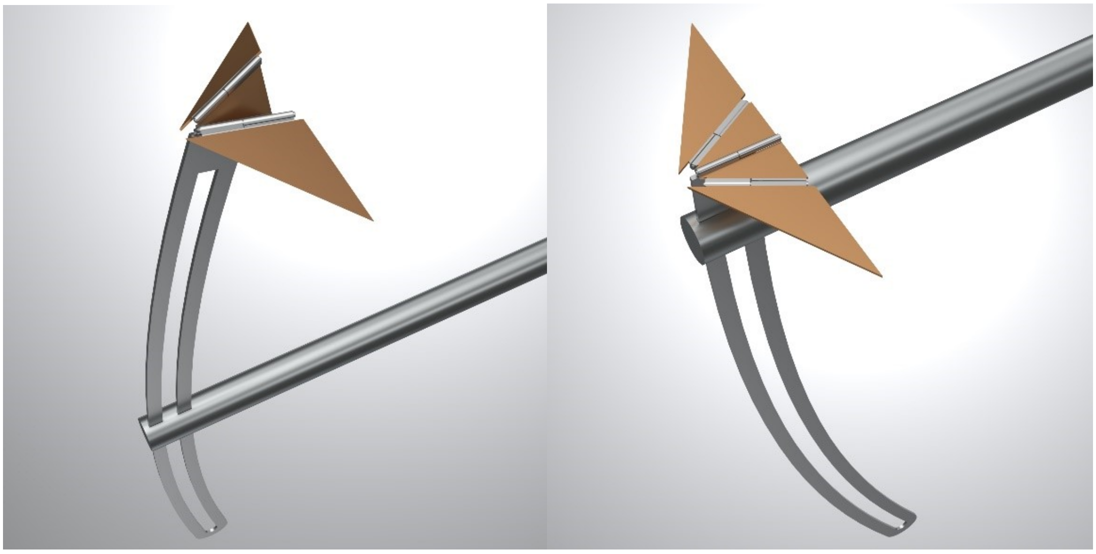


Fig. 7.11. View of point C without panel and film

Point C, as a "driven point", moves followed the movement of the "active point", and its trajectory can be regarded as an arc-shaped motion trajectory moving in the z-axis direction, so we present the point with a track to ensure its stability movement in a specific direction. And since the point is a "driven point", a device to prevent the device from moving in the reverse direction should be set inside the track. A gear device with damping is installed at the connection between the fixed rod and the slide, and the gear will rotate with the member when it moves in one direction, and if a sudden force in the reverse direction is generated, the gear will prevent the device from moving in the reverse direction.

On the other hand, point C takes also bridging the two fixed-layout corner points, because the trajectory is in an arc upwards, so we need this four-blade hinge to meet the needs of that motion trajectory, and the device folds to a minimum area when the adaptive façade tends to open while it expands to a maximum area when the façade tends to close. The outermost triangle-shaped hinges are welded to a rigid material to ensure structural stability.

7.2.4 AD edge rigid panel material connection:

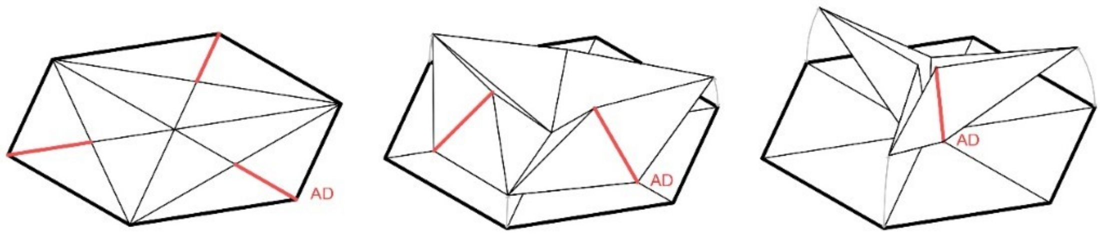


Fig. 7.12. Movement of edge AD in space

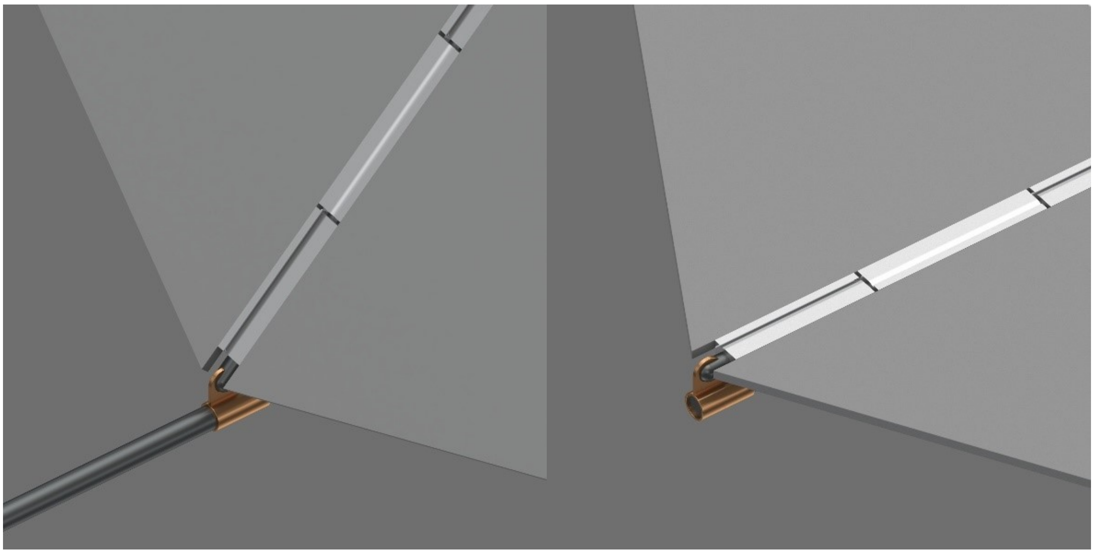


Fig. 7.13. Construction details of ***edge AD***

Due to the relationship between the hard panels in the process of moving, the AD edge is always rotated vertically around the moving point, so we only need to set such a hinge between the two panels, which can meet the panel's moving trajectory and leave enough space for moving.

Fig. 7.14. Commercial solutions for folding systems

7.2.5 The connection of CD edge rigid panel material and light laminated membrane material:

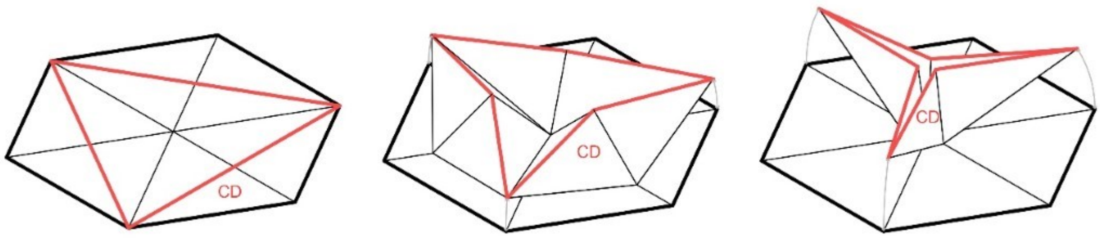


Fig. 7.15. Movement of edge CD in space

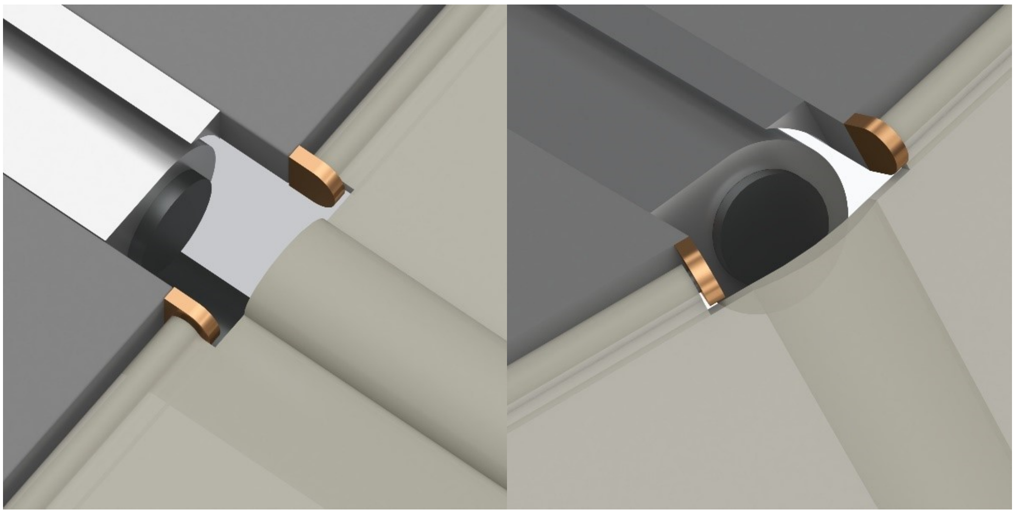


Fig. 7.16. Construction details of edge CD.

The shaft of this connection is the swivel, so only a swivel rod needs to be added to the edge of the rigid panel material, and the connection method is nested.

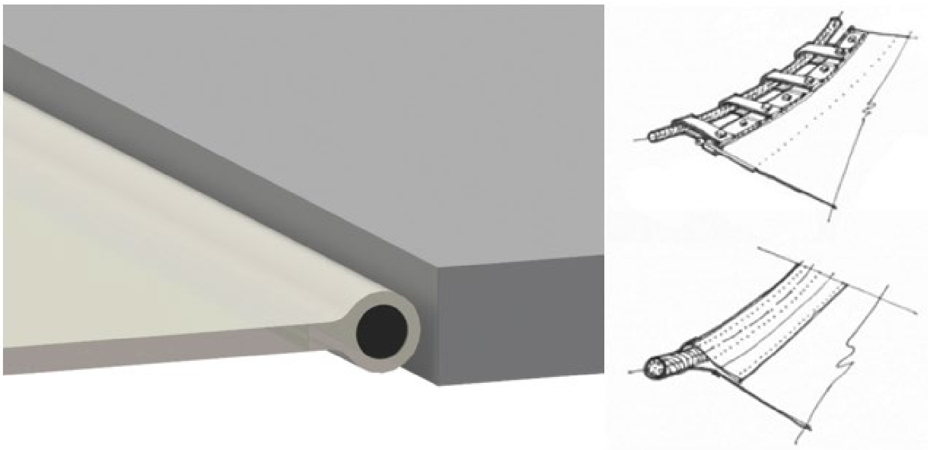


Fig.7.17. Schematic diagram of connection CD. Image on the right credits to https://www.pinterest.com/pin/136093219980139734/

7.2.6 Connection between BC & BD light laminated membrane material:

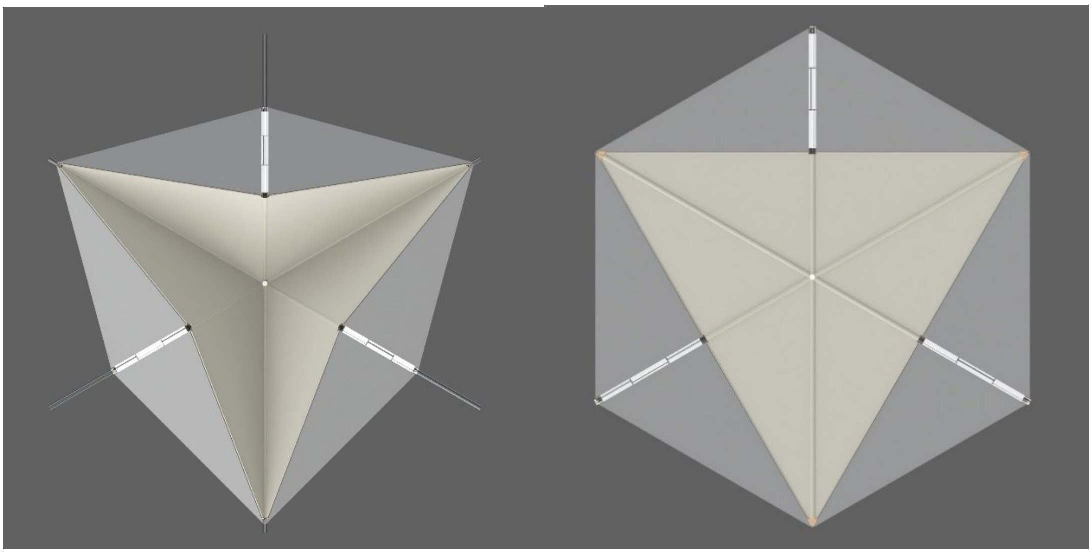


Fig. 7.18. Model view of the facade

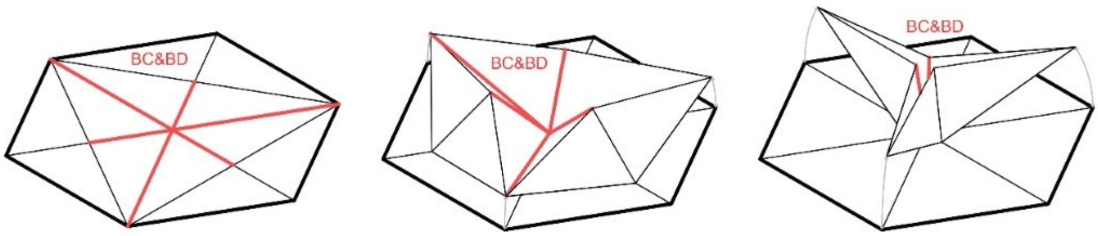


Fig. 7.19. Movement of the edge BC&BD in space

In the previous chapter, we introduced the bionic technology of laminated membrane materials, which imitates the microstructure of insect wings to achieve the effect of prefabricated folds, requiring only a small external force to deform the structure.

The possible optimizations of this structure are as follows:

1. Reduce the plastic deformation of the membrane structure itself due to folding, and extend the service life.

2. As an auxiliary force for driving the folding, it assists the overall facade to achieve the effect of movement.

Therefore, we choose to preset an inflatable device as our "elastin" in the crease between the laminated film materials to achieve the above optimization effect. When the gas fills the fold position, the cavity expansion will lead to thrust towards outward, which will assist the adaptive façade to achieve the effect of opening movement. On the contrary, when the adaptive façade needs to be closed, a blower is needed to pump out the gas, the fold will be bent due to the gas evacuation, and the device will be closed with the pushing of the active moving device on the A'B' slide bar.

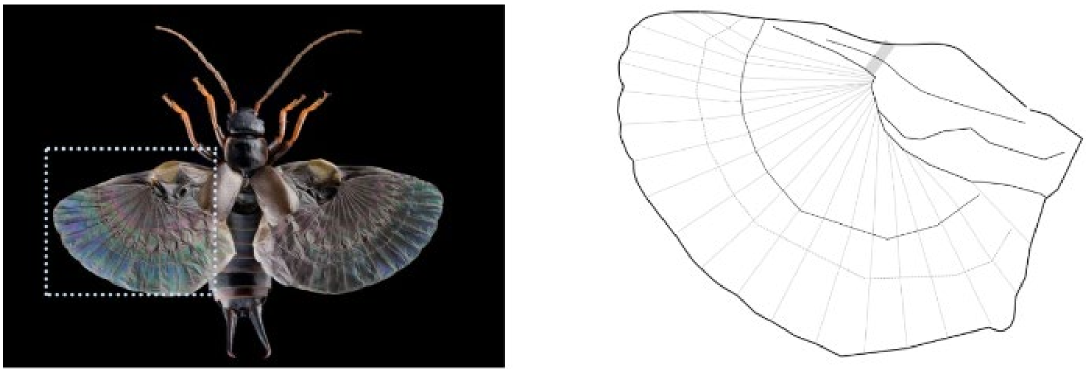


Fig.7.20.Wings of earwigs

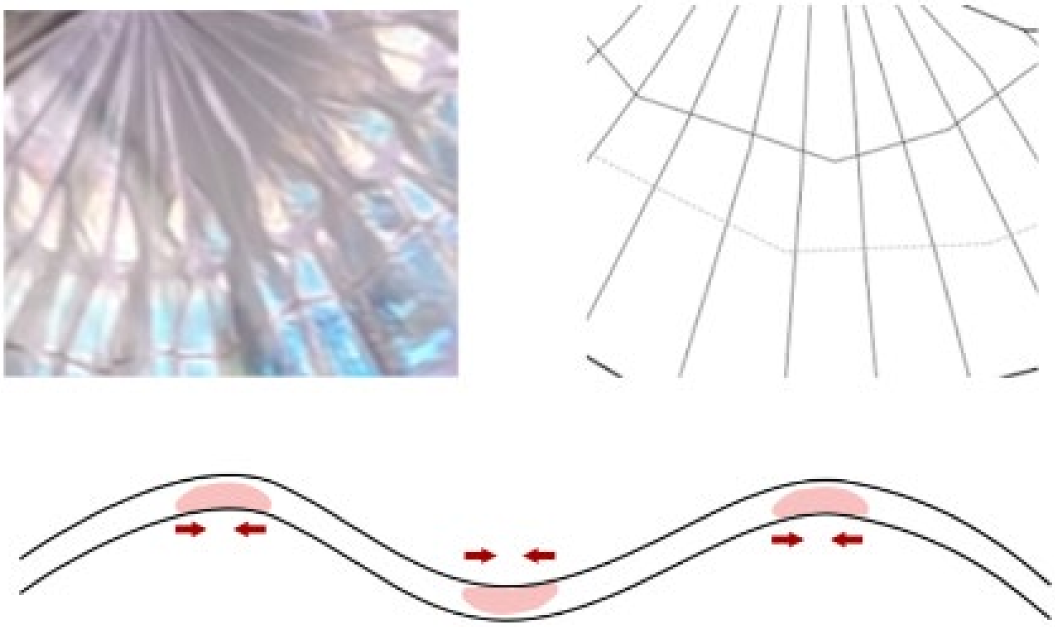


Fig. 7.21. The structure of the Wing Vein

According to our description in Chapter 4, a lightweight drive structure powered by airbags is proposed by us：

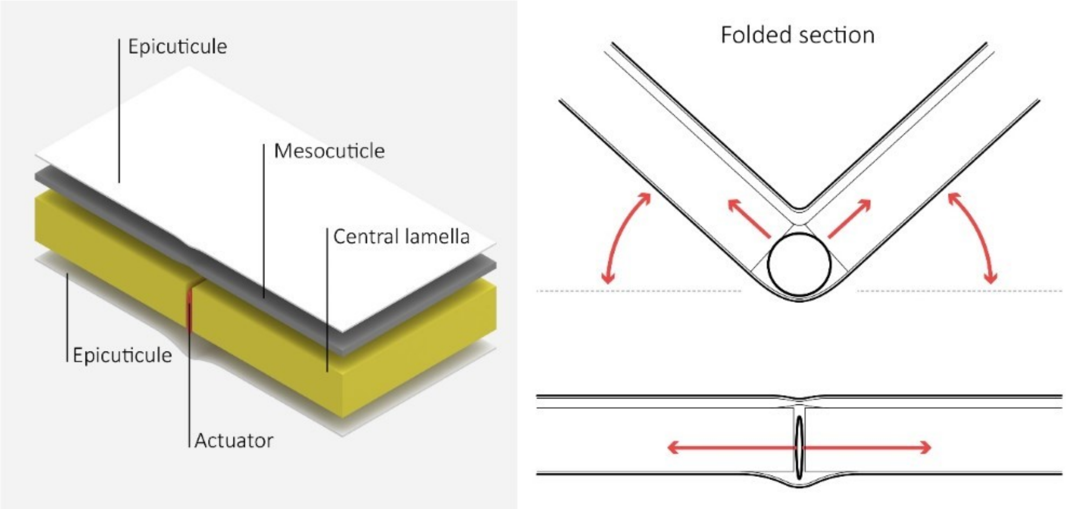


Fig. 7.22. The contraction of the airbag assists the folding of the membrane structure.

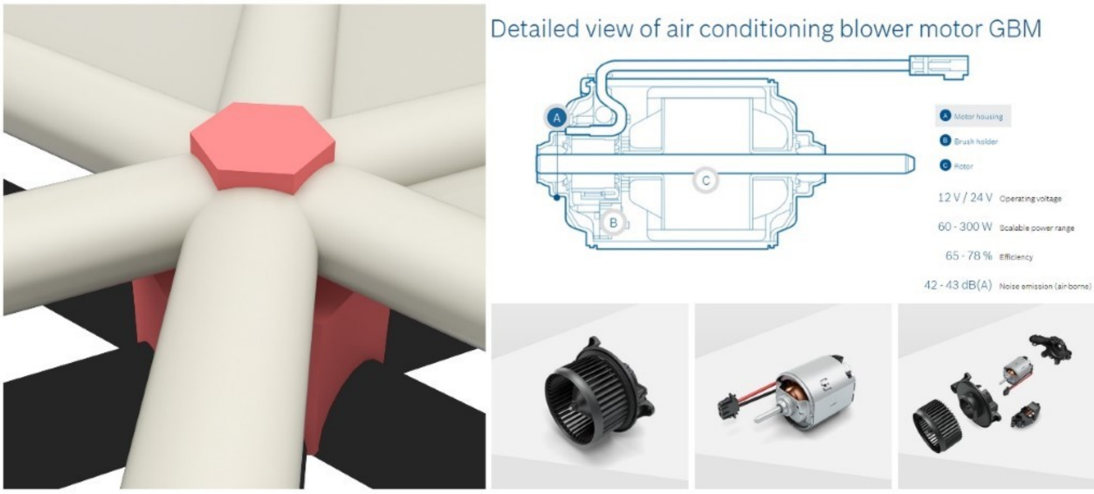


Fig. 7.23. Left, connection of airbag and blower, right, schematics credits to bosch product https://www.bosch-mobility-solutions.com/en/products-and-services/passenger-cars-and-light-commercial-vehicles/powertrain-systems/thermal-management-for-combustion-engines/global-blower-motor-gbm/

As shown in the figure 7.23 the red part is where the blower is placed, it is fixed on top of the steel structure at the back of the light laminated membrane materials, while six directional airbags are installed to control the blowing in and out of the gas.

To verify that our design can be implemented, we conducted simulation experiments with the real model. The principle of an Airbag is simple: the deformation of the airbag during expansion and shrink brings lateral thrust to the adjacent plates, thus assisting the unfolding and folding of the whole structure. If the airbag is placed in an upward position, the slight deformation of the airbag will cause the cross-section to lift significantly; on the contrary, if the airbag is located in a downward position, its deformation will cause little change to the structure. At the same time, it should be noted that in the outermost layer on both sides of the section, we need to leave enough space to meet its folding needs, because the thickness will cause the upper and lower boundaries to move at unequal lengths, for which we only need to measure the length of each boundary in the limit state and take the maximum value, to leave enough space.

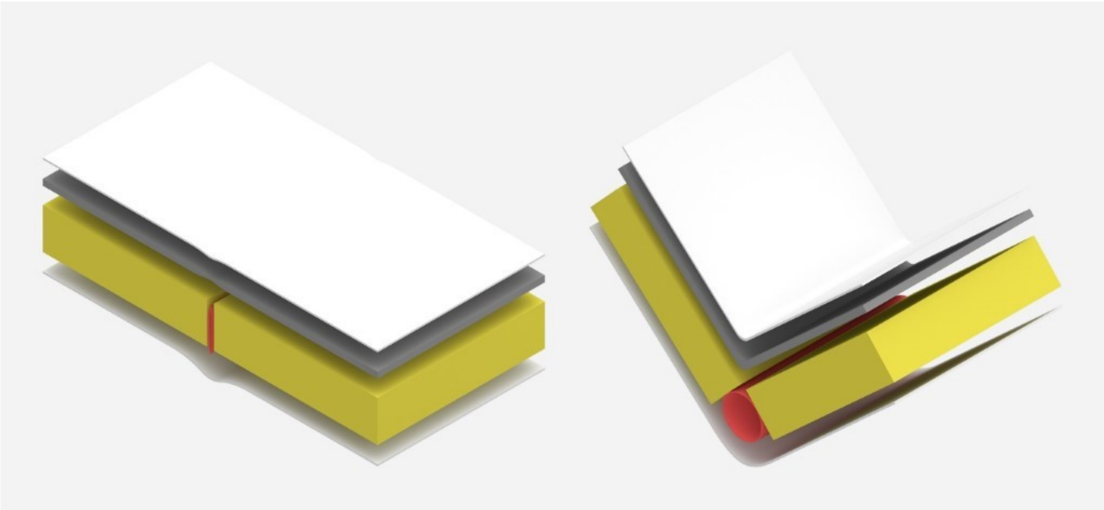


Fig. 7.24 Rhino model of the airbag structure 5:1

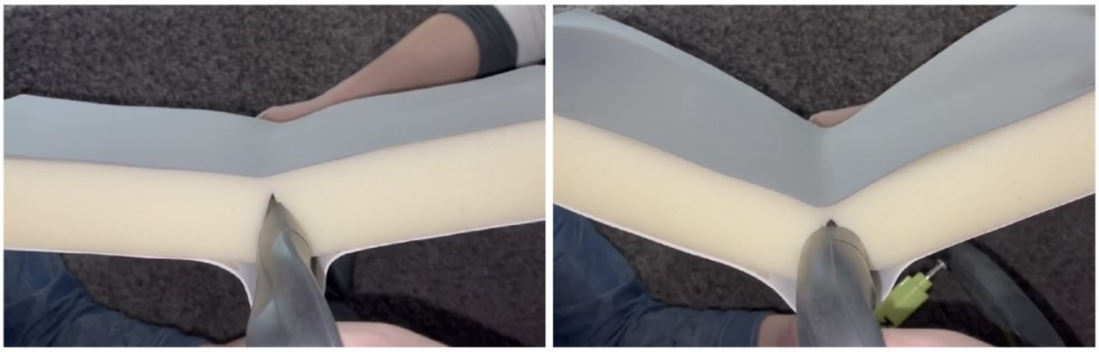


Fig. 7.25. Model of the airbag structure 5:1

We found some simple materials on the market to simulate the change of the airbag, its thickness and the size of the airbag are magnified, when we fix the material and inflate the airbag can clearly see the structure of the fold.

7.3 Materials

The selection of materials is described in three parts: the hard shell part, the laminated film part, and the elastic structure part connecting the two.

Opaque Shell

Our requirements for hard shells are light weight, considerable hardness, compressive and tensile strength, and small thermal expansion ratio. These conditions can ensure that the shell is strong enough to protect the membrane structure and work normally when subjected to mechanical conduction forces. .

In addition, we have an additional requirement for the shell. This requirement is caused by the slight geometric deformation of the shell structure during the deformation process.

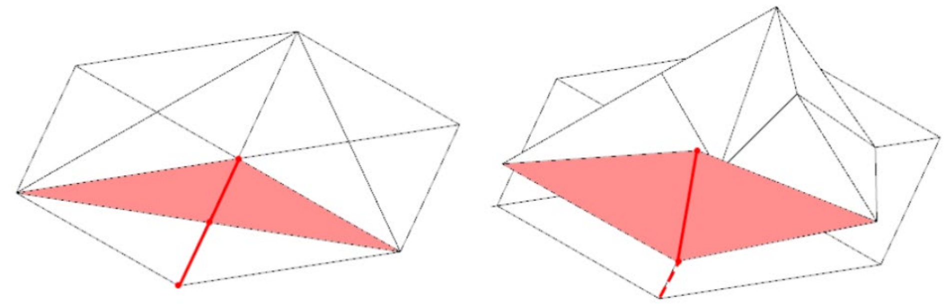


Fig. 7.26. Movement of one panel

Here shows how will the panel move during the deformation process. And during this process, the length of the side is not fixed to a certain length, it has around 0-10% of shorten.

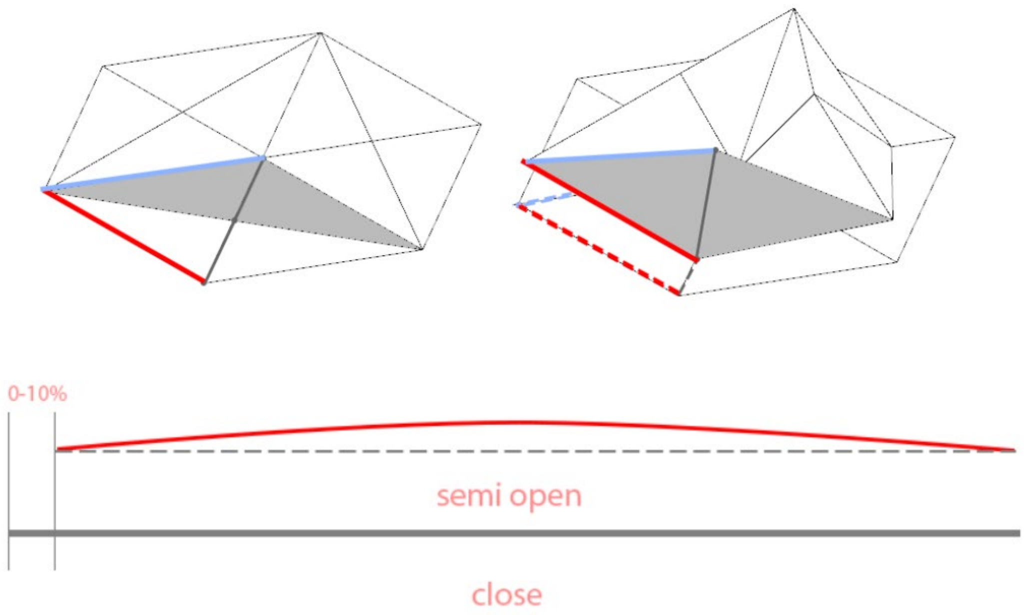


Fig. 7.27. Bending of the panel

If we convert this distance to the arc of shell deformation, then this angle will be between 0-22 degrees, which means that our shell needs to be able to withstand 22 degrees of bending.

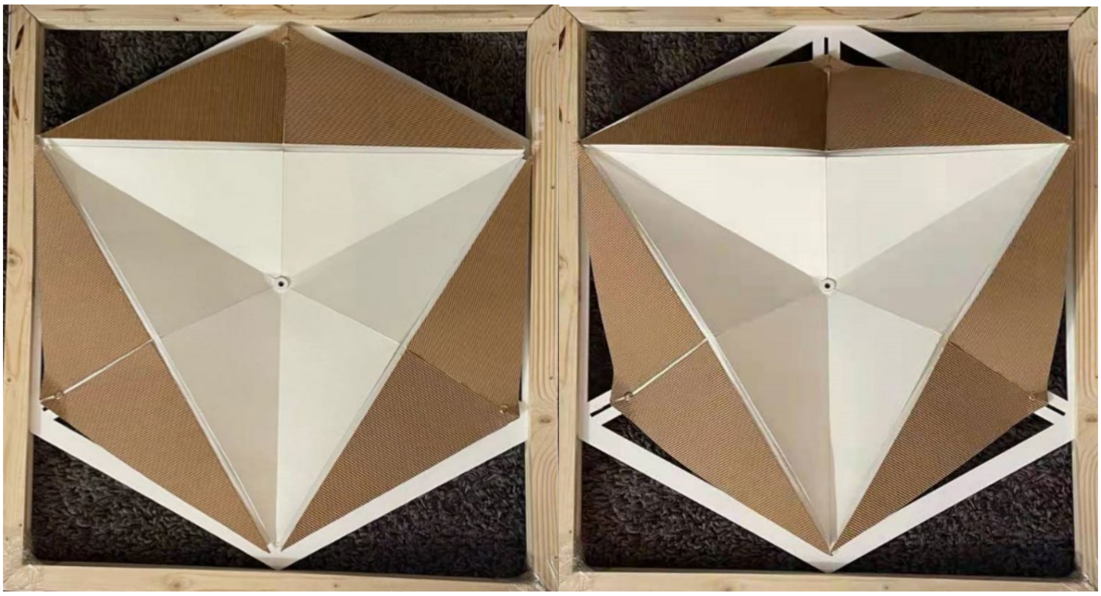


*Fig.7.28. M*odel view, This can be seen more clearly in the model photos. During the unfolding process, the shell part will bend to a certain degree.

Therefore, the shell needs a certain degree of elasticity to meet the small deformation during the unfolding and storage process. Based on this consideration, we chose CFRP (Carbon fiber reinforced polymer) as the material. This material has considerable tensile and compressive capabilities, has a lower coefficient of thermal expansion than aluminum, and can still maintain a lighter density and a certain degree of elasticity under the condition of higher hardness.

We choose 5.2mm thick CFRP sheet as the material of the shell.

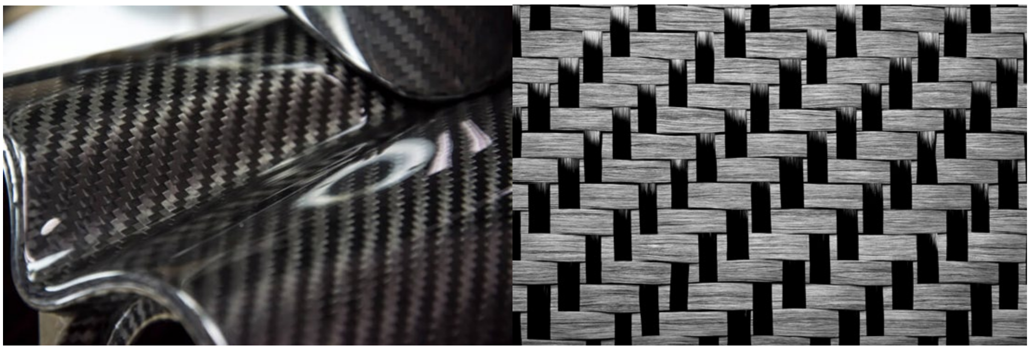


*Fig. 7.29. CFRP mate*rial for the shell

The elastic structure between Shell and Film

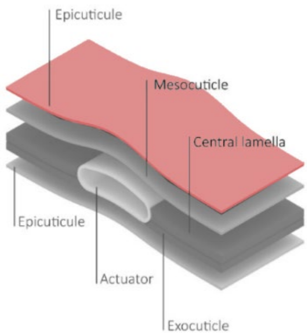
For this part, CFRP material is still a better choice. Because this part has higher requirements for elasticity than the shell part, the strength requirements are lower, and thinner CFRP can be selected. 1 or 2mm material may be a more suitable material choice.

Laminated Film

In the laminated film structure, we have different material requirements for each layer, but there is a basic selection requirement: light weight and cheap.

Epicuticle: polyester fabric with PVC coating: (640g/m2)

For the outermost membrane material, we choose a membrane material composed of high strength polyester fabric and UV-stabilized soft PVC coating to resist external erosion and damage, while also having certain waterproof and self-cleaning properties.



High-strength, lacquered polyester fabric with increased UV-stabilized soft-PVC coating on both sides and fungicidal protection. Flame-retardant according to EN13501-1.

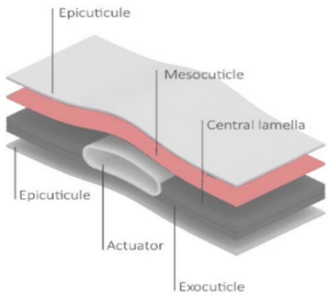
Weight:	640 g/m²
Width:	250 - 300 cm
length:	65 - 300 m
Max. tensile strength:	2600/2500 N/5cm
Tear strength:	250/250 N
Application:	Halls & Tents
Surface:	high gloss, lacquered
Properties:	flame-retardant, fungicide finish

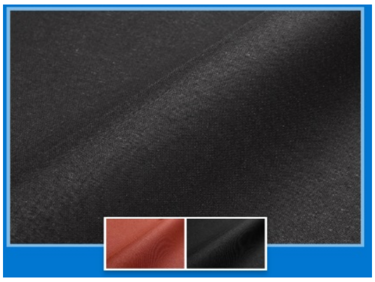
Flame retardant membrane for small halls and tents. Due to a special ingredient in the coating, the textile is protected against mold and algas. Applications: halls and tents.

Fig. 7.30. PVC coating for the Epicuticle

Mesocuticle: lighter polyester fabric (200g/m2)

For the structure of the inner layer, we choose a lighter similar membrane material, the weight of the material is about 200g/m2.





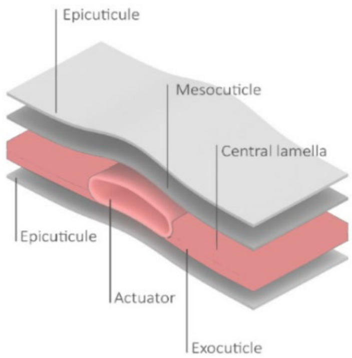
AIRTEX® CLASSIC | airtex® classic

AIRTEX® classic is perfect for solar protection applications. This 200 g/m² light fabric is a 100% polyester fabric, which is coated with acrylate on one side and impregnated. The special coating gives AIRTEX® classic a distinctively textile character. AIRTEX® classic has outstanding properties in comparison with dyed materials made of polyester fabric or cotton. Its lightness and ease of handling make AIRTEX® classic an impressive sunshade fabric. With a total weight of just 200 g/m², this material achieves a very good sunshade effect in accordance with UV Standard 801.

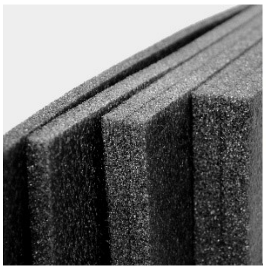
Material properties	Value	Unit	Measuring Methods/Norm
Total weight	200	g/m²	EN ISO 2286-2
Tensile strength warp/weft	2200 / 1000	N/50 mm	EN ISO 1421/V1
Tear strength warp/weft	280 / 80	N	DIN 53363
Cold resistance	-40	°C	EN 1876-1
High Temperature	+70	°C	PA 07.04 (intern)
Sun protection factor	80		UV standard 801

Fig. 7.31. lighter polyester fabric for the Mesocuticle

Central lamella：Glass wool/Foam (50g/m2)



For the internal structure adjacent to the airbag, due to the function of supporting the airbag and transmitting the force, this material needs to have a certain strength and also a certain elasticity to protect the membrane structure and the airbag from the process of folding and deformation. At the same time, based on the requirements of lightweight materials, porous materials have become a good choice. We choose glass wool as the material, which can not only meet the required structural requirements, but also provide sound absorption and heat preservation performance.



properties	udm	reference standard	values
Water vapor permeability	μ	EN 12086	1,1
Class of reaction to fire	/	EN 13501	A1
Termal conductivity	W/m*K	EN 12667	0,040
Operating conductivity	°C	/	-50/+250
Specific weight	Kg/m³	/	18 minimum

Fig. 7.32. Glass wool/Foam for the Central lamella.

7.4 Frame connection

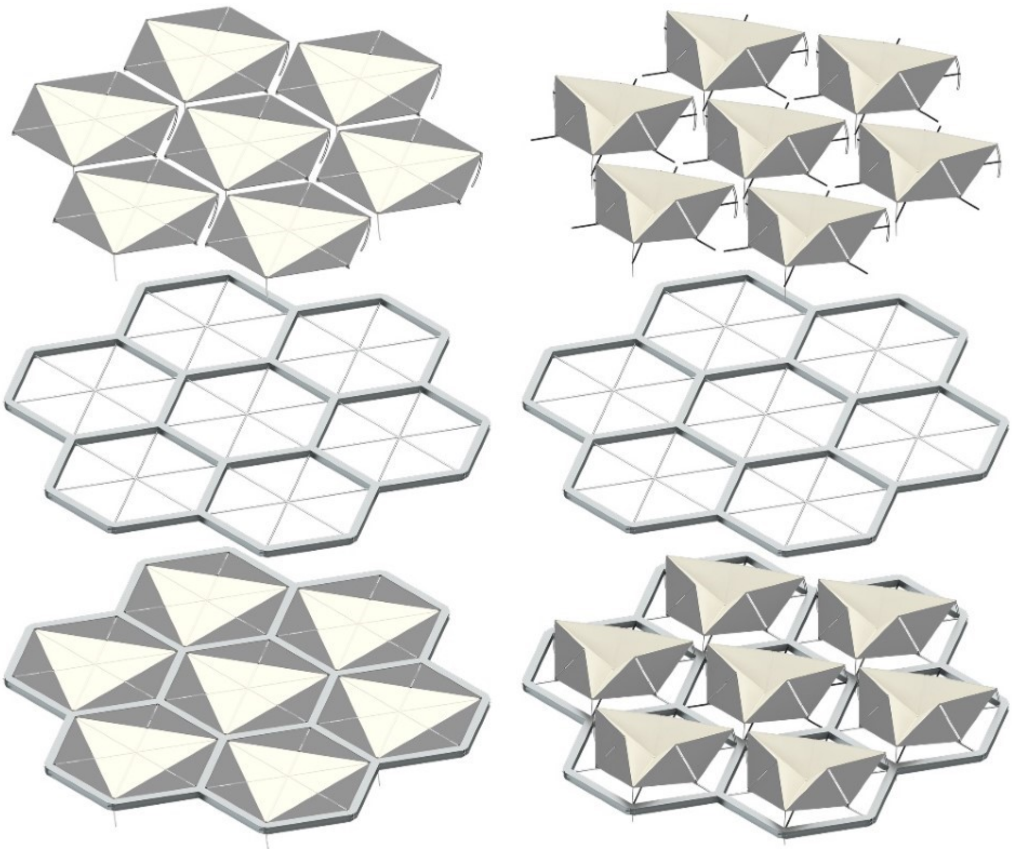


Fig. 7.33. Frame connection of the facade

After the introduction of each mechanical component and sensor in the unit, we need to introduce the connection between the unit and the steel structure which takes responsibility for joining all the units together. We choose to use the HE-A Steel beam as the basic frame, the geometry is hexagonal splicing, so each corner point needs to be connected to three HEA-beams, the angle is 120 degrees. Also, this structural frame needs to be connected to the support structure from the backside of each unit, so we need to weld on the location of the corner points to be able to connect the cylindrical steel, the specific shapes are shown in the figure 7.34 below:

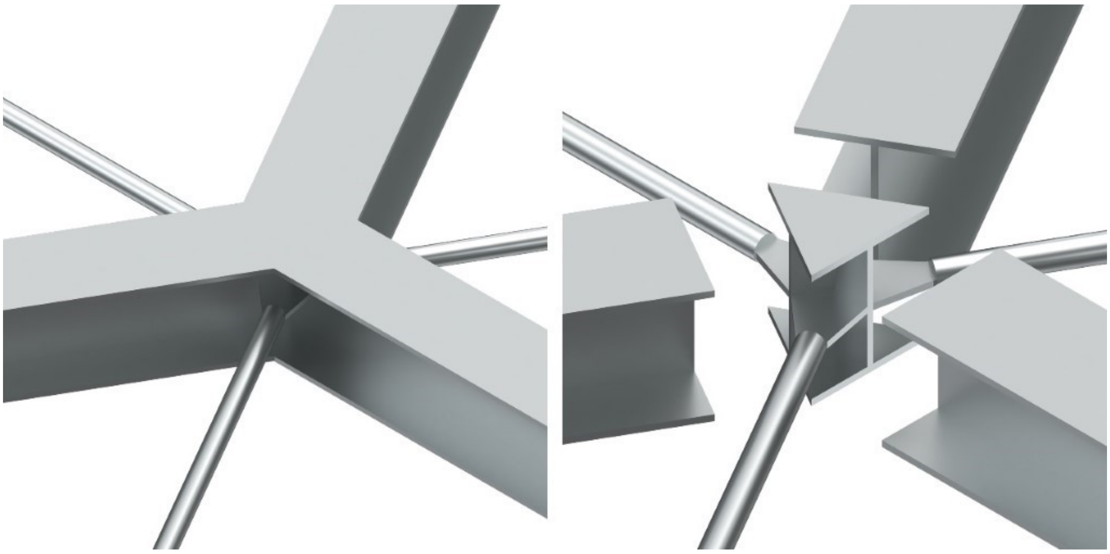
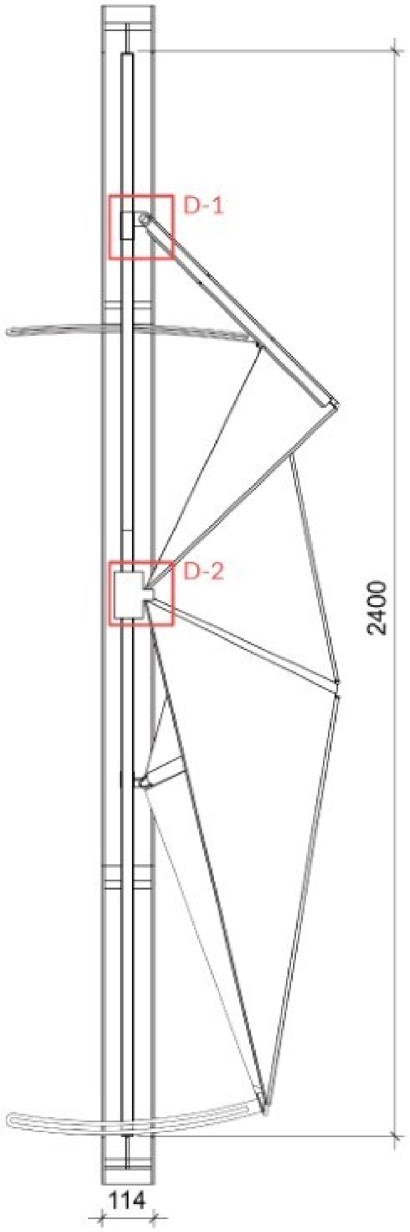
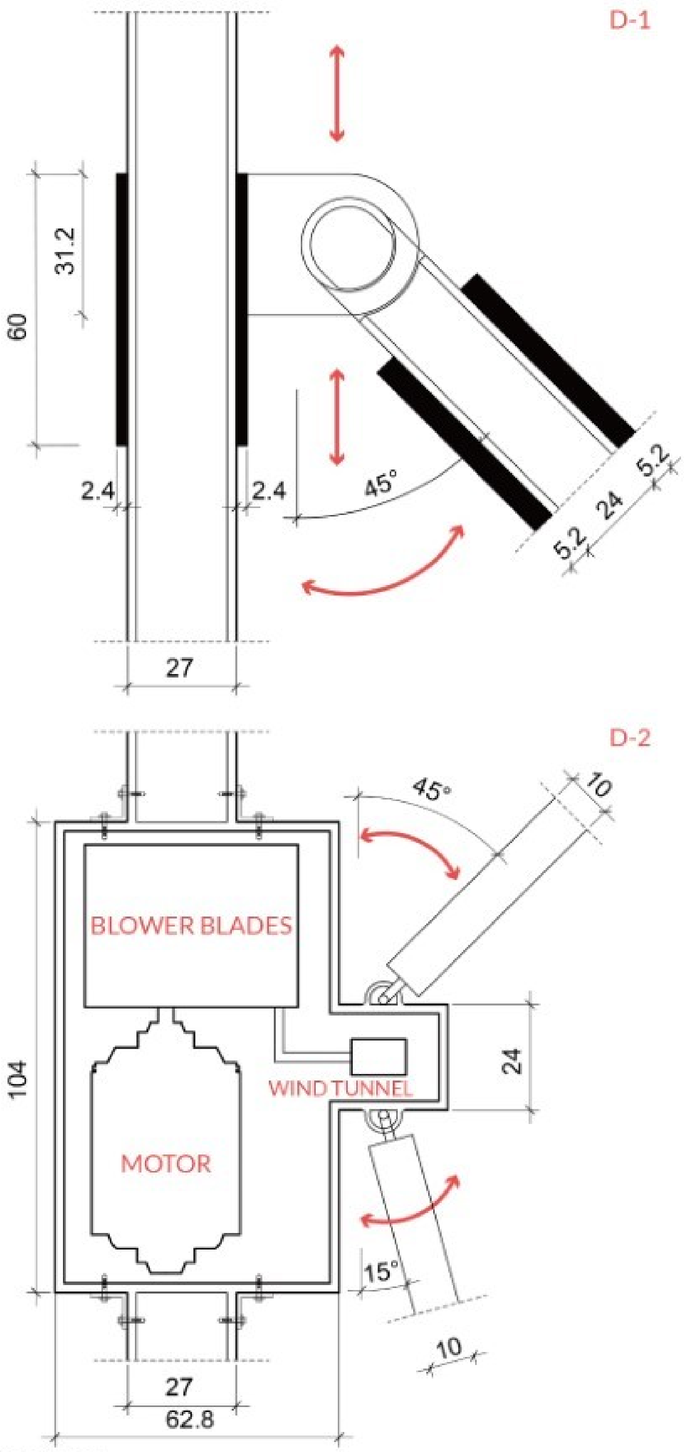
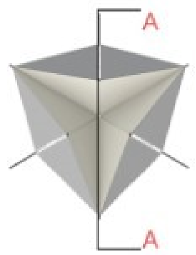


Fig. 7.34, Schematic diagram of frame connection, see the next subsection for specific dimensions.

7.5 Details



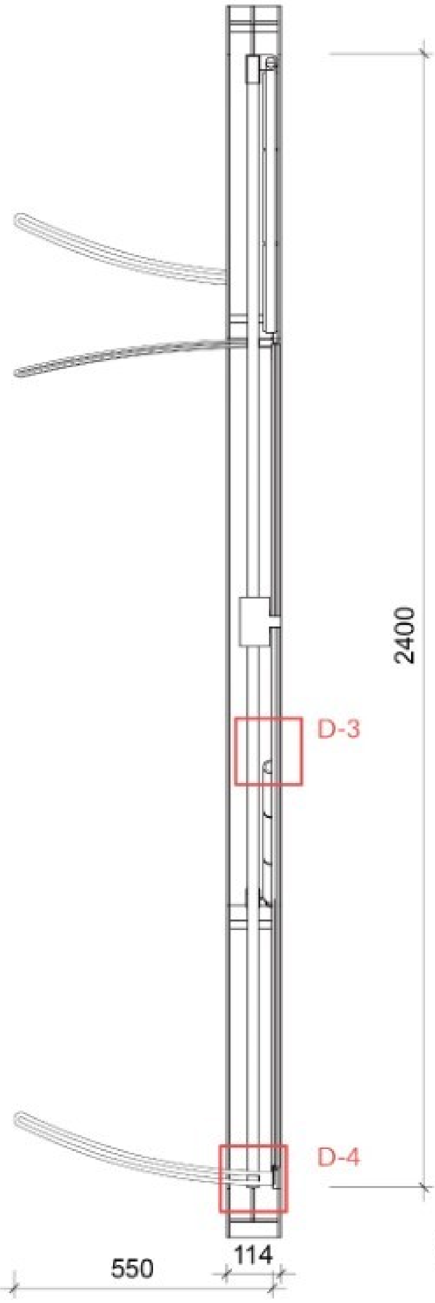


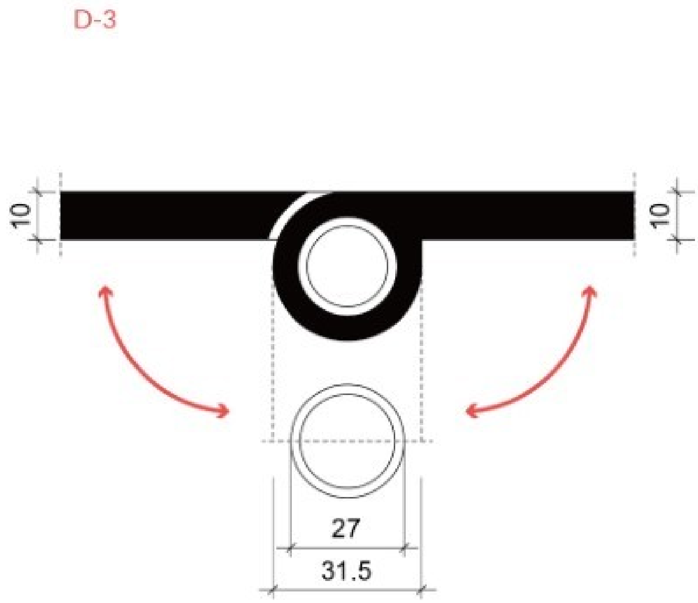


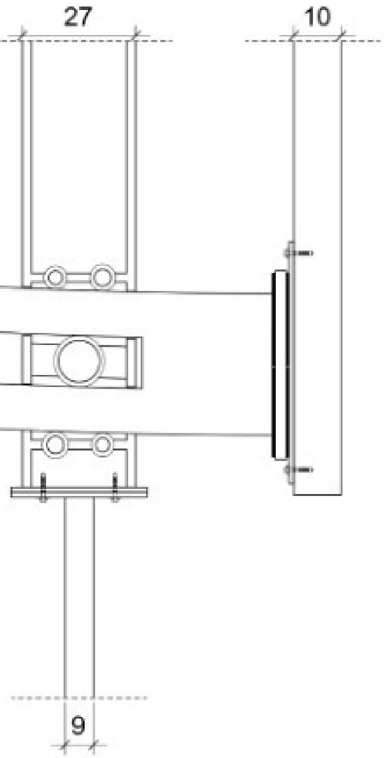
CIRCULAR STRUCTURAL

M - weight A - area cross section Au - external surface area I - moment of inertia
W - section modulusn Wp - plastic section modulus i - radius of gyration Iv - torsion modulus
Wv - section modulus in torsion Theoretical density = 7,85 kg/dm3

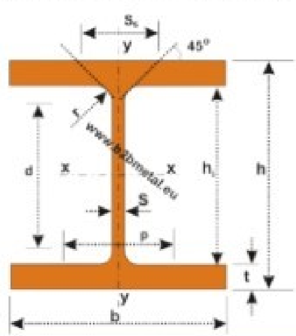
D	t	M	A	Au	I	W	Wp	i	Iv	Wv
mm	mm	kg/m	cm2	m2/m	cm4	cm3	cm3	cm	cm4	cm3
26,9	2,0	1,23	1,56	0,09	1,22	0,91	1,24	0,88	2,44	1,81







HEA 120 STRUCTURAL



Identification	Nominal weight 1m	Nominal dimensions					Cross-section	Dimensions for detailing					Surface	
HEA		b	h	s	t	r	A	h1	d	Ø	emin	emax	AL	AG
	kg/m			mm			cm2	mm	mm		mm		m2/m	m2/m
HEA 120	19,9	120	114	5	8	12	25,3	98	74	M 12	58	68	0,677	34,06

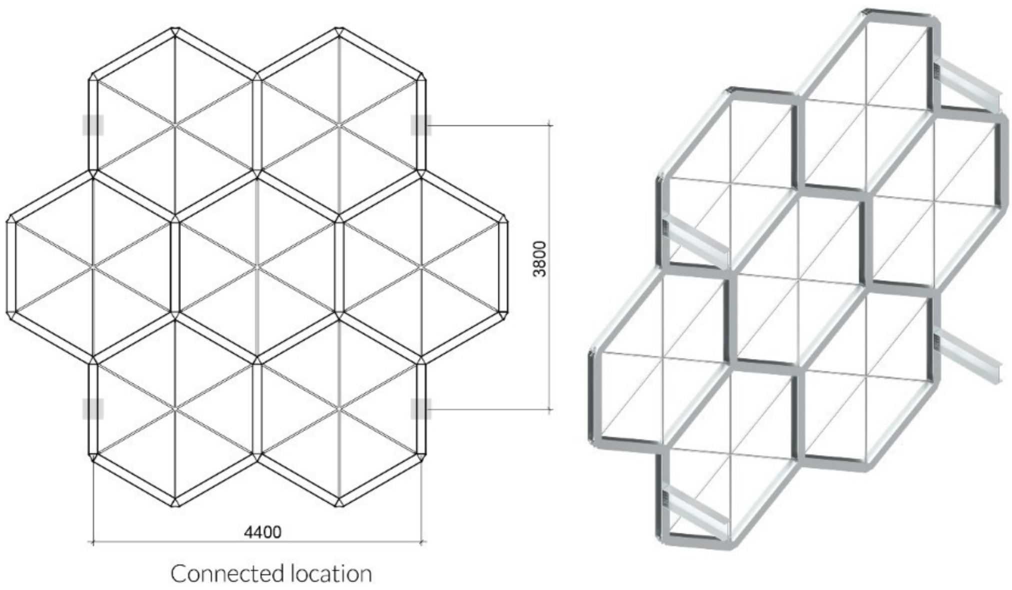


Fig.7.35*, Connection method of main building and façade frame, double angle cleat.*

Identification	Nominal weight 1m	Nominal dimensions					Cross-section	Dimensions for detailing					Surface	
	kg/m	mm					A	h1	d	Ø	pmin	pmax	AL	AG
		b	h	t1	t2	R1	cm2	mm	mm		mm	mm	m2/m	m2/m
IPE 240	30,7	120	240	6,2	9,8	15,0	39,10	220,4	190,4	M12	66	68	0,922	30,02

Fig. 7.36. *Connection method of main building and façade frame.*

7.6 Entity model

7.6.1 General information

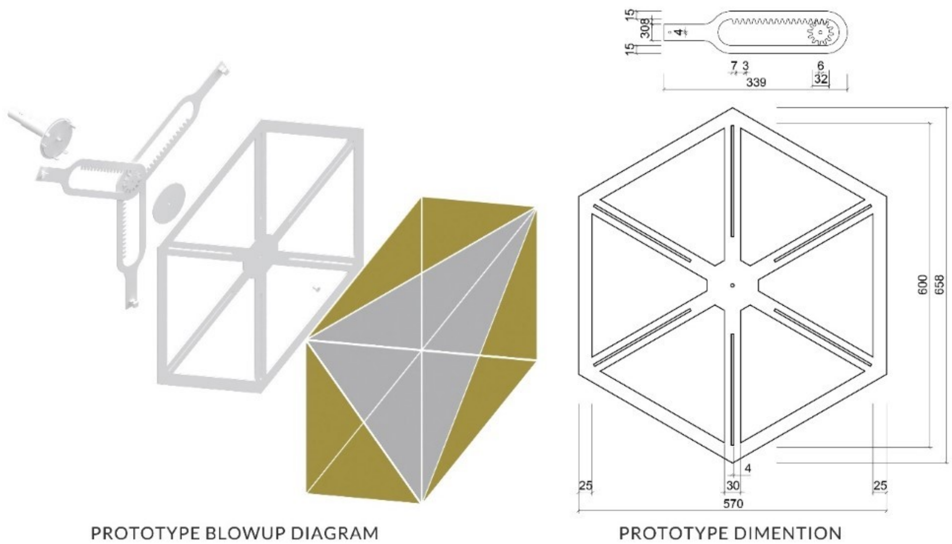


Fig. 7.37. *Prototype in Rhinoceros before laser cut.*

In the production of the solid model, in order to ensure the unity of the movement of the three vertices and to complete the movement at the same time, we designed a gear with three linkages. In the solid model, we obtained and designed the other parameters of the gear through the software according to the length of the motion trajectory and the size of the model (see Figure 7.38), such as the number of teeth Z, modulus m, pressure angle α, etc. of the gear. And through laser cutting to make the actual model, to ensure the normal operation of the gear. It is worth noting that due to the problem of making solid models, the size of the components does not match the scale-up relationship of the actual building. It is only used as a reference for the conception of epidermal movement.

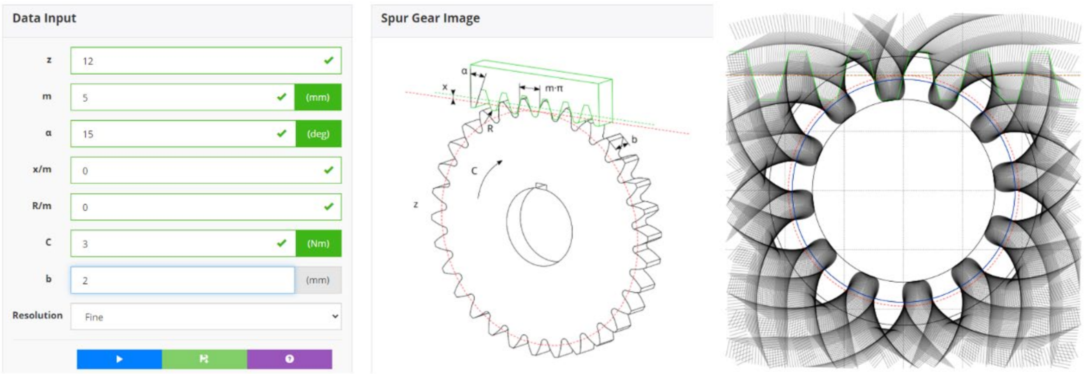


Fig. 7.38. The meshing of standard spur gear and rack. Gear generation credits to plugin: http://www.me-bac.com/index.php?task=gear.

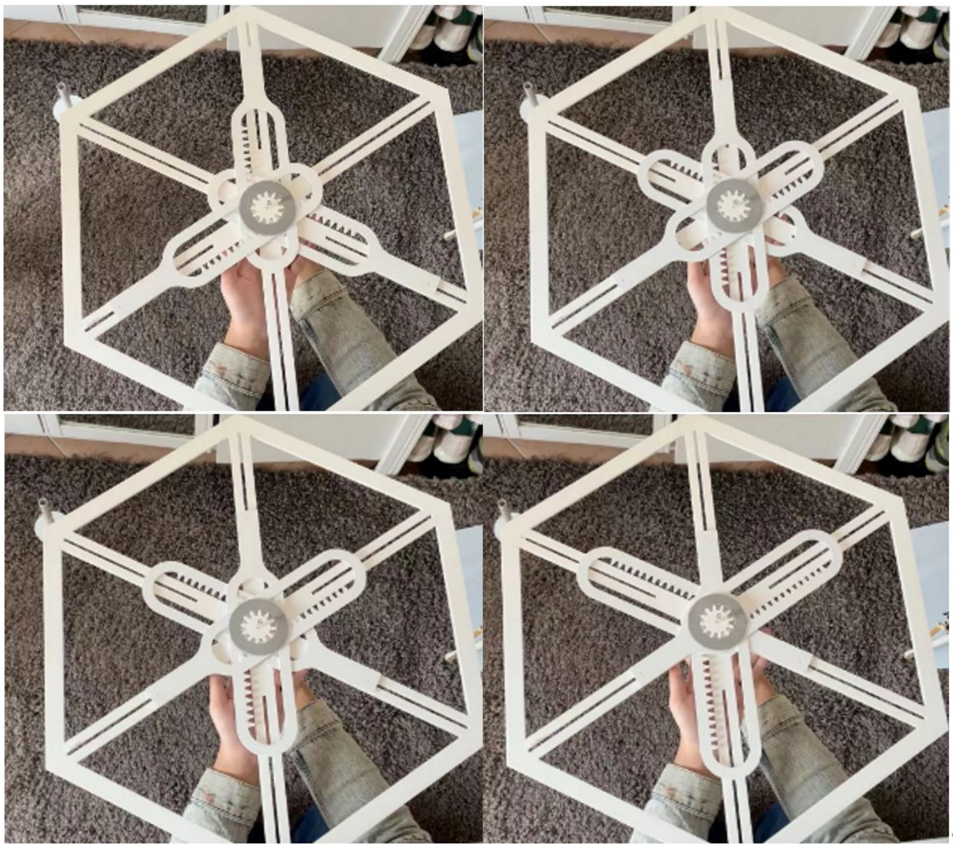


Fig. 7.39. Movement of the gear

It can be seen that when we rotate the main gear through the lever behind the gear, we can drive the three auxiliary gears in the frame to move synchronously, ensuring the synchronous movement of the three levers. In order to be able to see the relationship between the movement of the frame members and the movement of the skin more clearly, we attach a movement photo of the model's back after adding the skin to the figure below.

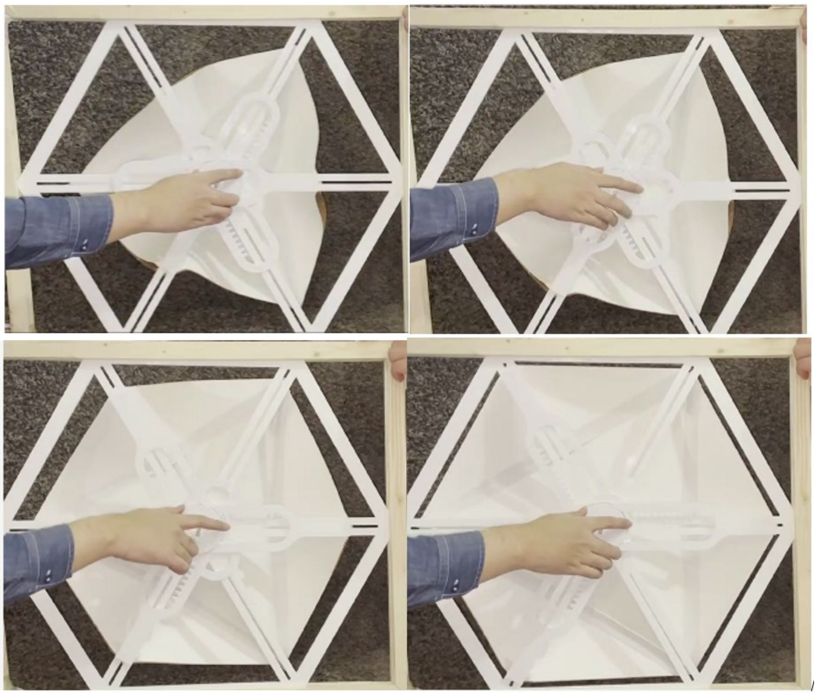


Fig. 7.40 , back view of the model

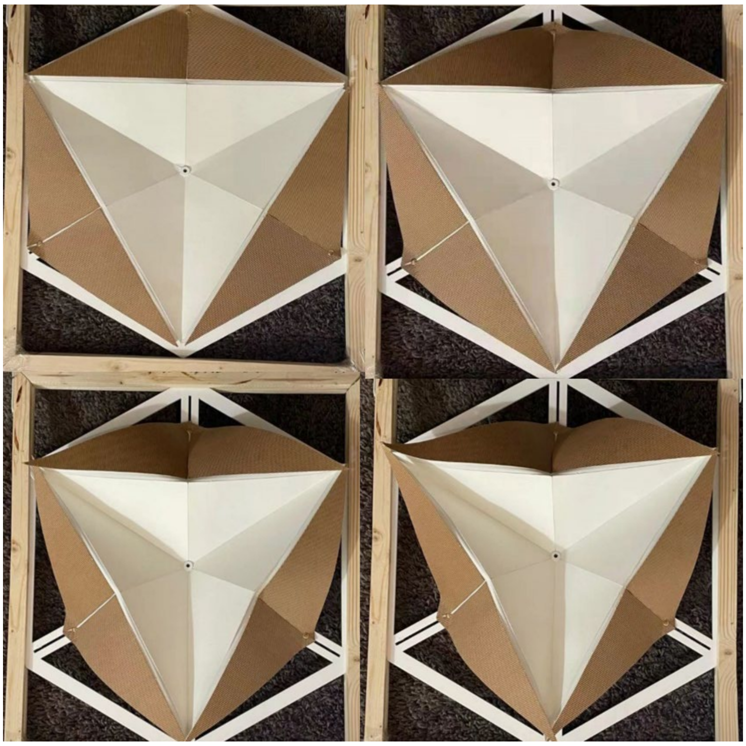


Fig. 7.41. Front view of the model

7.6.2 Properties of the model:

actuating time

For the gear part, with our model, in ideal situations, it will take us 15seconds to complete the folding process from opening to closing. And when it comes to the reality structure, the time will not change very much. And according to the requirement, the value can change in ±10 seconds.

For the airbag, in our model, it takes 20 seconds to finish the Inflated procedure and takes same time to let the air out. And in reality, we need to calculate the ratio of the volume of the air to the power of the air pump.

Weigh (kg/m2)

Density without the frame:

Shell:10.4kg/m2 + film:1.1kg/m2 + joint material: 5kg/m2

= 10.4*0.45+1.1*0.45+5+0.1 = 5.68kg/m2

Density of the frame: 35kg/m2

7.7 Architectural graphs

Fig. 7.42. Perspective from inside. User's view.

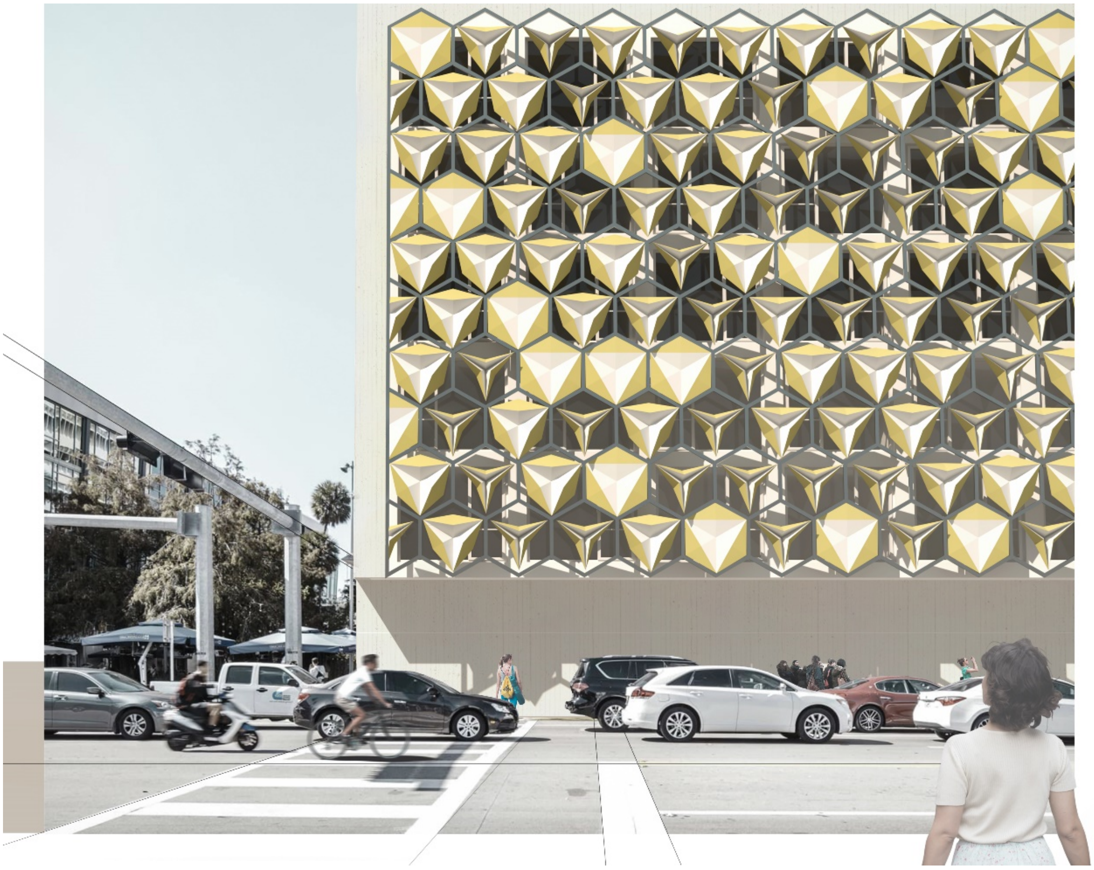


Fig. 7.43. Perspective from outside.

Background texture copyright to RASMUS HJORTSHØJ

CHAPTER 8：CONCLUSIONS

The buildings of the future should not only be high-performance and low-energy buildings, but also have enthusiasm and adaptability. In addition to providing a stimulating climatic environment, the development of adaptive buildings and skins can also learn from other biological ways to cope with the environment. Bionic architecture and skins are directions with high potential, and biological features can completely become the geometry of skin design. , The source of inspiration for structure and material design.

According to international research on adaptive façade and bionic design, we have summarized the design process from biology to inspiration to specific design and the evaluation process of adaptive façade design (in chapters 1-3). In the evaluation process, the parameterized analysis using the rhino plug-in grasshopper was adopted, and the ladybug and honeybee plug-ins were used for dynamic daylighting and energetic analyses to obtain relevant data on the indoor light quality (explained and introduced in Chapter 2 Software and parameters).

According to the bionic design process we summarized, we got inspiration from ladybug's wings, absorbed the advantages of form, material, and structure, and explored the possibility of geometry from the movement and folding mechanism of ladybug and similar insect wings.

After a simple screening of the design results, the three geometric schemes became candidates. They have the same movement principles and materials, but they differ only in geometric shapes.

In the sixth chapter, grasshopper3D is used to simulate and analyze the three scenarios and the room without shading conditions. The data of UDI, DLA, DGP, Heating load, Cooling load and other data are compared and compared. One of the schemes was selected and improved for reference.

In Chapter 7, we ensured the rationality of various structures and materials of the entire facade and the feasibility of movement through the actualization and modeling of the structure.

Our final result is not only a feasible model, but also confirms the feasibility of this whole set of design process and inspection process. This kind of bionic design method and process is universal and can be widely used.

Main remark

This thesis follows the logical chain of theoretical research-methodology-application methodology-practical design product. In this part, we briefly describe the methodology and application methodology.

The first is summarized in the second chapter, our process of bionic design:

1 Look for advantages from four aspects: form, material, structure and function (double skin structure of ladybug elytra, laminated material obtained from wing veins and aerodynamic structure)

2Generate preliminary concepts (double skin, pneumatic structure, laminated film material)

3 Introduce architectural requirements (light, durability, high indoor daylight quality)

4 Improve concept and generate design (research on movement mechanism and design of geometric shape)

5 Parametric analysis

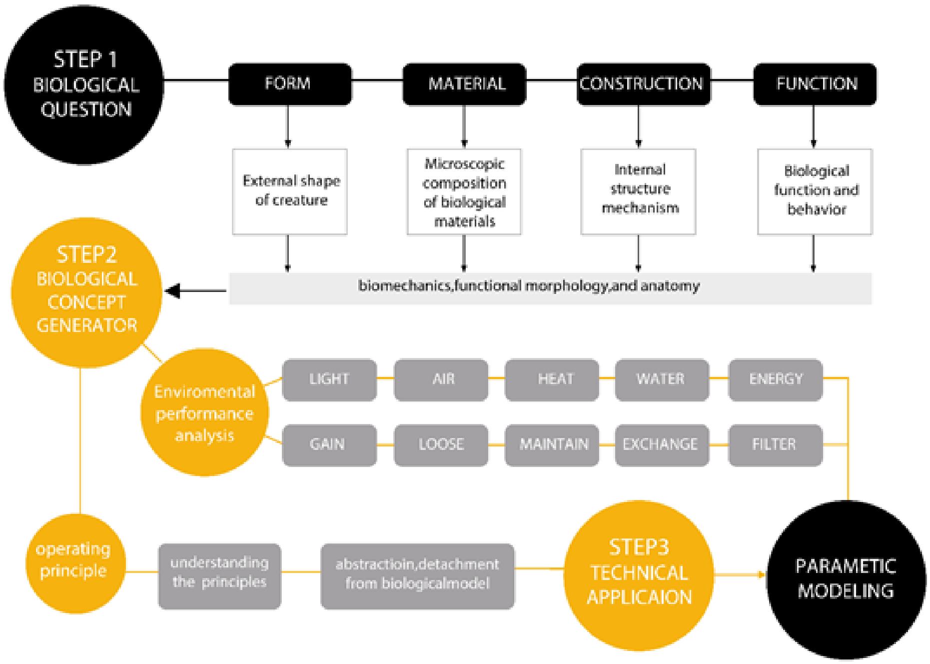


Fig. 8.1, bionic design process

The second is the data establishment, experimental process and comparison conclusions during the inspection process:

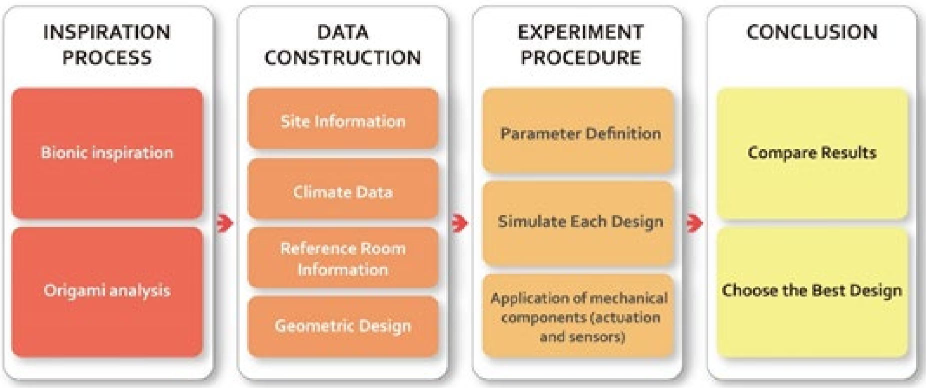


Fig. 8.2, experimental process

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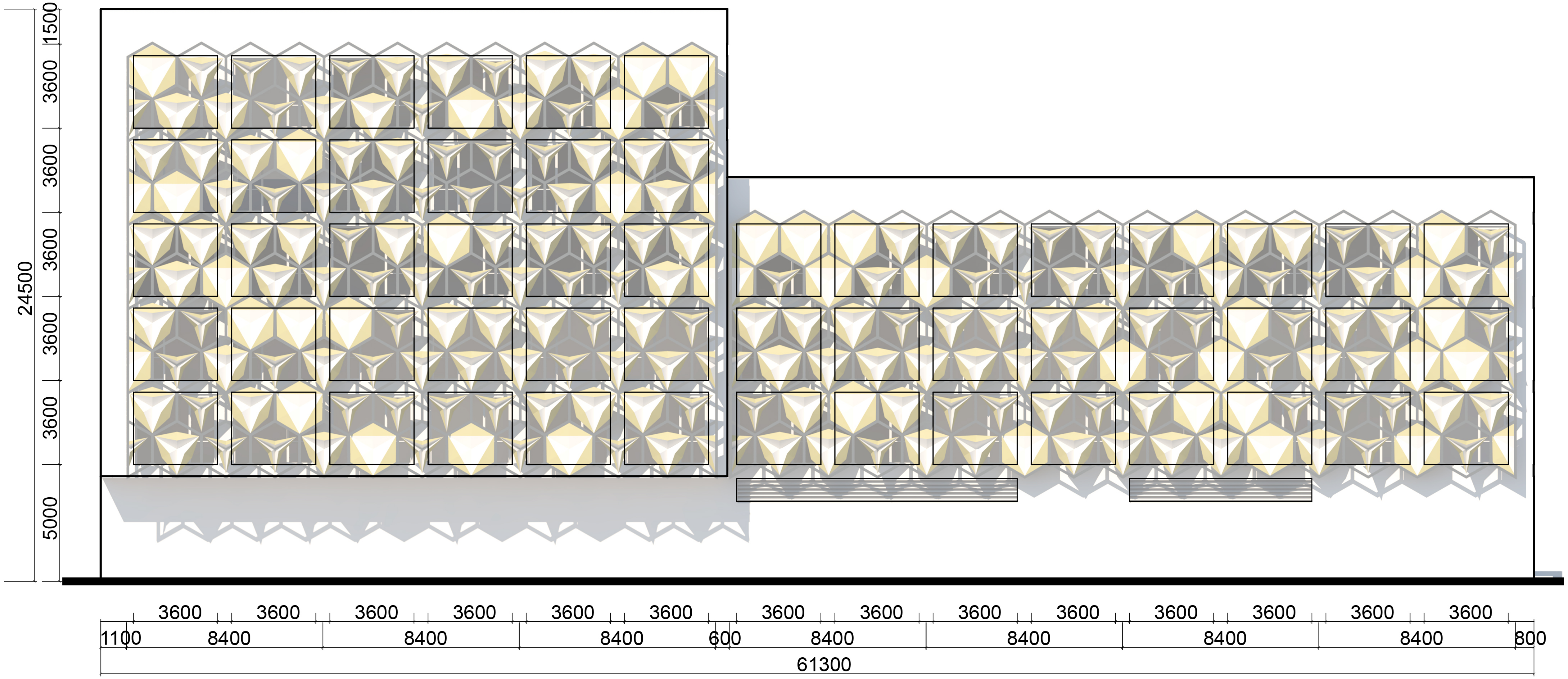
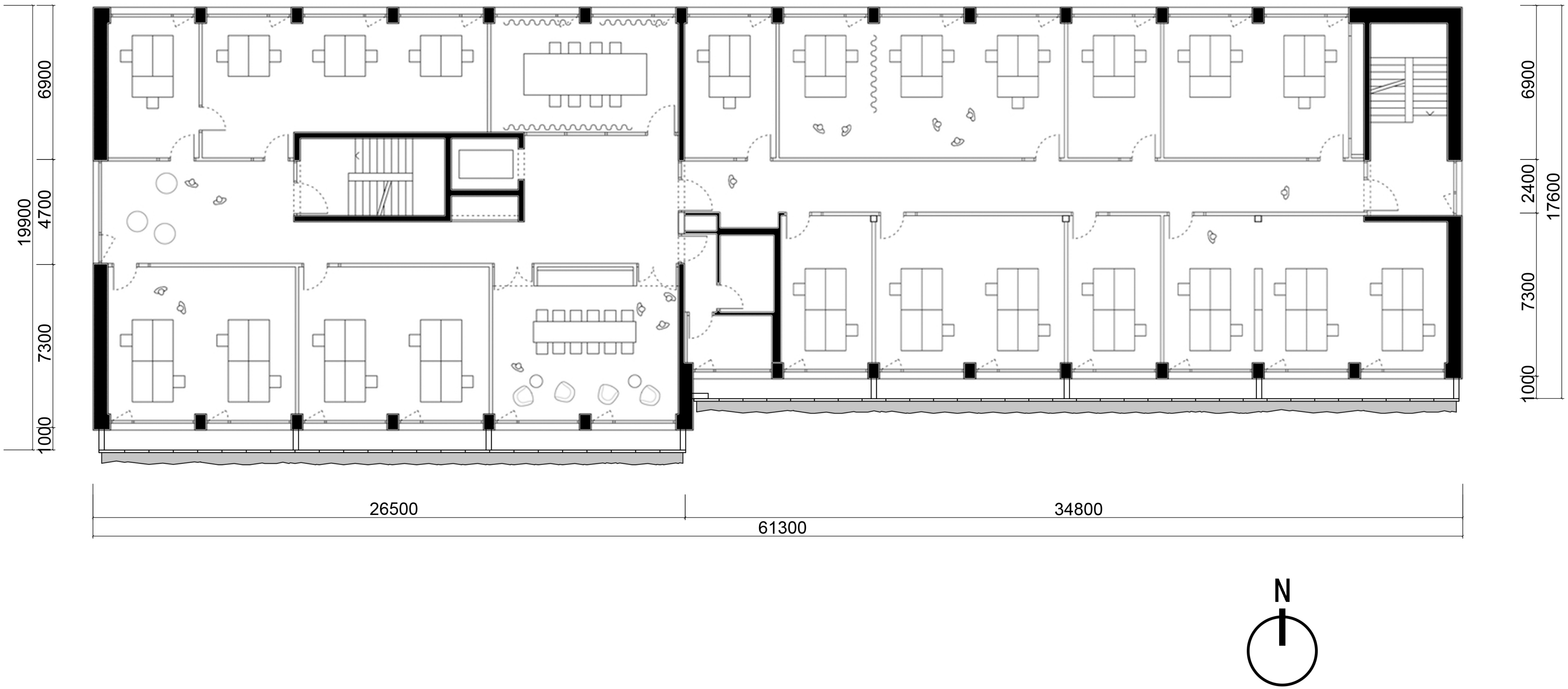
LIST OF FIGURES AND TABLES



South Elevation



Standard Floor Plan